Heat and Mass Transfer Relationships

74g/61802

APPLICATION FOR PHOTOGRAPHIC WORK

Name of Applicant......UNIVERSITY OF NAIROBI......
(BLOCK CAPITALS)

Address or Department......P.O. BOX 30197, NAIROBI, KENYA......

Date......20-8-73......   *When required*......A.S.A.P......

If Scale A	**If Scale B**
Charge to...... *Dept.*	*Charge to*......
Authorized by......*Head of Dept.*	*Sponsored by* ......I.L.L......

DECLARATION (A, B or C to be signed personally by applicants as appropriate)

A. Copyright Act 1956. 1. I hereby request you to make and supply to me a copy of the article/part of the work mentioned on the verso, which I require for the purposes of research or private study. 2. I have not previously been supplied with a copy of the said article/part by any librarian. 3. I undertake that if a copy is supplied to me in compliance with the request made above, I will not use it except for the purposes of research or private study.

Signed......

B. The work to be copied is not copyright. *Signed*......

C. (Where multiple copies are required). **Either** 1. I have received the permission of the owner of the copyright **or** 2. I am the owner of the copyright.

Signed......

University of Newcastle Upon Tyne

January 1971

Heat and Mass Transfer Relationships

NATURE OF WORK *(Slide, print, microfilm, etc.)*		FOR OFFICIAL USE
No. of copies required	SUBJECT *(Specimen, negative or book reference IN FULL)*	7142/6/03
ONE	MICROFILM	
		782
	MENZIES DJ.	

University of Newcastle Upon Tyne

January 1971

Heat and Mass Transfer Relationships in the Drying of Grass

by

D. J. MENZIES B.E. N.U.I.

VOL.1

A thesis submitted for the degree of
Doctor of Philosophy
in the
University of Newcastle Upon Tyne

January 1971

ACKNOWLEDGEMENTS

This work was carried out under the supervision of Professor J. [illegible] O'Callaghan.

We would [illegible] to the National University [illegible] Ireland, [illegible] Petroleum [illegible] for providing [illegible] scholar- [illegible].

[illegible] also due to [illegible] Ivett of the National [illegible], [illegible], for [illegible].

Abstract

Experimental apparatus was constructed and used to determine the drying characteristics of grass. Thin layer samples of Italian and Perennial Ryegrasses were dried by through-flow of air under controlled conditions. Samples of grass were also split into leaves and stems, and these were dried separately. The temperature, humidity and velocity of the air, and the maturity, length of chop and species of grass were varied. A computer programme was written to process the recorded experimental data.

It was found that the form of the drying equation varied with the air temperature. Above 200°C, drying took place entirely within the constant rate period. Below this temperature, the drying rate was proportional to the moisture content. At temperatures below 80°C, up to three such linear periods were observed. The constants in the different equations were correlated with the experimental variables.

The results have been interpreted in the light of the physiology of the grass. The melting of the cuticular waxes is shown to be responsible for the increase in drying rate at high temperatures.

Mathematical models of two types of drier were developed as an aid to design. The models were tested by programming them on a digital computer.

The static deep-bed drier model was validated by simulating laboratory experiments on hay, barley and wheat.

The rotary drier model was validated by simulating a farm grass drier.

TABLE OF CONTENTS

5. CALCULATIONS AND RESULTS CONT.

7. SIMULATION OF A DEEP-BED DRIER CONT.

10. FIGURES

11. TABLES

12. DERIVATIONS, SAMPLE CALCULATIONS

13. COMPUTER PROGRAMMES.

LIST OF SYMBOLS

A	Cross-sectional Area of Bed
A'	Area of a particle projected in the direction of flow
A_d	Cross-sectional Area of Rotary Drier
A_{ht}	Area available for Heat Transfer
A_{ms}	Mean area of a Stoma
A_{mt}	Area through which mass transfer takes place
A_s	Cross-sectional area of rotary drier
A_x'	Area of particle projected in x-direction
A_y'	Area of particle projected in y-direction
a	Constant, size of step input to system.
a_c	Surface area of particles per unit volume of cascade
a_s	Surface area of particles in a bed per unit volume of bed
$a_o, a_1....a_n$	Coefficients of Polynomial
B	Constant
B_s	Breadth of surface
b	Constant
C	Dimensionless concentration of water
c	Concentration of water
$\bar{c}$	Mean concentration of water
c_o	Initial concentration of water
c_p	Specific heat
c_{pa}	Specific Heat of air
c_{pd}	Specific Heat of Dry-matter in a moist solid
c_{pg}	Specific Heat of Dry-matter in grain or grass
c_{pw}	Specific Heat of water

c_{pwv}	Specific Heat of Water vapour
c_s	Concentration of water at surface
D	Diffusion coefficient
D'	Constant
D_d	Diameter of a Rotary Drier
D_m	Mean Diffusion Coefficient
D_o	Constant
D_t	Diameter of a wetted-wall Tower
D_v	Vapour Diffusion Coefficient
d	Differential
d_p	Particle diameter
E	Term in flow rate calculations
E'	Enthalpy of water vapour
F	Grass or solids feed rate
F'	Constant in (7.13)
F_s	Solids feed rate per unit cross-sectional area
f	$\sqrt{g(1 - \rho/\rho_s)/K_y}$
G	Mass flow rate of dry air per unit area
G_o	Total Mass flow rate of dry air
g	Acceleration due to gravity
H	Rate of heat loss from sides of a rotary drier, per unit length
id	Internal Pipe diameter
J	Constant = 1.5 for spheres, = $4/\pi$ for a cylinder with its axis perpendicular to the direction of flow
$J_o(x)$	Bessel Function of zero order
j_h	Heat transfer factor = $Nu\,\psi(Pr)/RePr$

K	$J \rho \phi(Re)/d_p \rho_s$
Ka, K_a', K_a'', K_b, K_b', K_b'', K_c, K_c', K_d, K_e, K_f, K_g, K_g', K_h, K_j, K_m, K_n, K_p, K_p', K_q, K_q', K_r, K_r', K_s, K_t, K_w, K_{1a}, K_{2a}, K_{1b}, K_{2b}, K_{1r}, K_{2r}, K_{1s}, K_{2s}	Constants
K_u	Constant
k	Drying constant
k'	Decay constant of exponential input to system
k_a	Thermal conductivity of air
k_f	Film transfer coefficient
k_g	Mass Transfer coefficient
k_o	Constant drying rate
k_p	Permeability
k_1, k_2, k_3	Drying constants in first, second and third periods of composite curves
k_s	Thermal conductivity of solid
L_d	Length of rotary drier
L_{eff}	Effective length of rotary drier
L_{ms}	Mean length of a stomatal tube
L_s	Length of surface
L_v	Latent heat of vaporisation of water
L_{vc}	Latent heat of vaporisation of water at temperature T_c
l	Distance along the drier
l/d	Length to diameter ratio of a piece of grass
l_s	Leaf to stem ratio of a batch of grass
m	Moisture content, dry basis
m_{av}	Average moisture content of a deep bed, dry basis
m_{c1}	First critical moisture content, dry basis

m_{c2}	Second critical moisture content, dry basis
m_e	Equilibrium moisture content
m_{e1}, m_{e2}, m_{e3}	Equilibrium moisture contents in first, second and third periods of composite curves
m_f	Moisture content of product of a rotary drier
m_o	Initial moisture content
N	Number of moles
N_c	Number of times a particle cascades
N_r	Speed of rotation of a rotary drier
Nu	Nusselt Number
n	constant
n_f	Number of flights in a rotary drier
n_s	Number of stomata per unit surface area of a leaf
n_1, n_2	Constants
od	Diameter of orifice in orifice plate
P	Resistance force
Pr	Prandtl Number
p	Vapour Pressure
p_a	Vapour pressure of water in the atmosphere
p_{at}	Atmospheric pressure
$(p_b)_{lm}$	Log mean partial pressure of dry air
p_i	Partial pressure of water vapour in intercellular spaces
p_o	Partial pressure of water vapour in atmosphere
p_s	Saturated vapour pressure of water in material
Q	Rate of heat transfer
Q_a	Flow rate of air, cfm
Q_s	Hold-up in Rotary drier

Q_w	Evaporation rate of water from plant surface, cfm
R	Gas constant
R'	Resistance force per unit projected area of particle
R_d	Drying Rate
Re	Reynold's Number
Re_x	Reynold's Number in x-direction
Re_y	Reynold's Number in y-direction
R_t	t_f/t_c
r	Correlation coefficient
r_f	Film resistance to mass transfer
r_t	Total resistance to mass transfer
rh	Relative humidity, decimal
r_p	Particle radius
r_s	Mean radius of a stoma
r_{turb}	Turbulent zone resistance to mass transfer
S	Exposed surface area of a bed
s^2	Variance
s_p	Suction
s_x, s_y	Standard deviations of x and y
$s_{y/x}$	Standard error of estimate
T	Temperature
T_a	Air temperature
T_{abs}	Absolute Temperature
T_{ao}	Reference temperature for air enthalpy determination
T_e	Temperature at which evaporation takes place
T_g	Grain or Grass temperature
T_o	Initial Air temperature
T_s	Temperature of solid

T_{wo}	Reference temperature for calculating enthalpy of water
t	Time
t_c	Cascade time (per cascade)
t_{c1}	Time to reach the first critical moisture content
t_{c2}	Time to reach the second critical moisture content
t_f	Soak time (per cascade)
U_v	Volumetric Heat transfer coefficient
u	Fluid velocity
u_i	Value of ψ at $t = 0$
V	Volume of solid
V_d	Volume of rotary drier
V_s	Velocity of solids along drier
v	Velocity of air
v_x	Velocity in the x-direction
W	Evaporation Rate in still air
W'	Evaporation rate
X	Fractional hold-up in a rotary drier
x	Input to a system, parameter, spatial co-ordinate, distance along rotary drier axis
$\bar{x}$	Mean value of x
x_a	Absolute humidity of the air
y	Response of system, parameter, spatial co-ordinate, distance in vertical direction in rotary drier
$\bar{y}$	Average value of y
y_{av}	Average length of fall of a particle in a rotary drier
z	spatial co-ordinate, distance, depth in bed
z_f	Film thickness

α	Constant, angle of inclination of rotary drier
$\beta\ \gamma\ \delta$	Constants
δ	Travel ratio
∂	Partial differential
ϵ	Voidage
$\varepsilon\ \zeta\ \eta$	Constants
θ	Angular position of flight in a rotary drier, with rexpect to the horizontal
$\iota\ \kappa\ \lambda$	Constants
λ_n	Roots of $J_o(x) = 0$
μ	Viscosity, constant
$\nu\ \pi$	Constants
ρ	Density
ρ_c	Cascade density in rotary drier
ρ_d	Bulk density of dry-matter in deep-bed
ρ_f	Bulk density of solid in flights
ρ_p	Particle density
ρ_{po}	Particle density at $m = m_o$
ρ_s	Solid density
ρ_x	Average density of dry-matter in drier
σ	Constant, surface tension
τ	Time constant of system, residence time in rotary drier
ϕ	Function of Re
ψ	Function of Pr
Δ	Difference
ΔP	Pressure drop across orifice plate
Σ	Sum of
∇^2	Operator $\dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2}$

CHAPTER 1

FORAGE CONSERVATION BY GRASS DRYING

1.1. Introduction

Man has always tried to preserve the surplus products of his work for a time when he may be in need. For many centuries, the traditional method of crop conservation, hay-making, was used without question. In the last fifty years, however, new ideas in fodder conservation have been accepted, albeit to a limited extent, by the farming community.

The high-temperature drying of young leafy herbage was first introduced in Britain on a commercial scale in 1936(83). Although farmers were slow to accept this new idea, by 1951 there were 850 installations producing over 200,000 tons of dried grass and green crops a year(83), but as post-war rationing was reduced, many farmers changed to imported concentrates so that the total production of dried grass in 1968 was only 80,000 tons. 90% of Britain's fodder is still conserved as hay in spite of the advantages of dried grass.

1.2. Fundamentals of Fodder Conservation

All agricultural materials must be dried so that they can be stored during the winter for feeding to livestock or for sowing at a later date. If the moisture content is too high, the material will rot. Ideally, forage materials should be stored at a moisture content of not greater than 12% (wet basis).

The easiest way to dry forage materials is by making hay in the field, where the drying power of the sun and the atmosphere can be used. There are, however, many disadvantages in this method. It takes several days for the material to dry, even if conditions are favourable. The sunlight reduces the content of carotene and other nutrients in the grass, whilst the uneven drying of the leaves and stems shatters the sheaths at the nodes and some of the crop is left in the field as the hay is being lifted.

Silage-making overcomes some of these difficulties, but the unpredictable nature of the process, together with the losses incurred, reduces its appeal as a fodder conservation method.

1.3. The Advantages of a Grass Drying System

In a grass drying system, grass is cut at intervals varying from four to eight weeks. Several crops can thus be taken from a sward in one season. The grass is chopped as it is cut, and is fed unwilted into a high temperature drier. The moisture content of the freshly cut grass can be as high as 90% (wet basis) in wet weather. In the drier, this is reduced to about 10%.

The system has several advantages over haymaking and silage production:

(a) The content of nutritious materials in the grass increases with regrowth to a maximum about four weeks after cutting, and thereafter it decreases. It is thus advantageous to crop grass after four to six weeks regrowth. Grass is also a crop which is very responsive to the application of nitrogenous fertilizers. By cutting frequently, the maximum benefit can be gained from the application of fertilizers.

(b) The use of an artificial drier ensures that the conservation process is independent of the weather conditions. Haymaking is notoriously dependent on the weather.

(c) Dried grass is much easier to handle and store than hay or silage. The crude product can be ground, wafered or pelletized. It is also much more uniform in quality. Feed concentrates such as molasses can be added to the meal before pelletizing to produce an even better product. It is easy to blend pelletized grass with such feeds as barley, to give a balanced diet.

(d) The greatest advantage of grass drying is its ability to preserve the nutrients of the fresh material. Bolt(7) says: "Dried grass must not be confused with hay. It is in no sense of the word a roughage feed and should not therefore be classified with hay. It is a concentrate, highly digestible, very palatable, rich in protein, vitamins and minerals, and can be substituted in a dairy cow's ration on a nutriment basis".

The high digestibility and crude protein content of young grass are maintained during the drying process. The comparison of losses and feeding value between haymaking and grass drying is shown in the table below(78). The superiority of dried grass is very clear.

Irrespective of the temperature at which the drier is operated, the crude protein digestibility and the carotene content are maintained at almost the same level.

Component	Loss of Component as a Percentage of the Total in the Fresh Crop	
	Hay	Dried Grass
Dry-matter	20	4
Crude Protein	20	6
Starch Equivalent	33	3
Protein Equivalent	30	3
Carotene	100	10
Vitamins	40	0

1.4. The Disadvantages of a Grass Drying System

Grass Driers are expensive to instal and operate. In 1969 a small unit of the pneumatic type cost £10,000. This figure does not include the cost of field cutting machinery or pelletizing and bagging equipment, which can add £6,000 to the capital outlay. Labour and fuel make the operation of grass driers costly.

Dried Grass can be produced on the farm at about £20 per ton. Of this figure, about 28.6% is capital depreciation, 44.6% is fuel, and 8.9% is labour. Some farms have experienced difficulties with the operation of field machinery and packaging equipment, but much development work is being carried out to improve these items. Very little attention, however, has been paid to accurate design methods which are needed to reduce the capital and operating costs of the drier itself.

The rate of growth of grass varies throughout the year as shown in figure 1.1(77). This is a graph of the yield of grass, cut at six-weekly intervals, against time of cutting. It can be seen that there is a peak of growth in May. If the drier can dry at a maximum rate indicated by the horizontal line AA, there will be a wastage of grass in May and a shortage from July onwards. There will be periods, therefore, when the drier is working twenty-four hours a day, and is still unable to cope with all the grass, and others when it will be working only a few days in the week.

1.3. Grass Driers

Three types of grass drier have been produced. The first type is the simple tray drier (fig.1.2). Hot air, up to 300^{o}F, is passed through a bed of grass which is about one foot thick. The grass is usually arranged in a tray and enclosed in a cabinet. When the grass has dried sufficiently, it is removed and is replaced by another batch. Typical evaporative requirements are 2000 Btu/lb dry-matter, but this figure can be reduced to 1150 Btu/lb by recirculation of some of the hot air.

In the conveyor type (fig.1.3), the grass is carried on a perforated continuous belt through a stream of hot air which flows at right-angles to the direction of motion of the grass. Several passes of the grass through the air may be used to give a higher thermal efficiency and to reduce space requirements.

The pneumatic or rotary type (fig.1.4) is the most popular, and there are many designs on the market. This is also the most expensive type, though costs are falling.

The grass is chopped into lengths of about four inches and fed into a rotating cylinder through which hot gases are passed in the same direction as the grass, i.e. it is a co-flow system. The grass is kept falling through the hot air by lifters on the inside of the cylinder. This action also advances the grass through the drier until it becomes light enough to be carried out of the drier by the airstream. The different rates of drying of the stems and the leaves are thus balanced by their different residence times. Very effective control systems can be applied to this kind of drier.

Various types of fuel are used in grass driers, but oil is most common for rotary driers. Electricity and gas are sometimes used in tray and belt driers.

1.6. Previous work on Grass Drying

In order to improve the design of grass driers it is necessary to know the drying characteristics of the grass. Little research seems to have been done in this field. Most workers have been concerned with testing existing driers, with field drying of herbage, or with comparisons between different treatments to grass to improve its field drying characteristics.

Scott(62) investigated the effect of drying air temperature on the scorching of the grass, and on the rate of evaporation. He confined his experiments to mat drying and concluded that the best air supply temperature for mat driers was 300°F and certainly should not exceed 350°F.

At higher temperatures very definite local scorching occurred. He also maintained that the efficiency of a carefully designed low temperature drier should be almost equal to that of a high temperature drier.

Whitney and Hall(81) and Whitney, Agrawal and Livingston(82) dried alfalfa leaves at temperatures up to 1400°F and investigated the effect of stomatal opening. They claimed that the drying process obeyed the first order rate equation and that the rate constant increased logarithmically with the temperature.

Belt(7) discussed the relative merits of different varieties of grass for drying and concluded that the most suitable were the pasture types of perennial grasses. He also maintained that the high temperature driers are more efficient than the low temperature ones. Byers and Routley(11) have examined the natural drying of alfalfa (lucerne) and have interpreted their findings in terms of the biological structure of the plant. Cashmore(12) was disappointed that the quality of dried grass was not as high as had been hoped, but he pointed out that grass does not suffer from case-hardening.

Jones and Palmer(35) analysed the natural drying of fodder crops with special emphasis on the water movements that occur in the living plant. Pederson and Buchele(52) investigated the drying of alfalfa hay, particularly considering the effects of mechanical treatments.

Ramp(56) examined the effects of drying and storage on the food value of dried grass. Bagnall(4,5) investigated the drying of the alfalfa stem and concluded that the principal impediment to rapid drying was in the geometry and structure of the plant stem.

All researchers(52, 29, 28, 44) agree that the use of crushers and crimpers as well as steaming and the application of chemicals increase the drying rate of fodder by altering the effective structure and geometry of the stem. These treatments, however, add to the cost of producing the grass and need extra equipment.

Although much work has been done into those aspects of fodder conservation (field hay making, mechanical treatments, drier testing), there is a great shortage of accurate design data on the artificial drying of grass. It was decided that research should be undertaken to obtain more of this data in order to facilitate the design of new, cheaper and more reliable driers. It was hoped that the results of the work would also enable a mechanism of drying to be proposed for grass.

CHAPTER 11

THEORY

2.1. Introduction

Research workers in drying have tended to specialize in investigating the theory of drying, or in the design and development of better hardware. In many cases, the theory is based on experimental results and not derived from first principles. All drying technology, however, is based on experimental observations and on scale-up techniques. In this chapter, some of the theories of solid drying that have been proposed will be explained.

2.2. Moisture Retention in Solids

When a moisture-containing solid is exposed to air, it will produce a steady pressure of water vapour in the air. The vapour pressure depends on many factors: the nature of the moisture and the nature of the solid, the temperature and the moisture content of the solid. The moisture content which produces a particular vapour pressure at a certain temperature is known as the equilibrium moisture content for those conditions.

Most solids, however, are not in equilibrium with the air around them. The moisture content in excess of the equilibrium moisture content is known as the free moisture content. Some solids are not well-behaved during drying: extra moisture is generated by chemical means, for example; break-down of water of crystallization. It then becomes difficult to distinguish moisture from the products of the decomposition of other constituents.

There are two ways of expressing moisture content: on a wet basis or on a dry basis (m_w and m respectively).

$$m = \frac{\text{weight of water removed by drying to "bone-dryness"}}{\text{weight of solid left after drying to "bone-dryness"}} \qquad \ldots \quad (2.1)$$

$$m_w = m/(1 + m) \qquad \ldots \quad (2.2)$$

Both m and m_w can be expressed on either a percentage or a decimal basis.

2. 3. Drying Mechanisms

The object of drying a solid is to remove some or all of the water from it. There are three stages in this process: (i) the moisture is moved from the interior of the solid to a point where it can be vaporized, (ii) it is vaporized, and (iii) the vapour is moved from the vaporization point to the air. The last part may involve moving the vapour through some of the dry solid before it reaches the surface.

The manner or mechanism of movement of moisture depends on the state of the moisture and on the nature and structure of the material being dried. Many mechanisms have been proposed to explain the drying phenomena observed in different situations.

If the nature of the mechanism which controls the drying is known, certain useful conclusions can be drawn. For example, the external variables which govern the drying rate will be those which govern the controlling mechanism. If the drying is controlled by a mechanism inside the solid, then the rate of drying can be changed by altering the solid dimensions or temperature, whereas changing the properties of the air will have no effect.

Some drying mechanisms are discussed below.

2.4. Diffusion

Sherwood(64) and Newman(48) were the first to suggest the drying mechanism which has come to be known as the diffusion mechanism. They proposed that the rate of movement of the moisture was a function of the moisture concentration gradient in the solid. This can be described by the equations:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \qquad \text{(one dimension)} \quad \ldots \quad (2.3)$$

or

$$\frac{\partial c}{\partial t} = D \nabla^2 c \qquad \text{(three dimensions)} \quad \ldots \quad (2.4)$$

where the operator $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$

c = concentration of water at time t and position x (x, y, z in three dimensions)

x, y, z = spatial co-ordinates

t = time

D = Diffusion Coefficient

A similar equation can be written if the moisture is diffusing as a vapour:

$$\frac{\partial p}{\partial t} = D_v \frac{\partial^2 p}{\partial x^2} = D_v \nabla^2 p \qquad \ldots \quad (2.5)$$

where

p = vapour pressure

D_v = vapour diffusion coefficient.

2.4.1. Solutions

The above equations have been solved for many initial and boundary conditions and many solid shapes. The solution is generally in the form of a rapidly-converging series. The simplest cases are those for which there is symmetry about a point, line or plane. The differential equations for a constant diffusion coefficient are of the general form(6).

$$D\left(\frac{\partial^2 c}{\partial r^2} + \frac{n}{r}\frac{\partial c}{\partial r}\right) = \frac{\partial c}{\partial t} \qquad \ldots \qquad (2.6)$$

where r is a spatial co-ordinate which is everywhere perpendicular to the bounding surface and whose origin is at the centre of symmetry.

$n = 0$ for planar symmetry

$= 1$ for axial symmetry

$= 2$ for spherical symmetry.

Assuming that no shrinkage occurs, that there is a uniform initial moisture concentration c_o and a constant surface moisture concentration c_s, the solution for an infinite plate is(6)

$$\bar{C} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left\{-\frac{(2n+1)^2\pi^2}{4}X^2\right\} \qquad (2.7)$$

where $\bar{c}$ = mean moisture concentration in the plate

$\bar{C}$ = dimensionless mean moisture concentration

$$= \frac{\bar{c} - c_s}{c_o - c_s} \qquad \ldots \qquad (2.8)$$

c_s = moisture concentration at surface.

X = dimensionless time = $S\sqrt{Dt}/V$

S = exposed surface area of solid

V = Volume of solid

The solution for an infinitely long cylinder is(6)

$$\bar{C} = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp\left\{ - \frac{\lambda_n^2}{4} X^2 \right\} \qquad \ldots \qquad (2.9)$$

where $J_0(x)$ is the Bessel function of zero order

λ_n are the roots of $J_0(x) = 0$

The solution for a sphere is(6)

$$\bar{C} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \exp\left(- \frac{n^2 \pi^2}{9} X^2 \right) \qquad \ldots \qquad (2.10)$$

For very large values of X the three equations (2.7), (2.9), (2.10) are approximated by

$$\bar{C} = \frac{\alpha}{\beta^2} \exp\left(- \beta^2 X^2 \right) \qquad \ldots \qquad (2.11)$$

where α and β are constants ... (2.11a)

2.5. Capillary Action

Another widely accepted mechanism of drying is capillary flow. Ceaglske and Hougen(13) introduced this idea to explain the drying of porous solids and beds of granular material in both of which there are continuous networks of very small passages. If the material is saturated when drying starts, these are full of water which is said to be in the capillary state (see fig.2.3). As the water is continually evaporated from the surface of each capillary, the surface tension forces draw more water up to the surface to replace it.

Air moves in through the larger pores to replace the water that has moved out. As air spaces appear in the water system, the state changes to the funicular state in which there is still a continuous network of water throughout the bed.

When the forces due to the surface tension at the menisci at the top of the capillaries can no longer support the weight of the column of water, it breaks up and the pendular state is reached. The water is held in lens-shaped rings around the contact points of the particles$^{(51)}$.

The speed at which the water moves through the capillaries depends on the frictional characteristics of the bed or material.

2.3.1. Mathematics

Ceaglske and Hougen$^{(13)}$ derived formulae for the suction or pressure deficiency in three types of pore space in a bed of uniform spherical particles. The shape of the pores depends on the method of packing the spheres. In a tetrahedral space the suction is $12.9\ \sigma/r_p$ where σ is the surface tension (dyne/cm) and r_p is the particle radius. In a rhomboidal space the suction is $6.1\ \frac{\sigma}{r_p}$, and in the nodoid of revolution that occurs in the pendular state it is $4.1\ \frac{\sigma}{r_p}$.

The tetrahedral and rhomboidal spaces occur at the two extremes of packing efficiency of uniform spheres. In practice not all the particles are the same size or shape. The pores, therefore, have a suction whose value is between those for tetrahedral and rhomboidal spaces. The authors predicted the moisture distributions in porous beds of solids more accurately than Sherwood$^{(64)}$ did, but their methods were based on empirical results.

Ceaglske and Kiesling(14) proposed an equation for steady-state flow in porous beds, which was similar to Sherwood's diffusion equation:

$$v_x = - \frac{k_p}{\rho} \frac{ds_p}{dx} \qquad \ldots \qquad (2.12)$$

where v_x is the velocity in the x-direction

k_p = permeability

ρ = density of fluid

s_p = suction

To include the effect of gravity, the equation is modified to

$$v_x = - \frac{k_p}{\rho} \frac{d}{dx} (s_p + \rho x) \qquad \ldots \qquad (2.13)$$

k_p is generally suction-dependent. For unsteady-state flow, the authors expressed the suction as a linear function of the concentration of water

$$c = a\, s_p + b \qquad \ldots \qquad (2.14)$$

where a and b are constants, and used the equation

$$\frac{\partial c}{\partial t} = - \frac{k_p}{\rho \rho_s} \frac{\partial^2 c}{\partial x^2} \qquad \ldots \qquad (2.15)$$

where ρ_s = solid density.

This is almost identical to the diffusion equation; it seems logical, therefore, to treat diffusion and capillarity by the same equation. However, the dependence of the diffusion and capillarity coefficients on temperature and other factors may not be the same. Ceaglske and Kiesling also showed that the fluid flow in the pores obeyed

Darcy's law.

2.6. Vapour Film Diffusion Mechanism

When the water has reached the surface at which evaporation takes place, and has been evaporated, the vapour must move into the bulk of the drying air. The mechanism by which it moves in the pores of the dry solid (if the evaporation surface is within the solid), and that by which it moves in the air surrounding the solid, are essentially the same.

Whilst the resistance to the evaporation process itself is very small, the structure of the air at the surface of the solid offers very considerable resistance to the movement of the newly-released water vapour. Gilliland(27) has described the process very fully.

The velocity with which the air flows over the surface of the solid increases from zero at the surface to a maximum value at some distance from it. This distance and the type of velocity gradient depend on the nature of the surface and on the properties and velocity of the air. Examples of velocity gradients are shown in fig.2.2.

In laminar or layer flow, the air moves so that all the particles travel along smooth curved trajectories and there is no bulk movement of air across these trajectories. Thus, any movement of water vapour across the flow must be by molecular diffusion, and is very slow.

When the air is in turbulent flow, there is very considerable cross-mixing in the bulk of the air so that the velocity reaches a maximum value at a very small distance from the surface. Thus, when water vapour enters into the turbulent zone, it is rapidly dissipated. There remains, however, a thin film of air which is in laminar flow, near the solid surface, and this offers a considerable resistance to the passage of water vapour. The transfer of the water-vapour across the turbulent zone is said to be by eddy diffusion, whereas in the laminar zone, it is by molecular diffusion.

In laminar flow, the transfer of water vapour is described by the equation

$$-\frac{dN}{dt} = \frac{D}{RT_{abs}} \frac{dp}{dz} \qquad \ldots \qquad (2.14)$$

where

$-\frac{dN}{dt}$ = rate of transfer

p = partial pressure of water vapour

D = Diffusivity (Diffusion Coefficient)

R = Gas Constant

T_{abs} = Absolute Temperature

z = distance

The film resistance r_f is given by

$$r_f = \frac{1}{k_f} = \frac{z_f\ (p_b)_{lm}}{D_m} \qquad \ldots \qquad (2.15)$$

where

z_f = film thickness

k_f = film transfer coefficient

D_m = Mean Diffusivity

$(p_b)_{lm}$ = Log Mean partial pressure of air.

Where there is a turbulent zone as well as a laminar zone, the total resistance is given by

$$r_g = \frac{1}{k_g} = r_{turb} + r_f = r_{turb} + \frac{z_f\ (p_b)_{lm}}{D_m} \quad .. \quad (2.16)$$

where

r_{turb} = resistance offered by the turbulent zone.

It has been found(27) that for evaporation of pure liquids into an air stream in a wetted-wall tower

$$\frac{1}{k_g} = (903 + \frac{135}{D_t})\ Re^{0.8} \quad ... \quad (2.17)$$

where

D_t = Tower Diameter

Re = Reynold's Number

The relative proportions of the resistance due to turbulent and laminar zones are 903 : 135/D_t

Very often the drying of a saturated solid surface can be approximated by the evaporation of water from a free surface(27). The Imperial College formula for evaporation from a free liquid surface as verified by Hinchley and Himus(33) is

$$W = \text{Evaporation Rate is still air } (kg/m^2\ hr) = \left(\frac{p_s - p}{50}\right)^{1.2} \quad ... \quad (2.18)$$

where p_s and p are the saturated and actual vapour pressures of the vapour (mm Hg).

If there is airflow, then

$$W = (0.031 + 0.0135v)(p_s - p) \quad ... \quad (2.19)$$

where

v = velocity of air (m/sec)

The Powell and Griffith formula(55) is

$$W' = 2.12 \times 10^7 \, L_s^{0.77} \, B_s (p_s - p)(1 + 0.121 \, v^{0.85}) \quad (2.20)$$

where

W' = Evaporation Rate (gm/sec)

L_s = Length of surface (cm)

B_s = Breadth of surface (cm).

However, a more fundamental approach to the problem by Sutton(69) based on Taylor's theory of eddy diffusion gives

$$W \propto L_s^{0.89} \, v^{0.78} \quad \ldots \quad (2.21)$$

There are various difficulties with evaporation over a large surface since the conditions are not constant, but these can be overcome by taking average values.

2.7. Applications of Theory

The drying characteristics of many solids have been investigated and it has been found that their drying curves are very similar. The drying curve can be divided into a number of sections.

After an initial heating-up period which is represented in fig.2.1 by AB, there is a constant-rate period (BC) during which the resistance to drying lies entirely in the drying air. Generally, the surface of the solid is very wet, or in the case of hygroscopic solids, the moisture content is greater than the maximum hygroscopic moisture content. After some time, dry patches appear on the surface (or the moisture content in some regions start to drop below the maximum hygroscopic moisture content). This marks the start of the first falling rate period (CD).

The drying rate decreases linearly with moisture content during this period and the movement of liquid water controls the drying rate.

When the surface is completely dry, the second falling rate period (DE) starts, and the drying face retreats into the solid. Water vapour must diffuse through the dry solid before it reaches the surface, but the liquid has a shorter distance to travel to the evaporation surface. The drying rate continues to drop, but generally not linearly with moisture content.

The three periods (constant rate, first falling rate and second falling rate) may be described by the same general equation:

$$-\frac{dm}{dt} = k\,(m - m_e)^n \qquad \ldots \qquad (2.22)$$

where

m = moisture content, dry basis, i.e. water ratio.

k, m_e, and n are constants.

$n = 0$ for the constant rate period, and the equation becomes

$$-\frac{dm}{dt} = k_o \qquad \ldots \qquad (2.23)$$

$n = 1$ for the first falling rate period, giving

$$-\frac{dm}{dt} = k\,(m - m_e) \qquad \ldots \qquad (2.24)$$

and $n > 1$ for the second falling rate period.

Some, or all of these periods are observed during the drying of all solid materials.

2.7.1. Diffusion Mechanism

Many workers have used the diffusion mechanism, with its various assumptions and simplifications, to explain the drying of solids.

Wang and Hall(76) agreed with Babbitt(3) that the vapour pressure is the main driving force for the movement of moisture in the drying of grain. Babbitt found that the direction of the moisture content gradient was often opposite to that in which the movement occurred. Using the equations

$$\frac{\partial m}{\partial t} = D \frac{\partial^2 p}{\partial x^2} \quad \ldots \quad (2.25)$$

and

$$\frac{\partial T}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2} - \frac{L_v}{c_p} \frac{\partial m}{\partial t} \quad \ldots \quad (2.26)$$

where

T = Temperature

L_v = Latent heat of vaporisation of water

c_p = Specific heat

k_s = Thermal conductivity of the material.

Wang and Hall (loc.cit.) predicted the drying rates of corn and compared these with the data of Rodriguez-Arias(59). The theory and experiment agreed to within 10%.

Pabis and Henderson(50) considered the maize kernel as a brick and assumed the liquid diffusion equation. They obtained good agreement by using the solution of this equation to predict the drying of unshelled maize. Chen and Johnston(15,16 introduced the concept of tertiary moisture content for hygroscopic materials. This is the moisture content at which the first falling rate period stops and the second falling rate period starts. For moisture contents above the tertiary moisture content they used the Sherwood equation:

$$\frac{\partial m}{\partial t} = D \frac{\partial^2 m}{\partial x^2} \quad \ldots \quad (2.27)$$

Below the tertiary moisture content they proposed the equation

$$\frac{\partial m}{\partial t} = D \nabla^2 m + \frac{\partial D}{\partial m} (\text{grad } m)^2 \quad \ldots \quad (2.28)$$

to take care of the simultaneous diffusion of liquid and vapour. They showed that the first equation (2.27) could yield the experimentally determined constant rate and first falling rate equations, and they assumed that the second equation (2.28) would predict the second falling rate expression, but they did not verify their assumption.

Becker(6) proposed, for symmetrical bodies, the equation (2.4) above. From solutions of this equation, he concluded that the beginning of the drying curve could be described by a series expression and the remainder by an exponential expression. He applied his results to the drying of the wheat kernel and obtained good agreement.

Chu and Hustrulid(17) followed on Becker's work but obtained rather more complex solutions by considering variable diffusivity. Like many other workers they applied these to the drying of shelled corn and came to the same conclusion - that and exponential-type equation described the drying of the material in its latter stages, but with a varying diffusivity.

Allen(2) also decided that the initial part of the drying curve had to be treated separately, but that the equations for both parts of the curve were essentially the same, and that there was a smooth transition from one part to the other without a definite change-over point.

These, and other workers agree that although the solution of the simple diffusion equation does approximate to the drying curve obtained by experiment, it does not perfectly match it. Some workers have attempted to improve on this by using a variable diffusion coefficient, and others by considering vapour diffusion with liquid diffusion. The controversy over static and dynamic equilibrium moisture content is closely linked with the changing character of the drying curve.

2.7.2. Equilibrium Moisture Content

Equilibrium Moisture Content is the term applied to the moisture content which a material will attain if it is placed in contact with air of constant temperature and humidity. The equilibrium moisture content is a function of the air temperature and humidity. However, there is a short-term and long-term history effect. The former is a hysteresis effect. If the equilibrium moisture content is plotted against humidity for different temperatures, a different set of curves (isotherms) is obtained depending on whether the material gained or lost moisture whilst coming to equilibrium. The absorption isotherms are obtained if the equilibrium moisture content is approached from a lower moisture content, and the desorption isotherms are obtained if the equilibrium moisture content is approached from a higher moisture content.

In addition, the equilibrium moisture content depends on the initial moisture content of the material, and on the speed with which equilibrium is approached, because drying causes an irreversible chemical change as well as a physical change.

Two terms have thus arisen - the dynamic equilibrium moisture content (d.e.m.c.) and the static equilibrium moisture content (s.e.m.c.). The former applies to the value of the equilibrium moisture content obtained by extrapolation from the results of drying tests. The latter applies to the value obtained when the material is allowed to come very slowly to equilibrium with the air.

Experimental results confirm that while an agricultural material is being dried, the dynamic equilibrium moisture content changes. Thus it is impossible for a pure exponential equation to describe the drying characteristics. No satisfactory explanation of the relationship between the d.e.m.c. and the s.e.m.c., drying mechanism and chemical change has yet been given.

2.8. Heat Transfer

Drying is a process of heat and mass transfer, but sometimes the heat transfer aspect is neglected.

Heat is a form of energy in transit from one place to another. The transfer can be accomplished by three methods: conduction, convection and radiation. In any application, each may be in use in varying proportions. Whilst conduction and radiation transfer rates are fairly easily calculated, convection heat transfer rates must usually be estimated from empirical relationships.

For drying purposes, all three modes of heat transfer are treated together and the rate of heat transfer is expressed by

$$Q = h_{oA} A_{ht} \Delta T \qquad \ldots \qquad (2.29)$$

where

Q = Rate of Heat Transfer

h_{oA} = overall heat transfer coefficient

A_{ht} = Area available for heat transfer

ΔT = Temperature Difference.

The heat transfer coefficient h_{oA} is dependent on many variables and has to be experimentally determined for each situation.

2.9. Proposal of a Mechanism of Drying

When proposing a mechanism it is necessary to treat both heat and mass transfer. The fundamental equations are set up and solved. They are then plotted to see if they predict, at least qualitatively, what happens in practice. Finally, quantitative prediction is tested. Very often, it will be found that several mechanisms can explain a given set of experimental observations and it is necessary to extend the range of observations to eliminate the less suitable mechanisms.

CHAPTER III

APPARATUS AND EXPERIMENTAL PROCEDURE

3.1. Introduction

The drying rate of a material depends on many factors or variables, such as the moisture content and physical structure of the material and the temperature of the drying medium. In order to determine how the drying rate is influenced by the variables, they are all held constant except one, and attention is focussed on this one. Alternatively, all the variables may be varied simultaneously. The data obtained by this technique are more difficult to analyse than those obtained by the first technique, but more general conclusions can be reached.

The moisture content of a material, however, cannot be held constant during a drying test, since it must change if drying is to occur. The practice in drying tests is to hold all the variables, except the moisture content, constant, and to determine the equation which describes the relationship between the drying rate and the moisture content. By varying the other variables in further tests, it is possible to find out how they influence the constants (if any) in the equation.

It is more difficult to determine the drying characteristics of organic materials such as grass, than of inorganic materials. The physical properties of grass depend on the stage of growth, the time of the year, the soil in which the grass is growing and the amount of fertilizer it has received. The sample of grass which is dried must be large enough for the variation in the physical properties to be balanced. The sample, however, must not be too large, otherwise the structure of the layer of grass will affect the drying characteristics of the sample.

3.2. Techniques of Measurement of Weight Change

The weight of a sample of grass being dried may either be measured while the sample is in the drying environment, or the sample may be removed for weighing. The advantage of weighing the sample in the drying environment is that the drying process is not interrupted. The disadvantage is that the force of the air blowing against the sample (if it is in a vertical airstream) acts as a negative weight. If the resistance to airflow changes as the material dries, the negative weight force will not be constant. Removing the sample for weighing overcomes this disadvantage, but it can only be done when the drying rate is so slow that the drying process is not significantly affected by the removal. If the sample is suspended in a horizontal airstream, there is no appreciable vertical force exerted on the sample by the air, but the stabilizing effect of gravity is also absent.

3.3. The Apparatus

The experimental work was carried out on a number of specialised pieces of apparatus since the air temperature and humidity were to be varied widely. These were:

(1) Medium Temperature Rig for the air temperature range $40^{o}C$ to $140^{o}C$. There was no humidity control on this

piece of apparatus in which 50 gram samples of grass were dried in layers half an inch thick.

(2) Low Temperature Rig for the air temperature range 0°C to 80°C. A humidity control was available on this rig, in which 10 gram samples of grass were dried.

(3) High Temperature Rig for the air temperature range 100°C to 400°C. There was no humidity control on this rig, in which 10 gram samples of grass were dried.

The high temperature rig was built specially for this work, but the first two pieces of apparatus mentioned above were existing pieces of equipment. Only the first one required modification for the purpose of the grass tests.

Each piece of apparatus and its operation procedure is described separately below.

3.4. The Data Logger

Most of the measurements taken during the experiments were recorded by a Data logger. The model used had a capacity of twenty input channels. Voltages generated by measuring equipment (to correspond to the experimental variables being sampled) were fed into these channels and the appropriate range of voltage for each channel was selected by means of a plugboard.

The data logger incorporated a digitizer so that the values could be recorded on punched 8-hole tape or printed on a continuous paper strip. The logger could also be used to scan a number of channels just once. It was possible, using the plugboard, to pass voltages from selected channels through a linearizer before they were converted the voltages from copper-constantan thermocouples (with the reference junction at 0^oC) to tenths of a degree Centigrade.

The logger could be operated in a number of modes, but during the tests only two modes were used to any great extent:

(a) Single Channel Mode and (b) Single Scan Mode.

In the Single Channel mode, the voltage input to any one channel could be recorded at a frequency ranging from 1/3 second to 10 minutes.

In the Single Scan mode, the voltage inputs to certain channels could be scanned at a frequency ranging from 10 seconds to 1 hour. The frequency of sampling within each scan could also be selected, but was subject to being compatible with the scanning frequency. For example, channels 0, 1, 2, 3 and 4 could be scanned every 10 minutes with a one second gap between each channel. The recording of time (in hours and minutes) was optional.

3.5. Medium Temperature Rig

The apparatus is shown in figures 3.1, 3.2 and 3.3. Air was supplied by a fan fitted with an iris flow regulator. The airflow could be varied from 0 to 35 ft^3/min (0 to 0.044 lb/sec). The flow rate was measured by a $1\frac{3}{8}$" diameter B.S. orifice plate in a six inch diameter pipe with d and d/2 tappings, and inclined tube manometer. The air was heated by three finned electric heaters, two of one kilowatt capacity and one of $\frac{1}{2}$ kw. One of these was fed through a variable transformer so that a range of air temperatures could be attained, 40°C to 140°C.

The air was passed vertically upwards through a steel tube of one foot diameter. The tube was packed with paper honeycomb to straighten the airflow and to damp out variations in the air temperature. Just above the honeycomb a perforated metal tray was suspended. The grass to be dried was placed in this. Finally, the air was exhausted to atmosphere. The tray could be reached by a door in the tube (fig.3.3.). The whole unit was insulated with glass wool.

The tray was suspended from the underhook of a balance which stood on a rigid steel shelf above the drier tube. The weight of the sample being dried could thus be monitored. A device was designed, however, to automatically record the weight of the sample (see fig.3.2.). A displacement transducer was set up so that the vertical movement of the top pan of the balance was imparted to the slug of the transducer. The transducer coil was held in a fixed position over the balance. The transducer was fed with an A.C. signal from a transducer-convertor and the magnitude of the return signal depended on the distance the slug protruded into the coil. This signal was converted to D.C. and fed to one channel of the data logger.

The transducer-converter could be adjusted so that the output signal was 100 for a 100 gram loading. Tests showed that the output of the transducer was a linear function of the weight applied to the balance (fig.3.4.). An almost continuous record of the experimental variables could be thus obtained. Temperatures were measured by copper-constantan thermocouples.

The apparatus lacked many sophistications, but the greatest disadvantage was the lack of an automatic temperature controller. The rig also needed long heat-up periods. However, these disadvantages were quickly minimized and an analysis of the temperatures recorded during the experiments showed that the variation was acceptable. The standard deviation of the temperature of the drying air during a run was about ± 0.5°C.

When the apparatus had warmed up to the desired temperature at the required airflow, the weighing system was calibrated. A sample of the grass was weighed and placed on the tray which was then loaded into the drier. The data logger was started. Thereafter, the experiment needed no operator intervention other than to reduce the scanning rate as the drying rate decreased. Usually, a run started with one scan every ten seconds, and this was progressively reduced to one every twenty seconds, and then one per minute. The run was terminated when the drying rate had dropped to less than 0.1 gram/minute, or after one hour.

The weighing system was recalibrated before each run, to eliminate long-term temperature effects. The moisture content of the grass was determined after each run by drying a sample in an oven at 105°C for 16 hours.

3.6. Low Temperature Rig

The apparatus for drying under closely controlled conditions of air temperature and humidity had been built(30). Its principle of operation was very similar to those of the medium and high temperature rigs.

Air was supplied by a fan and the flowrate was measured by a one inch diameter orifice plate in a four inch diameter pipe, and manometer. The desired air condition (as defined by the dry-bulb and dew-point temperatures of the air) was obtained by passing the air through a glass tube packed with glass Raschig rings. Water was allowed to pass down the tube in the opposite direction to the air so that the air was humidified. The water was maintained at the required dewpoint temperature of the air. A refrigeration unit was used to cool the water below room temperature so that very low dew-point temperatures could be obtained (for high humidities at low temperatures). The air was saturated by the time it left the top of the tower.

The dry-bulb temperature of the air was raised to the required value by passing it over mineral-coated electric heating elements (7 kw). The dew-point temperature of the air remained at the temperature of the water in the tower, since no moisture was added to the air by heating. The duct on either side of the heaters was insulated to prevent condensation inside the duct. In addition, the duct upstream of the heaters was warmed by heating coils which were wrapped around the outside of the duct. The moistened hot air was then passed through mixers into a plenum. The plenum was attached to the drying tray and the assembly was suspended from the underhook of an electronic balance. The drying tray was placed on the plenum through a door in the cover.

The maximum weight capacity of the balance was one thousand grams and in addition 800 grams could be tared out. Three principal weight ranges were available: 10 gram, 100 gram, 1000 gram. The weight could be read by analogue on a gauge, or by other means if a recording or monitoring device was connected to the balance. The data logger was used for this purpose. The balance also possessed the advantage that the vertical displacement of the pan was very small. (A deflection of about 0.003" was measured for a 1000 gram load). An oilseal was placed at the base of the plenum to ensure that all the air entering the plenum passed through the grass sample.

The temperatures of the water in the tank and of the air entering the plenum were controlled by thyristors activated control units. These were very accurate, as shown by the steadiness of the temperatures (fig.3.15). Only one airflow (13 $ft^3/min = 0.0511\ lb/sec\text{-}ft^2$) was used on this rig. Temperatures were once again measured by copper-constantan thermocouples.

The procedure was as follows: The desired air temperature and humidity were obtained by adjusting the controllers. When steady-state conditions were reached, the prepared grass sample was weighed and inserted into the drier. The balance was switched on, tared and set, and the data logger was started.

The length of the tests on this rig varied with the drying air conditions, and ranged from twenty minutes to three hours. At the end of the run, the grass was removed and weighed. The final moisture content was determined by oven-drying.

3.7. High Temperature Rig

This piece of apparatus was designed to achieve a high air temperature. It is shown in figures 3.5., 3.6., 3.7. and 3.8.

Once again, air was supplied by a fan and the flowrate was measured by a 1¼" diameter orifice plate in a 2" diameter pipe. The air was passed over mineral-coated electric heater elements (six sets of three kilowatts each) fitted into a one foot diameter mild steel duct. One heater was fed through a variable transformer. The heated air was agitated in a spiral mixer to achieve a uniform air temperature, and finally the flow was straightened in a bank of ⅛" diameter tubes. The air was passed horizontally through an expanded metal mesh container, (fig.3.7.) in which 10 grams of grass was placed. The container consisted of two discs of expanded metal, one foot diameter. The grass was placed between the discs which were then fastened together. The disc was held by guides in a strip of aluminium (bent to form a U) which was suspended from the underhook of the electronic balance described above (3.6).

The container system was held in a two inch gap in the duct so that the air passed through it horizontally. The air was exhausted to atmosphere after passing through the weighing section. To prevent the container system from swinging and rotating in the airflow (and thus fouling the sides of the duct) the U was fastened to the duct walls on the upstream side by three wires. The very small vertical displacement of the balance pan ensured that the wires did not affect the response of the balance to the weight changes. The weighing section was sealed to prevent air movement in the laboratory from affecting the readings (fig.3.6.).

Temperatures were measured by copper-constantan thermocouples fitted with radiation shields. The duct was insulated with mineral wool.

The required air temperature was obtained by switching on the appropriate heating elements and adjusting the transformer. When steady-state conditions had been reached, the balance was adjusted and a grass sample was prepared and weighed. In order to protect the balance whilst the grass container was removed, a dummy weight was placed on the top pan of the balance. Two push-buttons started the data logger and removed the dummy weight by means of a solenoid (fig.3.8.). As the grass sample was placed in the U, the buttons were pressed and recording started. In this way, only a very small part of the drying curve was lost whilst the balance and recording equipment were set in operation.

The experimental runs were short, ranging from 15 seconds to five minutes. With this rig, the data logger was operated mainly in the single channel mode, with the sampling frequency varying from 1/3 second to 2 seconds. At the end of the run, the grass sample was weighed again and its moisture content was determined in the usual manner by drying it in an oven at 105°C for 16 hours.

3.8. Suitability of the Apparatus

A number of checks were made to determine the suitability of the apparatus for the work. These will be discussed below under five headings: Air speed and temperature; Air Resistance; Balance Response; Steadiness of Balance; Moisture Content Determination.

3.8.1. Air Speed and Temperature

It was desirable that the velocity and temperature of the air would be uniform across the duct and would not vary during the run.

In each rig, air was supplied by a fan driven by a three-phase electric motor. The air flow rate was steady throughout all the runs as verified by readings taken at intervals during drying runs. The baffles and flow-straighteners ensured that the airflow was uniform across the duct.

The copper-constantan thermocouples used to measure the temperatures were all correct to within ± 0.2°C. Radiation shields were fitted at high air temperatures but the readings from thermocouples with and without shields were not significantly different, indicating that there was not much radiation heat transfer, probably due to the baffles and mixers.

The temperature varied across the airstream by about 5°C in the medium temperature rig, and by 20°C in the high temperature rig. The temperature profile in the high temperature rig is shown in fig.3.9. The temperature variation during a run was very small. The approximate standard deviations of the air temperature in the medium temperature rig was ± 0.5°C, in the low-temperature rig ± 0.25°C and in the high temperature rig ± 3°C. These values were considered acceptable.

3.8.2. Air Resistance

A free-body diagram of the container and grass is shown for the two types of rig in fig.3.10. It can be seen that for the high temperature rig, air resistance had almost no effect, due partly to the small pan displacement. For the low and medium temperature rigs, however, the air resistance was significant. It tended to give a low reading on the balance or data logger. However, since the weights measured were relative weights rather than absolute weights, the air resistance was unimportant unless it varied.

It has been suggested that the resistance offered to air by forage materials decreases as the grass dries, due to shrinkage. In the present work, however, it was not likely that the shrinkage would have much effect on the resistance since the grass was very loosely arranged. To confirm this, experimental runs were carried out noting the initial and final weights of the sample on a laboratory balance and on the data logger. The results are shown in table 3.1. It can be seen that the change in weight is recorded substantially correctly by the data logger. If the resistance had changed significantly, the weight changes would have been different for each case.

3.8.3. Balance Response

There was no question of the balance used on the medium or low temperature rigs being unable to record the changes in weight accurately due to inertia. Tests showed that they weighed correctly. However, in the case of the high-temperature rig, there was a possibility of the balance being unable to record the changes in weight correctly, because of the fast drying rate.

Tests were conducted to examine the characteristics of the balance. A step input was fed to the balance by placing a 10 gram mass on the top pan. The output both of the balance and of the data logger was measured. The output of the balance was recorded on an ultra-violet recorder (paper speed = 2 inches/second) and the output of the data logger was recorded on punched paper tape (3 readings per second). The response was identical in all tests and on each recording device, and indicated a first-or second- order system (see fig.3.11.). The readings are set out in table 3.2.

For a step input of size a, the response of a first order system of time constant τ is given by

$$y = a\,(1 - \exp(-t/\tau)) \qquad \ldots \qquad (3.1)$$

For a second-order, critically damped system, the response is

$$y = a\,(1 - (1 + t/\tau)\,\exp(-t/\tau)) \qquad \ldots \qquad (3.2)$$

(The derivations of these formulae are given in Appendix 12.1). For a value of a = 10, the response y was plotted against time t and it was found that equation (3.2) with $\tau = 0.3$ second fitted the experimental data perfectly, see fig.3.12. The first order expression (3.1) did not fit the data.

The response of a second-order critically damped system to an exponential input of the form

$$x = a\left(1 - \exp(-k' t)\right) \qquad \ldots \quad (3.3)$$

is given by

$$y = a\left[1 - \frac{e^{-k' t}}{(k'\tau - 1)^2} - \left(1 + \frac{1}{k'\tau - 1}\right)\left(1 - \frac{1}{k'\tau - 1} + \frac{t}{\tau}\right)\exp(-t/\tau)\right] \qquad \ldots \quad (3.4)$$

This equation was plotted for $= 0.3$ and values of k' found in the experimental work (see figs.3.13 and 3.14). It was found that for values of k' less than 1 $\sec^{-1}$ (= 60 $\min^{-1}$), the input and output curves were almost identical. Since the greatest value of k encountered in practice was 0.1 $\sec^{-1}$, it was concluded that the balance response was fast enough for this work.

Tests showed that the balance was also able to record the correct weights. The apparatus was set up with dry blotting paper in the container, to simulate grass, and the fan was set in operation. Masses of 5 gram and 10 gram were placed on the top pan of the balance, after it had been tared to zero. In each case, the balance recorded the true weight.

3.8.4. Steadiness of the balance

In order to determine the steadiness of the zero setting on the electronic balance, on the high temperature rig, readings were taken every two seconds using the data logger. The container, empty, was in position. With the fan in operation, the standard deviation over 5 minutes was +0.317 gram and with the fan off it was ±0.315 gram.

3.8.5. Moisture content determination

All moisture contents were determined by drying the samples in an oven at 105°C for 16 hours. Errors could be introduced from a number of sources.

If the sample used to estimate the moisture content of the grass in the field was not a truly random sample, this moisture content could have been in error. The final moisture content of the grass would have been in error if moisture had been absorbed by the sample from outside before it was weighed. To avoid this, the oven-dried samples were either weighed directly from the oven or they were cooled in a dessicator in the presence of silica gel before they were weighed. The samples from all experimental runs were weighed immediately after the run and therefore there was not much error likely in their moisture content.

CHAPTER IV

COLLECTION OF DATA

4.1. Introduction

The experiments were carried out during three growing seasons. The growing season of grass extended from April to October and experimental work could be done only in this period. Attempts were made to preserve the grass by freezing so that experiments could be done during the winter, but the grass was lacerated by the freezing and was unsuitable for drying tests. The three rigs described above were used in the tests.

4.2. Experimental Design

Experiments designed to determine the effect of one or several factors on a measurable quantity must be conducted so that the variations in background conditions (conditions which are not of direct interest) will not affect the results obtained. If a particular background condition can be held constant, the experimenter may ignore it. If it cannot be controlled, however, the experiments should be conducted in a random order so that changes in the condition will be uniformly distributed through the results. A random order is advisable generally, in case there may be unseen background conditions.

The factors of interest should also be varied randomly amongst themselves so that any interaction between them will be detectable. In the present work, however, it was not possible to apply all the niceties of statistical experimental design. The nature of the apparatus was such that the operating conditions could not be rapidly changed. As there was only a short time in which to do the experiments, not all the combinations of factors could be used, nor could the possible combinations be performed in random order. Since the exact type of relationship between the different factors was not known, the results of the experiments would have been very difficult to analyse if the operating values of the factors had not been suitably chosen.

4.3. Grass Sampling and Collection

Two species of grass were used - Italian Rye Grass and Perennial Rye Grass. Italian Rye was used in the majority of runs. Grass was obtained from five sources, all at Cockle Park Farm, Northumberland. (see Table 4.1). A total of 42 cuts or batches of grass were taken over a wide range of maturity. It was difficult to preserve the grass for more than a short time after it had been cut. Usually a sample of sufficient size for a day's tests was cut early in the morning and was used in experiments during the day on which it was cut. After thirty-six hours storage, even at a temperature of 2°C, the condition of the grass had changed (it became limp and discoloured) and it had lost a lot of moisture by respiration.

Two properties of each batch of grass were determined - the maturity and moisture content. The maturity was measured by the leaf to stem ratio (by weight). Although this may not have been the most accurate or useful measure of maturity, it was the most easily determined. Other measures of maturity which could have been used were the coarse fibre content and the leaf area index (ratio of leaf area to ground area). The leaf to stem ratio varied with time of regrowth as shown in figure 4.1. For most batches the leaf to stem ratio was measured by taking a sample, separating the leaves from the stems and weighing them.

The moisture content, as in the field, of each batch of grass was measured by taking a random sample from the batch and drying this sample in an oven for sixteen hours at 105°C. The weight of the sample at the end of that time was assumed to be the "bone-dry" weight. The data on the various grass batches in shown in table 4.2.

4.4. Measurement of the Variables

For each experimental run the following variables were measured and recorded:

(a) Air temperature

The air temperature was measured using copper-constantan thermocouples, fitted with radiation shields where appropriate. The reference junctions of all the thermocouples were kept at 0°C. The temperature was recorded using a multipoint recorder, or the data logger described in section 3.2. The multipoint recorder was used in all runs on the high temperature rig and in the first twenty-eight runs on the medium temperature rig. The voltages were read from the chart and converted to temperatures using tables.

When the data logger was operated in the single-scan mode, five channels scanned, on the low and medium temperature rigs, the air temperature was recorded through one of the channels (No.4 on the medium temperature rig and No.1 on the low temperature rig).

The data logger was operated in the single channel mode on some runs on the low temperature rig, and in these cases, the five channels were sampled by a single scan before and after the run.

(b) Air Flow Rate

The air flow rate was measured by means of the orifice plates and manometers described in chapter 3. The pressure drop across the orifice plate was recorded in inches of water, and the air flow rate was calculated according to British Standard 1042(9). A sample calculation is given in Appendix 12.2.

(c) Humidity of the Air

The humidity of the air was calculated from measurements of the wet and dry bulb temperatures of the inlet air to the fan, or the dry-bulb and dew-point temperatures of the heated air. During the high temperature runs and the first twenty-eight runs on the medium temperature rig, the wet and dry-bulb temperatures of the air entering the fan were recorded on the multipoint recorder from copper-constantan thermocouples. The wet-bulb temperature was sensed by placing a thermocouple in the middle of a wet wick over which the air was passed. In all the drying rigs, the humidity of the air at the sample being dried was the same as that of the air just upstream of the heaters since no water was added by the heating. When the data logger was operated in the single scan mode on the medium temperature rig those wet and dry bulb temperatures were recorded along with the temperature of the heated air.

The humidity of the air on the low temperature rig was calculated from the dry bulb temperature of the heated air and its dew point temperature. The latter was calculated from the mean of the wet and dry bulb temperatures of the air at the top of the humidification tower, since they were almost equal, indicating 100% relative humidity. These temperatures were recorded in the same way as the air temperature.

(d) Final Moisture Content of the Sample

The final moisture content of the grass at the end of a run was determined by drying it at 105°C for sixteen hours. When considerable charring of the sample occurred, the final moisture content was not determined and the weight of dry-matter was calculated from the initial moisture content.

(e) Other Data

For most runs, the grass batch number, grass state (leaves, stems or unseparated grass), grass variety and approximate length of chop were recorded. The initial and final weights of the sample were determined for all the runs on the high and low temperature rig by weighing the sample on a laboratory balance.

A sample data sheet is shown in fig.4.2.

4.5. Experimental Tests

Initially, tests were carried out to determine how much variation in drying characteristics could be expected within a given batch of grass, i.e. the repeatibility of the drying runs. This was done by drying samples of grass under the same conditions.

Most of the other tests were conducted in order to observe the effect of air temperature, humidity and velocity, and of grass maturity, state, variety and length of chop on the drying characteristics. The number of tests which could be conducted on any one batch of grass was limited since the grass deteriorated if it was stored for long (see section 4.3). Nevertheless, nearly 500 runs were carried out.

which ?

4.5.1. Repeatibility tests

These tests were conducted on the medium temperature rig, using the grass from batches 1 to 8, (run numbers 5 to 58). All the variables except grass maturity were held constant, in order to determine if the drying characteristics varied much from batch to batch or within each batch. Leaves and stems were dried separately. The layout of the runs is given in tables 4.3 to 4.10.

The maturity of the grass ranged from (leaf to stem ratio) 0.5 to 1.9. The depth of the layer was also varied randomly, and the air temperature was held constant for most of the runs at about 100°C. The air velocity was held at 0.06 lb/sec-ft^2.

4.5.2. Medium temperature rig tests

The grass from batches 9 to 24 was dried in runs 59 to 237. The air temperature and velocity and grass maturity were varied. The layout of these runs is shown in tables 4.11 to 4.26. For each batch, leaves and stems were dried separately at about 100°C. Samples of the unseparated grass were dried at from three to eight air temperatures, from 40°C to 140°C. Up to six values of air velocity were used ranging from 0.0287 lb/sec-ft^2 to 0.084 lb/sec-ft^2. The air temperature and velocity were maintained at about the same values in the different grass batches so that the batches could be easily compared. The maturity was varied from 3 to 8 weeks regrowth (leaf to stem ratio from 0.5 to 4.5). The grass from batches 9 to 19 and 23 was subjected mainly to temperature variations, and the grass from batches 20 to 22 was dried under a wide range of both temperature and velocity conditions.

4.5.3. Low Temperature Rig Tests

Runs 301 to 315 were conducted on the low temperature rig. The air temperature was set at approximately 20°C. 40°C, 60°C and 80°C (four values), and the relative humidity at about 10%, 20%, 40%. 60% and 80% (five values). Some combinations of air temperature and relative humidity could not be obtained since the dewpoint was too high or too low in some cases, i.e. beyond the capacity of the water heaters and refrigerator unit. The layout of the runs is shown in table 4.27 and in fig.4.3. Only one batch of Italian Rye Grass was used on this rig (no.25), and only one run was conducted using Perennial Rye Grass. The air velocity was held constant at 0.051 lb/sec-ft^2.

4.5.4. High temperature rig tests

Runs 316 to 480 and 501 to 568 were carried out on grass batches 29 to 42 on the high temperature rig. The layout of the runs is given in Tables 4.28 to 4.41. A summary of the runs is given below. The air velocity was held constant at 0.072 lb/sec-ft^2.

Series I (Runs 316 to 377 and 402 to 410).

Italian Rye Grass, with five weeks regrowth, from batches 29 to 32 was dried in this series. The runs can be subdivided into those using:

(i) Unseparated Italian Rye Grass

(ii) Italian Rye leaves

(iii) Italian Rye stems

(iv) Unseparated Perennial Rye Grass.

Each type of sample was dried at six equally spaced air temperatures, and each run was done in triplicate.

Series II (Runs 378 to 401).

In this series, Italian Rye Grass from batch 31, five weeks regrowth, was dried at six equally-spaced air temperature. At each temperature, samples of grass chopped into lengths of 1", 2", 3" and 4" were dried.

Series III (Runs 411 to 480).

In this series, the maturity of Italian Rye Grass was varied from two weeks regrowth to six weeks regrowth. Four maturities were examined. In each case the grass was dried at five equally-spaced air temperatures, and each run was done in triplicate. The runs can be subdivided as follows:

(i) Two weeks regrowth (Runs 411 to 427) (Batch 33)

(ii) Three weeks regrowth (Runs 428 to 444) (Batch 34)

(iii) Four weeks regrowth (Runs 445 to 460) (Batch 35)

(iv) Six weeks regrowth (Runs 461 to 480) (Batch 36)

Series IV (Runs 501 to 568)

In this series the maturity of Italian Rye Grass was varied from about four weeks regrowth (from the start of the growing season) to seven weeks regrowth, leaf to stem ratio from 0.6 to 2.7. Five maturities were examined. The number of air temperatures used varied from two to eight. Whole grass of each maturity was dried, and each run was done in duplicate. Leaves and stems were dried separately for two of the maturities. The runs can be subdivided as follows:

(i) Batch 37. Whole Italian Rye Grass dried at two temperatures, four weeks growth from the start of the season. (Runs 501 to 504)

(ii) Batch 38. Whole Italian Rye Grass dried at three temperatures, five weeks growth, (Runs 505 to 509).

(iii) Batch 39. Whole Italian Rye Grass dried at five temperatures, five weeks growth, (Runs 510 to 520).

(iv) Batch 40. Unseparated grass, leaves and stems, dried at eight air temperatures, six weeks regrowth, (Runs 521 to 548).

(v) Batch 41. Unseparated grass, leaves and stems dried at one air temperature, seven weeks growth, (Runs 549 to 568).

CHAPTER V

CALCULATIONS AND RESULTS

5.1. Introduction

The recorded data were analysed in order to determine the relationship between the drying rate of the grass and the other parameters. In each run, all the variables except moisture content were held constant. The remaining variables were changed in different runs. In all the runs, a continuous loss of weight was observed, i.e. a decrease in moisture content. The rate of decrease of moisture content, the drying rate, however, was not constant in all runs. It was desirable, therefore, as a first step in the analysis, to obtain a graphical relationship between the drying rate and the moisture content for each run, so that the nature of the change in the drying rate could be ascertained.

5.2. Calculation of Moisture Contents

The moisture contents at different times were calculated from the weights recorded at those times. The weight of dry-matter was calculated from the initial or final moisture content of the sample and the initial or final sample weight, i.e.

$$\text{moisture content (dry basis) at time } t = \frac{\text{weight at time } t}{\text{initial weight}} (1 + \text{initial m.c.d.b.}) - 1 \quad \ldots \quad (5.1)$$

or

$$\text{moisture content (dry basis) at time } t = \frac{\text{weight at time } t}{\text{final weight}} (1 + \text{final m.c.d.b.}) - 1 \quad \ldots \quad (5.2)$$

The derivations of these formulae are given in

Appendix 12.3.

One or other of these formulae was used, depending on the temperature of the drying air. At high air temperatures, there was a considerable loss of dry-matter (charring of the grass was evident in some runs) and the weight of the dry-matter calculated from the final moisture content was therefore in error. The initial moisture content was determined from a random sample from the batch of grass. It was found that a significant variation occurred in the moisture content in each batch of grass, and the value of the moisture content determined for a random sample was only an estimate of the initial moisture content of the sample of grass dried in the experiments. Table 5.55 shows the variation in moisture content obtained by taking several samples for a batch of grass. When the air temperature was high, however, the error in the dry-matter weight calculated from the initial moisture content of the sample, assumed to be equal to that of the random sample, was less than if it were calculated from the final moisture content. Therefore, the second formula was used for runs carried out on the Low and Medium Temperature Rigs, and the first formula was used for runs carried out on the High Temperature Rig.

5.3. Methods of Calculating Drying Rates

A typical scatter plot of moisture content against time is shown in fig.5.1. The points do not lie on a smooth curve, due to both experimental error and to the buffetting of the air against the sample in the drier.

There are several ways of calculating the drying rate at various points on the curve.

(a) Graphical Method

A smooth curve is drawn by eye through the scatter plot of moisture content against time. Tangents are drawn to the curve at a number of points and the slopes of the tangents are measured (see fig.5.2). The drying rate is then given by:

$$\text{drying rate} = -\ \text{slope of tangent} \quad \ldots \quad (5.3)$$

(b) Segmentation Method

This method considers the moisture content-time curve to be made up of a series of straight lines connecting adjacent points in the scatter plot (see fig.5.3). The slope of each segment gives the average drying rate (= - slope) over the interval, and this is approximately the drying rate at the mid-point of the interval.

(c) Polynomial Approximation

A third way to calculate the drying rates is to fit a polynomial to the scatter plot of moisture content against time, i.e. the moisture content (m) is expressed by a series in time (t) as

$$m = a_o + a_1 t + a_2 t^2 + \ldots\ldots + a_n t^n \quad \ldots \quad (5.4)$$

where a_o, a_1, $a_2 \ldots\ldots a_n$ are constants, the coefficients of the polynomial. The curve-fitting may be done using a least squares technique. The polynomial obtained is then differentiated to give an expression for the drying rate as a function of time:

$$-\frac{dm}{dt} = -a_1 - 2a_2 t - 3a_3 t^2 - \ldots - na_n t^{n-1} \quad (5.5)$$

The drying rates at various times can be found by substituting these time values into the above expression. Figure 5.8 shows the polynomial of eighth order fitted to a set of experimental points. This method can be used successfully if there are no sudden changes in the moisture content - time relationship or in its first derivative.

5.4. Calculation of Drying Rates

The points obtained by plotting moisture content against time do not lie on a smooth curve. The errors in the values of moisture content are not large, but if they are not corrected, considerable errors appear in the drying rates calculated from this data. The graphical method removes a lot of the scatter, but it is not accurate, it is very tedious, and the user is likely to be biassed in the drawing of the tangents.

The segmentation method does not remove any of the scatter, and unless it is modified, it is not a very successful method.

The polynomial approximation method is a good technique for smoothing out errors, but the polynomial is not valid outside the limits within which it is calculated, i.e. it cannot be used to calculate moisture contents or drying rates at times longer than the experimental drying time. In addition, the drying rate at the very beginning and end of the curve tends to deviate from the actual drying rate.

If there are many experimental points, the scatter can be reduced by taking the means of groups of points, i.e.

of moisture contents and the corresponding time values. e.g. the means of the first five points, of the second five points, and so on. The segmentation method can then be applied to the new set of points. (See fig.5.6. and Appendix 12.4.)

The polynomial approximation method and the segmentation method, after grouping and averaging the points, were used on all sets of data. Tables D, D and E in Appendix 12.4 show the drying rates calculated for a set of data by various methods.

5.5. Analysis of the Drying Curve

The graph of drying rate against moisture content is called the drying curve. Some examples are shown in figs. 5.11 to 5.14. These are really scatter plots, but the scatter is very small in the case of the drying rates calculated by the polynomial approximation method, and the plot is almost a continuous curve.

It was found that there were three types of drying curve:

(a) The drying rate was constant, i.e.

$$-\frac{dm}{dt} = k_0 \qquad \ldots \qquad (5.6)$$

where k_0 is a constant.

(b) The drying rate decreased linearly with moisture content (after an initial heat-up period), i.e. the curve could be described by

$$-\frac{dm}{dt} = a + bm \qquad \ldots \qquad (5.7)$$

where a and b are constants. The equation could also be written as

$$-\frac{dm}{dt} = k\ (m - m_e) \qquad \ldots \qquad (5.8)$$

where k and m_e are constants, k = b and m_e = -a/b

(c) The drying curve was made up of two or three linear sections (see fig.5.7), i.e. the drying rate decreased linearly with moisture content until a critical moisture content m_{c1} was reached, the rate of decrease of drying rate changed and a second linear section began, but with a smaller slope (k). This continued in some cases until a second critical moisture content was reached, m_{c2}, when the slope of the drying curve again decreased. These composite curves could be described by

$$m \geqslant m_{c1} \qquad -\frac{dm}{dt} = k_1\ (m - m_{e1}) \qquad \ldots \qquad (5.9a)$$

$$m_{c2} \leqslant m \leqslant m_{c1} \qquad -\frac{dm}{dt} = k_2\ (m - m_{e2}) \qquad \ldots \qquad (5.9b)$$

$$m \leqslant m_{c2} \qquad -\frac{dm}{dt} = k_3\ (m - m_{e3}) \qquad \ldots \qquad (5.9c)$$

Expressions (5.6), (5.8), and (5.9) can be integrated, with the initial condition

$$t = 0,\ m = m_o \qquad \ldots \qquad (5.10)$$

to give

from (5.6) $$m = m_o - k_o t \qquad \ldots \qquad (5.11)$$

from (5.8) $$\frac{m - m_e}{m_o - m_e} = e^{-kt} \qquad \ldots \qquad (5.12)$$

from (5.9)

$$m \geq m_{c1} \qquad \frac{m - m_{c1}}{m_0 - m_{c1}} = \exp(-k_1 t) \qquad \ldots \qquad (5.13a)$$

$$m_{c2} \leq m \leq m_{c1} \qquad \frac{m - m_{c2}}{m_{c1} - m_{c2}} = \exp(-k_2(t - t_{c1})) \qquad (5.13b)$$

$$m \leq m_{c2} \qquad \frac{m - m_{c3}}{m_{c2} - m_{c3}} = \exp(-k_3(t - t_{c2})) \qquad (5.13c)$$

where t_{c1} = time at $m = m_{c1}$ and t_{c2} = time at $m = m_{c2}$.

The derivations of these formulae and others is given in Appendix 12.5. The air temperature, T_a, determined which equation fitted the data. As a general guide, the range of validity of the equations can be stated thus:

$T_a > 200^\circ C$	Equations (5.6) and (5.11)
$80^\circ C < T_a \leq 200^\circ C$	Equations (5.8) and (5.12)
$T_a \leq 80^\circ C$	Equations (5.9) and (5.13)

5.6. <u>Calculation of Constants</u>

The values of the constants in an equation fitted to a set of data are very often taken as those values which give the smallest sum of the squares of the deviations of the points from the curve described by the equation. Many equations can be reduced to linear equations by suitable transformations of the variables and the least-squares regression method can be applied. The constants in equations (5.6), (5.8) and (5.9) can be determined as described below.

The constants in equation (5.6) can be obtained by fitting a straight line to the scatter-plot of moisture content against time using a least squares technique, or by a graphical method.

The constants in equation (5.8) can be determined by two methods:

(a) a straight line is fitted to the scatter plot of drying rate against moisture content using a least squares technique. This was done for two sets of points, the set obtained by the polynomial approximation method and the set obtained by the grouping and segmentation method. The drying rates were calculated from equation (5.5) for all the experimental curves after the values of the constants a_o, $a_1 \ldots a_n$ had been determined, and plotted against the actual moisture contents at those times. The drying rates calculated from the segmentation and grouping method were plotted against the average moisture contents of the intervals, see figs. 5.4 and 5.7.

A special case of equation (5.8) is where the term m_e is zero, and the equation becomes

$$-\frac{dm}{dt} = km \qquad \ldots \qquad (5.14)$$

then equation (5.12) becomes

$$m = m_o e^{-kt} \qquad \ldots \qquad (5.15)$$

The values of k and m_o in (5.15) can be found by using the least squares technique on a plot of $\log_e m$ against t since

$$\log_e m = \log_e m_o - kt \qquad \ldots \qquad (5.16)$$

The value of m_o should be the same as the initial moisture content. This value can be forced on the fitted line if $\log_e(m/m_o)$ is plotted against t and a straight line fitted, but forced to pass through the origin.

The constants in equation (5.9) can best be obtained graphically.

5.7. Choice of the Most Suitable Equation

In a previous section, the approximate limits of validity of each equation were set out. The choice of the most suitable equation for a set of data must be governed by some criterion. The correlation coefficient, standard error of estimate and average absolute deviation are sometimes used as criteria to compare the goodness of fit of equations.

5.7.1. Correlation coefficient

A measure of the scatter of a set of values about their mean is given by the variance s^2. The square root of the variance is known as the standard deviation. When the trend in a scatter of points, obtained by plotting a set of y values against a corresponding set of x values, is summarised by a straight line, the y-variance is due partly to the straight line trend and partly to the scatter of the points about the straight line. The square root of the fraction of the variance that is due to the straight line trend is called the correlation coefficient, r.

The correlation coefficient is calculated from

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{(n - 1)\ s_x\ s_y} \qquad \ldots \qquad (5.17)$$

$$= \frac{\sum xy - \sum x \sum y}{\sqrt{\left[n \sum x^2 - (\sum x)^2\right]\left[n \sum y^2 - (\sum y)^2\right]}} \qquad (5.18)$$

where

$\bar{x}$ = The mean value of x

$\bar{y}$ = The mean value of y

s_x = Standard deviation of the x values

s_y = Standard deviation of the y values

n = Number of pairs of x and y values.

The correlation coefficient measures the linear correlation between two variables, i.e. the degree to which a straight line relating x and y can summarise the trend in the scatter plot of y against x. Even if x and y are related non-linearly, the correlation coefficient indicates the extent to which the data can be described by a straight line relationship. The correlation coefficient always has a value between 0 and 1.

Very often non-linear relationships between variables can be reduced to linear relationships by taking suitable functions of the variables. Various non-linear relationships can be tested to see which is most suitable. The correlation coefficients are determined for the linear relationships to which they are reduced. In special situations, the relationship which gives the highest correlation coefficient can be chosen as the most suitable. Sometimes the scatter in the points may be so large that the correlation coefficients from different non-linear relationships may not be significantly different.

5.7.2. Standard Error of Estimate

The square root of the part of the y-variance which is unexplained by the straight-line trend is called the standard error of estimate and is calculated from

$$s_{y/x}^2 = \frac{n - 1}{n - 2} \left(s_y^2 - b^2 s_x^2\right)$$

where b = slope of the straight line

$s_{y/x}$ = standard error of estimate.

5.7.3. Average Absolute Deviation

The average deviation in the y-direction of a set of points from a line, (all deviations being considered positive), which summarises the trend in the points is a measure which is useful for comparing different relationships where the correlation coefficients cannot be compared. This deviation, however, measures the average deviation, and the deviation of the points from the line may be greater at one location than another. For example, if the trend in a set of points is parabolic, and a straight line is fitted, the correlation coefficient may be high, and the average absolute deviation and standard error of estimate may be low, but the straight line will fit better at the ends than in the middle.

5.7.4. Graph

In order to decide upon the most suitable equation, a fitted equation should be superimposed on the scatter plot. It can then be seen which equation fits best, and also how the scatter of the points varies along the line. Figure 6.6. shows some equations fitted to a set of experimental points by various means superimposed on the original points.

5.7.5. Choice of Criterion

The correlation coefficient r was used to compare the equations fitted to the results, but the graphical method was also used to examine how well the equations fitted.

5.8. Computer Programme

A computer programme was written to analyse the data. All the data was stored in a standard form on magnetic tape in one-dimensional blocks. The data for each run could be reformed in the core of the computer, and the calculations performed. All the different input forms of the data were converted into a standard form when the data was being written onto the magnetic tape, and simultaneously other calculations were performed such as calculating the humidity data from the readings taken, converting millivolt readings to temperatures, and determining the air flow rate from the pressure drop measurements.

The programme text, block diagram and a set of sample results are given in Appendix 13.1. A sample calculation is given in Appendix 12.4.

The action of the programme is described briefly below:

(1) After initializing the devices and declaring the variables, the first two blocks of data, containing information on the location and amount of the data for the various runs, were read from the magnetic tape.

(2) A number was read from the paper tape. If this was -1, then the programme terminated, otherwise, the number was taken as the number of the run whose data was to be processed and the action went to (3)

(3) The location and size of the block containing the data for the run to be processed was retrieved from the two directory blocks. The magnetic tape was unspooled to the appropriate point and all the data was read in from the magnetic tape and stored.

(4) If the run had been carried out on the High Temperature Rig or on the Low Temperature Rig, the weights were multiplied by a factor of 0.01 to allow for the scale setting on the electronic balance. Then a tare weight was subtracted from all the weights.

(5) The weight of dry-matter in the sample was calculated from the initial or final moisture content (see above).

(6) The moisture contents at different times were calculated from the weights, and the position of the first non-positive moisture content was noted, "newp".

(7) A straight line was fitted to the moisture content - time points, to "newp" points.

(8) A straight line was fitted to the moisture content - time points, up to ("newp"/2) points, i.e. the early part of the drying curve.

(9) The grouping frequency, s, was calculated.

(10) The moisture content and time values were taken in groups of s and averaged.

(11) The average drying rate and average moisture contents were calculated for the intervals.

(12) A straight line was fitted to the plot of average drying rate against moisture content.

(13) The values of the averaged times and moisture contents, and of the average drying rates and their corresponding moisture contents were printed out.

(14) The values of $\log_e(m/m_o)$ were calculated for all moisture contents greater than 0.3. A straight line was fitted to the plot of $\log_e(m/m_o)$ against time.

(15) The segmentation method was applied to the original moisture content - time points, calculating average drying rates and moisture contents.

(16) A straight line was fitted to the plot of average drying rate against average moisture content.

(17) The values of the average moisture contents and average drying rates were printed out.

(18) A polynomial of the eighth order was fitted to the moisture content - time points.

(19) The drying rates were calculated for all the times, from the coefficients of the polynomial.

(20) The values of time, moisture content and drying rates were printed out for selected points.

(21) A straight line was fitted to the drying rate - moisture content points, ignoring the first and last quarters of the points.

(22) Miscellaneous data and the main results were printed out.

(23) The co-ordinates of the curve calculated by the constants determined in steps (12), (21) and (14) were calculated and printed out at twenty equally spaced time values.

(24) The main results were punched onto paper tape.

5.9. Results of Calculations

The results of the calculations are given in tabular and graphical form.

5.9.1. Tables

For all runs, the values of k and m_e were determined by linear regression on the drying rates calculated by both the polynomial method and the segmentation and grouping method. The average drying rate, k_o, was determined for all the runs conducted on the high temperature rig. The values of k and m_e are shown in tables 5.1 to 5.24 for the medium temperature experiments, in table 5.29 for the low temperature experiments, and the values of k, m_e and k_o for the high temperature experiments are shown in tables 5.31 to 5.44. For those runs which showed more than one drying period, the values of k_1, k_2, k_3, m_{e1}, m_{e2}, m_{e3}, m_{c1}, m_{c2} were determined graphically and they are given in table 5.28 for the medium temperature experiments, and in table 5.30 for the low temperature experiments. The number of periods in the drying curve depended on the temperature and humidity of the drying air, but generally for temperatures above 80°C only one period of drying was observed.

5.9.2. Graphs

The values of k are plotted against air temperature in figs.5.16 to 5.30 for the medium temperature experiments, and in figs.5.37 to 5.49 for the high temperature experiments. The values of M_e are plotted against temperature in figs. 5.50 to 5.52 for the medium temperature experiments.

The values of k obtained for the different parts of the drying curve for the low temperature runs are plotted against temperature in fig.5.31 and the corresponding values of M_e are plotted against temperature in fig.5.53.

k is plotted against leaf to stem ratio (l_s) in figures 5.67 to 5.69 for 100°C for whole grass, leaves and stems.

k is plotted against air velocity for different temperatures, in figs.5.34 to 5.36 for batches 20, 21 and 22.

k_o is plotted against air temperature for the high temperature runs in figs.5.54 to 5.66.

5.10. Correlation of the Results

The relationship between the drying parameters and the operating parameters is given in the form of equations below.

5.10.1. k and Air Temperature, T_a

It can be seen from the plots of k against air temperature, that the relationship is not linear. A plot of $\log_e k$ against T_a, however, is almost linear, and therefore, the following equation is proposed:

$$\log_e k = K_a + K_b T_a$$

$$k = K_a' \exp(K_b T_a) \qquad \ldots \quad (5.19).$$

where K_a, K_b and K_a' ($= \exp(K_a)$) are constants. The values of these constants are given for the different run series in tables 5.45, 46, 47 and 49a, together with the correlation coefficients.

5.10.2 k and Air Velocity, v

The relationship between k and the velocity of the air was determined only for experiments on the medium temperature rig. The results can be approximated by

$$\log_e k = K_c + K_d v$$

$$k = K_c' \exp(K_d v) \qquad \ldots \qquad (5.20)$$

where K_c, K_d and K_c' ($= \exp(K_c)$ are constants. Rather than interpolate the results, however, since the air temperature was not held absolutely constant while varying the velocity, the following equation was fitted to the data by multiple linear regression:

$$\log_e k = K_g + K_h T_a + K_j v$$

$$k = K_g' \exp(K_h T) \exp(K_j v) \qquad \ldots \qquad (5.21)$$

where K_g, K_h, K_j and K_g' ($= \exp(K_g)$) are constants. The values of these constants are given in tables 5.48 and 5.49. Note that the constant K_h and the constant K_b are comparable.

5.10.3. k and the Leaf to Stem Ratio, l_s

The relationship between k and leaf to stem ratio at constant temperature and velocity is approximated by

$$k = K_m + K_n l_s \qquad \ldots \qquad (5.22)$$

where K_m and K_n are constants. The values of these constants are given in table 5.51 for 100°C. Another way of showing the dependency on leaf to stem ratio is to relate the constants in equation (5.19) or (5.21) to l_s, i.e.

$$K_a = K_{1a} + K_{2a}\, l_s \qquad \ldots \qquad (5.23)$$

$$K_b = K_{1b} + K_{2b}\, l_s \qquad \ldots \qquad (5.24)$$

where K_{1a}, K_{2a}, K_{1b} and K_{2b} are constants. The values of these constants are given in table 5.52.

5.10.4. m_e and Air Temperature and Humidity

The parameter m_e is dependent on both the air temperature and humidity. The relationship can be expressed by

$$m_e = K_p + K_q \sqrt{\frac{x_a}{T_a^2}} \qquad \ldots \qquad (5.25)$$

where K_p and K_q are constants and x_a is the absolute humidity of the air. The values of K_p and K_q are given in table 5.48.

At constant humidity, the dependency of m_e on the air temperature can also be given by

$$m_e = K_t + K_w T_a \qquad \ldots \qquad (5.26)$$

where K_t and K_w are constants. The values of K_t and K_w are given in table 5.48.

5.10.5. The constant drying rate k_o and Air Temperature

The constant drying rate k_o is related to the air temperature by

$$k_o = K_r + K_s T_a \qquad \ldots \qquad (5.27)$$

where K_r and K_s are constants. The values of these constants are given in table 5.53.

5.10.6. k_o and the maturity, l_s

The constants in equation (5.26) are related to the leaf to stem ratio by

$$K_r \quad = \quad K_{1r} + K_{2r}\, l_s \qquad \ldots \qquad (5.28)$$

and

$$K_s \quad = \quad K_{1s} + K_{2s}\, l_s \qquad \ldots \qquad (5.29)$$

where K_{1r}, K_{2r}, K_{1s} and K_{2s} are constants, which are given in table 5.54.

5.10.7. The Effect of Chop Length

From the plots of k and k_o against the temperature, in figs.5.37 and 5.54, it can be seen that the chop length has no significant effect on the drying properties in the range 1" to 4".

5.11. Summary

Above 200°C the drying of whole grass can be described by

$$-\frac{dm}{dt} = k_o$$

where $k_o = -\,1.5043 + 0.02497\ T_a$

Taking all the results, leaves and stems included,

$$k_o = -\,0.18396 + 0.02468\ T_a.$$

Below 200°C, the drying equation is

$$-\frac{dm}{dt} = k(m - m_e)$$

where $k \quad = \quad 0.02565 \exp(0.01957\ T_a)$

$m_e \quad = \quad 32924 - 0.22455\sqrt{x_a}/T_a^{\,2}$

Below 80°C, the equation consists of up to three parts, each of the form

$$-\frac{dm}{dt} = k_i(m - m_{oi})$$

where k_i and m_{oi} are related to the air temperature and humidity by (5.19) and (5.25). The constants in these equations are given in tables 5.47 and 5.50.

CHAPTER VI

DISCUSSION OF RESULTS

6.1. The Biology of Grass

In order that the results may be discussed in terms of the structure of the grass, a short description of some of the relevant topics is given.

6.1.1. Anatomy of Grass

A grass plant is made up of roots, leaves and stems. The roots are usually numerous and fine and their many branches form a dense fibrous mass.

The stems are cylindrical and hollow, except at the nodes where they are solid. The leaves are arranged on the stem in two alternating rows and consist of two distinct parts - the sheath which is attached to the stem at a node and encloses the younger folded leaves, and the blade which is free. The leaf blades may vary considerably in size and shape, but they are usually long and narrow. The leaf blade may also be folded, rolled, expanded or very much thickened, and it is often covered with ribs or ridges. The sheath is a tubular structure which may be split or entire.

6.1.2. The Cellular Structure

All plants are made up of cells, units consisting of an outer wall enclosing an inner space. The size, shape and contents of cells varies considerably from plant to plant and within the plant according to the function they perform. The cell walls consist mainly of cellulose arranged in layers. There is also a complex system of interfibrillar spaces which are very narrow and act as fine irregular capillaries. When the plant is exposed to very humid air, these spaces are filled with water and water also lies on the outside of the cell walls adjoining the intercellular spaces (see below). The cell walls are very permeable to water and solutes.

The living part of the cell is the protoplast and consists of the cytoplasm and the nucleus. The cytoplasm is a viscous fluid and the nucleus rests in it. As a cell grows older, it becomes larger, but the cytoplasm is greatly reduced in size until it forms a lining around the inside of the wall, from which it is separated by a membrane called the plasmalemma. The space previously occupied by the cytoplasm is taken up by the vacuole. This occupies the large central region and is filled with a watery fluid called the cell sap. The vacuole is separated from the cytoplasm by the vacuolar membrane or tonoplast.

Figure 6.1. shows a cross-section of a leaf of Italian Rye Grass as seen under a microscope$^{(10)}$. The following features should be noted (The letters refer to figure 6.1):

A. The ribs. These are upward.

B. The vascular bundles or veins lie in parallel lines running from the base of the leaf to its apex and are connected cross-wise at irregular intervals. They usually lie between the ribs and each bundle is surrounded by a sclerotic sheath.

C. The epidermal cells are regularly shaped and lie just below the cuticle (D), which is waxy and very impervious to water. Together, these act as a covering for the interior of the leaf.

E. The mesophyll, a mass of soft spongy cells takes up most of the interior of the leaf. Most of the living processes of the plant take place here. The mesophyll is characteristically green due to the presence of the substance chlorophyll. There are also air spaces throughout the mesophyll called intercellular spaces (F).

G. At the base of the ribs are the stomata. Through these the plant receives carbon dioxide and oxygen, and releases water vapour. There are many stomata on a plant, 50 to 500 per square millimeter, and they are very well controlled in order to regulate the passage of vapours and gases through them.

H. Two guard cells surround each stoma. The moisture content of these cells changes with the humidity of the atmosphere. When the moisture content decreases, by water diffusing to an adjacent cell, the guard cells become less turgid, or stiff, and relax. The stoma is thereby closed, and loss of moisture is prevented. The reverse happens if the moisture content of the cells increases. These guard cells and other motor cells are responsible for the leaf rolling up to prevent loss of moisture.

Figure 6.2. is a cross-section of a shoot, and it can be seen that it is made up of a number of rolled young

leaves. Figure 6.3 is a schematic cross-section of a stem showing the vascular bundles which carry the water and minerals to the various parts of the plant.

6.2. Transpiration and Respiration

Water accounts for most of the matter in a living plant, up to 95% in some plants, and is absolutely essential for life. However, a plant needs many elements for healthy growth, and it obtains these from salts dissolved in water around its roots. The solutions are absorbed almost continuously by the roots and pass to all parts of the plant. Most of the water taken in by the roots is lost in transpiration from the leaves, for example, 98% in maize plants. A small portion of the remainder which is retained combines chemically with carbon dioxide, which is absorbed through the stomata on the leaves, by photosynthesis, to form sugars and other carbohydrates. In the maize plant, this portion is about 0.2% of the water taken in by the roots. The carbohydrates which are formed combine with the mineral salts to form new cell walls and other protoplasmic substances. Plants also respire like animals, thereby releasing carbon dioxide and energy from the carbohydrates. Respiration is the reverse of photosynthesis. Photosynthesis requires solar energy and occurs only in daylight, when the effects of the respiration process are completely masked by those of the photosynthesis process(58).

The soil solutions pass through the roots to the various parts of the plants through vessels or channels formed by the walls of the xylem, collected to form vascular bundles.

Transpiration involves the processes of evaporation and diffusion. Under suitable conditions, molecules of water detach themselves from exposed cell surfaces adjoining the intercellular spaces inside the leaves, and they diffuse through the stomata to the outside air. Most of the water is lost through the stomata although diffusion through the walls of the epidermal cells, cuticular transpiration, also occurs. The ratio of stomatal transpiration to cuticular transpiration ranges from 4:1 in thin-leaved plants to 1000:1 in thick-leaved succulents.

The most important external factor controlling transpiration in a well-watered plant, in still air and sunlight, is the humidity of the atmosphere, i.e. so long as the vapour pressure of the water in the intercellular space is greater than the vapour pressure in the outside air diffusion through the open stomata will take place. The rate of diffusion through the stomata is extremely high for their size and a leaf with fully-open stomata can lose as much water as a free water surface(58).

The rate of water loss can be expressed by(58):

(After Browne & Escombe)

$$Q_w = \frac{D\ (p_i - p_o)\ n_s\ A_{ms}}{L_{ms} + \frac{\pi r_s}{2}} \qquad \ldots \qquad (6.1)$$

where Q_w = Volume of water vapour lost per hour $ft^3/hr.ft^2$

D = Diffusion constants $ft^4/lbf\ hr.$

p_i = Partial Pressure of water vapour in the intercellular space. lbf/ft^2

p_o = Partial Pressure of Water vapour in the atmosphere. lb/ft^2

n_s = Number of stomata per unit surface area of leaf.

A_{ms} = Mean area of a Stoma ft^2

L_{ms} = Mean length of a stomatal tube ft.

r_s = Mean radius of a stoma ft.

Water is continuously moving through the plant by diffusion from cell to cell. When it reaches an intercellular space it is vaporised and is carried out through the stomata. The water moves by diffusion under a negative pressure force. It can be shown that evaporation of water from a porous pot produces exactly the same negative pressure effect. Jones and Palmer(35) list the natural forces responsible for the passage of water through living stems as (1) Capillarity; (2) Osmotic pressure; (3) The "Pull of Transpiration".

6.3. The Form of the Drying Equation

It is not possible to say precisely at what stage one type of equation ceases to describe the drying of grass and another one takes over. This is because often at least two types of equation can fit a set of data. For example, an exponential equation with a very small rate constant, k, and a very negative asymptote can fit a set of data obtained at high temperatures just as well as a straight line (see fig.6.6). The point at which an exponential equation gives way to a linear equation is, therefore, rather vague. Neither is the change from a two or three-period exponential equation to a single-exponential equation clearly defined. The approximate limits of validity for each type of equation, however, can be stated as:

$$T_a \geqslant 200^\circ C \qquad -\frac{dm}{dt} = k_o \quad \ldots \quad (6.2)$$

$$80^\circ C \leqslant T_a \leqslant 200^\circ C \qquad -\frac{dm}{dt} = k(m - m_o) \quad (6.3)$$

$$T_a \leqslant 80^\circ C \quad \begin{cases} m \geqslant m_{c1} & -\frac{dm}{dt} = k_1(m - m_{e1}) \quad (6.4a) \\ m_{c2} \leqslant m \leqslant m_{c1} & -\frac{dm}{dt} = k_2(m - m_{e2}) \quad (6.4b) \\ m \leqslant m_{c2} & -\frac{dm}{dt} = k_3(m - m_{e3}) \quad (6.4c) \end{cases}$$

The choice of these limits is based on an examination of the drying curves, although it is arbitrary.

An examination of the plots of k against temperature shows that the scatter in a plot increases as the temperature increases. This is because the drying rate is constant at high temperatures, so that k has no real meaning. The value of k should, in fact, be zero:

$$-\frac{dm}{dt} = 0.m + k_o \quad \ldots \quad (6.5)$$

Due to experimental error, however, the drying curve is not a perfectly horizontal line, giving k = 0, and consequently k can assume a wide range of values, depending on the scatter, even to the extent of becoming negative.

6.4. The Constant Rate Equation - Effect of High Temperatures

Equation (6.2) indicates a constant drying rate, independent of the moisture content of the grass. This phenomenon is usually associated with evaporation from a free-water surface, and it implies that the controlling resistance to moisture movement does not lie within the grass. The constant rate was only found at temperatures above 200°C and the rate was found to depend on the air temperature as follows:

$$k_o = K_r + K_s T \qquad \ldots \qquad (6.6)$$

where K_r and K_s are constants. When grass is dried artificially, it is subjected to much higher temperatures than it is in the field and the rate of water loss by drying is much greater than the loss by transpiration. Since the grass is still alive for some time after it has been cut, the automatic reflexes of the guard cells will close the stomata as the air temperature is raised so that transpiration cannot take place. Whitney et al(82) claimed that at very high air temperatures the drying rate of alfalfa was affected by the degree of opening of the stomata. A closer examination of their results, however, shows that the degree of aperture has little effect, and, if anything, open stomata tend to give a lower drying rate than closed stomata. In addition, the degree of aperture of the stomata is very unlikely to remain at the value at which it is measured prior to drying.

An increase in the temperature of the drying air increases the rate of loss of water from a plant very much. This could be explained by the increase in the diffusion coefficient with temperature which is usually expressed by an Arrhenius type of equation

$$D = D_o \exp(-B/T_{abs})$$

where D = Diffusion Coefficient

D_o and B are constants

T_{abs} = Absolute Temperature.

This increase would result in a decrease in the cuticular resistance. The high air temperature, however, probably produces a fundamental physical change in the grass(72). Dyers and Routley(11) exposed alfalfa stems to steam and then examined them under a microscope. They found indications of melted wax. In addition, the drying rate was increased considerably by the steaming. The melting point of the cuticular waxes is about 80°C, but the grass temperature probably remains below the air temperature during drying because of evaporative cooling. The wax, therefore, will probably not melt until the air temperature is raised considerably above 80°C.

The work of Thaine(70) proved that the removal of the cuticular waxes increased the rate of drying. He removed the waxes by immersion of the plant in petroleum vapour, and compared the drying rate of treated and untreated grass. A considerable improvement in the drying rate was observed after treatment, and the drying rate was almost constant during the first stages of drying. The removal of the cuticular waxes also reduced the resistance to heat transfer, so that the leaf heated up more quickly and to a higher temperature. This explained part of the increase in the drying rate. The removal of the cuticular waxes must also reduce the resistance to mass transfer in the plant to less than the resistance in the surrounding air. The air resistance then becomes the controlling resistance and a constant drying rate results.

6.5. The Exponential Equation - Diffusion

Equation (6.3) above is the same as that proposed by Allen(2), Henderson and Pabis(32), Simmonds, Ward and McEwen(65), O'Callaghan(49) and Boyce(8) to describe the drying of thin layers of grain. The equation postulates that the drying rate is directly proportional to the difference between the moisture content (dry basis) of the grass and a limiting value of the moisture content. This implies that the controlling resistance to drying lies within the grass. The limiting value of the moisture content is known as the equilibrium moisture content. In order to have a physical interpretation, the equilibrium moisture content should be positive, unless there is a loss of dry-matter. It follows that if there is a loss of dry-matter the equilibrium moisture content may be negative. This loss of dry-matter does occur at high air temperatures, as shown by the charring of the edges of the grass. Whitney et al(79, 80, 81, 82) described the drying of alfalfa leaves at high temperatures, up to 800°C by the equation

$$-\frac{dm}{dt} = km \qquad \ldots \quad (6.7)$$

This is a special case of (6.3) with $m_c = 0$ and implies that there is no dry-matter loss at high temperatures. There is, however, a loss, and therefore equation (6.7) is not suitable for high temperatures. At about 100°C, the value of m_c is zero, and then equation (6.7) is valid. In addition, an examination of Whitney's data(79) shows a considerable scatter so that either (6.2), (6.3) or (6.7) could equally well have been fitted to them. In cases like this, where many equations can be fitted to one set of data, the simplest equation should be chosen unless there are strong reasons for choosing another one.

Equation (6.3) can also be obtained by postulating that the drying rate is proportional to the difference between the saturated vapour pressure of the material and the vapour pressure of water in the drying air, i.e.

$$-\frac{dm}{dt} = k_g\, A_{mt}\, \frac{p_s - p_a}{\Delta z} \qquad \ldots \qquad (6.8)$$

where k_g = overall mass transfer coefficient, ft/lbf hr.

A_{mt} = Area through which mass transfer takes place, ft^2

p_s = Saturated water vapour pressure of the material, lbf/ft^2

p_a = Water vapour pressure of the air, lbf/ft^2

Δz = Distance through which mass transfer takes place, ft.

This is a diffusion equation.

The moisture content of the material which is in equilibrium with air of vapour pressure p_a is m_e, and m is the moisture content which is in equilibrium with air whose water vapour pressure is p_s, thus the equation (6.8) reduces to (6.3).

The drying constant k was related to the air temperature T_a by

$$k = K_a' \exp(K_b T_a) \qquad \dots \quad (6.9)$$

where K_a' and K_b are constants. This is the same form as that found by Whitney et al$^{(81)}$ for the k in (6.7). Boyce$^{(8)}$ and Henderson and Pabis$^{(32)}$, however, showed that for thin-layer grain drying

$$k = K_a'' \exp(K_b''/T_{abs}) \qquad \dots \quad (6.10)$$

where T_{abs} is the absolute air temperature. It was proved, however, that (6.10) did not describe the temperature dependency of k for grass.

At low temperatures, on the medium temperature rig, it was found that the drying constant k was affected by the velocity of the air. The form of the relationship was

$$k = K_c' \exp(K_d v) \qquad \dots \quad (6.11)$$

at constant temperature

where K_c' and K_d are constants and v is the mass velocity of the air (lb/min.ft^2). The data however, was in such a form that it was easier to fit a composite equation of the form

$$k = K_g' \exp(K_h T_a) \exp(K_j v) \qquad \dots \quad (6.12)$$

where K_g', K_h and K_j are constants. The velocity of the air should not have affected the drying characteristics of the grass if the controlling resistance to drying lay within the grass. It may have been that the thickness of the layer of grass in the experiments, ½", was too thick for the assumptions of thin-layer conditions to be justified. This would also account for the long heat-up periods in some of the runs.

The parameter m_e, known as the equilibrium moisture content, was found to depend on the temperature of the air, and to a lesser extent on the humidity. McEwen and O'Callaghan(41) and Boyce(8) proposed the relationship

$$m_e = K_p + K_q \sqrt{x_a}/T_a^2 \qquad \ldots \qquad (6.13)$$

where K_p and K_q are constants, and x_a is the absolute humidity of the air.

Henderson(31) proposed

$$\frac{\log_e(1 - rh)}{-n_2 \, T_{abs}} = m_e^{n1} \qquad \ldots \qquad (6.14)$$

where rh = Relative humidity of the air, decimal.

n1 and n2 are constants

A simpler relationship is

$$m_e = K_p + K_q \, T_a \qquad \ldots \qquad (6.15)$$

which ignores the effect of humidity.

All of these relationships were fitted, but (6.13) was found to give the best fit by a small margin.

6.6. The Low-Temperature Equations

It was found that at air temperatures below 80°C, the drying curve showed as many as three distinct periods of drying, each period being described by an exponential equation (6.4) see fig. 6.7. The relationship between the rate constant k_i ($i = 1, 2, 3$) in each period and the air temperature was of the form (6.9), and the relationship between the asymptote in each period, m_{ci} ($i = 1, 2, 3$) and the air temperature and humidity was of the form in (6.13). However, the correlation between m_c and humidity was very low. The second critical moisture content, m_{c2}, did not seem to be related to any variables, but there was a correlation of 0.609 between m_o and m_{c1} for the low temperature runs.

One way of interpreting the three periods of drying is as follows: Water in a living plant exists in three different forms, each form being distinguished by the ease with which it can be removed by drying. When the grass is dried, water is removed at first from those regions where it is held most loosely. As the water store is depleted, the resistance to drying increases and the drying rate decreases. When a critical moisture content m_{c1} is reached the second region also loses water, as the resistance to removal in the first and second regions is equal. There is now a much larger quantity of water which can be removed, so that the drying rate does not drop off so steeply. The resistance to removal does, however, increase as more and more water is removed, and the drying rate decreases further. When a second critical moisture content m_{c2} is reached, the resistance to removal of water in the first two regions is equal to that in the third and this also loses water. The rate of decrease of the drying rate is lowered further still as more water becomes available for removal. When the equilibrium moisture content m_{e3} is reached, the drying ceases, as each region is at equilibrium with the air.

One may conjecture as to what the three forms of water are. A possible explanation is:

(a) Liquid water exists on the outsides of the cell walls adjoining the intercellular spaces and on the external surface of the leaf.

(b) Water is present in weak aqueous solutions in the vacuoles.

(c) Water is present in strong aqueous solutions in the cytoplasm.

The relationship between the initial moisture content and the first critical moisture content suggests that there is in grass a certain amount of moisture which is easily removed and the amount of which is independent of the moisture content of the grass. This agrees with the postulation of water existing in the intercellular air spaces and on the surface of the plant, given above. When grass is dried, this water is the first to be released. When it has all been driven off, the first critical moisture content is reached. Grass which is left undisturbed will probably always have some of this loosely held water, and hence will always have a first critical moisture content, if it is dried.

At higher temperatures, this critical moisture content was not evident, probably because the removal of the loosely held water took place so quickly that the event was not detectable. The difference between the initial moisture content and the first critical moisture content represents the amount of water held in this loose state. Suppose that the grass is dried to beyond its first critical moisture content and then left undisturbed for a while. When the drying is started again, another critical moisture content will be observed. The moisture content gradients within the grass are removed while it is left undisturbed, and some water migrates from the regions where it is held more tightly, into the intercellular air spaces. Randall(57) showed that by suspending the drying process, the moisture content gradient in the grass was removed, and upon resumption of the drying, the initial drying rate was much higher than the rate when the drying was stopped.

In Appendix 12.6., a mathematical treatment of the three-part curve is given.

6.7. Effect of Grass Physical Properties

The general conclusions on the effects of the grass physical properties may be summarised as:

(a) On average, leaves dried twice as fast as stems of Italian Rye Grass.

(b) Younger grass dried slightly faster than older grass, including leaves and stems alone.

(c) The drying characteristics were unaffected by chopping the grass into lengths from 1" to 4".

(d) Perennial Rye Grass dried about twice as fast as Italian Rye Grass.

These conclusions are substantiated by an examination of the physical properties of the grass.

Leaves dry more rapidly than stems for two reasons (a) the epidermis and cuticle of a stem are about 5 times thicker than those of a leaf and (b) the water has further to travel to the surface in a stem than in a leaf.

Bagnall(4,5) has shown that the axial diffusion coefficient of stems of alfalfa is ten times greater than the radial diffusion coefficient, and 1000 times greater than the epidermal diffusion coefficient. A large proportion of the drying takes place through the cylindrical sides, however, since the end area is very small relative to the area of the sides unless the stems are chopped into very short lengths. Mears and Roberts(44) showed that unless the stem length is reduced to near the stem diameter (i.e. $\ell/d = 1$), which is about 1/10" for rye grass, not much improvement in drying can be expected. It is also to be expected that leaves which are chopped into very small pieces will dry faster since the moisture will be able to escape through the open sides as well as through the epidermis and cuticle.

As grass grows older, it becomes tougher and the thickness of the epidermis increases. Younger grass therefore dries more quickly than older grass.

Perennial Rye Grass generally dries twice as fast as Italian Rye Grass. This is probably due to the smaller leaves and lower leaf to stem ratio, which is a property of Perennial Rye Grass.

6.8. Mechanism of Moisture Movement within the Plant

The water in the grass being dried will always move along the path of least resistance. Since resistance in the leaves and stems is different in distribution and magnitude, due to the different structure, the path along which the water moves will be different in each. At low temperatures water in the stems moves in an axial direction and in a radial direction. When the whole grass is dried, some of the water moves into the leaves from the stems, since the resistance to water removal is lower in the leaf than in the stem. In the leaves, water is probably lost through the stomata at low temperatures (up to 80°C) and through the epidermis and stomata together at higher temperatures.

It has been noted by Slatyer(66) that the **rate** of moisture flow under normal conditions along the cell walls is fifty times that through the cell walls (see fig.6.4). Although the resistance in the cell walls is low, the cytoplasm on the inside offers a considerable resistance to the movement of water. The water probably moves along its path under the overall concentration difference $(m - m_e)$ or $(p_s - p_a)$.

In high temperature pneumatic driers, the grass is subjected to temperatures up to 1000°C for short times, but very little of it is burnt. The loss of heat from the grass due to evaporation of water keeps it cool until it passes to a region of colder air where it will not burn. The moisture, therefore, moves within the leaf as a liquid rather than as a vapour and the plane of vaporisation does not retreat into the grass to a significant extent. If the drying is carried on for long enough, however, it is likely that the surface of evaporation eventually retreats into the interior of the grass and the water moves part of the way as a vapour.

Sections of grass which had been dried at about 100°C were cut and studied under a microscope. A burst cell was observed in only one case out of many sections, indicating that the temperature of the leaf was below 100°C. If the leaf temperature had suddenly jumped to 100°C, some of the cells would have burst.

The high resistance of the cytoplasm at low temperatures is probably also maintained at high temperatures so that the water moves along the cell walls rather than across them. It is almost certain that the cuticular waxes melt at high temperatures so that all the loss of water occurs through the epidermis.

6.9. Heat Transfer Aspects of Grass Drying

It has been pointed out, that due to the evaporative cooling the temperature of the grass is probably much lower than that of the drying air. It is very difficult to measure the temperature changes in such a small particle as a piece of grass, but an attempt was made, using very large stems, to measure the changes in temperature of the stems as they dried. One of the plots of temperature against time is shown in fig.6.5. It can be seen that it took some time for the stems to reach the temperature of the drying air. This was due to both evaporative cooling and slow heat conduction and convection heat transfer. Calorimetric techniques are difficult to apply to grass and grain, due to the phenomenon of heat of solution and also to the bulky nature of the material and its low specific heat.

The specific heat of a moist material may be expressed as

$$c_p = \alpha + \beta m \quad \text{Btu/lb.dry matter}^{\circ}\text{F} \qquad \ldots \qquad (6.18)$$

where α and β are constants and m is the moisture content dry basis. α may or may not be a function of moisture content. (6.18) can be rewritten as

$$c_p = c_{pd}\,(1 + \gamma m) \qquad \ldots \qquad (6.19)$$

where γ is a constant and c_{pd} is the specific heat of the dry matter at $m = 0$. If $\gamma = 1$ then the specific heat of the dry matter is independent of the moisture content. It has been found that for grain $\gamma = 1$, and $c_{pd} \cong 0.3$.

Moran(47) has shown that the momentum transfer data obtained by measuring the pressure drop characteristics of grass can be correlated by considering the grass as infinitely long circular cylinders. Convective heat transfer coefficients can be calculated for grass on this basis also using an equation of the form:

$$h_c = c\ Re^a\ Pr^b \qquad \ldots \qquad (6.20)$$

where a, b and c are constants, and h_c is the convective heat transfer coefficient, Btu/hr ft^2 °F.

6.10. Conclusions

The drying of grass can be described by equations (6.2), (6.3) and (6.4) within the limits of validity shown. The influence of air temperature, velocity and humidity and grass maturity, are given by equations (6.5), (6.9) and (6.12). The constants in the equations are given in the tables in Chapter 5.

The mechanism of drying is probably liquid diffusion along the cell walls and the veins. At temperatures below 80°C, water is released at first from those regions where it is held least tightly, the intercellular spaces, and out through the stomata. At high temperatures, the different states of the water do not seem to influence the drying.

At very high temperatures, the cuticular waxes melt and water is lost directly through the epidermis. The temperature of the grass is kept below the temperature of the drying air by evaporative cooling.

CHAPTER 7

SIMULATION OF A DEEP-BED DRIER

7.1. Introduction

If the drying characteristics of thin layers of a material are known, the changes in moisture content and temperature which occur during the through-flow drying of deep beds of the material can be predicted. The calculation process is basically a numerical integration with respect to time and position, the deep bed being considered as a stack of thin layers.

A number of workers have developed mathematical models of deep-bed drying, but most of the work has been confined to grain drying. Boyce(8) and Spencer(67) have simulated a static deep-bed grain drier and Ahn et al(1) have simulated a cross-flow grain drier. Thygeson and Grossman(71) developed a technique for optimizing the performance of a static deep-bed drier.

7.2. Theory

When a thin layer of material is dried by through-flow of air, the conditions of the material and of the air are altered. The changes which occur are specified by the changes in the temperature and humidity of the air and in the temperature and moisture content of the material. Four independent equations are needed to determine the changes in the conditions: the drying rate equation, the mass balance equation, the heat balance equation, and the heat transfer equation.

7.2.1. The Drying Rate Equation

The drying rate of most materials can be simply related to the moisture content and temperature of the material and the humidity and temperature of the air. It has been shown that the drying equation for grass in the temperature range 80°C to 200°C is

$$-\frac{dm}{dt} = k(m - m_e) \qquad \ldots \qquad (7.1)$$

i.e.

$$dm = -k(m - m_e)dt \qquad \ldots \qquad (7.2)$$

where m = moisture content of the grass or grain, lb/lb, dry basis

t = time, minutes

k, m_e are constants, functions of the temperature and humidity.

Thus, after an interval of time Δt, the moisture content of the layer has changed from m to $m' = m + \Delta m$ (7.3)

where

$$\Delta m = -k(m - m_e)\Delta t \qquad \ldots \qquad (7.4)$$

m is assumed to be constant for the purpose of evaluating Δm. If the average moisture content over the time interval is taken as $m + \Delta m/2$, the equation becomes

$$\Delta m = \frac{-k(m - m_e)\Delta t}{(1 + \frac{1}{2}k\Delta t)} \qquad \ldots \qquad (7.5)$$

7.2.2. Mass Balance Equation

Let the cross-sectional area of the layer be A ft^2 and its thickness Δz ft. After a time Δt, a quantity $A G \Delta t$ of dry air will have flowed through the layer in the z-direction, where G is the mass flow rate of dry air, lb dry air/min-ft^2. The temperature and humidity of the air will change from T_a to T'_a and from x_a to x'_a respectively. The temperature and the moisture content of the material in the layer will change from T_g to T'_g and from m to m' respectively. Letting ρ_d = the bulk density of dry matter in the layer, lb/ft^3, and taking a mass balance about the layer, over a time interval Δt:

$$A\ G\ \Delta t\ x_a + A\ \Delta z\ \rho_d\ m = A\ G\ \Delta t\ x'_a + A\ \Delta z\ \rho_d\ m' \qquad (7.6)$$

hence

$$x'_a - x_a = \Delta x_a = \frac{\rho_d\ \Delta z}{G\ \Delta t}\ \Delta m \qquad \ldots \qquad (7.7)$$

Δx_a can be evaluated since Δm is known from equation (7.5).

7.2.3. Heat Balance Equation

Let c_{pd} be the specific heat of the dry matter in the material, Btu/lb-^oF, let 32^oF be the reference temperature for calculating the enthalpy of water, and let h be the enthalpy of the air, Btu/lb dry air. Then:

Energy lost by air = Energy gained by material

$$A\ G\ \Delta t\ (h-h') = A\ \rho_d \Delta z \left[(c_{pd} + m)(T'_g - T_g) + \Delta m\ (T'_g - 32)\right] \qquad (7.8)$$

or

$$A\ G\ \Delta t\ (h-h') = A\ \rho_d \Delta z \left[(c_{pd} + m')(T'_g - T_g) + \Delta m\ (T_g - 32)\right] \qquad (7.9)$$

A study of these equations will show that they are equivalent.

The enthalpy of moisture bearing air, h, is expressed thus, in Btu/lb dryair:

$$h = c_{pa}\ (T_a - T_{ao}) + x_a \left[c_{pwv}\ (T_a - T_e) + L_{ve} + c_{pw}\ (T_e - T_{wo})\right] \qquad \ldots \qquad (7.10)$$

where

c_{pa} = Specific Heat of Air = 0.2405 Btu/lb dry air-°F

c_{pwv} = Specific Heat of Water Vapour = 0.448 Btu/lb-°F

c_{pw} = Specific Heat of Water = 1 Btu/lb °F

T_a = Dry bulb temperature of the air, °F

T_{ao} = Reference temperature for air = 0°F

T_{wo} = Reference temperature for water = 32°F

T_e = Temperature at which the Latent heat of vaporisation is calculated, °F

L_{ve} = Latent heat of vaporisation of water at T_e = 1075.8965 Btu/lb for $T_e = 32$°F

Let $T_e = 32$°F, then

$$h = 0.2405\ T_a + x_a\ (0.448 T_a + 1061.54) \qquad \ldots \qquad (7.11)$$

Substituting into (7.9) above

$$0.2405\ T'_a + x'_a\ (0.448\ T'_a + 1061.54) - \left[0.2405\ T_a + x_a\ (0.448\ T_a + 1061.54)\right] =$$

$$- \frac{\Delta z\, \rho_d}{G\ \Delta t} \left[(c_{pd} + m')(T'_g - T_g) + \Delta m\ (T_g - 32)\right] \qquad (7.12)$$

$$\text{Let } F' = - \frac{\Delta z\, \rho_d}{G\ \Delta t} \qquad (7.13)$$

Then

$$T'_a(0.2405 + 0.448\ x'_a) = T_a(0.2405 + 0.448\ x_a) + T'_g \left[F'(c_{pd} + m')\right] + T_g \left[-F'(c_{pd} + m' - \Delta m)\right] + \left[(1061.54\ (x_a - x'_a) - 32\ F'\, \Delta m\right] \qquad \ldots \qquad (7.14)$$

i.e. $$\xi T'_a = \eta T'_g + \iota T_g + \kappa T_a + \lambda \quad \ldots \quad (7.15)$$

where

$$\left.\begin{aligned} \xi &= 0.2405 + 0.448\, x'_a \\ \eta &= F'(c_{pd} + m') \\ \iota &= -F'(c_{pd} + m) \\ \kappa &= 0.2405 + 0.448\, x_a \\ \lambda &= 1061.54\,(x_a - x'_a) - 32\, F' \Delta m \end{aligned}\right\} \quad \ldots \quad (7.16)$$

Or

$$T'_a = \pi T'_g + \sigma \quad \ldots \quad (7.17)$$

where

$$\left.\begin{aligned} \pi &= \eta / \xi \\ \sigma &= (\iota T_g + \kappa T_a + \lambda)/\xi \end{aligned}\right\} \quad \ldots \quad (7.18)$$

7.2.4. Heat Transfer Equation

The heat transfer equation describes what happens to the heat that is transferred from the air to the grain. It both raises the temperature of the grain and the residual moisture and it evaporates the moisture which is lost and raises its temperature to T'_a.

Letting h_c = Heat Transfer coefficient, Btu/min ft^2 $^\circ$F
and a_s = Specific surface of bed, ft^2/ft^3 = surface area per unit volume of bed

then

$$h_c\, a_s\, A\, \Delta z\, \Delta t \left(\frac{T_a + T'_a}{2} - \frac{T_g + T'_g}{2} \right)$$

$$= A\, \Delta z\, \rho_d \left[(c_{pd} + m')(T'_g - T_g) + (-\Delta m) \left\{ E' - 1(T_g - 32) \right\} \right] \quad (7.19)$$

where

E' is the enthalpy of water vapour at temperature T'_a and pressure 14.7 $\mathrm{lb/in^2}$

$$E' = 0.448\, T'_a + L_v \qquad \ldots \qquad (7.20)$$

where L_v is the Latent heat of vaporisation of the water in the material. It has been established that the latent heat of vaporisation of water from hygroscopic solids like grass is not the same as for pure water at the same temperature. This phenomenon can be taken into account by writing L_v as $L_{vo} f$, where f is a function of the moisture content of the material.

Letting $D' = \dfrac{2\,\rho_d}{h_c\, a_s\, \Delta t}$, and substituting for D' and E':

$$T_a + T'_a - T_g - T'_g = D' \Big[(c_{pd} + m')(T'_g - T_g)$$

$$- \Delta m \ (0.448\, T'_a + L_v - T_g + 32) \Big] \qquad \ldots \qquad (7.22)$$

Rearranging the terms

$$(1 + 0.448\, D' \Delta m)\ T'_a = \Big[D'(c_{pd} + m') + 1 \Big] T'_g +$$

$$\Big[1 - D'(c_{pd} + m' - \Delta m) \Big]\ T_g + (-1)\ T_a + \Big[-D' \Delta m\ (L_v + 32) \Big]$$

$$\ldots \qquad (7.23)$$

or

$$\alpha T'_a = \beta T'_g + \gamma T_g + \delta\, T_a + \varepsilon \qquad \ldots \qquad (7.24)$$

where

$$\alpha = 1 + 0.448\, D' \Delta m \quad : \quad \beta = D'(c_{pd} + m') + 1$$

$$\gamma = 1 - D'(c_{pd} + m) \quad : \quad \delta = -1 \qquad \ldots \qquad (7.25)$$

$$\varepsilon = - D' \Delta m\ (L_v + 32)$$

that is,

$$T'_a = \mu T'_G + \vartheta \qquad \ldots \quad (7.26)$$

where

$$\mu = \beta/\alpha$$
$$\vartheta = (\gamma T_G + \delta T_a + \varepsilon)/\alpha \qquad \ldots \quad (7.27)$$

from (7.17) and (7.27)

$$T'_a = \pi T'_G + \sigma = \mu T'_G + \vartheta \qquad \ldots \quad (7.28)$$

Solving simultaneously:

$$T'_G = \frac{\vartheta - \sigma}{\pi - \mu} \qquad \ldots \quad (7.29)$$

T'_a may be found by substituting for T'_G in (7.17) or (7.28).

7.3. Method of Calculation

In order to predict the drying of a deep bed accurately, it is necessary to divide it into layers that are sufficiently thin for the application of the thin-layer equations, i.e. the properties of the air and of the solid must be constant, or nearly so, within a thin layer. Both the number of layers and the number of time intervals, however, must be kept as small as possible, so that the calculation time may be of a reasonable length.

Having selected values of Δt and Δz, and determined the physical properties of the material, the calculations are as follows:

The temperature and humidity of the air entering the first layer at time = 0 are those of the drying air, T_o and

x_{ao}. Values of k and m_o are calculated for T_o and x_{ao}. The temperature and moisture content of the material in each layer are initially T_{go} and m_o, respectively.

Fig.7.3. is a schematic representation of the calculation process in terms of location in space and time. The horizontal axis represents time, with each division equal to Δt. The vertical axis represents distance through the bed, with each division equal to one layer. The arrows symbolise the calculations for the layers. The inlet conditions to the first layer at time = 0 are located at A (0,1), the inlet conditions to the second layer at time = 0 are at B (0,2), and the inlet conditions to the second layer at time = 1.Δt are at C (1,2). The calculations in the first layer in the first time iteration are thus represented by the arrow from A to C.

The change in moisture content in the first layer over the first time interval Δt is calculated from (7.4). The change in the humidity of the air is calculated from (7.7). The resulting humidity is that of the air leaving the first layer and entering the second layer at time = 1.Δt.

The changes in the temperatures of the air and the material are calculated from (7.17) and (7.29). The resulting air temperature is that of the air entering the second layer at time = 1.Δt. In fig.7.3., C represents the condition of the air entering the second layer at time = 1.Δt.

The calculations are repeated for the second layer, the inlet air conditions for which are located at B and the exit conditions at D in Fig.7.3. The arrow from B to D represents the calculation process. It is important to note that the inlet air conditions to the second layer in the first time iteration are not at C, but at D.

The calculations are repeated for all the other layers in the bed, until the last layer is reached. The state of the bed at time = 1.Δt is now known.

The calculation process is repeated, starting again with the first layer. This time, however, the inlet air conditions to the second and succeeding layers are those which were calculated during the first time iteration.

Each time the calculations are carried out, the properties of the air and of the material are altered, and the drying is thus simulated.

The calculations are stopped when either the desired average moisture content or total drying time is reached.

7.4. The Computer Programme

A computer programme was written to perform these calculations. A block diagram of the programme, a print-out of the text, and specimen results are shown in Appendix 13.2. ! ?

In the programme, the sequence of calculations was carried out until both a target time TF and a target moisture content WF were reached, but a limit of 2500 iterations was set. A number of checks were written into the program so that unrealistic situations would be detected before they degenerated into impossible mathematical tasks, e.g. division by zero, logarithm of a negative number, etc.

The action of the programme is described briefly below. The numbers in parentheses refer to the block diagram, Appendix 13.2.

(1) Each set of data started with a data set number. If this was -1, then the programme terminated. Several sets of data could thus be processed in one run.

(2) Most of the constants in the equations, as well as the operating parameters, were read in for each run. It was possible to choose one of a number of formulae for the calculation of the heat transfer coefficient by means of the parameter CODE fed in with the data. The frequency and quantity of output were controlled by the two parameters [illegible] and NN, fed in with the data.

(3) The values of certain physical constants, e.g. the gas constant for air, were set, and the values of TIMECOUNT and MCCOUNT were set to zero. These were two counters used to indicate whether the conditions TT $\geqslant$ TF and OAMC $\leqslant$ MF respectively had been fulfilled.

(4) The moisture content of the material in each layer was set at M0, and the temperature at TG0. The humidity of the material in each layer was set at H0, and the temperature of the air entering each layer was set at TG0, except for the first layer, where it was set at T0.

(5) The values of the constants and parameters were printed out if the parameter A, fed in with the data, was not 100.

(6) The total drying time, TT, was set to zero.

(7) The time iteration loop was entered, and the total drying time was increased by DT.

(8) The layer iteration loop was entered, and the values of L and ML were calculated for the current layer. The constants in the drying equation for hay depended on the moisture content range, and an alternative version of the programme was therefore prepared to take account of a changing drying equation.

(9) For each layer, the drying rate was calculated as zero if either the moisture content of the layer was less than the equilibrium moisture content, or the relative humidity of the entering air was greater than a specified maximum relative humidity, MAXRH, about 98%. This was an attempt to take account of the phenomenon of condensation which does occur in deep beds, but for which there is little experimental data.

(10) The values of the humidity and the temperature of the air leaving the layer at the end of the time interval were calculated, as well as the temperature of the material at the end of the time interval.

(11) A printout of the bed profile was given every MM iterations, but within this printout, only the conditions of the first and every NNth layer were given.

(12) Where there were very large differences in temperature between the air and the material, the rate of heat transfer tended to be so great that, after the time interval Δt, the temperature of the air leaving the layer was calculated to be lower than the temperature of the material in the layer. This overshoot was a result of the failure of the numerical integration method to

approximate closely to the actual process. In many cases, however, these erroneous temperatures corrected themselves by reverse heat transfer in subsequent iterations. As this temperature overshoot does not occur in practice, a check was made in each layer to see if the air temperature had dropped below the material temperature by more than a specified amount, usually 20F°. If it had, the calculations were terminated and a failure message was printed out. The tolerance of 20 F° was to allow mild cases of temperature overshoot to correct themselves.

(13) Having finished the calculations for all the layers in the bed, the average moisture content of the bed, OAMC, was calculated.

(14) The values of the temperature and humidity of the air were transferred from the temporary storage arrays NT and NH to the arrays T and H, in preparation for the next time iteration.

(15) When the total drying time was equal to or greater than the experimental drying time, the bed profile was printed out if the value of TIMECOUNT was 0. Then the value of TIMECOUNT was set to 1. Similarly, when the average moisture content of the bed was less than or equal to the experimental final moisture content, the bed profile was printed out if the value of MCCOUNT was 0, and then the value of MCCOUNT was set to 1. In this way, the bed profile was printed out only the first time the condition $TT \geqslant TF$ and the first time the condition $OAMC \leqslant MF$ were satisfied.

(16) When both the target time TF and the target moisture content MF had been reached, the calculations were stopped, and the action returned to (1).

(17) A limit of 2500 time iterations was set to the calculations, after which the action returned to (1).

7.4.1. Data required for the simulation

(a) Drying Parameters

For the simulation of the barley drying, the equations derived by Boyce(8) were used:

$$k = 8358 \exp(-7967/T_{abs}) \qquad T_{abs} \text{ in } {}^{o}R$$

$$k \text{ in } min^{-1}$$

$$m_o = 7040 \sqrt{x_a}/T_a^{\,2} + 0.06015 \qquad T_a \text{ in } {}^{o}F$$

For the simulation of wheat drying, the data of Simmonds et al(65) were correlated into the same form as Boyce's:

$$k = 120000 \exp(-9169/T_{abs})$$

$$m_e = 7040 \sqrt{x_a}/T_a^{\,2} + 0.06015$$

For the simulation of hay drying, data collected in this department(74) was correlated into those forms:

$$m \quad 0.271 \qquad \begin{cases} k = 0.00296 \exp(0.07214\ T_a) & T_a \text{ in } {}^{o}C \\ & k \text{ in } min^{-1} \\ m_e = 120.579 \sqrt{x_a}/T_a^{\,2} + 0.23635 & T_a \text{ in } {}^{o}C \end{cases}$$

$$m \quad 0.271 \qquad \begin{cases} k = 0.000555 \exp(0.07675\ T_a) & T_a \text{ in } {}^{o}C \\ m_e = 73.2819 \sqrt{x_a}/T_a^{\,2} + 0.1688 \end{cases}$$

(b) Material properties:

The physical properties of Barley and Wheat were taken from the work of Boyce(8), Simmonds et al(43) and unpublished work in this department(75).

	Barley	Wheat	Hay	
ρ_d	41.45	37.6	7	lb/ft^3
c_{pd}	0.31	0.32	0.3	Btu/lb ^oF

(c) Heat Transfer Coefficient

For the heat transfer coefficient to a deep bed of grain, Boyce(8) proposed the relationship

$$h_c^* = 0.5738\left(\frac{G\ T_{abs}}{P_{at}}\right)^{0.6011} \qquad \ldots \qquad (7.18)$$

where h_c^* = Heat transfer coefficient, Btu/min-^oF-ft^3 of bed

G = Mass velocity of the air, lb dry air/min-ft^2

T_{abs} = Air temperature, ^oR

P_{at} = Atmospheric pressure, lb/in^2

Figure 7.4. shows the results obtained by a number of workers for heat transfer coefficients in packed beds, together with the original data of Boyce(8). This figure is a plot of the j_h-factor against the particle Reynold's Number. The j_h-factor is given by

$$j_h = \frac{Nu}{Re\ Pr}\ \psi(Pr)$$

where Nu = Nusselt Number and $\psi(Pr)$ is a function of the Prandtl Number, usually $Pr^{2/3}$

Although the relationship proposed by Boyce does not reduce to this form, it can be seen that his original data is not very far removed from the data obtained by other workers for non-organic materials.

The correlation proposed by Perry(53) for heat transfer to circular cylindrical pipes is also shown on this plot, and it is also within the same range of values. The correlation is

$$j_h = a\,Re^b \qquad \ldots \qquad (7.19)$$

where $a = 0.26$ to 0.33 $b = -0.4$ for Re 3000

$a = 0.548$ to 0.695 $b = -0.492$ for 1000 Re 3000

$a = 0.855$ to 1.086 $b = -0.592$ for 1 Re 300

It was mentioned in Chapter 6 that a bed of grass can be considered as a bed of infinitely long circular cylinders. Equation (7.19) was therefore used for the simulation of hay drying.

7.5. Results

The deep-bed drying model was tested by simulating drying experiments with barley, wheat and hay.

The work of Boyce on barley drying(8), comprising 21 runs, was simulated, and the results are given in table 7.1. The experimental run time is compared with the time predicted to reach the final experimental moisture content. The final experimental moisture content is also compared with the moisture content predicted by the programme after a time equal to the experimental run time.

Experiments conducted in this department on wheat drying(73) were simulated, and the results are given in table 7.2.

Experiments were conducted by Clark and Lamond(18) on deep beds of hay, and the results of simulating these are given in table 7.3.

7.6. Discussion of the Results

7.6.1. Drying of Deep Beds

When deep beds of material are dried by through-flow of air, there is a preliminary heat-up period during which the drying rate rises to the level at which it is maintained during the second period, the constant rate period. This is usually the predominant period, at the end of which the drying rate drops off as the average moisture content of the bed approaches the equilibrium moisture content (see fig.7.1).

These three periods are produced by the three zones in the bed: the zone of completely dry material, the zone of drying material, and the zone of completely undried material (see fig.7.2). The drying zone moves through the bed, and within this zone the drying rate is constant. When the drying zone is bounded by a dry zone, and an undry zone, the drying rate of the bed is constant. When the drying zone reaches the top of the bed, and whilst it is being established, the drying rate is less than the constant rate.

Although there is no mass transfer in the undry zone, there is heat transfer. The temperature of the material changes to a value known as the pseudo-wet-bulb temperature. The temperature at a point in the bed remains at this value until the drying zone reaches it. This temperature is approximately equal to the wet bulb temperature of the air leaving the top of the drying zone (see fig.7.5). The depth of the drying zone, and its velocity through the bed depend on the properties of the system. If the total bed depth is less than the depth of the drying zone, there is no constant rate period, since the drying zone is never completely established.

7.6.2. Comparison of the Predicted Results with the Experimental Results

The model of the deep bed drier predicted the general phenomena observed in practice - the moving drying zone, the pseudo-wet-bulb temperature, and the moisture gradients within the bed. The model predicted the experimental run time to within, on average, 10%.

Although Boyce(8) claimed an accuracy of 5% for his simulation method, it should be noted that he used a correction factor of 0.83 on the value of m_o and he used the exit conditions of the air from one layer as the inlet conditions to the next layer in <u>same</u> time iteration.

The constant rate period was observed in almost all runs in the grain drying simulation, i.e. the drying curves were straight lines. The experimental and predicted values of the drying time and final bed moisture content are given in tables 7.1. and 7.2. The comparison of an experimental temperature profile with a predicted one is shown in fig.7.6, and a predicted moisture content profile is shown in figs. 7.7 and 7.8.

Only one of the experimental hay drying runs showed a constant rate period. In all the others the depth of the bed was insufficient to allow the drying zone to become fully established. The model predicted a constant rate period for the hay in all cases but the final moisture content predicted by the model was very near to the experimental value in each case (see fig.7.9). The sharp bend in the predicted curves is due to the programming of the critical moisture content.

The model was very stable with respect to the heat transfer coefficient. When this parameter was varied from 20 to 80 Btu/min-ft^3-^{o}F for a set of barley drying data, very little difference was observed in the time required to dry the bed to the specified moisture content. Similarly, the form of the heat transfer coefficient equation did not affect the results of the hay drying simulations. This stability was due partly to the low specific heat of the grain and the relatively high air flow rate, i.e. the heat capacity of the air was much greater than that of the grain. The air temperature, therefore, did not drop much when heat was transferred to the grain, and consequently the value of k did not change since it was evaluated from the air temperature.

7.7. Conclusions

The drying of granular and fibrous materials in deep-beds by through-flow of air can be simulated by a mathematical model. The predicted and experimental values of moisture content and temperature compare favourably. The model is stable with respect to the heat transfer coefficient, a quantity which is difficult to estimate.

CHAPTER 8

SIMULATION OF A ROTARY DRIER

8.1. Introduction

The main component of a rotary drier is a hollow cylinder that rotates about its longitudinal axis which may be inclined to the horizontal. The material to be dried enters the cylinder at one end. If the system is co-current flow, then the drying medium, usually air, enters at the same end as the material, and at the opposite end if the system is counter-current flow. The inside of the cylinder is generally fitted with flights or raisers which lift the material up and let it fall in a shower through the airstream, as the cylinder rotates.

Many workers have studied rotary driers and coolers with special reference to the drying of granular materials, slurries and pastes. The principle performance variables have been correlated in terms of the operating parameters on a theoretical basis. It is, however, very difficult to determine experimentally what happens inside a rotary drier, and many theories have been tested only by COMPARISONS WITH OVERALL HEAT AND MASS BALANCES. Mathematical Models of the drying of fertilizer granules in rotary kilns have been developed by Sharples, Glikin and Warne(63), Davidson, Robson and Roesler(20) and Garside, Lord and Reagan(26).

A schematic diagram of a rotary drier is shown in fig.8.1.

8.2. Mechanism of Solid Movement

The velocity with which the solid material moves through the cylinder depends on three actions: Gravity acting along the incline, the cascading action, and the force of the drying air.

Unless there is a large rolling mass of solids in the bottom of the drier, or unless the angle of inclination of the drier is very steep, gravity acting along the incline does not play much part in moving the solids since the coefficient of friction between the solids and the cylinder is too great to permit significant movement.

The cascading action works as follows: A solid particle is carried by a flight around the periphery of the cylinder until the inter-particle friction can no longer retain it in the flight, and it falls down through the air to the bottom of the cylinder. Some particles may only be carried a short distance around the periphery, if they are near the surface of the material in the flight, while others may be carried right to the top of the cylinder and even beyond. If the cylinder is inclined, or if there is an airflow, the particle advances along the drier by a distance which is related to the distance through which it falls.

The drying air tends to oppose or assist the axial motion of the cascading particle, depending on whether the system is co-current or counter-current flow. In co-current flow, those particles which offer a high resistance to the air are carried further than those which are streamlined in shape, both because they take longer to fall and because they are carried further by the air.

It is usually the cascade action and the airflow which promote the movement of a particle through a rotary drier. A solid particle, therefore, can be either "soaking" in a flight or in the rolling mass of solids at the bottom of the cylinder, or it can be cascading from a flight. The passage of the particle through the drier consists of a series of alternate soaking and cascading periods.

8.3. The Residence Time

Two of the parameters that are most difficult to describe mathematically in a rotary drier are the flight shape and the cascade distribution. The particles are carried upwards in a flight so that the surface of the particles is at an angle to the horizontal, which is called the dynamic angle of repose. This angle changes as the flight moves around the periphery, due to the change in direction of the centrifugal forces. The orientation of the flight relative to the horizontal also changes as the cylinder rotates, so that less and less solid is held in it (see fig.8.2). The rate at which the particles leave the flight depends on the shape of the flight, on the dynamic angle of repose, and on the angular position of the flight.

The ideal is to have a uniform cascade density so that the maximum contact between the solids and the air may be achieved, and much research has been done to determine the best shape of flight to achieve this. If the cascade is locally dense, the air tends to channel through the more open regions. Porter(54) has analysed the characteristics of cascades and flights and has produced design methods for rotary coolers and driers. Kelly and O'Donnell(37) have analysed the Equal Angle Distribution flight and have related the flight hold-up to the drier hold-up on the basis of a drier design loading, which is the loading which produces a perfectly filled, but not over-filled, flight at an angular position of 0°. If the drier is overloaded, there is a bed of rolling material at the bottom of the drier, and if it is underloaded, a disproportionate amount of the cascading will take place in the second half of the drier (when $\theta > 90^\circ$).

8.3.1. Calculation of the Residence Time

The three actions described above together determine how long a solid particle remains in the drier, i.e. the residence time, and also how much solid will be present in the drier at any one time, i.e. the hold-up. In practice, each particle has a different residence time, but a mean residence time can be calculated.

The mean residence time, τ, and the hold-up, Q_s, are related to the feed rate, F, by the equation

$$F = Q_s/\tau \qquad \ldots \quad (8.1)$$

where F is in lb/hr, τ is in hours, and Q_s is in lb. The hold-up is sometimes expressed as a fraction of the drier volume:

$$X = Q_s/(\rho_f V_d) \qquad \ldots \quad (8.2)$$

where X is the fractional hold-up

ρ_f is the bulk density of the solids in the flights

V_d is the volume of the drier.

The mean residence time can be expressed as

$$\tau = N_c(t_c + t_f) \qquad \ldots \qquad (8.3)$$

where t_c = The average time of cascading, or falling, hour

t_f = Average time of soaking in a flight, hour

N_c = The number of times a particle cascades during its passage through the drier.

When there is relative motion between a solid particle and a fluid, the fluid exerts a force on the particle. If A' is the area of the particle projected in the direction of the fluid flow, the resistance force P can be written as

$$P = R' A' \qquad \ldots \qquad (8.4)$$

where R' is the resistance force per unit projected area. It has been shown that the dimensionless group $R'/\rho_a u^2$ is related to the Reynold's number of flow, Re.

where ρ_a = Fluid density, lb/ft^3

u = Fluid velocity, ft/hr

$Re = \rho_a u d_p/\mu$

d_p = Particle diameter, ft

μ = Fluid Viscosity, lb/ft-hr

The form of the relationship for spherical particles is shown in fig.8.3. The same general form also holds for non-spherical particles, but the values of the constants depend on the shape of the particle and on its orientation with respect to the airflow. Equation (8.4) can be rewritten as

$$F = \frac{R'}{\rho_a u^2} \rho_a u^2 A' \qquad \ldots \qquad (8.5)$$

Substituting for $R'/\rho_a u^2$

$$F = \phi\,(Re)\,\rho_a u^2 A' \qquad \ldots \qquad (8.6)$$

where ϕ is a function of the Reynold's number.

The motion of a particle which falls through an airstream that has a horizontal velocity component can be described by the following equations, if $u \gg \dot{x}$ and u and $\dot{x}$ are positive (see fig. 8.4).

$$x = \tfrac{1}{2}\left[g(1 - \rho_a/\rho_p)\sin\alpha + K_x u^2\right] t^2 \qquad \ldots \qquad (8.7)$$

$$y = ft + \frac{1}{K_y}\log_e \frac{1}{2f}\left[f + u_i + (f - u_i)\exp(-2fK_y t)\right] \qquad (8.8)$$

where x = distance along the direction of flow of fluid, ft.

y = distance in vertical direction, ft.

α = angle which x-direction makes with the horizontal (x is not perpendicular to y unless $\alpha = 0$)

g = acceleration due to gravity, ft/hr^2

ρ_p = particle density, lb/ft^3

$K_x = \dfrac{J\,\rho_a}{d_p\,\rho_p}\,\phi(Re_x)$, ft^{-1}

J = 1.5 for spheres

= $4/\pi$ for a cylinder with its axis perpendicular to the direction of the fluid flow.

t = time, hours

$f = \sqrt{g(1 - \rho_a/\rho_p)K_y}$, ft/hr

$$K_y = \frac{J \rho_a}{d_p \rho_p} \phi (Re_y) \text{ , ft}^{-1}$$

$$Re_x = \rho_a (u - \dot{x}) d_p/\mu$$

$$Re_y = \rho_a \dot{y} d_p/\mu$$

u_i = Value of $\dot{y}$ at $t = 0$, ft/hr

Schofield and Glikin(61), on the assumptions that $t_c \ll t_f$ and $u \gg \dot{x}$, solved (8.7) and (8.8) and hence derived an expression for the average residence time of a particle in a rotary drier as:

$$= \frac{L_d}{y_{av} \delta N_r (\sin \alpha \pm K u^2/g)} \qquad \ldots \qquad (8.9)$$

where L_d = Length of drier, ft.

y_{av} = Average length of fall of a particle, ft.

δ = Travel ratio = (Circumference of cylinder)/ (average distance travelled by a particle on the periphery of the cylinder).

N_r = Speed of Rotation of cylinder, rev/hr.

The sign of the term in the denominator is positive in co-flow drying and negative in counter flow drying.

Equation (8.9) is essentially the same equation as the expression derived by other authors, but Kelly and O'Donnell(37) related the residence time to the flight design and number by

$$= \frac{L_{eff}}{y_{av} \sin \alpha - f(G)} \left[\frac{1}{N_r}(1 - q_o) + \sqrt{2y_{av}/g} \right] \qquad \ldots \qquad (8.10)$$

where L_{eff} = effective length of drum over which the granules progress by cascade motion only.

$f(G)$ is a function of the volumetric air flow rate

q_o = ratio of actual to design flight hold-up when the
flight is at $\theta=0$ (see below)

The assumptions of Schofield and Glikin (loc.cit.), however, are not always fulfilled in practice, so that equations (8.7) and (8.8) must be solved more rigorously. If $\alpha = 0$, $\rho_a \ll \rho_p$ and u is not very much greater than $\dot{x}$, then (8.7) is replaced by

$$x = ut - \frac{1}{K_x} \log_e (uK_x t + 1) \qquad \ldots \qquad (8.11)$$

and (8.8) is replaced by

$$\tau = \frac{L}{u\,t_c - \frac{1}{K_x} \log_e (uK_x t_c + 1)} (t_c + t_f) \qquad \ldots \qquad (8.12)$$

where $t_f = 1/\delta N_r$

and t_c is to be estimated from (8.8)

Let $y_{av} = \omega D_d$, where ω is a factor, and D_d is the diameter of the drier. It can be seen (see fig.8.5) that

$$\omega = \sin (2\pi/\delta - \pi/2) \qquad \ldots \qquad (8.13)$$

Substituting in (8.7) for $y = \omega D_d$, and assuming that $u_i = 0$ and that $2fK_y t_c$ is very large so that $0 < \exp(-2fK_y t_c) \ll 1$,

$$\omega D_d = f t_c + \frac{1}{K_y} \log_e \tfrac{1}{2} \qquad \ldots \qquad (8.14)$$

whence $t_c = \omega D_d/f - \frac{1}{K_y f} \log_e \frac{1}{2}$ $\qquad \ldots \qquad (8.15)$

thus

$$\tau = \frac{L_d}{\frac{u}{f}\left(\omega D_d - \frac{1}{K_y} \log_e \frac{1}{2}\right) - \frac{1}{K_x} \log_e \left[\frac{uK_x\, \omega D_d}{f} - \frac{u}{f} \log_e \frac{1}{2} + 1\right]} \times \left[\frac{\omega D_d}{f} - \frac{1}{K_y f} \log_e \frac{1}{2} + \frac{1}{\delta N_r}\right] \qquad \ldots \qquad (8.16)$$

This formula is based on the assumptions

(1) $\alpha = 0$

(2) $u_i = 0$

(3) $0 < \exp(-2fK_y t_c) \ll 1$

(4) $\phi(Re_x)$ and $\phi(Re_y)$ are constant.

The derivation of the formulae is given in Appendix 12.7.

8.4. Heat Transfer

In a Rotary drier, heat transfer can take place between the air, the solid material and the cylinder. The most suitable conditions for air-solid heat transfer occur when the solid is cascading through the air from the flights, but during the soaking periods, some heat transfer occurs between the particles and there is intra-solid temperature adjustment. The effective heat transfer rate depends, therefore, not only on the air temperature and velocity and on the solids surface area and temperature, but also on the density of the cascade and on the proportion of the time spent by the solids in the cascade. There is also a heat loss through the walls of the cylinder, but this is not great unless the temperature is very high, and the insulation very poor.

The overall heat transfer coefficient for a rotary drier is usually expressed on the basis of unit cascade volume, or unit drier volume. Unless the hold-up is very large, the cascade volume is approximately equal to the volume of the drier. This volumetric coefficient, like

h_c^* above, is a product of a surface-area based coefficient and the specific surface of the solid in the cascade, i.e.

$$U_v = h_c a_c \qquad \ldots \qquad (8.17)$$

where U_v = Volumetric heat transfer coefficient, Btu/hr-ft^3-^{o}F

h_c = Heat transfer coefficient based on surface area, Btu/hr-ft^2-^{o}F

a_c = Surface area of particles per unit cascade volume, ft^2/ft^3

The value of a_c depends largely on the cascade density and uniformity.

Miller et al(45) found that

$$U_v = K_u\, G^n/D_d \qquad \ldots \qquad (8.18)$$

where for 6 flights $K_u = 0.477\ (n_f - 1)/2\ :\ n = 0.46$

for 12 flights $K_u = 0.132\ (n_f - 1)/2\ :\ n = 0.60$

n_f = Number of flights.

McAdams(39) and Schofield and Glikin(61) give

$$Nu = h_c d_p/k_a = 0.33\ Pr^{1/3}\ Re^{0.6} \qquad \ldots \qquad (8.19)$$

where k_a = Thermal conductivity of the air, Btu/hr ft ^{o}F

Re = Reynold's number based on the particle diameter and the velocity of the air through the voids.

Schofield and Glikin, however, found that the practical values of the heat transfer coefficient were much smaller in practice than those calculated by this equation.

Friedman and Marshall(24) and Porry(53) proposed:

$$U_v = 10\ G^{0.16}/D_d \qquad \ldots \qquad (8.20).$$

but Perry recommended that the constant 10 be replaced by 20 or 25 for driers with a diameter in excess of 3 feet and hold-up ranging from 5% to 15%.

McCormick(40) proposed a general correlation, based on an examination of the data of other workers. For the data of Miller et al (loc.cit.) he found

$$U_v = 0.255 \frac{(n_f - 1)}{2} \frac{G^{0.67}}{D_d} \qquad \ldots \qquad (8.21)$$

$$= 0.318\, G^{0.67}/D_d \qquad \ldots \qquad (8.22)$$

He recorrelated the data of Friedman and Marshal (loc.cit.) into

$$U_v = 0.28\, G^{0.67}/D_d \qquad \ldots \qquad (8.23)$$

Hiraoka and Toei(34) proposed

$$U'_v = 0.476\, Re^{0.75}/d_p \qquad \ldots \qquad (8.24)$$

where U'_v is the volumetric heat transfer coefficient in kcal/hr-m^3-$^\circ$C

d_p is the particle diameter in metres.

8.5. Mass Transfer

In contrast to heat transfer, drying occurs during both the cascade phase and the soak phase during the solids passage through the drier. The rate of drying depends on the temperature of the solid and of the air, and on the ability of the air to remove the moisture. It would be expected, therefore, that a small amount of drying occurs in the soaking phase, but that most of the drying takes place in the cascade phase. It has been suggested by Davidson et al(20), however, that drying can be considered to occur at a rate independent of the location of the solid, i.e. whether it is cascading or soaking. The basis for this suggestion was that moisture concentration changes occurred only in the outer regions of a solid particle during the soaking period, since there was not a sufficient time for substantial changes in the moisture content of the particle.

If, however, there is very rapid drying, and a large hold-up, then the drying of the material in the flights may be inhibited by the drying power of the air in the voids among the particles in the flights. Subject to the condition that the moisture movement within the solid is the controlling mechanism, then, the drying of solid particles in a rotary drier can be considered to be very similar to the drying of thin layers of the material.

General correlations for mass transfer are not used much for rotary driers, since there is a wide variation in the drying characteristics of materials.

8.6. Heat and Mass Transfer Relationships

The mathematical treatment of a rotary drier is very similar to that of a deep-bed drier. A few modifications, however, are needed. Sharples, Glikin and Warne(63) developed a set of equations to describe a rotary drier. They were:

(a) Mass Transfer Equation:

$$\frac{dm}{dl} = \frac{dm}{dt} \Big/ \frac{dl}{dt} = R_d / v_s \qquad \ldots \qquad (8.25)$$

where l = Distance along the drier, ft.

R_d = Drying Rate, hr^{-1}

v_s = Velocity of solids along the drier = $F/A_{s\ x}$, ft/hr

A_s = Cross-sectional area of the drier occupied by solids, ft^2

ρ_x = Dry Solids Bulk Density in drier, lb/ft^3

(b) Mass Balance Equation:

$$F \frac{dm}{dl} + G_o \frac{dx_a}{dl} = 0 \qquad \ldots \qquad (8.26)$$

where x_a = Air Humidity, lb/lb

G_o = Air Mass Flow Rate, lb/hr.

(c) Heat Transfer Equation:

$$U_v A_{ht} (T_a - T_s) = F (c_{pd} + c_{pw} m) \frac{dT_s}{dl} - F L_v \frac{dm}{dl} + H \quad (8.27)$$

where A_{ht} = Cross-sectional area of drier which is available for heat transfer (cross-sectional area of Cascade) = $A_d - A_s$, ft^2

A_d = Total cross-sectional Area of Drier, ft^2

c_{pd} = Specific Heat of Solid dry matter, Btu/lb ^oF

c_{pw} = Specific Heat of moisture in solid, Btu/lb ^oF

H = Rate of Heat Loss from Drier Shell, Btu/hr.

T_a = Temperature of Air, ^oF

T_s = Temperature of Solid, ^oF

L_v = Latent Heat of Vaporisation of moisture in solid, Btu/lb.

(d) Heat Balance Equation:

$$- c_{pwv} G_o (T_a - T_s) \frac{dx_a}{dl} - G_o (c_{pa} + c_{pwv} x_a) \frac{dT_a}{dl}$$

$$= F (c_{pd} + c_{pw} m) \frac{dT_s}{dl} - F \frac{dm}{dl} + H \qquad \ldots \qquad (8.28)$$

where c_{pa} = Specific Heat of Air, Btu/lb ^oF

c_{pwv} = Specific Heat of Water Vapour, Btu/lb ^oF.

8.7. Simulation of a Rotary Drier

The deep bed drier simulation computer programme described in chapter 7 contained equations similar to those above, and this programme was modified to predict the performance of a rotary drier. It was necessary to take account of the movement of the grass through the drier, the different drying equations at high temperatures, and the different aerodynamic characteristics of the grass as it dried.

The Programme was used to simulate the grass drier at Cockle Park Farm. This drier had a drum 18 ft long and 7 ft diameter, but it had three passes as shown in fig.8.6. The dimensions of the passes are given in the diagram. The drum rotated at 15½ rev/min and the air was heated by an oil burner. The fresh grass was fed in by an auger at one end of the drum, to the centre pass, and the dry grass was separated from the air by a system of cyclones at the other end. The airflow rate was 237.5 lb/min and the grass feed rate was 7.94 lb/min of dry-matter. The residence time was measured as 1.25 minutes, giving a hold-up of 9.9 lb.

Various assumptions were made to facilitate the calculations: It was assumed that:

(a) The resistance coefficient, $\phi(Re)$ for grass was constant, independent of moisture content, temperature, etc.

(b) The grass particle did not shrink. The local particle density was calculated as

$$\rho_p = \rho_{po} \frac{1 + m}{1 + m_o} \qquad \ldots \qquad (8.29)$$

where ρ_p = Local Particle density

ρ_{po} = Particle density at $m = m_o$ (See Appendix 12.8)

(c) The drier was operating at design loading, i.e. the flights were just full at $\theta = 0^o$, and there was no rolling mass of grass at the bottom of the drier.

(d) The three passes could be considered as one pass, with a varying cross-sectional area, and a length equal to the sum of the lengths of the individual passes.

(e) The heat transfer coefficient was constant throughout the drier.

(f) There was no heat loss through the shell of the drier, nor was there any inter-pass heat transfer.

A block diagram of the rotary drier simulation programme, a printout of the text and specimen results are given in Appendix 13.3. The action of the programme is as follows (The numbers refer to the block diagram):

(1) After initializing the devices, declaring the variables and procedures and calculating the formats, the code number for a set of data was read. If this was -1, the programme terminated, otherwise, the action went to (2).

(2) The data for the simulation was read in.

(3) The values of the physical constants were set. The cross-sectional area of each pass of the drier was calculated, as well as the mass velocity of the air in each pass. The cross-sectional areas of the second and third passes were annular, not circular, and the effective diameter of the drum in each of these passes was calculated as the diameter of a circle whose area was equal to the cross-sectional area of the appropriate pass. The residence time and various other parameters, such as travel ratio and cascade density were calculated at the feed conditions. The cascade density was calculated from

$$\rho_c = \frac{\rho_x \; \rho_f}{(R_t + 1)\,\rho_f - R_t\,\rho_x} \qquad \ldots \qquad (8.30)$$

where ρ_c = Density of dry-matter in cascade, lb/ft^3

ρ_f = Density of dry-matter in flights, assumed constant through drier, lb/ft^3

ρ_x = Average density of dry-matter in drier, lb/ft^3

$= \dfrac{F\,\Delta t}{\Delta z \; A_d}$

A_d = Cross-sectional area of Drier, ft^2

R_t = Ratio of soak time to cascade time

$= t_f/t_c$ (See Appendix 12.9)

(4) The initial conditions of the grass and air were set.

(5) The length of each stage or interval was calculated from the data fed in.

(6) The input data and values of the aerodynamic parameters at the initial conditions were printed out, but if the value of the code A, fed in with the data, was 100, then this printing was bypassed.

(7) The headings for the profile were printed out, and the iteration loop was entered.

(8) The cross-sectional area of the drier and the mass-velocity were selected, depending on current position in the drier. The local particle density, and hence the local cascade density, was calculated. The local residence time, travel ratio, etc., were calculated.

(9) If the air temperature was greater than 600°F, a constant drying rate was assumed, otherwise the decreasing drying rate equation was used.

(10) If the decreasing drying rate equation was used, the valuesof k and m_e were calculated.

(11) If the air temperature was greater than 212°F, or if the value of m_e was negative, then m_e was set at zero.

(12) The change in moisture content was calculated.

(13) If the air temperature was greater than 600°F, then the (constant) drying rate was calculated.

(14) The change in moisture content was calculated.

(15) The exit air humidity and temperature, and the temperature of the grass were calculated from (7.17) and (7.27). It was assumed, however, that heat transfer took place only in the cascade phase, and the time interval in (7.21) was divided by a term $(R_t + 1)$.

(16) The values of the various parameters for the layer were printed out only for the first stage, and for every NNth stage, where NN was a parameter fed in with the data.

(17) If the moisture content of the grass in the stage was less than zero, a failure message was printed, the calculations were stopped, and the action returned to (21).

(18) If the air temperature fell below the grass temperature by more than an allowed amount, a failure message was printed out, the calculations were stopped, and the action returned to (21).

(19) The air and grass properties were moved to the next stage.

(20) When the end of the drier had been reached, steady-state conditions existed, and the moisture content of the product was printed out.

(21) The values of the aerodynamic and other parameters at the final (or failure) conditions were printed out, if A was not 100.

(22) The mean residence time was calculated as

$$\tau = \sum_{i=1}^{n} \tau_l = \sum_{i=1}^{n} \Delta t$$

where τ_l is the local residence time = time it took the grass to pass through a stage. The mean residence time, and mean travel ratio were printed out. Then the action returned to (1).

8.8. Data for the Programme

The following values were used for the various parameters:

Grass: Bulk density in flights $= \rho_d = 7$ lb/ft^3

Particle Density $= \rho_p = 55$ lb/ft^3 at $m = m_o$ (see below)

Particle Diameter $= d_p = 1/10'' = 0.00833$ ft.

Specific heat $= c_{pd} = 0.3$ Btu/lb dry-matter °F.

Resistance coefficient $= \phi(Re) = 1.0$ (see below)

Travel Ratio $= \delta = 3$

Initial Moisture content $= m_o = 4.26$ (dry basis)

Initial Temperature $= T_{go} = 50^\circ F$

Air: Inlet humidity $= x_{ao} = 0.007$ lb/lb

Volumetric Heat transfer coefficient $= U_v$

$$= 0.374\ v^{0.46}$$

Drying T_a 600°F (see below $\quad -dm/dt = k_o$

$$k_o = -1.8396 + 0.02468\ T_a,\ T_a \text{ in } ^\circ C$$

T_a 600°F $\quad -dm/dt = k(m - m_o)$

$$k = 0.0204\ \exp(0.02028\ T_a)\ ,\ T_a \text{ in } ^\circ C$$

$$m_o = 32924\sqrt{x_a}/T_a^{\,2} - 0.22455 \quad T_a \text{ in } ^\circ C$$

8.9 . Results and Discussion

8.9 .1. Establishing the Model

The values of three parameters were important for testing the model of the rotary drier, but were not easily obtainable. These were the density of the grass particle, ρ_p, the resistance coefficient, $\phi(Re)$ and the travel ratio, δ. A set of data was taken from experimental tests conducted on the grass drier(68) and was used to evaluate the model. The three parameters were varied within this set of data. It was found that the quotient $\rho_p/\phi(\text{Re})$ described the effects of ρ_p and $\phi(\text{Re})$ adequately, i.e. ρ_p and $\phi(\text{Re})$ could be varied independently, so long as their ratio was constant. It was found that the travel ratio, δ, did not affect the results very much. The effect of varying δ is shown in table 8.2. The observed value of δ was about 3.

It was found that changing the drying equation from constant rate to falling rate at 400°F (200°C), as the thin-layer experimental work suggested, did not give a good simulation. An improvement was obtained by raising the changeover temperature to 600°F.

The validity of the model was assessed by the accuracy with which it predicted the product moisture content, m_f, the exhaust air temperature, T_f and the residence time of the grass in the drier, τ. By systematically varying the parameters ρ_p, $\phi(\text{Re})$ and δ, and the air temperature, it was found that a value of $\rho_p/\phi(\text{Re}) = 55$, an air temperature of 1180°F and $\delta = 3$ predicted the measured performance of the drier quite well. The values of the grass density and resistance coefficient which were assumed, agreed well with this value of $\rho_p/\phi(\text{Re})$, i.e. 50 lb/ft^3 and 0.6(46) respectively. It would be expected that the resistance coefficient for grass would be much greater than that for a cylinder, since a piece of grass is very irregular, and much more bluff, so that $\phi(Re) = 1$ is a reasonable figure.

The comparison of the predicted performance variables, M_f, T_f and τ with their experimentally determined values is given in table 8.1. The predicted and experimental temperature profiles are shown in fig.8.7. The predicted moisture content profile is shown in fig.8.8. The experimental and predicted temperature profiles agree well. The slight disparity could be due to the omission of the heat loss term in the equations, or if the heat transfer coefficient was not constant through the drier. Radiation heat transfer would also be considerable in the first pass, and no special allowance was made for this. Another reason may have been the existence of a considerable temperature gradient across the drier and the initial air temperature was therefore, probably well below 1337°F.

8. 9.2. <u>Use of the Model</u>

The model was used to predict the effects of varying the inlet air temperature, the air flow rate and the grass feed rate. The results are shown in figs.8.9 to 8.15.

8. 9.3. <u>Effect of Air Temperature</u> (figs.8.9 and 8.10)

An increase in the temperature of the inlet air led to a reduction in the product moisture content. At very high air flow rates and very low grass feed rates, the model tended to predict a negative product moisture content, indicating burning of the grass. A check was built into the programme to terminate the calculations when the moisture content went negative. It was also found that the residence time changed with the air temperature, and this must have been due to alterations in the particle and air density because of the increase in drying.

8. 9.4. Effect of Air Flow Rate (fig.8.11)

The effect of increasing the air flow rate was to reduce the product moisture content. This was due to the increase in the drying power of the air. Above 400 lb/min, however, the product moisture content increased, particularly at higher air temperatures. This was because the increase in the air flow rate both tended to increase the product moisture content by reducing the residence time, and to reduce the product moisture content by virtue of the increase in air heat input rate. These two effects depend on the air flow rate to different extents, and hence there is a minimum in the plot of product moisture content against air flow rate. It can be seen that increasing the air flow rate reduces the residence time.

8. 9.5. Effect of Grass Feed Rate (fig.8.12)

There was an almost linear relationship between the product moisture content and the grass feed rate, the product moisture content increasing as the feed rate increased. This was because there was only a certain amount of drying power in the air, and as the load on the drier increased, the amount of drying possible per unit weight of grass decreased.

8.9.6. Interpretation of Results

The parameters m_f, T_f and τ were inter-related. The moisture content of the product, m_f, depended both on the temperature of the inlet air and on the length of time spent in the drier by the grass. The exhaust air temperature T_f depended on the inlet air temperature and on the product moisture content.

The product moisture content is plotted against the exhaust air temperature for a grass feed rate of 7.94 lb/min in fig.8.13. Two sets of curves are shown - those for constant air flow rates and those for constant inlet air temperatures. The form of this plot agrees with that obtained by Sharples, Glikin and Warne$^{(63)}$.

The product moisture content is plotted against the exhaust air temperature for an airflow rate of 238 lb/min and different air temperatures in fig.8.14. The grass feed rate varies along each curve. This is the form of the relationship measured for the Cockle Park Drier. It can be seen that the inlet air temperature had a negligible effect on the inter-dependency of m_f and T_f, thus making it very suitable to control the product moisture content by sensing the exhaust air temperature and feeding the signal back to alter the grass feed rate. The control unit need not be complicated since the inlet air temperature does not affect the control characteristics very much.

The product moisture content is plotted against the air heat input rate in fig.8.15. The datum is taken at 0^{o}F. The form of the plot also agrees with that of Sharples et al. (loc.cit.).

8.10. Conclusions

The drying of grass in rotary driers can be predicted by means of the mathematical model developed. The model can be used to show the effects of varying different operating parameters. The model also shows that the use of the exhaust air temperature to control the product moisture content is a suitable method.

CHAPTER 9

BIBLIOGRAPHY

1 Ahn Y.K., Chen H.C., Fan L.T. and Wan C.G.,
A Modified Moving Bed Grain Drier,
Ind.Engng.Chem., Process Des.Dev., 3, 96, 1964.

2 Allen J.R.,
Application of Grain Drying Theory to the Drying of
Maize and Rice,
J.Agric.Engng.Res., 5, 363, 1960.

3 Babbit, J.D.,
Observations on the Permeability of Hygroscopic
Materials to Water Vapour
Can.J.Res., A, 18, 105, 1940

4 Bagnall, L.O.,
Moisture Movement in the Alfalfa Stem during Drying
Ph.D. Thesis, Cornell Univ.1967.

5 Bagnall, L.O.,
Drying of the Alfalfa Stem,
Am.Soc.Agric.Engrs. Paper No.67-673, 1967.

6 Becker, H.A.,
A Study of Diffusion in Solids of Arbitrary Shape,
with Application to the Drying of the Wheat Kernel
J.Appl.Polym.Sci., 1, 212, 1959.

7 Belt, N.O.,
Drying of Young Grasses for Feed,
Agric.Engng., St.Joseph, Mich., 23, 257, 1942

8 Boyce, D.S.,
Heat and Moisture Transfer in Ventilated Grain,
Ph.D. Thesis, University of Newcastle upon Tyne, 1967.

9 British Standards Institution, Methods for the
Measurement of Fluid Flow in Pipes - Part 1, Orifice
Plates, Nozzles and Venturi Tubes,
B.S.1042. Part 1. 1964.

10 Burr, S., and Turner, D.M.,
British Economic Grasses,
Arnold, Lond., 1933.

11 Byers, G.L., and Routley, D.G.,
Alfalfa Drying - Overcoming Natural Barriers,
Agric.Engng., St.Joseph, Mich., 47, 476, 1966

12 Cashmore, W.H.,
Drying of Farm Crops,
J.Soc.Chem.Ind., Lond., 62, 278, 1943.

13 Ceaglske, N.H., and Hougen, O.A.,
Drying Granular Solids,
Ind.Engng.Chem., 29, 805, 1937.

14 Ceaglske, N.H., and Kiesling, F.C.,
Capillary Flow in Porous Solids,
Trans.Am.Inst.Chem.Engrs., 36, 211, 1940.

15 Chen, C.S., and Johnson, W.H.,
Kinetics of Moisture Movement in Hygroscopic
Materials - Part 1, Theoretical Considerations of
Drying Phenomena,
Trans.Am.Soc.Agric.Engrs., 12, 478, 1969.

16 Chen, C.S., and Johnson, W.H.,
Kinetics of Moisture Movement in Hygroscopic
Materials - Part 2, An Application to Foliar
Materials,
Trans.Am.Soc.Agric.Engrs., 12, 668, 1969.

17 Chu, S.T., and Hustrulid, A.,
Numerical Solution of Diffusion Equations,
Trans.Am.Soc.Agric.Engrs., 11, 705, 1968.

18 Clark, R.G., and Lamond, W.J.,
Forced Drying of Herbage: Effect of Drying Conditions,
J.Agric.Engng.Res., 13, 19, 1968.

19 Coulson, J.M., and Richardson, J.F.,
Chemical Engineering, Vol.2,
Pergamon Press, Oxford, Lond., New York and Paris, 1962.

20 Davidson, J.F., Robson, M.W.L. and Roesler, F.C.,
Drying of Granular Solids Subjected to Alternating
Boundary Conditions,
Chem.Engng.Sci., 24, 815, 1969.

21 Dayton, R.W., Fawcett, S.L., Grimble, R.E., and
Sealander, C.E.,
Improved Measurement of Surface Heat Transfer by
the Method of Cyclic Temperature Variations,
Rep. BMI-747, Battelle Memorial Institute,
Columbus, O., 1952.

22 De Acetis J., and Thodos, G.,
Mass and Heat Transfer in Flow of Gases Through
Spherical Packings,
Ind.Eng.Chem., 52, 1003, 1960.

23 Eckert, E.R.G., and Drake, R.M.,
Heat and Mass Transfer, 2nd Ed.,
McGraw-Hill, Lond. and New York, 1959.

24 Friedman, S.J., and Marshall, W.R.,
Studies in Rotary Drying - Part 2, Heat and Mass
Transfer,
Chem.Engng.Prog., 45, 573, 1949.

25 Gallagher, G.L.,
A Method of Determining the Latent Heat of
Agricultural Crops,
Agric.Engng., St.Joseph, Mich., 32, 34, 1951.

26 Garside, J., Lord, L.W. and Reagan, R.,
The Drying of Granular Fertilizers,
Chem.Engng.Sci., 25, 1133, 1970.

27 Gilliland, E.R.,
Fundamentals of Drying and Air Conditioning,
Ind.Eng.Chem., 30, 506, 1938.

28 Greenhill, W.L.,
The Effect of Laceration on the Drying of Pasture
Plants,
J.Aust.Inst.Agric.Sci., 25, 61, 1959.

29 Greenhill, W.L.,
The Effect of Crushing on the Drying of Pasture Plants,
J.Aust.Inst.Agric.Sci., 25, 58, 1959.

30 Greig, D.J.,
The Determination of the Rate Constant in Thin Layer
Drying of Agricultural Crops,
J.Agric.Engng.Res., 15, 106, 1970.

31 Henderson, S.M.,
A Basic Concept of Equilibrium Moisture,
Agric.Engng., St.Joseph, Mich., 33, 29, 1952.

32 Henderson, S.M., and Pabis, S.,
Grain Drying Theory - I, Temperature Effect on
Drying Coefficient,
J.Agric.Engng.Res., 6, 169, 1961.

33 Hinchley, J.W., and Himus, G.W.,
Evaporation in Currents of Air,
Trans.Instn.Chem.Engrs., 2, 57, 1924.

34 Hiraoka, M., and Toei, R.,
Studies on through-flow Rotary Drier,
Mem.Fac.Engng.Kyoto Univ., 25, 144, 1963.

35 Jones, T.N., and Palmer, L.O.,
Natural Drying of Forage Crops,
Agric.Engng., St.Joseph, Mich., 17, 433, 1936.

36 Kazarian, E.A., and Hall, C.W.,
Thermal Properties of Grain,
Trans.Am.Soc.Agric.Engrs., 8, 33, 1965.

37 Kelly, J.J., and O'Donnell, J.P.,
Dynamics of Granular Material in Rotary Driers
and Coolers,
Instn.Chem.Engrs.Symposium Series No.29, Lond. 1968.

38 Lydersen, A.,
(Investigation of Heat Transfer and Pressure Loss
in Stacked Spheres traversed by Air),
Diss.Techn.Hochschul., Trondheim, 1950.

39 McAdams, W.H.,
Heat Transmission, 2nd Edn.,
McGraw-Hill, Lond., 1951.

40 McCormick, P.Y.,
Gas Velocity Effects on Heat Transfer in Direct
Heat Rotary Driers,
Chem.Engng.Prog., 58, 57, 1962.

41 McEwen, E., and O'Callaghan, J.R.,
Through-drying of Deep Beds of Wheatgrain,
Engineer, 198, 817, 1954.

42 McEwen, E., Simmonds, W.H.C., and Ward, G.T.,
The Drying of Wheatgrain - IV The Resistance to
Airflow of Beds of Agricultural Products:
Experimental Work,
Trans.Instn.Chem.Engrs., 32, 121, 1954.

43 McEwen, E., Simmonds, W.H.C., and Ward, G.T.,
The Drying of Wheatgrain - V Resistance to Airflow
of Beds of Agricultural Products: A Correlation
of Results,
Trans.Instn.Chem.Engrs., 32, 130, 1954.

44 Mears, D.R., and Roberts, W.J.,
Methods of Accelerating Forage Drying,
Am.Soc.Agric.Engrs., Paper No.69-162, 1969.

45 Miller, C.O., Smith, B.A., and Schuette, W.H.,
Factors Influencing the Operation of Rotary Driers
- II, The Rotary Drier as a Heat Exchanger,
Trans.Am.Inst.Chem.Engrs., 38, 841, 1942.

46 Mohsenin, N.N.,
Physical Properties of Plant and Animal Materials,
Gordon & Breach, , 1970.

47 Moran, F.J.,
Private Communication,
University of Newcastle upon Tyne, 1969.

48 Newman, A.B.,
Drying of Porous Solids - Diffusion Calculations,
Trans.Am.Inst.Chem.Engrs., 27, 203, 1931.

49 O'Callaghan, J.R.,
Drying of Wheatgrain - Effects of Air Condition on Through-Flow Drying,
M.Sc. Thesis, King's College, University of Durham, 1954.

50 Pabis, S., and Henderson, S.M.,
Grain Drying Theory - II, A Critical Analysis of the Drying Curve for Shelled Maize,
J.Agric.Engng.Res., 6, 169, 1961.

51 Pearse, J.F., Oliver, T.R., and Newitt, D.M.,
The Mechanism of the Drying of Solids - I,
Trans.Instn.Chem.Engrs., 27, 1, 1949.

52 Pedersen, T.T., and Buchele, W.F.,
Drying Rate of Alfalfa Hay,
Agric.Engng., St.Joseph, Mich., 41, 86, 1960.

53 Perry, J.H., (Ed.),
Chemical Engineers' Handbook, 4th Edn.,
McGraw-Hill, , 1963.

54 Porter, S.J.,
The Design of Rotary Driers and Coolers,
Trans.Instn.Chem.Engrs., 41, 272, 1963.

55 Powell, R.W., and Griffiths, E.,
The Evaporation of Water from Plane and Cylindrical Surfaces,
Trans.Instn.Chem.Engrs., 13, 175, 1935.

56 Ramp, R.M.,
Drying of Grasses,
Agric.Engng., St.Joseph, Mich., 21, 472, 1940.

57 Randall, B.E.,
Thin Layer Grass Drying,
M.Sc. Thesis, University of Newcastle upon Tyne, 1968.

58 Richardson, J.A.,
Physics in Botany,
Pitman, Lond., 1964.

59 Rodriguez-Arias, J.H.,
Ph.D, Thesis, Michigan State University, 1956.

60 Satterfield, C.N., and Resnick, H.,
Simultaneous Heat and Mass Transfer in a Diffusion-controlled Chemical Reaction - II, Studies in a Packed Bed,
Chem.Eng.Prog., 50, 504, 1954.

61 Schofield, F.R. and Glikin, P.G.,
Rotary Driers and Coolers for Granular Fertilizers,
Trans.Instn.Chem.Engrs., 40, 183, 1962.

62 Scott, A.W.,
Temperature Effects in Grass Drying,
Engineering, 150, 7, 1940.

63 Sharples, K., Flikin, P.G., and Warne, R.,
Computer Simulation of Rotary Driers,
Trans.Instn.Chem.Engrs., 42, 275, 1964.

64 Sherwood, T.K.,
The Drying of Solids - I,
Ind.Engng.Chem., 21, 12, 1929.

65 Simmonds, W.H.C., Ward, G.T., and McEwen, E.,
The Drying of Wheatgrain - I, The Mechanism of Drying,
Trans.Instn.Chem.Engrs., 31, 265, 1953.

66 Slatyer, R.O.,
Plant-Water Relationships,
Academic Press, Lond. and New York, 1967.

67 Spencer, H.B.,
A Mathematical Simulation of Grain Drying,
J.Agric.Engng.Res., 14, 226, 1969.

68 Stuart, J.C.,
Measurement of the Performance of a Rotary Grass
Drier,
Private Communication, University of Newcastle upon Tyne,
1970.

69 Sutton, O.G.,
Wind Structure and Evaporation in a Turbulent Atmosphere,
Proc.R.Soc., A., 146, 701, 1934.

70 Thaine, R.,
Investigation into Water Loss from Blotting Paper,
grass leaves and stem internodes.
Rep.Grassld.Res.Inst., Hurley, Berks, 1969.

71 Thygeson, J.R., and Grossman, E.D.,
Optimization of a Continuous Through-Flow Circulation
Drier,
Am.Inst.Chem.Engrs.J., 16, 749, 1970.

72 Tullberg, J.N.,
An Investigation into the Effects of Stomatal Control
on the Drying Rate of Alfalfa,
Thesis, New Brunswick State University, 1965.

73 University of Newcastle upon Tyne,
Unpublished Results of Drying Deep Beds of Wheatgrain,
Agric.Engng.Dept., Univ.Newcastle upon Tyne, 1966-1969.

74 University of Newcastle upon Tyne,
Unpublished Results of Drying Thin Layers of Hay,
Agric.Engng.Dept., Univ.Newcastle upon Tyne, 1969.

75 University of Newcastle upon Tyne.
Unpublished Results of Determination of Physical Properties of Grain,
Agric.Engng.Dept., Univ.Newcastle upon Tyne, 1969.

76 Wang, J.K., and Hall, C.W.,
Moisture Movement in Hygroscopic Materials,
Trans.Am.Soc.Agric.Engrs., 4, 33, 1961.

77 Warlow, A.J.,
Management of a Tower Silo System,
M.Sc.Thesis, University of Newcastle upon Tyne, 1968.

78 Watson, S.J.,
Grass Drying - Chemical Aspects,
Trans.Instn.Chem.Engrs., 22, 86, 1944.

79 Whitney, L.F.,
Design Parameters of Fluidization Principles for Forage Harvesting and Processing,
Ph.D.Thesis, Michigan State Univ., 1964.

80 Whitney, L.F., and Hall, C.W.,
Harvesting and Drying Alfalfa Leaves,
Trans.Am.Soc.Agric.Engrs., 7, 339, 1964.

81 Whitney, L.F., and Hall, C.W.,
Design Parameters for Drying Fluidized Alfalfa Leaves,
Trans.Am.Soc.Agric.Engrs., 10, 467, 1967.

82 Whitney, L.F., Agrawal, K.K., and Livingston, R.B.,
Stomatal Effects on High-Temperature Short-Time Drying of Alfalfa Leaves,
Trans.Am.Soc.Agric.Engrs., 12, 769, 1969.

83 Whyte, R.O., and Yee, H.J.,
Green Crop Drying,
Faber & Faber, Lond. 1952.

Heat and Mass Transfer Relationships in the Drying of Grass

by

D. J. MENZIES B.E. N.U.I.

VOL. 2

A thesis submitted for the degree of
Doctor of Philosophy
in the
University of Newcastle Upon Tyne

January 1971

INDEX TO VOLUME 2

11 Figures

X

TABLES

TABLES

ABBREVIATIONS

I	Italian ryegrass
P	Perennial ryegrass
G	Whole grass
L	Leaves only
S	Stems only
AV	Average of values obtained by polynomial (p) and grouping and segmentation (g) methods
C	k_0

Table 3.1

To Show that the air Resistance does not change substantially

Run	Loss of weight as shown by lab. balance	Loss of weight as shown by Data Logger
301	8.42 gm	8.51 gm
308	9.32 gm	9.16 gm
399	10.90 gm	9.60 gm
401	9.98 gm	9.70 gm

Table 3.2

Readings from Balance Response Tests

(a) Data Logger: Input : step of size 10 or 5

t secs.	Test 1 Response	Test 2 Response	Test 3 Response	Test4 Response
0	0.03	0.04	0.07	0.03
$\frac{1}{3}$	3.39	2.03	3.33	3.51
$\frac{2}{3}$	6.21	3.46	6.63	6.72
1	8.36	4.39	8.62	8.70
$1\frac{1}{3}$	9.49	4.83	9.60	9.64
$1\frac{2}{3}$	9.92	5.01	9.98	9.99
2	10.05	5.06	10.09	10.09
$2\frac{1}{3}$	10.08	5.07	10.11	10.11
$2\frac{2}{3}$	10.08	5.06	10.12	10.10

(b) Ultra-violet Recorder : Input : step of size 10 or 5

t secs.	Test 1 Response	Test 2 Response	Test 3 Response	Test4 Response
0	0	0	0	0
0.25	3	2	1.5	1
0.5	5	4.2	2.7	2.4
0.75	7	6.2	3.5	3.4
1.0	8.4	7.7	4.2	4.1
1.25	9.3	8.7	4.6	4.5
1.5	9.6	9.3	4.8	4.8
1.75	9.9	9.7	5.0	4.9
2.0	10.0	9.9	5.0	5.0

Table 3.3

Resistance Test on Medium Temperature Rig

	Heavy Duty Balance		Test Balance (Light Duty)	
			No air	Full Air
Weight of Tray empty	210.8		212.2	211.0
Weight of tray and undried grass*	268.2	267.2	267.8	265.2
Weight of tray and dried grass*	220.2 220.5	220.1 220.6	220.8	217.9

* Not same sample

Thus Resistance when dry = 2.6 gm approx.
Resistance when wet = 2.9 gm approx.

Table 4.1

Sources of Grass

Source	Description	No. of cuts taken
A	Field of second Season Italian Ryegrass (I.R.G.) (1968)	8
B	Discard Plot of I.R.G. at N.I.A.B. plots at Cockle Park (1968)	16
C	Plot of I.R.G. at N.I.A.B. (1969)	8
D	Plot of Perennial Ryegrass (P.R.G.) (1969)	4
E	Plot of I.R.G. at N.I.A.B. (1970)	6

Table 4.2

Grass Sampling Data

Batch	Variety	l_s	Time of Regrowth	Date of Cut	Moisture Content(d.b.)
1	I	1.875		20. 6.68	5.6613
2	I	1.247		26. 6.68	6.4944
3	I	1.017		28. 6.68	6.7171
4	I	0.825		1. 7.68	5.6824
5	I	0.542		3. 7.68	7.2728
6	I	0.545		5. 7.68	5.3203
7	I	1.166	14	5. 7.68	6.7873
8	I	0.681		8. 7.68	4.6559
9	I	1.02		29. 7.68	4.3486
10	I	0.681		2. 8.68	4.7093
11	I	0.998		6. 8.68	4.8851
12	I	0.576		9. 8.68	4.2162
13	I	0.772		13. 8.68	4.3778
14	I	0.506		15. 8.68	3.9603
15	I	0.470		20. 8.68	4.5053
16	I	1.78	22	20. 8.68	5.0715
17	I	3.1	21	23. 8.68	6.5356
18	I	4.42	24	28. 8.68	7.4378
19	I	3.1	22	31. 8.68	5.1510
20	I	4.54	36	2.10.68	4.3000
21	I	4.49	36	5.10.68	7.2641
22	I	3.09	56	9.10.68	6.3364
23	I	7.33	44	11.10.68	6.8329
24	I	2.15	72	23.10.68	4.7298
25	I	0.531	29	29. 7.69	4.9970
26	P	-	29	29. 7.69	6.0330
27	I	-	34	3. 8.69	2.8050
28	P	-	34	3. 8.69	4.4828
29	I	0.358	39	8. 8.69	2.5975
30	P	-	39	8. 8.69	4.6017
31	I	0.39	41	10. 8.69	2.8295
32	P	-	41	10. 8.69	4.7536
33	I		14	24. 8.69	5.1918
34	I	8.638	21	29. 8.69	4.9663
35	I	6.742	28	31. 8.69	5.1336
36	I	1.470	42	9. 9.69	3.7663
37	I	2.71	20	11. 5.70	6.1317
38	I	1.34	29	20. 5.70	4.3348
39	I	1.22	31	22. 5.70	3.3290
40	I	1.068	35	26. 5.70	3.1370
41	I	0.90	42	2. 6.70	2.9021
42	I	0.63	49	9. 6.70	2.5280

Table 4.3.

ORIGINAL EXPERIMENTAL DATA

BATCH NO 1 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.87

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS:

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
13	GRASS	33.0	1.90	97.1	9.8	15.3	120	5.2834	0.2629
14	GRASS	18.5	1.90	100.1	9.8	15.3	64	4.3655	0.0373
15	GRASS	20.2	1.90	103.0	9.8	15.3	71	5.8246	0.4891
16	GRASS	40.0	1.90	95.8	9.8	15.3	133	5.8072	0.1252
17	GRASS	34.0	1.90	97.7	10.3	15.6	127	5.6613	0.1561
18	GRASS	35.0	1.90	100.9	10.3	15.6	130	5.5262	0.6430

Table 4.4

ORIGINAL EXPERIMENTAL DATA

BATCH NO 2 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.24

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS!

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
5	GRASS	54.0	1.90	88.4	7.5	13.6	183	6.8321	0.6450
6	STEMS	27.0	1.90	96.8	10.5	16.3	116	7.2791	0.8732
7	LEAVES	23.0	1.90	96.6	12.3	20.3	95	4.7579	0.2259
8	GRASS	40.0	1.90	98.3	12.0	20.6	157	6.4944	0.5381
9	GRASS	44.0	1.90	101.3	12.6	21.1	115	6.0163	1.1901
27	GRASS	60.0	1.90	100.1	13.3	18.6	168	6.0164	0.1732
28	GRASS	51.0	1.90	97.5	14.1	18.1	175	6.1223	0.3350

Table 4.5

ORIGINAL EXPERIMENTAL DATA

BATCH NO 3 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.02

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS.

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
19	GRASS	62.0	1.90	88.4	9.3	12.6	189	6.7171	0.2139
20	STEMS	31.0	1.90	91.9	7.7	13.1	106	5.1229	0.8903
21	LEAVES	20.0	1.90	94.3	13.8	17.6	83	5.2560	0.1192
22	GRASS	44.0	1.90	96.2	13.8	17.8	149	6.7392	0.2596
23	GRASS	35.0	1.90	97.1	14.3	18.8	114	6.2674	0.4321
24	GRASS	35.0	1.90	97.1	13.8	18.1	116	6.6492	0.6422
25	GRASS	30.0	1.90	98.6	14.1	18.6	110	6.9007	1.9649
26	GRASS	60.0	1.90	97.5	14.1	18.6	198	6.6324	0.3534

Table 4.6

ORIGINAL EXPERIMENTAL DATA

BATCH NO 4 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.83

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
36	GRASS	46.0	1.90	93.7	11.3	18.3	132	5.6824	0.1122
37	LEAVES	34.0	1.90	94.5	12.7	17.5	91	5.0512	0.0070
38	STEMS	45.0	1.90	91.6	11.0	16.3	123	6.3090	0.0449
39	GRASS	50.0	1.90	91.7	10.7	16.0	173	6.3477	1.0202
40	GRASS	65.0	1.90	91.3	13.0	19.5	184	5.2615	0.3076

Table 4.7

ORIGINAL EXPERIMENTAL DATA

BATCH NO 5 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.54

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
29	GRASS	53.0	1.90	95.0	14.3	20.3	199	7.4558	0.0419
30	GRASS	64.0	1.90	95.3	13.8	20.6	212	5.7178	1.1525
31	LEAVES	33.0	1.90	95.9	13.9	20.6	135	5.8937	0.0136
32	STEMS	78.0	1.90	97.0	13.6	20.3	180	7.1502	0.0309
33	GRASS	51.0	1.90	95.5	12.6	19.3	158	5.8885	0.3733
34	GRASS	66.0	1.90	95.5	12.9	19.5	194	7.2728	0.2649
35	GRASS	45.0	1.90	96.1	14.0	19.5	119	7.2728	0.0312

Table 4.8

ORIGINAL EXPERIMENTAL DATA

BATCH NO 6 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.55

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS:

RUN NO		TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
41	LEAVES	32.0	1.90	92.5	13.7	20.5	93	5.1479	0.1379
42	STEMS	55.0	1.90	93.5	14.3	21.2	149	4.8546	0.1999
43	GRASS	51.0	1.90	93.9	14.5	21.0	159	6.2037	0.1717
49	GRASS	51.0	1.90	95.9	9.0	15.9	146	5.3203	0.2056

Table 4.9

ORIGINAL EXPERIMENTAL DATA

BATCH NO 7 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.17

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
44	GRASS	42.0	1.90	94.2	13.1	19.8	143	6.7873	0.1062
45	LEAVES	53.0	1.90	96.0	13.1	19.7	138	6.3305	0.0188
46	STEMS	46.0	1.90	95.6	13.0	19.7	135	7.5699	0.1596
47	GRASS	58.0	1.90	96.9	12.5	19.1	165	6.9552	0.1366
48	GRASS	47.0	1.90	95.8	10.0	16.5	146	6.3501	0.2170

Table 4.10

ORIGINAL EXPERIMENTAL DATA

BATCH NO 8 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.68

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
50	LEAVES	32.0	1.90	91.2	25.6	29.2	135	5.2735	0.0772
51	LEAVES	33.0	1.90	93.0	26.3	30.1	110	5.2735	0.0221
52	STEMS	52.0	1.90	93.2	26.5	30.6	183	5.1223	0.1422
53	STEMS	43.0	1.90	93.5	26.9	30.6	138	5.1223	0.2732
54	GRASS	44.0	1.90	96.0	26.5	30.0	139	4.6559	0.0561
55	GRASS	46.0	1.90	94.5	25.6	29.3	128	4.6559	0.5998
56	GRASS	42.0	2.00	96.5	25.9	29.1	130	4.6559	0.0238
57	GRASS	20.0	2.00	114.4	26.9	29.3	118	4.6559	0.0220
58	GRASS	65.0	2.00	59.6	26.0	29.6	110	4.6559	1.4129

Table 4.11

ORIGINAL EXPERIMENTAL DATA

BATCH NO 9 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.02

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
59	GRASS	29.0	1.90	89.2	15.2	20.8	118	4.3486	0.0157
60	GRASS	40.0	1.90	87.5	13.4	18.0	153	5.6722	0.0242
61	LEAVES	31.0	1.90	90.5	13.8	18.8	145	5.1936	0.0125
62	STEMS	28.7	1.90	89.1	13.8	19.2	141	4.0362	0.0439
63	GRASS	24.7	1.90	91.6	13.7	19.5	148	5.6722	0.1960
64	GRASS	59.0	1.90	53.8	11.3	16.3	169	4.5522	1.2079
65	GRASS	54.0	1.90	57.7	12.5	17.4	123	5.4487	1.6010

Table 4.12

ORIGINAL EXPERIMENTAL DATA

BATCH NO 10 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.68

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS:

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
66	GRASS	36.0	1.90	91.4	10.5	15.4	124	4.7093	0.0274
67	LEAVES	23.0	1.90	90.2	11.5	15.9	115	4.6353	0.0122
68	STEMS	33.0	1.90	89.2	12.0	16.3	144	4.0612	0.1727
69	GRASS	35.0	1.90	80.0	15.3	17.7	121	4.7093	1.6951
70	GRASS	67.0	1.90	63.0	16.2	18.4	193	4.7093	0.7660
71	GRASS	38.0	1.90	70.0	17.1	18.8	108	4.7093	1.1757
72	GRASS	27.0	1.90	90.0	17.6	19.0	91	4.7093	0.0222
73	GRASS	24.0	1.90	113.0	18.9	19.3	108	4.7093	0.0392

Table 4.13

ORIGINAL EXPERIMENTAL DATA

BATCH NO 11 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.00

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS:

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
74	GRASS	26.0	2.00	118.1	15.4	19.1	108	4.8851	0.0736
75	GRASS	29.0	1.90	96.9	15.9	19.7	87	4.8851	0.0226
76	LEAVES	24.0	1.90	97.9	15.9	19.6	95	4.9858	0.0012
77	STEMS	29.0	1.90	97.6	16.0	20.0	129	4.6472	0.0567
78	GRASS	41.0	1.90	63.6	16.7	20.8	128	4.8851	1.5432
79	GRASS	58.0	1.90	62.6	16.6	20.7	117	4.8851	1.3324
80	GRASS	61.0	1.90	29.5	16.4	20.2	78	4.8851	3.1208
81	GRASS	61.0	1.95	70.0	15.1	18.9	164	4.8851	0.2710
82	GRASS	27.0	1.90	111.2	15.6	20.0	107	4.8851	0.0381

Table 4.14

ORIGINAL EXPERIMENTAL DATA

BATCH NO 12 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.57

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
83	GRASS	31.0	1.91	132.4	13.9	19.5	104	4.2162	0.0154
84	GRASS	36.0	1.92	105.0	14.1	19.4	134	4.2162	0.0253
85	LEAVES	28.7	1.92	106.7	14.4	19.7	148	1.8621	0.0116
86	STEMS	45.0	1.92	107.6	14.4	19.8	135	2.8776	0.0241
87	GRASS	64.0	1.93	65.4	14.3	19.6	138	4.2162	0.6970
88	GRASS	60.0	1.02	78.4	14.0	19.2	128	4.2162	0.3533

Table 4.15

ORIGINAL EXPERIMENTAL DATA

BATCH NO 13 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.77

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
89	GRASS	24.0	1.85	129.0	15.4	17.8	123	4.3778	0.0273
90	GRASS	30.0	1.85	105.0	15.1	18.4	108	4.3778	0.0310
91	GRASS	63.0	1.86	40.7	16.2	18.9	141	4.3778	2.1916
92	GRASS	55.0	1.86	70.6	16.1	19.5	138	4.3778	0.4349
93	LEAVES	17.0	1.86	105.6	16.2	19.5	73	6.1834	0.0167
94	STEMS	23.0	1.86	106.5	16.1	19.6	108	4.5174	0.0474
95	GRASS	61.0	1.88	66.7	16.1	19.5	120	4.3778	0.5980
96	GRASS	44.0	0.85	83.2	15.7	19.3	145	4.3778	0.0956
97	GRASS	54.0	1.40	77.1	15.7	19.9	144	4.3778	0.1469
98	GRASS	51.0	1.69	75.9	15.8	19.4	119	4.3778	0.3383
99	GRASS	45.0	1.08	83.1	14.8	18.8	151	4.3778	0.0985
100	GRASS	46.0	0.73	88.1	13.9	18.3	118	4.3778	0.2044

Table 4.16

ORIGINAL EXPERIMENTAL DATA

BATCH NO 14 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.51

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS)

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
101	GRASS	14.3	1.89	125.6	11.7	16.6	79	3.9603	0.0685
102	GRASS	118.0	1.90	37.6	12.7	17.5	129	3.9603	1.8459
103	GRASS	35.0	1.87	103.3	13.6	18.2	113	3.9603	0.0306
104	LEAVES	26.7	1.89	105.4	13.8	18.4	160	5.0760	0.0092
105	STEMS	27.0	1.89	105.7	13.8	18.4	113	2.7088	0.0329
106	GRASS	56.0	1.90	65.3	13.6	18.7	136	3.9603	1.0335
107	GRASS	35.0	1.90	78.5	13.4	18.8	167	3.9603	0.3125
108	GRASS	43.0	0.72	84.1	12.6	17.9	147	3.9603	0.3196
109	GRASS	52.0	1.59	76.4	13.3	18.5	128	3.9603	0.0993

Table 4.17

ORIGINAL EXPERIMENTAL DATA

BATCH NO 15 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.48

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
110	GRASS	19.7	1.91	100.7	15.4	17.1	118	4.5053	0.1024
111	LEAVES	12.8	1.91	101.6	15.0	17.2	78	4.8233	0.0980
112	STEMS	27.0	1.91	101.8	14.6	17.7	123	3.6279	0.0422
118	GRASS	18.0	1.87	132.2	16.9	20.0	70	4.5053	0.0226
119	GRASS	19.0	1.87	113.2	17.1	20.2	74	4.5053	0.0381
122	GRASS	31.0	1.90	74.8	16.7	20.2	125	4.5053	0.6268
124	GRASS	26.0	1.89	105.9	15.9	20.3	116	4.5053	0.0334
125	GRASS	21.0	0.73	143.5	16.0	20.2	86	4.5053	0.0184
128	GRASS	41.0	0.73	88.8	16.0	20.4	168	4.5053	0.2715
130	GRASS	30.0	0.73	105.7	16.5	20.9	103	4.5053	0.0286

Table 4.18

ORIGINAL EXPERIMENTAL DATA

BATCH NO 16 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.78

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
113	GRASS	19.0	1.90	102.7	14.9	18.2	105	5.0715	0.0585
114	LEAVES	12.0	1.90	104.2	15.1	18.4	52	4.7781	0.0082
115	STEMS	14.0	1.90	105.6	15.1	18.7	80	5.0431	0.1317
116	GRASS	15.0	1.90	105.6	15.7	18.9	53	5.0715	0.0270
117	GRASS	13.0	1.87	131.9	16.9	19.7	64	5.0715	0.0067
120	GRASS	10.8	1.87	115.3	17.5	20.5	66	5.0715	0.1781
121	GRASS	35.0	1.89	74.4	16.8	20.0	97	5.0715	0.1218
123	GRASS	17.0	1.87	103.2	22.2	24.5	72	5.0715	0.0322
126	GRASS	14.0	0.73	145.7	16.0	20.7	85	5.0715	0.0489
127	GRASS	30.0	0.73	86.9	15.6	19.9	84	5.0715	0.1462
129	GRASS	17.0	0.73	107.2	16.2	21.1	103	5.0715	0.1257

Table 4.19

ORIGINAL EXPERIMENTAL DATA

BATCH NO 17 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 3.10

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
131	GRASS	26.0	1.87	106.5	15.7	18.0	85	6.5356	0.0071
132	LEAVES	15.0	1.87	106.7	17.4	20.6	75	5.6377	0.0020
133	STEMS	24.0	1.87	107.1	17.6	21.3	64	6.2795	0.0092
134	GRASS	13.0	1.83	136.6	18.5	22.5	79	6.5356	0.0057
135	GRASS	37.0	1.91	68.6	18.8	23.0	103	6.5356	0.5596
136	GRASS	81.0	1.91	40.6	19.4	23.8	97	6.5356	1.6347
137	GRASS	40.0	1.92	83.0	19.8	24.2	102	6.5356	0.0463
138	GRASS	17.0	1.87	125.1	19.8	24.5	71	6.5356	0.0496
139	GRASS	15.0	1.22	130.3	19.7	24.3	47	6.5356	0.0237
140	GRASS	9.0	1.22	161.7	19.8	24.3	48	6.5356	0.0080

Table 4.20

ORIGINAL EXPERIMENTAL DATA

BATCH NO 18 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 4.42

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
141	LEAVES	22.0	1.92	102.6	15.5	19.4	52	6.1040	0.0028
142	STEMS	21.0	1.91	104.6	15.6	19.6	77	8.4967	0.0411
143	GRASS	23.0	1.91	105.7	15.9	19.9	71	7.4378	0.0206
144	GRASS	18.0	1.91	106.7	16.1	20.2	92	7.4378	0.0086
145	GRASS	15.0	1.91	106.5	16.1	20.3	76	7.4378	0.0470
146	GRASS	17.0	1.90	134.0	16.3	21.0	81	7.4378	0.0069
147	GRASS	23.0	1.92	114.2	16.2	20.8	68	7.4378	0.0241
148	GRASS	31.0	1.92	73.3	16.2	20.8	126	7.4378	0.4987
149	GRASS	36.0	1.93	37.1	15.8	20.7	109	7.4378	3.7949
150	GRASS	26.0	0.73	96.4	16.0	20.5	100	7.4378	0.1550
151	GRASS	20.0	0.73	154.2	16.2	20.7	76	7.4378	0.0063
152	GRASS	24.0	0.76	108.7	54.8	57.6	96	7.4378	0.2967
237	GRASS	19.0	1.92	102.1	15.1	18.9	96	7.4378	0.1742

Table 4.21

ORIGINAL EXPERIMENTAL DATA

BATCH NO 19 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 3.10

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
153	GRASS	16.0	1.89	129.8	11.5	14.1	52	5.1510	0.0093
154	GRASS	18.0	1.90	109.1	12.3	14.3	60	5.1510	0.0258
155	GRASS	17.0	1.91	101.8	12.3	14.9	54	5.1510	0.0263
156	LEAVES	14.0	1.89	103.3	12.1	15.0	59	5.5301	0.0024
157	STEMS	18.0	1.89	104.6	12.0	15.2	56	6.5971	0.0449
158	GRASS	33.0	1.90	77.1	12.0	15.6	83	5.1510	0.2640
159	GRASS	46.0	1.92	62.6	11.6	15.4	112	5.1510	0.5745
160	GRASS	34.0	0.73	86.0	11.4	15.6	95	5.1510	0.0697
161	GRASS	18.8	1.05	84.6	11.5	15.6	114	5.1510	0.2783
162	GRASS	17.0	1.69	85.2	11.4	15.6	53	5.1510	0.2173

Table 4.22

ORIGINAL EXPERIMENTAL DATA

BATCH NO 20 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 4.54

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
163	GRASS	28.0	1.90	97.6	9.3	14.4	103	1.4839	0.0204
164	LEAVES	19.0	1.90	97.9	9.5	14.6	64	4.5458	0.0077
165	STEMS	23.3	1.90	97.6	9.2	14.9	141	4.0349	0.1239
166	GRASS	17.0	1.90	124.7	12.8	16.5	64	1.4839	0.0267
167	GRASS	23.3	0.83	129.9	9.0	15.1	139	1.4839	0.0000
168	GRASS	13.7	1.56	119.3	12.2	15.9	82	1.4839	0.3231
169	GRASS	16.0	1.24	132.6	12.5	16.8	58	1.4839	0.0323
170	GRASS	16.0	1.00	135.0	11.9	15.9	73	1.4839	0.0270
171	GRASS	37.0	1.00	79.4	10.5	14.2	113	1.4839	0.0758
172	GRASS	30.0	1.57	76.5	11.3	14.2	96	1.4839	0.1642
173	GRASS	36.0	1.23	75.8	13.4	17.0	122	1.4839	0.3767
174	GRASS	39.0	0.81	81.1	14.5	17.7	86	1.4839	0.2997
175	GRASS	31.0	0.81	97.5	16.3	19.4	119	1.4839	0.0733
176	GRASS	33.0	1.26	105.1	20.3	23.1	103	1.4839	0.0149

Table 4.23

ORIGINAL EXPERIMENTAL DATA

BATCH NO 21 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 4.49

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
177	GRASS	23.0	1.92	103.2	17.1	18.4	92	7.2641	0.1038
178	LEAVES	19.0	1.92	103.5	17.1	18.7	67	6.7652	0.0196
179	STEMS	22.7	1.92	103.6	17.0	18.8	137	5.3927	0.0567
180	GRASS	29.0	1.92	128.0	18.1	19.3	100	7.2641	0.0022
181	GRASS	29.0	0.76	137.3	16.3	18.9	105	7.2641	0.0073
182	GRASS	21.0	1.25	137.7	17.0	19.6	73	7.2641	0.0008
183	GRASS	17.0	1.01	139.2	16.8	19.9	60	7.2641	0.0566
184	GRASS	17.0	1.51	137.0	16.8	19.8	91	7.2641	0.0382
185	GRASS	27.0	1.51	100.3	16.2	19.5	68	7.2641	0.0418
186	GRASS	27.0	1.24	94.7	16.0	19.5	112	7.2641	0.1421
187	GRASS	27.0	0.99	93.4	15.9	19.7	93	7.2641	0.0926
188	GRASS	30.0	0.76	95.0	15.5	19.2	104	7.2641	0.0792
189	GRASS	36.0	0.22	89.8	15.8	19.2	117	7.2641	0.5347
190	GRASS	60.0	0.22	63.4	16.1	20.0	114	7.2641	1.0370
191	GRASS	35.0	0.76	66.6	16.1	20.0	111	7.2641	0.9171
192	GRASS	44.0	1.28	72.0	15.9	19.5	125	7.2641	0.4458
193	GRASS	30.0	1.94	67.8	16.5	20.3	119	7.2641	0.6140

Table 4.24

ORIGINAL EXPERIMENTAL DATA

BATCH NO 22 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 3.09

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
194	GRASS	26.0	1.90	100.4	9.2	14.5	102	6.3364	0.0251
195	LEAVES	25.0	1.90	101.4	10.0	14.9	77	6.8948	0.0249
196	STEMS	29.0	1.90	102.6	10.4	16.7	152	5.4459	0.0370
197	GRASS	16.0	1.88	129.4	10.2	15.4	83	6.3364	0.0575
198	GRASS	24.0	1.52	130.3	9.7	14.8	79	6.3364	0.0109
199	GRASS	21.0	1.25	128.4	9.6	15.1	76	6.3364	0.0133
200	GRASS	17.0	0.99	130.5	9.2	14.7	72	6.3364	0.0526
201	GRASS	20.0	0.75	138.7	8.5	14.5	97	6.3364	0.1045
202	GRASS	26.0	0.22	146.6	8.4	13.8	123	6.3364	0.1561
203	GRASS	45.0	0.22	64.9	7.3	12.9	235	6.3364	1.5739
204	GRASS	29.0	0.75	96.3	6.7	12.2	146	6.3364	0.0925
205	GRASS	26.0	1.01	96.1	6.3	12.0	116	6.3364	0.1721
206	GRASS	23.0	1.25	96.4	5.9	11.6	90	6.3364	0.1910
207	GRASS	19.0	1.53	95.9	5.9	11.4	70	6.3364	0.2119
208	GRASS	32.0	1.89	68.6	13.5	16.1	137	6.3364	0.5529
209	GRASS	47.0	1.50	68.3	13.7	17.6	127	6.3364	0.9123
210	GRASS	30.0	1.25	70.2	13.7	18.5	141	6.3364	1.2307
211	GRASS	40.0	0.99	60.5	13.2	18.7	137	6.4589	1.3762
212	GRASS	40.0	0.75	65.1	13.1	18.8	134	6.3364	1.0168
213	GRASS	59.0	0.22	70.0	13.0	18.7	125	6.3364	0.9660
214	GRASS	31.0	0.22	112.9	12.6	18.1	125	6.3364	0.1432
215	GRASS	19.0	1.93	116.7	15.0	18.2	77	6.3364	0.1492
216	GRASS	20.0	1.50	114.4	15.3	18.6	103	6.3364	0.0880
217	GRASS	19.0	1.25	118.1	15.6	18.9	89	6.3364	0.0488
218	GRASS	24.3	1.00	111.8	16.0	18.9	147	6.3364	0.0402

Table 4.25

ORIGINAL EXPERIMENTAL DATA

BATCH NO 23 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 7.33

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO- METER IN-WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
219	GRASS	26.0	1.90	103.2	15.8	19.0	92	6.8329	0.0796
220	LEAVES	20.0	1.90	104.0	16.1	18.7	81	6.1867	0.0144
221	STEMS	18.0	1.90	104.3	16.1	18.8	73	5.5030	0.0401
222	GRASS	12.0	1.90	132.5	16.5	18.9	53	6.8329	0.0713
223	GRASS	16.0	1.90	114.3	16.5	18.7	80	6.8329	0.0406
224	GRASS	16.0	1.90	108.6	15.6	18.1	67	6.8329	0.0618
225	GRASS	25.0	1.90	86.9	13.6	17.4	111	6.8329	0.1421
226	GRASS	36.0	1.90	71.0	13.2	17.4	113	6.8329	0.4527
227	GRASS	72.0	1.90	62.6	11.9	18.3	133	6.8329	0.2095
228	GRASS	61.0	1.90	51.2	12.4	18.6	144	6.8329	0.5144
229	GRASS	38.0	1.90	68.1	12.2	18.1	127	6.8329	0.4106
230	GRASS	17.0	1.90	109.6	12.8	18.1	75	6.8329	0.2488
231	GRASS	14.0	1.90	109.2	12.8	18.0	85	6.8329	0.4197

Table 4.26

ORIGINAL EXPERIMENTAL DATA

BATCH NO 24 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 2.15

NOTE : WET AND DRY BULB TEMPERATURES ARE THOSE OF THE INLET AIR
EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS;

RUN NO		TOTAL RUN TIME MINS	MANO-METER IN.WG	AIR TEMP DEG C	WET BULB TEMP DEG C	DRY BULB TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
232	GRASS	27.0	1.90	95.9	6.1	11.6	68	4.7298	0.0361
233	LEAVES	26.7	1.90	97.2	5.9	11.5	81	5.1026	0.0001
234	STEMS	46.0	1.90	97.8	5.8	11.3	138	4.2804	0.0093
235	GRASS	21.0	1.90	96.7	5.6	11.2	59	4.7298	0.1824
236	GRASS	26.0	1.90	96.5	9.0	11.7	77	4.7298	0.0180

Table 4.27

ORIGINAL EXPERIMENTAL DATA

EXPERIMENTS CARRIED OUT ON LOW TEMPERATURE RIG
ITALIAN RYE GRASS

BATCH NO	RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	DEW POINT TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
25	301	I	G	2	147.7	1.00	41.7	32.1	444	4.9970	1.3110
25	302	I	G	2	60.8	1.00	60.8	29.8	365	4.9970	0.6420
25	303	I	G	2	25.4	1.00	80.6	35.0	763	4.9970	0.2613
26	304	P	G	2	28.8	1.00	81.4	35.3	864	6.0330	0.2500
25	305	I	G	1	26.8	1.00	80.2	34.6	806	4.9970	0.1445
25	306	I	G	4	28.8	1.00	80.1	34.6	864	4.9970	0.2030
25	307	I	G	2	158.7	1.00	39.7	36.4	476	4.9970	1.7457
25	308	I	G	2	73.0	1.00	60.0	40.8	275	4.9970	0.9980
25	309	I	G	2	18.2	1.00	81.4	42.9	109	4.9970	0.8740
25	310	I	G	2	136.7	1.00	40.6	24.1	410	4.9970	1.1520
25	311	I	G	2	125.0	1.00	20.1	15.7	326	4.9970	2.5000
25	312	I	G	2	160.0	1.00	20.1	12.8	273	4.9970	2.7500
25	313	I	G	2	146.0	1.00	20.2	7.1	301	4.9970	2.0638
25	314	I	G	2	125.0	1.00	39.5	13.2	292	4.9970	1.8495
25	315	I	G	2	53.7	1.00	60.4	18.3	285	4.9970	1.2810

Table 4.28

ORIGINAL EXPERIMENTAL DATA

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
ITALIAN RYE GRASS

BATCH NO	RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANOMETER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
29	316	I	G	2	5.5	4.00	104.7	999	2.5975	0.2346
29	317	I	G	2	5.5	4.00	104.7	999	2.5975	0.0153
29	318	I	G	2	6.5	4.00	104.7	589	2.5975	0.1032
29	328	I	G	2	1.6	4.00	190.8	293	2.5975	0.2150
29	329	I	G	2	2.0	4.00	192.7	358	2.5975	0.0254
29	330	I	G	2	2.4	4.00	188.9	436	2.5975	0.0627
29	340	I	G	2	0.8	4.00	258.7	142	2.5975	0.1263
29	341	I	G	2	1.3	4.00	264.0	233	2.5975	0.0217
29	342	I	G	2	1.0	4.00	260.4	177	2.5975	0.0824
31	352	I	G	2	1.2	4.00	331.2	224	2.8295	0.0000
31	353	I	G	2	0.5	4.00	331.2	100	2.8295	0.0000
31	354	I	G	2	0.9	4.00	331.2	158	2.8295	0.0000
31	364	I	G	2	0.5	4.00	385.8	99	2.8295	0.0000
31	365	I	G	2	0.6	4.00	385.8	116	2.8295	0.0000
31	366	I	G	2	0.5	4.00	385.8	89	2.8295	0.0000
31	399	I	G	2	0.5	4.00	410.1	97	2.8295	0.0000
31	409	I	G	2	0.4	4.00	410.1	75	2.8295	0.0000
31	410	I	G	2	0.4	4.00	410.1	65	2.8295	0.0000

Table 4.29

ORIGINAL EXPERIMENTAL DATA

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
ITALIAN RYE LEAVES

BATCH NO	RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
29	322	I	L	2	4.8	4.00	106.9	864	2.5975	0.0904
29	323	I	L	2	4.7	4.00	106.9	842	2.5975	0.0837
29	324	I	L	2	5.1	4.00	106.9	917	2.5975	0.0823
29	338	I	L	2	2.9	4.00	196.5	521	2.5975	0.1039
29	339	I	L	2	2.2	4.00	192.7	394	2.5975	0.0613
29	349	I	L	2	0.8	4.00	262.2	147	2.5975	0.0670
29	350	I	L	2	1.2	4.00	262.2	213	2.5975	0.0000
29	351	I	L	2	1.0	4.00	258.7	174	2.5975	0.0000
31	363	I	L	2	0.7	4.00	331.2	127	2.8295	0.0000
31	374	I	L	2	0.1	4.00	385.8	26	2.8295	0.0000
31	375	I	L	2	0.5	4.00	385.8	95	2.8295	0.0000
31	376	I	L	2	0.4	4.00	385.8	68	2.8295	0.0000
31	377	I	L	2	0.4	4.00	385.8	74	2.8295	0.0000
31	408	I	L	2	0.4	4.00	410.1	71	2.8295	0.0000

Table 4.30

ORIGINAL EXPERIMENTAL DATA

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
ITALIAN RYE STEMS

BATCH NO	RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO- METER IN.WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
29	319	I	S	2	4.7	4.00	106.9	845	2.1721	0.3202
29	320	I	S	2	7.1	4.00	106.9	640	2.1721	0.1364
29	321	I	S	2	5.3	4.00	106.9	950	2.1721	0.2700
29	334	I	S	2	3.8	4.00	192.7	682	2.1721	0.0377
29	335	I	S	2	2.4	4.00	192.7	435	2.1721	0.0587
29	336	I	S	2	3.0	4.00	192.7	533	2.1721	0.0698
29	343	I	S	2	1.2	4.00	256.9	226	2.1721	0.0353
29	344	I	S	2	1.8	4.00	262.2	327	2.1721	0.0000
29	345	I	S	2	0.9	4.00	256.9	159	2.1721	0.1970
31	358	I	S	2	0.9	4.00	331.2	162	2.8295	0.0000
31	359	I	S	2	1.1	4.00	331.2	195	2.8295	0.0000
31	360	I	S	2	1.0	4.00	331.2	177	2.8295	0.0000
31	371	I	S	2	0.5	4.00	385.8	91	2.8295	0.0000
31	372	I	S	2	0.3	4.00	385.8	62	2.8295	0.0000
31	373	I	S	2	0.7	4.00	385.8	125	2.8295	0.0000
31	405	I	S	2	0.6	4.00	410.1	113	2.8295	0.0000
31	406	I	S	2	0.3	4.00	410.1	62	2.8295	0.0000
31	407	I	S	2	0.4	4.00	410.1	66	2.8295	0.0000

Table 4.31

ORIGINAL EXPERIMENTAL DATA

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
PERENNIAL RYE GRASS

BATCH NO	RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO. METER IN.WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
30	325	P	G	2	3.3	4.00	109.0	603	4.6017	0.5878
30	326	P	G	2	3.5	4.00	109.0	627	4.6017	0.5595
30	327	P	G	2	4.2	4.00	109.0	762	4.6017	0.4788
30	332	P	G	2	3.4	4.00	188.9	610	4.6017	0.0784
30	333	P	G	2	3.0	4.00	198.3	537	4.6017	0.1934
30	346	P	G	2	1.0	4.00	255.1	183	4.6017	0.1179
30	347	P	G	2	0.9	4.00	258.7	161	4.6017	0.2685
30	348	P	G	2	1.1	4.00	256.9	197	4.6017	0.0581
32	355	P	G	2	0.7	4.00	331.2	128	4.7536	0.0000
32	356	P	G	2	0.7	4.00	331.2	120	4.7536	0.0000
32	357	P	G	2	0.7	4.00	331.2	131	4.7536	0.0000
32	367	P	G	2	0.7	4.00	385.8	119	4.7536	0.0000
32	370	P	G	2	0.3	4.00	385.8	56	4.7536	0.0000
32	402	P	G	2	0.5	4.00	410.1	85	4.7536	0.0000
32	403	P	G	2	0.4	4.00	410.1	81	4.7536	0.0000
32	404	P	G	2	0.6	4.00	410.1	104	4.7536	0.0000

Table 4.32

ORIGINAL EXPERIMENTAL DATA

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
ITALIAN RYE GRASS

BATCH NO	RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
31	378	I	G	1	3.4	4.00	106.9	614	2.8295	1.0368
31	379	I	G	2	2.2	4.00	109.0	405	2.8295	0.7480
31	381	I	G	4	2.2	4.00	111.1	401	2.8295	0.7590
31	382	I	G	1	1.5	4.00	192.7	268	2.8295	0.3462
31	383	I	G	2	1.1	4.00	192.7	206	2.8295	0.5182
31	384	I	G	3	1.5	4.00	194.6	268	2.8295	0.5743
31	385	I	G	4	1.3	4.00	194.6	237	2.8295	0.1911
31	386	I	G	1	0.8	4.00	247.9	141	2.8295	0.2857
31	387	I	G	2	0.9	4.00	249.7	168	2.8295	0.1633
31	388	I	G	3	1.0	4.00	251.5	189	2.8295	0.1747
31	389	I	G	4	0.9	4.00	253.3	158	2.8295	0.1047
31	390	I	G	1	0.7	4.00	316.0	124	2.8295	0.0000
31	391	I	G	2	0.5	4.00	316.0	91	2.8295	0.0000
31	392	I	G	3	0.7	4.00	316.0	128	2.8295	0.0000
31	393	I	G	4	0.7	4.00	316.0	124	2.8295	0.0000
31	394	I	G	1	0.5	4.00	327.9	88	2.8295	0.0000
31	395	I	G	2	0.5	4.00	327.9	92	2.8295	0.0000
31	396	I	G	3	0.4	4.00	327.9	70	2.8295	0.0000
31	397	I	G	4	0.4	4.00	327.9	80	2.8295	0.0000
31	398	I	G	1	0.3	4.00	410.1	59	2.8295	0.0000
31	399	I	G	2	0.5	4.00	410.1	97	2.8295	0.0000
31	400	I	G	3	0.4	4.00	410.1	82	2.8295	0.0000
31	401	I	G	4	0.6	4.00	410.1	111	2.8295	0.0000

Table 4.33

ORIGINAL EXPERIMENTAL DATA

BATCH NO 33 OF GRASS

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO- METER IN.WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
411	I.RYE	GRASS	2	2.4	4.00	104.7	436	5.1918	0.9104
412	I.RYE	GRASS	2	1.4	4.00	104.7	254	5.1918	1.8188
413	I.RYE	GRASS	2	1.5	4.00	104.7	274	5.1918	1.7063
414	I.RYE	GRASS	2	2.2	4.00	104.7	389	5.1918	0.8780
415	I.RYE	GRASS	2	1.0	4.00	169.6	176	5.1918	0.4783
416	I.RYE	GRASS	2	1.2	4.00	169.6	215	5.1918	0.4820
417	I.RYE	GRASS	2	1.0	4.00	171.6	190	5.1918	0.2649
418	I.RYE	GRASS	2	0.7	4.00	235.3	123	5.1918	0.1450
419	I.RYE	GRASS	2	0.8	4.00	251.5	144	5.1918	0.2027
420	I.RYE	GRASS	2	0.8	4.00	249.7	148	5.1918	0.0667
421	I.RYE	GRASS	2	0.5	4.00	319.4	100	5.1918	0.0000
422	I.RYE	GRASS	2	0.5	4.00	331.2	93	5.1918	0.0000
423	I.RYE	GRASS	2	0.8	4.00	343.0	139	5.1918	0.0000
424	I.RYE	GRASS	2	0.5	4.00	326.2	98	5.1918	0.0000
425	I.RYE	GRASS	2	0.5	4.00	377.7	100	5.1918	0.0000
426	I.RYE	GRASS	2	0.5	4.00	385.8	86	5.1918	0.0000
427	I.RYE	GRASS	2	0.6	4.00	385.8	110	5.1918	0.0000

Table 4.34

ORIGINAL EXPERIMENTAL DATA

BATCH NO 34 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 8.64

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO- METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
428	I.RYE	GRASS	2	2.6	4.00	106.9	463	4.9663	0.6933
429	I.RYE	GRASS	2	1.8	4.00	106.9	320	4.9663	1.2201
430	I.RYE	GRASS	2	1.9	4.00	106.9	344	4.9663	1.2431
431	I.RYE	GRASS	2	1.0	4.00	163.8	175	4.9663	0.4390
432	I.RYE	GRASS	2	1.2	4.00	169.6	216	4.9663	0.1533
433	I.RYE	GRASS	2	1.2	4.00	173.5	217	4.9663	0.2029
434	I.RYE	GRASS	2	0.8	4.00	175.4	145	4.9663	0.3938
435	I.RYE	GRASS	2	0.8	4.00	240.7	150	4.9663	0.0600
436	I.RYE	GRASS	2	0.7	4.00	247.9	124	4.9663	0.0786
437	I.RYE	GRASS	2	0.7	4.00	251.5	136	4.9663	0.0662
438	I.RYE	GRASS	2	0.5	4.00	317.7	100	4.9663	0.0000
439	I.RYE	GRASS	2	0.6	4.00	321.1	116	4.9663	0.0000
440	I.RYE	GRASS	2	0.6	4.00	324.5	101	4.9663	0.0000
441	I.RYE	GRASS	2	0.5	4.00	362.9	93	4.9663	0.0000
442	I.RYE	GRASS	2	0.4	4.00	362.9	70	4.9663	0.0000
443	I.RYE	GRASS	2	0.5	4.00	366.2	85	4.9663	0.0000
444	I.RYE	GRASS	2	0.4	4.00	366.2	69	4.9663	0.0000

Table 4.35

ORIGINAL EXPERIMENTAL DATA

BATCH NO 35 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 6.74

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
445	I.RYE	GRASS	2	2.0	4.00	119.4	360	5.1336	0.7448
446	I.RYE	GRASS	2	2.0	4.00	117.4	363	5.1336	0.9407
447	I.RYE	GRASS	2	1.3	4.00	115.3	244	5.1336	1.4667
448	I.RYE	GRASS	2	1.2	4.00	177.4	211	5.1336	0.2566
449	I.RYE	GRASS	2	1.0	4.00	183.1	182	5.1336	0.3137
450	I.RYE	GRASS	2	0.9	4.00	183.1	170	5.1336	0.4459
451	I.RYE	GRASS	2	0.6	4.00	258.7	111	5.1336	0.1650
452	I.RYE	GRASS	3	0.8	4.00	258.7	151	5.1336	0.1956
453	I.RYE	GRASS	2	0.7	4.00	260.4	129	5.1336	0.1370
454	I.RYE	GRASS	2	0.6	4.00	322.8	105	5.1336	0.0000
455	I.RYE	GRASS	2	0.6	4.00	319.4	108	5.1336	0.0000
456	I.RYE	GRASS	2	0.8	4.00	309.2	153	5.1336	0.0000
457	I.RYE	GRASS	2	0.7	4.00	362.9	134	5.1336	0.0000
458	I.RYE	GRASS	2	0.5	4.00	362.9	86	5.1336	0.0000
459	I.RYE	GRASS	2	0.6	4.00	359.6	101	5.1336	0.0000
460	I.RYE	GRASS	2	0.4	4.00	359.6	80	5.1336	0.0000

Table 4.36

ORIGINAL EXPERIMENTAL DATA

BATCH NO 36 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.47

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
461	I.RYE	GRASS	2	6.4	4.00	85.3	388	3.7766	0.9158
462	I.RYE	GRASS	2	7.0	4.00	85.3	420	3.7766	1.1118
463	I.RYE	GRASS	2	6.6	4.00	78.7	395	3.7766	1.0750
464	I.RYE	GRASS	2	1.4	4.00	143.9	257	3.7766	0.6910
465	I.RYE	GRASS	2	0.9	4.00	147.9	165	3.7766	1.1333
466	I.RYE	GRASS	2	1.3	4.00	151.9	228	3.7766	0.9708
467	I.RYE	GRASS	2	0.8	4.00	204.0	144	3.7766	0.5027
468	I.RYE	GRASS	2	1.0	4.00	209.6	183	3.7766	0.3243
469	I.RYE	GRASS	2	0.6	4.00	220.7	101	3.7766	0.8085
470	I.RYE	GRASS	2	0.7	4.00	281.6	136	3.7766	0.2013
471	I.RYE	GRASS	2	0.6	4.00	285.1	103	3.7766	0.2500
472	I.RYE	GRASS	2	0.6	4.00	274.6	105	3.7766	0.2815
473	I.RYE	GRASS	2	0.4	4.00	353.0	70	3.7766	0.0000
474	I.RYE	GRASS	2	0.4	4.00	353.0	73	3.7766	0.0000
475	I.RYE	GRASS	2	0.5	4.00	353.0	83	3.7766	0.0000
476	I.RYE	GRASS	2	0.3	4.00	349.6	50	3.7766	0.0000
478	I.RYE	GRASS	2	0.4	4.00	385.8	79	3.7766	0.0000
479	I.RYE	GRASS	2	0.4	4.00	418.1	67	3.7766	0.0000
480	I.RYE	GRASS	2	0.4	4.00	418.1	68	3.7766	0.0000

Table 4.37

ORIGINAL EXPERIMENTAL DATA

BATCH NO 37 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 2.71

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
501	I.RYE	GRASS	3	14.0	4.60	106.9	47	6.1320	0.3492
502	I.RYE	GRASS	3	14.0	4.60	111.1	63	6.1320	0.1024
503	I.RYE	GRASS	3	5.3	4.60	153.9	159	6.1320	0.1400
504	I.RYE	GRASS	3	5.5	4.60	151.9	328	6.1320	0.3170

Table 4.38

ORIGINAL EXPERIMENTAL DATA

BATCH NO 38 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.34

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
505	I.RYE	GRASS	4	14.0	4.40	56.2	62	4.3348	0.6834
506	I.RYE	GRASS	4	8.0	4.40	60.7	43	4.3348	1.2938
507	I.RYE	GRASS	4	1.7	4.25	185.1	101	4.3348	1.0964
508	I.RYE	GRASS	4	1.0	4.25	183.1	60	4.3348	1.6671
509	I.RYE	GRASS	4	1.7	4.25	131.8	303	4.3348	2.9226

Table 4.39

ORIGINAL EXPERIMENTAL DATA

BATCH NO 39 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.22

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
510	I.RYE	GRASS	4	10.9	4.40	101.6	329	3.3290	0.5270
511	I.RYE	GRASS	4	9.6	4.40	106.9	288	3.3290	0.5940
512	I.RYE	GRASS	4	4.9	4.40	135.9	296	3.3290	0.5770
513	I.RYE	GRASS	4	4.6	4.40	135.9	278	3.3290	0.7240
514	I.RYE	GRASS	4	2.8	4.40	171.6	334	3.3290	0.3120
515	I.RYE	GRASS	4	2.8	4.40	171.6	332	3.3290	0.6740
516	I.RYE	GRASS	4	1.6	4.30	237.1	288	3.3290	0.6540
517	I.RYE	GRASS	4	1.2	4.30	238.9	224	3.3290	0.5000
518	I.RYE	GRASS	4	0.9	4.30	246.1	161	3.3290	1.0060
519	I.RYE	GRASS	4	0.7	4.25	285.1	122	3.3290	1.2940
520	I.RYE	GRASS	4	0.6	4.25	276.3	110	3.3290	1.0960

Table 4.40

ORIGINAL EXPERIMENTAL DATA

BATCH NO 40 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.07

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
521	I.RYE	GRASS	4	9.0	4.40	96.2	270	3.1370	0.8910
522	I.RYE	GRASS	4	9.5	4.40	102.6	286	3.1370	0.6260
523	I.RYE	LEAVES	4	6.5	4.40	105.8	195	3.1370	0.3890
524	I.RYE	STEMS	4	9.2	4.40	105.8	276	3.1370	0.7320
525	I.RYE	GRASS	4	2.4	4.30	171.6	289	3.1370	0.7170
526	I.RYE	GRASS	4	3.3	4.30	179.3	402	3.1370	0.4460
527	I.RYE	LEAVES	4	1.9	4.30	183.1	338	3.1370	0.3320
528	I.RYE	STEMS	4	3.7	4.30	185.1	441	3.1370	0.3290
529	I.RYE	GRASS	4	1.4	4.25	238.9	252	3.1370	0.5100
530	I.RYE	GRASS	4	1.1	4.25	238.9	204	3.1370	0.7590
531	I.RYE	LEAVES	4	1.1	4.25	249.7	203	3.1370	0.5930
532	I.RYE	STEMS	4	1.0	4.25	246.1	189	3.1370	1.4300
533	I.RYE	GRASS	4	0.4	4.25	319.4	74	3.1370	1.6800
534	I.RYE	GRASS	4	0.7	4.25	319.4	119	3.1370	0.9780
535	I.RYE	LEAVES	4	0.7	4.25	319.4	127	3.1370	0.6680
536	I.RYE	STEMS	4	0.8	4.25	319.4	146	3.1370	1.1960
537	I.RYE	GRASS	4	0.6	4.20	361.2	110	3.1370	0.5580
538	I.RYE	GRASS	4	0.4	4.20	361.2	73	3.1370	0.8800
539	I.RYE	LEAVES	4	0.5	4.20	361.2	83	3.1370	0.4700
540	I.RYE	STEMS	4	0.8	4.20	361.2	143	3.1370	1.0600
541	I.RYE	GRASS	4	0.6	4.20	326.2	118	3.1370	0.7620
542	I.RYE	GRASS	4	0.4	4.20	326.2	70	3.1370	0.9040
543	I.RYE	LEAVES	4	0.5	4.20	326.2	94	3.1370	0.5120
544	I.RYE	STEMS	4	0.6	4.20	326.2	113	3.1370	1.1570
545	I.RYE	GRASS	4	0.8	4.20	260.4	148	3.1370	1.2080
546	I.RYE	GRASS	4	0.8	4.20	256.9	141	3.1370	1.1490
547	I.RYE	LEAVES	4	0.6	4.20	253.3	118	3.1370	0.7370
548	I.RYE	STEMS	4	1.4	4.20	240.7	247	3.1370	0.8520

Table 4.41

ORIGINAL EXPERIMENTAL DATA

BATCH NO 41 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.90

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	TOTAL RUN TIME MINS	MANO-METER IN-WG	AIR TEMP DEG C	NO OF POINTS	INITIAL M.C. GM/GM	FINAL M.C. GM/GM
549	I.RYE	GRASS	4	6.1	4.40	100.5	185	2.9020	1.2770
550	I.RYE	GRASS	4	6.1	4.40	102.6	185	2.9020	1.0720
551	I.RYE	LEAVES	4	4.8	4.40	106.9	288	2.9020	1.0450
552	I.RYE	STEMS	4	11.2	4.40	104.7	337	2.9020	0.7011
553	I.RYE	GRASS	4	2.4	4.40	147.9	287	2.9020	1.0000
554	I.RYE	GRASS	4	2.8	4.40	149.9	333	2.9020	1.0030
555	I.RYE	LEAVES	4	1.7	4.40	159.8	199	2.9020	0.9850
556	I.RYE	STEMS	4	4.8	4.40	161.8	573	2.9020	0.5480
557	I.RYE	GRASS	4	1.0	4.25	242.5	176	2.9020	0.9960
558	I.RYE	GRASS	4	1.1	4.25	240.7	195	2.9020	0.9420
559	I.RYE	LEAVES	4	0.7	4.25	244.4	134	2.9020	0.8680
560	I.RYE	STEMS	4	1.4	4.25	238.9	253	2.9020	0.8510
561	I.RYE	GRASS	4	0.9	4.20	304.1	166	2.9020	0.6280

Table 5.1

SUMMARY OF RESULTS

BATCH NO 1 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.87

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
13	GRASS	97.1	0.06019	4.5	0.9	0.00522	0.1224	0.07267	-0.3795	0.07786	-0.1995
14	GRASS	100.1	0.06019	4.5		0.00522	0.1224	0.18908	-0.3777	0.16492	-0.4462
15	GRASS	103.0	0.06019	4.5		0.00522	0.1224	0.05435	-2.2823	0.04500	-2.6636
16	GRASS	95.8	0.06019	4.5	1.0	0.00522	0.1224	0.07721	-0.0159	0.07046	-0.1718
17	GRASS	97.7	0.06019	5.5	1.0	0.00559	0.1310	0.08747	-0.2075	0.08429	-0.2761
18	GRASS	100.9	0.06019	5.5		0.00559	0.1310	0.09834	0.8866	0.08736	0.6158

Table 5.2

SUMMARY OF RESULTS

BATCH. NO 2 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.24

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
5	GRASS	88.4	0.06019	0.6	1.0	0.00393	0.0923	0.04845	0.3463	0.04817	0.3263
6	STEMS	96.8	0.06019	5.3	1.0	0.00552	0.1293	0.04000	-2.4355	0.03662	-2.7747
7	LEAVES	96.6	0.06019	5.6	1.0	0.00561	0.1314	0.13381	-0.1018	0.13503	-0.0617
8	GRASS	98.3	0.06019	4.6	0.9	0.00525	0.1230	0.05648	0.0122	0.05229	-0.1666
9	GRASS	101.3	0.06019	5.4		0.00556	0.1302	0.06495	1.4178	0.05388	0.7304
27	GRASS	100.1	0.06019	9.5		0.00735	0.1716	0.05165	-0.1013	0.05110	-0.1155
28	GRASS	97.5	0.06019	11.3	1.5	0.00834	0.1946	0.05876	0.2463	0.06137	0.2515

Table 5.3

SUMMARY OF RESULTS

BATCH NO 3 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.02

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
19	GRASS	88.4	0.06019	6.3	1.5	0.00589	0.1380	0.04514	-0.1036	0.04500	-0.1391
20	STEMS	91.9	0.06019	2.0	1.0	0.00435	0.1020	0.04720	-0.9791	0.03319	-2.4996
21	LEAVES	94.3	0.06019	11.2	1.6	0.00828	0.1932	0.14500	-0.3110	0.13326	-0.3738
22	GRASS	96.2	0.06019	11.1	1.5	0.00818	0.1908	0.05978	-0.1443	0.06023	-0.1442
23	GRASS	97.1	0.06019	11.3	1.5	0.00830	0.1936	0.07660	0.1800	0.08008	0.2214
24	GRASS	97.1	0.06019	10.9	1.5	0.00808	0.1884	0.06463	0.2010	0.06526	0.1391
25	GRASS	98.6	0.06019	11.0	1.4	0.00814	0.1896	0.05885	1.3011	0.05310	0.8900
26	GRASS	97.5	0.06019	11.0	1.4	0.00814	0.1898	0.04707	0.1903	0.05460	0.3767

Table 5.4

SUMMARY OF RESULTS

BATCH NO 4 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.83

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
36	GRASS	93.7	0.06019	5.1	1.1	0.00545	0.1276	0.06364	0.0239	0.06651	0.0199
37	LEAVES	94.5	0.06019	9.1	1.4	0.00716	0.1672	0.26476	-0.0413	0.17842	-0.1474
38	STEMS	91.6	0.06019	6.5	1.3	0.00598	0.1399	0.04133	-1.6958	0.04254	-1.2129
39	GRASS	91.7	0.06019	6.1	1.3	0.00581	0.1361	0.03898	0.5780	0.04085	0.5865
40	GRASS	91.3	0.06019	8.0	1.5	0.00664	0.1553	0.05771	0.7486	0.04801	0.3003

Table 5.5

SUMMARY OF RESULTS

BATCH NO 5 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.54

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
29	GRASS	95.0	0.06019	10.1	1.5	0.00768	0.1792	0.05901	-0.6386	0.07002	-0.1944
30	GRASS	95.3	0.06019	8.8	1.3	0.00702	0.1641	0.03106	0.6678	0.03337	0.6999
31	LEAVES	95.9	0.06019	9.0	1.3	0.00713	0.1665	0.11739	-0.3882	0.12746	-0.2812
32	STEMS	97.0	0.06019	8.6	1.3	0.00693	0.1621	0.04428	-0.3486	0.04190	-0.4601
33	GRASS	95.5	0.06019	7.3	1.2	0.00632	0.1478	0.06657	0.6383	0.05790	0.2659
34	GRASS	95.5	0.06019	7.8	1.2	0.00654	0.1529	0.04496	0.2954	0.04490	0.1518
35	GRASS	96.1	0.06019	10.1	1.4	0.00768	0.1794	0.09652	0.2180	0.09683	0.1135

Table 5.6

```
                                          SUMMARY OF RESULTS

                     BATCH NO  6 OF GRASS          LEAF TO STEM RATIO (BY WEIGHT) = 0.55

                                EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
                                          AND USING ITALIAN RYE GRASS

RUN               AIR      AIR         DEW       REL.        ABS.      PARTL      KP         MEP        KG          MEG
NO                TEMP   VELOCITY     POINT    HUMIDITY    HUMIDITY    PRESS
                 DEG C   LB/S-FT2     DEG C       %         GM/GM     LB/IN2   (MIN)-1     GM/GM    (MIN)-1      GM/GM

 41  LEAVES      92.5    0.06019       8.7       1.5       0.00696    0.1626   0.13283     0.1224   0.09954     -0.2003
 42  STEMS       93.5    0.06019       9.4       1.5       0.00731    0.1706   0.03034    -1.3496   0.02662     -1.6388
 43  GRASS       93.9    0.06019      10.0       1.5       0.00760    0.1775   0.06176    -0.0657   0.06422      0.0033
 49  GRASS       95.9    0.06019       1.8       0.8       0.00430    0.1009   0.06457     0.0092   0.06518      0.0064
```

Table 5.7

SUMMARY OF RESULTS

BATCH NO 7 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.17

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
44	GRASS	94.2	0.06019	7.9	1.3	0.00662	0.1548	0.06742	-0.2595	0.06417	-0.3972
45	LEAVES	96.0	0.06019	8.0	1.2	0.00666	0.1558	0.10828	0.1681	0.09969	0.0411
46	STEMS	95.6	0.06019	7.8	1.2	0.00656	0.1534	0.03451	-3.0435	0.04236	-1.5342
47	GRASS	96.9	0.06019	7.2	1.1	0.00630	0.1473	0.06014	0.1414	0.06234	0.1461
48	GRASS	95.8	0.06019	3.8	0.9	0.00496	0.1162	0.05711	-0.3785	0.07030	0.1290

Table 5.8

SUMMARY OF RESULTS

BATCH NO 8 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.68

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
50	LEAVES	91.2	0.06019	24.4	4.2	0.01926	0.4414	0.08410	-0.3331	0.07931	-0.3645
51	LEAVES	93.0	0.06019	25.0	4.1	0.02008	0.4596	0.11739	-0.3441	0.11911	-0.2626
52	STEMS	93.2	0.06019	25.1	4.1	0.02022	0.4627	0.02463	-2.2380	0.02221	-2.4141
53	STEMS	93.5	0.06019	25.7	4.2	0.02093	0.4784	0.04645	-0.3225	0.03418	-1.1278
54	GRASS	96.0	0.06019	25.3	3.7	0.02047	0.4684	0.07765	0.1059	0.07154	-0.1346
55	GRASS	94.5	0.06019	24.3	3.7	0.01922	0.4405	0.08382	1.0508	0.07045	0.5877
56	GRASS	96.5	0.06175	24.8	3.6	0.01981	0.4537	0.13466	-0.2642	0.13172	-0.2148
57	GRASS	114.4	0.06175	26.1		0.02148	0.4907	0.23068	-0.1629	0.16234	-0.5510
58	GRASS	59.6	0.06175	24.8	16.1	0.01977	0.4528	0.05891	1.7983	0.04956	1.3450

Table 5.9

SUMMARY OF RESULTS

BATCH NO 9 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.02

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
59	GRASS	89.2	0.06019	11.6	2.0	0.00847	0.1974	0.17399	-0.0131	0.15868	-0.1475
60	GRASS	87.5	0.06019	10.2	2.0	0.00771	0.1800	0.12207	-0.1418	0.13055	-0.0524
61	LEAVES	90.5	0.06019	10.3	1.8	0.00776	0.1811	0.27754	0.0336	0.26102	-0.0042
62	STEMS	89.1	0.06019	10.0	1.8	0.00763	0.1782	0.16309	-0.0915	0.13160	-0.2224
63	GRASS	91.6	0.06019	9.5	1.6	0.00738	0.1723	0.12573	-0.0658	0.12998	-0.0382
64	GRASS	53.8	0.06019	7.0	6.8	0.00622	0.1456	0.06135	1.4157	0.05911	1.2695
65	GRASS	57.7	0.06019	8.8	6.3	0.00700	0.1636	0.05487	1.6162	0.05636	1.5804

Table 5.10

SUMMARY OF RESULTS

BATCH NO 10 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.68

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
66	GRASS	91.4	0.06019	6.3	1.3	0.00592	0.1386	0.13541	-0.1614	0.13015	-0.1742
67	LEAVES	90.2	0.06019	8.0	1.5	0.00664	0.1551	0.22147	-0.1410	0.20298	-0.2001
68	STEMS	89.2	0.06019	8.6	1.7	0.00695	0.1624	0.11508	0.0288	0.09940	-0.1066
69	GRASS	80.0	0.06019	13.9	3.4	0.00990	0.2302	0.05100	1.2179	0.05340	1.2798
70	GRASS	63.0	0.06019	14.9	7.5	0.01058	0.2459	0.06405	1.0639	0.05740	0.8796
71	GRASS	70.0	0.06019	16.1	5.9	0.01146	0.2659	0.07720	1.1675	0.07235	1.0646
72	GRASS	90.0	0.06019	16.9	2.8	0.01200	0.2782	0.18828	0.1278	0.18477	0.0618
73	GRASS	113.0	0.06019	18.7		0.01351	0.3126	0.25313	0.0299	0.23063	-0.0175

Table 5.11

SUMMARY OF RESULTS

BATCH NO 11 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.00

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
74	GRASS	118.1	0.06175	13.1		0.00940	0.2187	0.24731	0.1795	0.23844	0.1393
75	GRASS	96.9	0.06019	13.6	1.7	0.00969	0.2255	0.16489	-0.1250	0.15252	-0.1686
76	LEAVES	97.9	0.06019	13.7	1.7	0.00974	0.2267	0.16131	-0.3166	0.15799	-0.2616
77	STEMS	97.6	0.06019	13.7	1.7	0.00973	0.2264	0.10518	-0.4202	0.09392	-0.4848
78	GRASS	63.6	0.08424	14.3	7.0	0.01019	0.2368	0.07164	1.4008	0.06971	1.3604
79	GRASS	62.6	0.08424	14.3	7.3	0.01015	0.2361	0.05288	1.4146	0.04865	1.2266
80	GRASS	29.5	0.08424	14.2	39.2	0.01009	0.2346	0.02295	2.8069	0.02599	2.8203
81	GRASS	70.0	0.08534	12.8	4.8	0.00917	0.2135	0.06292	0.6209	0.05517	0.3453
82	GRASS	111.2	0.08424	12.9		0.00927	0.2157	0.15655	-0.0155	0.15361	-0.0542

Table 5.12

SUMMARY OF RESULTS

BATCH NO 12 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.57

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
83	GRASS	132.4	0.08446	9.9		0.00759	0.1771	0.18772	-0.0420	0.18833	-0.0189
84	GRASS	105.0	0.08468	10.4		0.00783	0.1826	0.16311	-0.0248	0.15632	-0.0249
85	LEAVES	106.7	0.08468	10.7		0.00801	0.1868	0.16038	-0.0546	0.23150	0.0368
86	STEMS	107.6	0.08468	10.7		0.00802	0.1870	0.14362	-0.0798	0.11580	-0.1603
87	GRASS	65.4	0.08490	10.6	5.0	0.00793	0.1849	0.05268	0.8200	0.05355	0.7302
88	GRASS	78.4	0.06172	10.4	2.9	0.00783	0.1828	0.06129	0.6270	0.05428	0.3449

Table 5.13

SUMMARY OF RESULTS

BATCH NO 13 OF GRASS

LEAF TO STEM RATIO (BY WEIGHT) = 0.77

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
89	GRASS	129.0	0.08313	14.0		0.00994	0.2311	0.17664	-0.0880	0.19331	-0.0172
90	GRASS	105.0	0.08313	13.1		0.00936	0.2178	0.13277	-0.0958	0.15008	0.0089
91	GRASS	40.7	0.08335	14.7	21.9	0.01042	0.2421	0.04286	2.2235	0.06098	2.3606
92	GRASS	70.6	0.08335	14.0	5.0	0.00996	0.2316	0.07947	0.8335	0.07774	0.6471
93	LEAVES	105.6	0.08335	14.2		0.01010	0.2349	0.24985	-0.3613	0.20823	-0.5055
94	STEMS	106.5	0.08335	14.0		0.00998	0.2321	0.11631	-0.5474	0.10542	-0.5896
95	GRASS	66.7	0.08380	14.1	6.0	0.01000	0.2326	0.06727	0.9417	0.07013	0.8067
96	GRASS	83.2	0.05635	13.4	2.9	0.00960	0.2233	0.07871	0.0596	0.07923	0.0410
97	GRASS	77.1	0.07231	13.2	3.6	0.00941	0.2191	0.07575	0.6265	0.07319	0.4103
98	GRASS	75.9	0.07945	13.6	3.9	0.00970	0.2257	0.08951	0.7958	0.08598	0.5952
99	GRASS	83.1	0.06351	12.3	2.7	0.00887	0.2066	0.07550	-0.0328	0.08111	0.0499
100	GRASS	88.1	0.05222	10.9	2.0	0.00812	0.1694	0.07463	0.3007	0.07570	0.2344

Table 5.14

SUMMARY OF RESULTS

BATCH NO 14 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.51

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
101	GRASS	125.6	0.08402	7.7		0.00650	0.1521	0.28708	-0.0096	0.25596	-0.0805
102	GRASS	37.6	0.08424	9.0	17.8	0.00713	0.1666	0.01820	1.6544	0.02993	1.8962
103	GRASS	103.3	0.08357	10.4		0.00784	0.1829	0.12750	-0.1167	0.12601	-0.1073
104	LEAVES	105.4	0.08402	10.6		0.00791	0.1846	0.32759	0.0056	0.24849	-0.0598
105	STEMS	105.7	0.08402	10.6		0.00791	0.1845	0.13413	-0.3416	0.11231	-0.4694
106	GRASS	65.3	0.08424	9.9	4.9	0.00758	0.1769	0.05053	1.0614	0.05438	1.0696
107	GRASS	78.5	0.08424	9.5	2.7	0.00735	0.1716	0.07947	0.2088	0.08053	0.1737
108	GRASS	84.1	0.05186	8.5	2.0	0.00690	0.1611	0.06278	0.1472	0.05843	0.0341
109	GRASS	76.4	0.07706	9.4	2.9	0.00730	0.1706	0.07417	0.2331	0.06858	0.0809

Table 5.15

SUMMARY OF RESULTS

BATCH NO 15 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 0.48

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
110	GRASS	100.7	0.08446	14.4		0.01023	0.2379	0.16768	-0.0854	0.17607	-0.0401
111	LEAVES	101.6	0.08446	13.6		0.00970	0.2257	0.26277	-0.1075	0.21519	-0.2613
112	STEMS	101.8	0.08446	12.6		0.00910	0.2120	0.13051	-0.1591	0.11426	-0.1982
118	GRASS	132.2	0.08357	15.2		0.01078	0.2503	0.23887	-0.3217	0.22560	-0.3516
119	GRASS	113.2	0.08357	15.4		0.01090	0.2531	0.20096	-0.4932	0.17810	-0.7001
122	GRASS	74.8	0.08424	14.6	4.4	0.01035	0.2405	0.07643	0.3325	0.08309	0.4583
124	GRASS	105.9	0.08402	13.2		0.00946	0.2201	0.16366	-0.1528	0.16790	-0.0992
125	GRASS	143.5	0.05222	13.4		0.00958	0.2230	0.20776	-0.2187	0.18500	-0.2728
128	GRASS	88.8	0.05222	13.4	2.3	0.00959	0.2232	0.06957	0.0985	0.07406	0.1399
130	GRASS	105.7	0.05222	13.9		0.00990	0.2303	0.11121	-0.4283	0.10976	-0.4114

Table 5.16

SUMMARY OF RESULTS

BATCH NO 16 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.78

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
113	GRASS	102.7	0.08424	12.8		0.00920	0.2143	0.24249	0.0318	0.20729	-0.0406
114	LEAVES	104.2	0.08424	13.0		0.00930	0.2164	0.39063	-0.2385	0.29779	-0.3610
115	STEMS	105.6	0.08424	12.9		0.00925	0.2155	0.17248	-0.3936	0.15248	-0.4583
116	GRASS	105.6	0.08424	13.8		0.00980	0.2280	0.31788	0.0892	0.28956	-0.0125
117	GRASS	131.9	0.08357	15.3		0.01085	0.2520	0.42015	-0.0296	0.33650	-0.1845
120	GRASS	115.3	0.08357	15.8		0.01121	0.2603	0.23584	-0.3805	0.24831	-0.2739
121	GRASS	74.4	0.08402	15.0	4.6	0.01062	0.2468	0.11524	-0.2551	0.12013	-0.0422
123	GRASS	103.2	0.08357	21.3		0.01595	0.3676	0.23279	-0.1037	0.20921	-0.3040
126	GRASS	145.7	0.05222	13.2		0.00945	0.2200	0.32158	0.0136	0.30122	-0.0417
127	GRASS	86.9	0.05222	13.0	2.4	0.00930	0.2164	0.14205	0.0955	0.12950	-0.0324
129	GRASS	107.2	0.05222	13.3		0.00952	0.2216	0.25013	0.0344	0.23184	-0.0244

Table 5.17

SUMMARY OF RESULTS

BATCH NO 17 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 3.10

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
131	GRASS	106.5	0.08357	14.3		0.01017	0.2366	0.27762	0.1151	0.25685	0.0011
132	LEAVES	106.7	0.08357	15.7		0.01114	0.2586	0.35018	-0.2252	0.28780	-0.3312
133	STEMS	107.1	0.08357	15.6		0.01104	0.2562	0.15776	-1.4878	0.16631	-0.8389
134	GRASS	136.6	0.08267	16.4		0.01163	0.2699	0.51581	0.0454	0.46794	-0.0316
135	GRASS	68.6	0.08446	16.7	6.5	0.01184	0.2746	0.09416	0.2894	0.11389	0.6879
136	GRASS	40.6	0.08446	17.3	25.9	0.01233	0.2857	0.02740	1.3835	0.06654	2.0159
137	GRASS	83.0	0.08468	17.6	3.8	0.01262	0.2922	0.14596	0.1941	0.14079	0.1163
138	GRASS	125.1	0.08357	17.6		0.01259	0.2916	0.30034	-0.0075	0.29106	-0.0529
139	GRASS	130.3	0.06750	17.5		0.01249	0.2894	0.52168	0.1769	0.42674	-0.0468
140	GRASS	161.7	0.06750	17.7		0.01265	0.2930	0.70115	0.0375	0.72176	0.0195

Table 5.18

SUMMARY OF RESULTS

BATCH NO 18 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 4.42

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
141	LEAVES	102.6	0.08468	13.0		0.00932	0.2170	0.26711	-0.7890	0.25450	-0.6697
142	STEMS	104.6	0.08446	13.2		0.00944	0.2198	0.19321	-0.2317	0.17877	-0.2293
143	GRASS	105.7	0.08446	13.5		0.00963	0.2241	0.34530	0.1336	0.32792	0.0583
144	GRASS	106.7	0.08446	13.6		0.00969	0.2255	0.31222	0.0563	0.41123	0.1127
145	GRASS	106.5	0.08446	13.6		0.00972	0.2261	0.43252	0.0885	0.59284	0.0915
146	GRASS	134.0	0.08424	13.5		0.00963	0.2242	0.42006	0.0255	0.37660	-0.0467
147	GRASS	114.2	0.08468	13.5		0.00963	0.2241	0.31336	0.2619	0.28878	0.1312
148	GRASS	73.3	0.08468	13.4	4.3	0.00958	0.2230	0.11201	0.2896	0.11979	0.4129
149	GRASS	37.1	0.08490	12.8	23.4	0.00918	0.2137	0.08521	4.0422	0.09403	4.0330
150	GRASS	96.4	0.05222	13.3	1.7	0.00948	0.2207	0.16261	0.0923	0.14294	-0.0440
151	GRASS	154.2	0.05222	13.4		0.00959	0.2231	0.39643	0.1830	0.31777	-0.0128
152	GRASS	108.7	0.05328	54.6		0.11092	2.2244	0.13038	0.0116	0.12603	-0.0084
237	GRASS	102.1	0.08468	12.6		0.00910	0.2119	0.23228	0.1345	0.22141	0.0674

Table 5.19

SUMMARY OF RESULTS

BATCH NO 19 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 3.10

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
153	GRASS	129.8	0.08402	9.4		0.00732	0.1711	0.50126	0.1415	0.41277	-0.0387
154	GRASS	109.1	0.08424	10.8		0.00803	0.1873	0.36428	0.1510	0.30142	-0.0205
155	GRASS	101.8	0.08446	10.4		0.00783	0.1828	0.30636	-0.1284	0.26253	-0.2558
156	LEAVES	103.3	0.08402	9.9		0.00756	0.1766	0.34268	-0.1853	0.28252	-0.3100
157	STEMS	104.6	0.08402	9.7		0.00746	0.1741	0.16609	-0.7601	0.18911	-0.3639
158	GRASS	77.1	0.08424	9.3	2.8	0.00725	0.1694	0.12472	0.1099	0.12151	0.1265
159	GRASS	62.6	0.08468	8.6	5.0	0.00694	0.1623	0.07837	0.3359	0.08265	0.4425
160	GRASS	86.0	0.05222	8.0	1.8	0.00663	0.1550	0.14013	-0.0435	0.12428	-0.1622
161	GRASS	84.6	0.06262	8.4	2.0	0.00681	0.1592	0.16837	0.0513	0.14803	-0.0689
162	GRASS	85.2	0.07945	7.9	1.8	0.00659	0.1542	0.23601	-0.1353	0.20810	-0.2168

Table 5.20

SUMMARY OF RESULTS

BATCH NO 20 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 4.54

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
163	GRASS	97.6	0.08424	4.4	0.9	0.00518	0.1214	0.23878	0.1379	0.22228	0.0370
164	LEAVES	97.9	0.08424	4.6	0.9	0.00524	0.1228	0.30123	-0.2357	0.25400	-0.3667
165	STEMS	97.6	0.08424	3.8	0.9	0.00494	0.1158	0.19602	0.0568	0.15966	-0.0239
166	GRASS	124.7	0.08424	10.0		0.00761	0.1776	0.34883	0.0382	0.32693	-0.0244
167	GRASS	129.9	0.05568	2.8		0.00460	0.1079	0.24588	-0.0730	0.22076	-0.1029
168	GRASS	119.3	0.07633	9.3		0.00729	0.1702	0.32202	0.3240	0.30005	0.2487
169	GRASS	132.6	0.06805	9.2		0.00721	0.1684	0.37004	0.0630	0.30380	-0.1243
170	GRASS	135.0	0.06111	8.7		0.00697	0.1629	0.32716	-0.0543	0.26832	-0.1693
171	GRASS	79.4	0.06111	7.4	2.3	0.00638	0.1493	0.12343	0.0694	0.10480	-0.1413
172	GRASS	76.5	0.07658	9.0	2.8	0.00713	0.1666	0.14822	0.1147	0.13722	0.0251
173	GRASS	75.8	0.06778	10.9	3.3	0.00810	0.1889	0.09517	0.2348	0.09307	0.2028
174	GRASS	81.1	0.05500	12.3	2.9	0.00891	0.2077	0.09242	0.2228	0.08808	0.1545
175	GRASS	97.5	0.05500	14.5	1.8	0.01028	0.2389	0.14349	-0.0259	0.13826	-0.0402
176	GRASS	105.1	0.06860	19.1		0.01381	0.3193	0.19965	0.0233	0.17319	-0.0805

Table 5.21

SUMMARY OF RESULTS

BATCH NO 21 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 4.49

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
177	GRASS	103.2	0.08468	16.3		0.01158	0.2686	0.25018	0.2151	0.21870	0.0638
178	LEAVES	103.5	0.08468	16.2		0.01152	0.2673	0.26171	-0.3212	0.22652	-0.4395
179	STEMS	103.6	0.08468	15.9		0.01130	0.2622	0.24422	0.0904	0.17425	-0.0755
180	GRASS	128.0	0.08468	17.5		0.01251	0.2897	0.29387	0.1961	0.26482	0.0950
181	GRASS	137.3	0.05328	14.9		0.01054	0.2449	0.16337	-0.0934	0.16565	-0.0764
182	GRASS	137.7	0.06833	15.5		0.01099	0.2552	0.29772	0.0053	0.25786	-0.1343
183	GRASS	139.2	0.06142	15.1		0.01073	0.2492	0.34890	0.0097	0.28549	-0.1531
184	GRASS	137.0	0.07510	15.1		0.01067	0.2479	0.34326	0.0943	0.31564	0.0042
185	GRASS	100.3	0.07510	14.2		0.01008	0.2343	0.22612	0.0818	0.19923	-0.0828
186	GRASS	94.7	0.06805	13.9	1.9	0.00986	0.2294	0.17511	0.0402	0.15409	-0.0950
187	GRASS	93.4	0.06081	13.5	2.0	0.00963	0.2241	0.15381	-0.0934	0.14441	-0.1432
188	GRASS	95.0	0.05328	13.2	1.8	0.00945	0.2200	0.13088	-0.1178	0.11676	-0.2907
189	GRASS	89.8	0.02867	13.7	2.3	0.00977	0.2273	0.08509	0.2349	0.07610	0.0240
190	GRASS	63.4	0.02867	13.8	6.8	0.00985	0.2292	0.03433	0.2371	0.03479	0.2556
191	GRASS	66.6	0.05328	13.8	5.9	0.00982	0.2285	0.06626	0.5031	0.06961	0.5516
192	GRASS	72.0	0.06914	13.7	4.6	0.00976	0.2270	0.07518	0.0486	0.08429	0.3420
193	GRASS	67.8	0.08512	14.3	5.8	0.01016	0.2362	0.09469	0.2558	0.11726	0.6189

Table 5.22

SUMMARY OF RESULTS

BATCH NO 22 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 3.09

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
194	GRASS	100.4	0.08424	4.2		0.00509	0.1192	0.18336	-0.0252	0.16765	-0.4131
195	LEAVES	101.4	0.08424	5.7		0.00565	0.1323	0.23229	-0.3616	0.19291	-0.5366
196	STEMS	102.6	0.08424	4.5		0.00522	0.1224	0.15878	-0.1524	0.12264	-0.3623
197	GRASS	129.4	0.08380	5.5		0.00558	0.1308	0.29552	-0.0466	0.26242	-0.1470
198	GRASS	130.3	0.07535	5.1		0.00542	0.1269	0.35232	0.0624	0.27632	-0.1358
199	GRASS	128.4	0.06833	4.3		0.00514	0.1205	0.24779	0.0440	0.23233	-0.0575
200	GRASS	130.5	0.06081	3.9		0.00498	0.1167	0.27422	-0.0054	0.24372	-0.1161
201	GRASS	138.7	0.05293	2.4		0.00448	0.1051	0.21004	-0.0426	0.19658	-0.0966
202	GRASS	146.6	0.02867	2.8		0.00462	0.1084	0.13853	-0.1909	0.10818	-0.4442
203	GRASS	64.9	0.02867	1.1	2.7	0.00407	0.0956	0.03529	0.3330	0.03787	0.5052
204	GRASS	96.3	0.05293	0.2	0.7	0.00383	0.0900	0.15147	0.0066	0.13741	-0.0957
205	GRASS	96.1	0.06142	-0.7	0.7	0.00359	0.0844	0.14907	0.0672	0.12945	-0.1266
206	GRASS	96.4	0.06833	-1.1	0.6	0.00347	0.0815	0.14818	-0.1196	0.13480	-0.2837
207	GRASS	95.9	0.07559	-1.2	0.7	0.00346	0.0813	0.20289	-0.0088	0.18446	-0.1457
208	GRASS	68.6	0.08402	11.8	4.7	0.00859	0.2002	0.07918	-0.2287	0.08552	0.0013
209	GRASS	68.3	0.07485	11.1	4.6	0.00818	0.1909	0.07815	0.8597	0.08240	0.9347
210	GRASS	70.2	0.06833	10.3	4.0	0.00776	0.1812	0.07554	0.5140	0.08104	0.6865
211	GRASS	60.5	0.06081	9.1	5.7	0.00715	0.1670	0.05213	0.6976	0.06382	1.1671
212	GRASS	65.1	0.05293	8.8	4.5	0.00704	0.1646	0.05466	0.1686	0.05764	0.3375
213	GRASS	70.0	0.02867	8.6	3.6	0.00693	0.1619	0.05553	0.9539	0.05203	0.8198
214	GRASS	112.9	0.02867	8.4		0.00682	0.1593	0.10430	-0.2226	0.08846	-0.4275
215	GRASS	116.7	0.08490	12.9		0.00929	0.2162	0.27853	0.3002	0.22553	-0.0217
216	GRASS	114.4	0.07485	13.3		0.00950	0.2212	0.19745	-0.0374	0.18720	-0.1054
217	GRASS	118.1	0.06833	13.6		0.00968	0.2252	0.20119	-0.2028	0.18300	-0.3050
218	GRASS	111.8	0.06111	14.2		0.01011	0.2350	0.18578	-0.0081	0.18127	-0.0460

Table 5.23

SUMMARY OF RESULTS

BATCH NO 23 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 7.33

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
219	GRASS	103.2	0.08424	13.9		0.00988	0.2299	0.19781	0.2252	0.18108	0.0921
220	LEAVES	104.0	0.08424	14.5		0.01029	0.2392	0.22512	-0.1714	0.18891	-0.3491
221	STEMS	104.3	0.08424	14.4		0.01024	0.2382	0.13585	-0.4446	0.12628	-0.4615
222	GRASS	132.5	0.08424	15.2		0.01074	0.2495	0.40217	-0.1342	0.31378	-0.3783
223	GRASS	114.3	0.08424	15.2		0.01080	0.2509	0.26874	-0.2329	0.23485	-0.3044
224	GRASS	108.6	0.08424	14.1		0.01002	0.2331	0.25916	-0.1907	0.22340	-0.3158
225	GRASS	86.9	0.08424	10.9	2.1	0.00812	0.1894	0.14176	-0.1586	0.12806	-0.2689
226	GRASS	71.0	0.08424	10.2	3.9	0.00773	0.1804	0.08431	0.0528	0.09133	0.2776
227	GRASS	62.6	0.08424	6.7	4.4	0.00607	0.1420	0.06720	0.2940	0.07610	0.3995
228	GRASS	51.2	0.08424	7.4	7.9	0.00637	0.1490	0.06268	0.9812	0.06469	0.7893
229	GRASS	68.1	0.08424	7.4	3.6	0.00639	0.1496	0.07287	-0.1368	0.08049	0.1222
230	GRASS	109.6	0.08424	8.8		0.00703	0.1643	0.17806	-0.2836	0.16911	-0.3269
231	GRASS	109.2	0.08424	8.9		0.00708	0.1655	0.22112	-0.0550	0.18252	-0.3078

Table 5.24

SUMMARY OF RESULTS

BATCH NO 24 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 2.15

EXPERIMENTS CARRIED OUT ON MEDIUM TEMPERATURE RIG
AND USING ITALIAN RYE GRASS

RUN NO		AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM
232	GRASS	95.9	0.08424	-0.7	0.7	0.00358	0.0841	0.18943	0.0466	0.17249	-0.C240
233	LEAVES	97.2	0.08424	-1.2	0.6	0.00344	0.0809	0.42604	0.0017	0.25876	-0.0422
234	STEMS	97.8	0.08424	-1.2	0.6	0.00344	0.0808	0.16097	-0.0101	0.11794	-0.0673
235	GRASS	96.7	0.08424	-1.6	0.6	0.00335	0.0788	0.20525	0.2361	0.20166	0.1873
236	GRASS	96.5	0.08424	6.5	1.1	0.00599	0.1402	0.21114	0.0182	0.16096	-0.0415

Table 5.25

k values for unseparated grass at 100°C

Run	l_s	T_a °C	k_p	k_g
59	1.02	89.2	0.1787	0.1552
60	1.02	87.5	0.1221	0.1306
63	1.02	91.6	0.1257	0.1300
66	0.681	91.4	0.1326	0.1287
72	0.681	90.0	0.1883	0.1848
73	0.681	113.0	0.2531	0.2306
74	0.998	118.1	0.2481	0.2384
75	0.998	96.9	0.1643	0.1525
82	0.998	111.2	0.1566	0.1536
84	0.576	105.0	0.1631	0.1563
90	0.772	105.0	0.1328	0.1501
103	0.506	103.3	0.1275	0.1260
110	0.470	100.7	0.1677	0.1761
119	0.470	113.2	0.1870	0.1698
124	0.470	105.9	0.1648	0.1653
113	1.78	102.7	0.2425	0.2073
123	1.78	103.2	0.2333	0.2073
131	3.1	106.5	0.2759	0.2541
237	4.42	102.1	0.2323	0.2214
154	3.1	109.1	0.3643	0.3014
155	3.1	101.8	0.3064	0.2625
163	4.54	97.6	0.2081	0.1869
177	4.49	103.2	0.2502	0.2187
194	3.09	100.4	0.1790	0.1681
219	7.33	103.2	0.1978	0.1811
224	7.33	108.7	0.2592	0.2234
230	7.33	109.6	0.1781	0.1691
231	7.33	109.2	0.2211	0.1825

Table 5.26

k values for leaves only at 100°C

Run	l_s	T_a °C	k_p	k_g
14	1.875	100.1	0.1891	0.1649
7	1.247	96.6	0.1338	0.1350
21	1.017	94.3	0.1450	0.1332
37	0.825	94.5	0.2783	0.1912
31	0.542	95.9	0.1271	0.1291
41	0.545	92.5	0.1328	0.0995
45	1.166	96.0	0.1083	0.0997
50	0.681	91.2	0.0841	0.0793
51	0.681	93.0	0.1251	0.1225
61	1.02	90.5	0.2775	0.2610
67	0.681	90.2	0.2183	0.1930
76	0.998	97.9	0.1653	0.1647
85	0.576	106.7	0.2934	0.2394
93	0.772	105.7	0.2431	0.2054
104	0.506	105.4	0.3308	0.2509
111	0.470	101.6	0.2628	0.2152
114	1.78	104.2	0.3906	0.2978
132	3.1	106.8	0.2998	0.2635
141	4.42	102.6	0.2493	0.2403
156	3.1	103.3	0.3427	0.2825
164	4.54	97.9	0.2810	0.2394
178	4.49	103.5	0.2588	0.2236
195	3.09	101.4	0.2204	0.1868
220	7.33	104.0	0.2251	0.1889

Table 5.27

k values for stems only at 100°C

Run	l_s	T_a °C	k_p	k_g
15	1.875	103.0	0.0544	0.0450
6	1.247	96.8	0.0400	0.0366
20	1.017	91.9	0.0472	0.0332
38	0.825	91.6	0.0413	0.0425
32	0.542	97.0	0.0433	0.0428
42	0.545	93.5	0.0303	0.0266
46	1.166	95.6	0.0345	0.0424
52	0.681	93.2	0.0246	0.0222
53	0.681	93.5	0.0465	0.0342
62	1.02	89.1	0.1450	0.1226
68	0.681	89.2	0.1151	0.0994
77	0.998	97.5	0.1052	0.0939
86	0.576	105.6	0.1436	0.1158
94	0.772	106.5	0.1163	0.1054
105	0.506	105.7	0.1172	0.1001
112	0.470	101.8	0.1305	0.1143
115	1.78	105.6	0.1725	0.1525
133	3.1	107.1	0.1306	0.1376
142	4.42	104.6	0.1932	0.1788
157	3.1	104.6	0.1660	0.1891
165	4.54	97.6	0.1960	0.1596
179	4.49	103.6	0.2442	0.1743
196	3.09	102.6	0.1523	0.1213
221	7.33	104.3	0.1382	0.1320

Table 5.28

Drying Parameters for two-period curves on M.T.Rig.

Run	T_a °C	k_1	k_2	m_{e1}	m_{e2}	m_{c1}
64	53.8	0.0755	0.0425	2.0	1.1	3.5
65	57.7	0.0767	0.045	2.35	1.4	3.85
69	80.0	0.065	0.04	1.75	1.0	2.75
79	62.6	0.055	0.025	1.5	0.65	2.4
87	65.4	0.07	0.035	1.3	0.5	2.05
88	75.5	0.07	0.035	0.95	0.05	1.95
91	40.7	0.125	0.035	3.1	2.1	3.5
92	70.6	0.1	0.05	1.3	0.3	2.35
95	66.7	0.13	0.0425	2.2	0.45	3.1
97	77.2	0.0975	0.04	1.0	0	2.0
98	75.9	0.1075	0.045	1.25	0	1.7
100	88.1	0.10	0.0525	0.7	0	1.6
102	37.6	0.06	0.02	2.8	2.0	3.15
106	65.3	0.085	0.04	1.95	0.75	3.0
107	78.5	0.0925	0.075	0.7	0.2	2.0
122	74.8	0.09	0.063	0.75	0	2.5
128	88.8	0.09	0.063	0.075	0	2.5
135	68.6	0.19	0.10	2.75	0.5	4.9
136	40.6	0.15	0.0225	3.75	1.4	4.2
148	73.3	0.165	0.11	1.65	0.35	4.3
149	37.1	0.085	0.0324	4.05	2.5	5.0
159	62.6	0.1533	0.0825	2.35	0.55	4.55
190	63.5	0.0425	0.03	1.25	0	4.6
191	66.7	0.09	0.06	1.7	0.3	4.25
192	72.0	0.125	0.0725	1.9	0.25	4.55
193	67.8	0.205	0.10	2.35	0.45	4.15
208	68.6	0.11	0.08	1.15	0	5.4
209	68.3	0.11	0.0775	2.1	0.9	5.4
210	70.2	0.1175	0.08	2.2	0.7	5.4
211	60.5	0.135	0.0525	3.55	0.8	5.35
203	64.9	0.0425	0.0325	1.35	0	4.1
226	71.0	0.13	0.0875	1.7	0.25	4.8
227	62.6	0.1275	0.065	2.25	0.45	4.5
228	51.3	0.11	0.045	2.15	0.2	3.45
229	68.1	0.1025	0.075	1.3	0.1	4.15

Table 5.29

SUMMARY OF RESULTS

EXPERIMENTS CARRIED OUT ON LOW TEMPERATURE RIG
ITALIAN RYE GRASS

RUN NO	CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	DEW POINT DEG C	REL. HUMIDITY %	ABS. HUMIDITY GM/GM	PARTL PRESS LB/IN2	KP (MIN)-1	MEP GM/GM	KG (MIN-1)	MEG GM/GM
301	2	41.7	0.05108	32.1	59.6	0.02877	0.6940	0.02040	1.5390	0.02606	1.6601
302	2	60.8	0.05108	29.8	20.4	0.02506	0.6080	0.05783	0.8026	0.06694	0.8613
303	2	80.6	0.05108	35.0	11.6	0.03391	0.8116	0.13013	0.0095	0.14477	0.0767
304	2	81.4	0.05108	35.3	11.5	0.03456	0.8263	0.20365	0.1522	0.18292	0.0994
305	1	80.2	0.05108	34.6	11.6	0.03323	0.7960	0.14184	0.1807	0.14596	0.1970
306	4	80.1	0.05108	34.6	11.7	0.03327	0.7971	0.08917	-0.3128	0.12283	-0.0115
307	2	39.7	0.05108	36.4	83.6	0.03692	0.8795	0.01374	2.2541	0.02320	2.5037
308	2	60.0	0.05108	40.8	38.6	0.04738	1.1112	0.05385	1.1917	0.06560	1.3136
309	2	81.4	0.05108	42.9	17.3	0.05336	1.2404	0.11104	0.1353	0.12635	0.3005
310	2	40.6	0.05108	24.1	39.6	0.01774	0.4352	0.01933	1.4541	0.02643	1.5946
311	2	20.1	0.05108	15.7	75.9	0.01042	0.2587	0.01312	2.8826	0.02226	3.1401
312	2	20.1	0.05108	12.8	62.6	0.00857	0.2134	0.01707	2.4266	0.02134	2.4259
313	2	20.2	0.05108	7.1	42.8	0.00586	0.1464	0.01670	2.6089	0.02254	2.7357
314	2	39.5	0.05108	13.2	21.1	0.00884	0.2200	0.01670	1.7124	0.02400	2.0128
315	2	60.4	0.05108	18.3	10.4	0.01231	0.3047	0.05524	0.9180	0.06716	1.0352

Table 5.30

Drying Parameters for Low Temperature Runs

Run	T_a °C	rh	k_1	k_2	k_3	m_{e1}	m_{e2}	m_{e3}	m_{c1}	m_{c2}
301	41.7	59.33	0.062	0.0226	0.0136	2.43	1.33	1.03	3.10	1.78
302	60.8	20.33	0.1325	0.0985	0.056	1.73	1.34	0.53	2.95	2.40
303	80.6	11.74	0.270	0.1388	0.1105	2.0	0.2	0	3.9	1.0
304	81.4	11.58	0.1825	-	-	0.2	-	-	-	-
305	80.2	11.68	0.26			1.78				
306	80.1	11.76	0.1825	0.1493	0.1	1.20	0.7	0	3.35	2.10
307	39.7	83.26	0.0585	0.0561	0.01313	2.57	2.25	1.58	3.20	2.65
308	60.0	38.29	0.132	-	0.049	2.32	-	0.97	3.15	
309	81.4	17.18	-	0.174	0.1115	-	1.33	0.2	-	3.28
310	40.6	39.35	0.0735	0.0222	0.0145	2.18	1.13	0.93	2.64	1.55
311	20.1	72.72	0.066	0.0208	0.00755	3.15	2.60	2.05	3.42	3.05
312	20.1	57.70	0.0495	0.016	0.00503	3.87	2.87	1.54	4.34	3.53
313	20.2	37.37	0.0646	0.0164	0.0123	2.92	2.00	1.78	3.22	2.65
314	39.5	19.45	0.081	0.0325	0.0155	3.2	2.52	1.50	3.68	3.45
315	60.4	10.10	0.1425	0.085	0.0535	2.73	1.88	1.07	4.0	3.25

Table 5.31

SUMMARY OF RESULTS

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
ITALIAN RYE GRASS

RUN NO	CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
316	2	104.7	0.07227	0.39197	-0.2290	0.42924	-0.1658	0.3531
317	2	104.7	0.07227	0.53872	-0.0445	0.46155	-0.1222	0.4218
318	2	104.7	0.07227	0.65470	0.0268	0.46800	-0.2628	0.4783
328	2	190.8	0.07227	0.22409	-8.0224	0.81508	-1.1200	1.9715
329	2	192.7	0.07227	2.06195	-0.0576	1.13211	-0.7631	2.0437
330	2	188.9	0.07227	1.57518	-0.2188	0.83292	-0.9158	1.5768
340	2	258.7	0.07227	0.31699	-10.1860	1.15019	-2.1574	3.4435
341	2	264.0	0.07227	2.22829	-0.2051	2.48003	-0.2083	2.1468
342	2	260.4	0.07227	1.81068	-1.0518	1.40812	-1.2490	3.3219
352	2	331.2	0.07227	4.62647	0.2129	2.33504	-0.3276	2.6705
353	2	331.2	0.07227	1.99034	-1.2686	1.79395	-1.7012	4.6540
354	2	331.2	0.07227	0.36127	-9.4990	1.34366	-2.0506	4.0848
364	2	385.8	0.07227	0.93019	-5.6971	2.31431	-1.6802	6.0670
365	2	385.8	0.07227	3.95163	-0.7624	2.10044	-1.7579	5.8227
366	2	385.8	0.07227	2.29688	-1.5244	3.65642	-0.8045	5.9676
399	2	410.1	0.07227	-0.14340	47.3274	-0.52240	13.2275	6.4163
409	2	410.1	0.07227	1.58174	-3.5058	0.82397	-7.5857	7.0003
410	2	410.1	0.07227	1.02702	-6.4075	1.66894	-3.5899	7.3077

Table 5.32

SUMMARY OF RESULTS

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
ITALIAN RYE LEAVES

RUN NO	CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
322	2	106.9	0.07227	0.61686	0.1432	0.54646	0.0635	0.5329
323	2	106.9	0.07227	0.54312	-0.3125	0.48778	-0.2175	0.6916
324	2	106.9	0.07227	0.59097	-0.0172	0.47963	-0.1354	0.5802
338	2	196.5	0.07227	1.79449	-0.6680	1.65265	-0.7266	2.6292
339	2	192.7	0.07227	3.77918	0.1283	2.61668	-0.1021	2.4883
349	2	262.2	0.07227	4.64587	-0.2031	3.01049	-0.5774	4.3101
350	2	262.2	0.07227	2.44501	-0.5429	1.79509	-0.9570	3.3365
351	2	258.7	0.07227	1.99813	-1.9795	1.16105	-3.5586	5.2512
363	2	331.2	0.07227	3.51008	-0.8211	3.73305	-0.7474	6.0471
374	2	385.8	0.07227	2.86318	-2.6149	2.14533	-3.5555	9.0609
375	2	385.8	0.07227	0.82359	-5.6556	0.62525	-7.0293	5.1091
376	2	385.8	0.07227	16.85598	0.2931	5.08762	-0.4838	4.4163
377	2	385.8	0.07227	-11.14507	1.1018	-4.87012	1.9932	6.5132
408	2	410.1	0.07227	1.63136	-4.6211	2.55667	-2.5365	8.7832

Table 5.33

SUMMARY OF RESULTS

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

ITALIAN RYE STEMS

RUN NO	CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
319	2	106.9	0.07227	0.17497	-2.1205	0.54174	0.2149	0.4386
320	2	106.9	0.07227	1.21125	0.4716	0.62027	0.4006	0.2092
321	2	106.9	0.07227	1.24379	0.8547	0.39743	0.1781	0.3964
334	2	192.7	0.07227	0.78259	-0.5047	1.00674	-0.2445	0.8369
335	2	192.7	0.07227	1.15801	-0.3120	0.94395	-0.4706	1.1685
336	2	192.7	0.07227	0.32321	-2.8039	0.74431	-0.6690	1.1574
343	2	256.9	0.07227	1.33799	-0.6463	1.43581	-0.6311	2.0076
344	2	262.2	0.07227	-1.47227	2.0039	2.26899	-0.3637	2.4849
345	2	256.9	0.07227	0.84658	-2.0183	1.02877	-1.3079	2.1645
358	2	331.2	0.07227	-0.38607	2.2096	1.60335	-0.1755	0.7749
359	2	331.2	0.07227	7.56389	0.0817	2.29875	-0.2695	1.0846
360	2	331.2	0.07227	2.13402	-0.4616	0.39069	-4.1843	1.8433
371	2	385.8	0.07227	0.24717	-17.0854	6.52869	-0.1812	6.8051
372	2	385.8	0.07227	1.83140	-3.6944	1.19161	-5.7575	8.7789
373	2	385.8	0.07227	0.54222	-8.1287	-0.02562	179.0398	4.8087
405	2	410.1	0.07227	3.73770	-0.5934	1.38708	-3.0626	5.7680
406	2	410.1	0.07227	-1.29856	5.3726	2.33337	-2.0324	6.1677
407	2	410.1	0.07227	1.80188	-2.9274	0.63525	-9.6472	6.6966

Table 5.34

SUMMARY OF RESULTS

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG
PERENNIAL RYE GRASS

RUN NO	CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
325	2	109.0	0.07227	-0.07887	18.5440	0.47779	0.2150	1.3362
326	2	109.0	0.07227	0.42068	-0.5961	0.70210	0.3021	0.9753
327	2	109.0	0.07227	0.63375	0.5759	0.59953	0.5003	0.8365
332	2	188.9	0.07227	1.10929	-0.0747	0.85390	-0.2102	0.7772
333	2	198.3	0.07227	0.61475	0.1565	0.25635	-2.8271	1.2606
346	2	255.1	0.07227	2.43836	-0.4185	1.83564	-0.8378	3.9495
347	2	258.7	0.07227	3.01100	-0.3479	2.68603	-0.4021	3.8890
348	2	256.9	0.07227	2.24708	-0.7194	2.12147	-0.7691	4.0081
355	2	331.2	0.07227	2.94122	-0.2104	1.96620	-1.2121	6.0539
356	2	331.2	0.07227	2.04090	-2.6206	1.16479	-4.5062	7.6457
357	2	331.2	0.07227	1.78736	-1.4795	2.23735	-0.9262	3.3640
367	2	385.8	0.07227	14.01859	0.5396	4.76080	-0.3823	5.9236
370	2	385.8	0.07227	3.38350	-2.6643	1.12088	-9.2071	13.2654
402	2	410.1	0.07227	3.46807	-1.3570	2.29443	-2.7918	9.3411
403	2	410.1	0.07227	2.09678	-3.5036	2.29089	-2.8954	9.5546
404	2	410.1	0.07227	1.56810	-4.4660	1.65013	-3.8389	8.8904

Table 5.35

SUMMARY OF RESULTS

EXPERIMENTS CARRIED CUT ON HIGH TEMPERATURE RIG
ITALIAN RYE GRASS

RUN NO	CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
378	1	106.9	0.07227	0.45248	-0.0325	0.28951	-0.7235	0.6288
379	2	109.0	0.07227	0.52703	-0.6476	0.46560	-0.7931	0.9145
381	4	111.1	0.07227	0.80299	0.0466	0.34812	-1.5329	1.1088
382	1	192.7	0.07227	1.13495	-0.5330	0.80834	-1.0121	1.6832
383	2	192.7	0.07227	1.25754	-0.0560	0.28961	-6.3415	2.3589
384	3	194.6	0.07227	0.31653	-4.0464	0.52314	-1.7953	1.7884
385	4	194.6	0.07227	0.96102	-0.9110	1.07312	-0.6663	1.7195
386	1	247.9	0.07227	2.48983	-0.3546	1.74378	-0.8270	2.7256
387	2	249.7	0.07227	0.99778	-2.0065	0.89578	-2.1583	2.8220
388	3	251.5	0.07227	2.25701	-0.3984	0.67622	-2.5463	2.5806
389	4	253.3	0.07227	1.80733	-0.7512	1.30197	-1.2747	2.9407
390	1	316.0	0.07227	-0.22783	22.1632	0.76425	-4.7793	4.6450
391	2	316.0	0.07227	1.32455	-2.9244	1.18909	-2.9495	4.7338
392	3	316.0	0.07227	3.21444	-0.5942	2.17526	-1.1313	4.5981
393	4	316.0	0.07227	1.67912	-1.8143	1.24224	-2.6428	4.5411
394	1	327.9	0.07227	-0.65359	12.9813	0.84327	-7.7685	7.6666
395	2	327.9	0.07227	3.32329	-1.1903	1.91202	-2.8881	7.7031
396	3	327.9	0.07227	-15.54351	1.4986	4.98100	-0.8648	9.6160
397	4	327.9	0.07227	5.39475	-0.3816	4.02685	-0.7660	5.7843
398	1	410.1	0.07227	7.34269	-0.2097	2.66734	-2.0693	7.4154
399	2	410.1	0.07227	-0.14340	47.3274	-0.52240	13.2275	6.4163
400	3	410.1	0.07227	-0.22889	27.7928	0.62111	-9.3788	6.1625
401	4	410.1	0.07227	0.79923	-6.5532	0.16622	-36.3993	6.3245

Table 5.36

SUMMARY OF RESULTS

BATCH NO 33 OF GRASS

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO		CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
411	I.RYE GRASS	2	104.7	0.07227	-0.33371	8.8251	-0.27824	11.6376	2.2144
412	I.RYE GRASS	2	104.7	0.07227	0.13495	-28.5942	0.20561	-17.4924	4.4804
413	I.RYE GRASS	2	104.7	0.07227	0.61810	-2.0525	0.08542	-44.1255	4.1309
414	I.RYE GRASS	2	104.7	0.07227	0.55573	-2.3714	0.45669	-3.0571	2.8526
415	I.RYE GRASS	2	169.6	0.07227	2.69897	-0.3525	1.74330	-1.2020	5.2441
416	I.RYE GRASS	2	169.6	0.07227	1.91262	-0.7665	1.49613	-0.9803	4.0128
417	I.RYE GRASS	2	171.6	0.07227	1.92510	-0.7833	1.12911	-2.3561	5.0446
418	I.RYE GRASS	2	235.3	0.07227	2.36279	-1.8537	2.65848	-1.0903	6.6888
419	I.RYE GRASS	2	251.5	0.07227	1.68422	-2.3821	1.64060	-2.3574	6.8880
420	I.RYE GRASS	2	249.7	0.07227	2.74442	-1.3019	1.86013	-2.2388	7.9869
421	I.RYE GRASS	2	319.4	0.07227	3.93124	-1.2475	2.46649	-2.9495	11.4486
422	I.RYE GRASS	2	331.2	0.07227	-0.19689	62.3631	0.78992	-12.4467	11.7731
423	I.RYE GRASS	2	343.0	0.07227	-1.93699	5.9339	-1.21424	5.7849	5.7531
424	I.RYE GRASS	2	326.2	0.07227	1.63765	-6.6630	2.10306	-3.6143	12.8375
425	I.RYE GRASS	2	377.7	0.07227	1.00554	-7.1500	2.17140	-2.8025	9.7531
426	I.RYE GRASS	2	385.8	0.07227	1.59052	-5.4766	3.73997	-1.6724	11.3210
427	I.RYE GRASS	2	385.8	0.07227	1.45605	-3.5705	3.03586	-1.3275	6.2015

Table 5.37

SUMMARY OF RESULTS

BATCH NO 34 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 8.64

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
428	I.RYE	GRASS	2	106.9	0.07227	0.47906	-1.0792	0.50103	-0.6650	1.7104
429	I.RYE	GRASS	2	106.9	0.07227	0.37551	-3.6920	0.28817	-4.9813	2.4069
430	I.RYE	GRASS	2	106.9	0.07227	0.43873	-2.5664	0.29313	-4.7581	2.2928
431	I.RYE	GRASS	2	163.8	0.07227	0.57354	-6.7046	0.97237	-2.4025	4.6142
432	I.RYE	GRASS	2	169.6	0.07227	1.95553	-0.9888	1.26027	-2.3309	6.2345
433	I.RYE	GRASS	2	173.5	0.07227	1.48970	-1.8265	0.89443	-3.4901	5.4714
434	I.RYE	GRASS	2	175.4	0.07227	1.46272	-3.7101	1.15315	-4.3059	8.4008
435	I.RYE	GRASS	2	240.7	0.07227	3.59335	-0.1567	2.32826	-1.4761	7.5453
436	I.RYE	GRASS	2	247.9	0.07227	1.36195	-3.9992	1.82149	-2.3670	7.3816
437	I.RYE	GRASS	2	251.5	0.07227	2.87113	-1.5008	3.15897	-1.2064	8.6105
438	I.RYE	GRASS	2	317.7	0.07227	1.15393	-6.9158	1.91418	-3.4347	9.8919
439	I.RYE	GRASS	2	321.1	0.07227	2.36298	-2.9074	1.73647	-4.1193	10.7442
440	I.RYE	GRASS	2	324.5	0.07227	3.45503	-1.2184	3.12452	-1.3642	8.8220
441	I.RYE	GRASS	2	362.9	0.07227	11.04528	0.0543	7.25876	-0.7795	12.3282
442	I.RYE	GRASS	2	362.9	0.07227	3.15224	-2.6505	1.42709	-7.0444	12.5125
443	I.RYE	GRASS	2	366.2	0.07227	2.12011	-3.9994	2.83009	-2.4829	12.8194
444	I.RYE	GRASS	2	366.2	0.07227	1.09226	-10.3313	1.87686	-5.6475	13.3579

Table 5.38

SUMMARY OF RESULTS

BATCH NO 35 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 6.74

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
445	I.RYE	GRASS	2	119.4	0.07227	0.42173	-5.1492	0.55802	-3.1100	3.3780
446	I.RYE	GRASS	2	117.4	0.07227	0.50457	-2.7966	0.77589	-0.9127	2.9069
447	I.RYE	GRASS	2	115.3	0.07227	0.34868	-9.0350	0.21820	-16.9205	4.6544
448	I.RYE	GRASS	2	177.4	0.07227	1.47220	-1.2082	1.24467	-1.4851	4.1759
449	I.RYE	GRASS	2	183.1	0.07227	0.24520	-22.0809	0.96539	-3.4359	5.8611
450	I.RYE	GRASS	2	183.1	0.07227	3.27375	0.4278	1.57668	-1.3292	5.5601
451	I.RYE	GRASS	2	258.7	0.07227	1.64979	-4.1182	3.98659	-0.9414	10.9795
452	I.RYE	GRASS	3	258.7	0.07227	1.34247	-3.1382	1.07582	-3.7303	6.3706
453	I.RYE	GRASS	2	260.4	0.07227	1.71203	-2.2133	3.12346	-0.5319	6.6542
454	I.RYE	GRASS	2	322.8	0.07227	4.80648	-0.6317	4.38789	-0.8612	10.8169
455	I.RYE	GRASS	2	319.4	0.07227	2.05868	-2.4040	1.85297	-2.8463	9.2200
456	I.RYE	GRASS	2	309.2	0.07227	3.49406	-0.7345	2.74328	-0.9409	6.5349
457	I.RYE	GRASS	2	362.9	0.07227	3.01272	-1.3345	2.28139	-2.1195	7.4104
458	I.RYE	GRASS	2	362.9	0.07227	1.59010	-5.9137	-0.79828	18.2150	13.0974
459	I.RYE	GRASS	2	359.6	0.07227	5.95199	0.0924	7.27909	-0.0327	6.4949
460	I.RYE	GRASS	2	359.6	0.07227	0.17542	-58.6496	1.63467	-4.8916	10.3415

Table 5.39

SUMMARY OF RESULTS

BATCH NO 36 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.47

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
461	I.RYE	GRASS	2	85.3	0.07227	0.36948	0.7516	0.24154	-0.3206	0.5451
462	I.RYE	GRASS	2	85.3	0.07227	0.23385	-0.6632	0.20708	-0.1769	0.4220
463	I.RYE	GRASS	2	78.7	0.07227	0.35334	0.6824	0.21050	0.0306	0.4076
464	I.RYE	GRASS	2	143.9	0.07227	1.43134	0.0237	0.62916	-1.5824	2.1133
465	I.RYE	GRASS	2	147.9	0.07227	-0.26534	14.7901	0.49180	-3.8164	3.0698
466	I.RYE	GRASS	2	151.9	0.07227	-1.49851	4.1885	0.05167	-48.8127	2.6192
467	I.RYE	GRASS	2	204.0	0.07227	2.14117	-0.3295	1.89988	-0.5025	3.3631
468	I.RYE	GRASS	2	209.6	0.07227	1.92105	-0.6545	1.46424	-0.9793	3.2517
469	I.RYE	GRASS	2	220.7	0.07227	8.03665	0.6724	4.71248	0.3021	4.4197
470	I.RYE	GRASS	2	281.6	0.07227	1.44490	-2.6395	1.81159	-1.6533	5.3655
471	I.RYE	GRASS	2	285.1	0.07227	0.47195	-11.1123	6.51900	-0.1572	6.7685
472	I.RYE	GRASS	2	274.6	0.07227	2.69007	-1.2729	3.19323	-0.9230	5.7057
473	I.RYE	GRASS	2	353.0	0.07227	-4.25815	4.1604	-1.80243	6.8079	9.1958
474	I.RYE	GRASS	2	353.0	0.07227	17.80167	0.0013	5.81843	-1.4977	14.2194
475	I.RYE	GRASS	2	353.0	0.07227	1.07184	-8.4964	-0.31762	28.7984	9.6028
476	I.RYE	GRASS	2	349.6	0.07227	-3.02182	5.0904	10.98566	-0.4368	12.2268
478	I.RYE	GRASS	2	385.8	0.07227	3.79797	-0.9578	1.16039	-6.3245	8.7742
479	I.RYE	GRASS	2	418.1	0.07227	9.23017	-0.1965	20.92180	0.2769	11.1371
480	I.RYE	GRASS	2	418.1	0.07227	-1.00184	13.6507	-2.97816	5.2135	11.4276

Table 5.40

SUMMARY OF RESULTS

BATCH NO 37 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 2.71

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
501	I.RYE	GRASS	3	106.9	0.07751	0.29204	0.2788	0.20625	-0.3321	0.4328
502	I.RYE	GRASS	3	111.1	0.07751	0.29969	-0.1481	0.22477	-0.4778	0.4451
503	I.RYE	GRASS	3	153.9	0.07751	0.83883	-0.0282	0.66704	-0.2611	1.1054
504	I.RYE	GRASS	3	151.9	0.07751	0.60039	-0.0334	0.50644	-0.2992	0.9606

Table 5.41

SUMMARY OF RESULTS

BATCH NO 38 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 1.34

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S.FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
505	I.RYE	GRASS	4	56.2	0.07580	0.21789	0.6995	0.16712	0.3388	0.1721
506	I.RYE	GRASS	4	60.7	0.07580	0.22461	0.2054	0.15278	-0.7401	0.4335
507	I.RYE	GRASS	4	185.1	0.07450	0.83872	-0.2309	0.41685	-1.9240	1.5626
508	I.RYE	GRASS	4	183.1	0.07450	0.20216	-8.5101	0.46287	-2.2850	2.2048
509	I.RYE	GRASS	4	131.8	0.07450	0.66064	1.3792	0.76138	1.2518	1.3125

Table 5.42

SUMMARY OF RESULTS

BATCH NO 39 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.22

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
510	I.RYE	GRASS	4	101.6	0.07580	0.19098	-0.3039	0.18117	-0.3622	0.2718
511	I.RYE	GRASS	4	106.9	0.07580	0.20897	-0.1122	0.16019	-0.4239	0.2959
512	I.RYE	GRASS	4	135.9	0.07580	0.43145	-0.3796	0.26316	-0.9823	0.6094
513	I.RYE	GRASS	4	135.9	0.07580	0.40941	-0.7412	0.26052	-1.4153	0.6547
514	I.RYE	GRASS	4	171.6	0.07580	0.38888	-1.7071	0.61695	-0.6028	1.0563
515	I.RYE	GRASS	4	171.6	0.07580	0.23469	-2.3291	0.49021	-0.5223	0.8349
516	I.RYE	GRASS	4	237.1	0.07494	0.98884	-0.3226	1.46179	0.0837	1.6138
517	I.RYE	GRASS	4	238.9	0.07494	1.00461	-0.6984	0.66825	-1.6331	1.9768
518	I.RYE	GRASS	4	246.1	0.07494	-2.20533	2.4319	-0.13832	14.5661	1.7622
519	I.RYE	GRASS	4	285.1	0.07450	-0.68585	5.8501	3.23688	0.2497	3.3459
520	I.RYE	GRASS	4	276.3	0.07450	2.14290	0.2988	0.56448	-2.9657	2.8765

Table 5.43

SUMMARY OF RESULTS

BATCH NO 40 OF GRASS   LEAF TO STEM RATIO (BY WEIGHT) = 1.07

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
521	I.RYE	GRASS	4	96.2	0.07580	0.26136	0.6169	0.19683	0.3491	0.2512
522	I.RYE	GRASS	4	102.6	0.07580	0.22616	0.3206	0.20873	0.2252	0.2525
523	I.RYE	LEAVES	4	105.8	0.07580	0.33550	-0.2332	0.18944	-1.0891	0.4431
524	I.RYE	STEMS	4	105.8	0.07580	0.10879	-1.3623	0.07619	-2.2931	0.3023
525	I.RYE	GRASS	4	171.6	0.07472	1.01008	0.1762	0.34147	-1.6188	1.0725
526	I.RYE	GRASS	4	179.3	0.07472	0.56520	-0.2645	0.32709	-1.1026	0.8899
527	I.RYE	LEAVES	4	183.1	0.07472	0.67451	-1.4427	0.29150	-3.7226	1.5098
528	I.RYE	STEMS	4	185.1	0.07472	0.22460	-2.1163	0.17352	-2.7295	0.6971
529	I.RYE	GRASS	4	238.9	0.07400	0.95403	-0.3424	0.31744	-2.6683	1.4097
530	I.RYE	GRASS	4	238.9	0.07400	-0.31796	6.9923	-0.29849	5.9854	1.4598
531	I.RYE	LEAVES	4	249.7	0.07400	-0.00421	479.8649	0.44888	-2.9708	1.8753
532	I.RYE	STEMS	4	246.1	0.07400	-0.06161	25.6353	-1.09156	2.9461	1.3077
533	I.RYE	GRASS	4	319.4	0.07400	-4.92167	2.3080	1.79448	-0.0796	3.0264
534	I.RYE	GRASS	4	319.4	0.07400	1.81488	-0.3506	2.02076	-0.1146	2.9741
535	I.RYE	LEAVES	4	319.4	0.07400	1.94847	-0.4908	1.46645	-1.0971	3.2652
536	I.RYE	STEMS	4	319.4	0.07400	0.34212	-5.8339	0.28817	-6.3399	2.4642
537	I.RYE	GRASS	4	361.2	0.07343	1.01457	-2.2697	1.73446	-0.7721	3.4590
538	I.RYE	GRASS	4	361.2	0.07343	-0.31603	14.0261	4.31101	0.0764	4.4051
539	I.RYE	LEAVES	4	361.2	0.07343	1.30841	-2.4337	2.18332	-1.1260	4.3667
540	I.RYE	STEMS	4	361.2	0.07343	0.28301	-6.2982	-0.45708	6.6806	2.3088
541	I.RYE	GRASS	4	326.2	0.07343	2.08157	-0.3642	1.89012	-0.3042	2.9770
542	I.RYE	GRASS	4	326.2	0.07343	0.37041	-10.1746	2.05534	-0.4710	4.0489
543	I.RYE	LEAVES	4	326.2	0.07343	0.53551	-7.5027	2.25488	-1.0707	4.6686
544	I.RYE	STEMS	4	326.2	0.07343	-1.11854	4.0981	0.77407	-0.9940	2.3184
545	I.RYE	GRASS	4	260.4	0.07343	-1.02075	3.7753	1.15474	-0.2728	2.1908
546	I.RYE	GRASS	4	256.9	0.07343	0.45086	-3.4493	1.27607	-0.2313	2.3663
547	I.RYE	LEAVES	4	253.3	0.07343	1.29437	-1.1590	2.10826	-0.3349	3.1047
548	I.RYE	STEMS	4	240.7	0.07343	1.43766	0.7717	0.30575	-2.9237	1.4405

Table 5.44

SUMMARY OF RESULTS

BATCH NO 41 OF GRASS LEAF TO STEM RATIO (BY WEIGHT) = 0.90

EXPERIMENTS CARRIED OUT ON HIGH TEMPERATURE RIG

RUN NO			CHOP LGTH INS	AIR TEMP DEG C	AIR VELOCITY LB/S-FT2	KP (MIN)-1	MEP GM/GM	KG (MIN)-1	MEG GM/GM	C (MIN)-1
549	I.RYE	GRASS	4	100.5	0.07580	0.25293	0.6363	0.10958	-0.7716	0.2803
550	I.RYE	GRASS	4	102.6	0.07580	0.11884	-1.3693	0.16048	-0.3922	0.3424
551	I.RYE	LEAVES	4	106.9	0.07580	0.15139	-1.5058	0.10678	-2.2830	0.4463
552	I.RYE	STEMS	4	104.7	0.07580	0.08863	-0.6289	0.03849	-3.0354	0.1911
553	I.RYE	GRASS	4	147.9	0.07580	0.16023	-3.4947	0.23738	-1.5060	0.7663
554	I.RYE	GRASS	4	149.9	0.07580	-0.27109	4.4631	0.08153	-6.6105	0.7046
555	I.RYE	LEAVES	4	159.8	0.07580	0.69084	-0.1825	0.64613	-0.3467	1.2367
556	I.RYE	STEMS	4	161.8	0.07580	0.18722	-1.2548	0.07477	-4.6730	0.4945
557	I.RYE	GRASS	4	242.5	0.07379	0.55051	-1.9272	0.92960	-0.6654	1.7477
558	I.RYE	GRASS	4	240.7	0.07379	0.38412	-4.0227	0.93925	-1.2431	1.7884
559	I.RYE	LEAVES	4	244.4	0.07379	0.68445	-1.5038	0.99077	-1.0939	2.3268
560	I.RYE	STEMS	4	238.9	0.07379	-0.77920	3.8920	0.05923	-19.2229	1.4470
561	I.RYE	GRASS	4	304.1	0.07336	0.09464	-25.4940	1.31283	-0.7216	2.4208

Table 5.45a

Constants in $\log_e k_p = K_a + K_b T_a$

Batch	Points	K_a	K_a'	K_b	Correlation Coefficient
9	5	-4.269	0.014	0.02568	0.9399
10	6	-4.801	0.007	0.03046	0.8518
11	7	-4.467	0.01135	0.02554	0.9813
12	4	-4.265	0.014	0.02073	0.9574
13	5	-3.749	0.02340	0.01605	0.9939
14	5	-5.037	0.00649	0.03010	0.9934
15	5	-3.907	0.02	0.01945	0.9596
16	5	-3.7419	0.0236	0.02150	0.9685
17	6	-4.482	0.01123	0.02828	0.9776
18	5	-3.240	0.039	0.01747	0.9786
19	5	-4.274	0.0139	0.02883	0.9848
20	12	-	-	0.01777	-
21	15	-	-	0.01851	-
22	23	-	-	0.01948	-
23	11	-4.161	0.01562	0.02441	0.9836
29 & 31					
(Whole Grass)	15	-1.103	0.3315	0.00467	0.4981
(Leaves Only)	9	-1.282	0.277	0.00889	0.8614
(Stems Only)	9	-0.084	0.92	-0.00173	-0.1933
30 & 32	15	-1.187	0.304	0.00634	0.7825
31					
(Chop Varied)	19	-1.234	0.29	0.00629	0.7097
33	15	-0.592	0.552	0.00377	0.4715
34	16	-1.132	0.322	0.00647	0.6937
35	15	-1.274	0.279	0.00612	0.5014
36	13	-1.539	0.2145	0.00906	0.7599
37	4	-3.398	0.0333	0.01998	0.9724
38	5	-1.712	0.18	0.00543	0.4979
39	11	-2.667	0.0885	0.01079	0.9133
40					
(Whole Grass)	10	-1.624	0.1967	0.00519	0.6509
(Leaves Only)	5	-1.343	-.266	0.00461	0.6831
(Stems Only)	5	-2.036	0.1302	0.00371	0.4023
41					
(Whole Grass)	9	-3.461	0.0329	0.01194	0.6925
(Leaves Only)	4	-3.266	0.038	0.01445	0.9496
(Stems Only)	3	-4.927	0.01435	0.02192	0.9931

Table 5.45b

Constants in $\log_e k_g = K_a + K_b T_a$

Batch	Points	K_a	K_a'	K_b	Correlation Coefficient
9	5	-4.267	0.0141	0.02551	0.9786
10	6	-4.854	0.00633	0.03056	0.8732
11	7	-4.413	0.01197	0.02441	0.9774
12	4	-4.3533	0.0128	0.02128	0.9568
13	5	-3.493	0.0303	0.01436	0.9799
14	5	-4.436	0.01177	0.02390	0.9963
15	5	-3.589	0.0276	0.01638	0.9329
16	5	-3.460	0.0314	0.01808	0.9980
17	6	-3.5078	0.02995	0.01934	0.9923
18	5	-3.0445	0.0476	0.01524	0.9793
19	5	-3.9989	0.0183	0.02491	0.9884
20	12	-	-	0.0143	-
21	15	-	-	0.01576	-
22	23	-	-	0.01624	-
23	11	-4.161	0.0155	0.02441	0.9836
29 & 31					
(Whole Grass)	15	-1.307	0.27	0.00601	0.9250
(Leaves only)	9	-1.439	0.237	0.00851	0.8704
(Stems only)	9	-1.724	0.178	0.00865	0.9413
30 & 32	15	-0.871	0.417	0.0377	0.5591
31					
(Chop varied)	19	-1.326	0.2655	0.00468	0.5195
33	15	-1.642	0.1935	0.00748	0.7387
34	16	-1.497	0.223	0.00778	0.8582
35	15	-1.384	0.25	0.00757	0.7799
36	13	-1.995	0.1358	0.0106	0.8402
37	4	-4.010	0.01795	0.02268	0.9870
38	5	-2.173	0.1137	0.00856	0.7768
39	11	-2.910	0.054	0.01194	0.8779
40					
(Whole Grass)	13	-2.819	0.0565	0.01060	0.9427
(Leaves Only)	5	-2.858	0.0571	0.01058	0.8906
(Stems Only)	5	-3.359	0.0247	0.00831	0.9113
41					
(Whole Grass)	10	-4.164	0.0155	0.01678	0.9130
(Leaves Only)	4	-3.5590	0.0284	0.01569	0.9692
(Stems Only)	4	-5.704	0.00328	0.01883	0.8151

Table 5.46

$$\log_e(k_p + k_g)/2 = K_a + K_bT_a$$

Batch	Points	K_a	K'_a	K_b	Correlation Coefficient
9	5	-4.266	0.0140	0.02557	0.9622
10	6	-4.830	0.00799	0.03058	0.8636
11	7	-4.437	0.01183	0.02495	0.9804
12	4	-4.342	0.01301	0.02119	0.9504
13	10	-3.659	0.02576	0.01472	0.9408
14	7	-4.735	0.00878	0.02650	0.9809
15	8	-3.723	0.02417	0.01620	0.8294
16	9	-3.176	0.04173	0.01568	0.8765
17	8	-3.888	0.02049	0.02295	0.9915
18	11	-3.023	0.04865	0.01540	0.8278
19	8	-4.084	0.01683	0.02654	0.9548
20	12	-3.5581	0.02849	0.01669	0.8569
21	15	-3.96715	0.01893	0.02015	0.8601
22	23	-3.9032	0.02018	0.01862	0.8326
23	11	-3.9933	0.01844	0.02231	0.9865
29 & 31					
(Whole grass)	15		0.3073	0.00549	0.7853
(Leaves only)	9		0.2562	0.00876	0.8723
(Stems Only)	9		0.3065	0.00568	0.8030
30 & 32	15		0.3426	0.00541	0.7529
31	19				
(Chop variation)			0.2770	0.00574	0.6872
33	15		0.3626	0.00545	0.6848
34	16		0.2723	0.00714	0.7952
35	15		0.2626	0.00716	0.7377
36	13		0.1678	0.01033	0.8741
37 & 38	9		0.1587	0.00722	0.5715
39	11		0.0573	0.01201	0.9798
40					
(Whole grass)	10		0.12841	0.00789	0.7973
(Leaves only)	5		0.1345	0.00770	0.9267
(Stems only)	5		0.0594	0.00707	0.6794
41					
(Whole grass)	5		0.05770	0.00946	0.9739
(Leaves only)	4		0.03347	0.01504	0.9638
(Stems only)	3		0.00498	0.02216	0.9922

Table 5.47

Constants in $\log_e k = K_a + K_b T_a$

for all runs, and groups of runs

Group	Points	K_a	K_a'	K_b	Correlation Coefficient
All Medium Temp. Runs Batches 9 - 23	144	-3.9859	0.0185	0.02102	0.8595
All Medium Temp. Runs, Batches 9 - 23, and High Temp. Runs, T_a 200°C	203	-3.8002	0.0222	0.02032	0.8487
Two-period Runs on Medium Temp. Rig, Batches 9 - 23					
k_1	35	-2.3986	0.09084	0.00122	0.04095 (Not significant)
k_2	35	-4.1578	0.01564	0.01799	0.51032

Table 5.48

Table of constants in $\log_e k_p = K_g + K_h T_a + K_j v$

Batch	K_g	K_g'	K_h	K_j	Correlation Coefficient
13	-4.3517	0.0128	0.01588	7.641	0.9693
14	-5.6659	0.00357	0.02993	7.964	0.9799
15	-5.0554	0.00641	0.01954	13.565	0.9558
16	-3.7876	0.0597	0.01726	6.533	0.8052
17	-4.4994	0.0111	0.02740	1.190	0.9625
18	-4.2607	0.0141	0.01781	12.705	0.9330
19	-4.4738	0.0256	0.02768	4.39	0.9195
20	-4.934	0.00715	0.01777	19.729	0.9508
21	-4.785	0.00833	0.01851	15.952	0.9095
22	-4.940	0.00715	0.01948	15.753	0.9267

Table of constants in $\log_e k_g = K_g + K_h T_a + K_j v$

Batch	K_g	K_g'	K_h	K_j	Correlation Coefficient
13	-4.285	0.0137	0.01450	10.423	0.9615
14	-5.5213	0.00403	0.02395	12.899	0.9933
15	-4.7523	0.00764	0.01649	13.722	0.9385
16	-3.6692	0.02535	0.01576	6.024	0.8505
17	-2.9197	0.0540	0.01891	-6.550	0.9904
18	-4.6202	0.0098	0.01668	19.536	0.7626
19	-4.3987	0.01227	0.02395	6.436	0.9301
20	-4.750	0.00968	0.01430	20.014	0.9296
21	-4.6483	0.0096	0.01576	17.369	0.9494
22	-4.7088	0.0090	0.01624	16.317	0.9311

Table 5.49

$$\log_e k = K_g + K_h T_a + K_j v$$

Batch	K_g	K_h	K_j	Correlation Coefficient
13	-4.5645	0.01735	8.2852	0.9483
14	-5.8039	0.02831	11.307	0.9969
15	-5.1921	0.02098	13.665	0.9449
16	-3.7218	0.01630	6.771	0.8476
17	-4.0682	0.02399	0.508	0.9741
18	-4.6639	0.01913	16.552	0.8363
19	-4.4129	0.02577	5.396	0.9184
20	-4.8686	0.01743	18.965	0.95517
21	-4.7859	0.01769	16.914	0.9210
22	-4.8410	0.01834	15.641	0.9347
All Runs, Batches 13-23	-4.9585	0.02081	14.138	0.8275

Table 5.49

Correlations for Low temperature runs

$$k_i = K'_a \exp(K_b T_a)$$

i	K'_a	K_b	Correlation Coefficient
1	0.03108	0.02418	0.9397
2	0.00781	0.03725	0.9520
3	0.002688	0.04636	0.9679

$$m_{ci} = K_o + K_z m_o$$

i	K_o	K_z	Correlation Coefficient
1	0.8302	0.5780	0.8091
2	1.8062	0.1664	0.1435

Table 5.50

Constants in $m_e = K_p + K_q \sqrt{x_a}/T_a^2$

Runs	Points	K_p	K_q	Correlation Coefficient
Batches 9 - 23 Programme Results	144	-0.2037	29830	0.8825
Batches 9 - 23 Graphical Results	144	-0.1942	29879	0.6746
Two-period curves on Medium Temp. Rig				
m_{e1}	35	0.7543	44490	0.7515
m_{e2}	35	-0.3175	35929	0.8444
Low Temp. Runs				
m_{e1}	13	1.8181	6763	0.7435
m_{e2}	12	0.9709	7114	0.7124
m_{e3}	11	0.5971	5517	0.7964

Constants in $m_e = K_p + K_q T_a$

Runs	Points	K_p	K_q	Correlation Coefficient
Batches 9 - 23 Programme Results	144	1.5016	-0.01332	0.5972
Batches 9 - 23 Graphical Results	144	1.2458	-0.01077	0.6328
Two-period Curves on Medium Temp. Rig				
m_{e1}	35	5.6191	-0.05725	0.8056
m_{e2}	35	3.2392	-0.04056	0.7942
Low Temp. Runs				
m_{e1}	13	3.7736	-0.0264	0.8285
m_{e2}	12	3.0146	-0.02738	0.7934
m_{e3}	11	2.2896	-0.02478	0.8971

Table 5.51

Constants in $k = K_m + K_n l_s$

for 100°C

Whole Grass	0.17552	0.007584	0.3523	28
Leaves Only	0.18537	0.01201	0.3000	24
Stems Only	0.06514	0.02007	0.6220	24

Table 5.52

Constants in $K'_a = K_{1a} + K_{2a}l_s$

	K_{1a}	K_{2a}	r	Points
k obtained by polynomial method, batches 9 - 41	0.05269	0.0259	0.4590	23
k obtained by grouping and segmentation method, batches 9 - 41	0.05056	0.01213	0.3464	23
Average of two values of k, batches 9 - 41	0.06170	0.01471	0.3241	26

Constants in $K_b = K_{1b} + K_{2b}l_s$

	K_{1b}	K_{2b}	r	Points
k obtained by polynomial method, batches 9 - 41	0.01854	-0.000689	0.198	26
k obtained by grouping and segmentation method, batches 9 - 41	0.01774	-0.000600	0.2159	26
Average of two values of k, batches 9 - 41	0.017066	-0.000582	0.1889	26

Constants in $K'_g = K_{1g} + K_{2g}l_s$

	K_{1g}	K_{2g}	r	Points
k obtained by polynomial method, batches 13 - 22	0.009991	0.0001827	0.0557	10
k obtained by grouping and segmentation method, batches 13 - 22	0.01408	0.0005488	0.0617	10

Constants in $K_h = K_{1h} + K_{2h}l_s$

	K_{1h}	K_{2h}	r	Points
k obtained by polynomial method, batches 13 - 22	0.02266	-0.0005831	0.1869	10
k obtained by grouping and segmentation method, batches 13 - 22	0.01897	-0.0005001	0.2315	10

Table 5.52 contd.

Constants in $K_j = K_{1j} + K_{2j}\ell_S$

	K_{1j}	K_{2j}	r	Points
k obtained by polynomial method, batches 13 - 22	6.8331	1.412	0.3948	10
k obtained by grouping and segmentation method, batches 13 - 22	8.1835	1.3079	0.2669	10

Table 5.53

Constants in $k_o = K_r + K_s T_a$

Batch	Points	K_r	K_s	Correlation Coefficient
29 & 31				
(Whole grass)	15	-1.6588	0.01829	0.9490
(Leaves only)	9	-2.0220	0.02416	0.9694
(Stems Only)	9	-2.5167	0.02122	0.9137
30 & 32	15	-3.3397	0.03080	0.9007
31				
(Chop Varied)	25	-2.0005	0.02266	0.8806
33	15	1.0666	0.02565	0.8176
34	16	-1.0553	0.03668	0.9530
35	16	0.9595	0.02436	0.7687
36	13	-2.8844	0.03432	0.9210
37	4	-1.0350	0.01352	0.9892
38	5	-0.3492	0.01221	0.9545
39	11	-1.4078	0.01460	0.9548
40				
(Whole Grass)	14	-1.4726	0.01445	0.9535
(Leaves Only)	7	-1.4283	0.01625	0.9404
(Stems Only)	7	-0.8119	0.00926	0.9710
41				
(Whole Grass)	10	-1.7883	0.01717	0.9442
(Leaves Only)	5	-3.2040	0.02835	0.9193
(Stems Only)	5	-1.5703	0.01396	0.9799
All	201	-1.8396	0.02468	0.7119
All, excepting leaves, stems and Batches 30 & 32	144	-1.5043	0.02497	0.69913

Table 5.54

Constants in $K_r = K_{1r} + K_{2r}l_s$

	K_{1r}	K_{2r}	Correlation Coefficient	Points
Batches 29 - 41	-1.8493	0.2653	0.7002	11

Constants in $K_s = K_{1s} + K_{2s}l_s$

	K_{1s}	K_{2s}	Correlation Coefficient	Points
Batches 29 - 41	0.01667	0.00154	0.5861	11

Table 5.55

Variation in Initial Moisture Content of Grass

Batch	Mean m.c. (d.b.)	Standard Deviation	Variance
1	5.4417	0.5149	0.2651
2	6.1938	0.6242	0.3896
3	6.2620	0.7041	0.4958
4	5.7385	0.6810	0.4637
5	6.7130	0.8052	0.6484
6	5.1193	0.4760	0.2266
7	6.6265	0.4730	0.2238

Table 7.1.

Results of Barley Drying Simulation

Run	Experimental Run time, min	Experimental Final m.c.	Predicted Run time	Predicted Final m.c.
S 139	157	0.2887	169.5	0.2926
S 137	568	0.1400	610	0.1514
S 138	440	0.1941	435	0.1955
S 141	327	0.2286	331.5	0.1909
S 142	206	0.2574	240	0.2655
S 122	93	0.2976	101	0.2958
S 147	491	0.1331	535.5	0.1481
S 118	390	0.1772	403	0.1819
S 120	303	0.2239	324	0.2317
S 121	185	0.2681	213	0.2728
S 145	105	0.3019	59.5	0.2659
S 134	260	0.1400	298	0.1594
S 146	211	0.1817	223	0.1892
S 126	160	0.2247	169	0.2308
S 125	105	0.2620	114	0.2684
S 136	317	0.1400	361	0.1570
S 140	430	0.1400	480	0.1566
S 144	256	0.1473	275.5	0.1576
S 143	355	0.1409	406	0.1623
S 148	149	0.1400	184.5	0.1667
S 135	203	0.1400	246.5	0.1656

Table 7.2

Results of Wheat Drying Simulation

Run	Experimental Run time, min	Experimental Final m.c.	Predicted Run time	Predicted Final m.c.
S 1	130	0.2519	142.5	0.2612
S 2	110	0.2293	107.5	0.2267
S 4	140	0.1522	186.5	0.1908
S 5	140	0.1461	155	0.1581

NOTE: The moisture contents referred to are the average moisture contents of the bed. Given the experimental run time, the programme will produce the predicted final moisture content, which may be compared with the experimental final moisture content. Alternatively, the programme may determine the predicted time required to reach the experimental final moisture content. This predicted time can then be compared with the experimental time.

Table 7.3.

Results of Hay Drying Simulation

Run	Exptl. Run time mins	Initial m.c.d.b.	Exptl. Final m.c.d.b.	Pred. Run time mins	Pred. Final m.c.d.b.	Accuracy **
S 201	1620	0.798	0.14	1030	0.178	5.78%
S 202	1560	0.815	0.23	1280	0.1795	-8.63%
S 203	1740	0.834	0.40	1495	0.3325	-15.50%
S 204	1560	0.812	0.16	895	0.1769	2.59%
S 205	1740	0.715	0.13	705	0.1766	7.98%
S 206	1680	0.712	0.18	1195	0.1814	0.26%
S 207	1020	0.760	0.10	-	0.1728	11.03%
S 208	1320	0.730	0.10	-	0.1739	11.72%
S 209	1680	0.687	0.13	-	0.1759	8.23%
S 210	1020	0.760	0.08	-	0.1719	13.50%

$$** \ \text{Accuracy} = \frac{\text{Predicted final m.c.} - \text{Experimental final m.c.}}{\text{Initial m.c.} - \text{Experimental final m.c.}} \ 100$$

NOTE: The moisture contents referred to are the average moisture contents of the bed. Given the experimental run time, the programme will produce the predicted final moisture content, which may be compared with the experimental final moisture content. Alternatively, the programme may determine the predicted time required to reach the experimental final moisture content. This predicted time can then be compared with the experimental time.

Table 8.1

PREDICTION OF ROTARY DRIER PERFORMANCE

Air flow rate = 238 lb/min

Feed rate of grass dry-matter = 9.55 lb/min

Inlet air temperature = 1100°F

Parameter	Experimental Value	Predicted Value
Exhaust air temperature	300°F	326°F
Product moisture content	0.19	0.505 **
Residence time	1.25 min	1.3156 min

** The grass feed rate was not known exactly, and therefore the predicted and experimental values of the product moisture content do not agree closely.

Table 8.2

EFFECT OF TRAVEL RATIO, δ

Inlet air temperature = 1000°F

Initial moisture content = 4.26

Air flow rate = 238 lb/min

Grass feed rate = 8.35 lb/min

	Predicted Values		
Travel Ratio δ	m_f	τ	T_f
1.71	0.5548	1.5889	322
2.0	0.6343	1.2729	337
2.4	0.6397	1.2604	338
3.0	0.5243	1.5856	327

XI

FIGURES

LEGEND

The legend for the diagrams is given in each figure, except in the plots of k and k_o against T. In these figures, the letter p means that the values were obtained by the polynomial method, the letter g indicates that the values were obtained by the segmentation and grouping method, and the letter v that the velocity of the air was varied

LEGEND

The legend for the diagrams is given in each figure, except in the plots of k and k_o against T. In these figures, the letter p means that the values were obtained by the polynomial method, the letter g indicates that the values were obtained by the segmentation and grouping method, and the letter v that the velocity of the air was varied

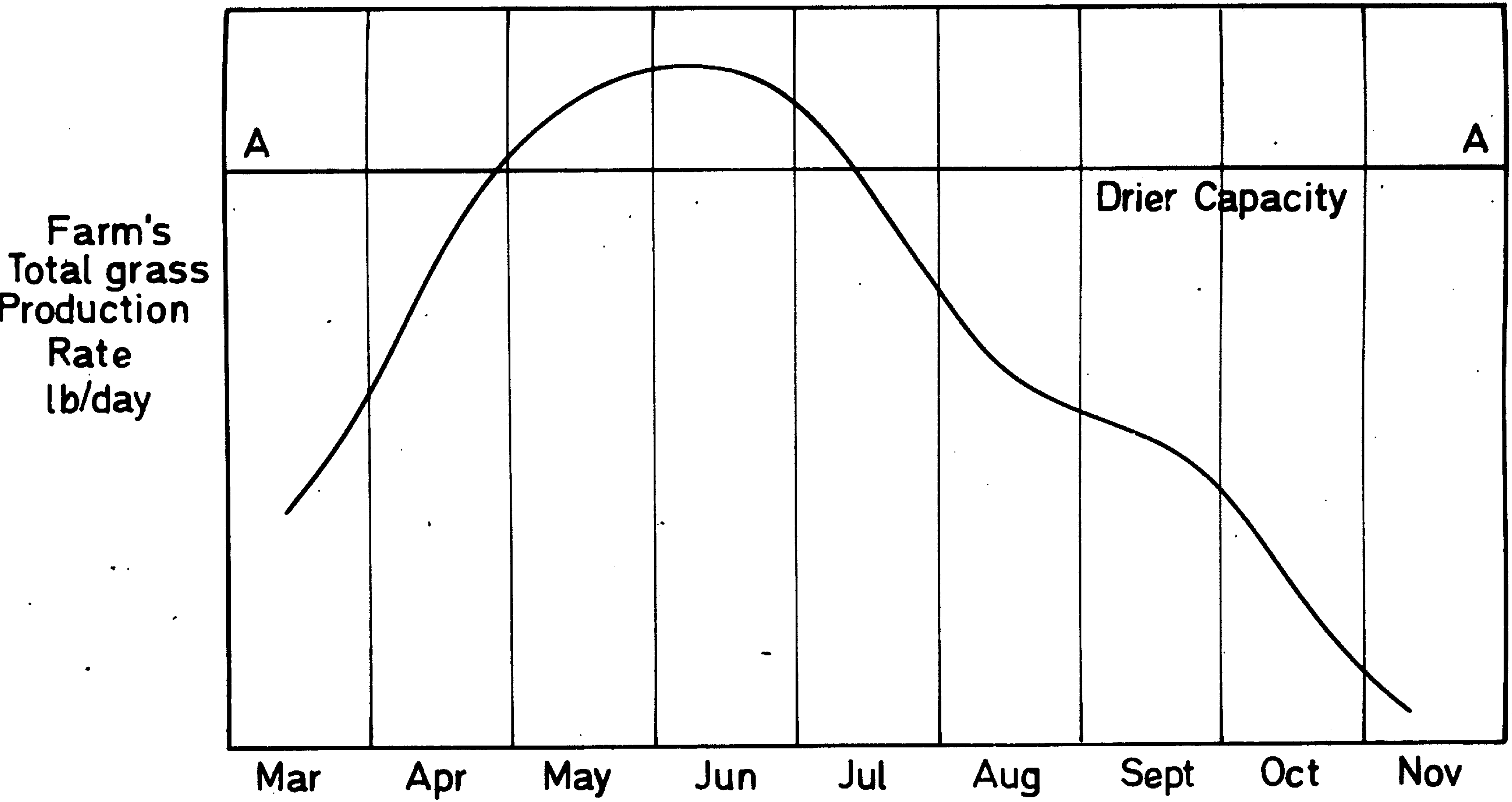


FIG.1.1. GROWTH CURVE FOR GRASS

FIG.1.2
TRAY DRIER

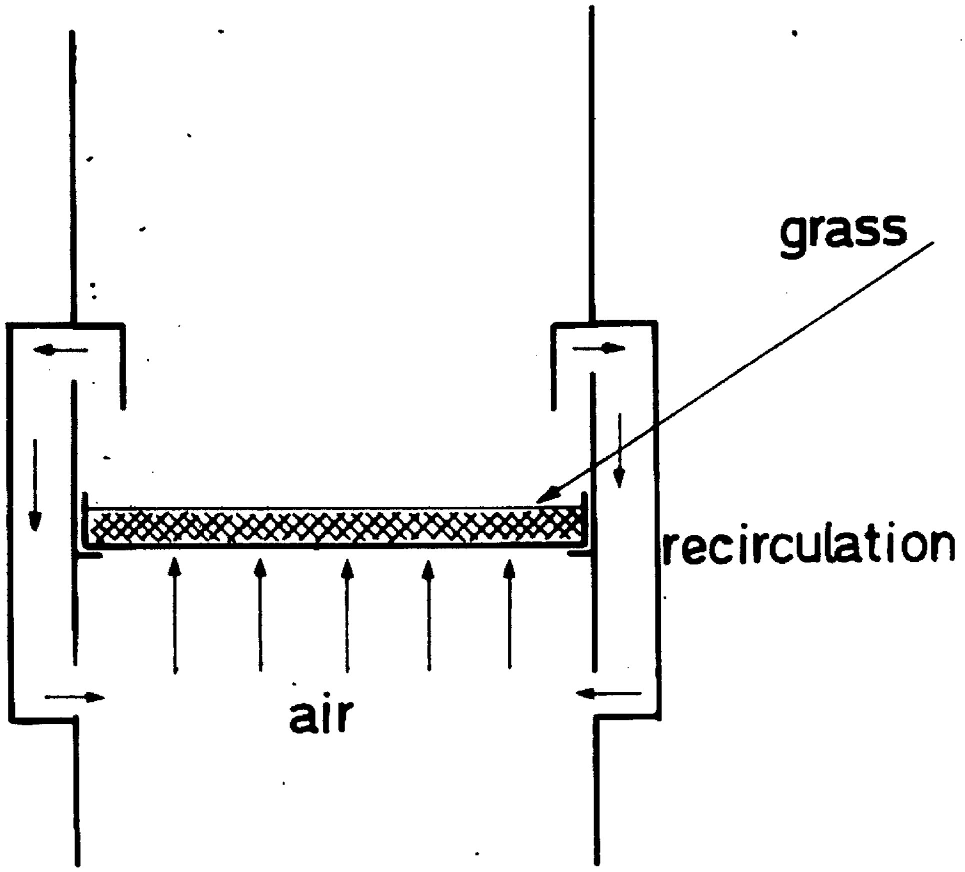


FIG.1.3.
CONVEYOR DRIER

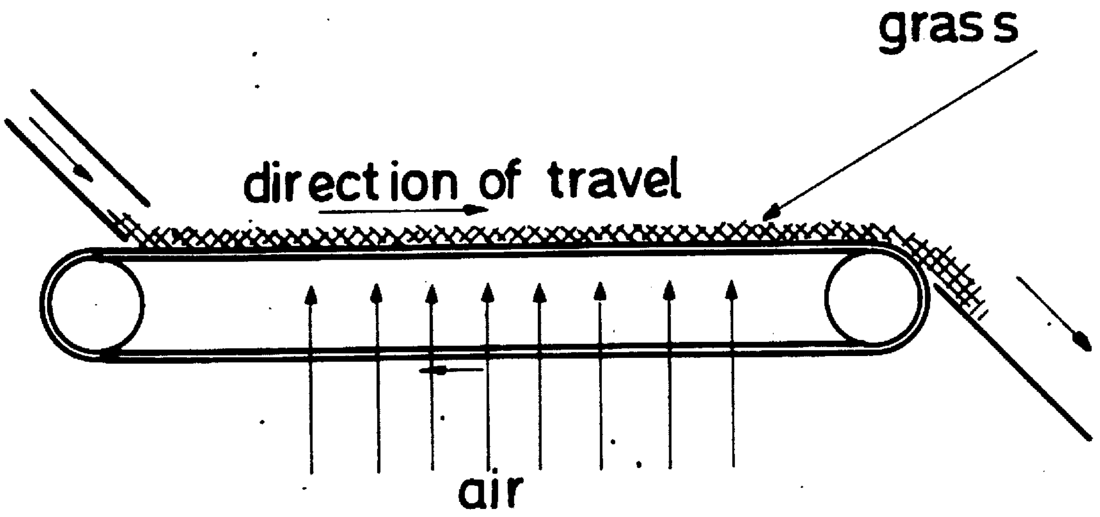


FIG.1.4.
ROTARY DRIER

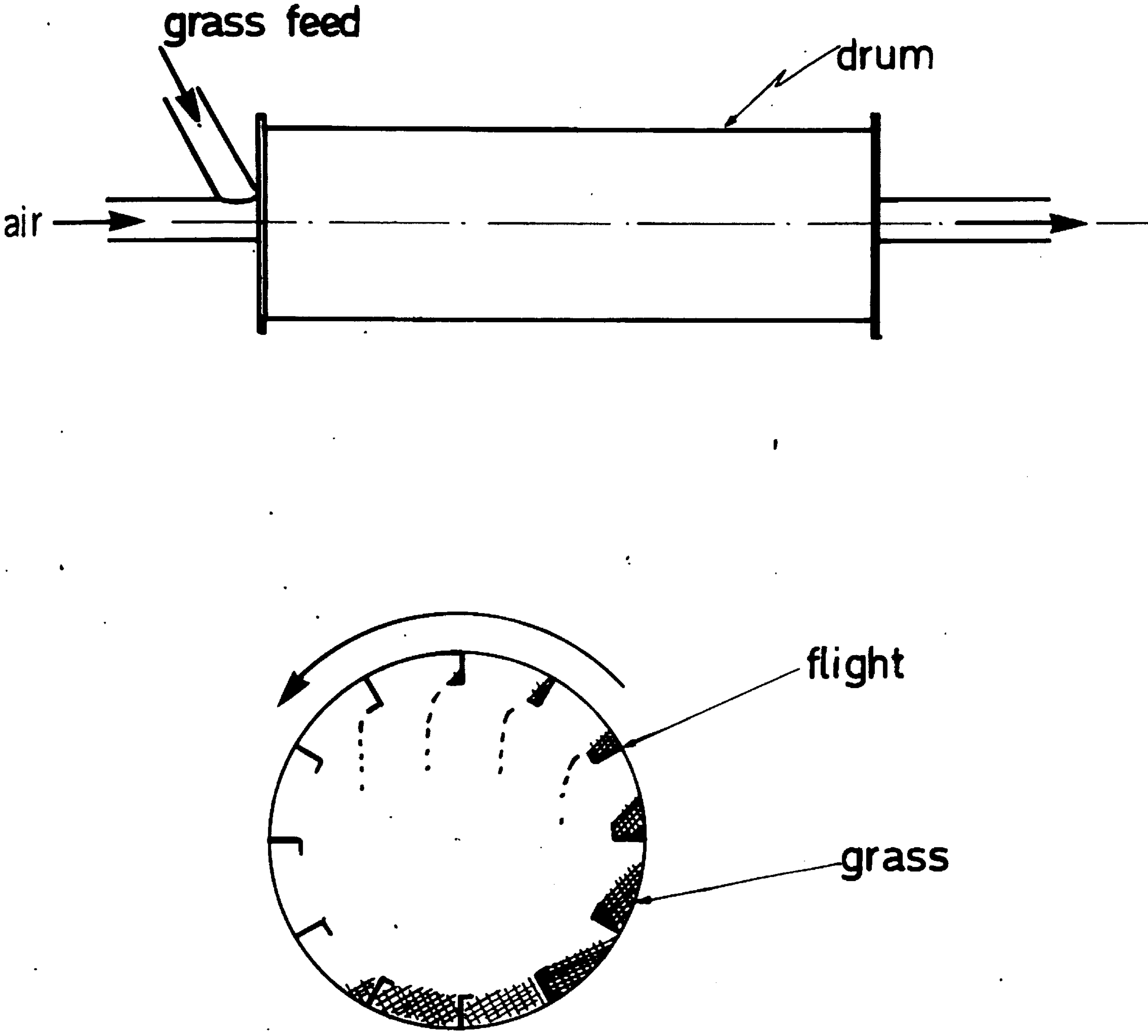


FIG. 2.1.

DRYING CURVE

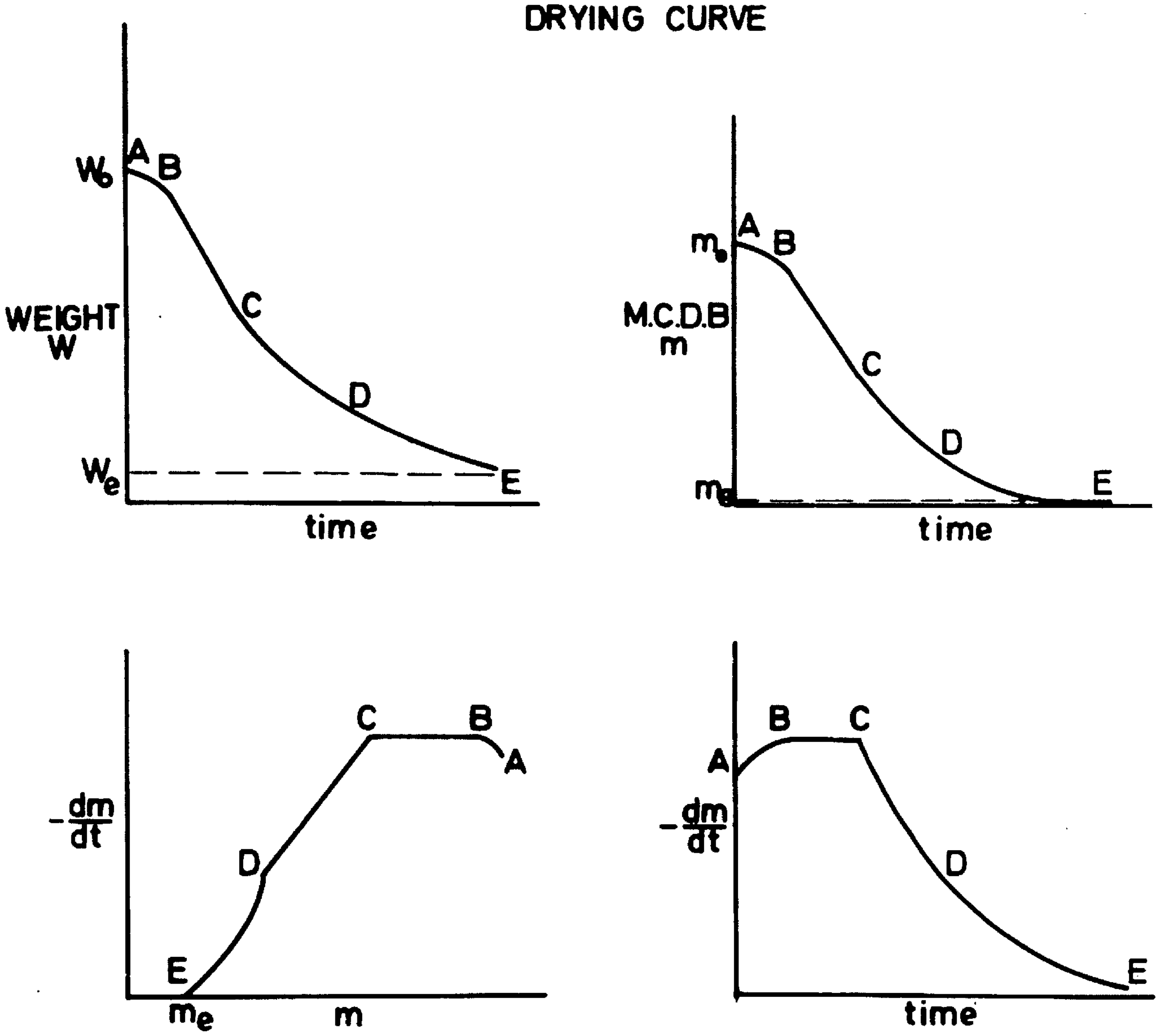
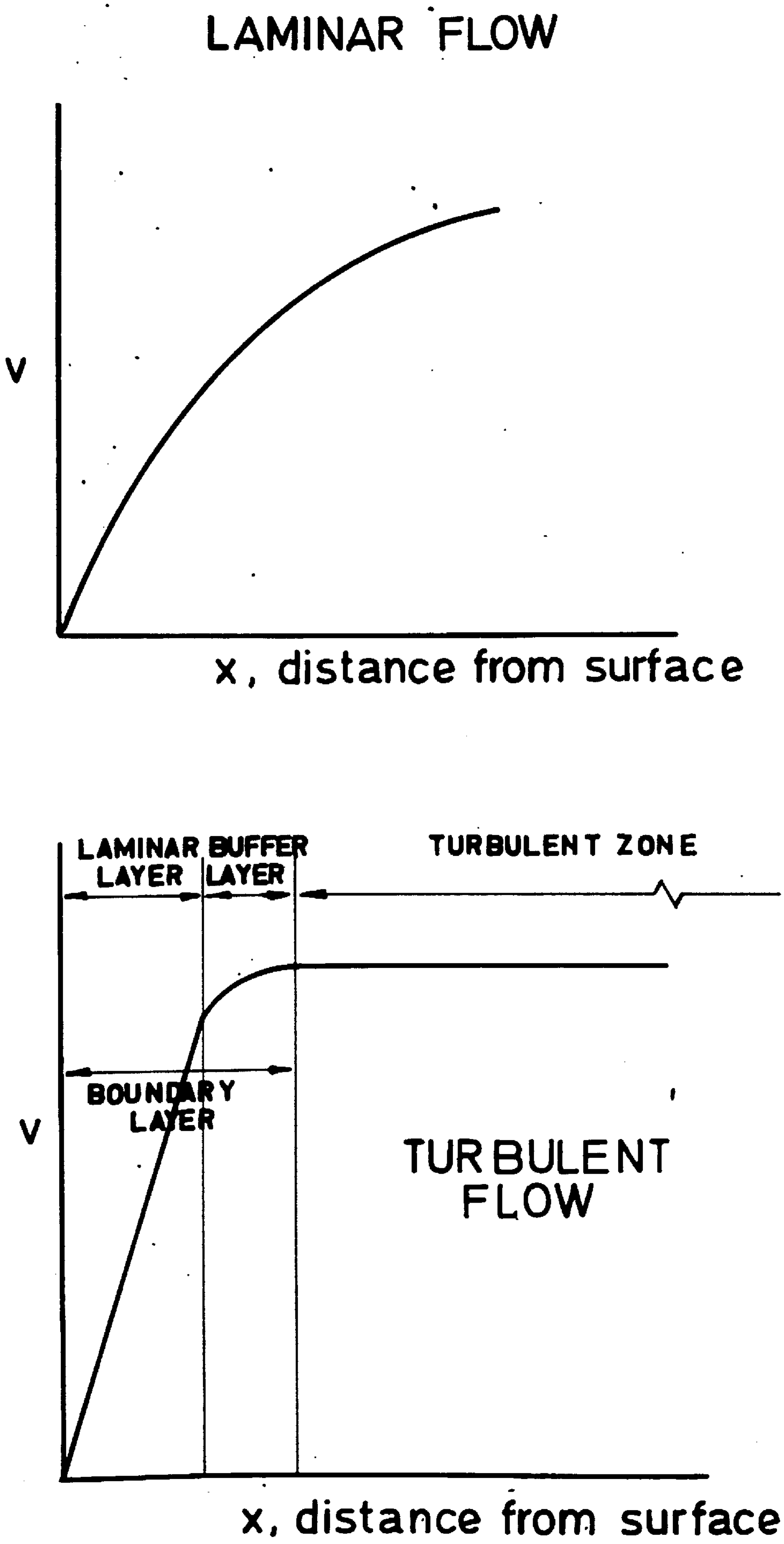


FIG. 2.2.

VELOCITY PROFILES



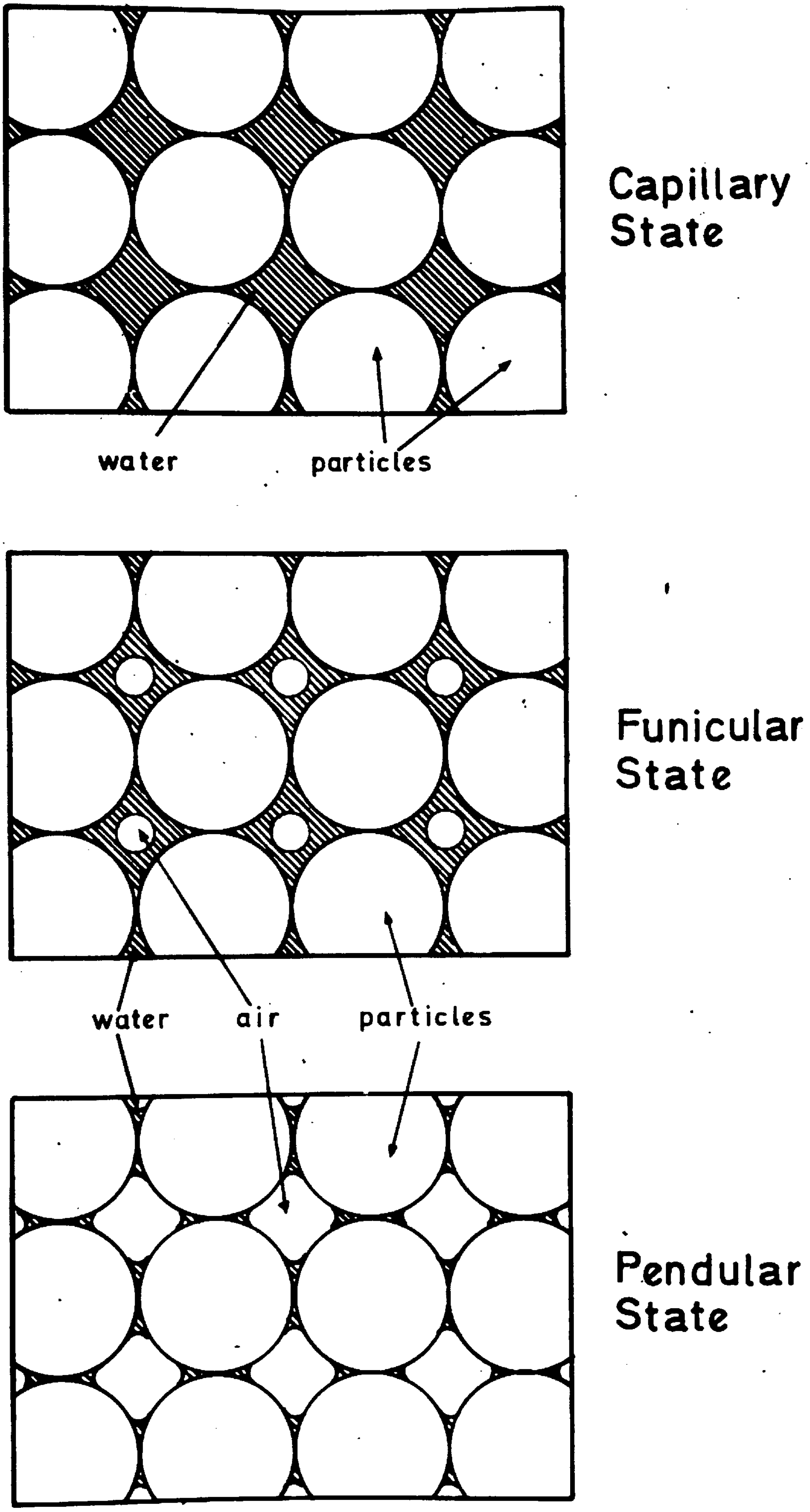


FIG.2.3. STATES OF WATER IN PORES OF A POROUS MEDIUM

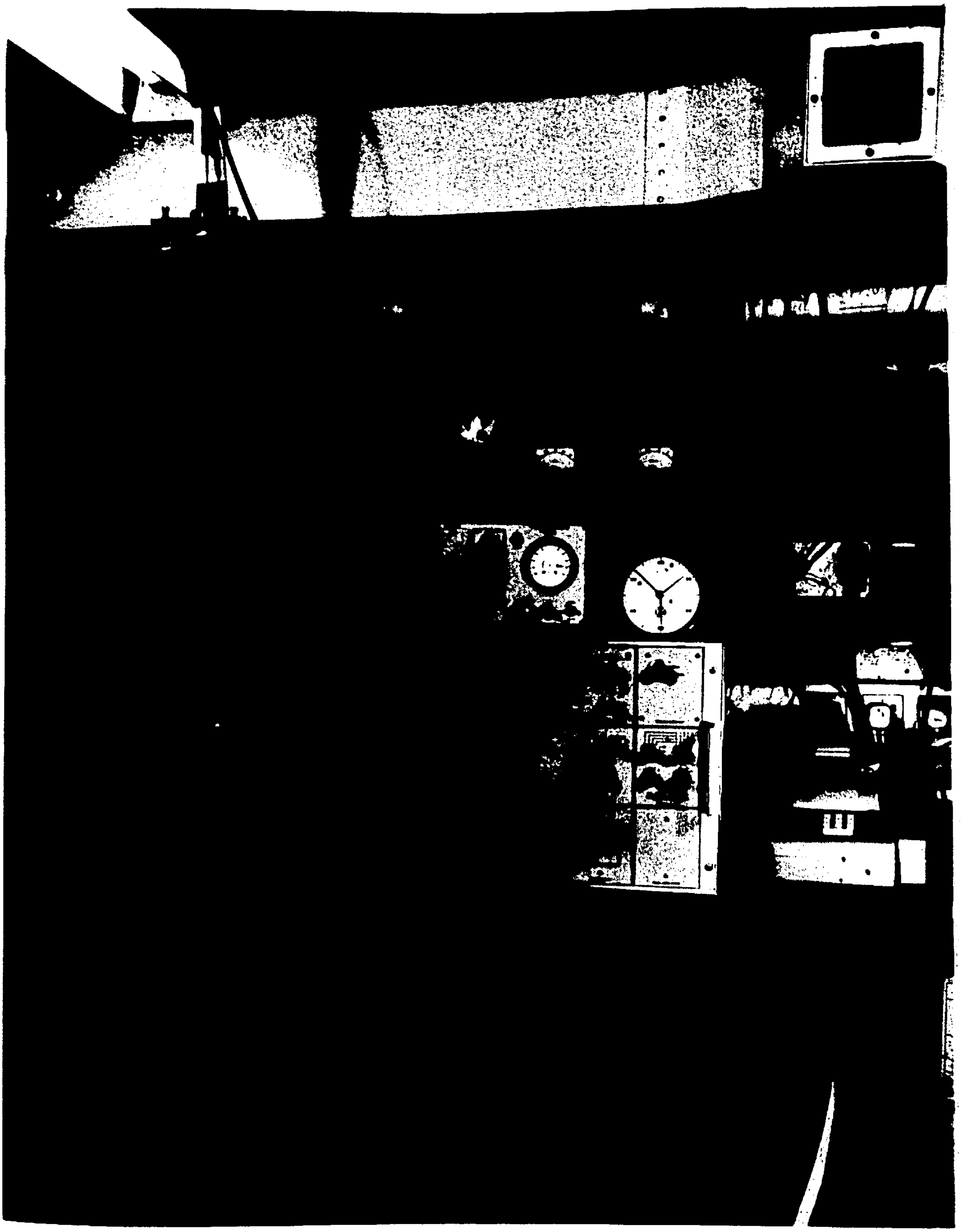
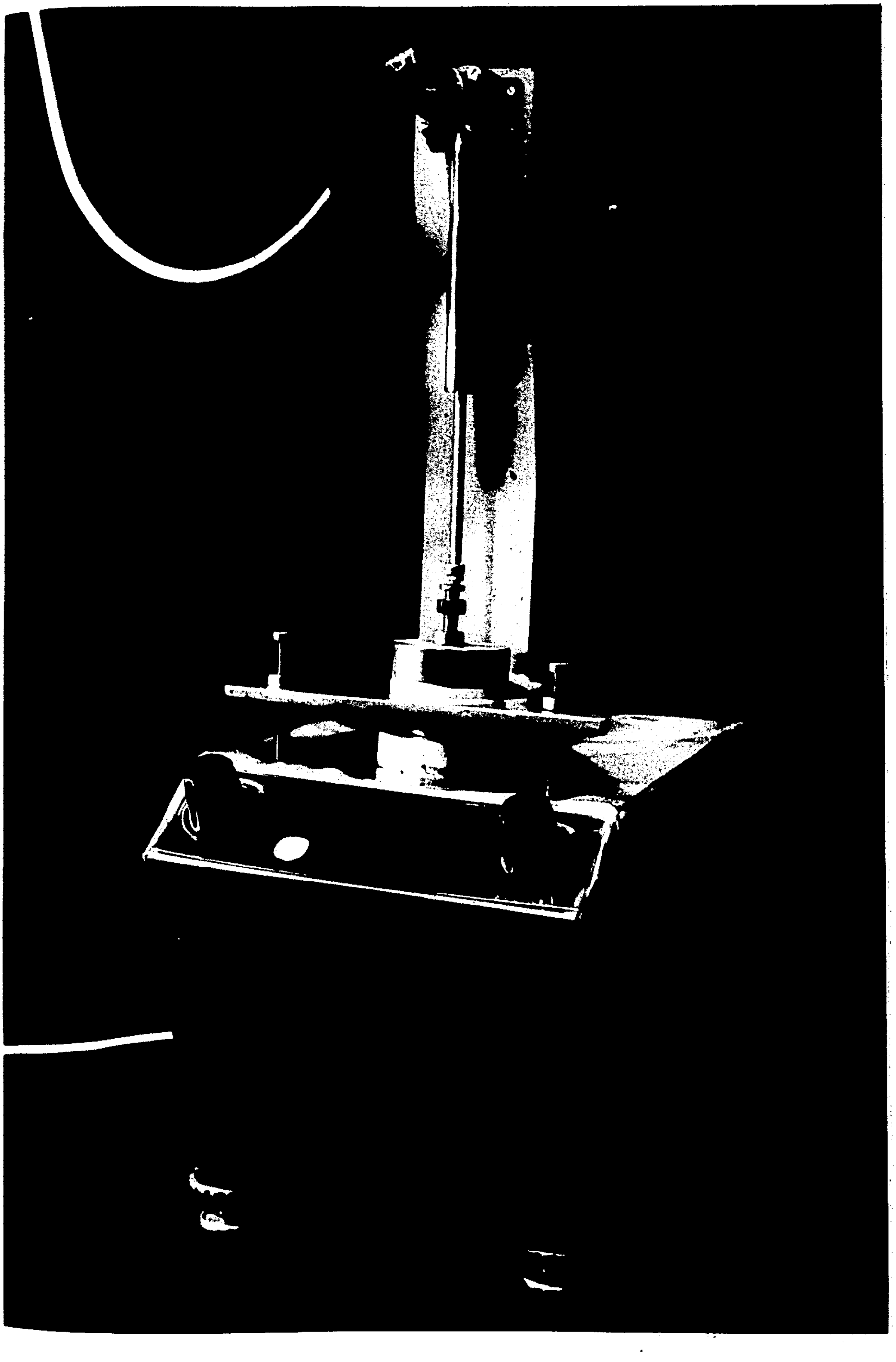
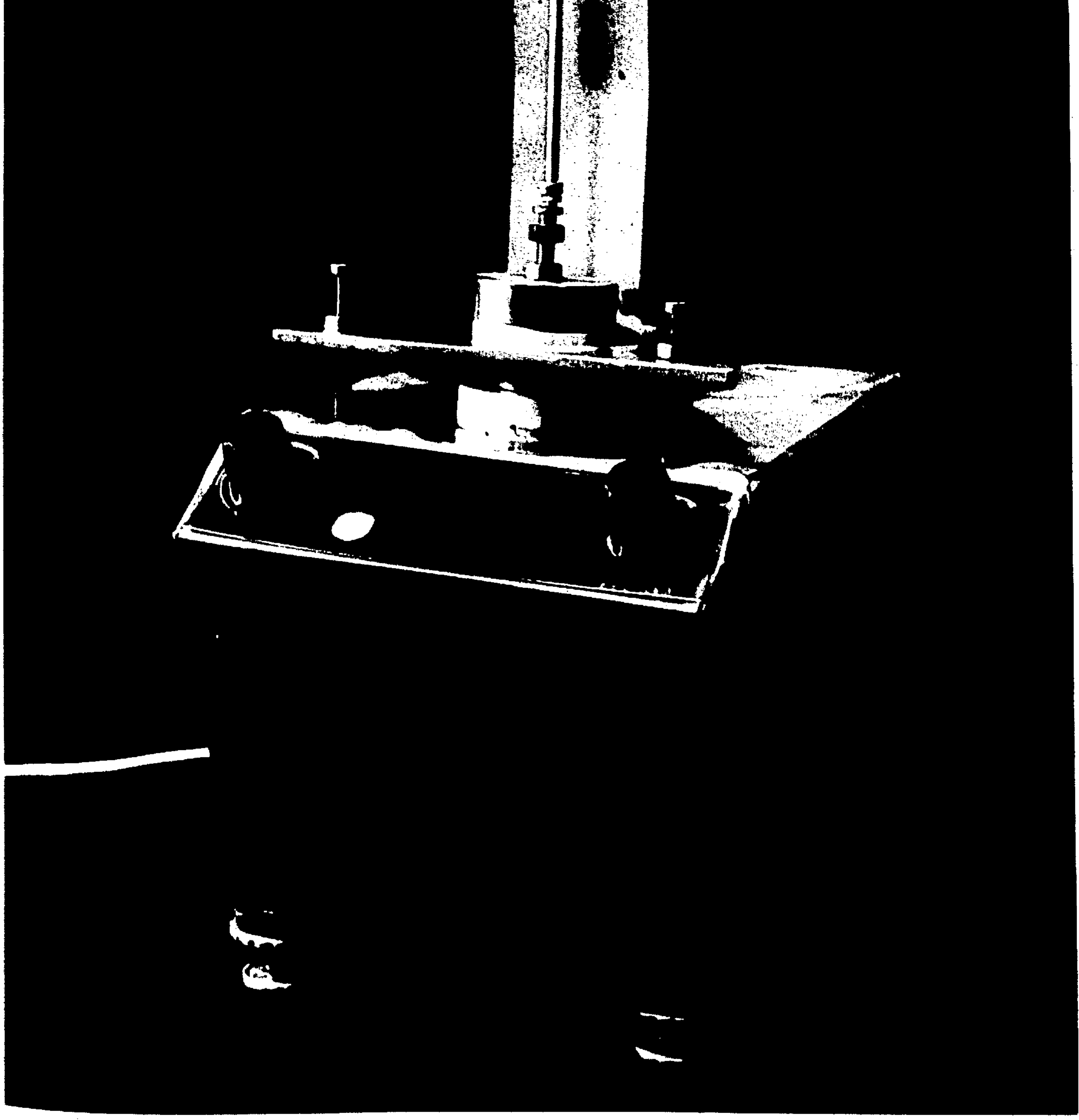


Fig.3.1. Medium Temperature Rig

Fig.3.2. Balance System on Medium Temperature Rig





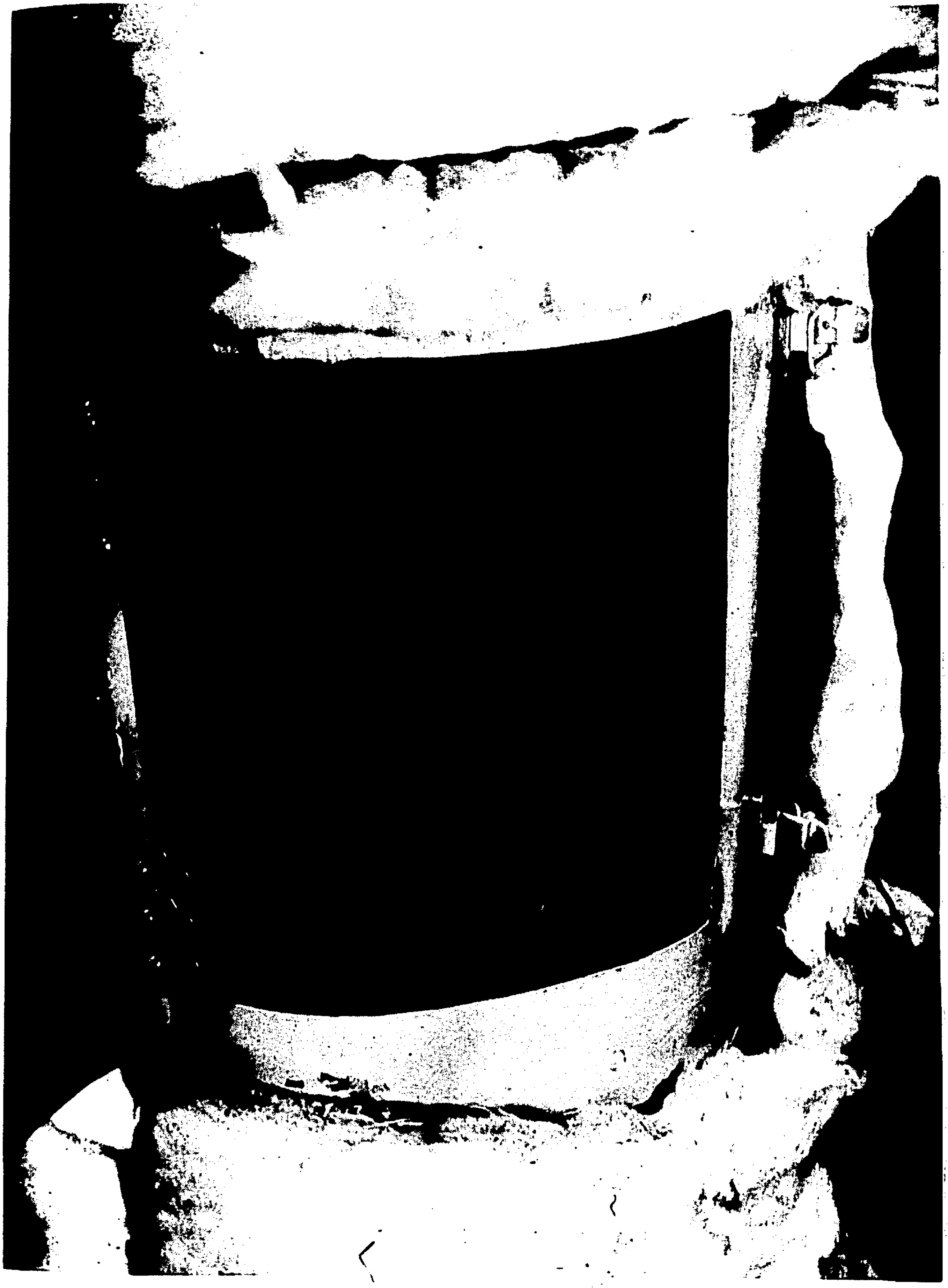


Fig.3.3. Medium Temperature Rig - Drying Tray in position

FIG.3.4

CALIBRATION CHART FOR
BALANCE ON
MEDIUM TEMPERATURE RIG

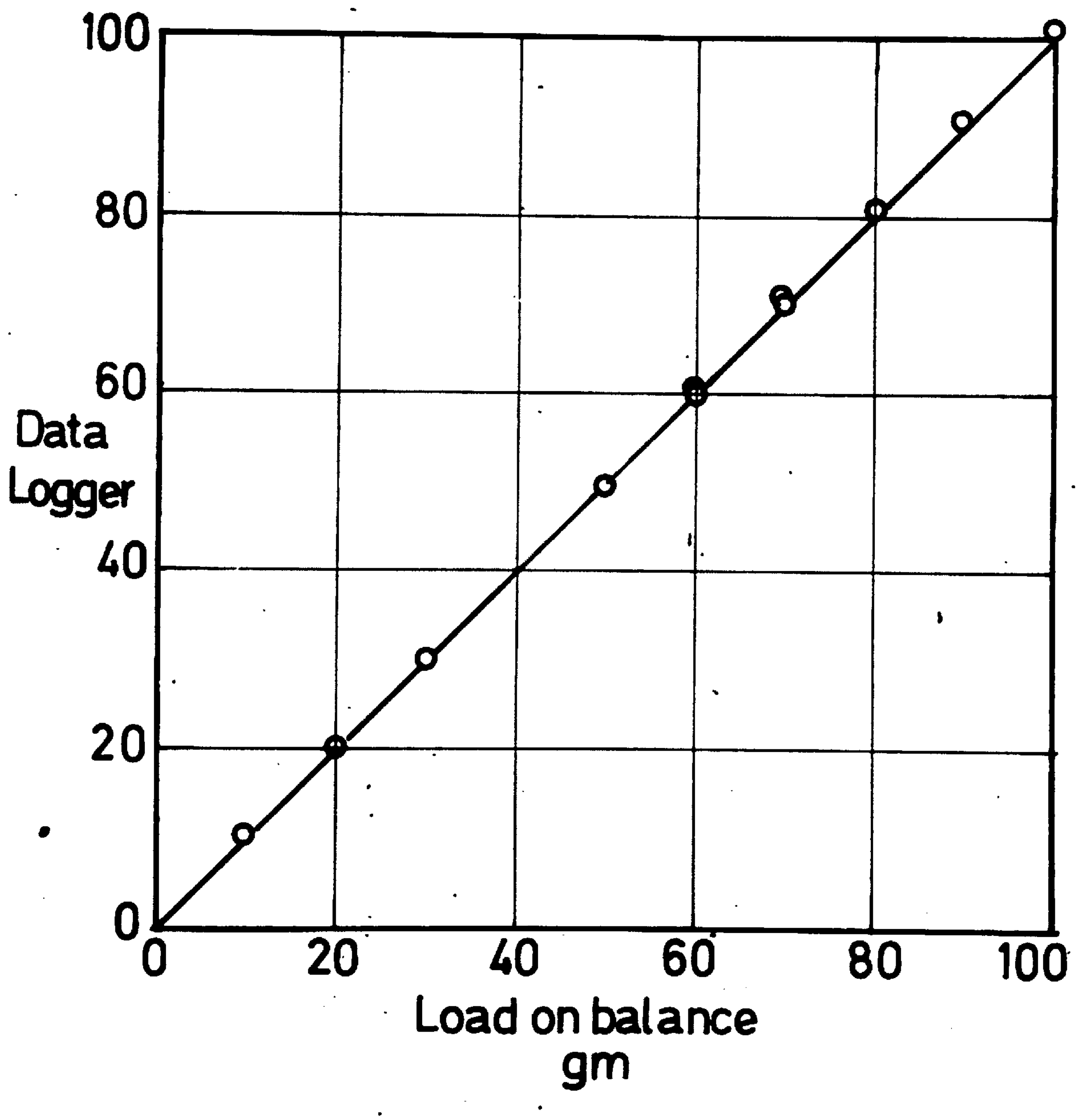


Fig.3.5. High Temperature Rig

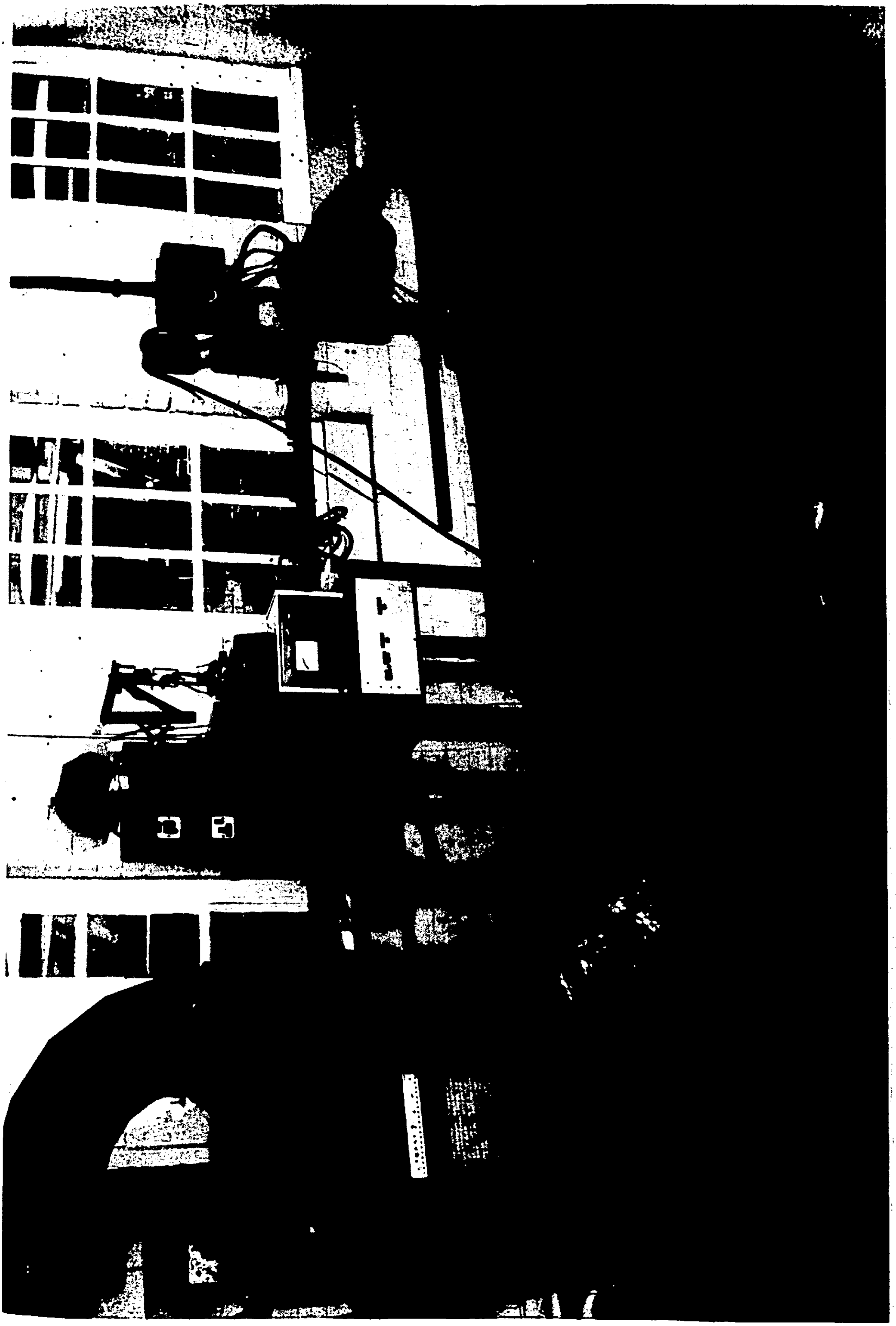


Fig.3.6. High Temperature Rig - Drying Chamber located in Duct

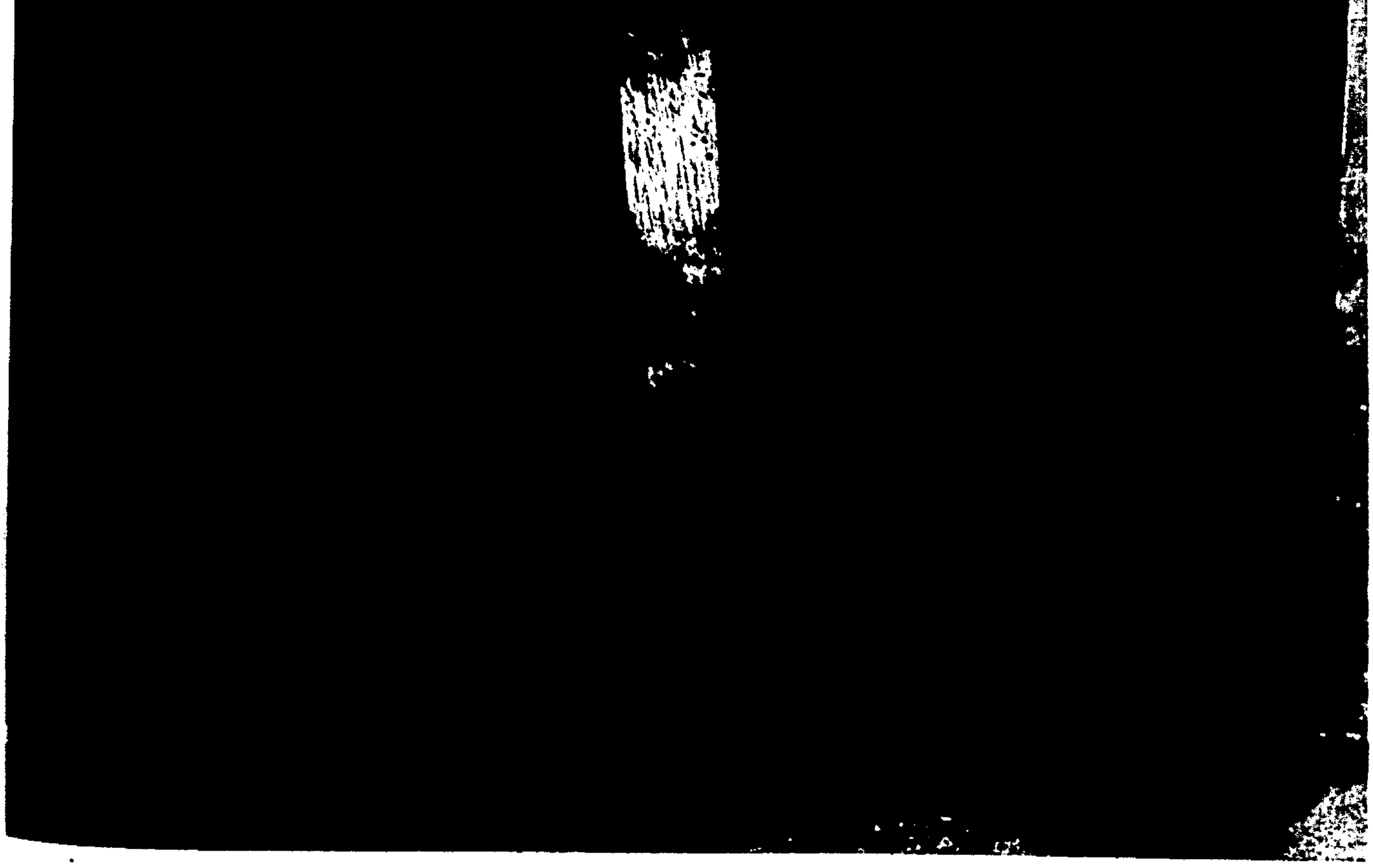


Fig.3.6. High Temperature Rig - Drying Chamber located in Duct

Fig.3.7. High Temperature Rig - Drying Chamber and Container

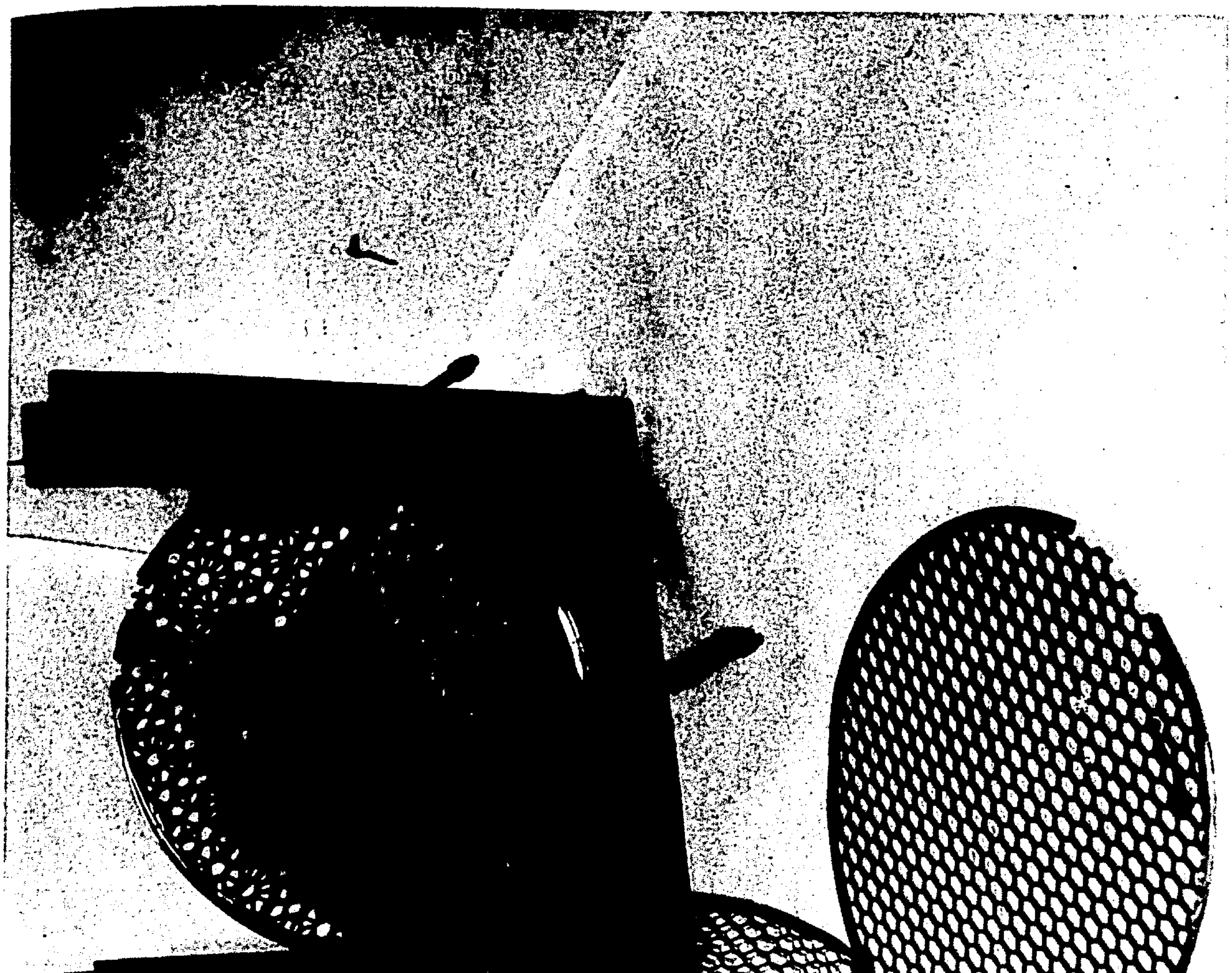


Fig.3.7. High Temperature Rig - Drying Chamber and Container

Fig.3.8. High Temperature Rig - Balance System

FIG. 39

TEMPERATURE PROFILE
IN
HIGH TEMPERATURE RIG

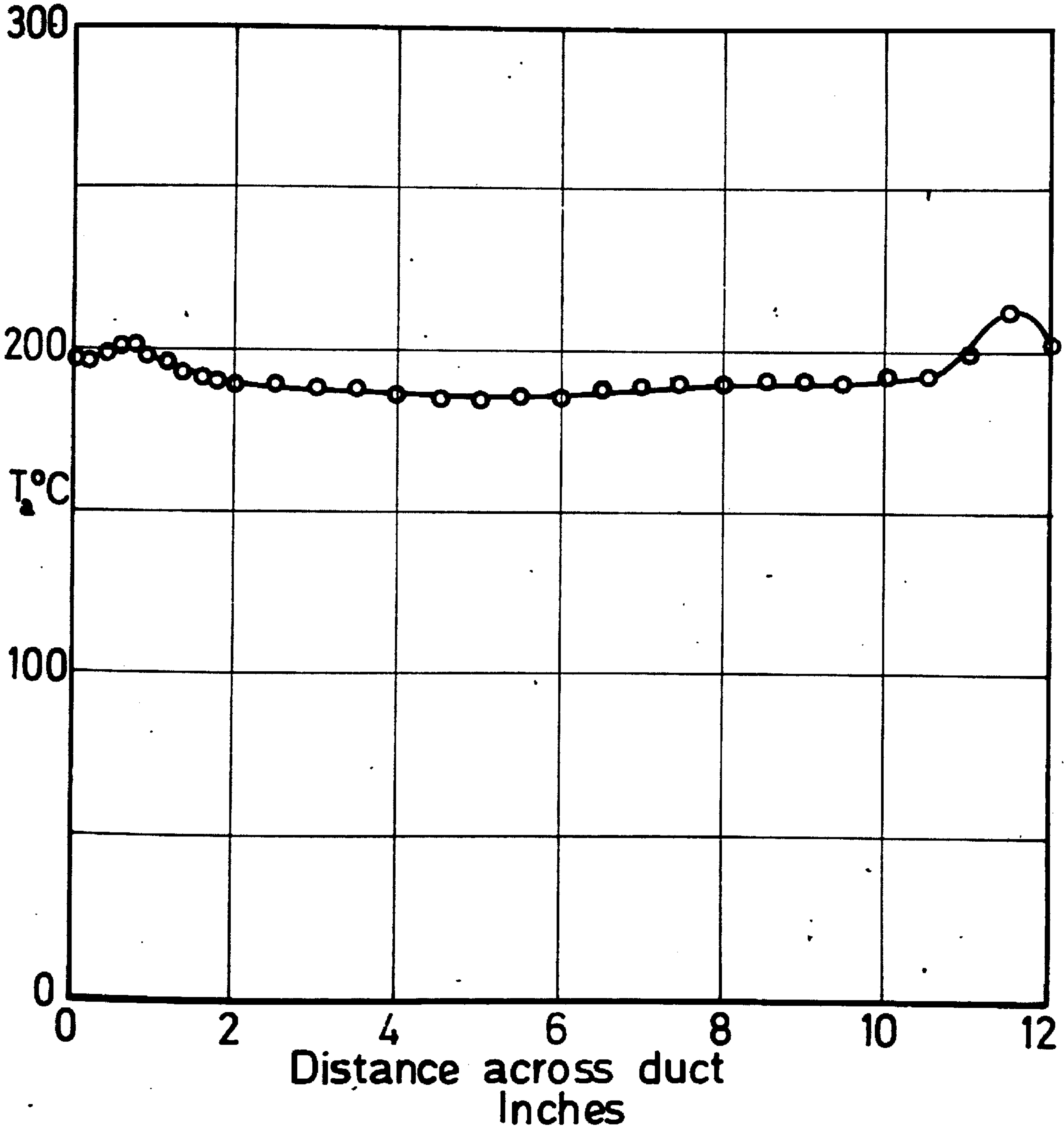


Fig.3.8. High Temperature Rig - Balance System

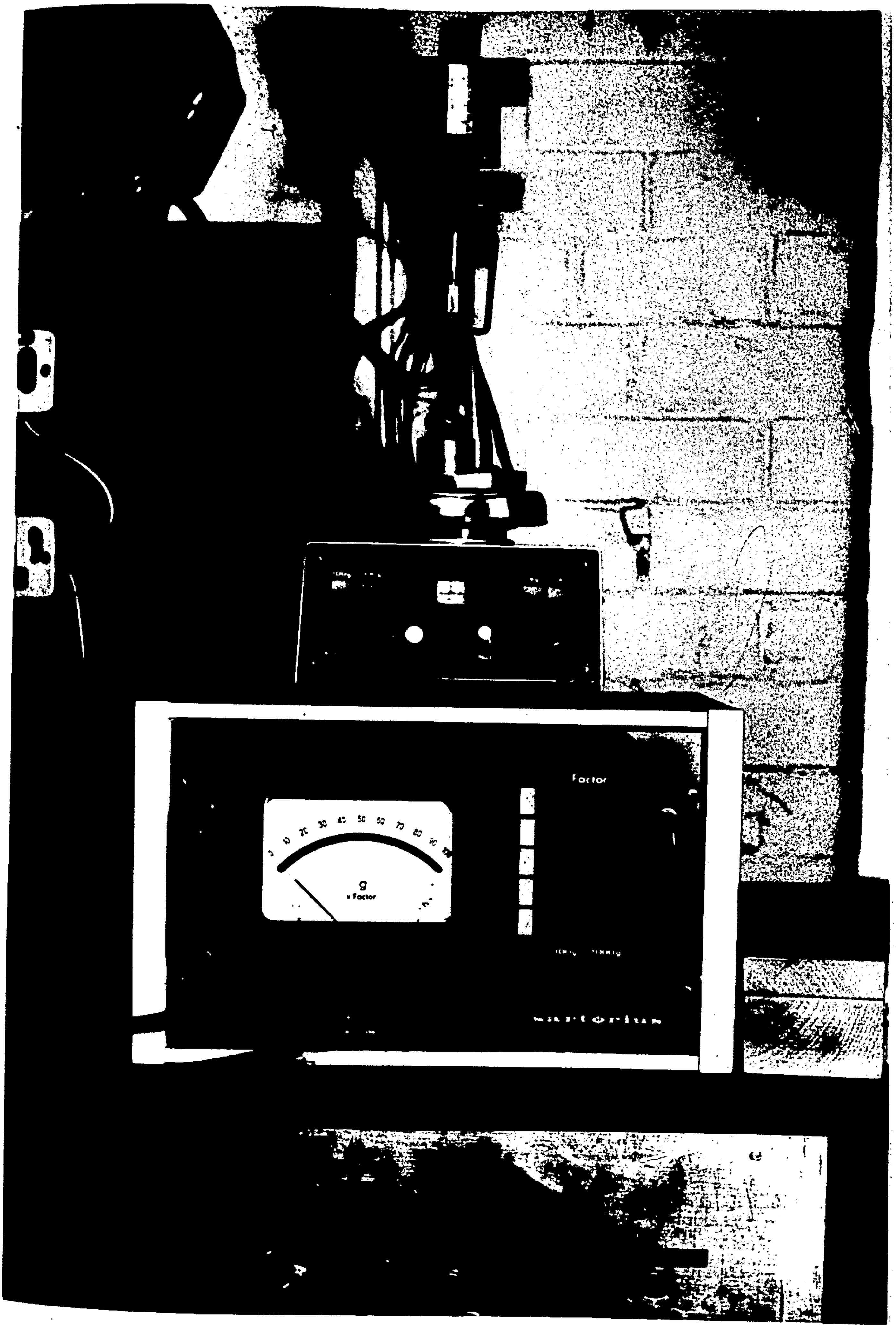


FIG. 39
TEMPERATURE PROFILE IN HIGH TEMPERATURE RIG

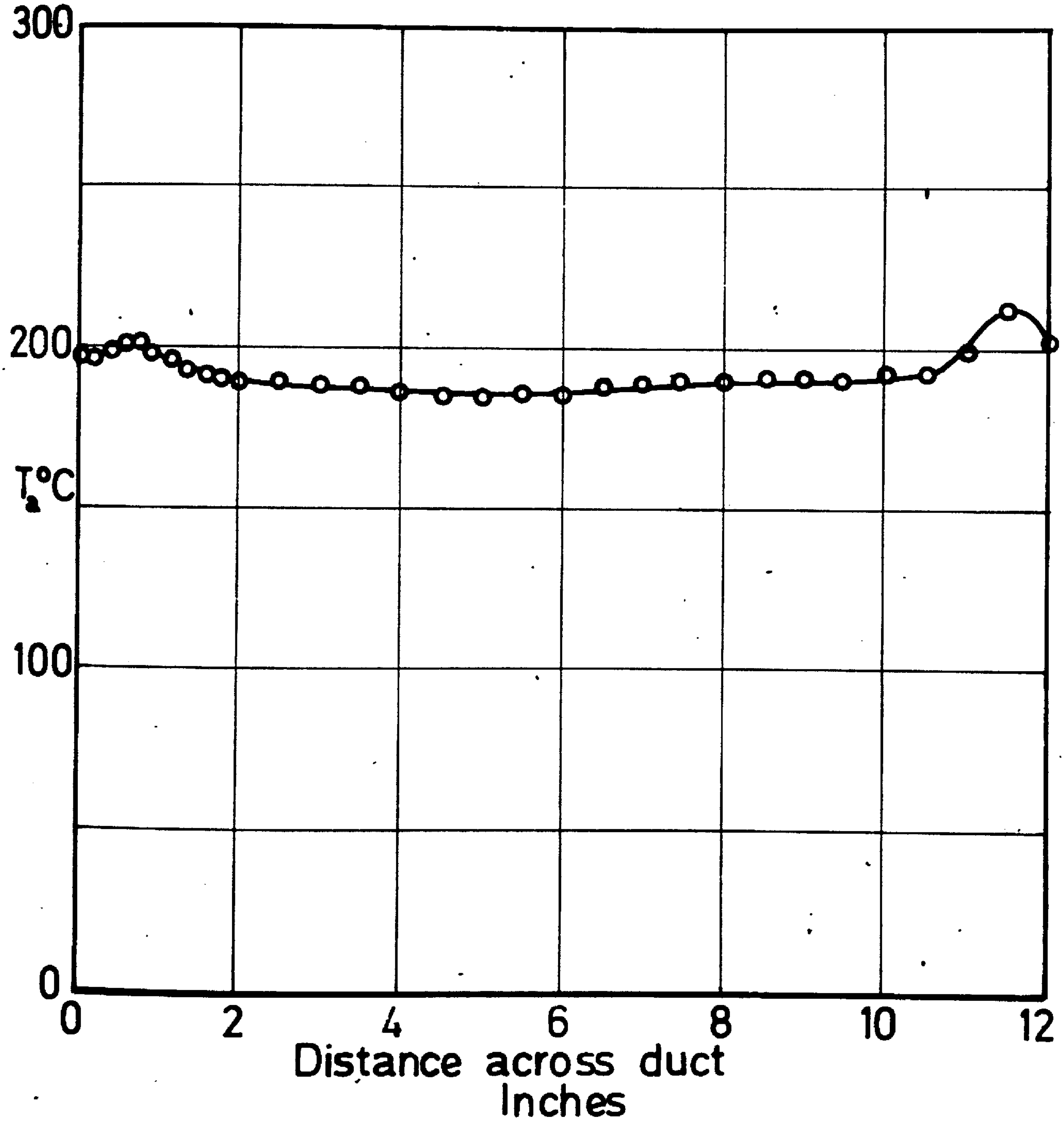
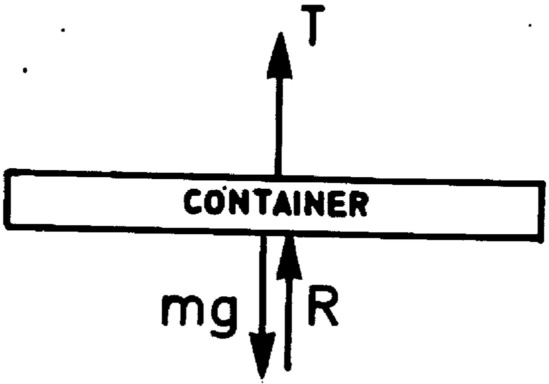
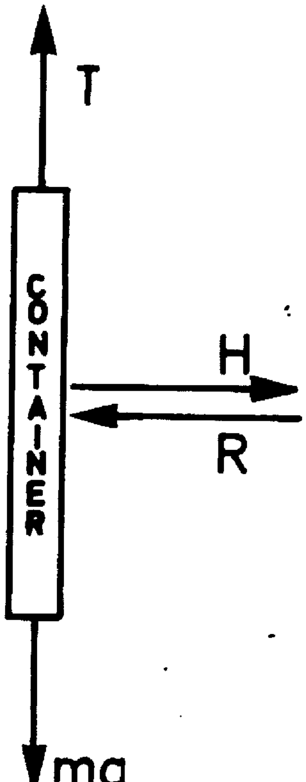


FIG.3.10
FREE-BODY DIAGRAMS
OF
WEIGHING SYSTEMS



LOW & MED. TEMP. RIGS

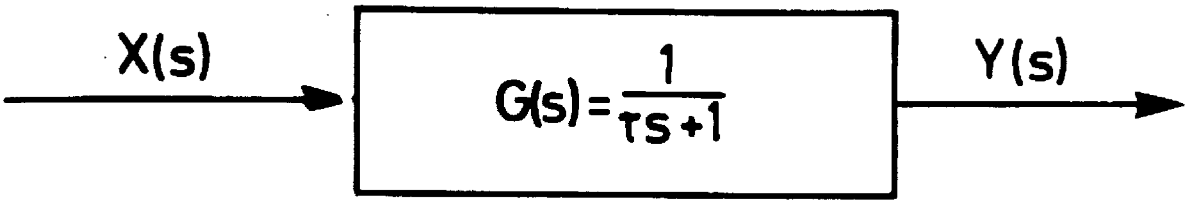
T = Force on balance
R = Force exertded by air
m = Mass of grass and container
g = Acceleration due to gravity
H = Force exerted by restrainers



HIGH TEMP. RIG

FIG.3.11

FIRST AND SECOND ORDER SYSTEMS



First order system

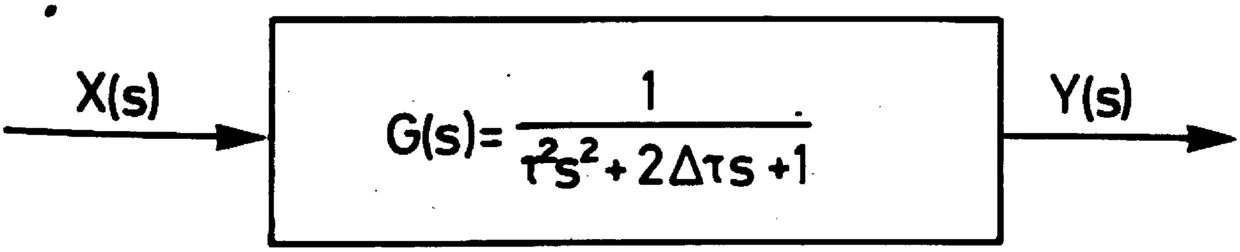
$G(s)$ = System Transfer Function

τ = Time Constant of System

$X(s)$ = Input to System

$Y(s)$ = Response from System

Δ = Damping Ratio =1 for critically damped system



Second order system

FIG.3.12.

SECOND ORDER SYSTEM EQUATION FITTED TO DATA

$\tau = 0.3$ sec $\Delta = 1$

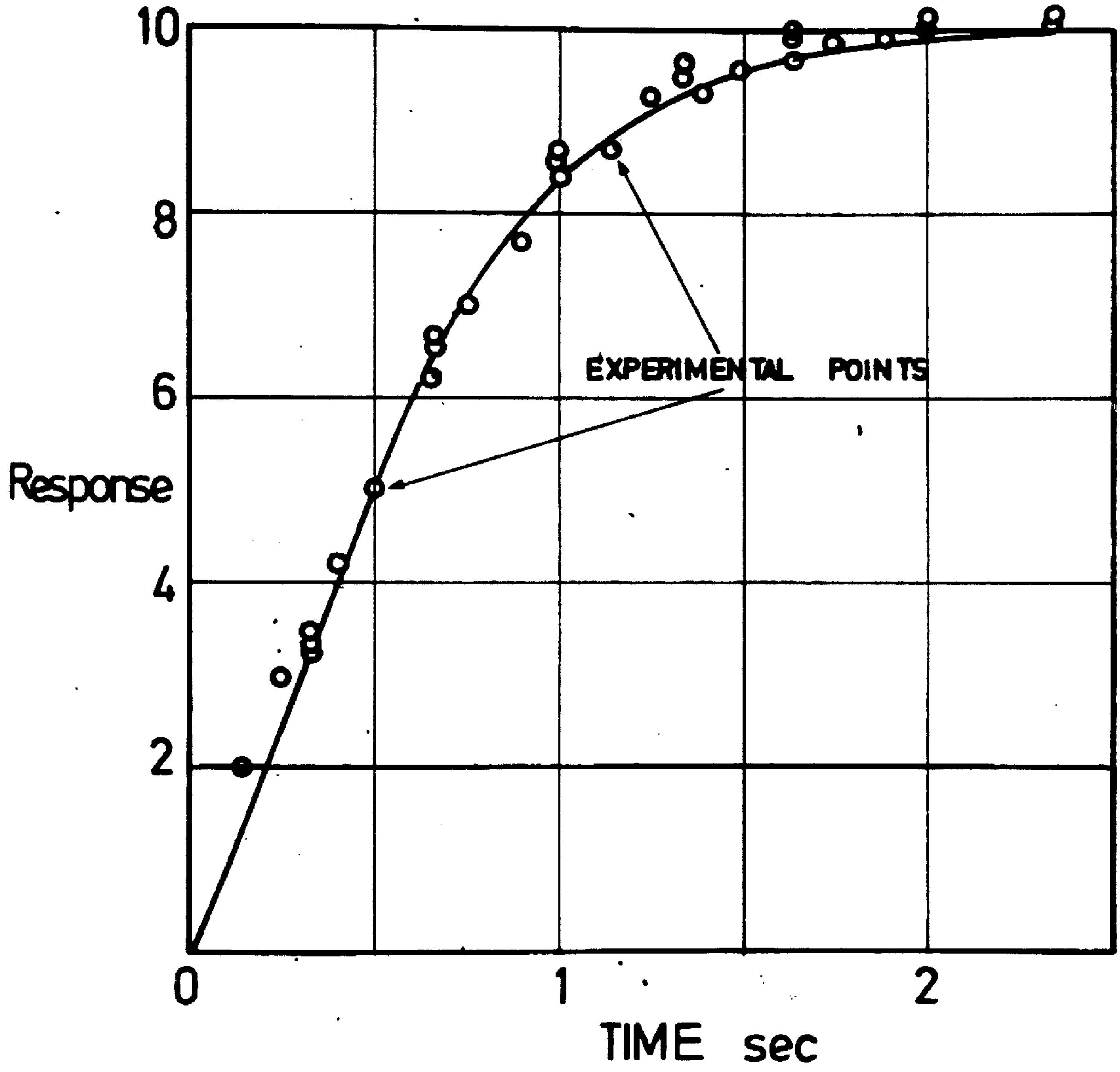


FIG. 3.13 RESPONSE OF SECOND ORDER SYSTEM TO EXPONENTIAL INPUT

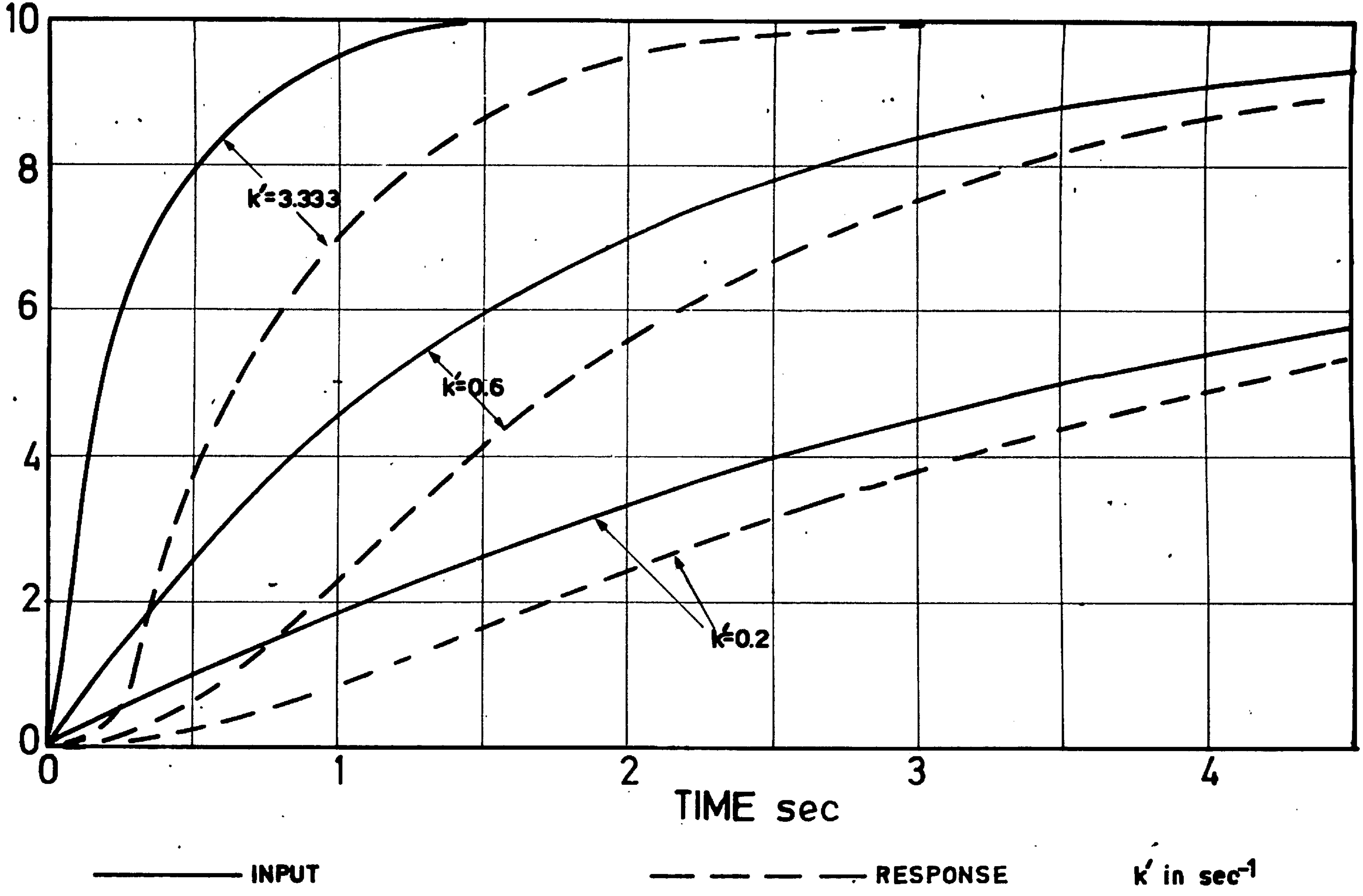


FIG.3.14. RESPONSE OF SECOND ORDER SYSTEM TO EXPONENTIAL INPUT

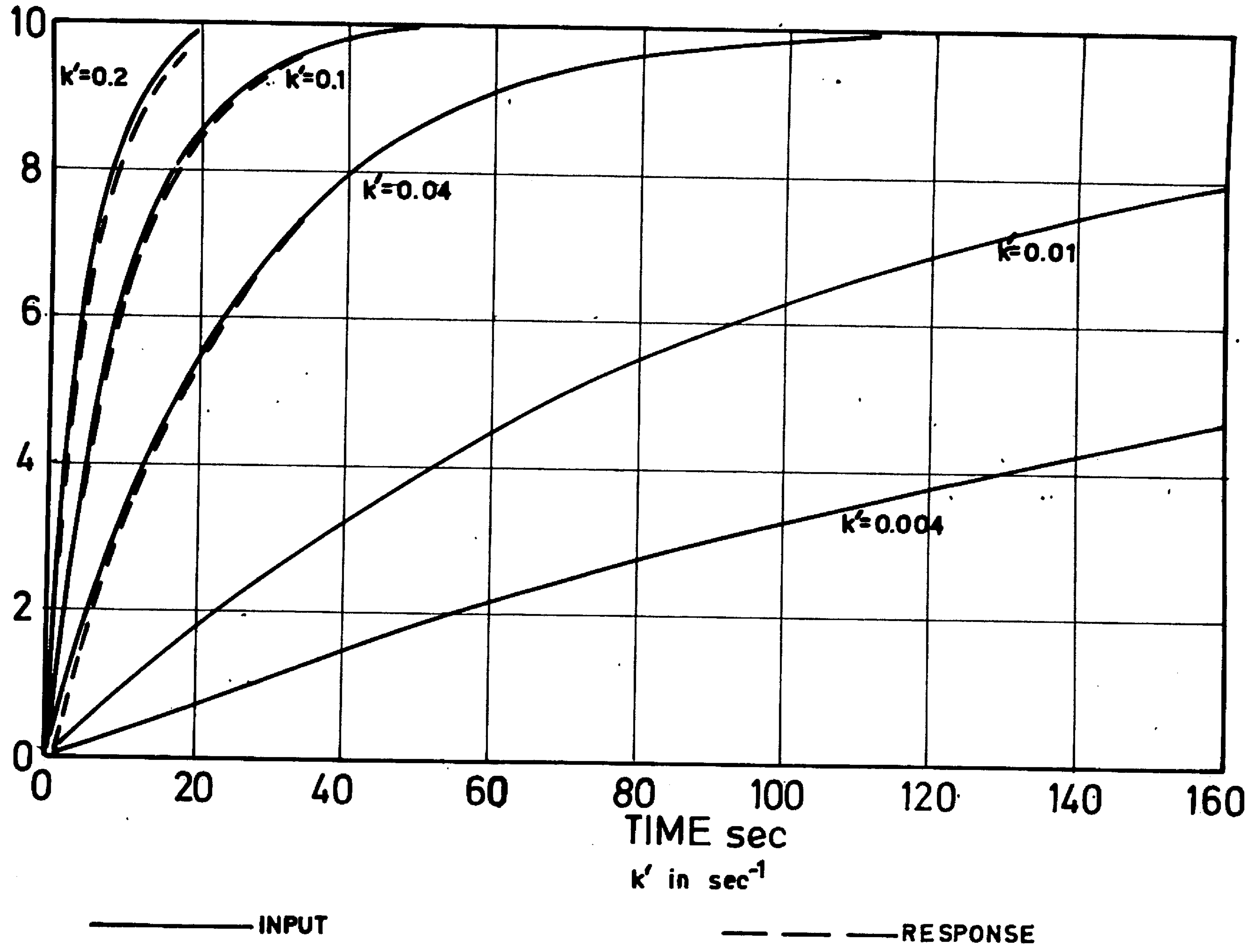


FIG. 3.15.

TEMPERATURES IN LOW TEMP. RIG

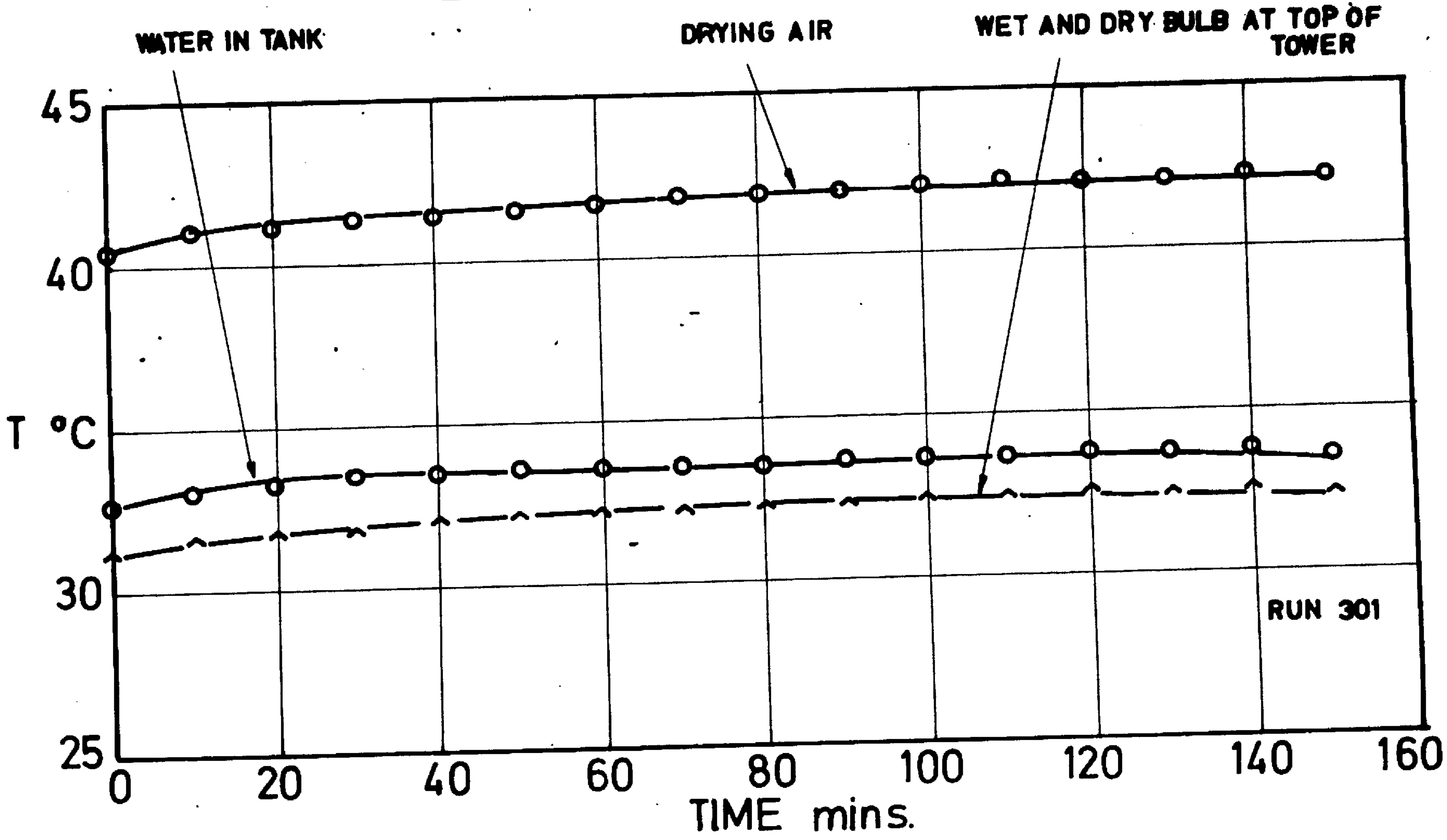


FIG. 4.1 PLOT OF LEAF TO STEM RATIO l_s VS. TIME OF REGROWTH

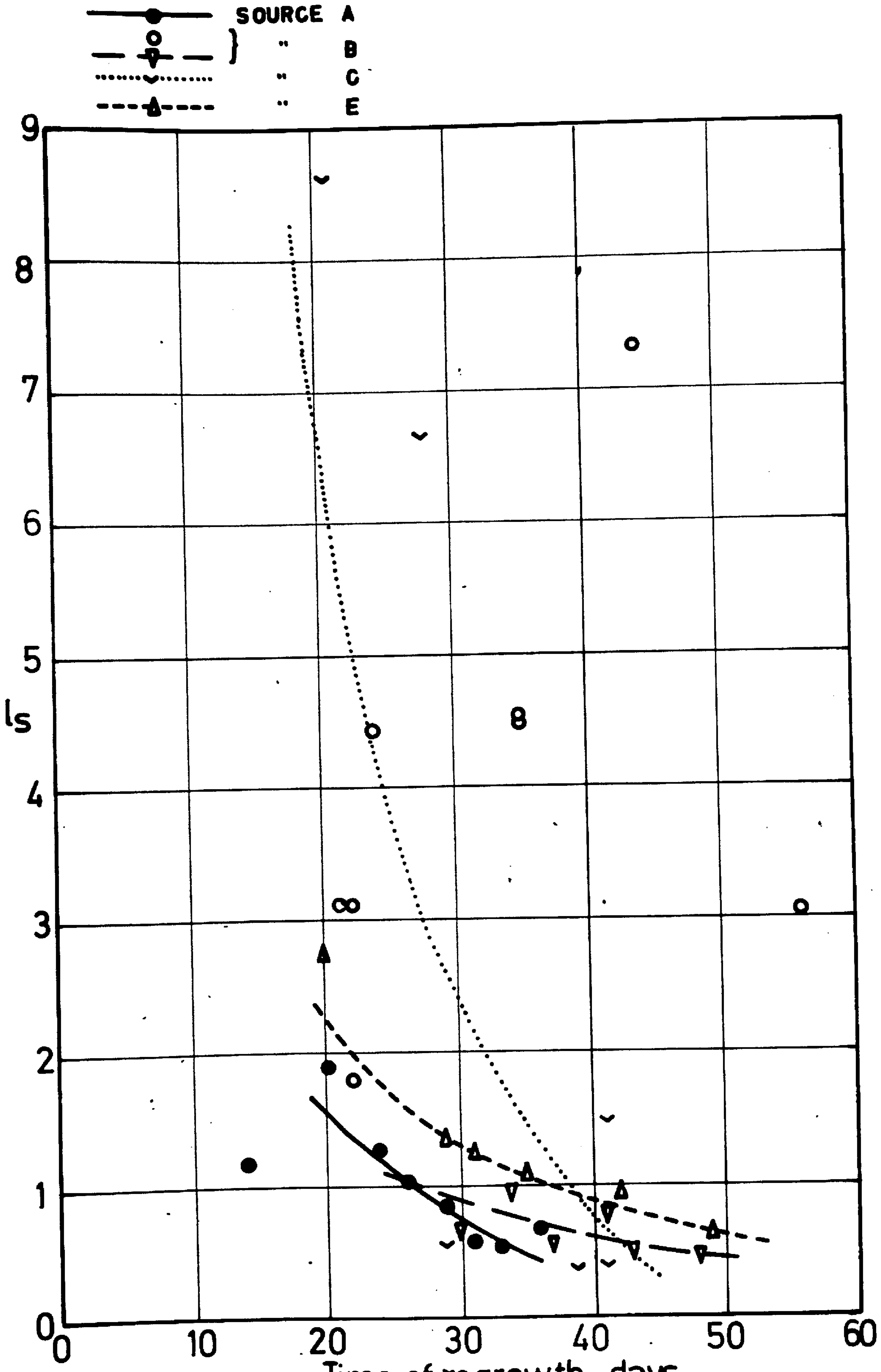


FIG.4.2. Sample Data Sheet

DEPARTMENT OF AGRICULTURAL ENGINEERING.

GRASS DRYING DATA. **RUN NO.** 89

DATE	GRASS SPECIES	GRASS BATCH	GRASS CHOP LENGTH	DATE OF CUT
13.8.1968	Italian Rye	13	6 in.	13.8.1968

AIRFLOW	ΔP	ORIFICE D	PIPE D
34 c.f.m.	1.85 in.wg.	$1\frac{3}{8}$ in.	6 in.

APPROX AIR TEMP	APPROX REL.HUM.	APPROX DEW POINT	SCAN TYPE
130 °C	— %	— °C	S [✓ SS]

START TIME	FINISH TIME	RUN TIME	SCALE FACTOR.	SCAN TIME
1400	1430	25	0.1	6 /min 3 /min 1 /min

RIG
MTR

TEMPS (°C)

	1.	2.	3.	4.
START	18.7	17.5	15.2	128.0
FINISH	19.3	18.3	15.8	130.2

INITIAL WEIGHT	FINAL WEIGHT	INITIAL M.C.D.B.	FINAL M.C.D.B.	TARE
66.6	19.0	4.3778	0.0273	8.1 gm

FIG. 4.3

LOW TEMPERATURE RUNS

→ T_a °C ↓ rh %	20	40	60	80
10	▨	▨	315	303- 306
20	▨	314	302	309
40	313	310	308	▨
60	312	301	▨	▨
80	311	307	▨	▨

FIG.5.1

TYPICAL SCATTER PLOT OF MOISTURE CONTENT vs. TIME RUN 89

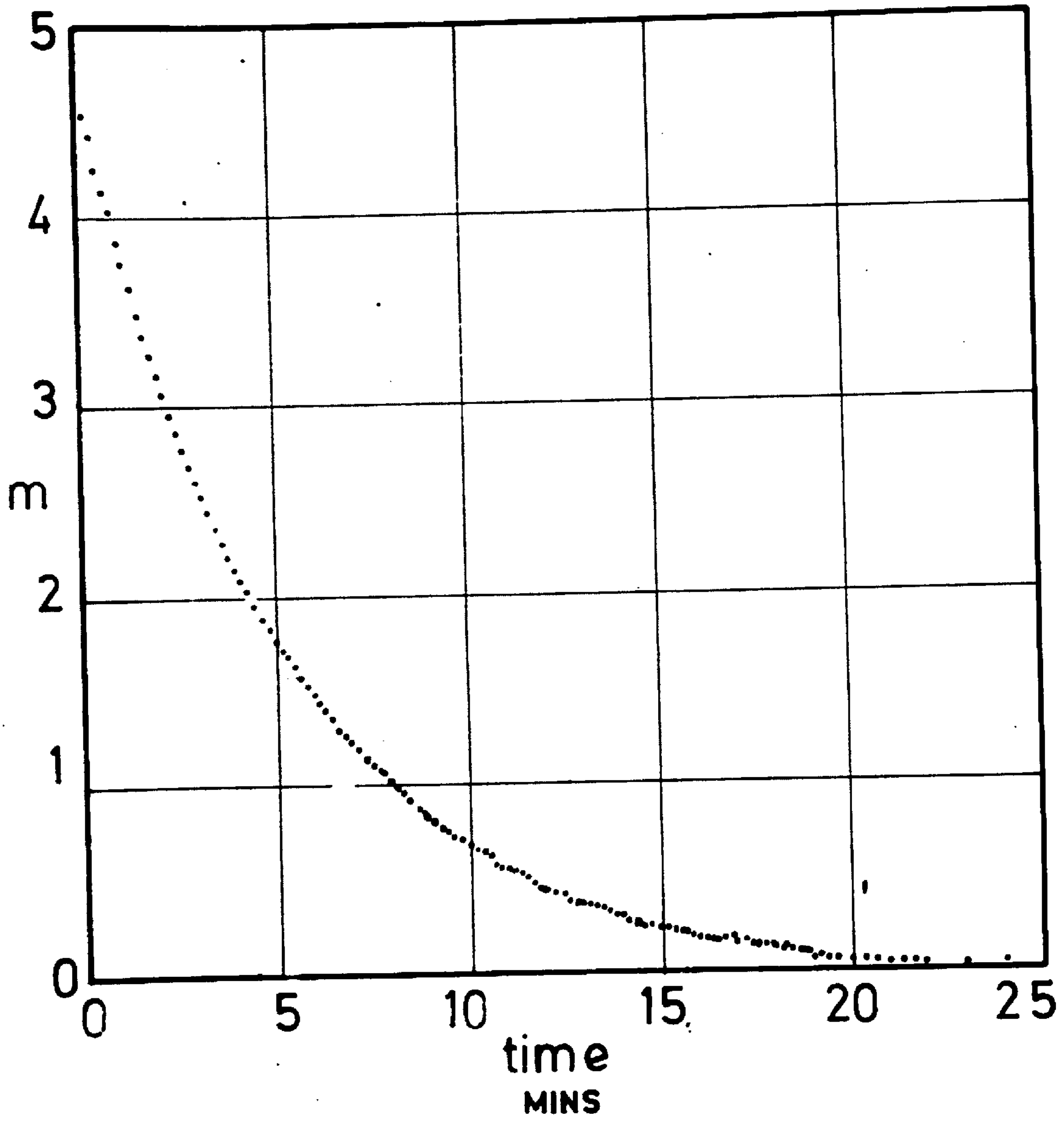


FIG.5.2

GRAPHICAL METHOD

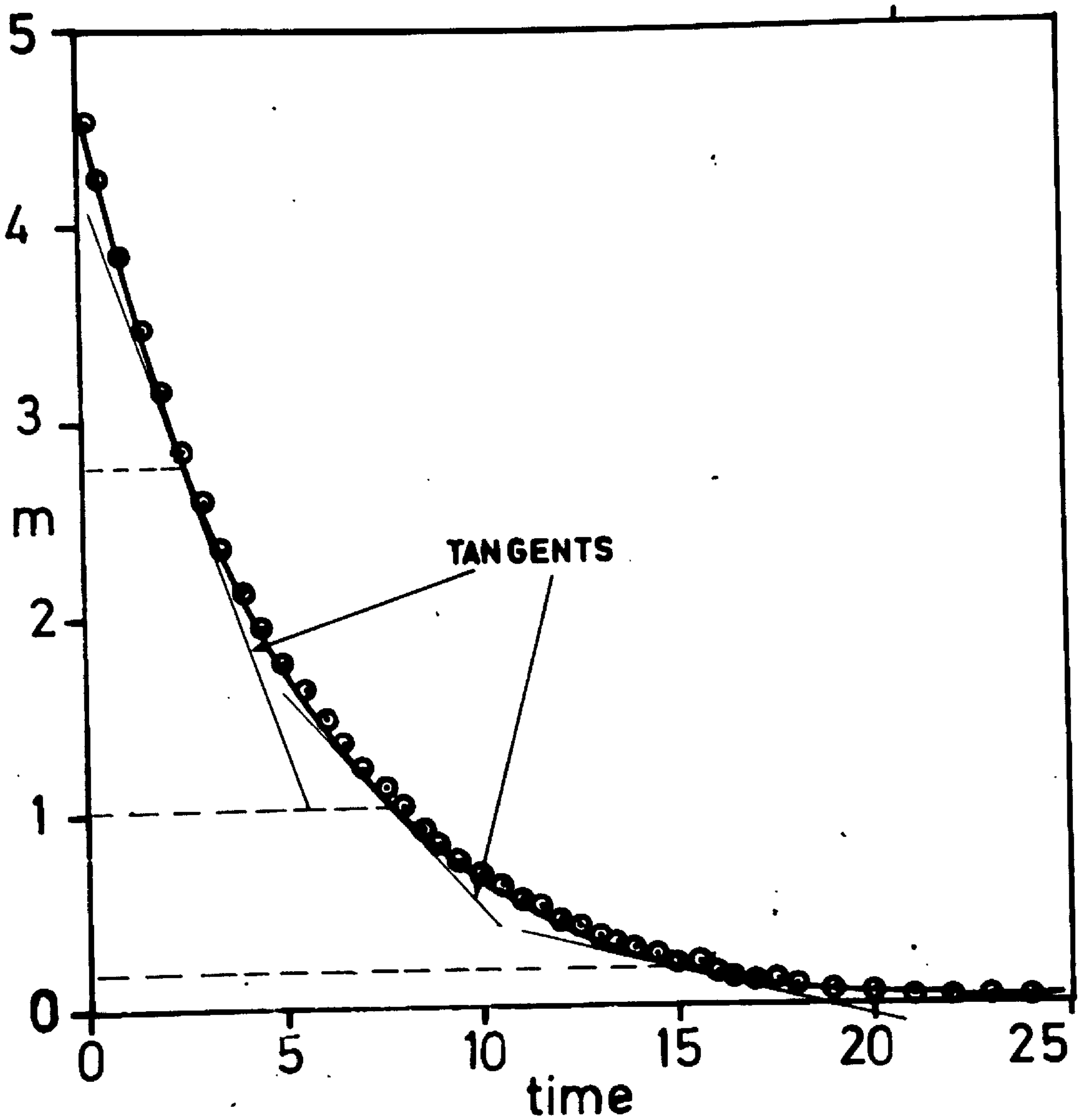


FIG.5.3

SEGMENTATION METHOD

ORIGINAL POINTS

NOT ALL POINTS SHOWN

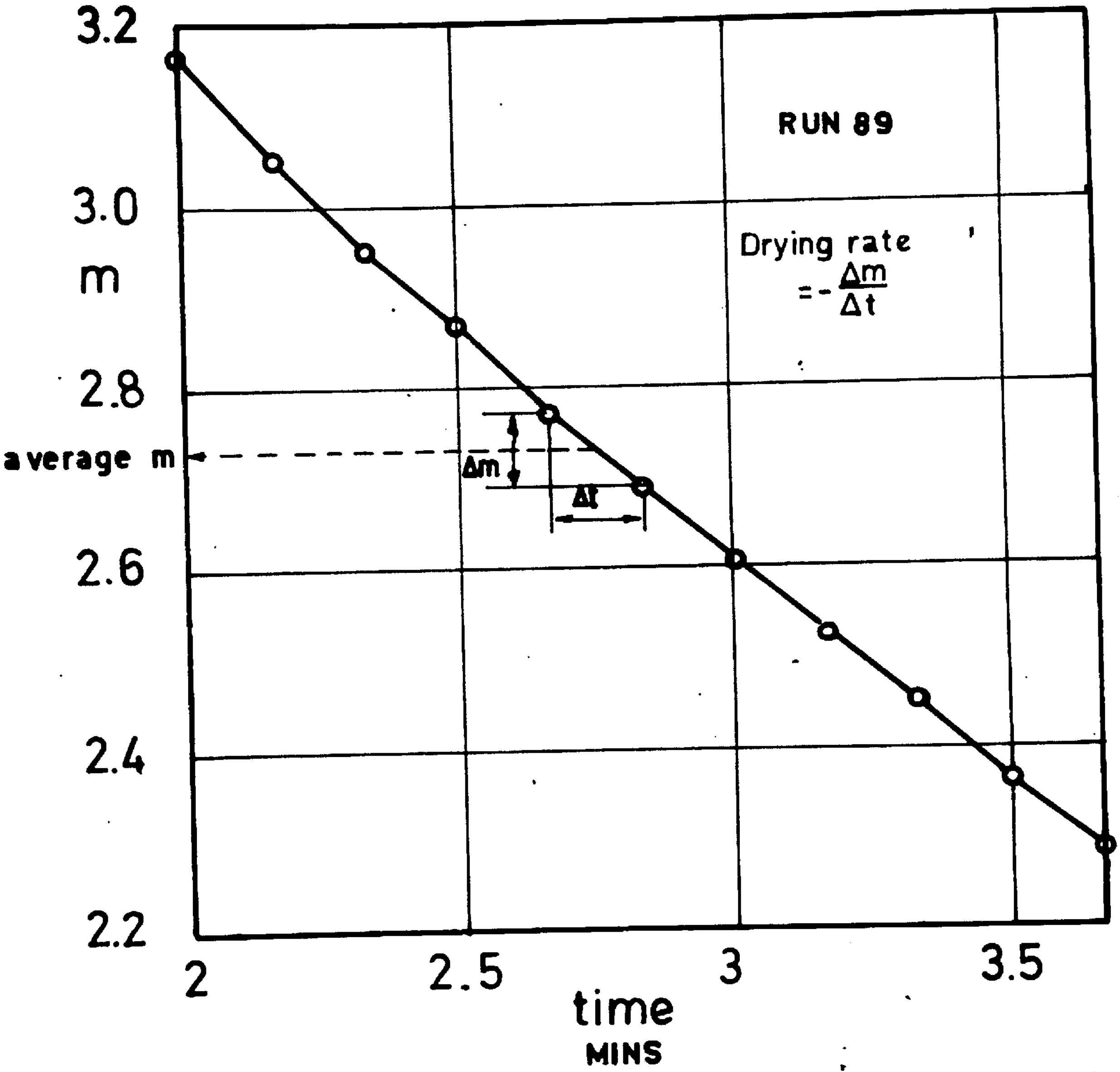


FIG.5.4. DRYING CURVE BY SEGMENTATION METHOD

RUN 89

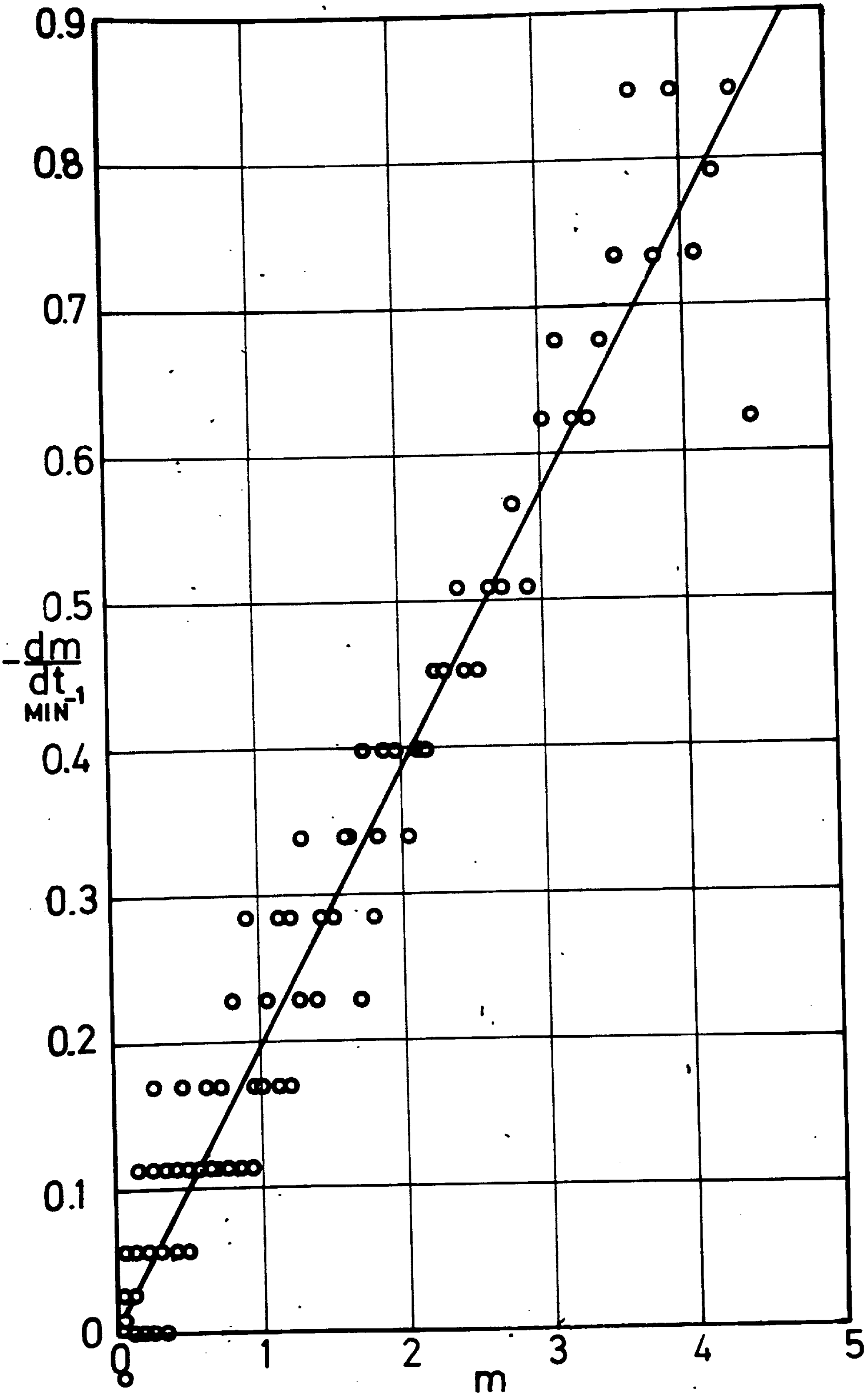


FIG.5.5.

PLOT OF $\frac{m - m_e}{m_o - m_e} = e^{-kt}$ FOR VALUES OF k and m_e obtained by SEGMENTATION METHOD

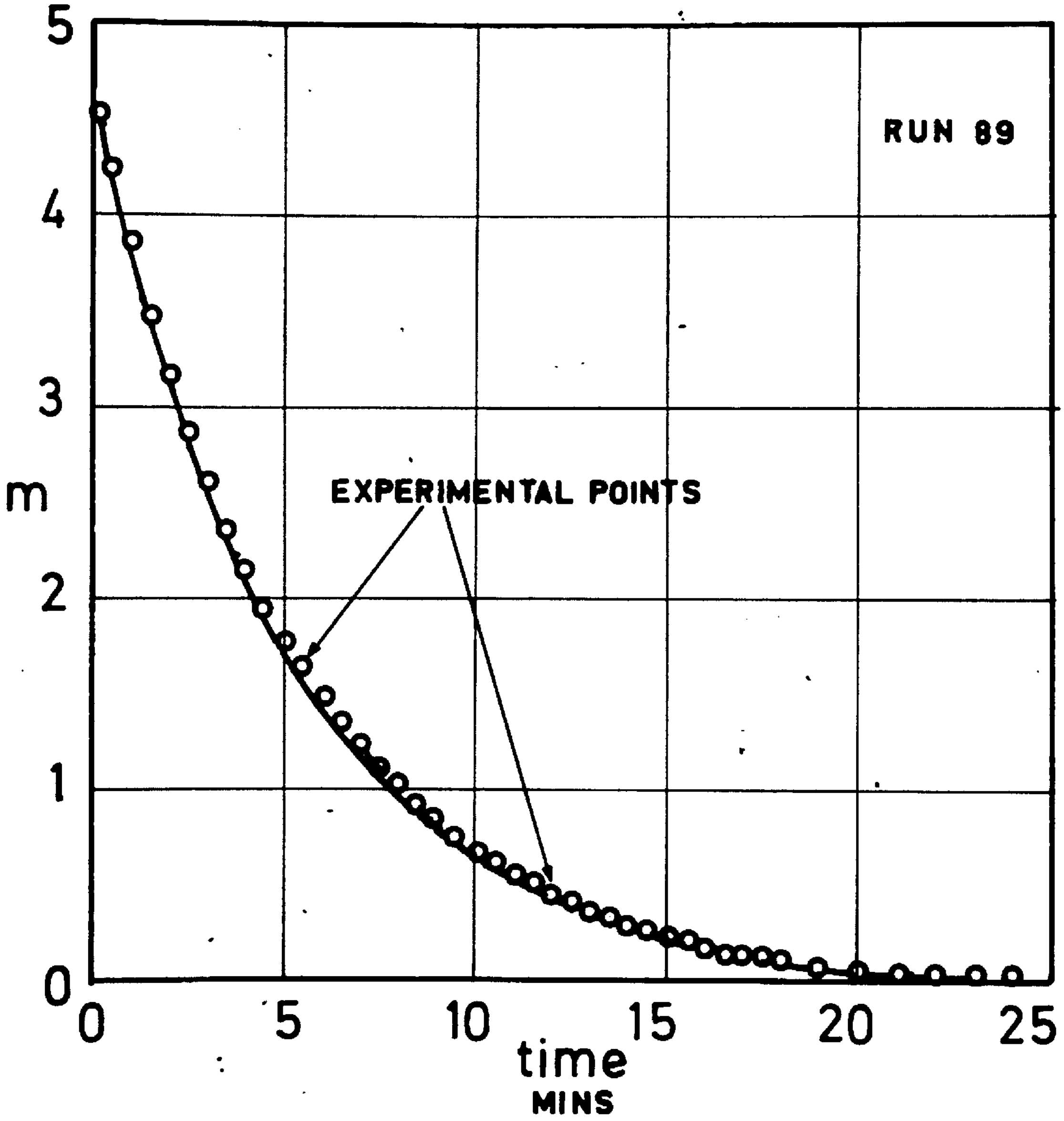


FIG. 5.6.

SEGMENTATION METHOD WITH GROUPED POINTS

RUN 89

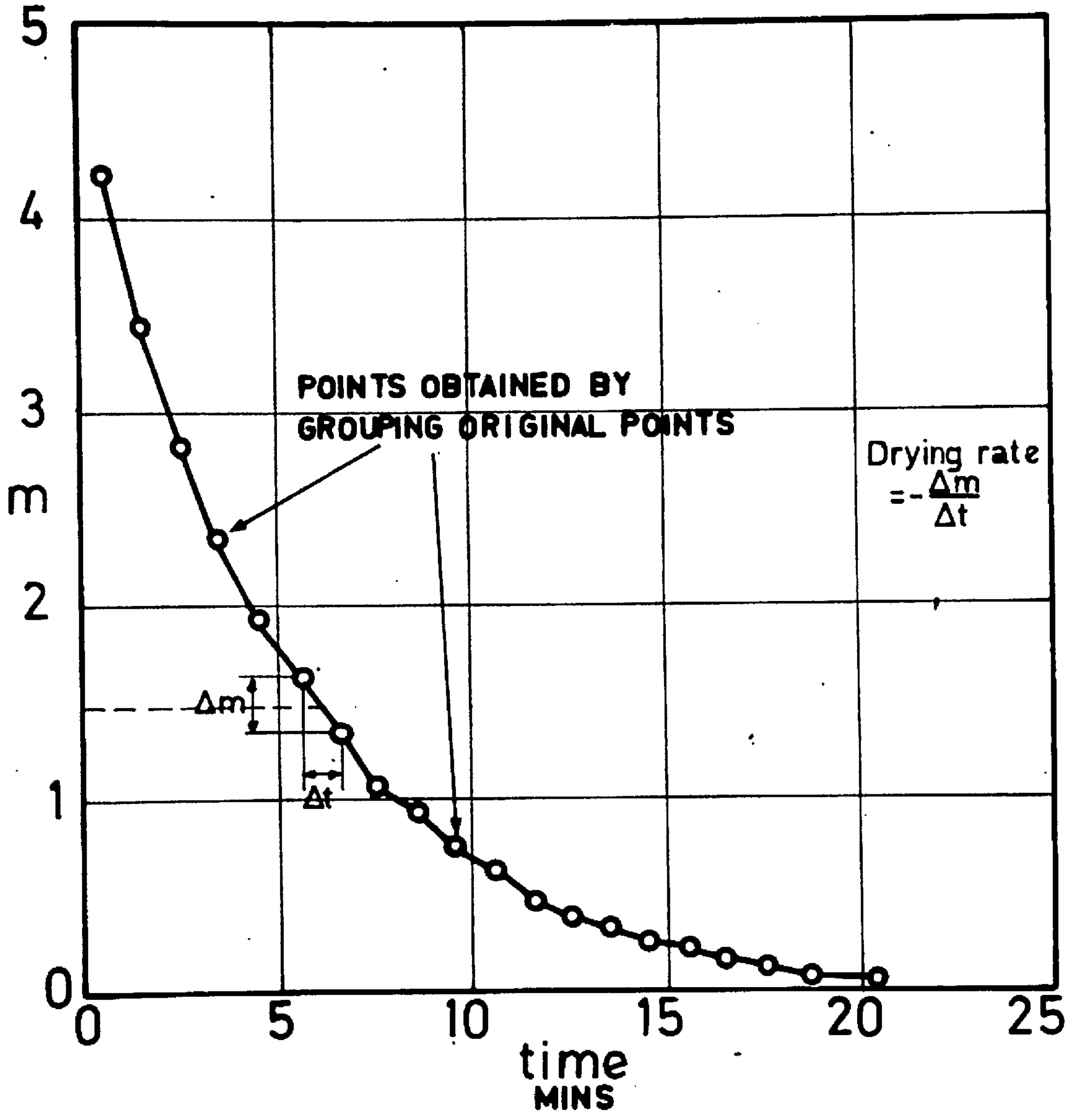


FIG.5.7. DRYING CURVE OBTAINED BY SEGMENTATION METHOD AFTER GROUPING

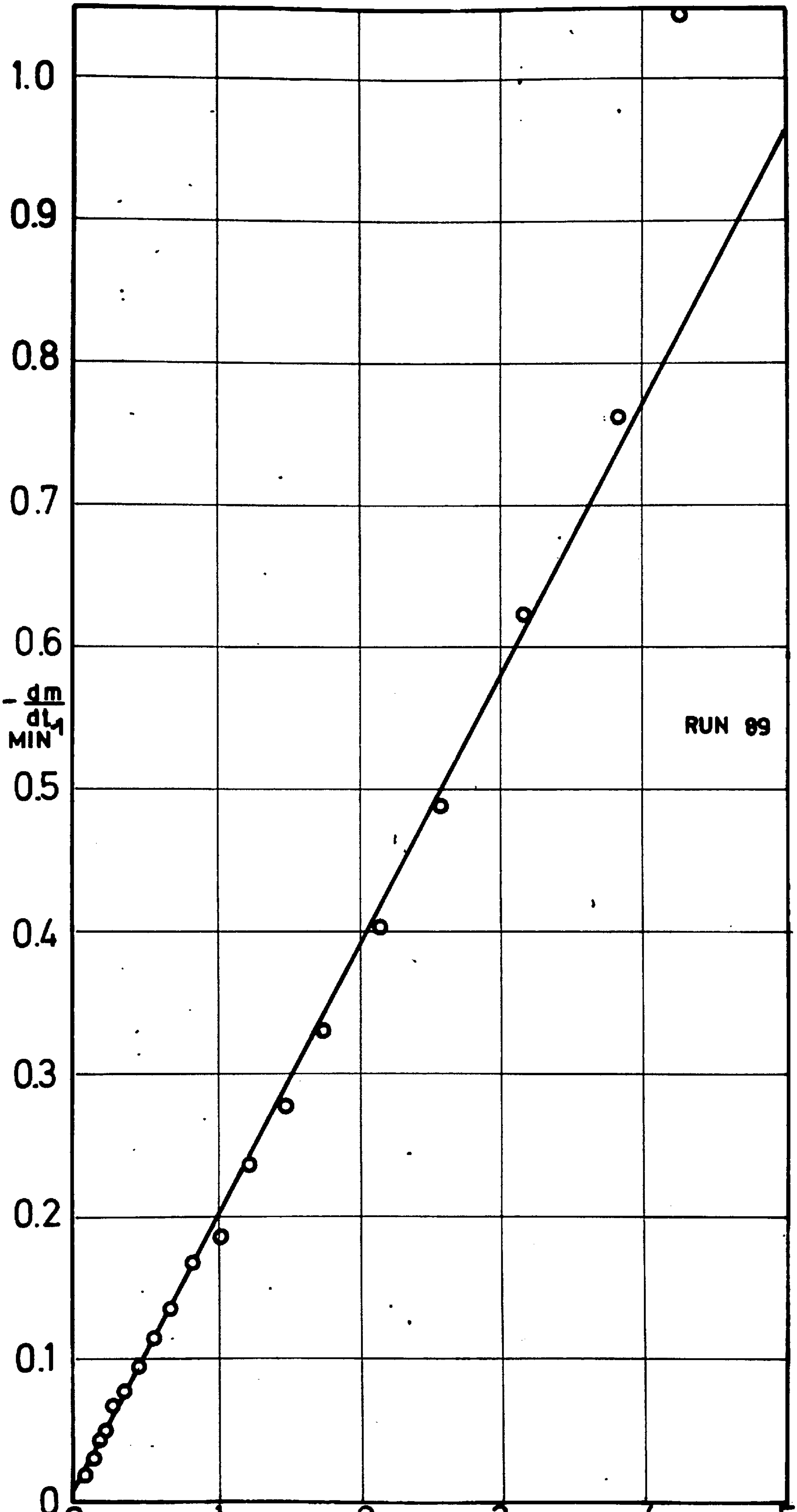


FIG.5.8.

EIGHTH ORDER POLYNOMIAL FITTED TO DATA OF RUN 89

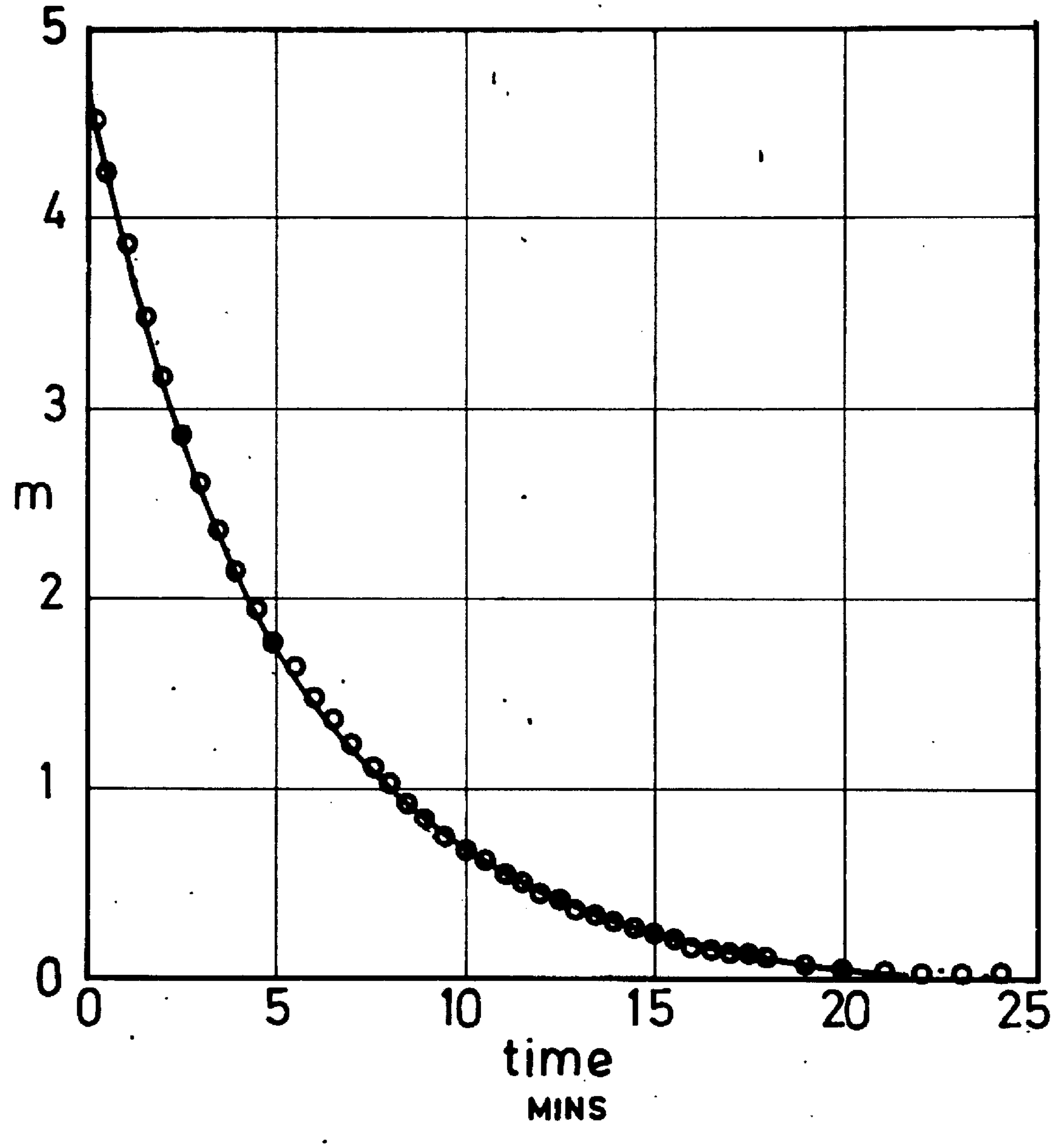


FIG.5.9. DRYING CURVE OBTAINED BY POLYNOMIAL METHOD

RUN 89

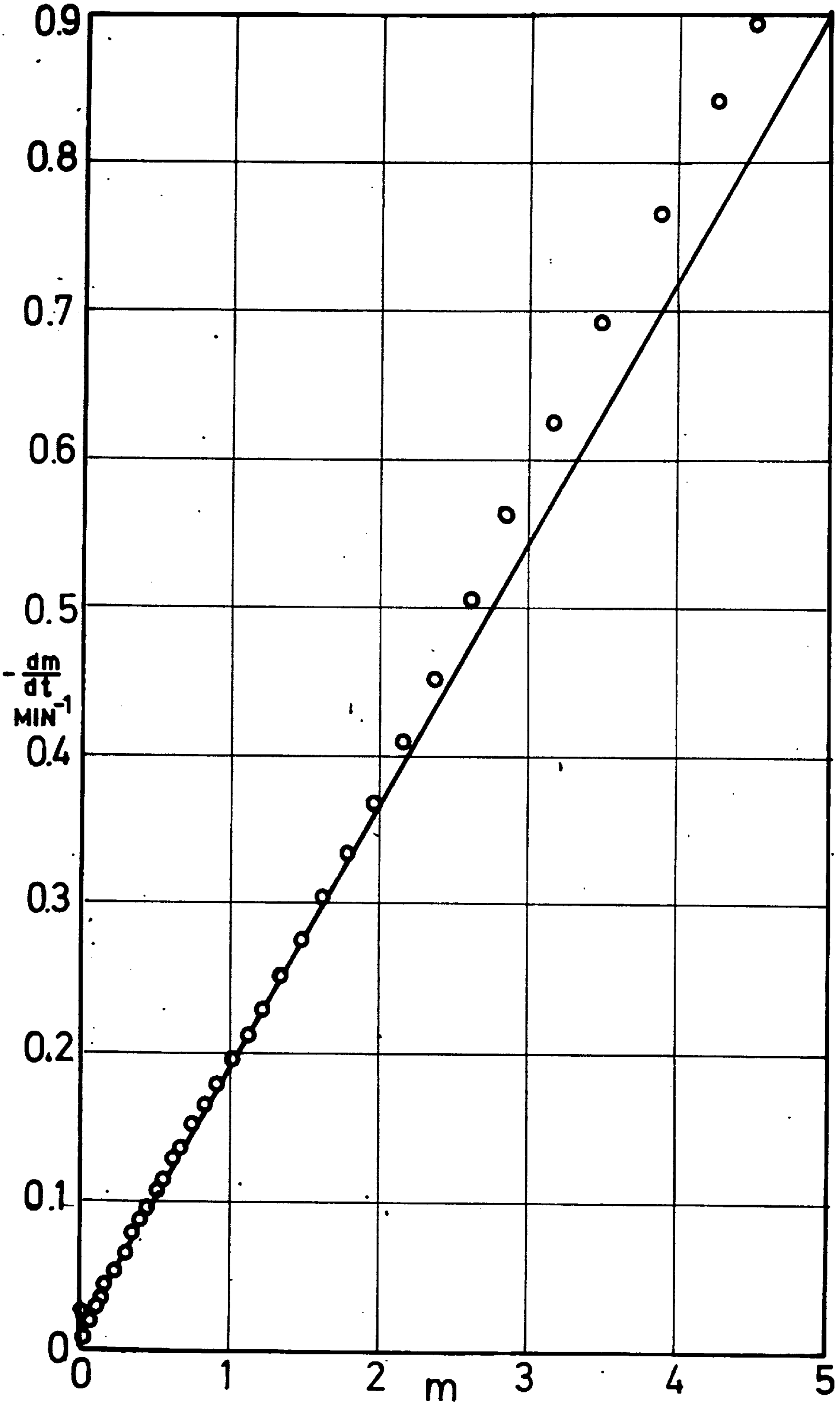


FIG.5.10

PLOT OF $\frac{m - m_e}{m_o - m_e} = e^{-kt}$ for values of k and m_e obtained by POLYNOMIAL METHOD

RUN 89

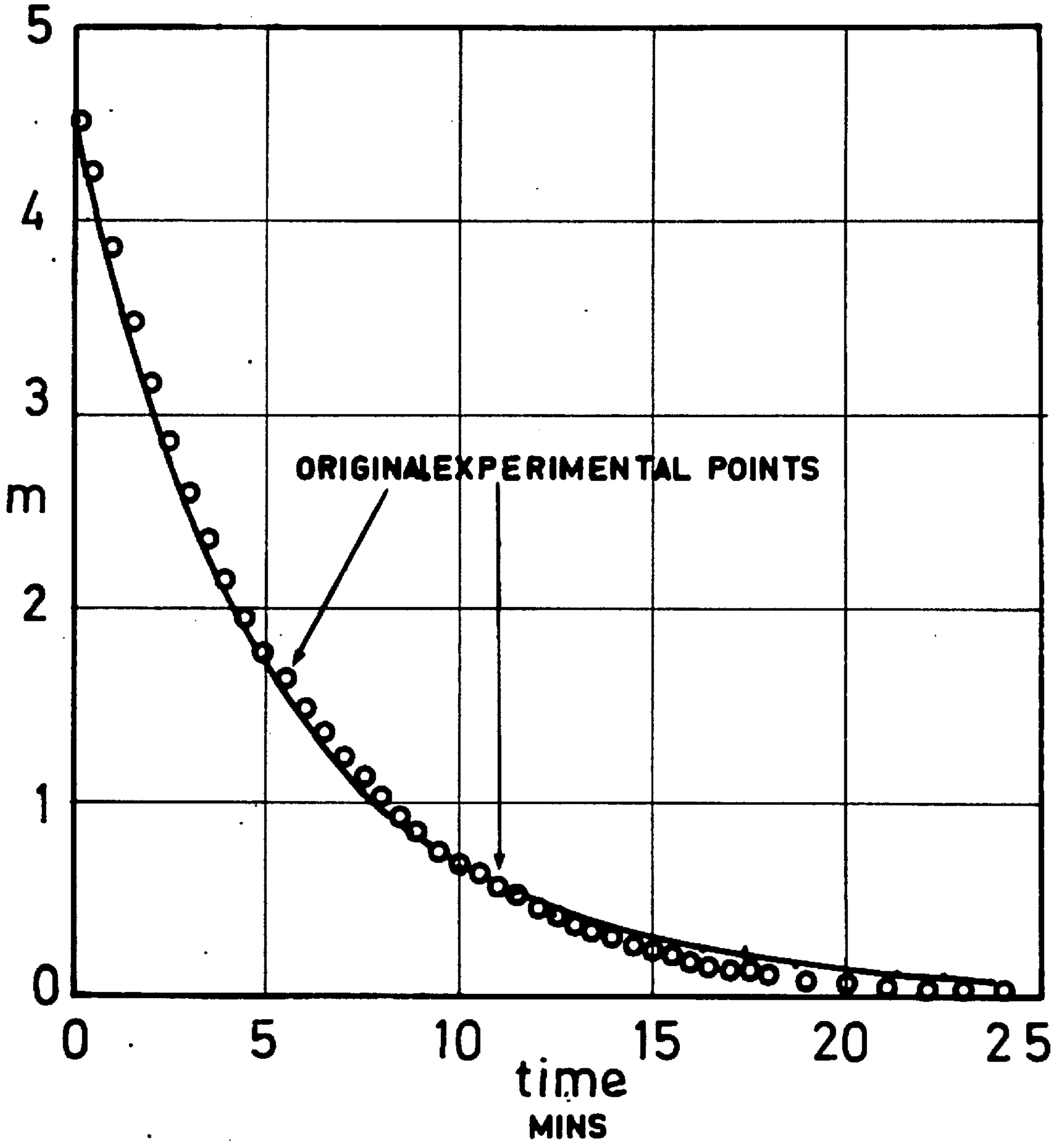


FIG. 5.11.

DRYING CURVES

NUMBERS REFER TO EXPERIMENTAL RUNS

L=LEAVES ONLY

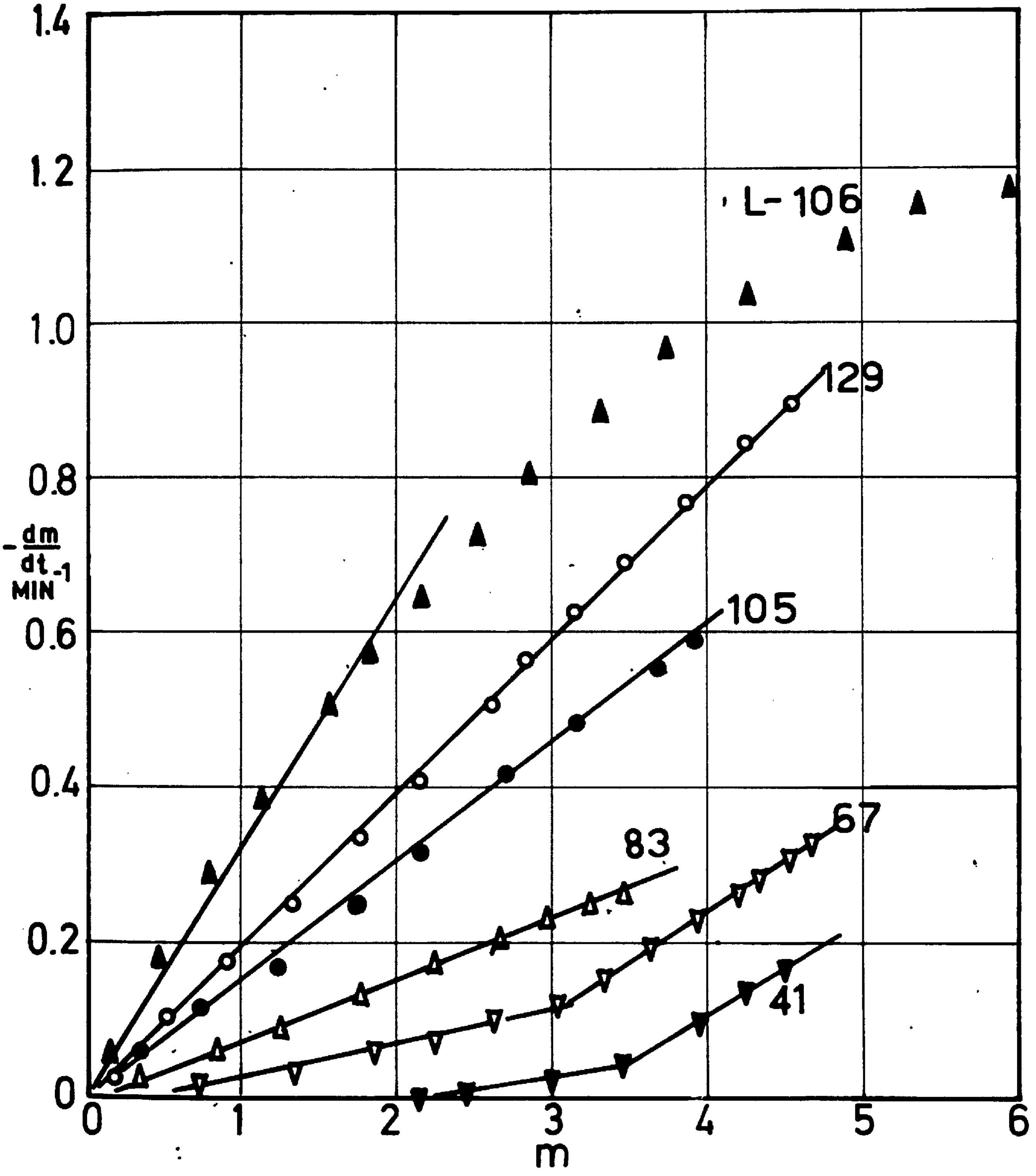


FIG. 5.12.

DRYING CURVES

NUMBERS REFER TO EXPERIMENTAL RUNS

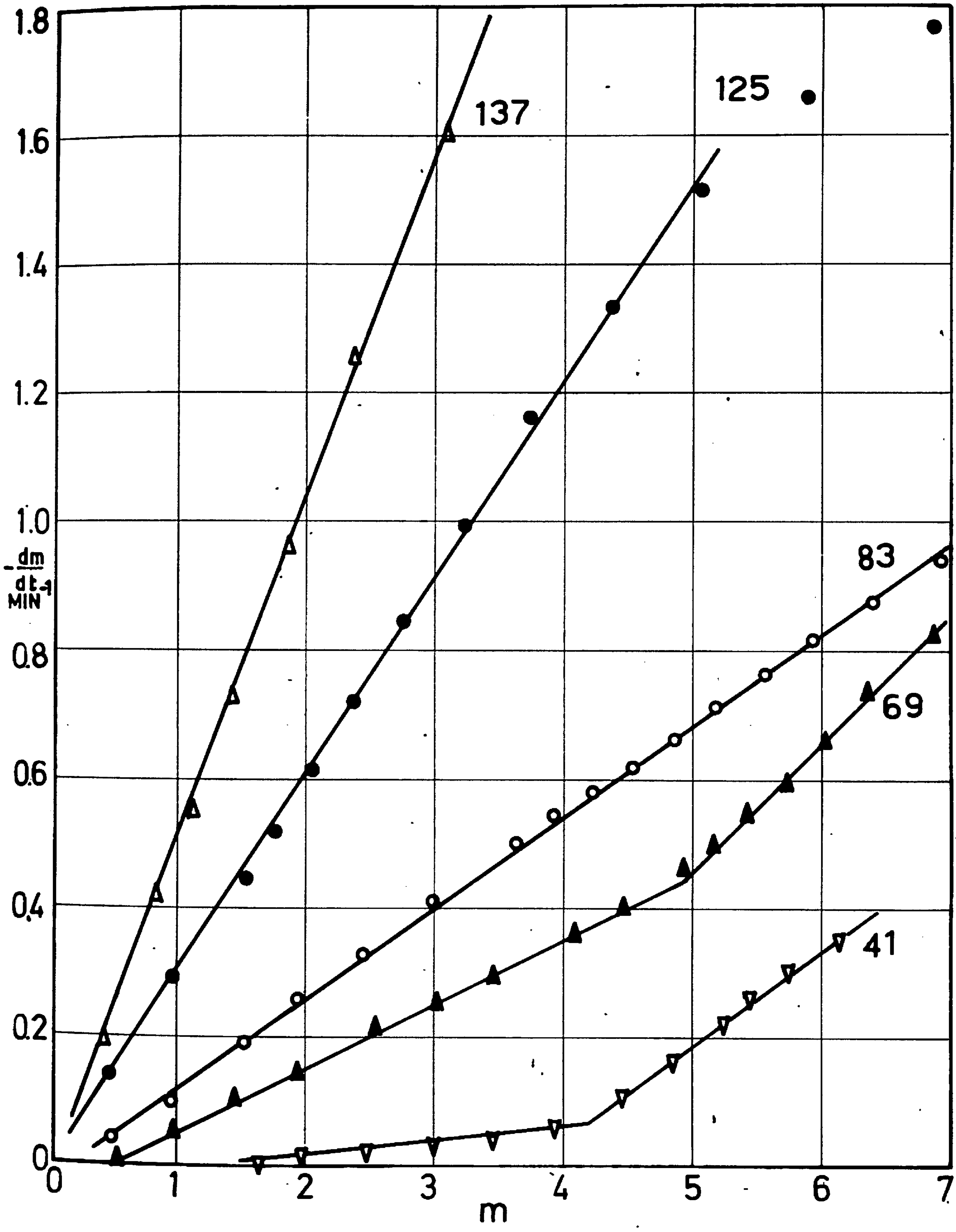


FIG.5.13 DRYING CURVES

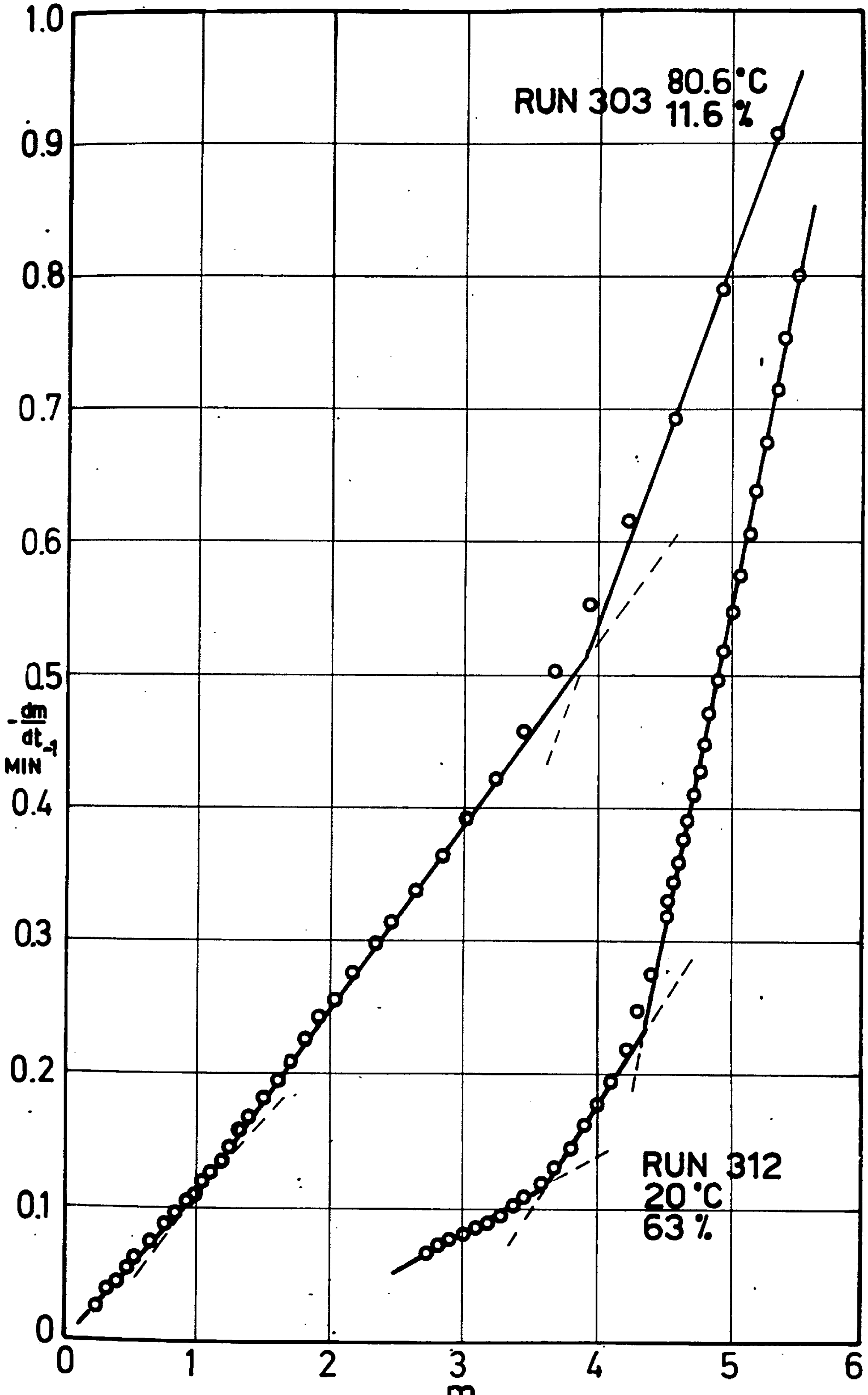


FIG. 5.12.

DRYING CURVES

NUMBERS REFER TO EXPERIMENTAL RUNS

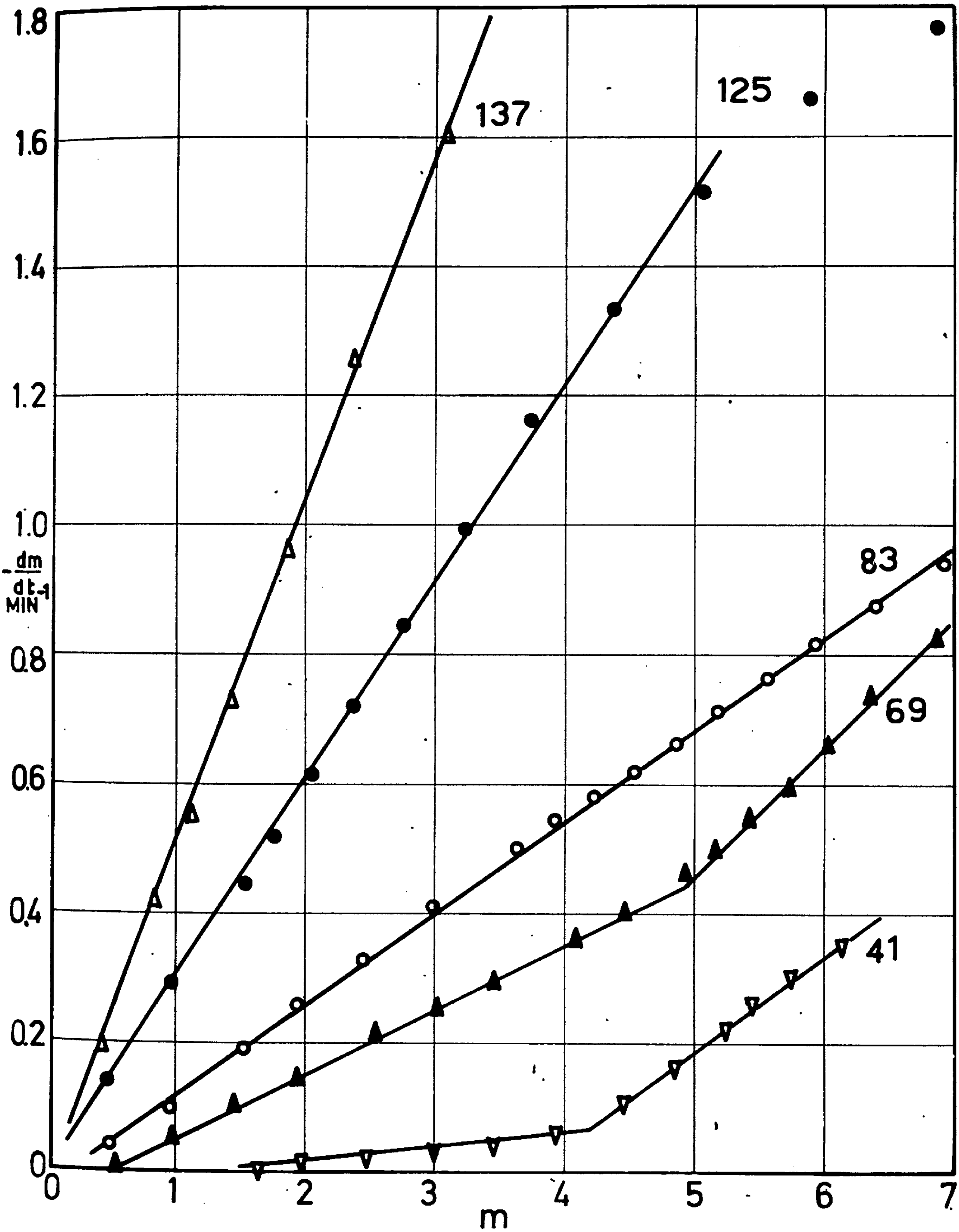


FIG. 5.14.

PLOT OF m vs. time FOR RUN 340

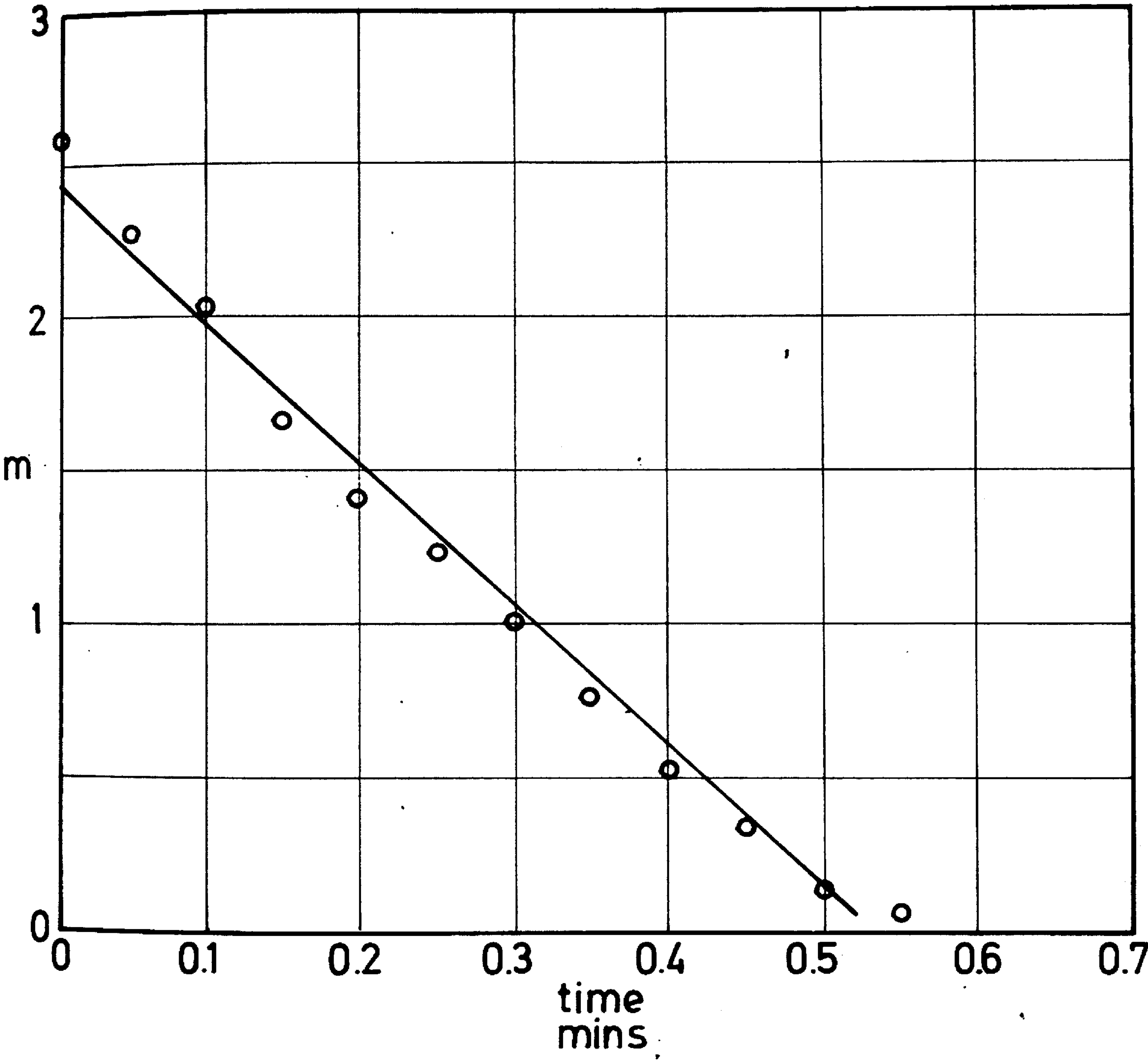


FIG. 5.15
DRYING CURVE RUN 340 259°C

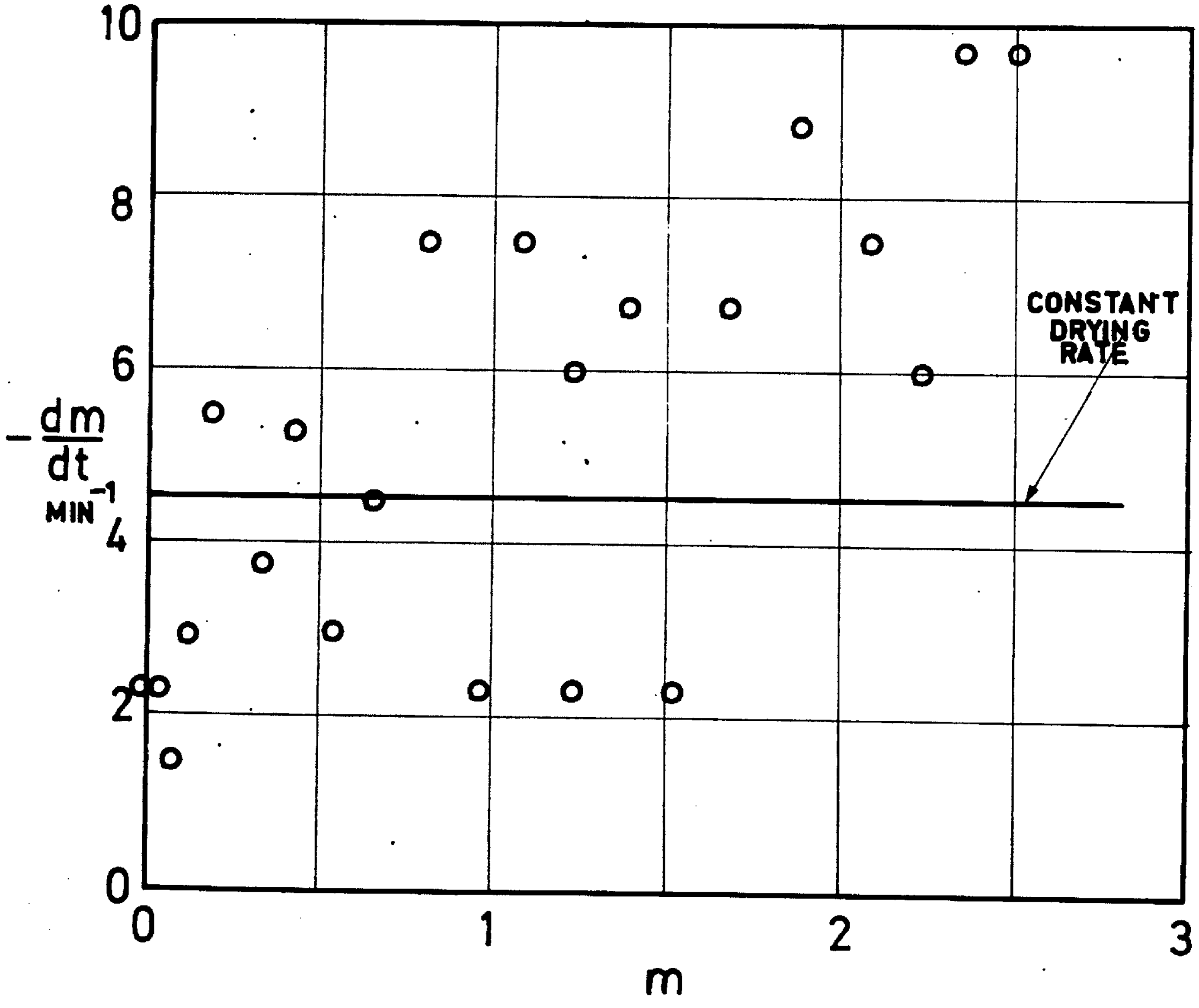


FIG.5.16. k vs. T_a BATCH 9

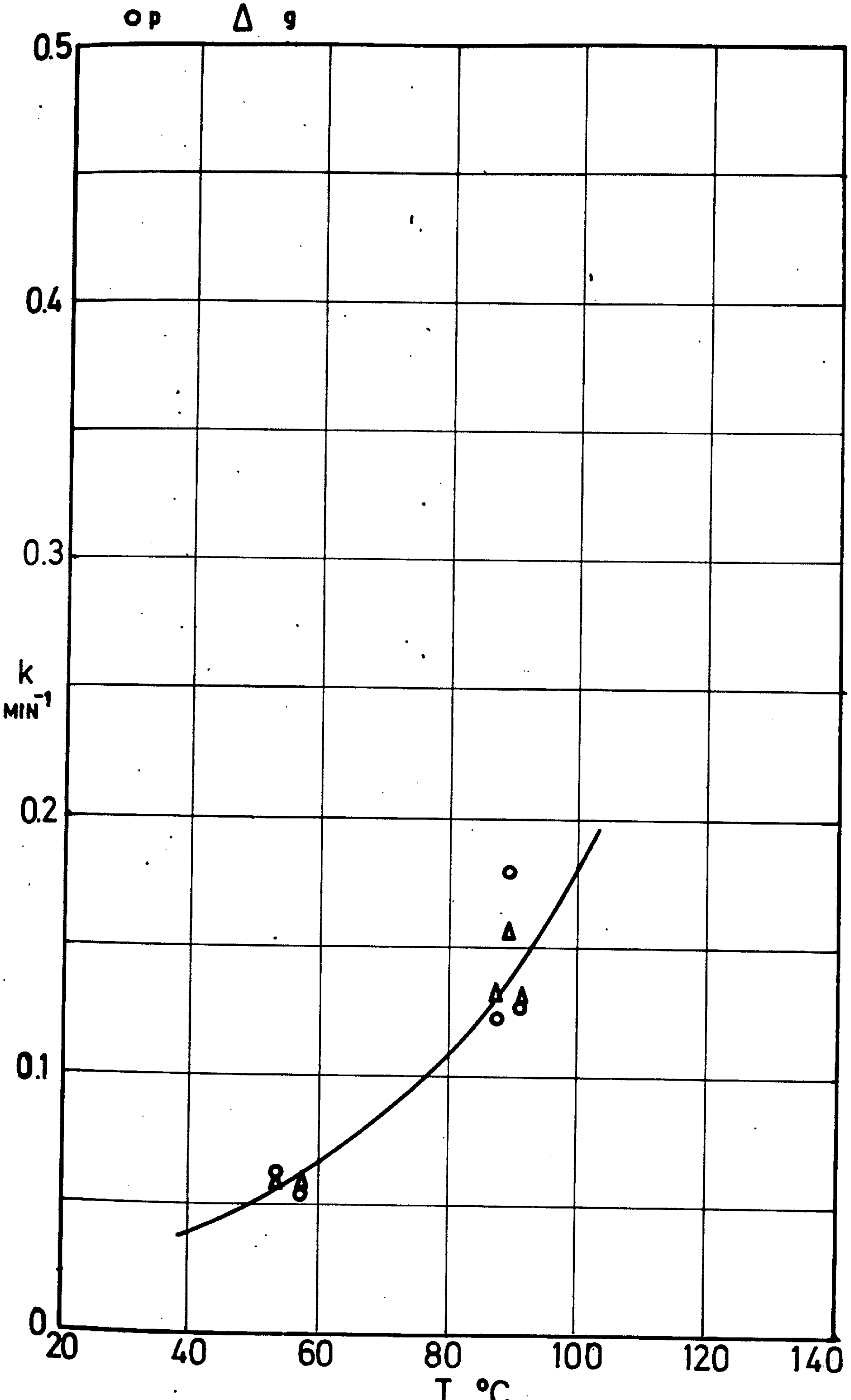


FIG.5.17. k vs. T_a BATCH 10

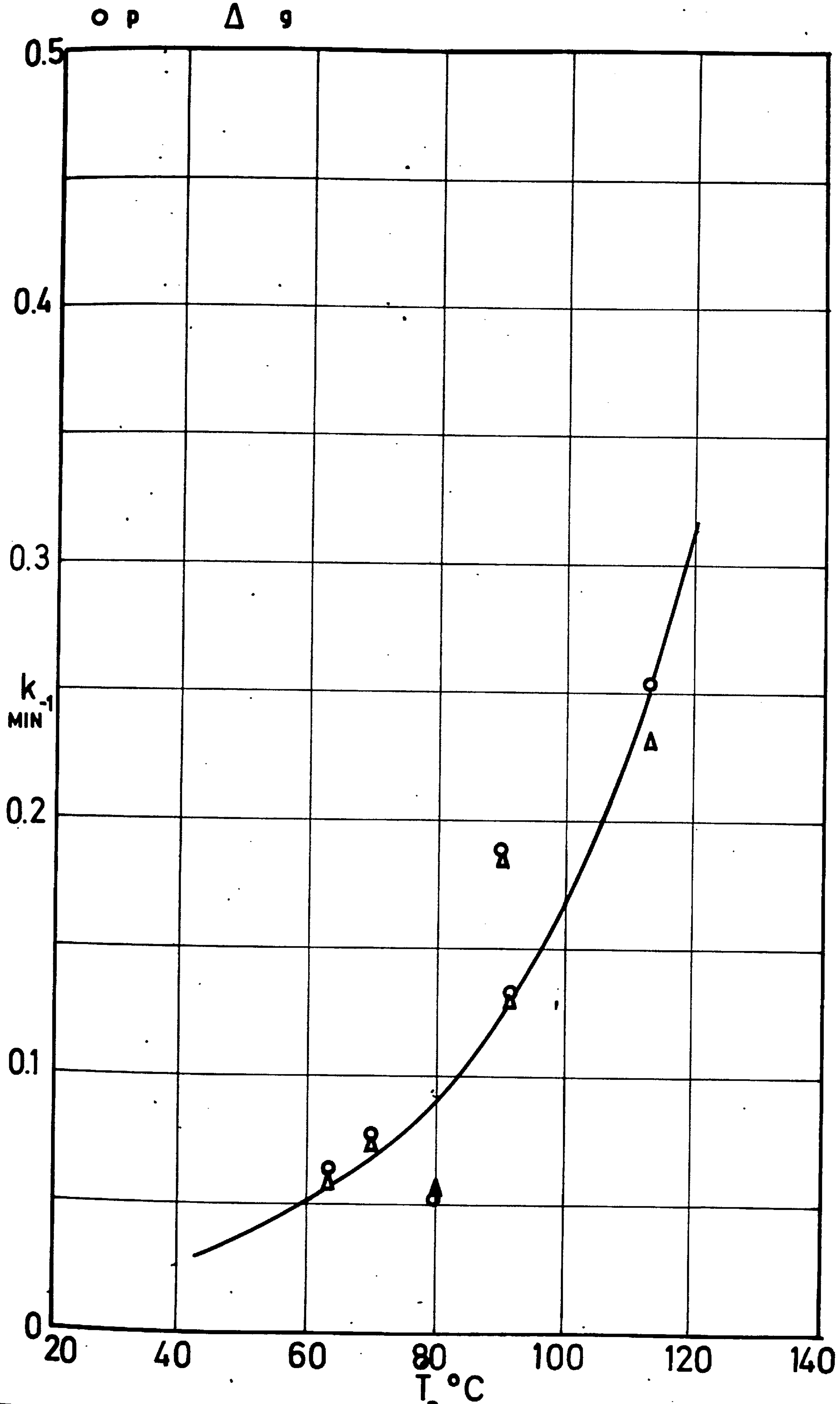


FIG. 5.18. k vs. T_a BATCH 11

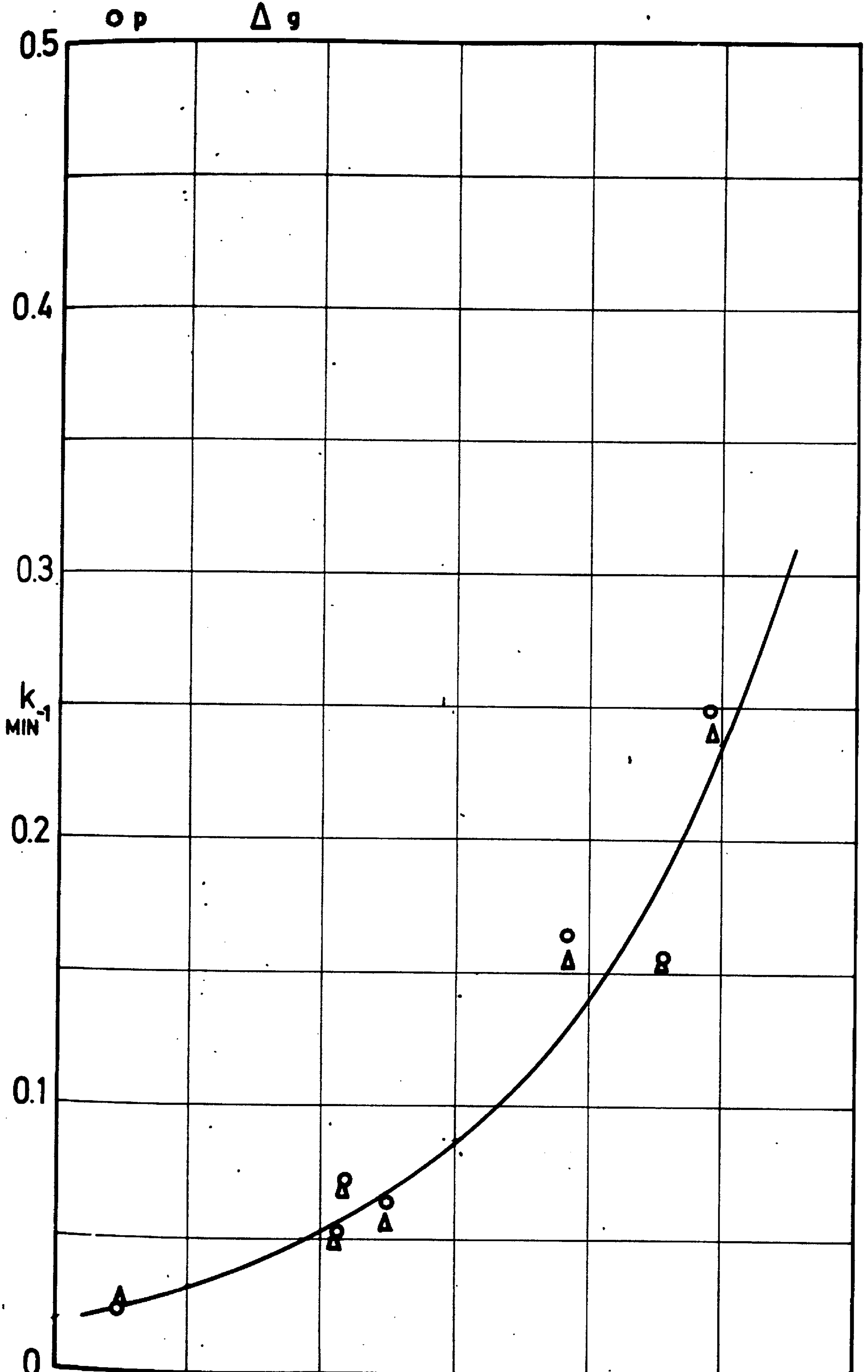


FIG.5.19. k vs. T_a BATCH 12

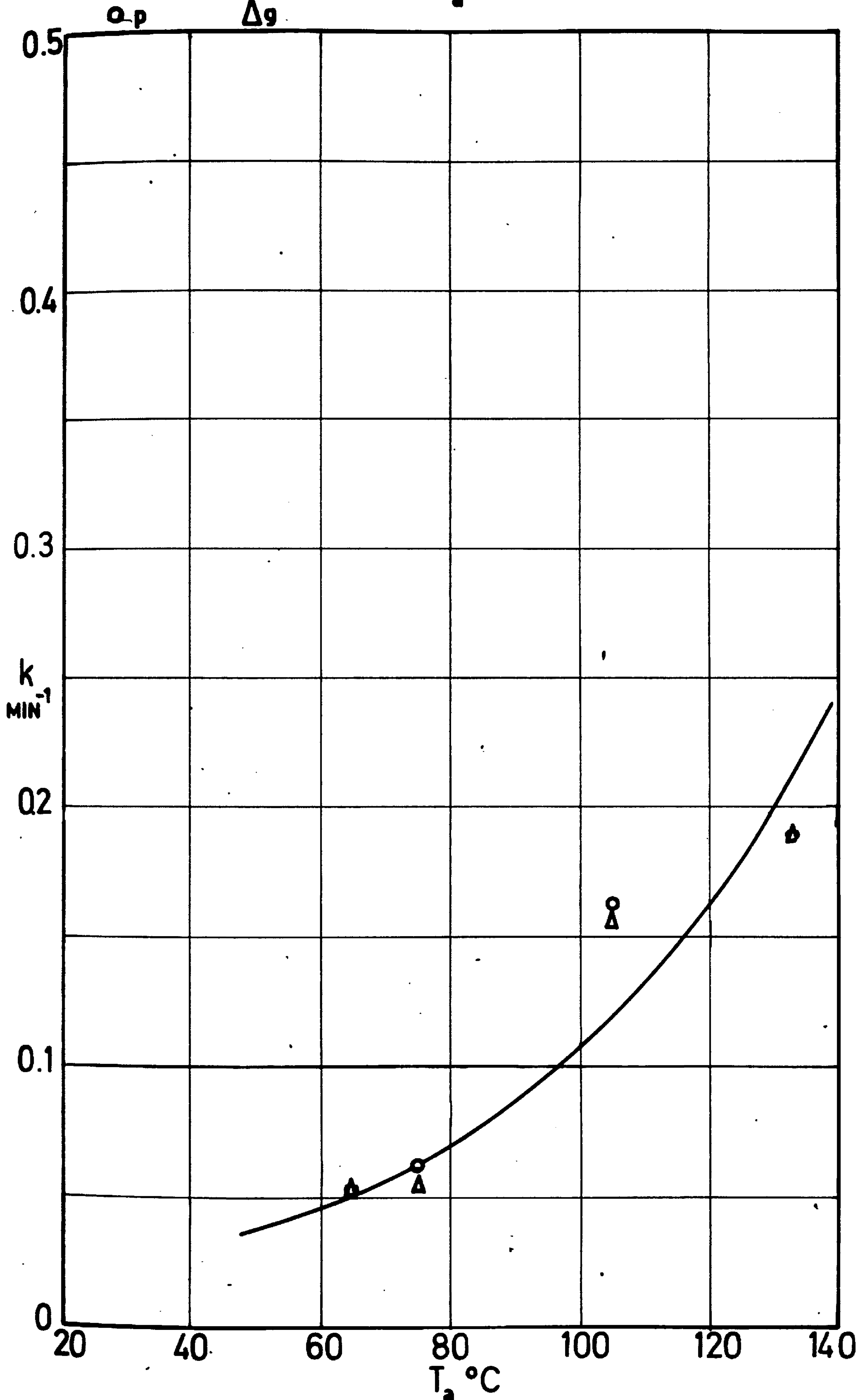


FIG. 520 k. vs. T_a BATCH 13

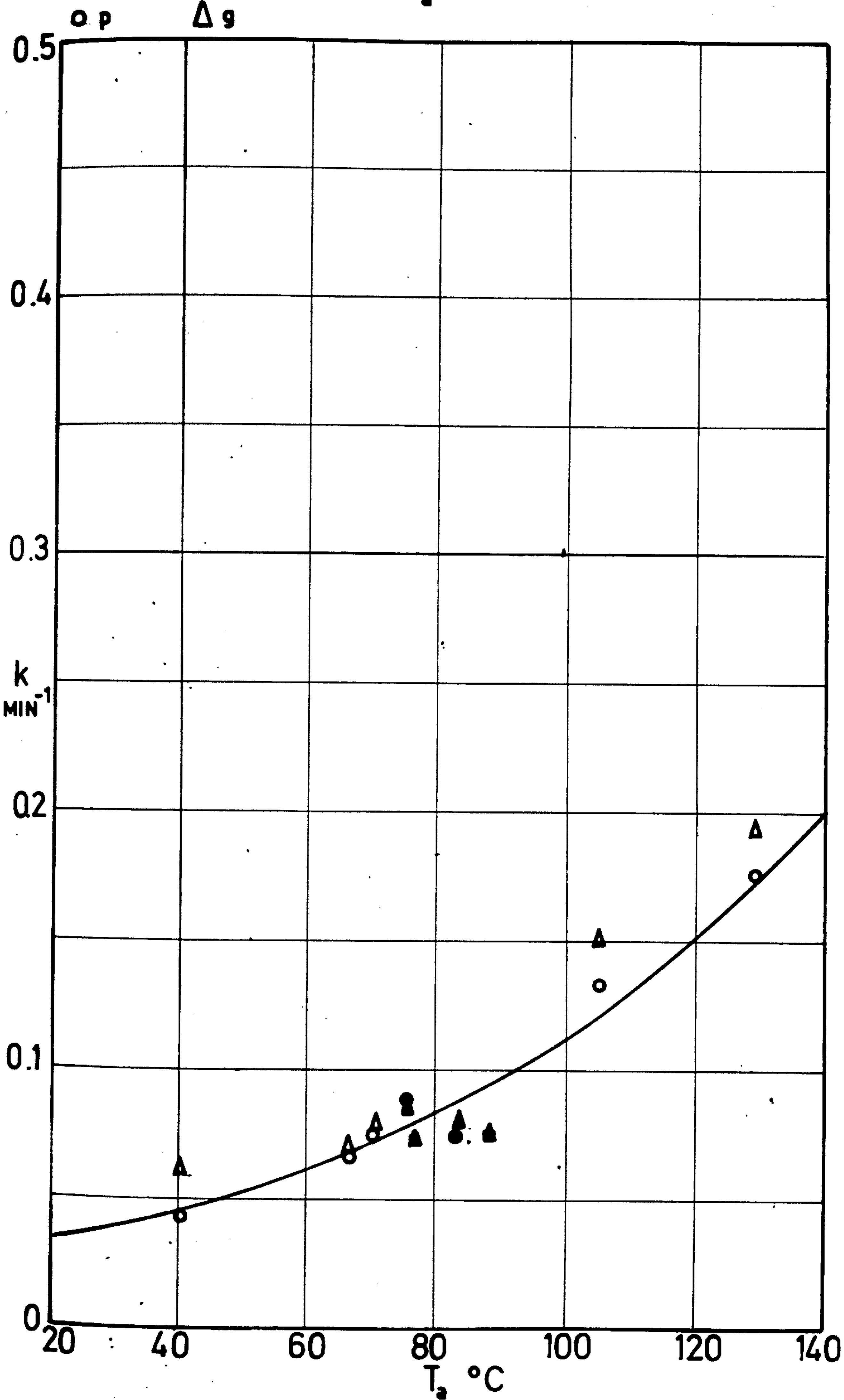


FIG.5.21. k vs. T_a BATCH 14

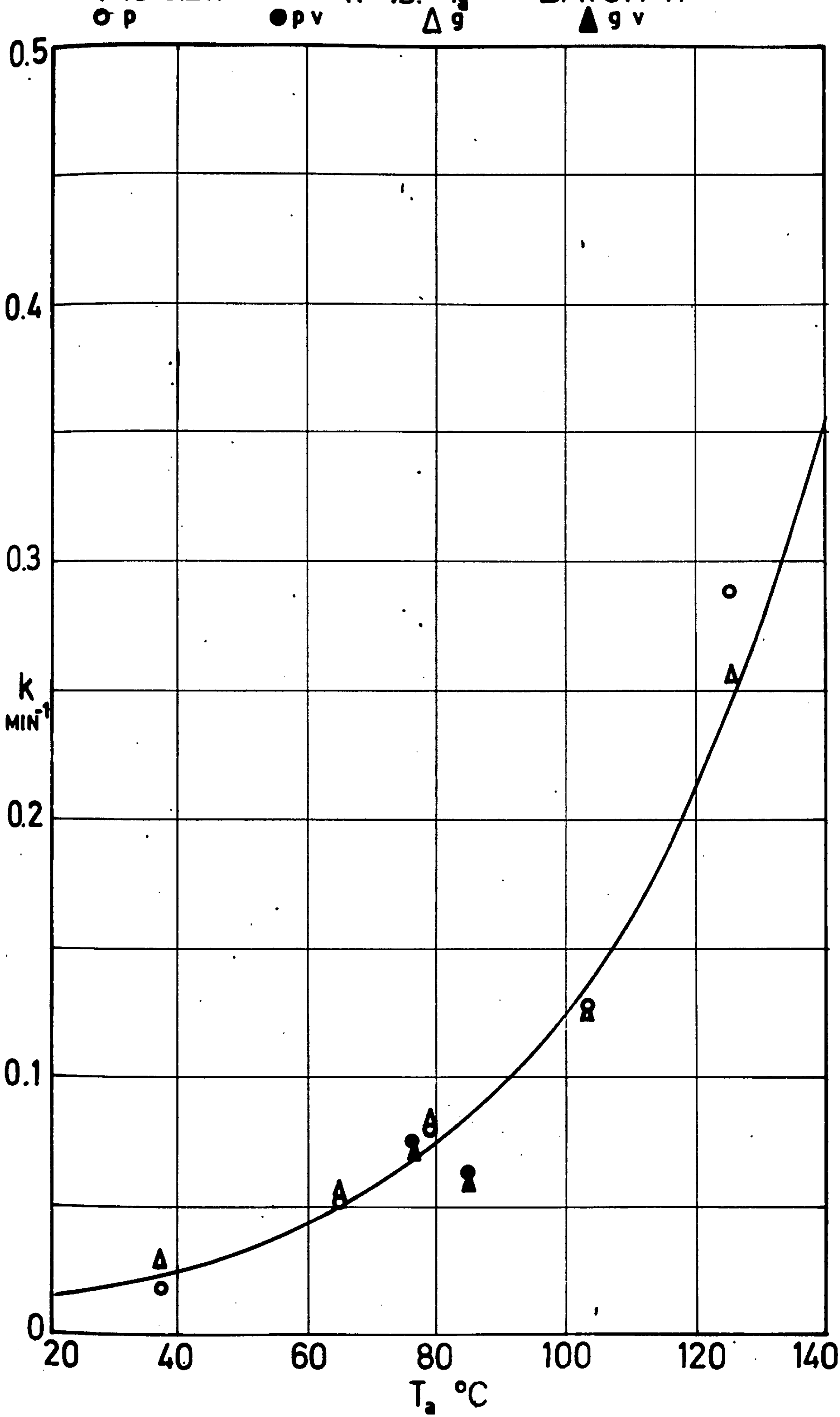


FIG.5.22. k vs. T_a BATCH 15

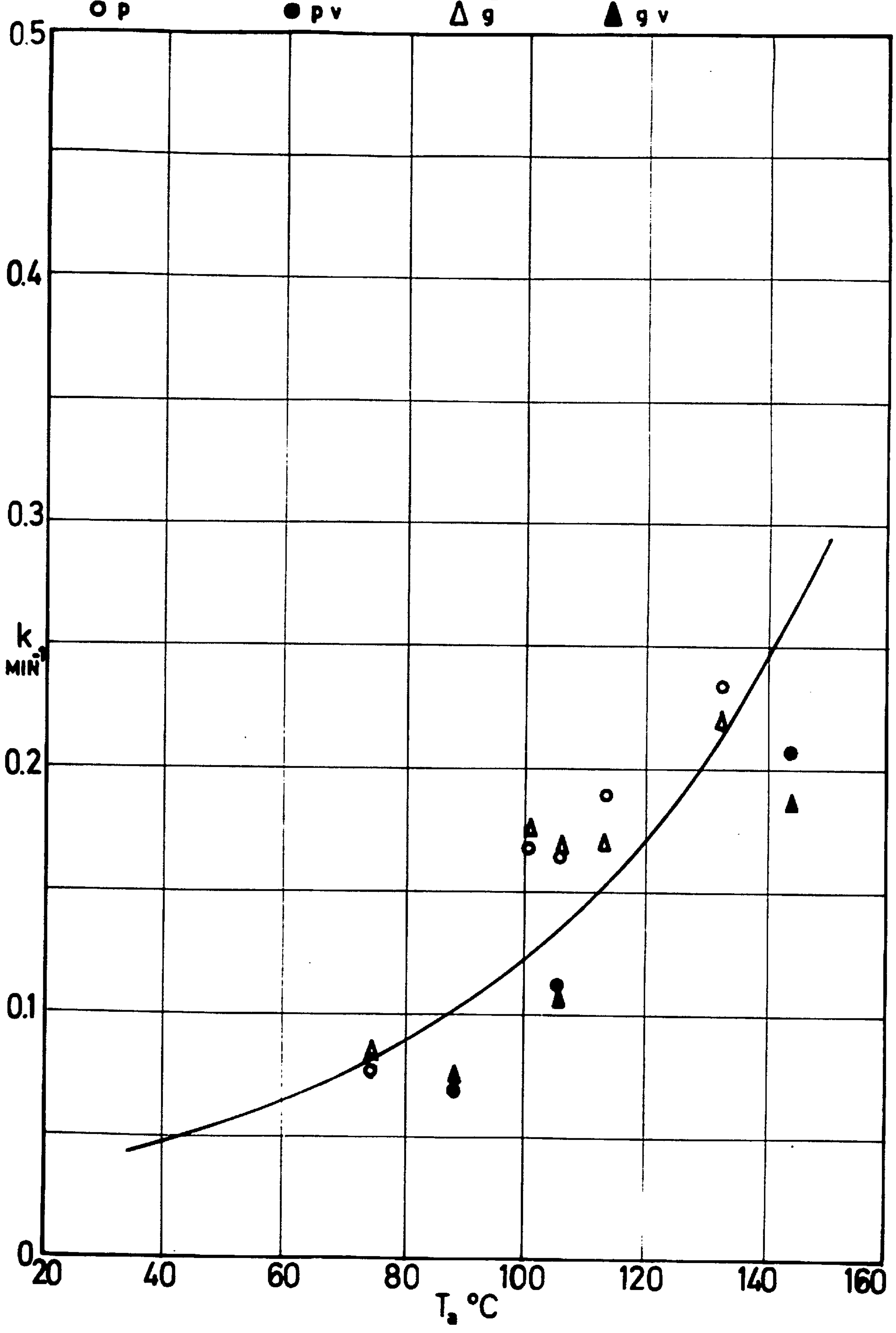


FIG.5.23. k vs. T_a BATCH 16

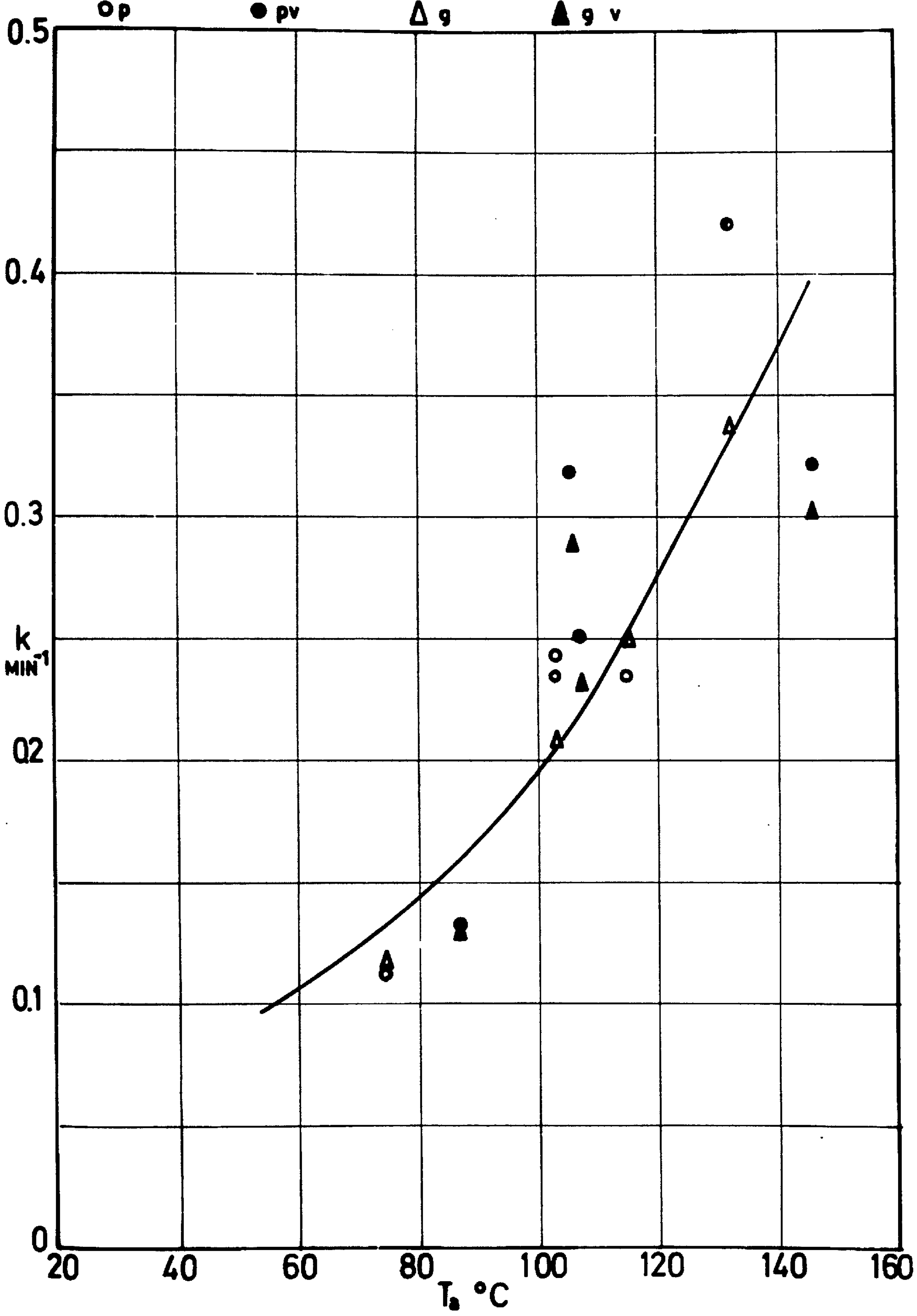


FIG.5.23. k vs. T_a BATCH 16

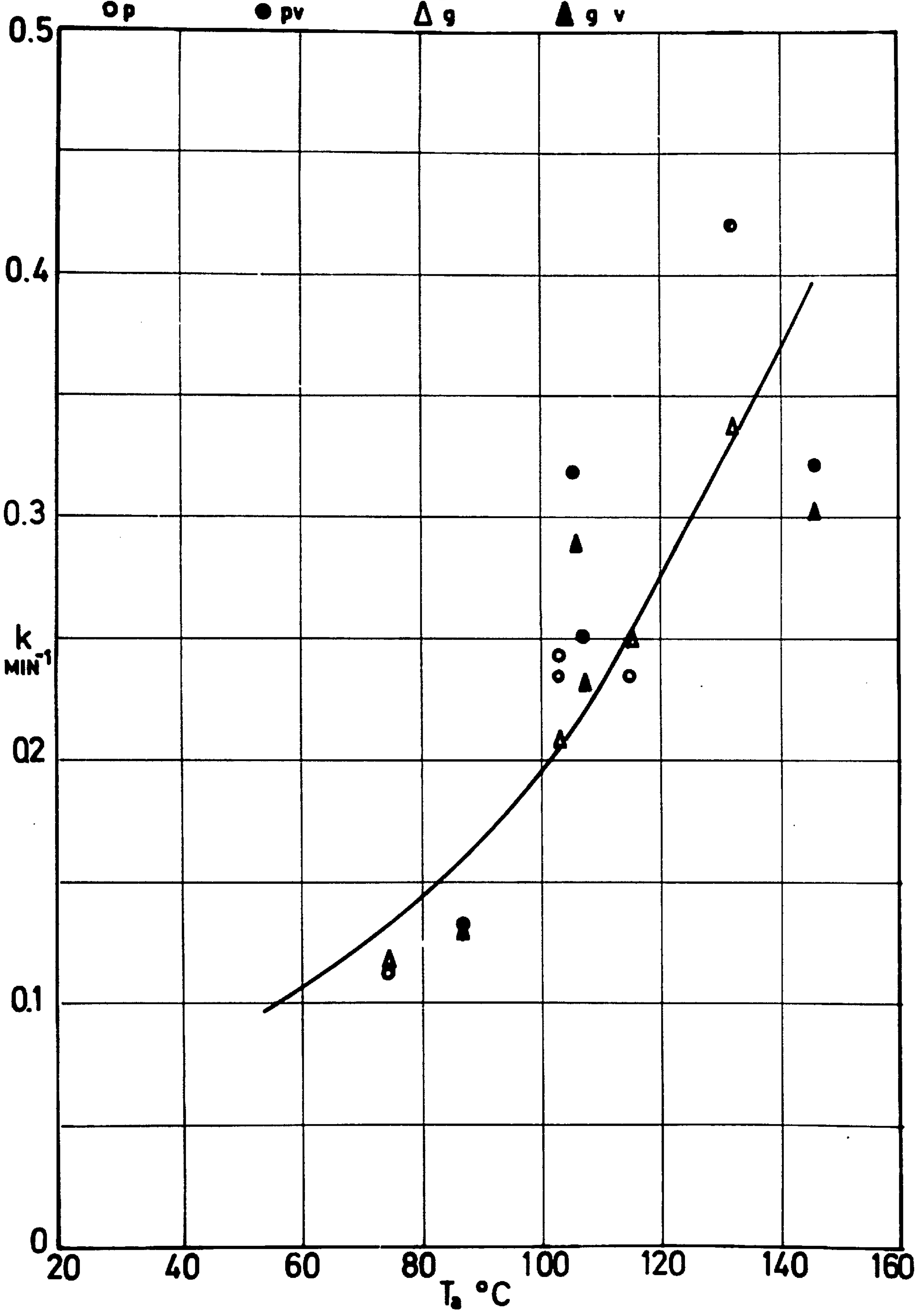


FIG. 5.24. k vs. T_a BATCH 17

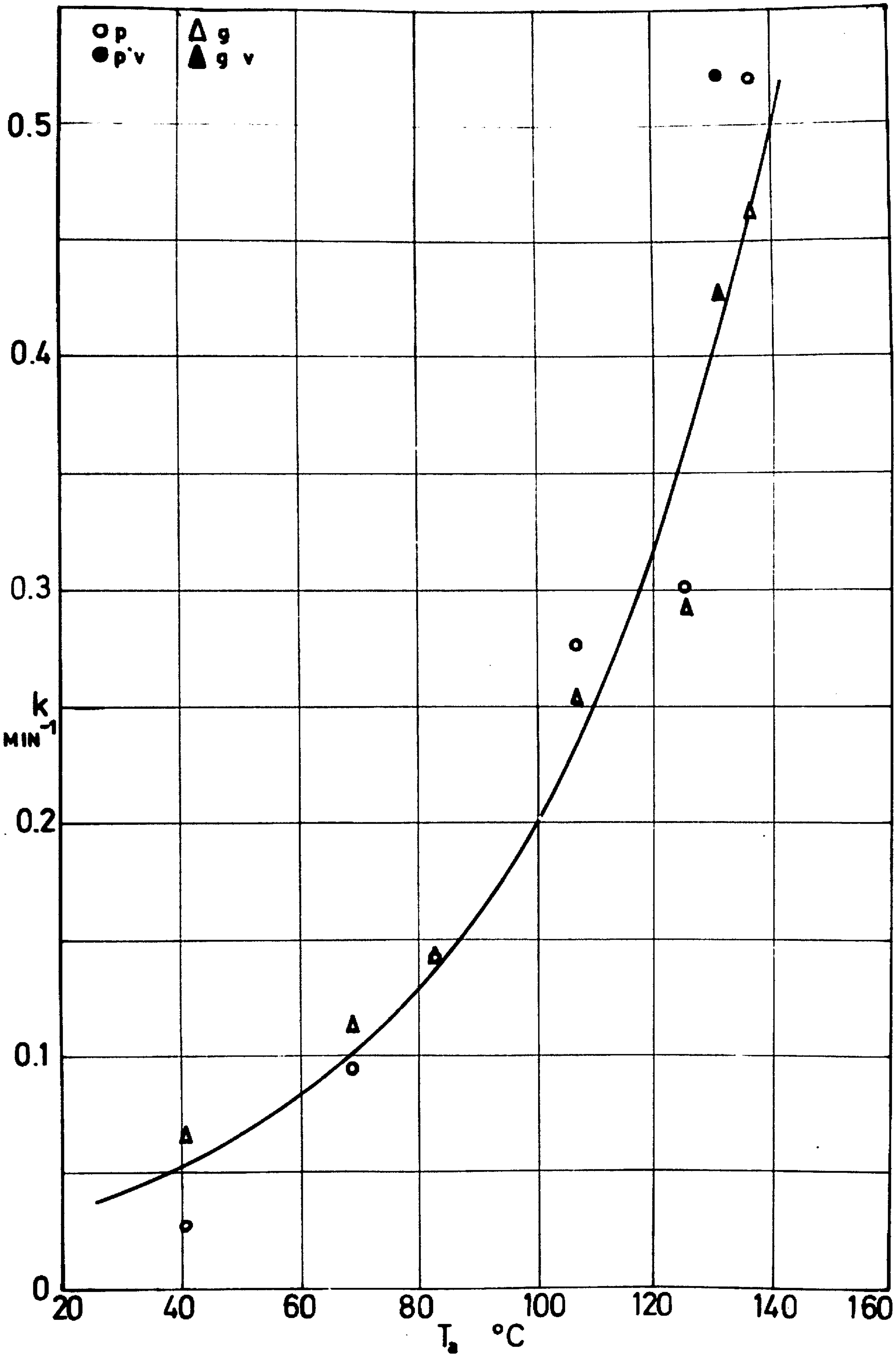


FIG.5.25. k vs. T_a BATCH 18

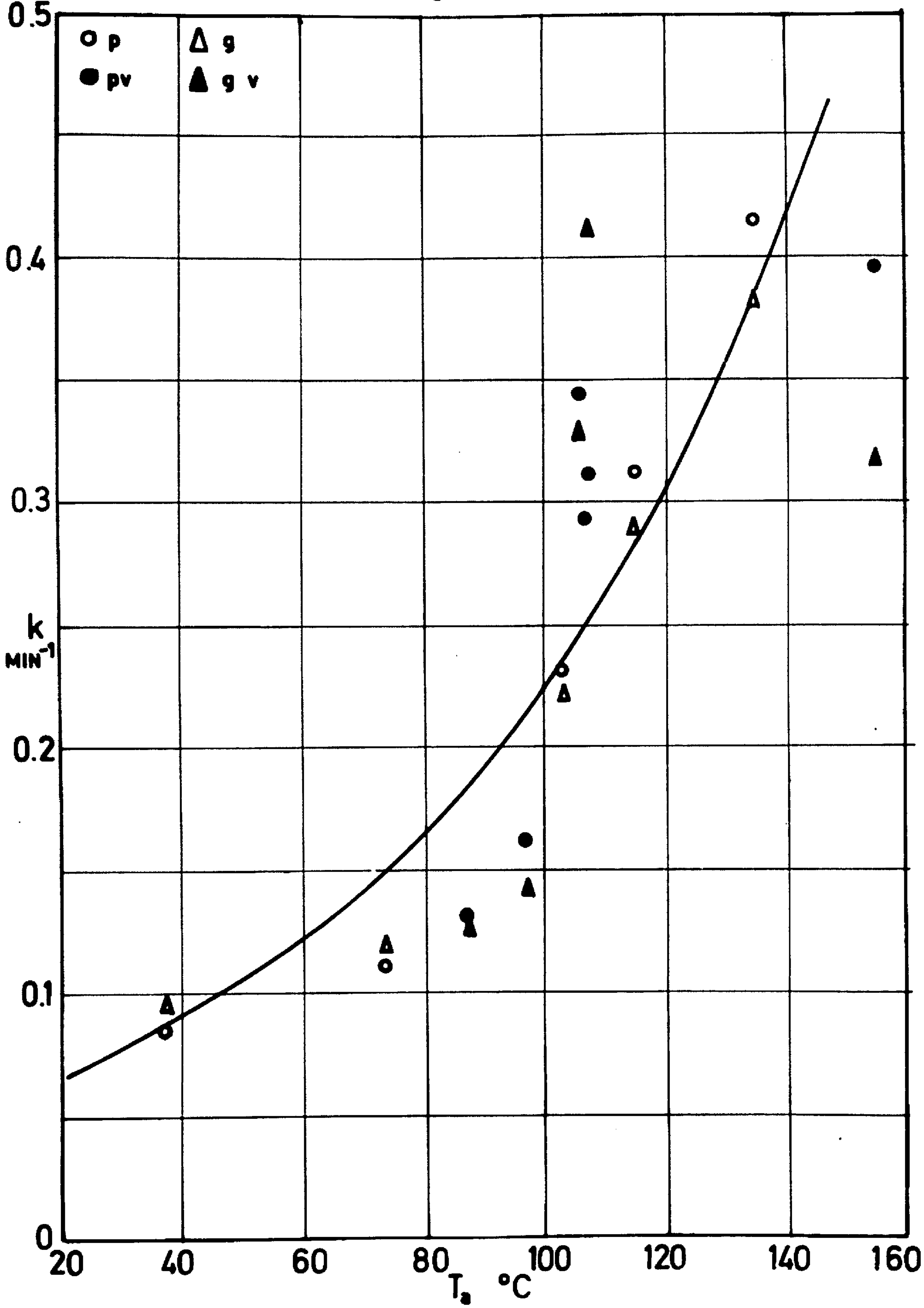


FIG. 5.26. k vs. T_a BATCH 19

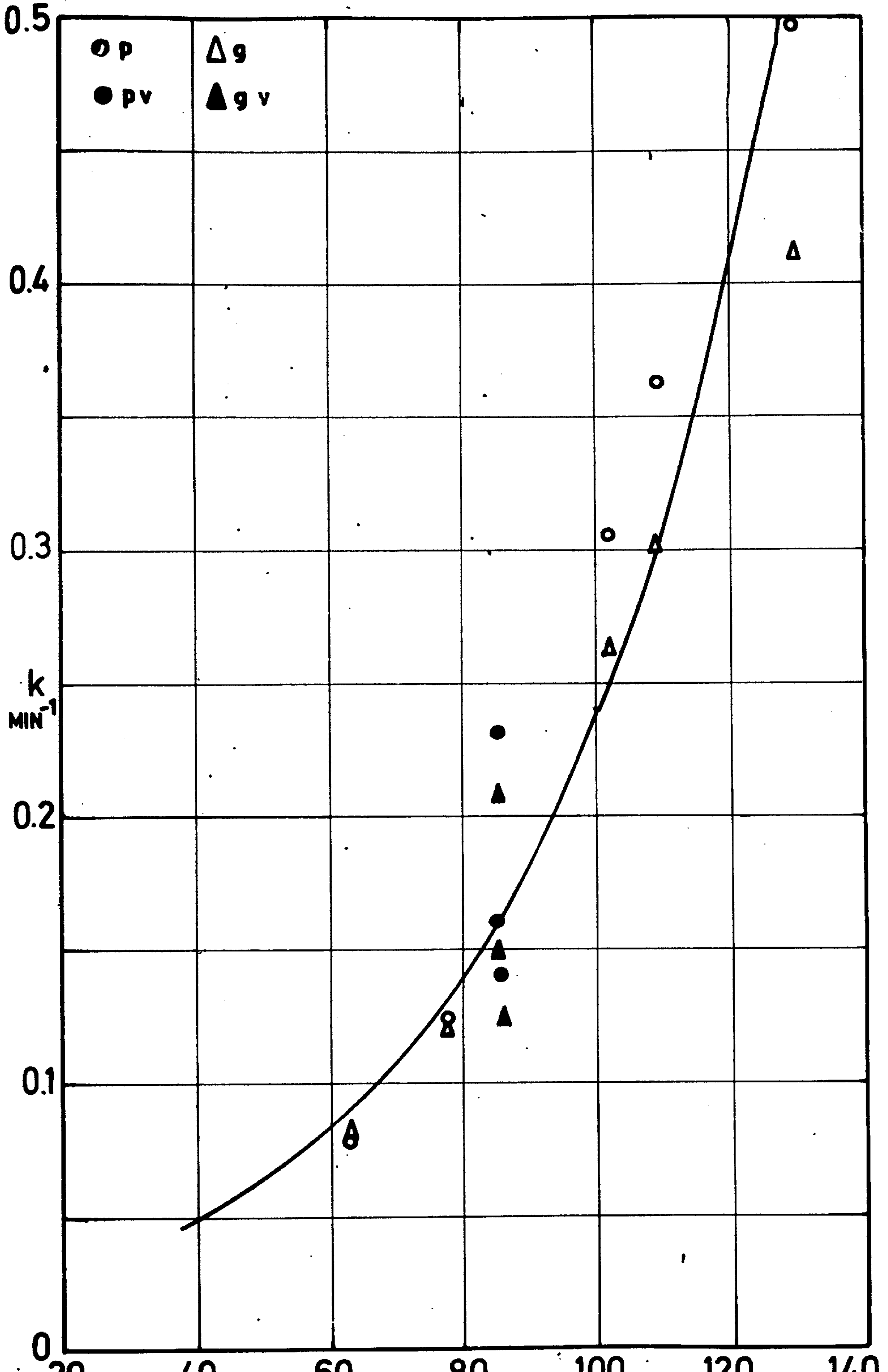


FIG. 5.27 k' vs. T_a BATCH 20

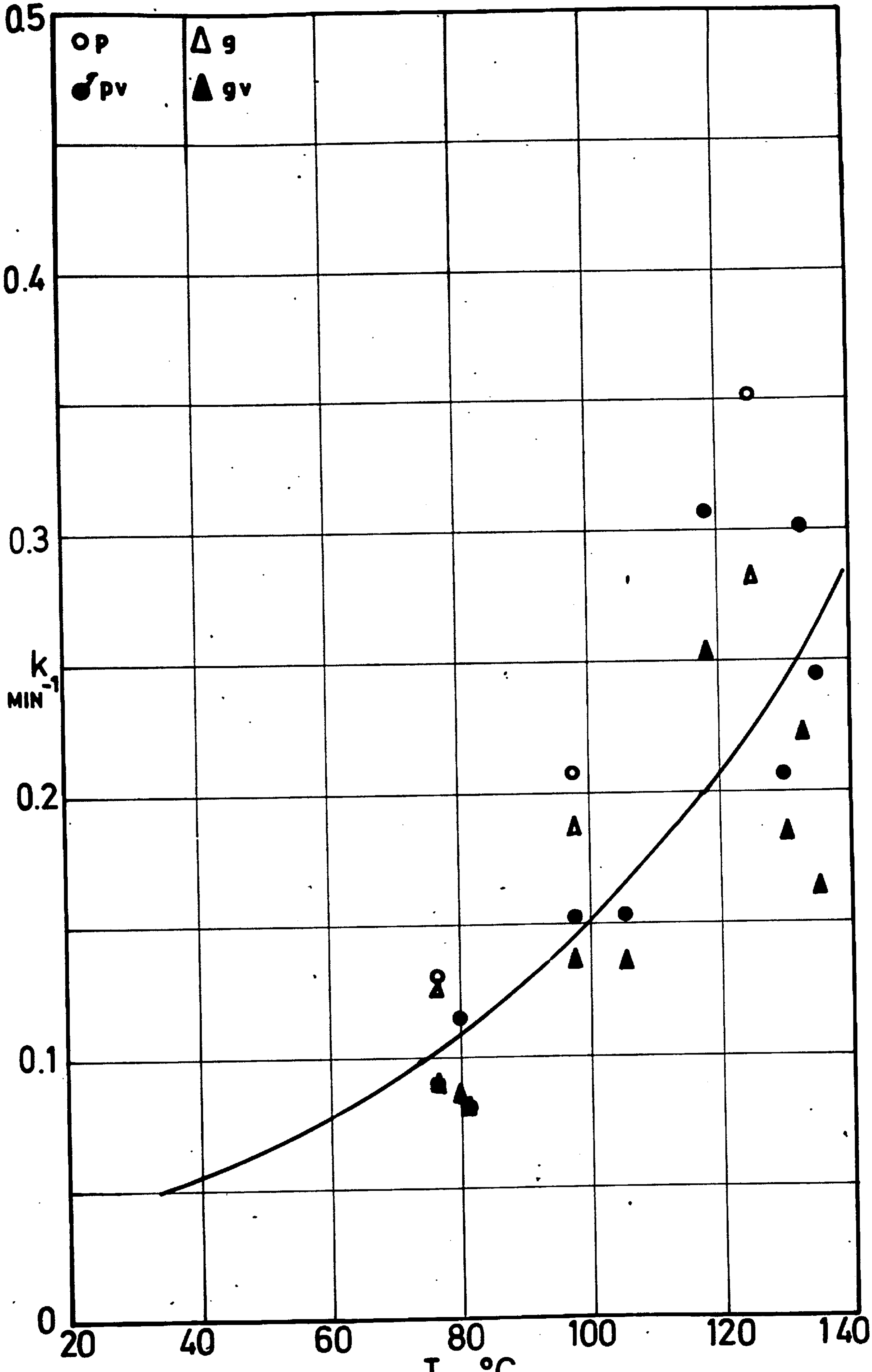


FIG.5.28. k vs. T_a BATCH 21

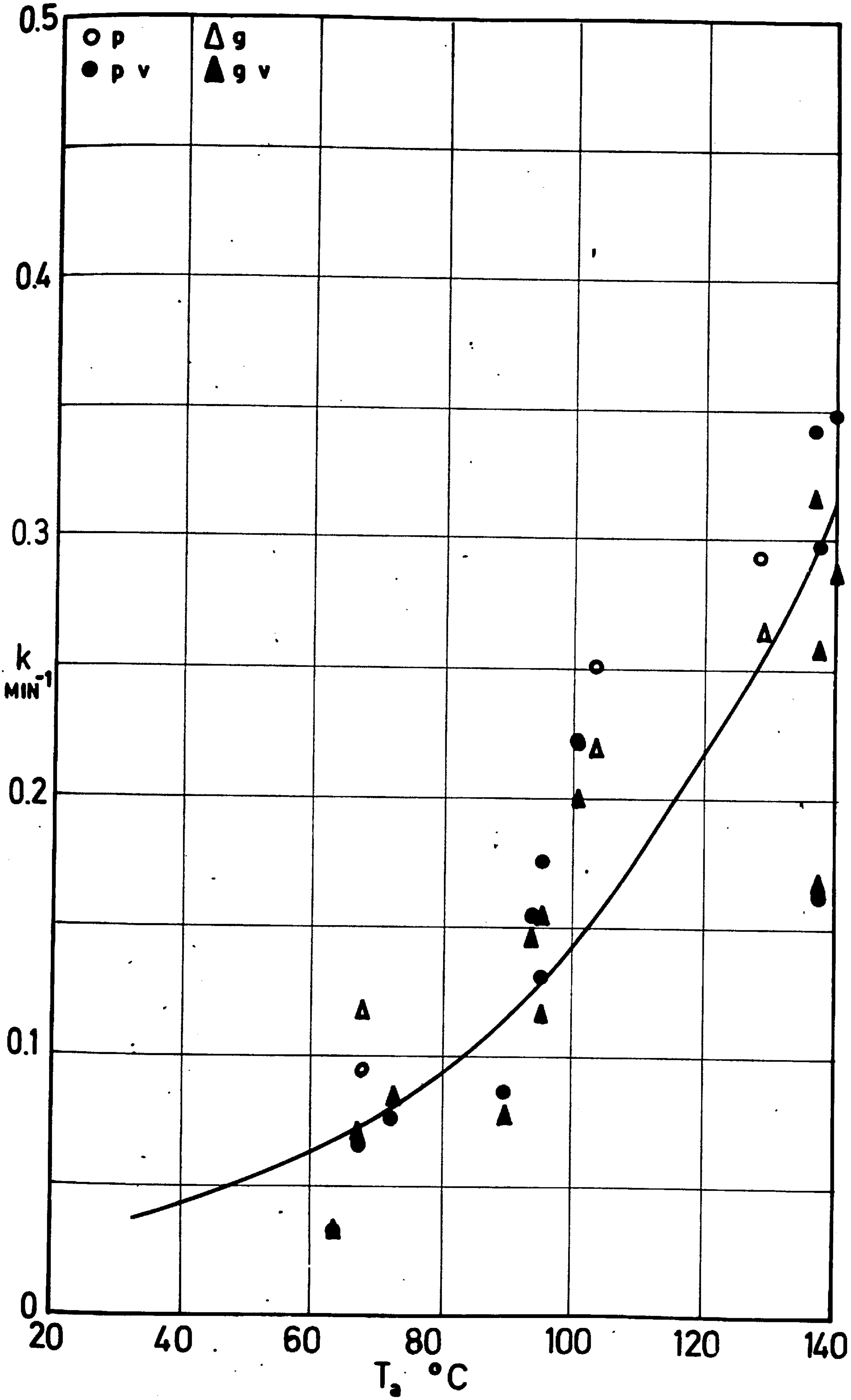


FIG. 5.29. k vs. T_a BATCH 22

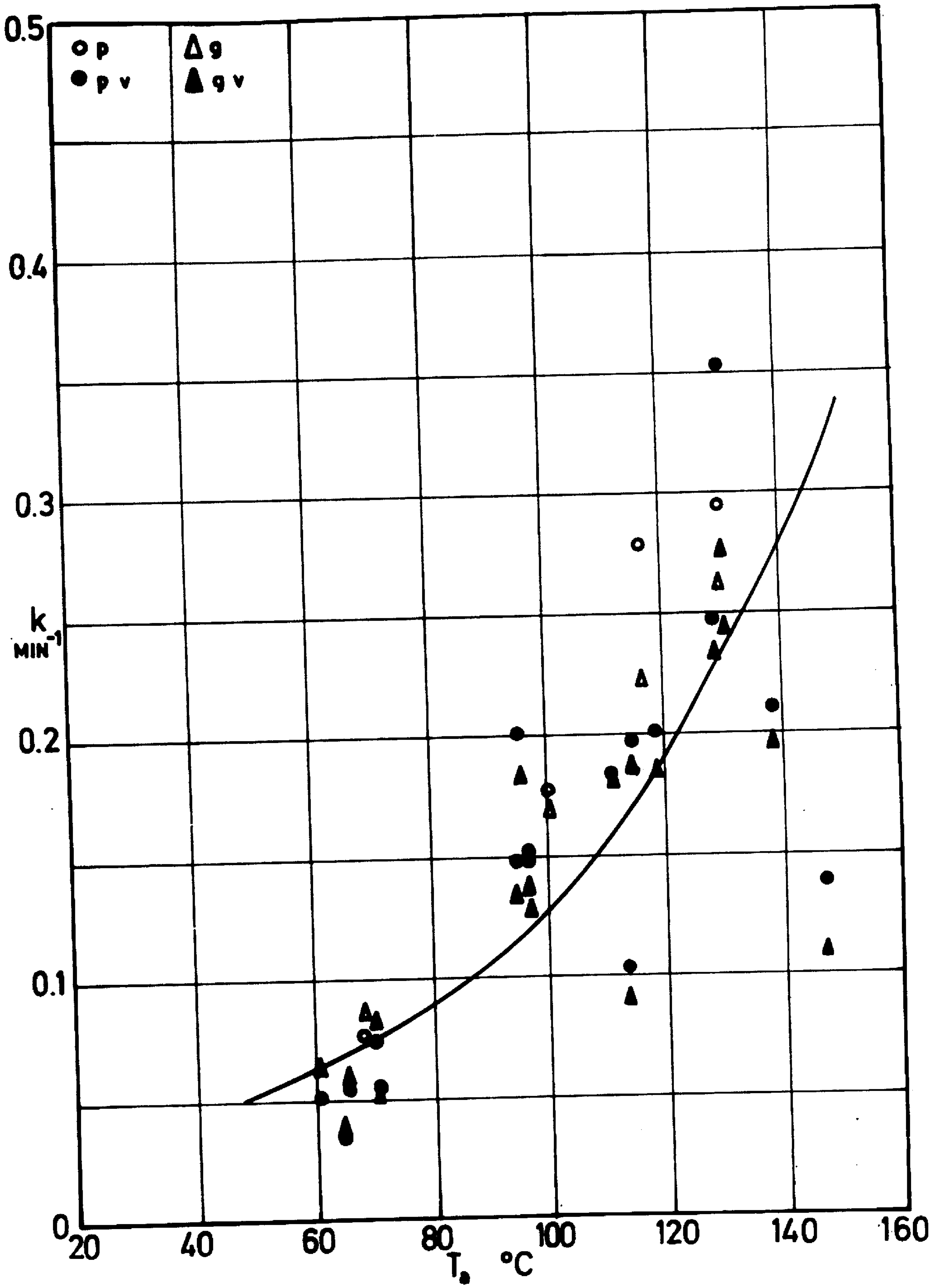


FIG. 5.30. k vs. T_a BATCH 23

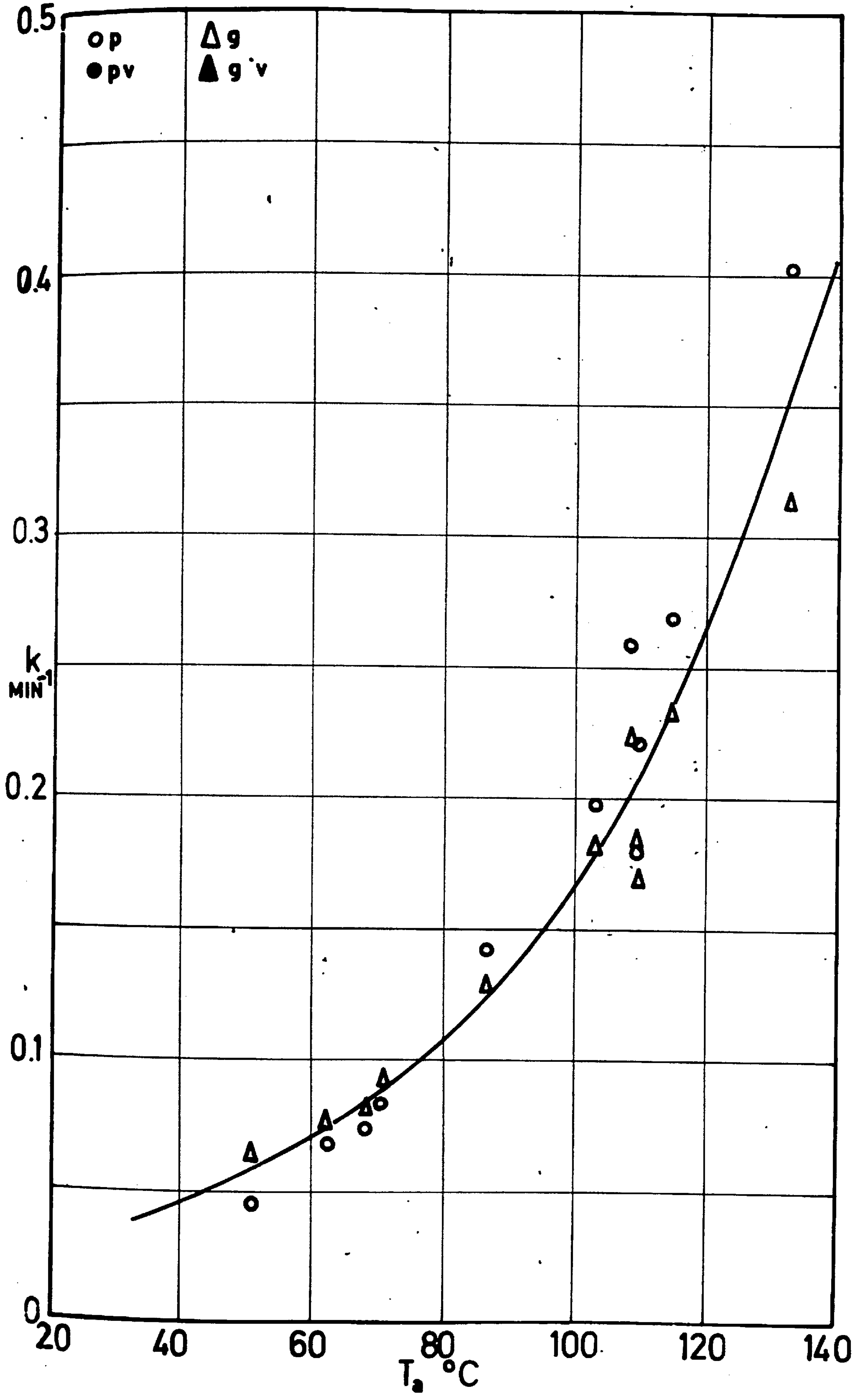


FIG.5.31 k_1, k_2, k_3 vs. T_a
LOW TEMPERATURE RUNS
301 - 315

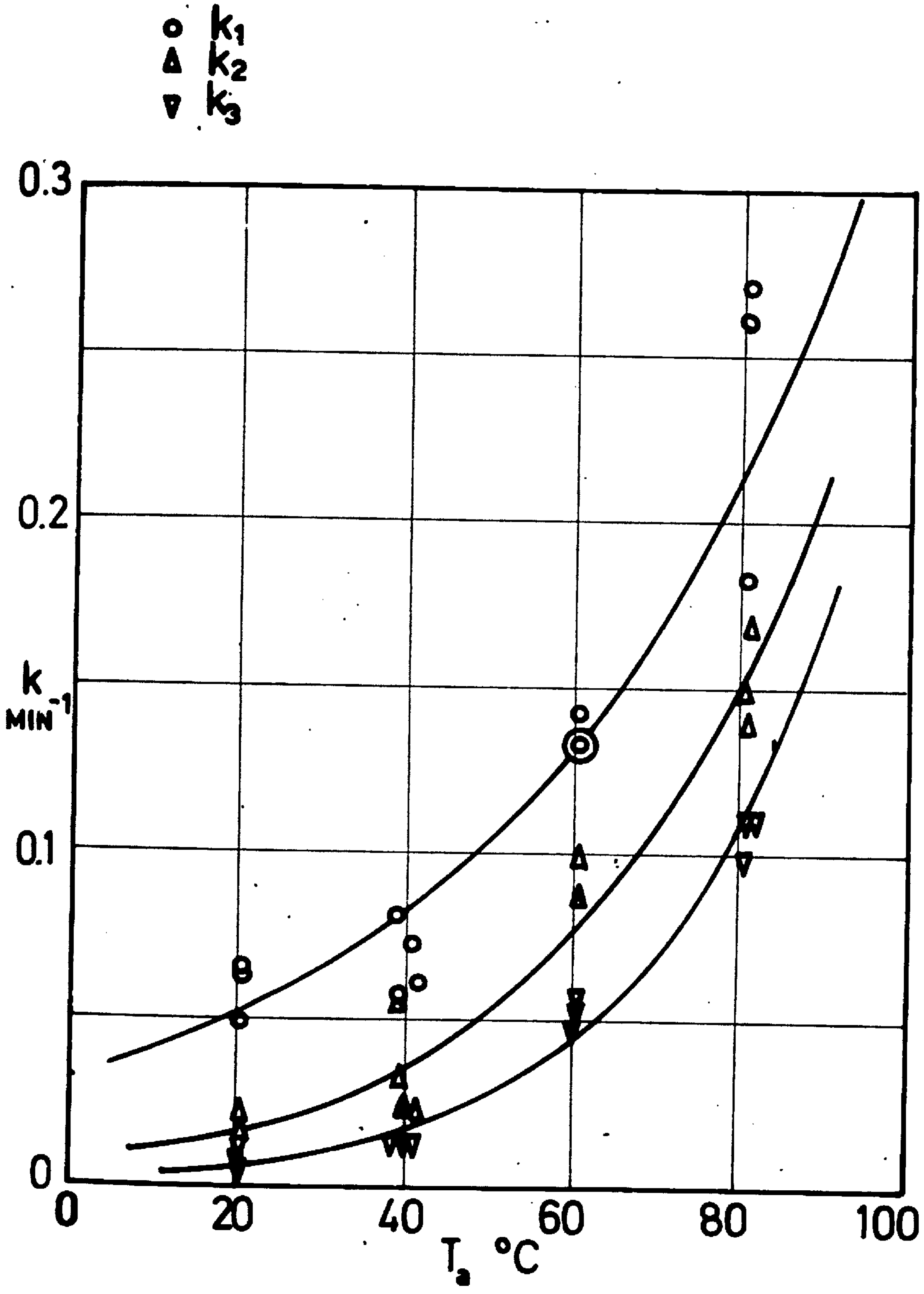


FIG.5.32. k_1 vs. T_a Two-period curves Medium Temp.Rig.

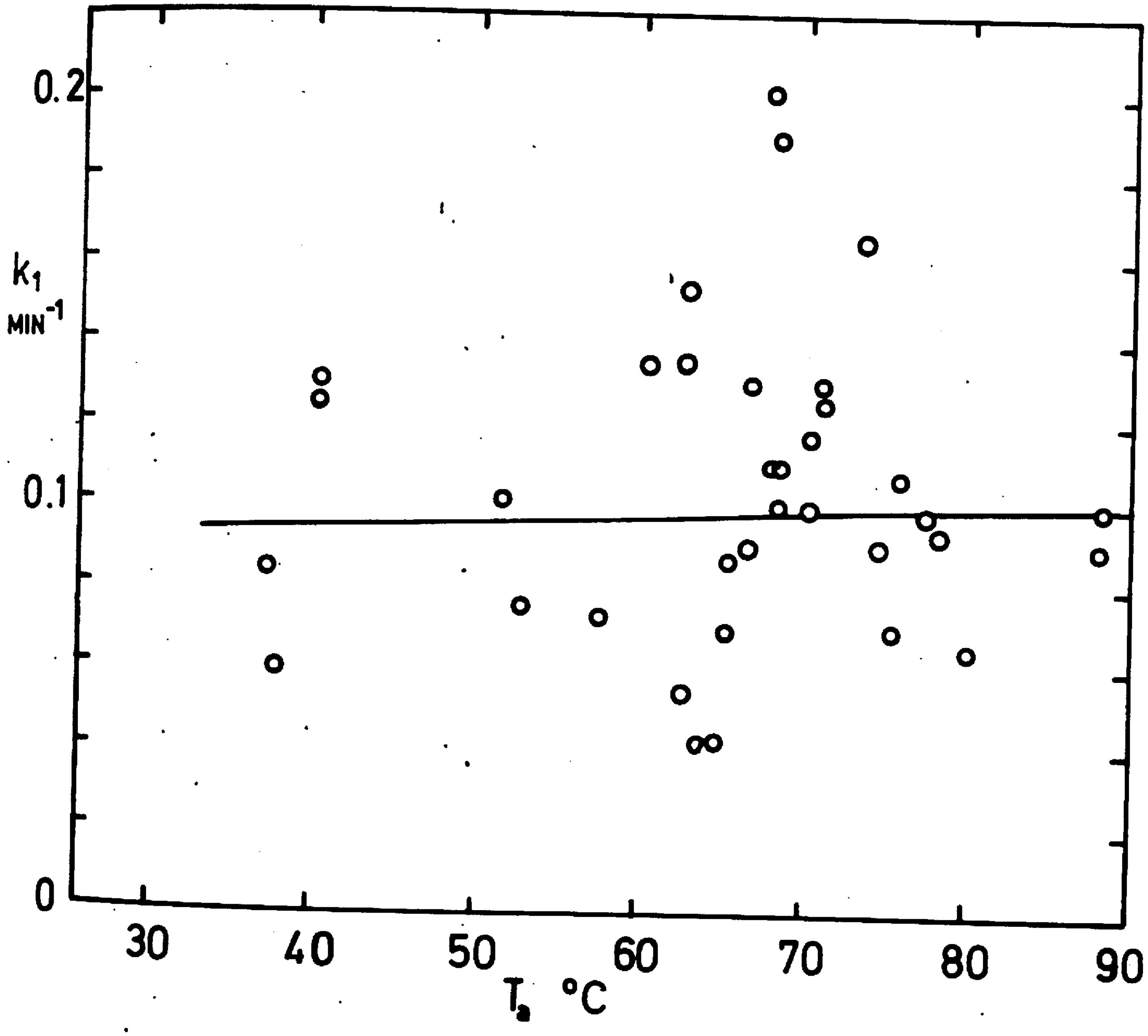


FIG.5.33. k_2 vs. T_a Two-period curves
Medium Temp. Rig

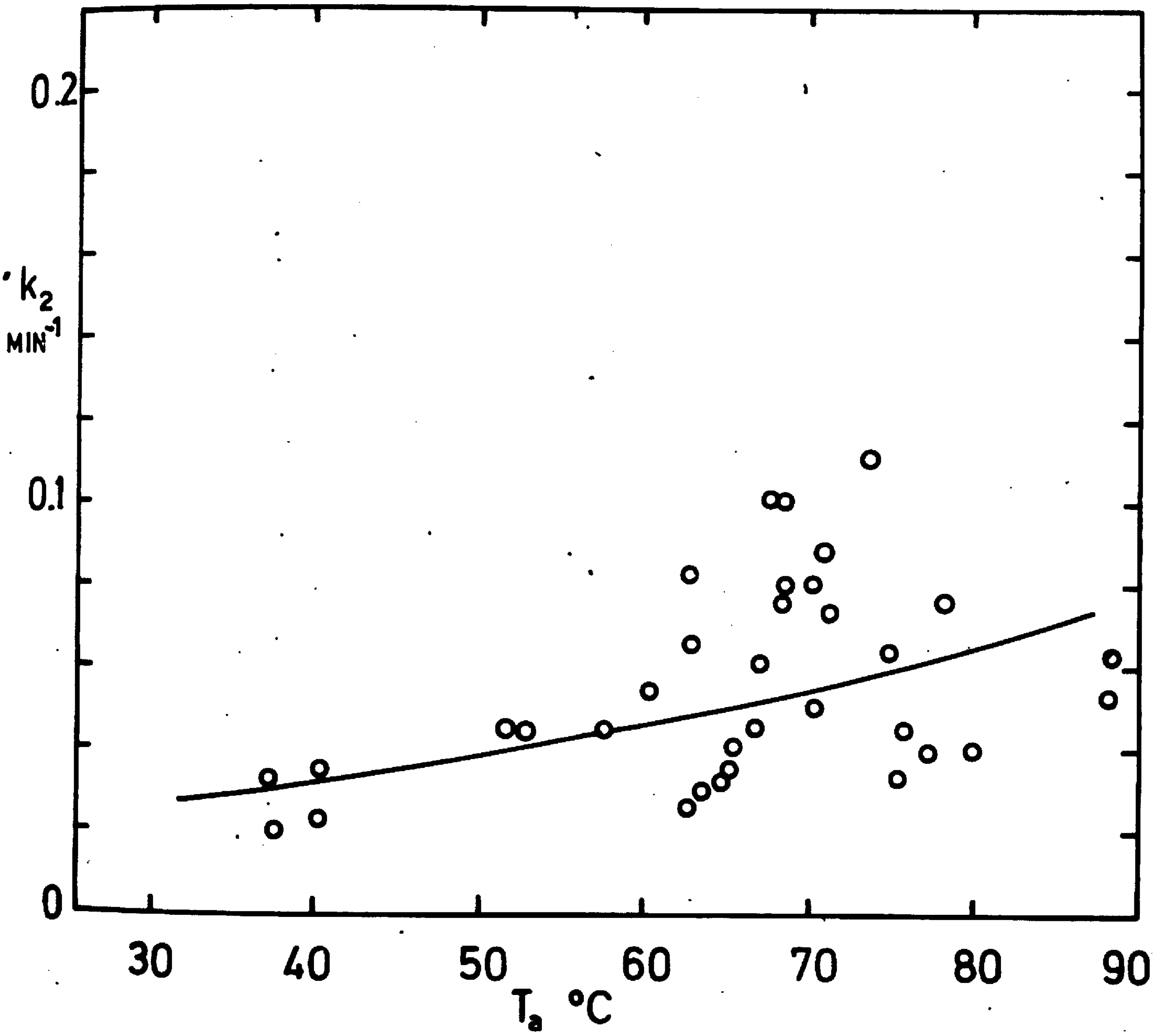


FIG.5.34. k vs. v BATCH 20

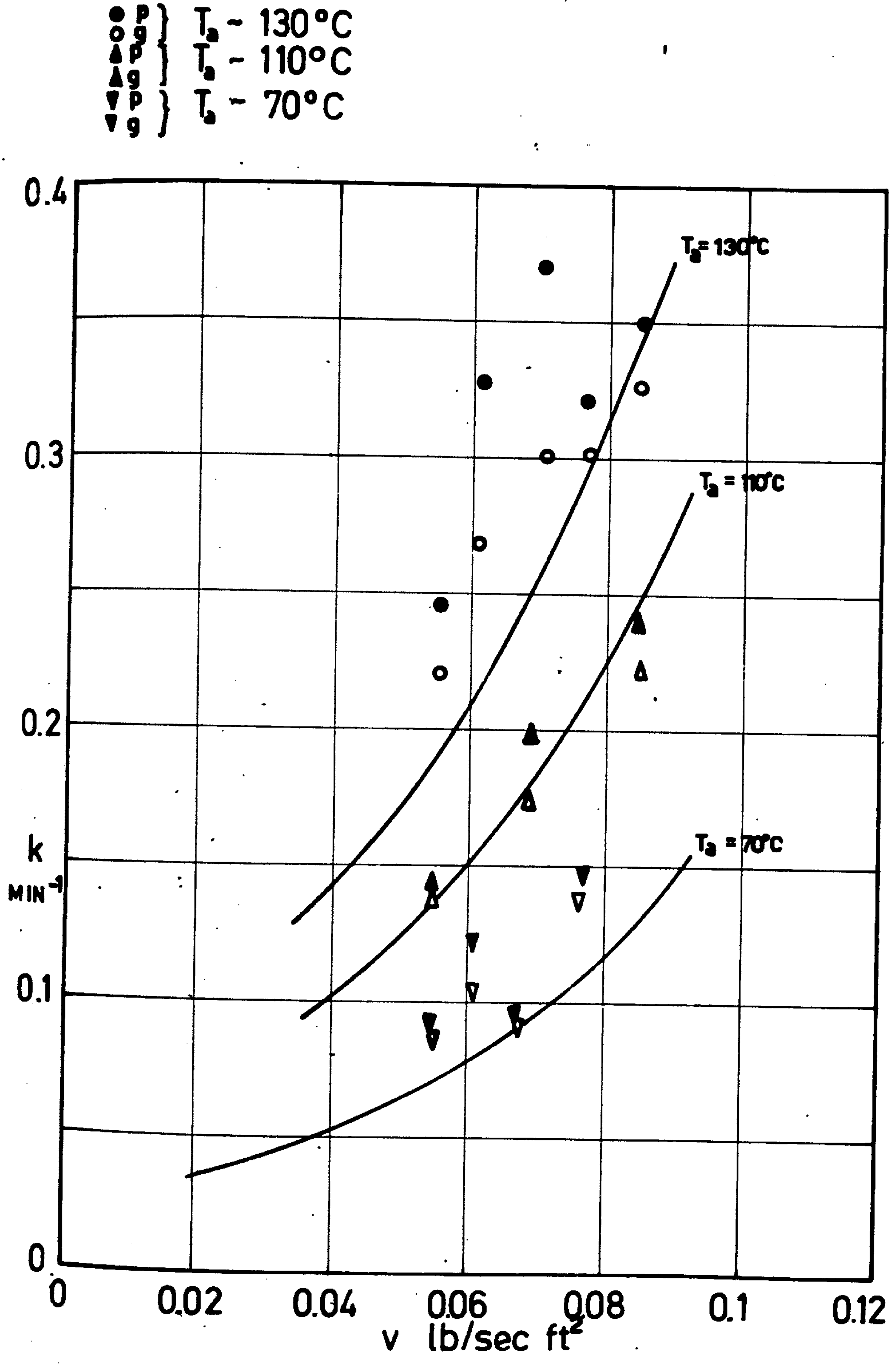


FIG. 5.35 k vs. v BATCH 21

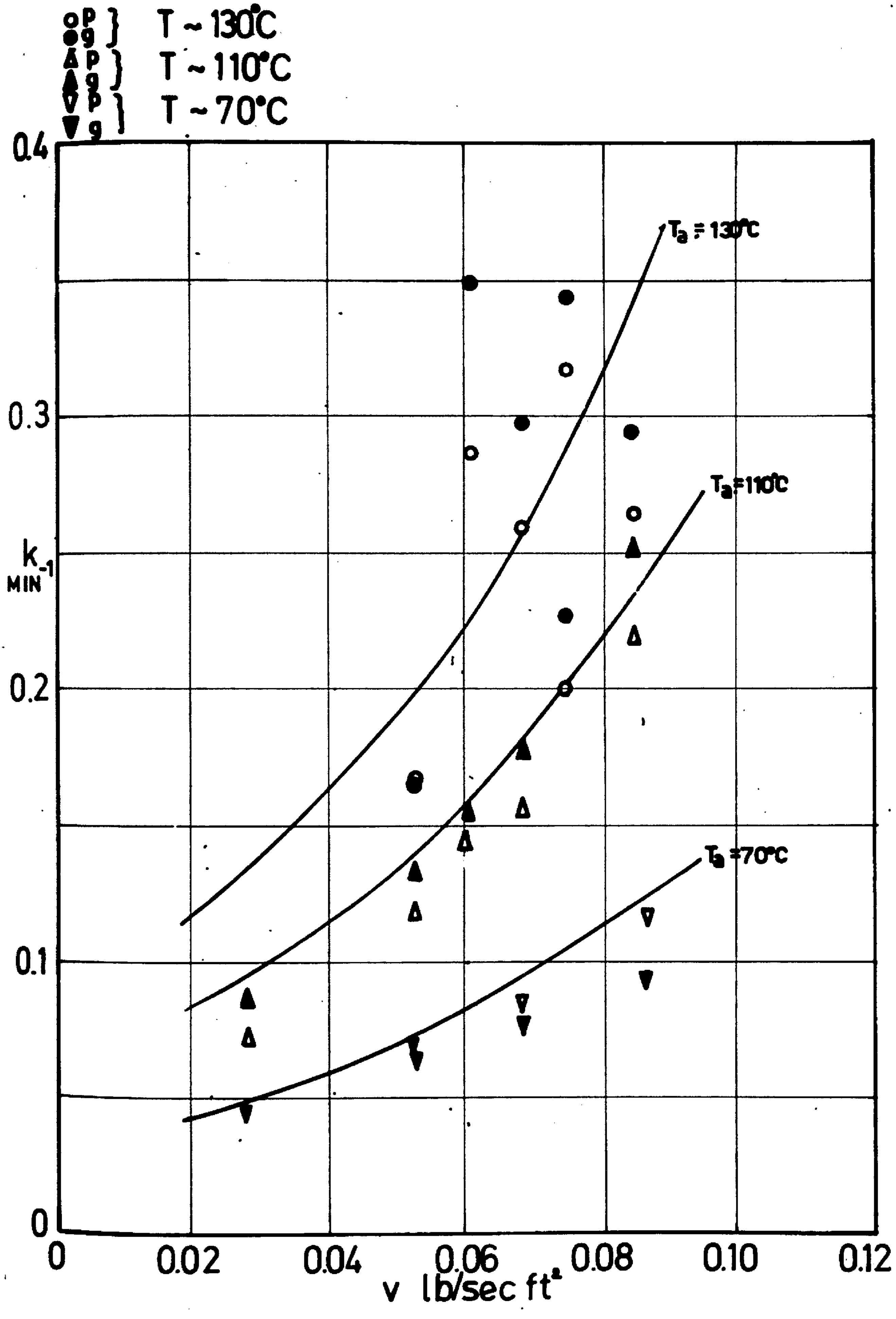


FIG.5.36. k vs. v BATCH 22

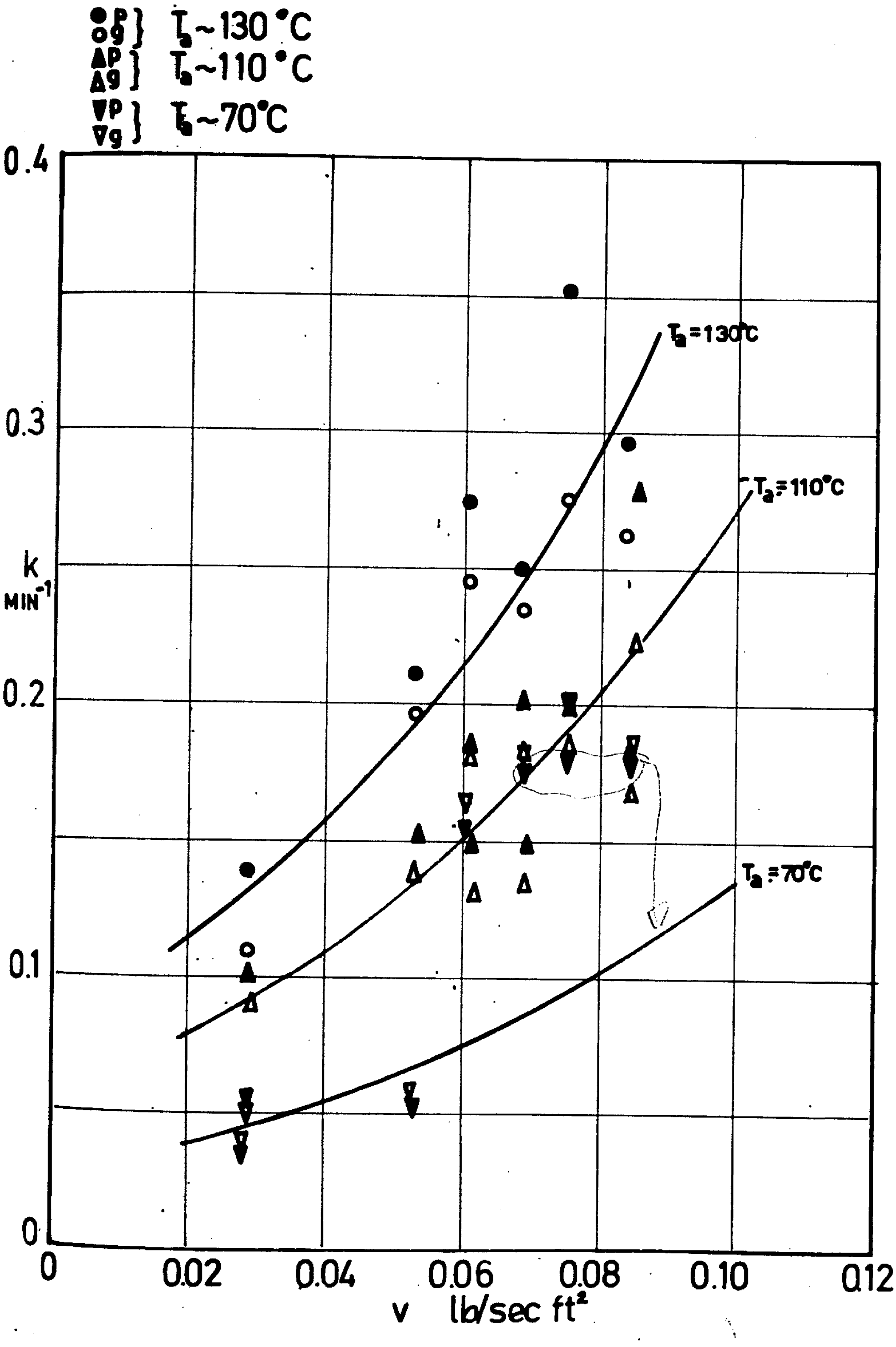


FIG.5.37. k vs T_a WHOLE GRASS RUNS 316-410

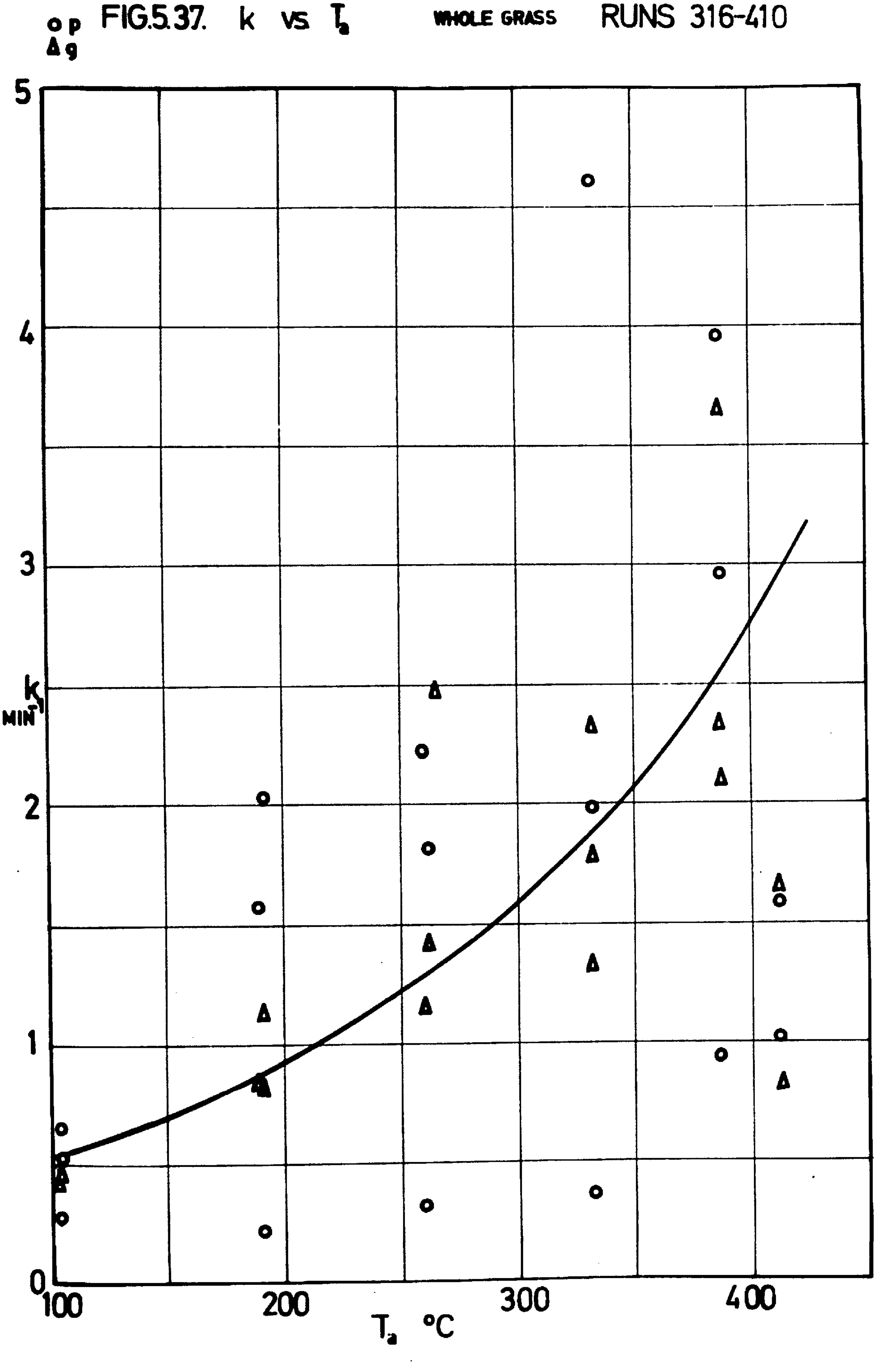


FIG.5.38 k vs. T_a

I.R.G.LEAVES
RUNS 322-408

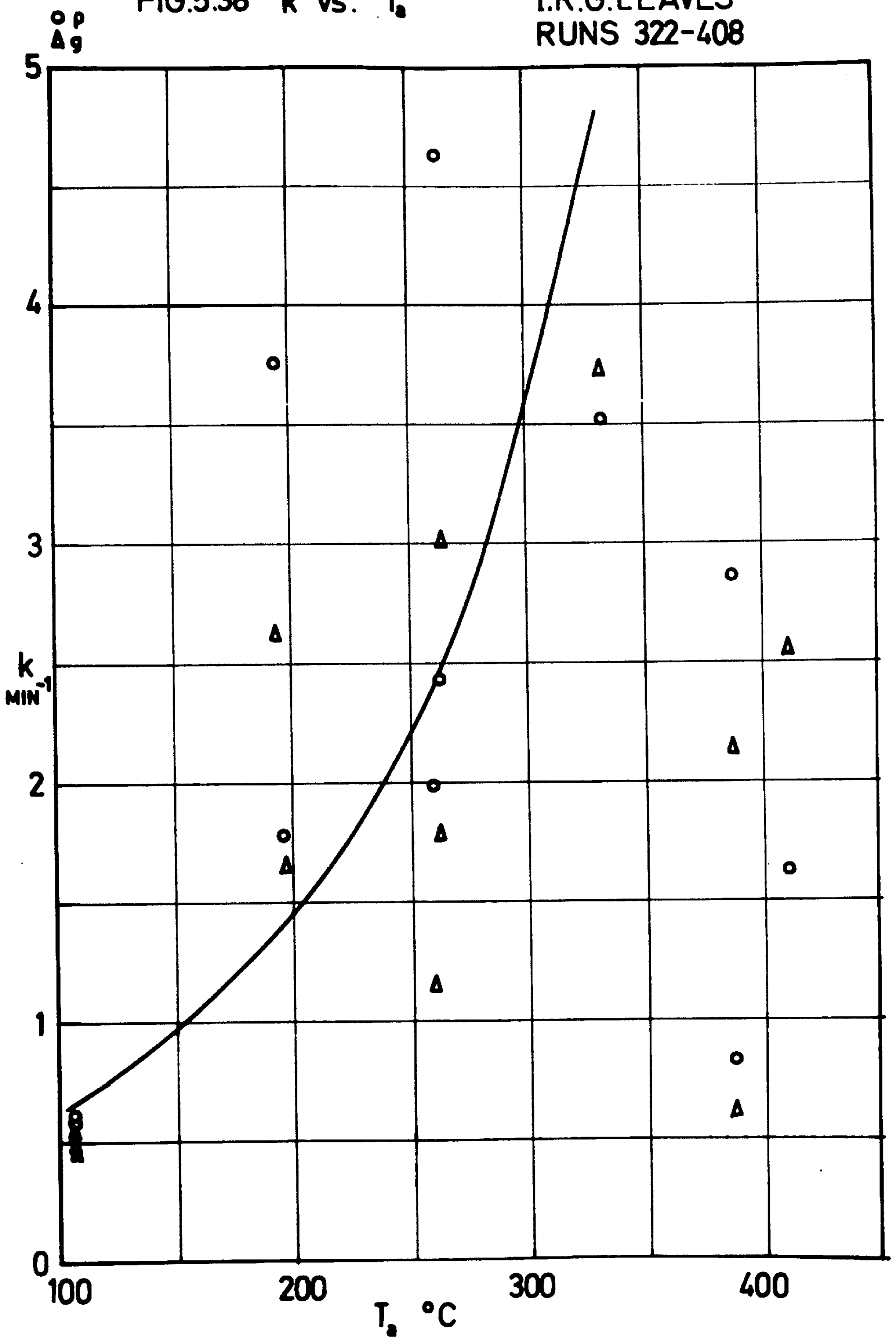


FIG.5.39. k vs. T_a I.R.G. STEMS RUNS 319-407

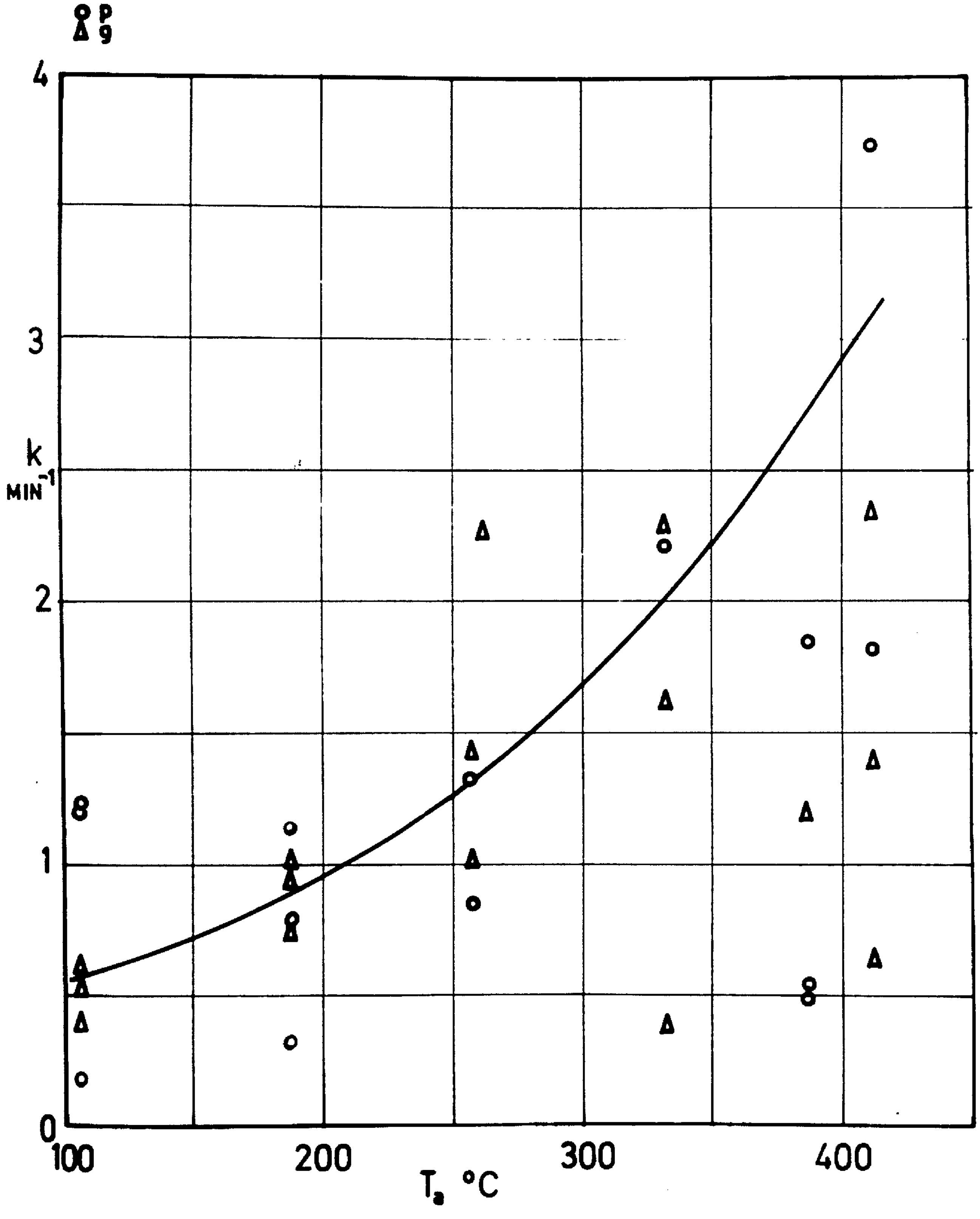


FIG.540 k vs. T_a PERENNIAL RYE GRASS
RUNS 315-404

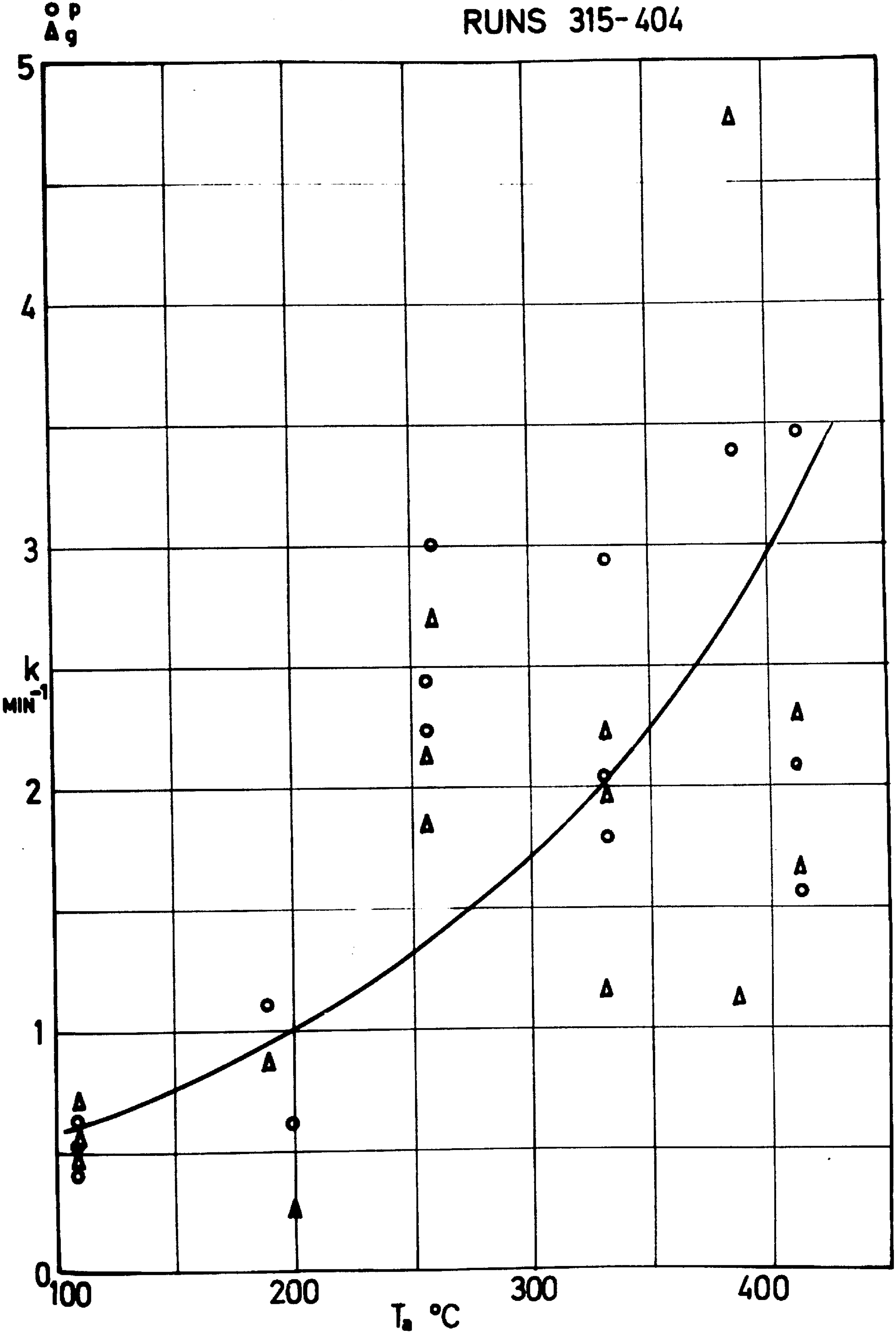


FIG.5.41 k vs. T_a RUNS 378-401

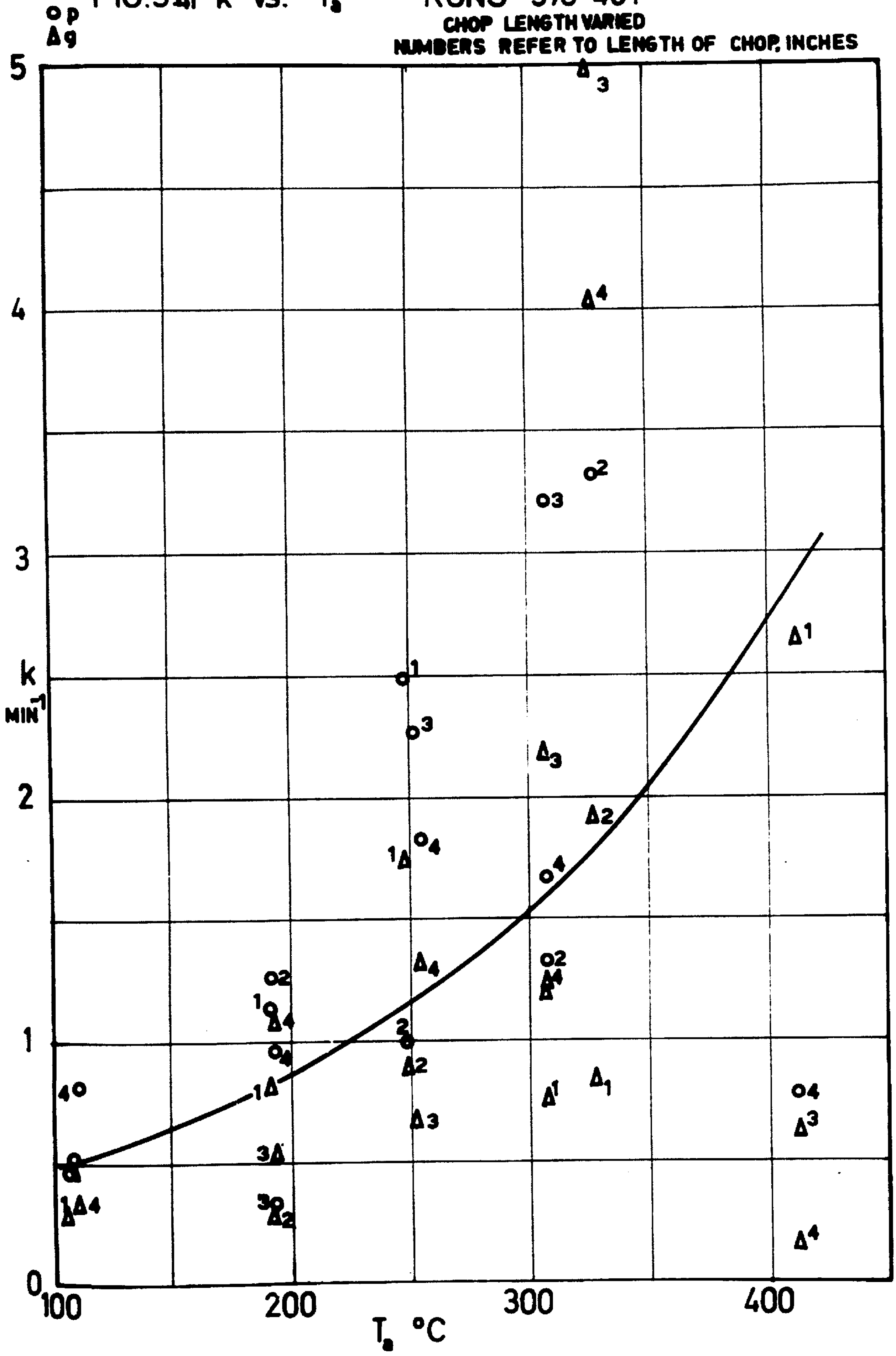


FIG.5.42. k vs. T_a BATCH 33

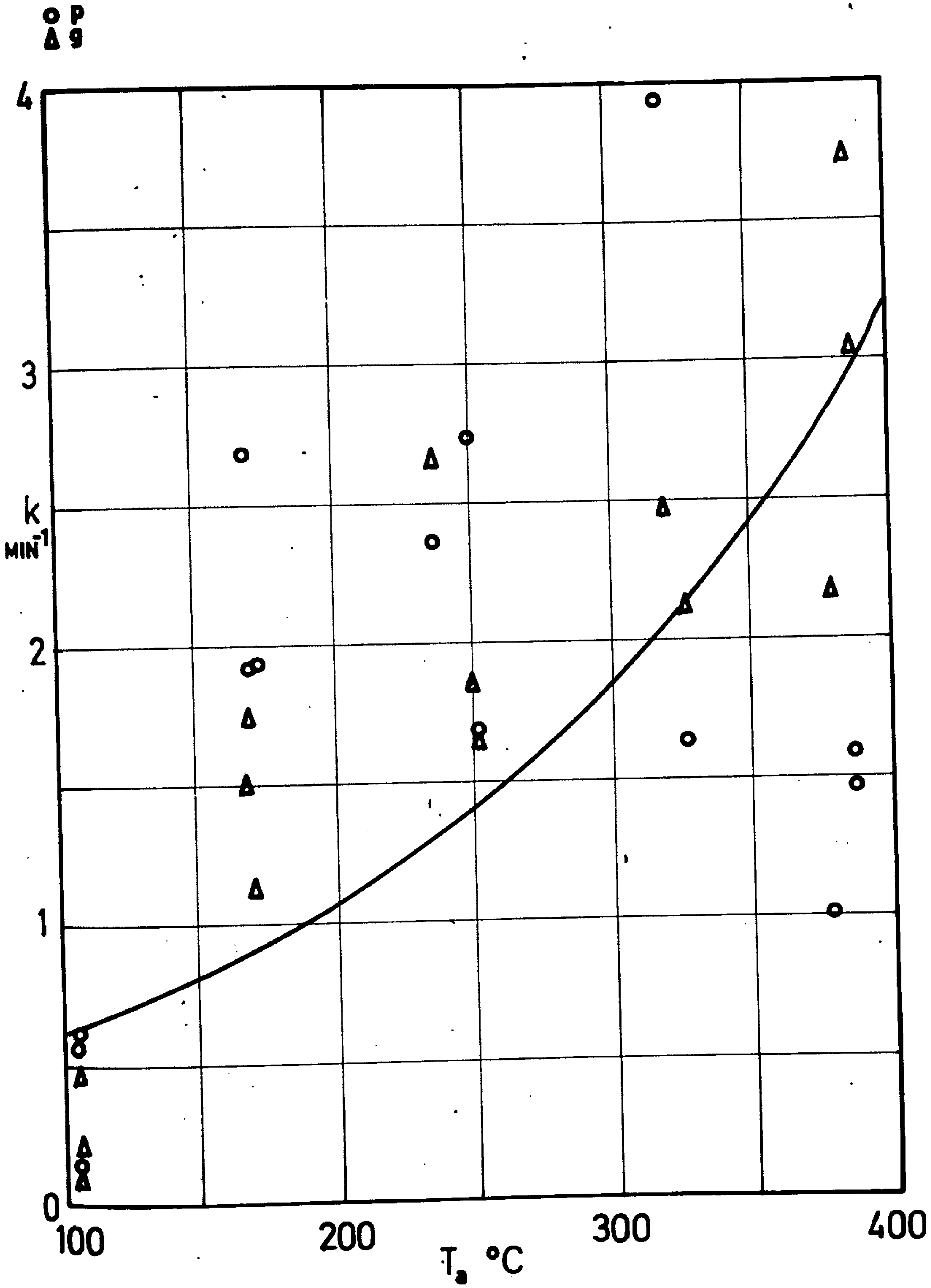


FIG.5.43. k vs. T_a BATCH 34

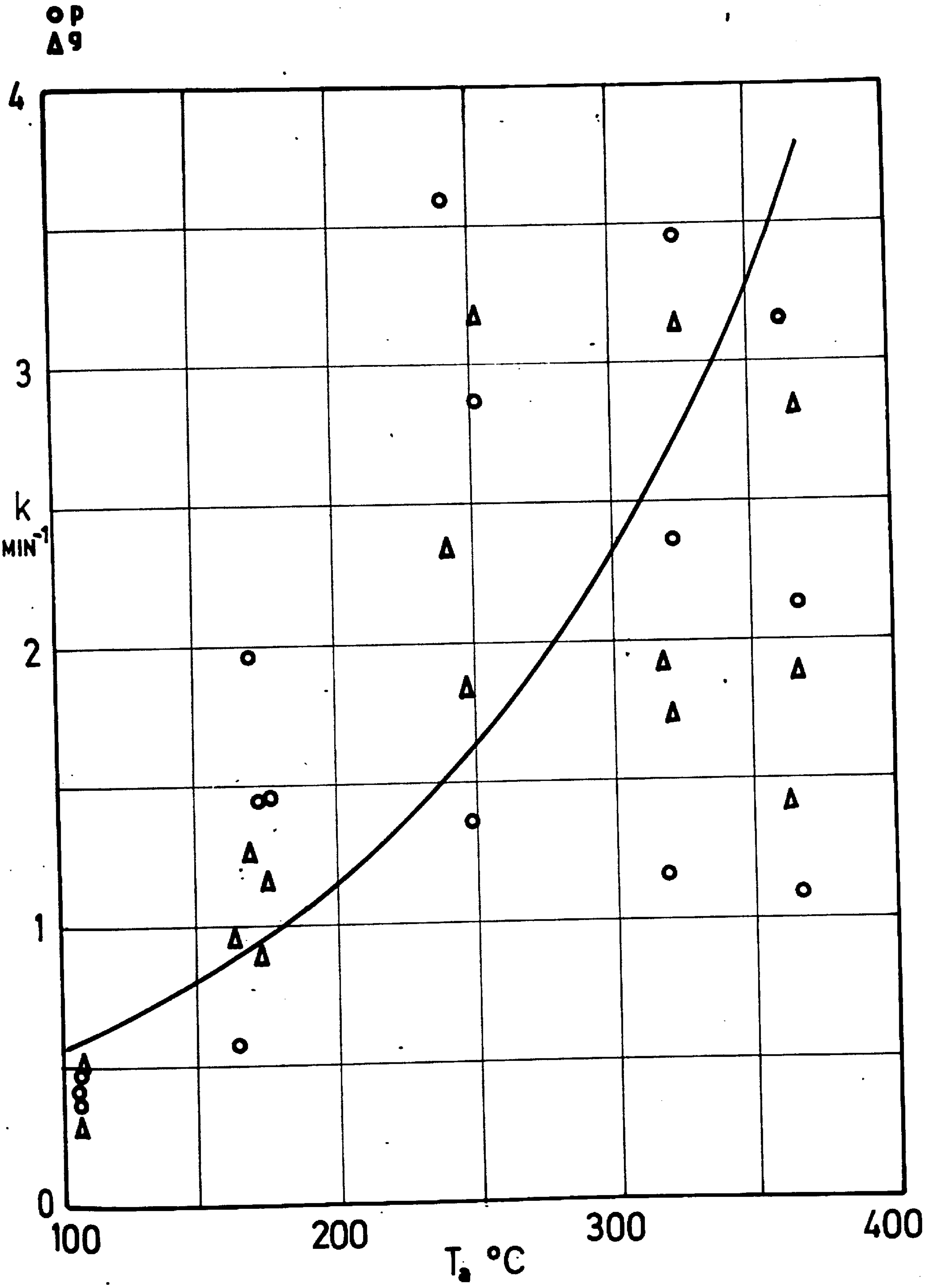


FIG.5.44 k vs. T_a BATCH 35

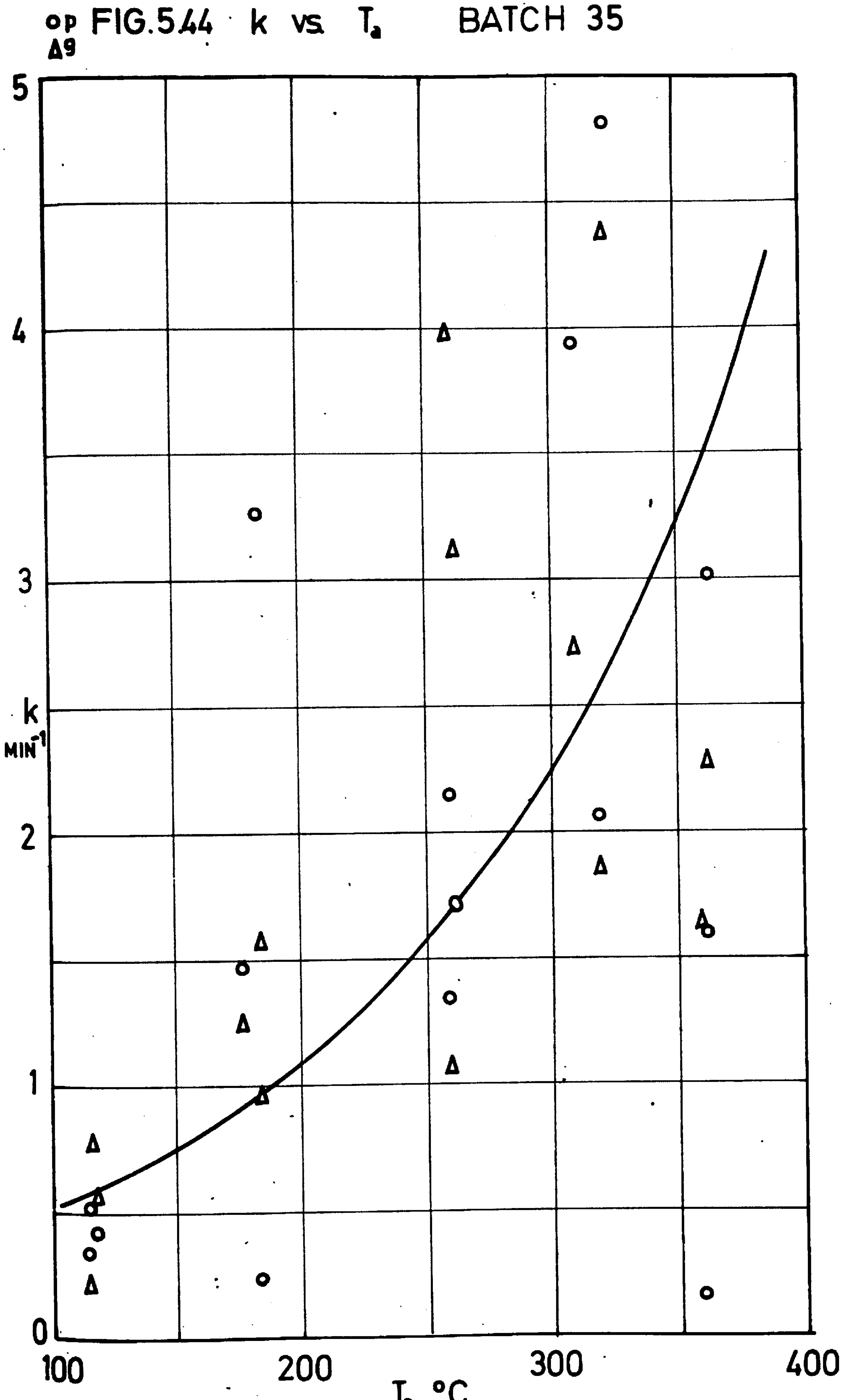


FIG.5.45. k vs. T_a BATCH 36

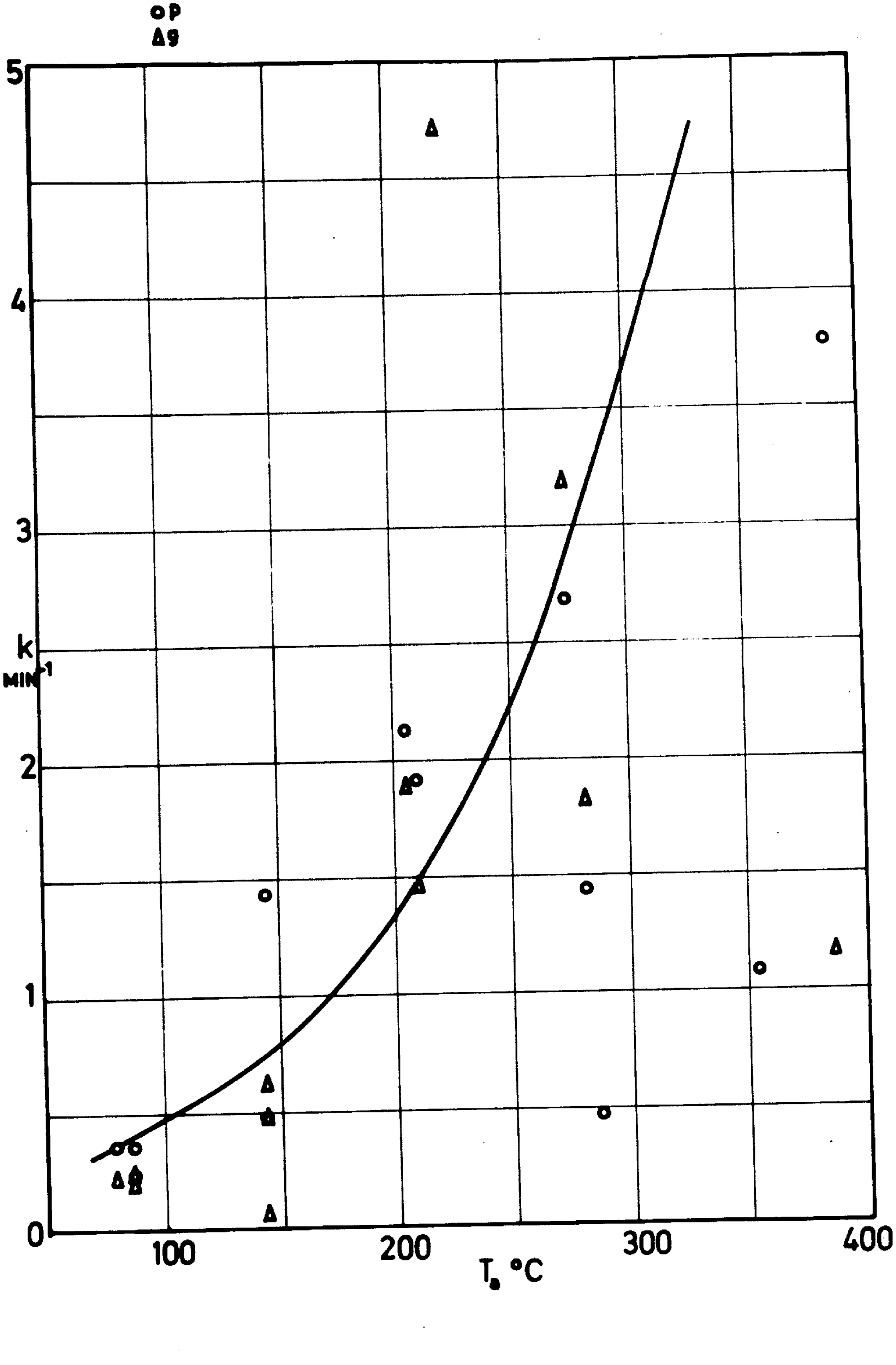


FIG.5.46. k vs. T_a BATCHES 37&38

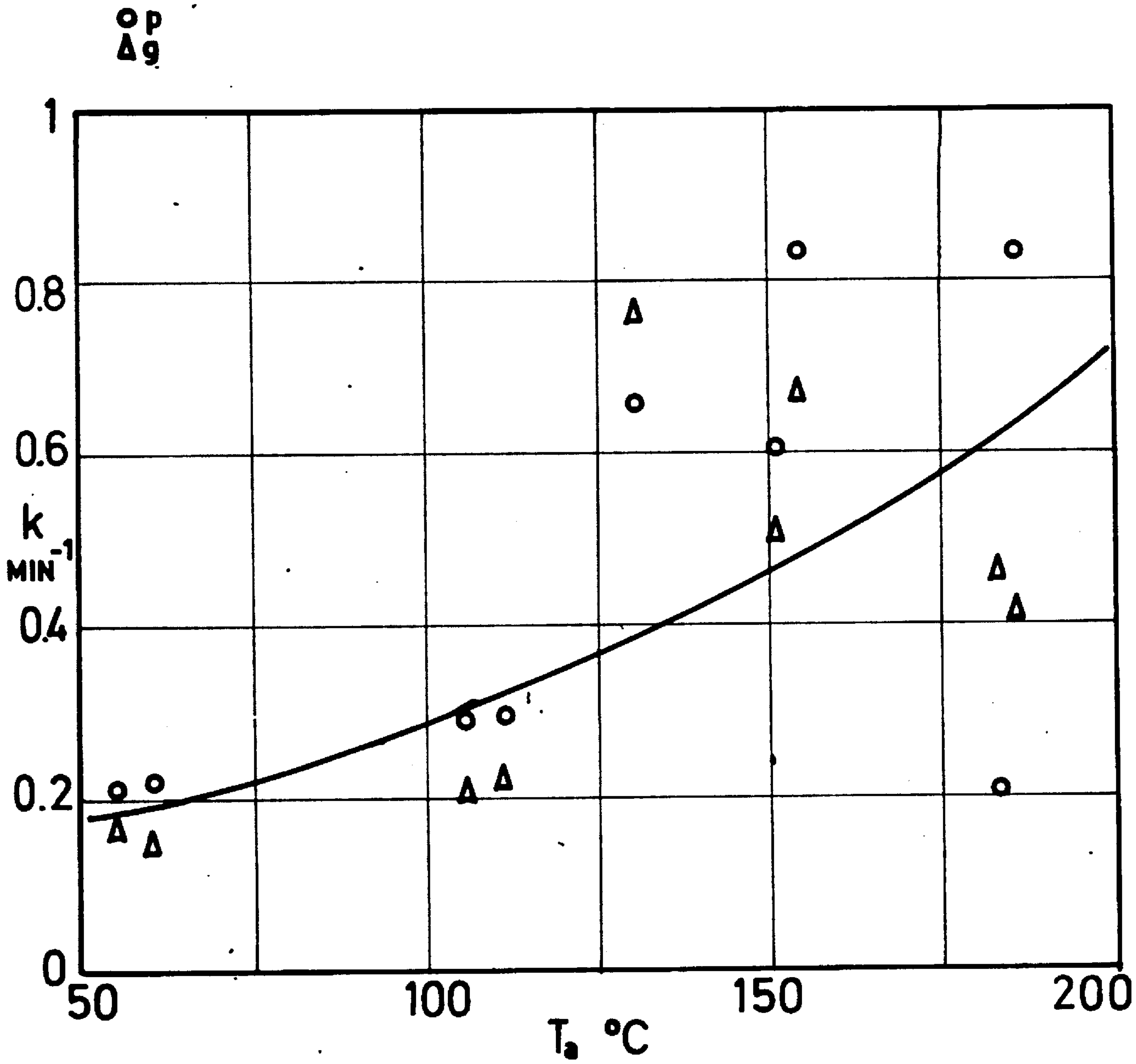


FIG. 5.47. k vs. T_a BATCH 39

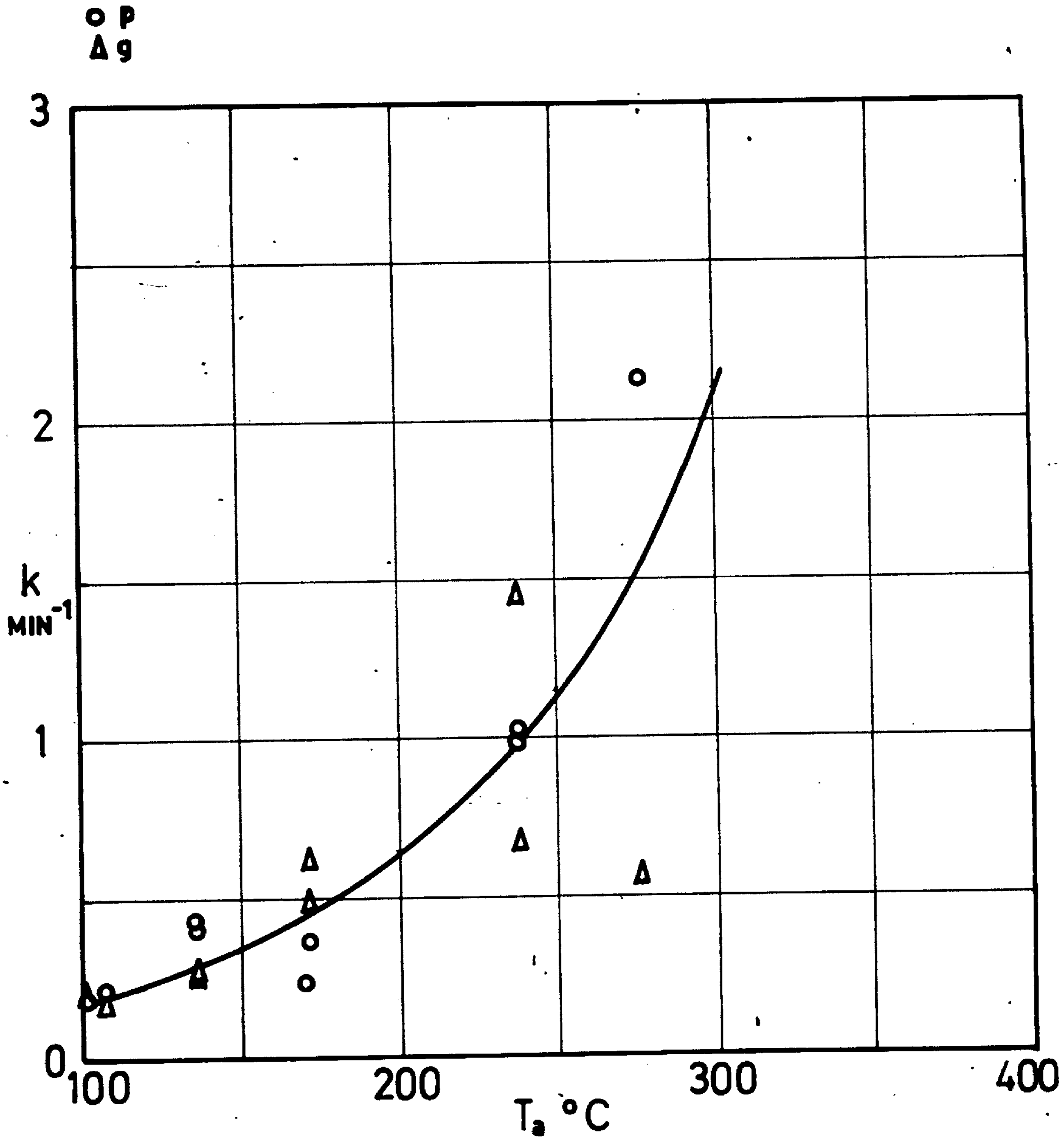


FIG.548 k vs. T_a BATCH 40

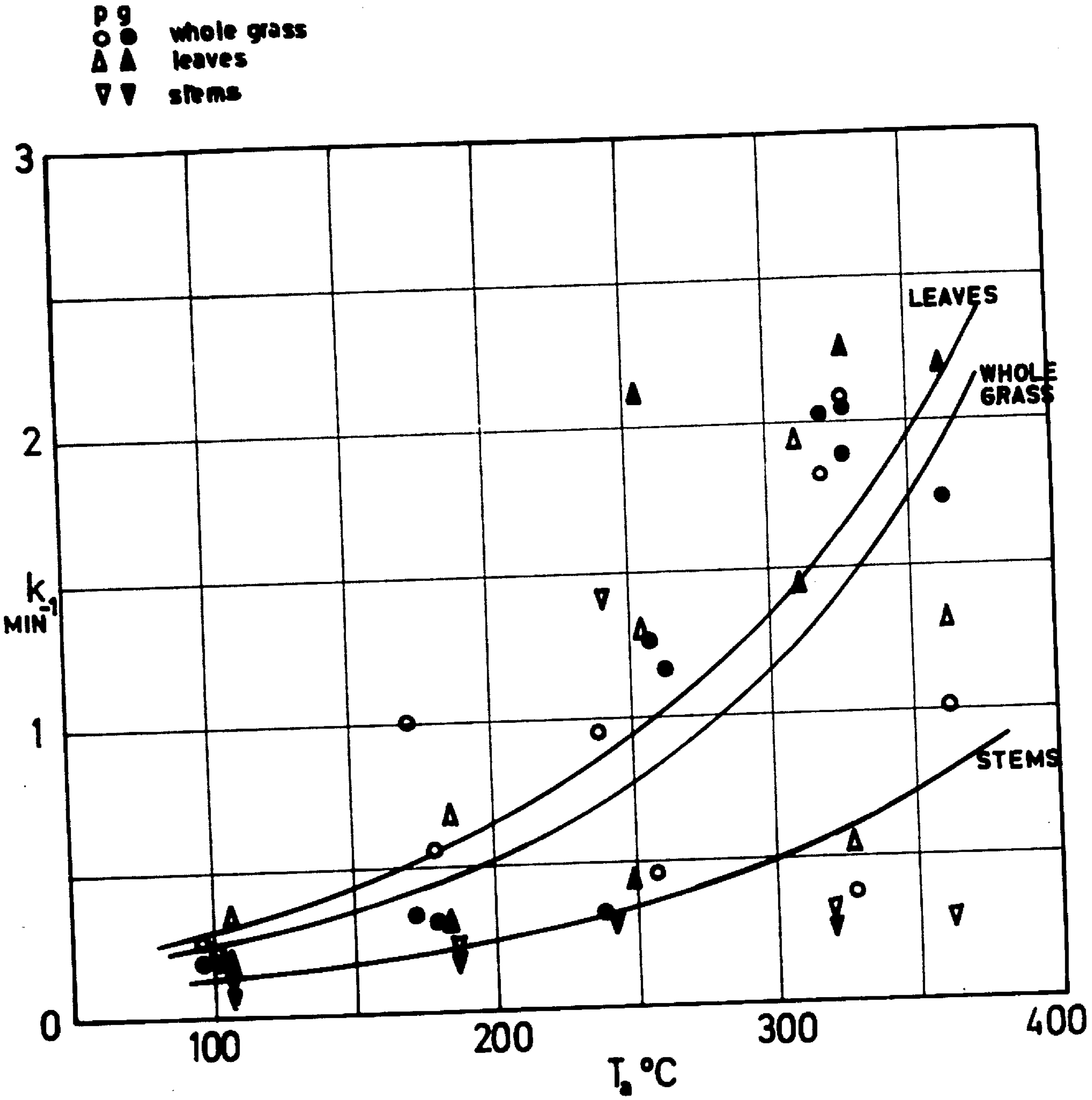


FIG.549 k vs. T_a BATCH 41

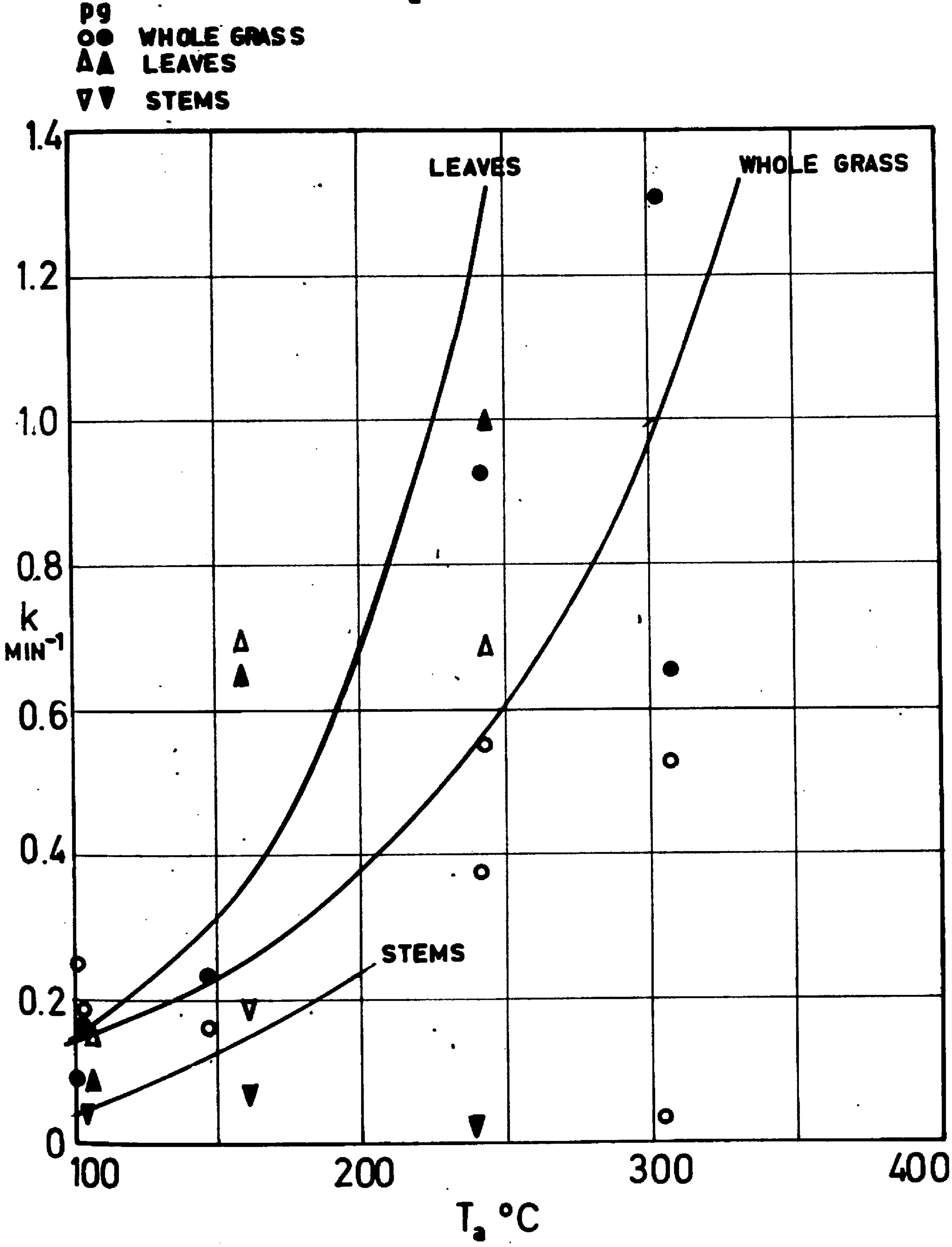


FIG.5.50.

m_e vs. T_a

MEDIUM TEMPERATURE EXPERIMENTS
PROGRAMME RESULTS

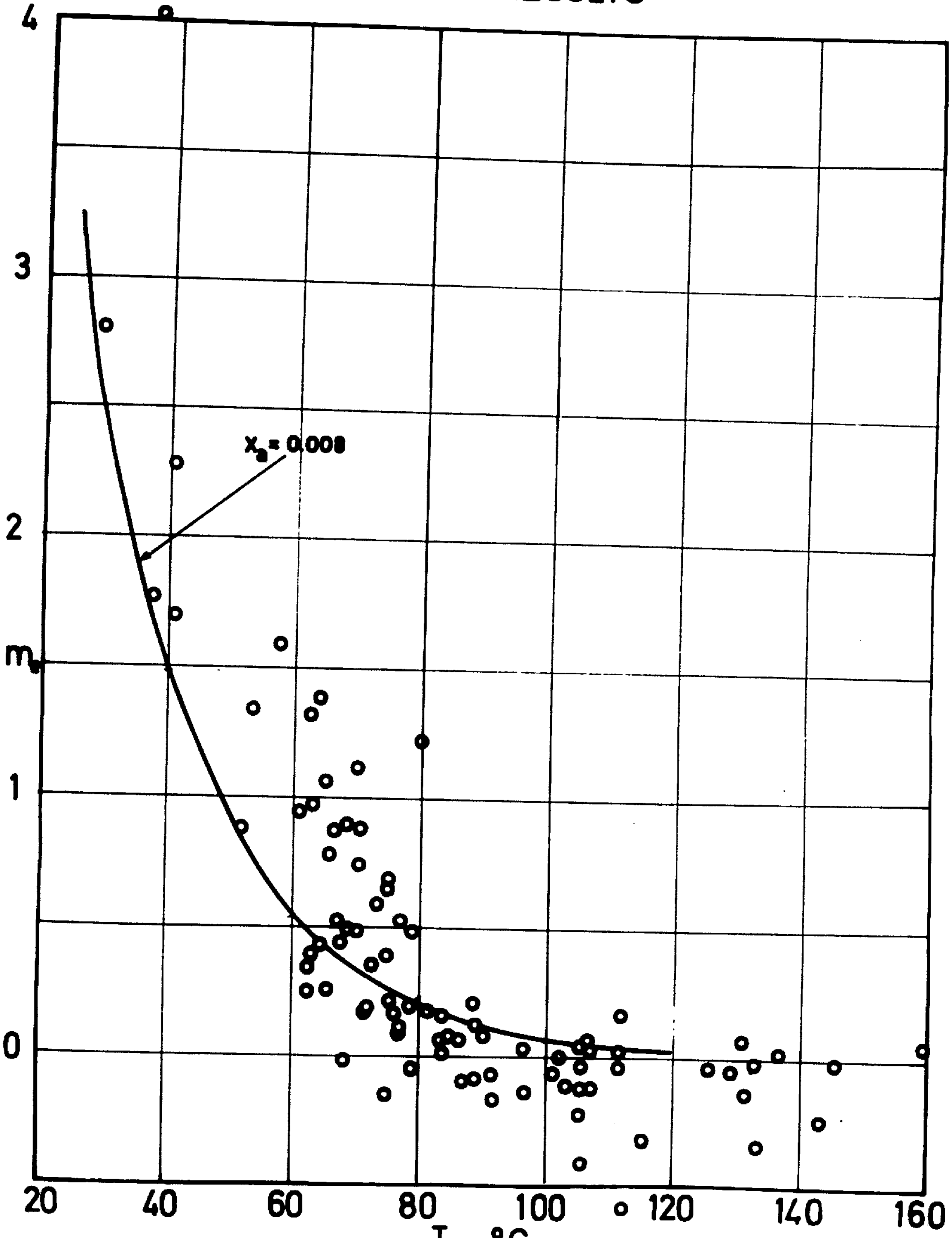


FIG.5.51.

MEDIUM TEMPERATURE EXPERIMENTS
m_e vs. T_a
GRAPHICAL RESULTS

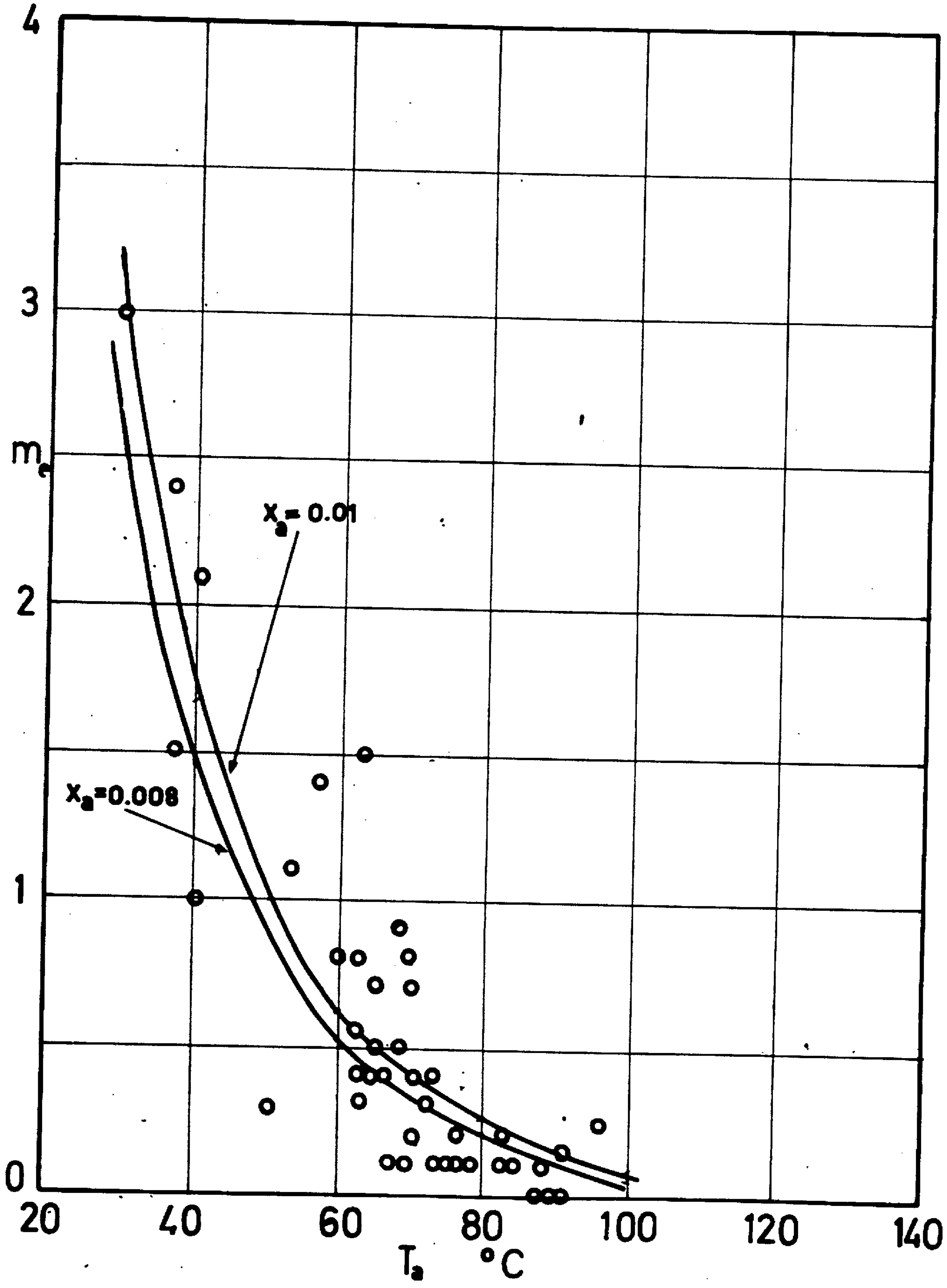


FIG. 5.52. m_{e1} vs. T_a MEDIUM TEMPERATURE EXPERIMENTS

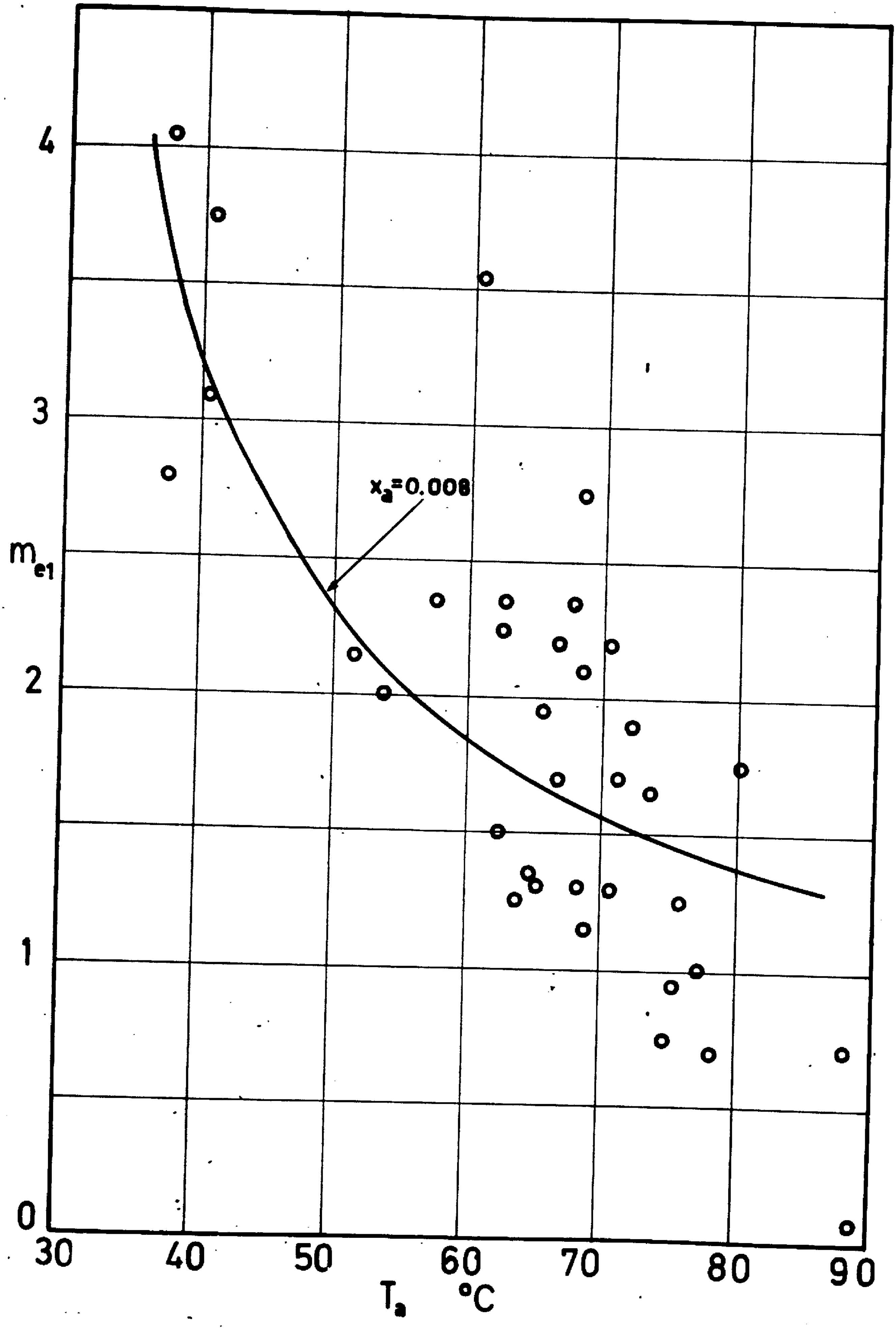
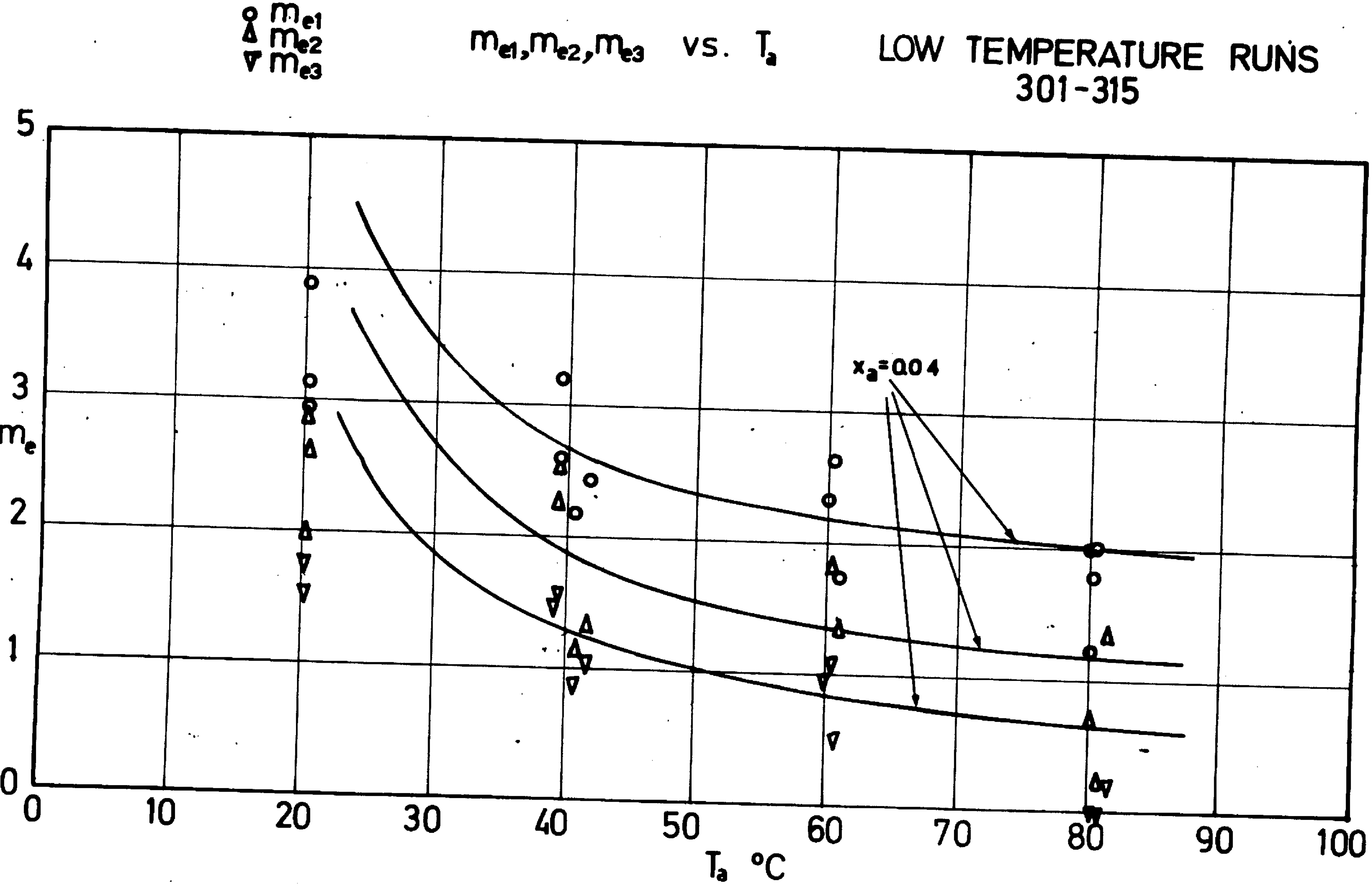


FIG.5.53.



m_{e1}, m_{e2}, m_{e3} vs. T_a

LOW TEMPERATURE RUNS
301-315

FIG.5.54 k_0 vs. T_a Whole grass
RUNS 316-410

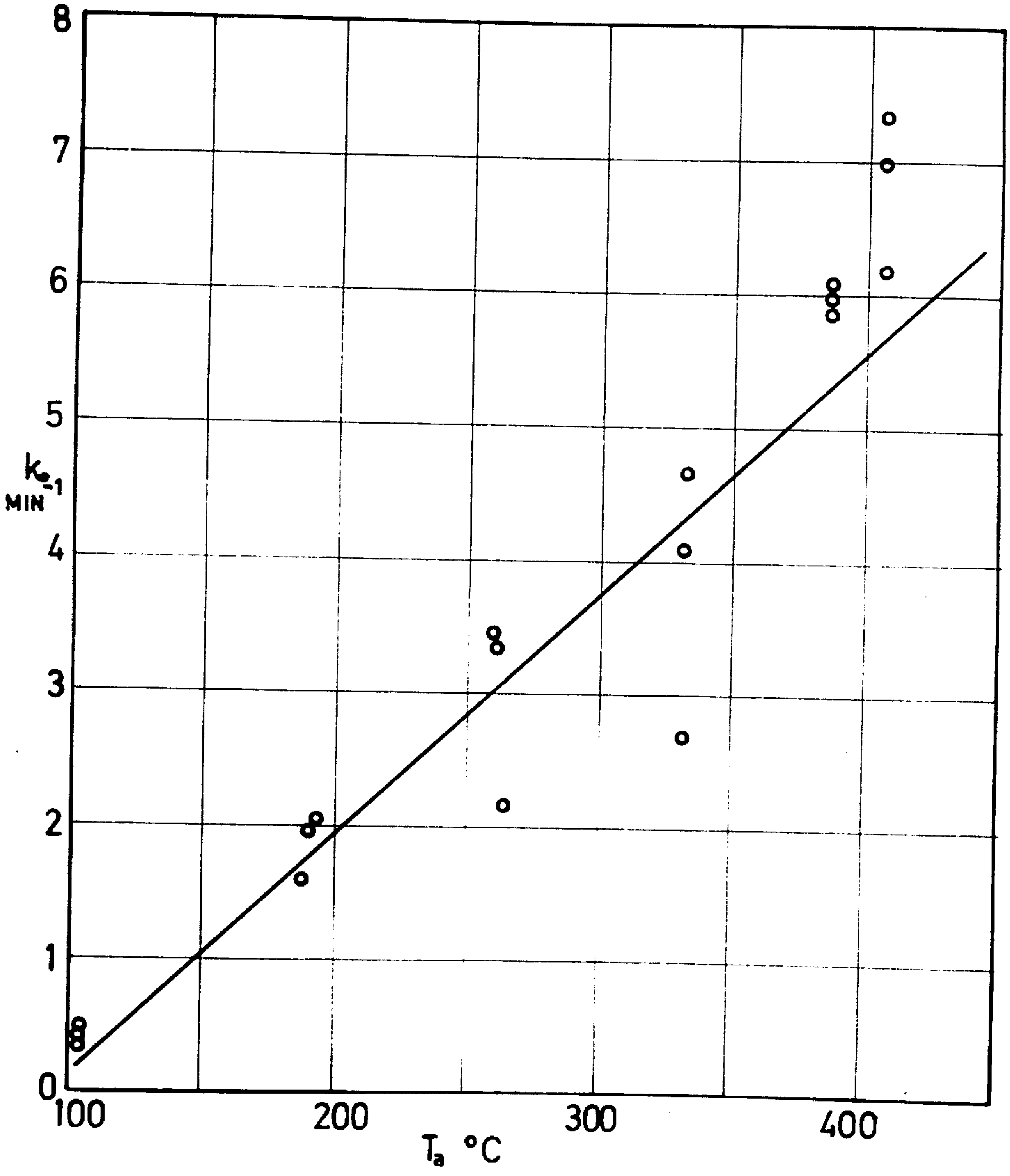


FIG.5.55. k_o vs. T_a Leaves RUNS 322-408

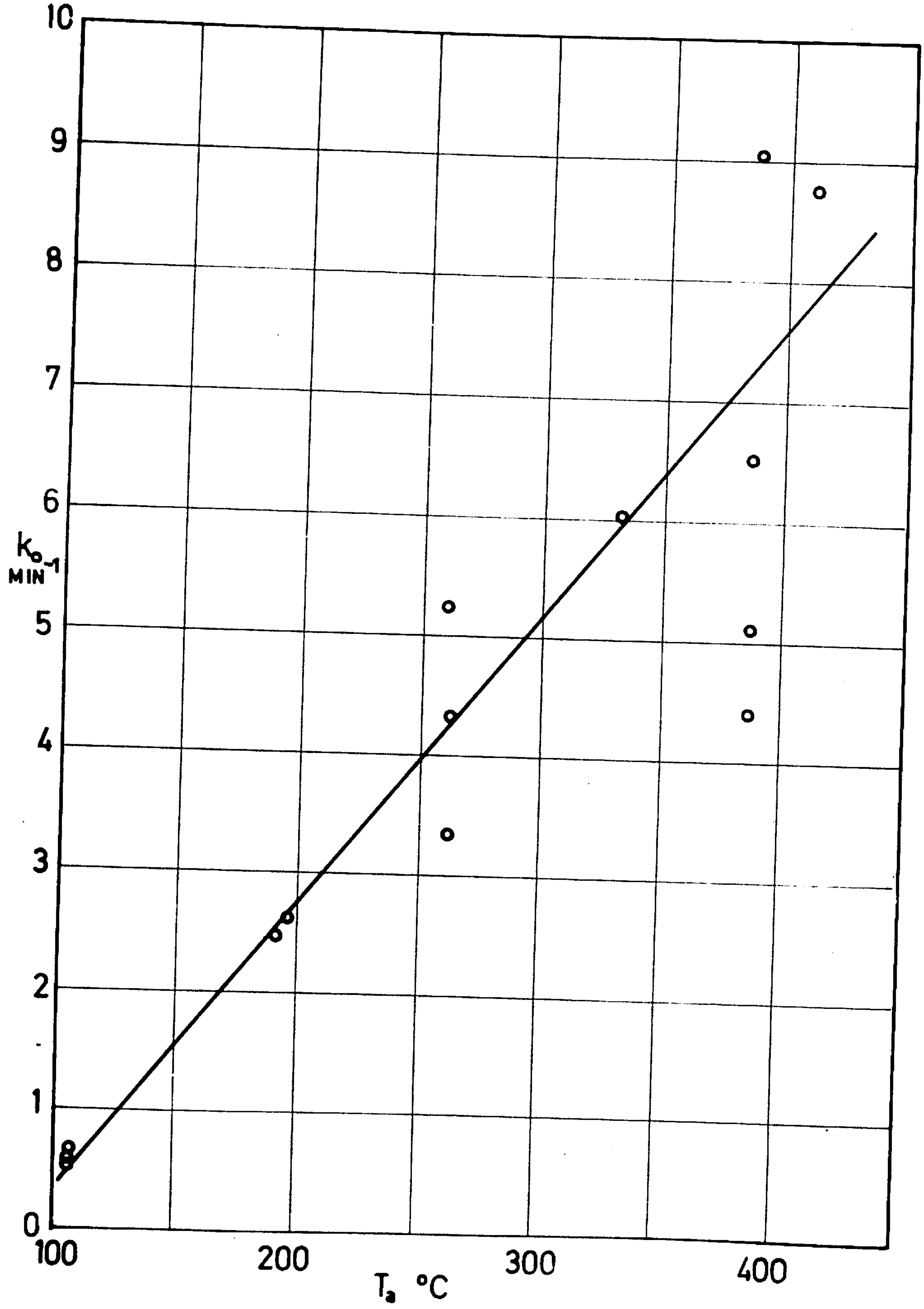


FIG. 5.56. k_o vs. T_a STEMS RUNS 319-407

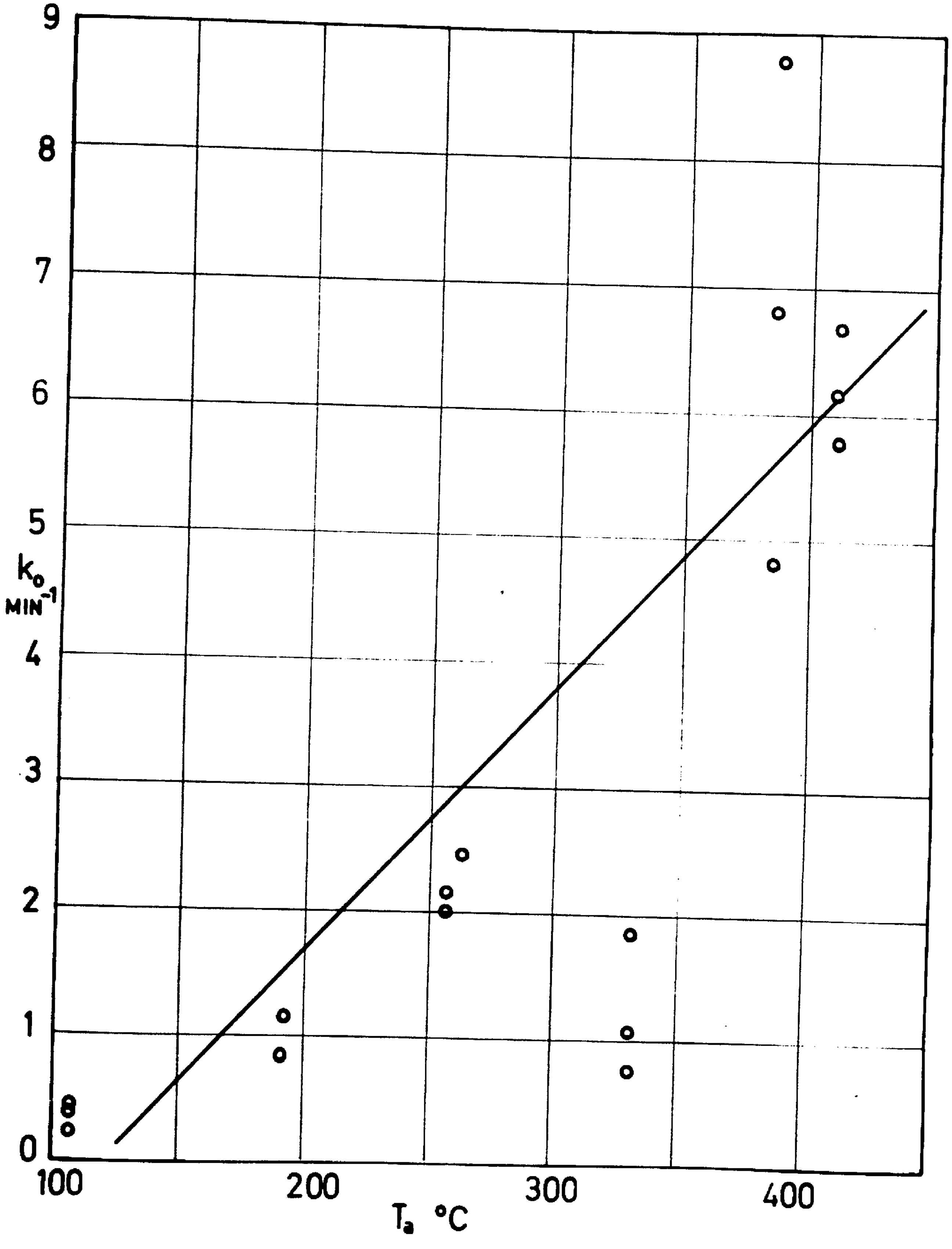


FIG. 5.57 k_o vs. T_a Perennial Rye Grass

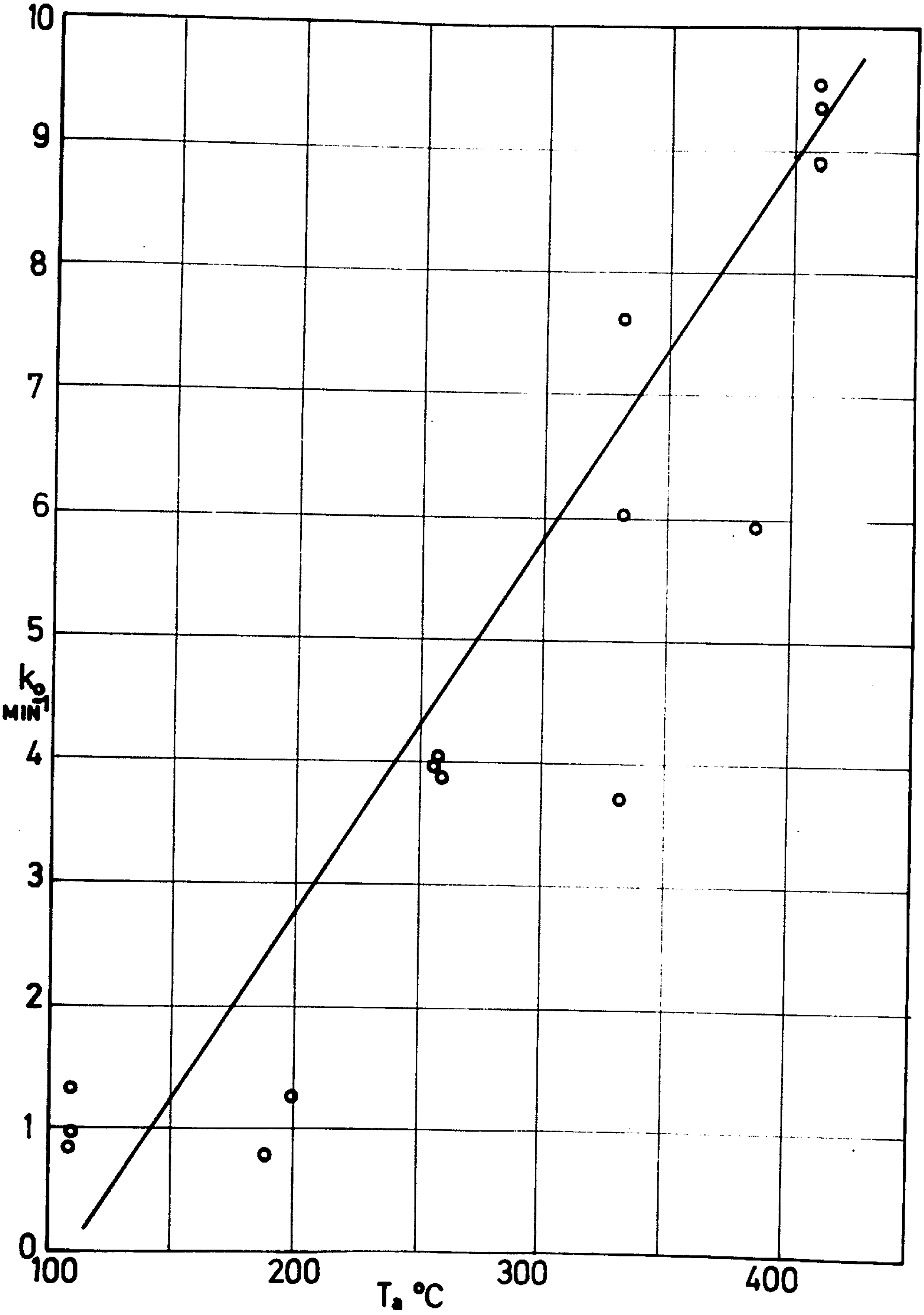


FIG. 558. k_o VS. T_a RUNS 378-401

NUMBERS REFER TO LENGTH OF CHOP. INCHES

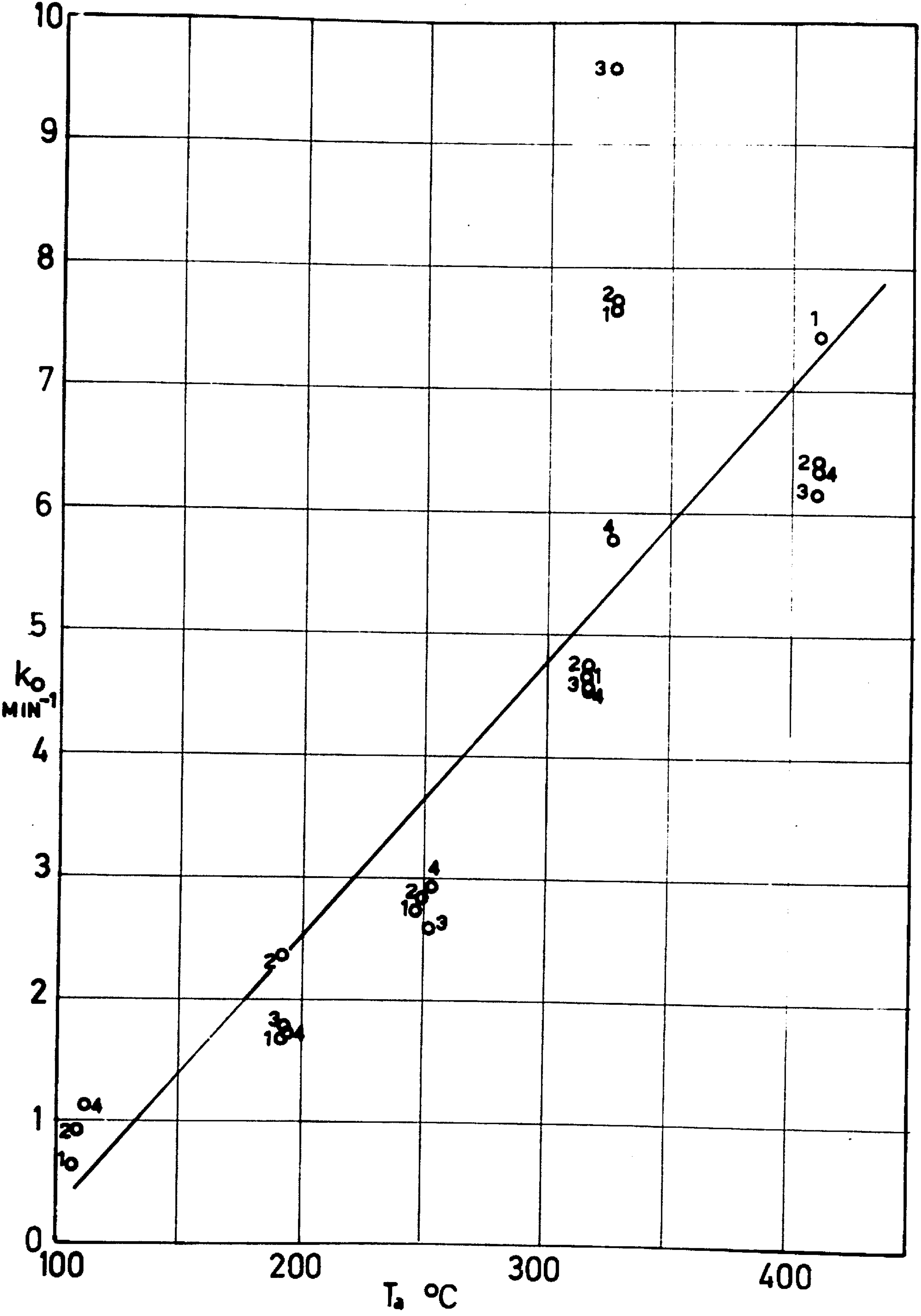


FIG. 5. 59 k_o vs. T_a BATCH 33

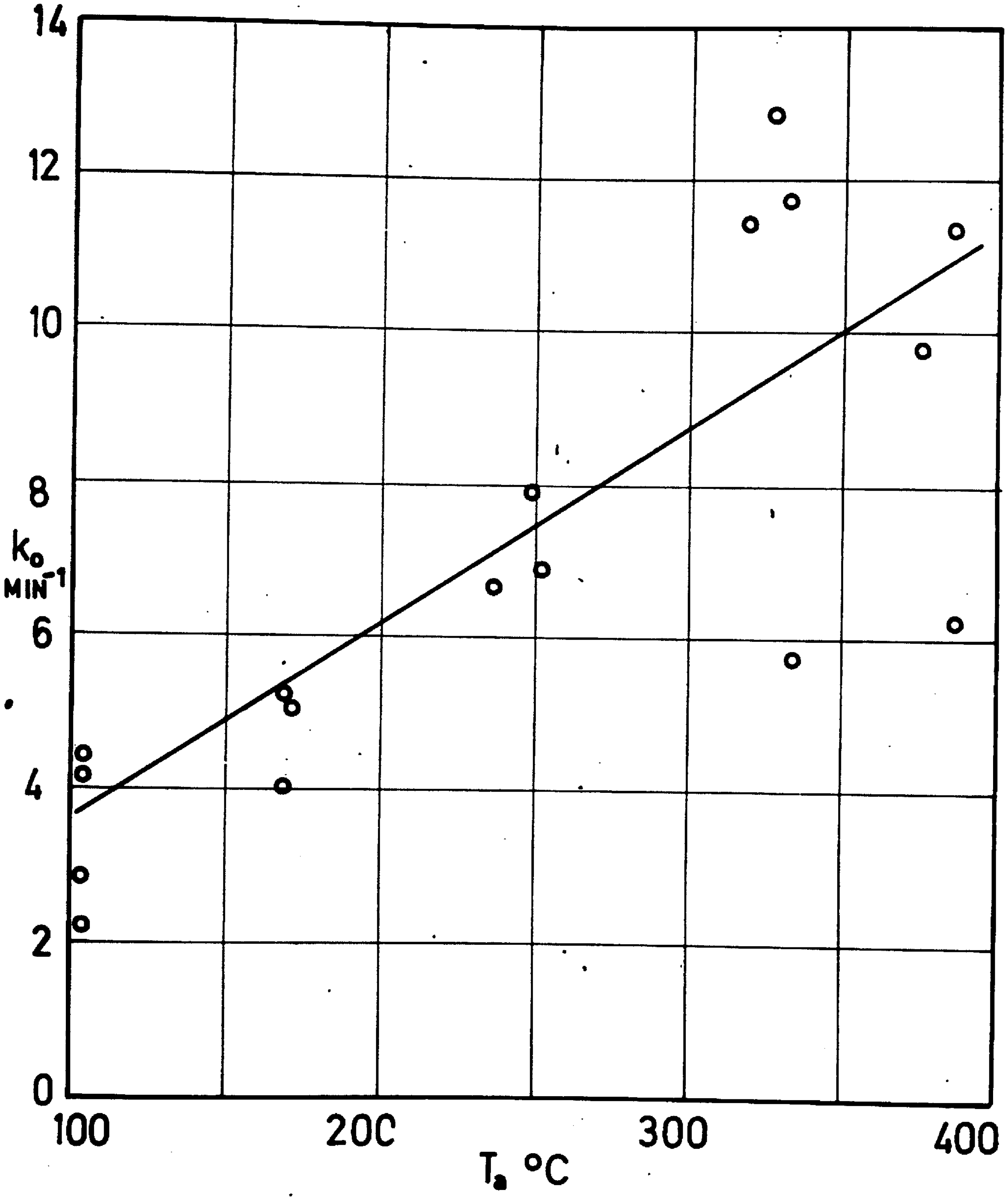


FIG.5.60 k_o vs. T_a BATCH 34

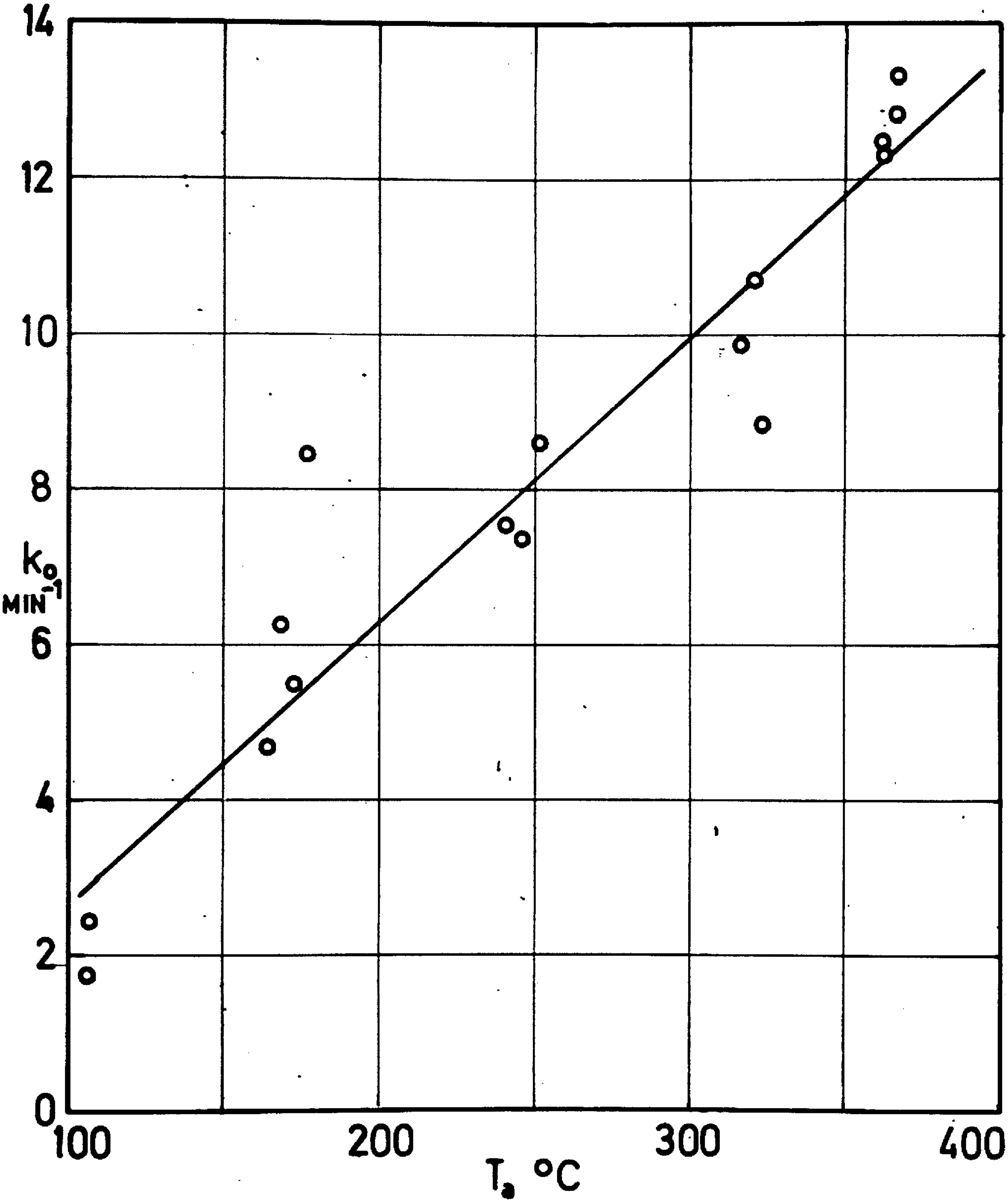


FIG.5.61. k_o vs. T_a BATCH 35

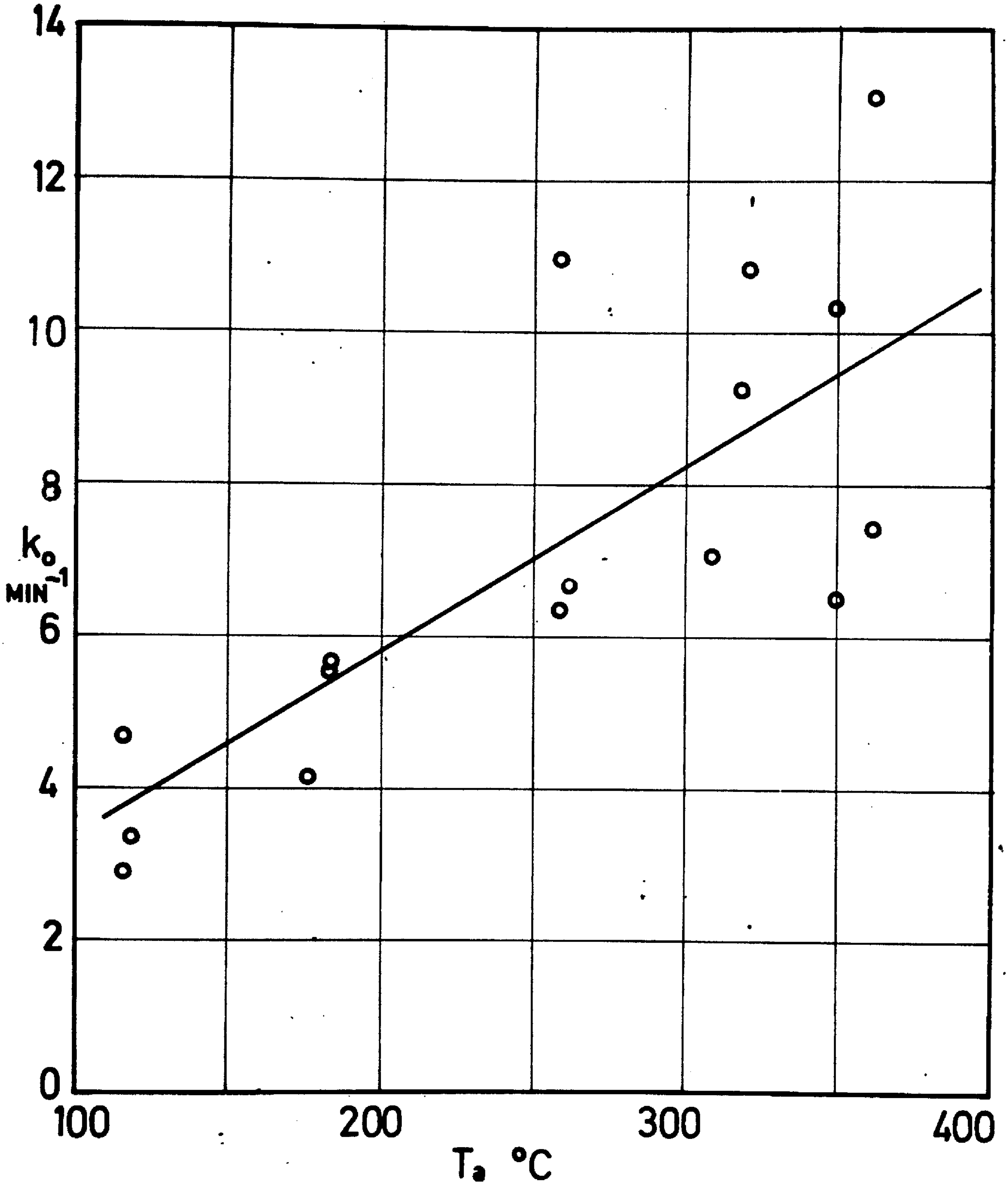


FIG. 5.62. k_o vs. T_a BATCH 36

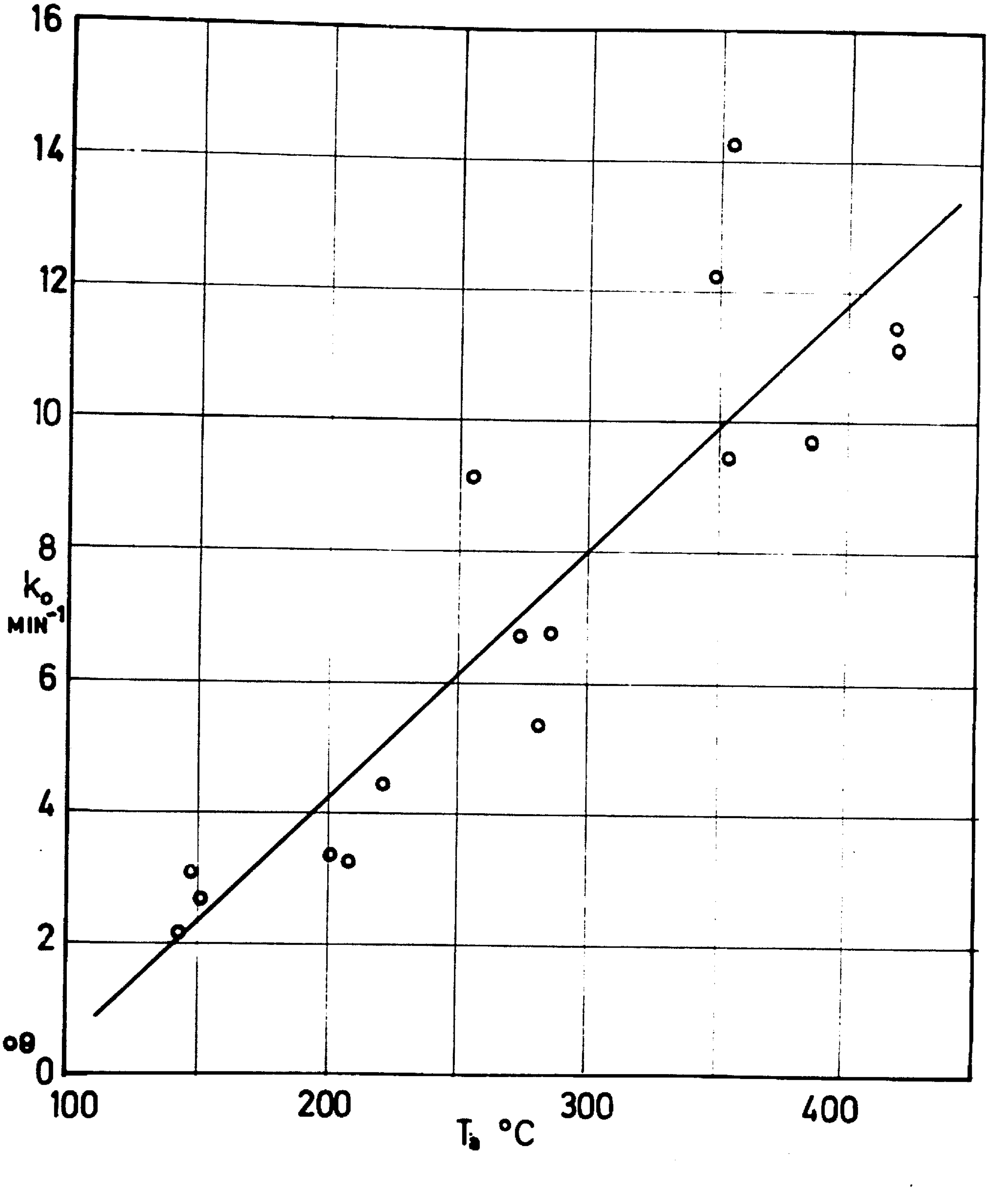


FIG.5.63. k_o vs. T_a BATCHES 37& 38

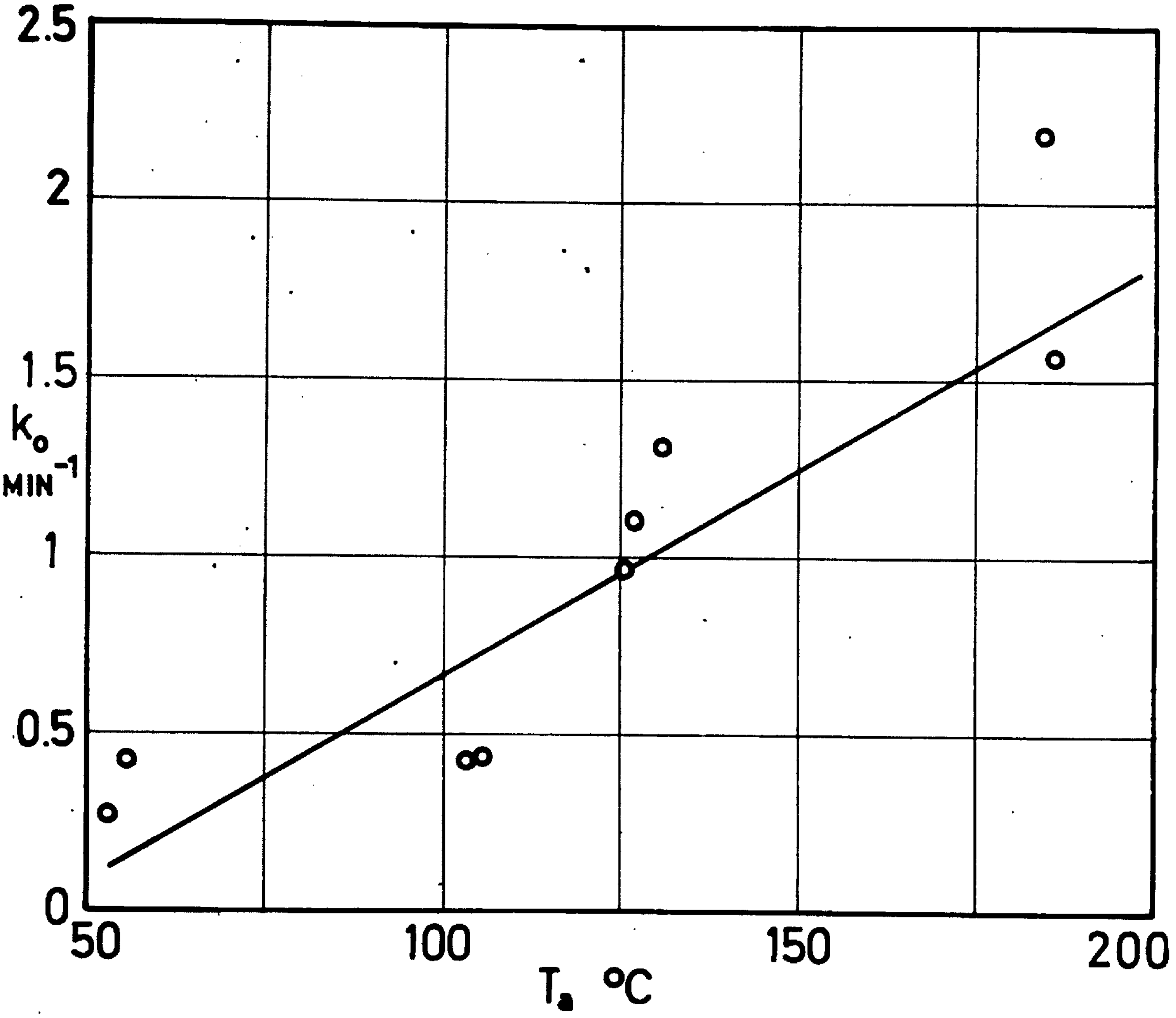


FIG.5.64. k_o vs. T_a BATCH 39

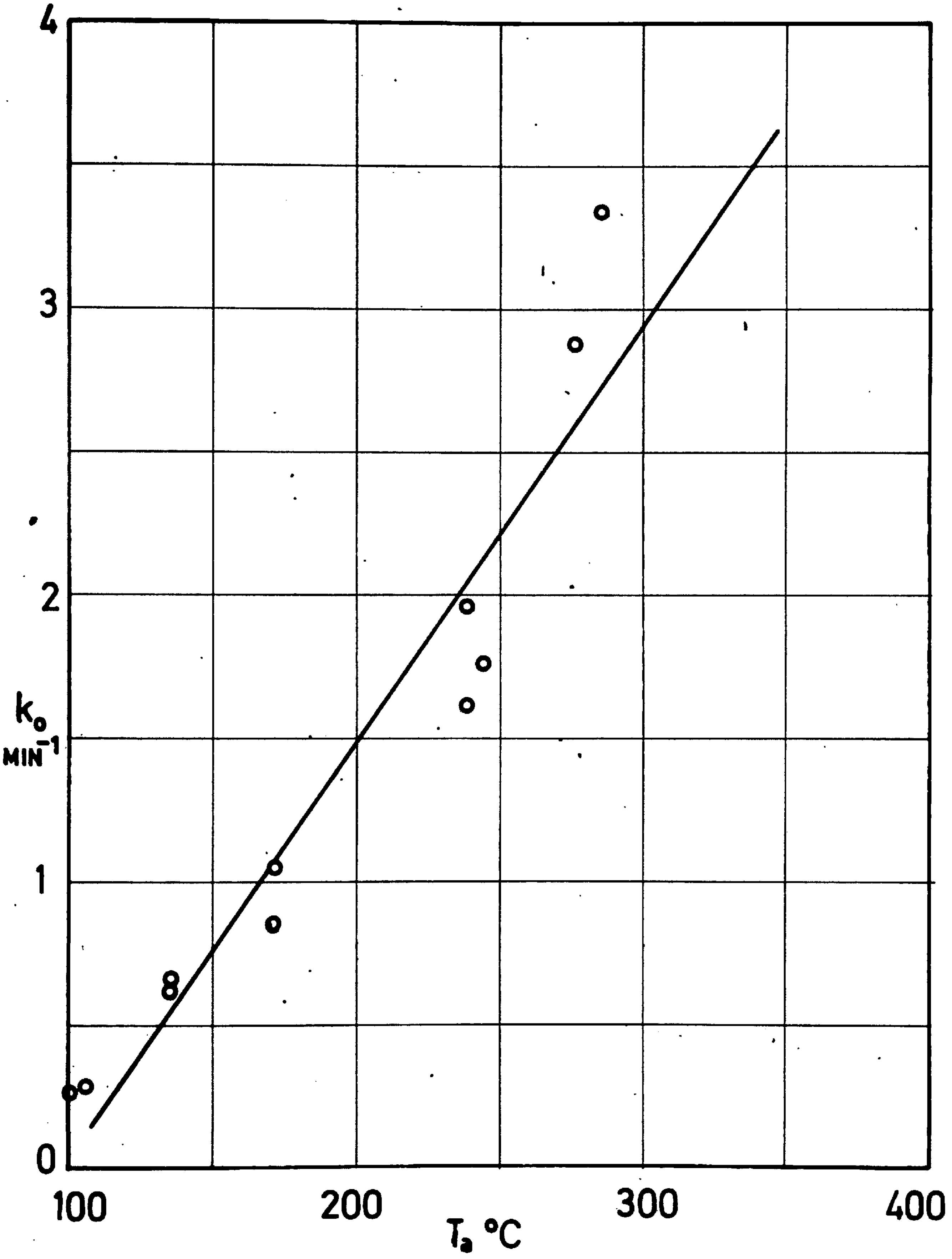


FIG.565. k_o vs. T_a BATCH 40

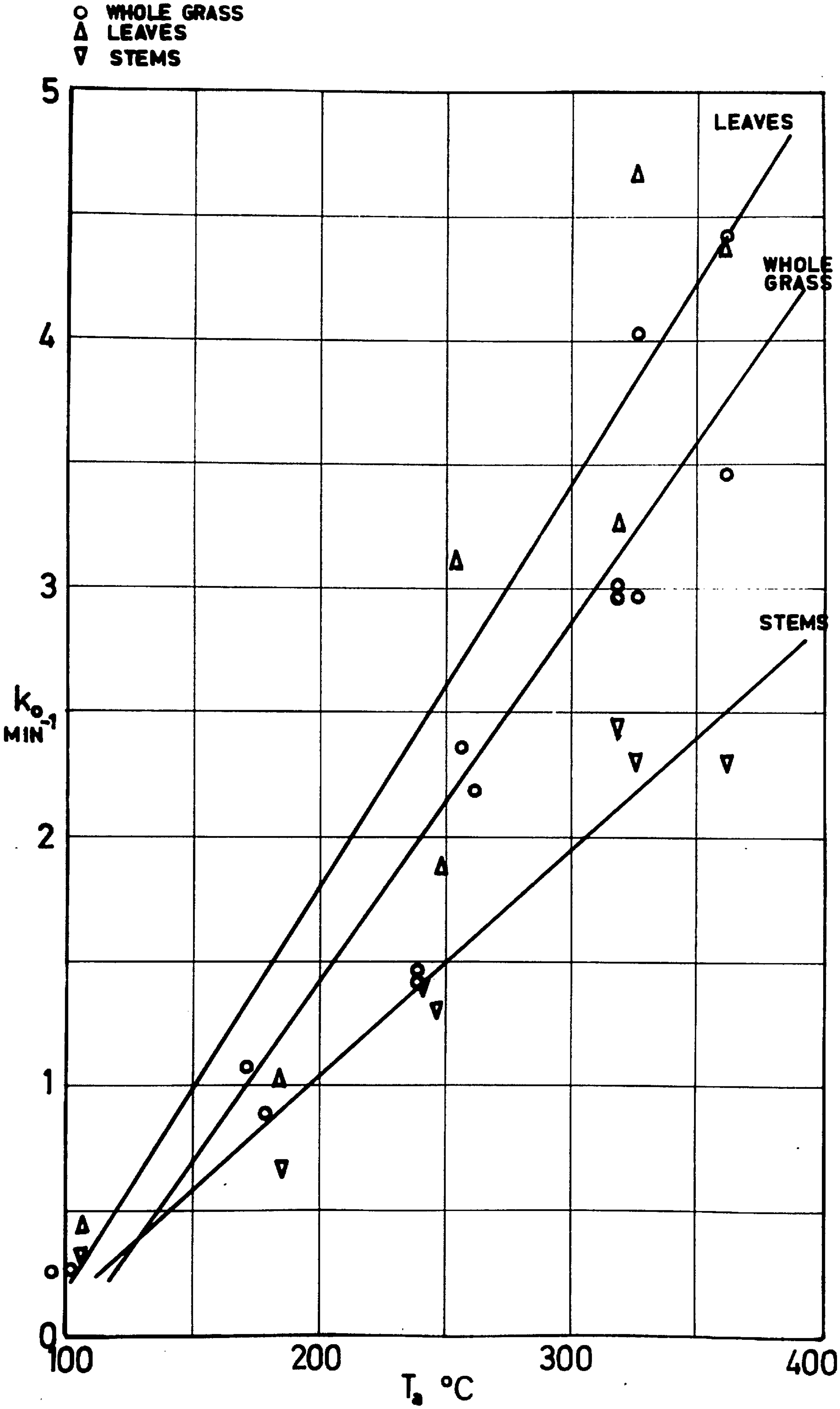


FIG.5.66. k_o vs T_a BATCH 41

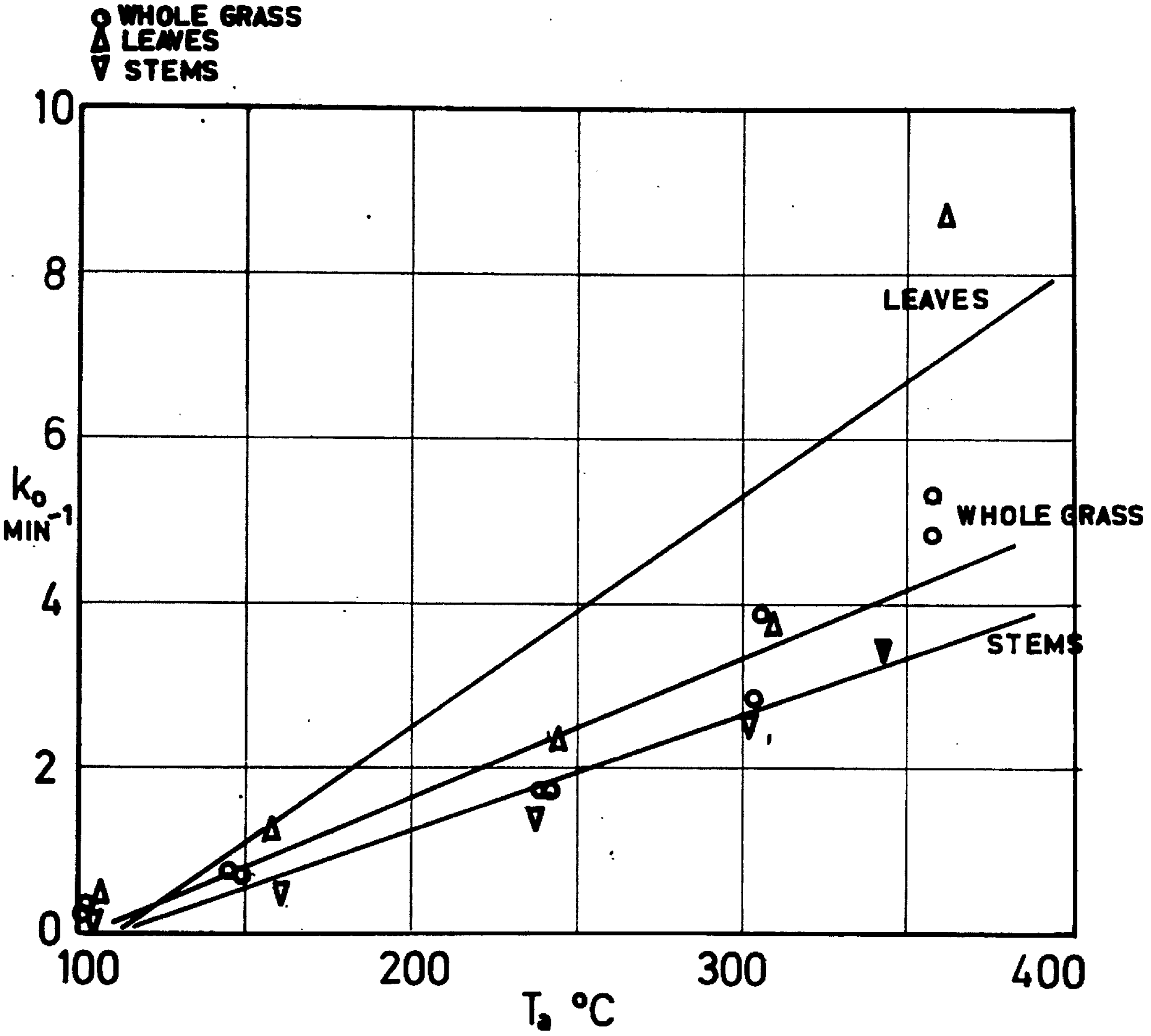


FIG. 5.67. k vs. l_s at 100° C

Wholegrass

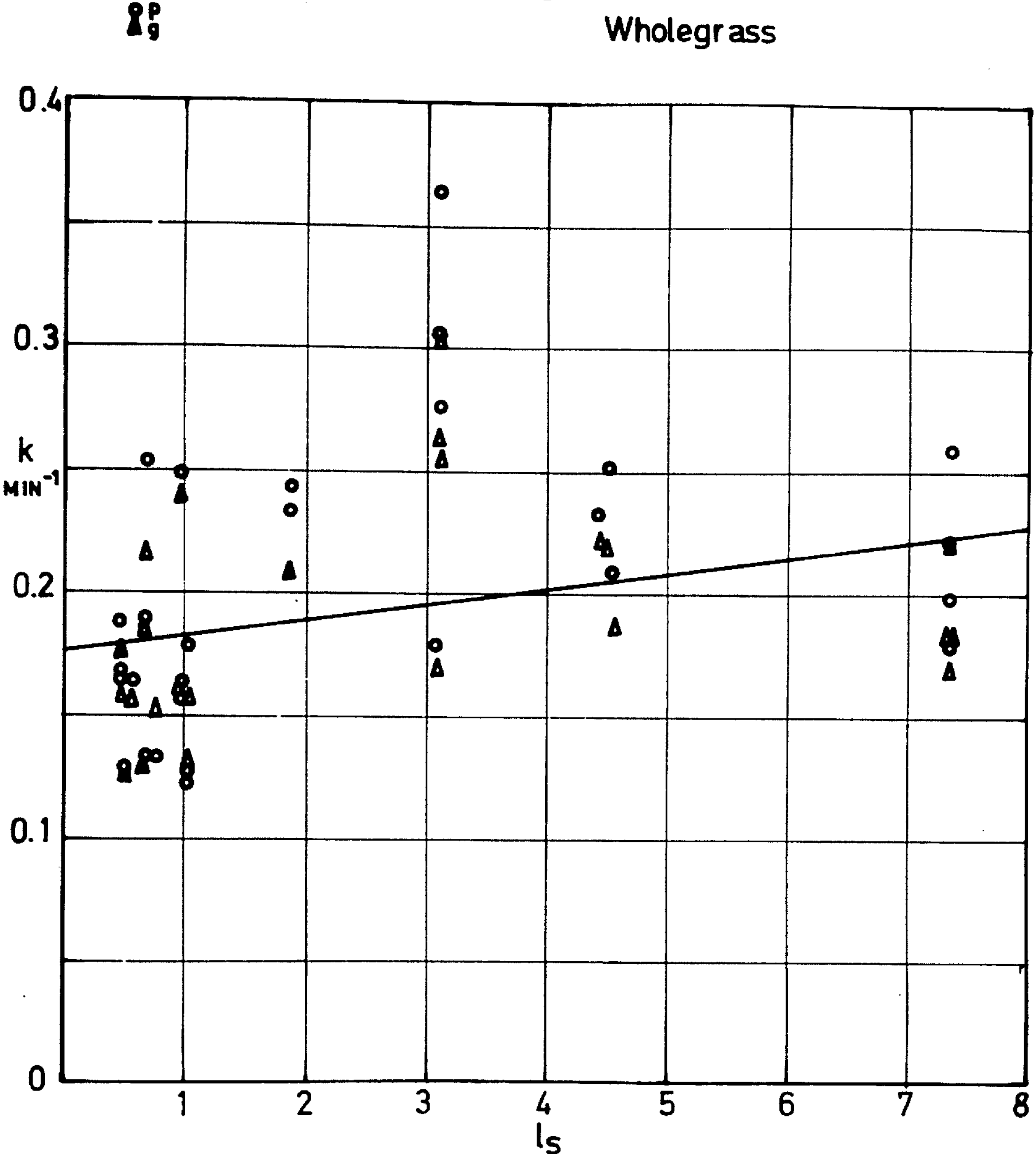


FIG. 5.68. k vs. l_s at 100°C Leaves

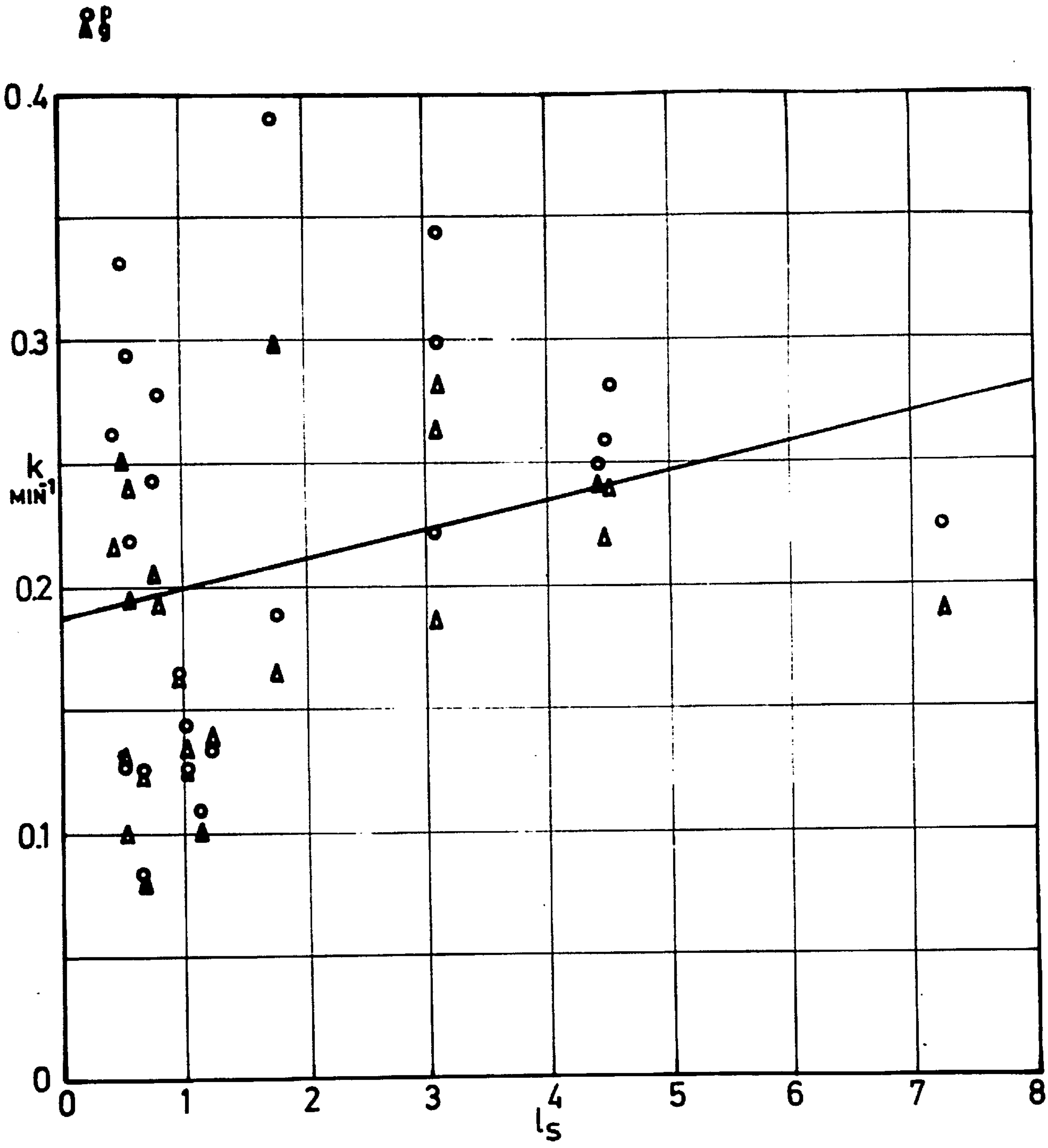


FIG.5.69. k vs. l_S at 100 °C Stems

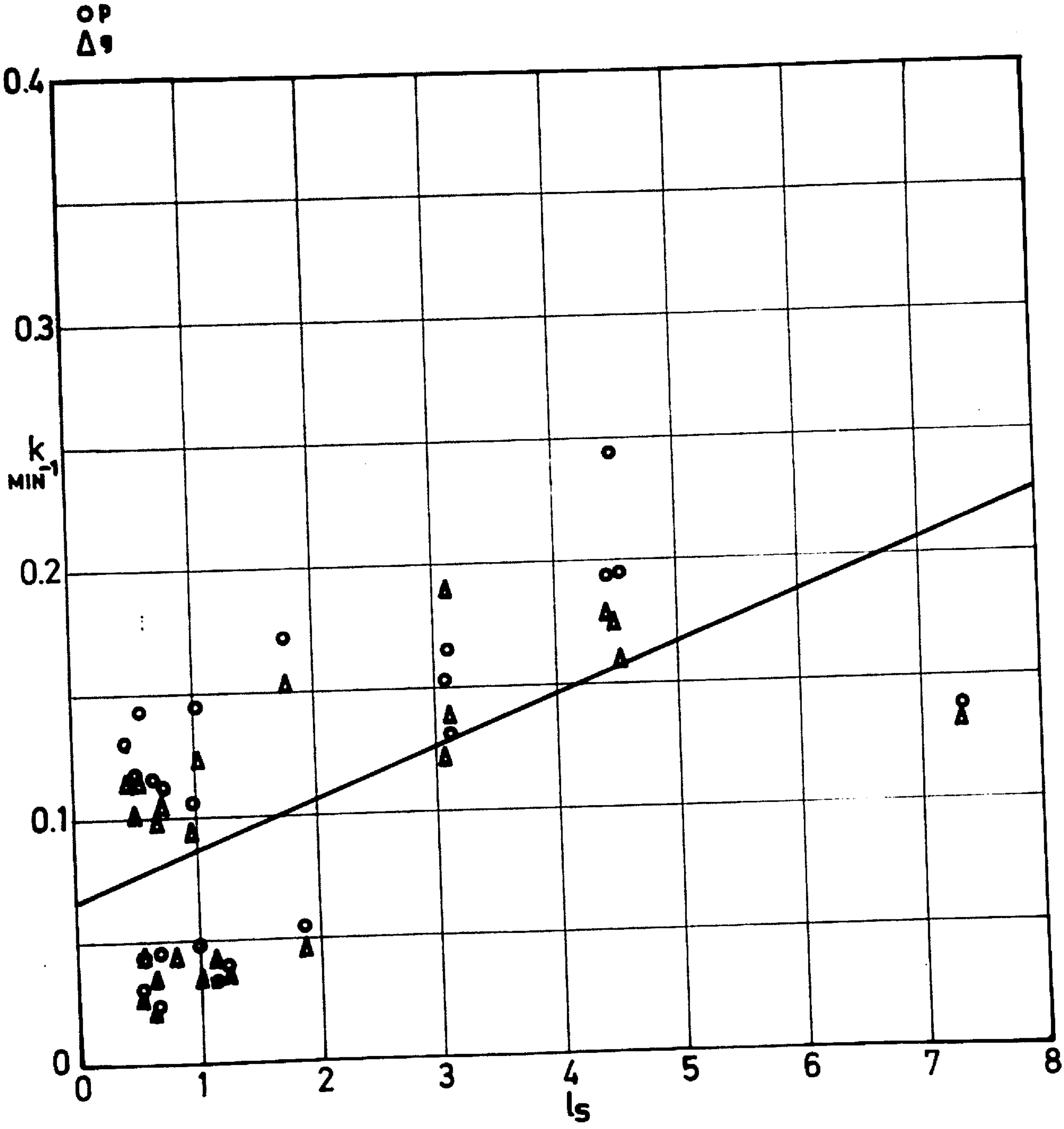


FIG.6.1.

CROSS-SECTION OF ITALIAN RYE GRASS LEAF

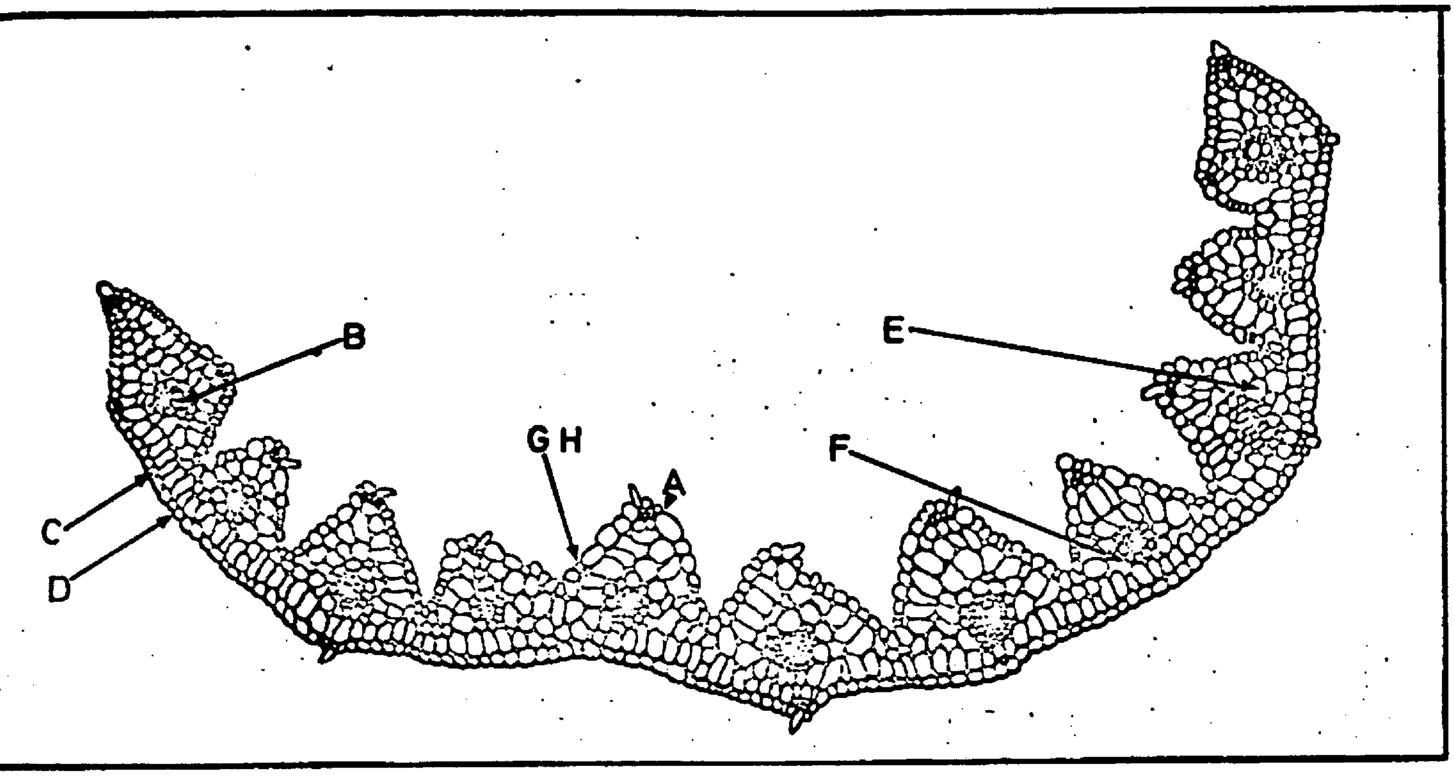
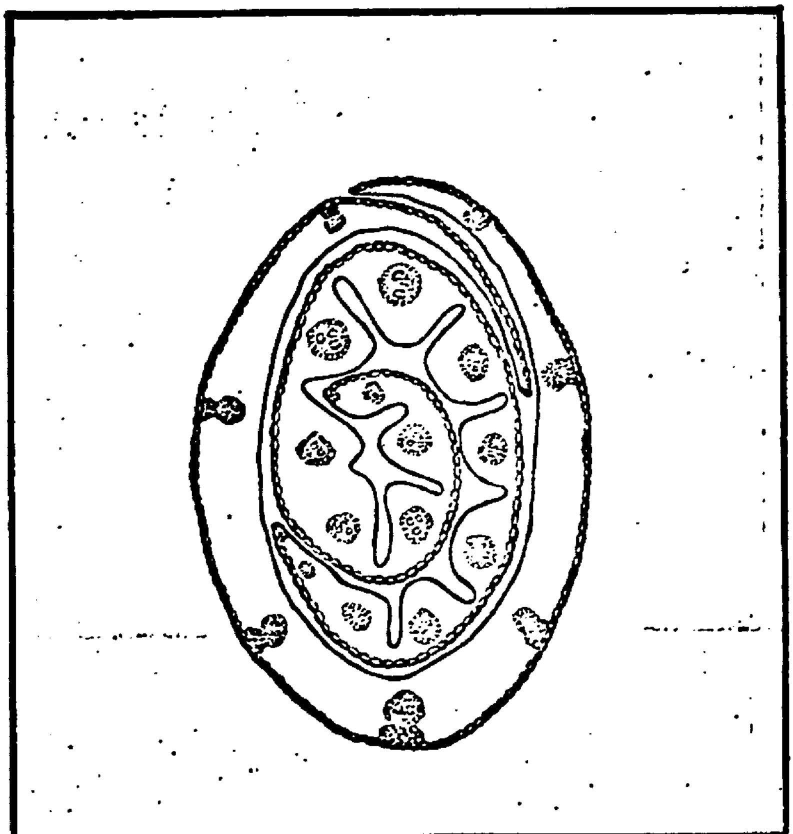


FIG.6.2.

CROSS SECTION OF ITALIAN RYE-GRASS SHOOT



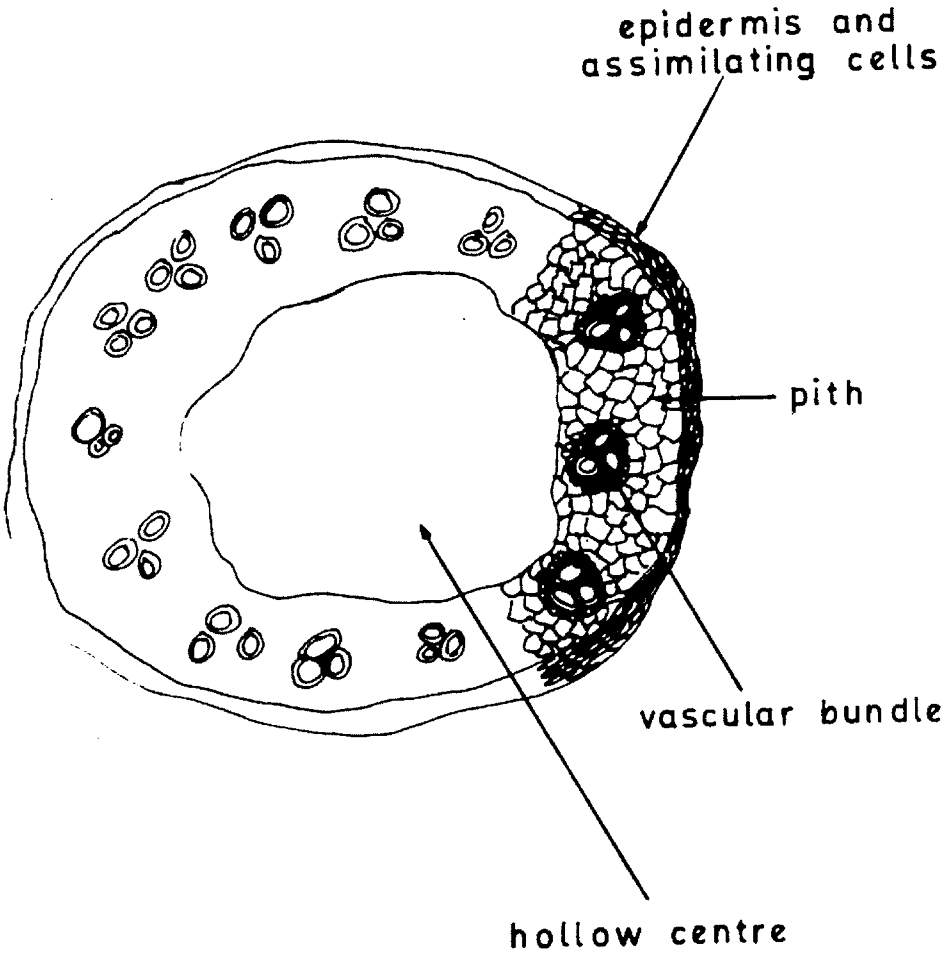


FIG.6.3. CROSS SECTION OF GRAMINACEOUS STEM (SCHEMATIC DIAGRAM)

PATH A—ALONG CELL WALLS
PATH B—ACROSS CELL AND THROUGH WALLS

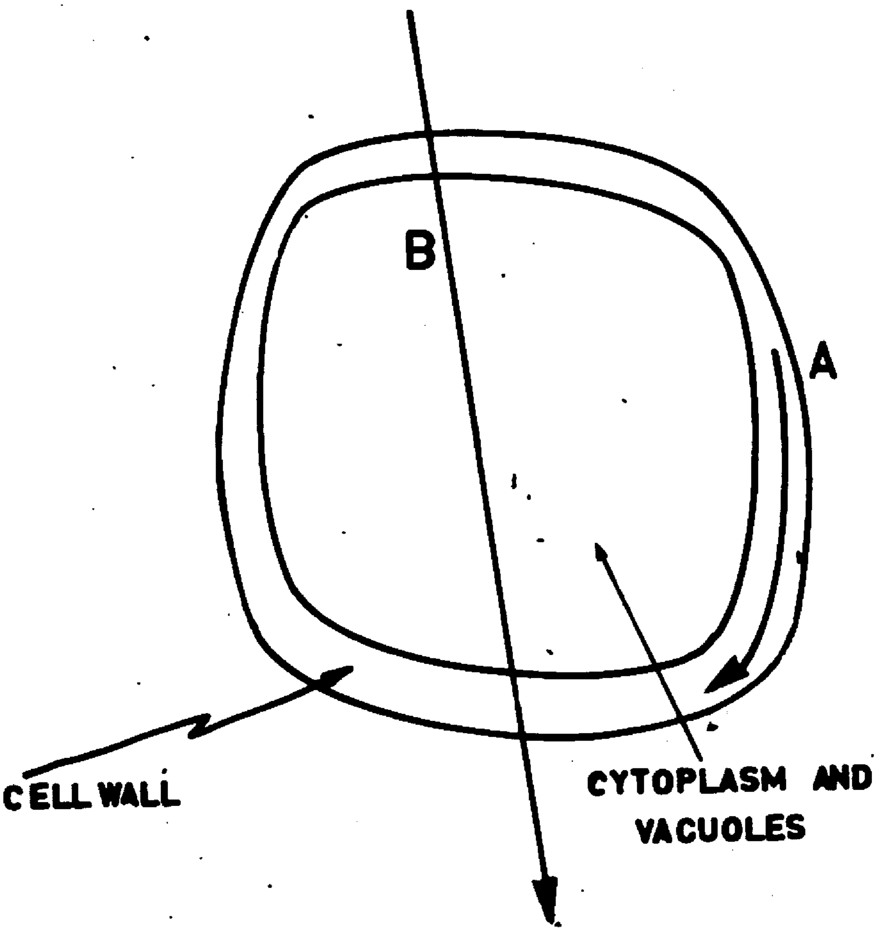


FIG. 6.4

PATHS OF WATER MOVEMENT IN CELLS

FIG.6.5 GRASS TEMPERATURE vs. TIME

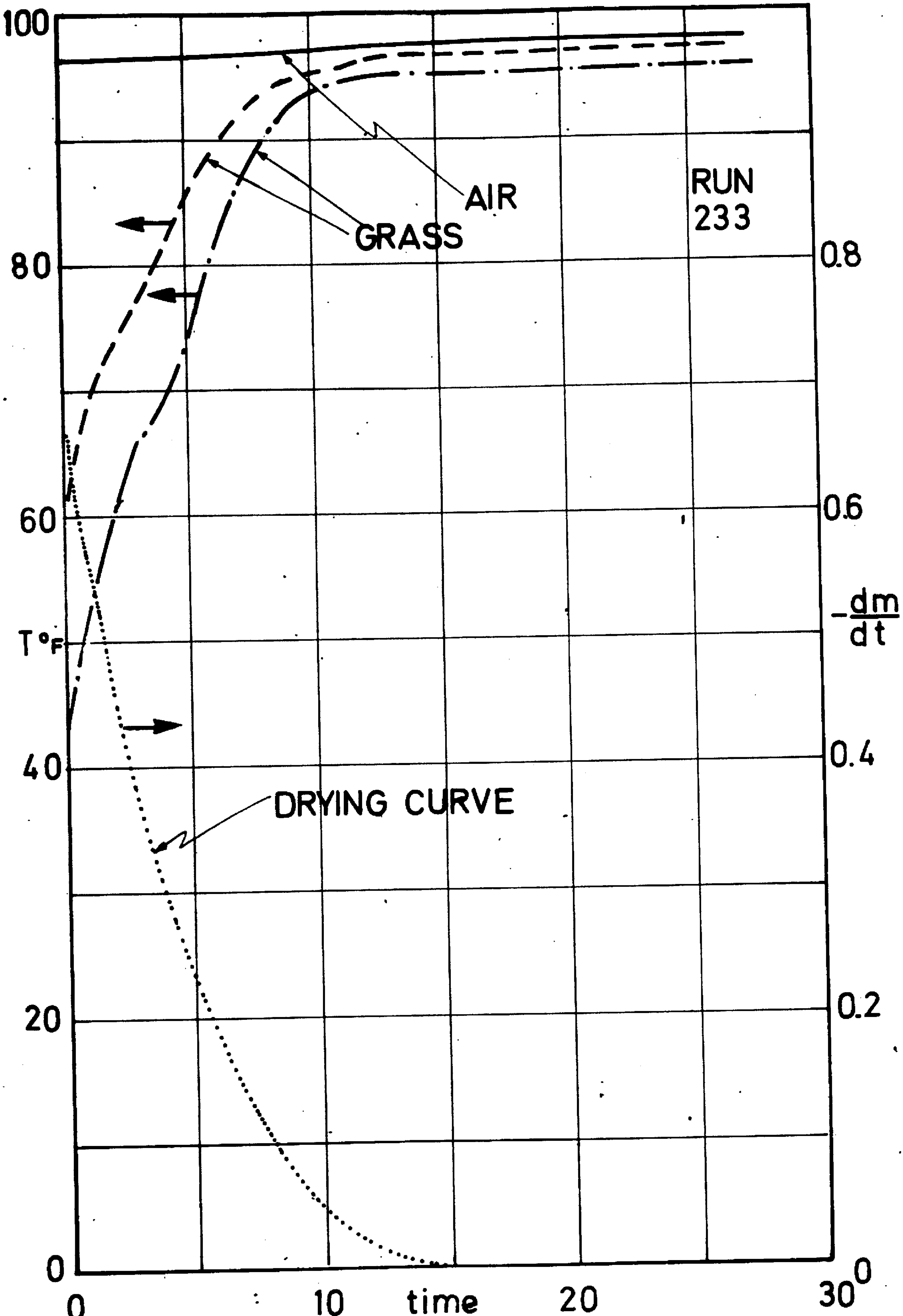


FIG.6.6.

SEVERAL EQUATIONS FITTING ONE SET OF DATA

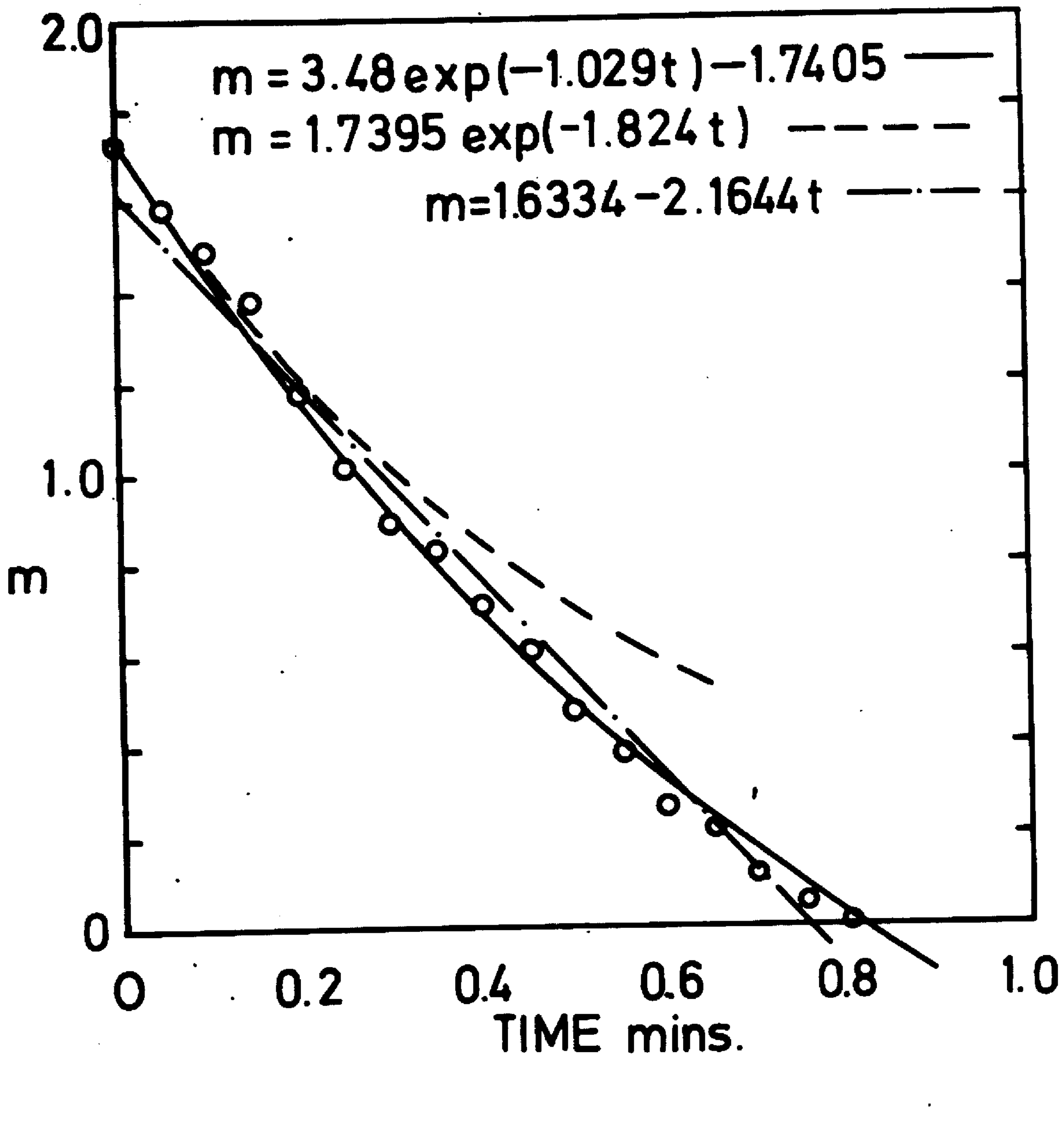
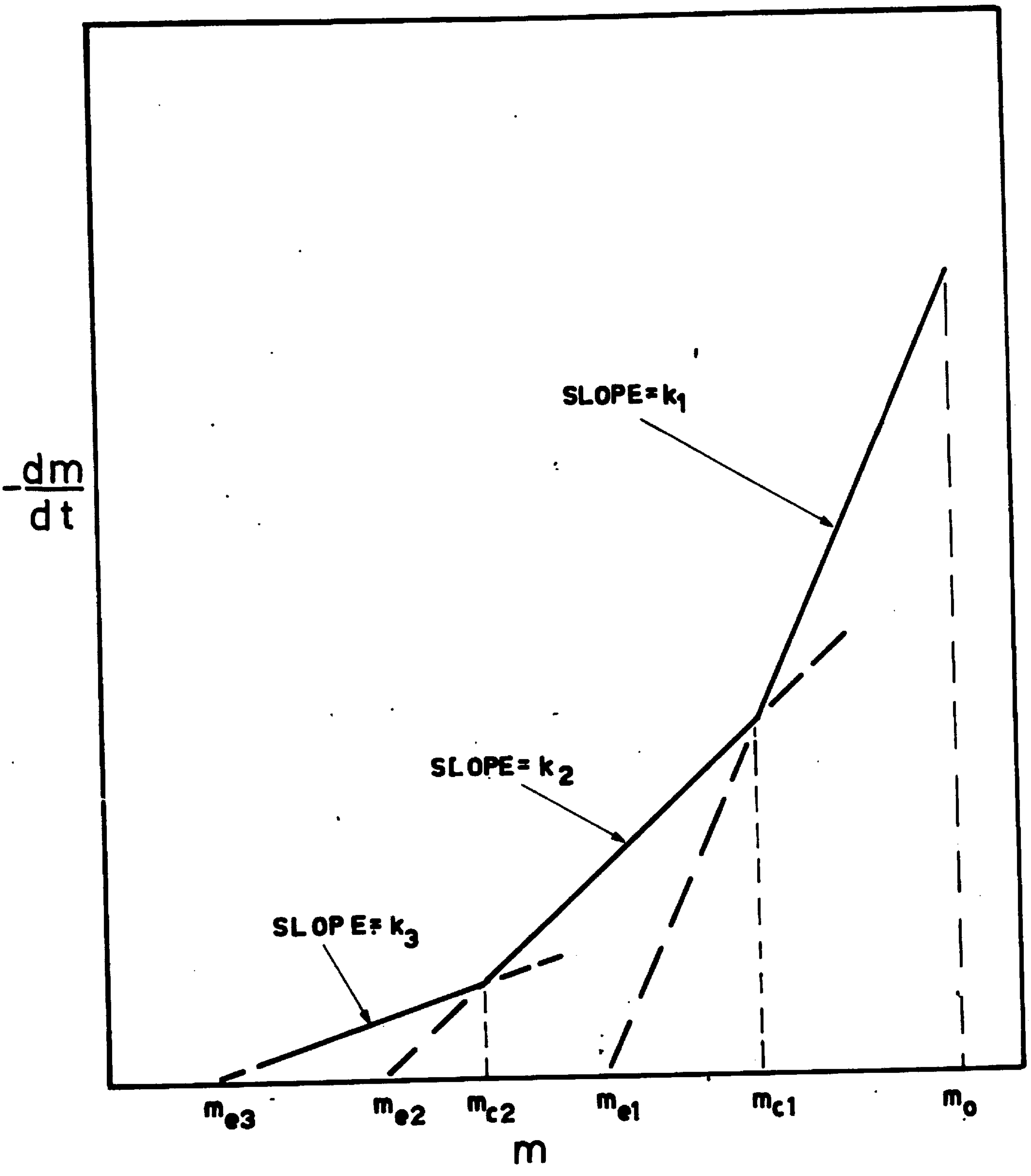


FIG.6.7 THREE-PART DRYING CURVE



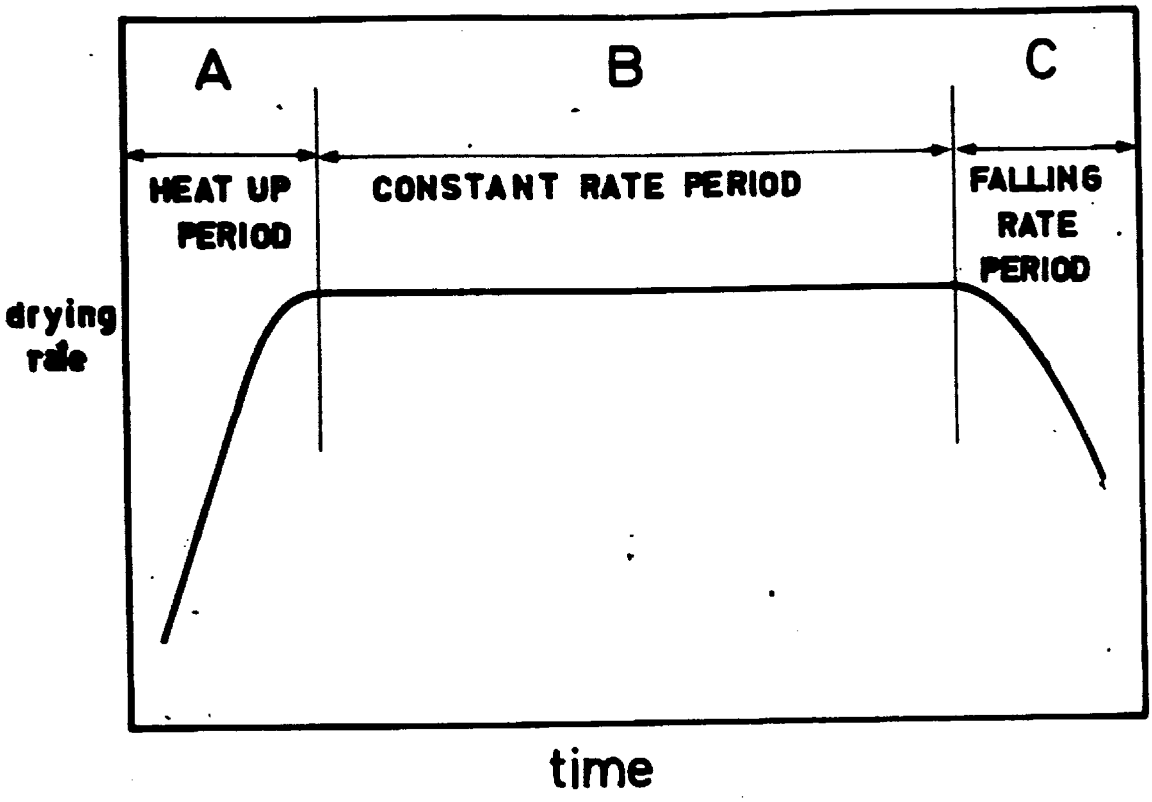


FIG.7.1. DRYING CHARACTERISTICS OF A DEEP BED

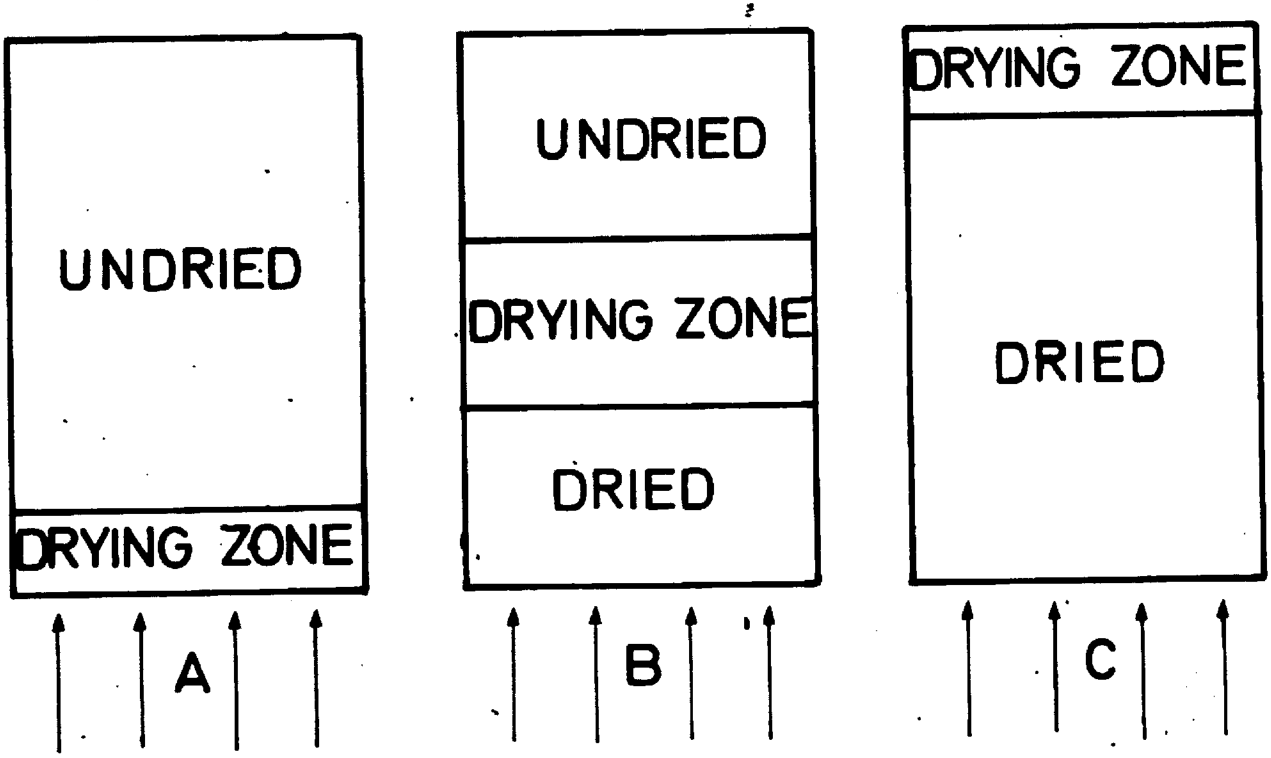


FIG.7.2 DRYING ZONE IN A DEEP BED

FIG.7.3.

SCHEMATIC REPRESENTATION OF THE DEEP BED CALCULATIONS

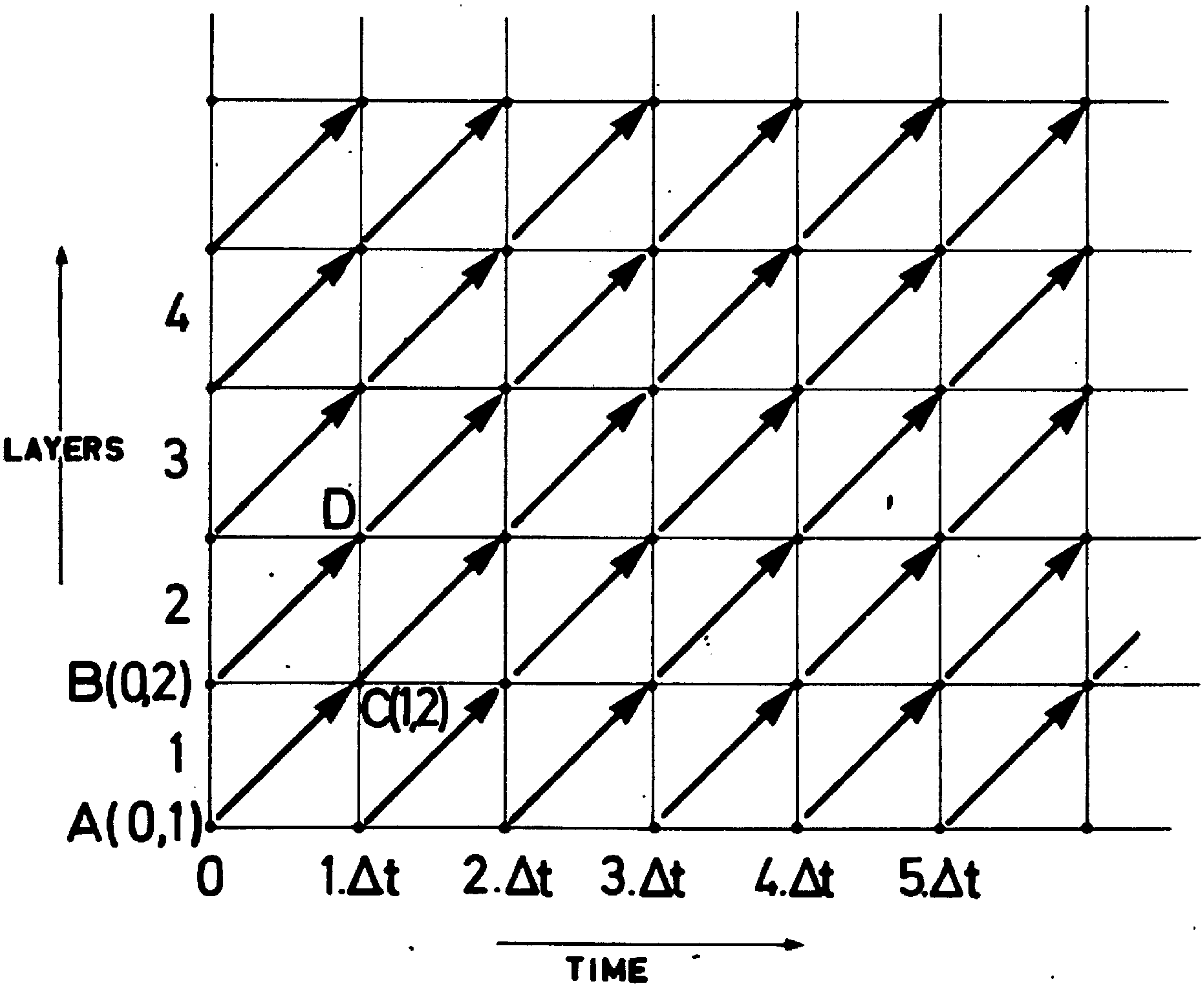


FIG.7.4. PLOT OF j_h vs. Re for packed beds

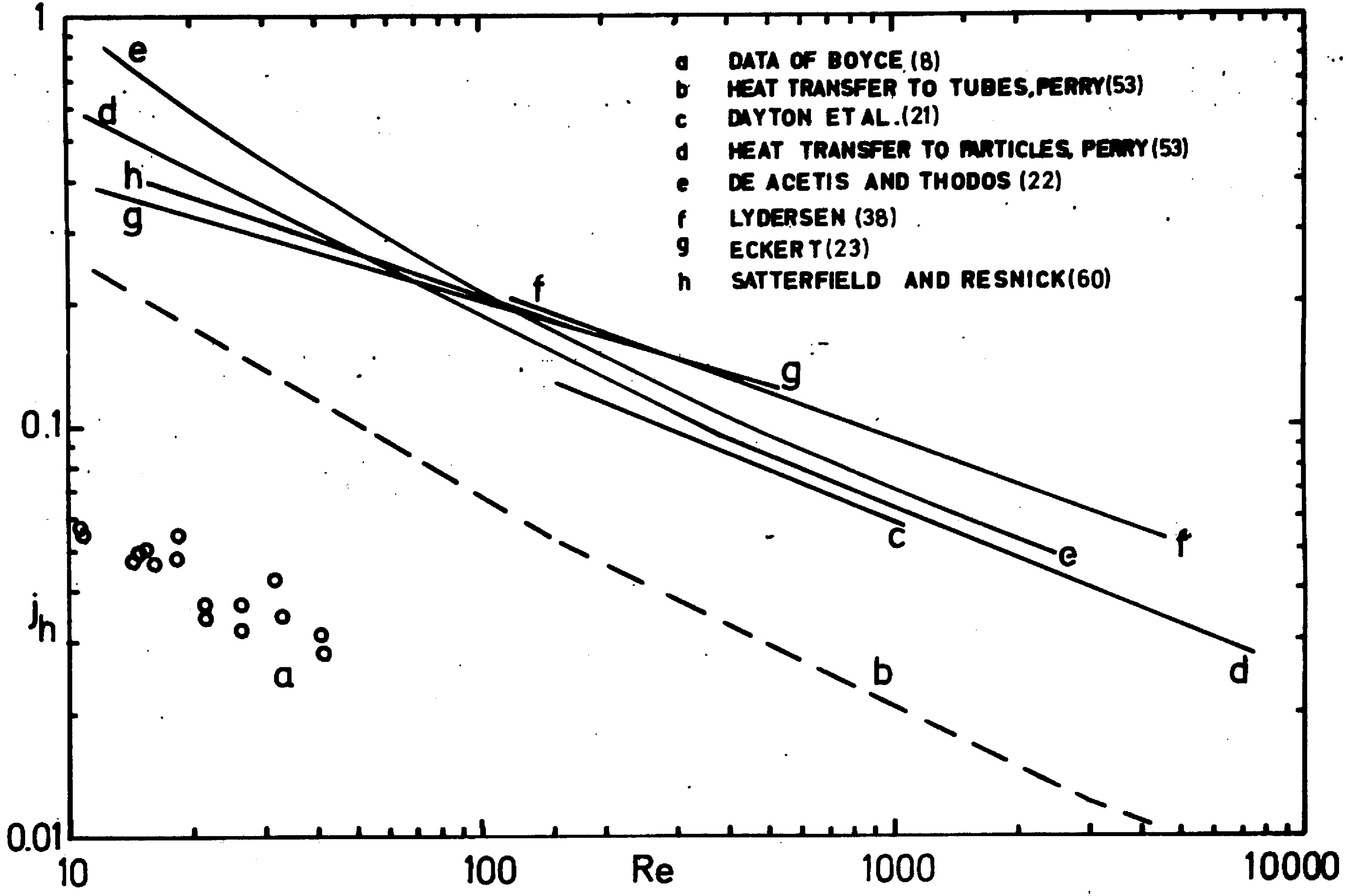
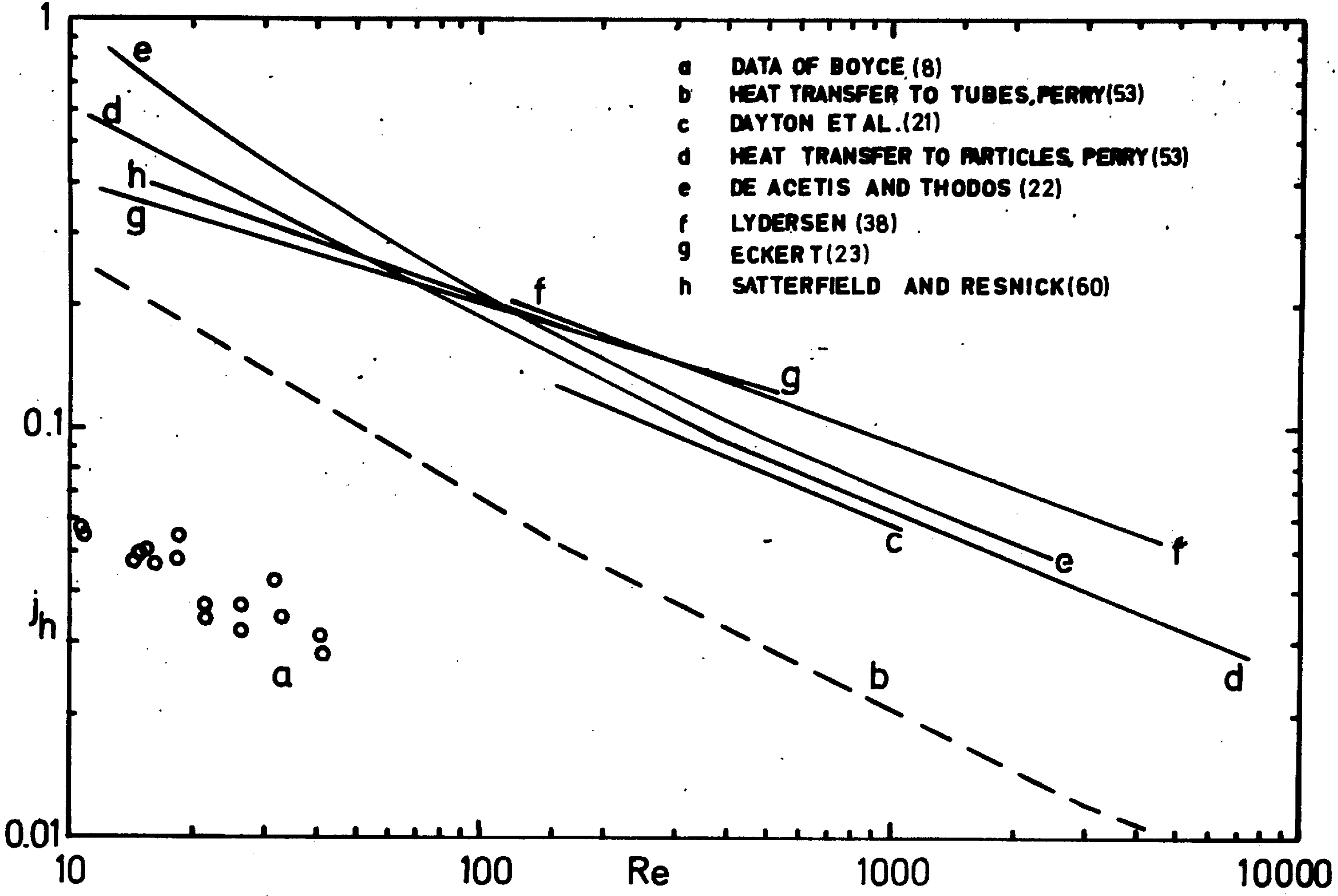


FIG.7.4. PLOT OF j_h vs. Re for packed beds



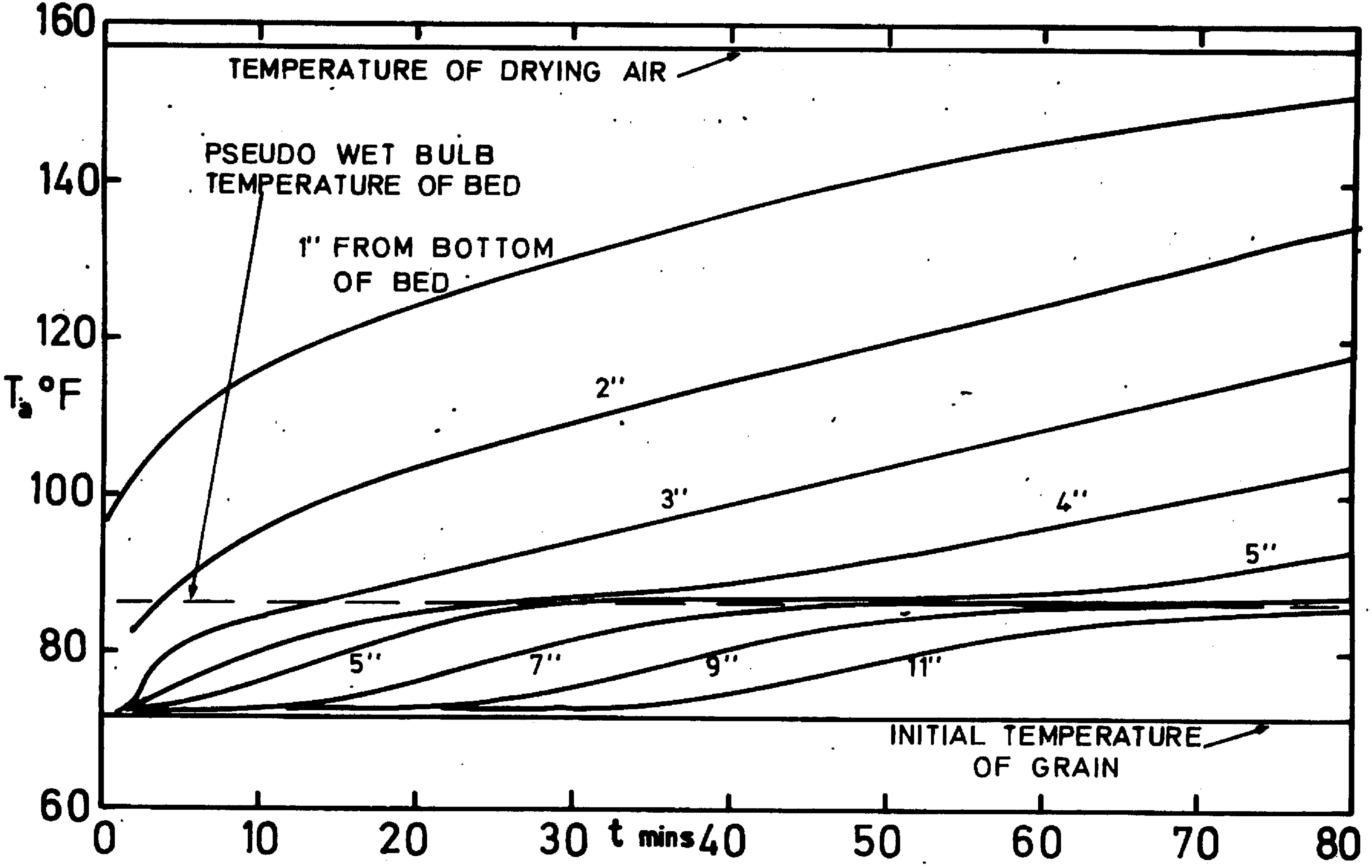


FIG.7.5. TEMPERATURE PROFILE IN DEEP BED

FIG.7.6. EXPERIMENTAL AND PREDICTED TEMPERATURE PROFILES
RUN S134

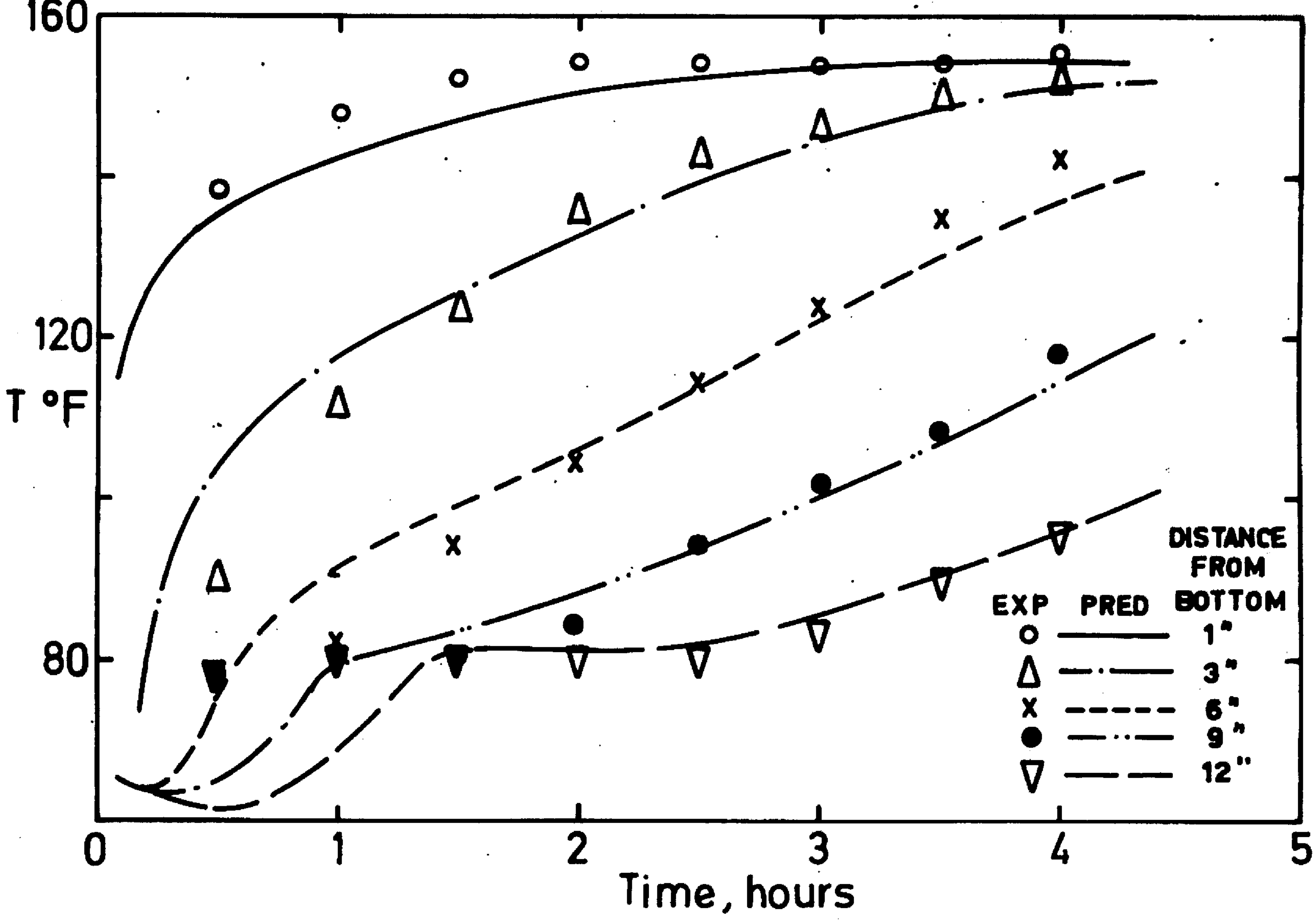


FIG.7.7 PREDICTED MOISTURE CONTENT PROFILE

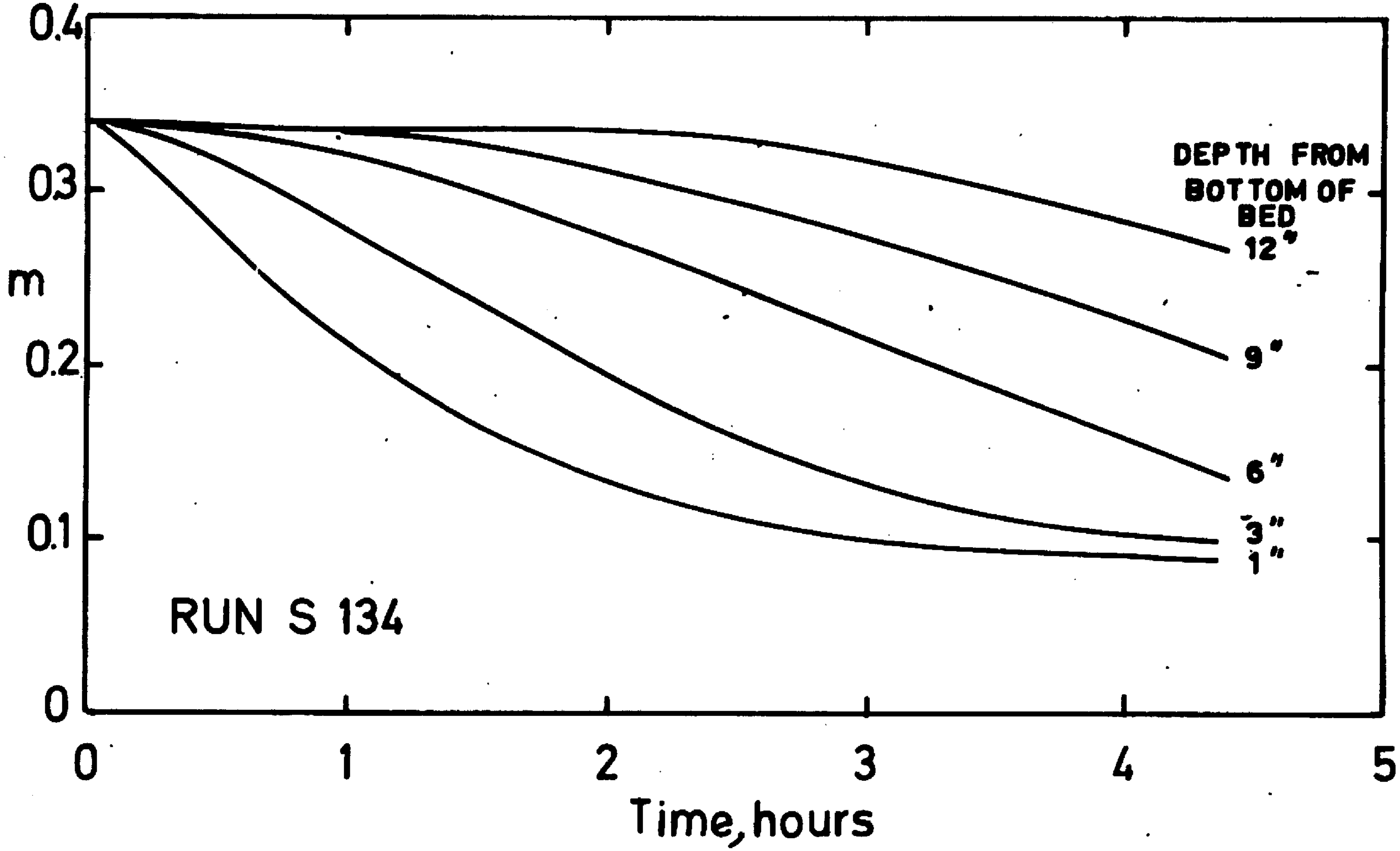


FIG.7.8.
EXPERIMENTAL AND PREDICTED
FINAL MOISTURE CONTENT GRADIENT

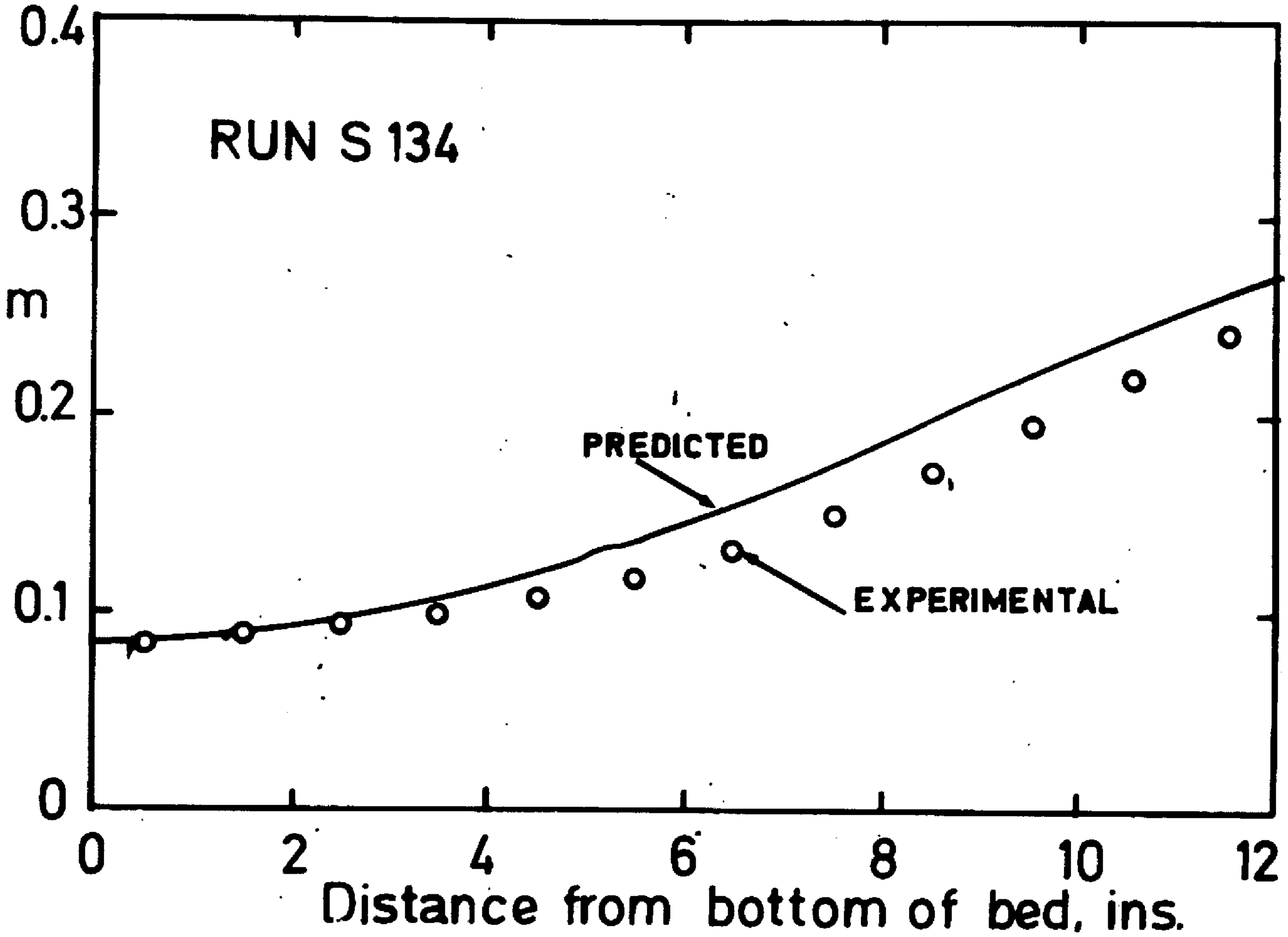
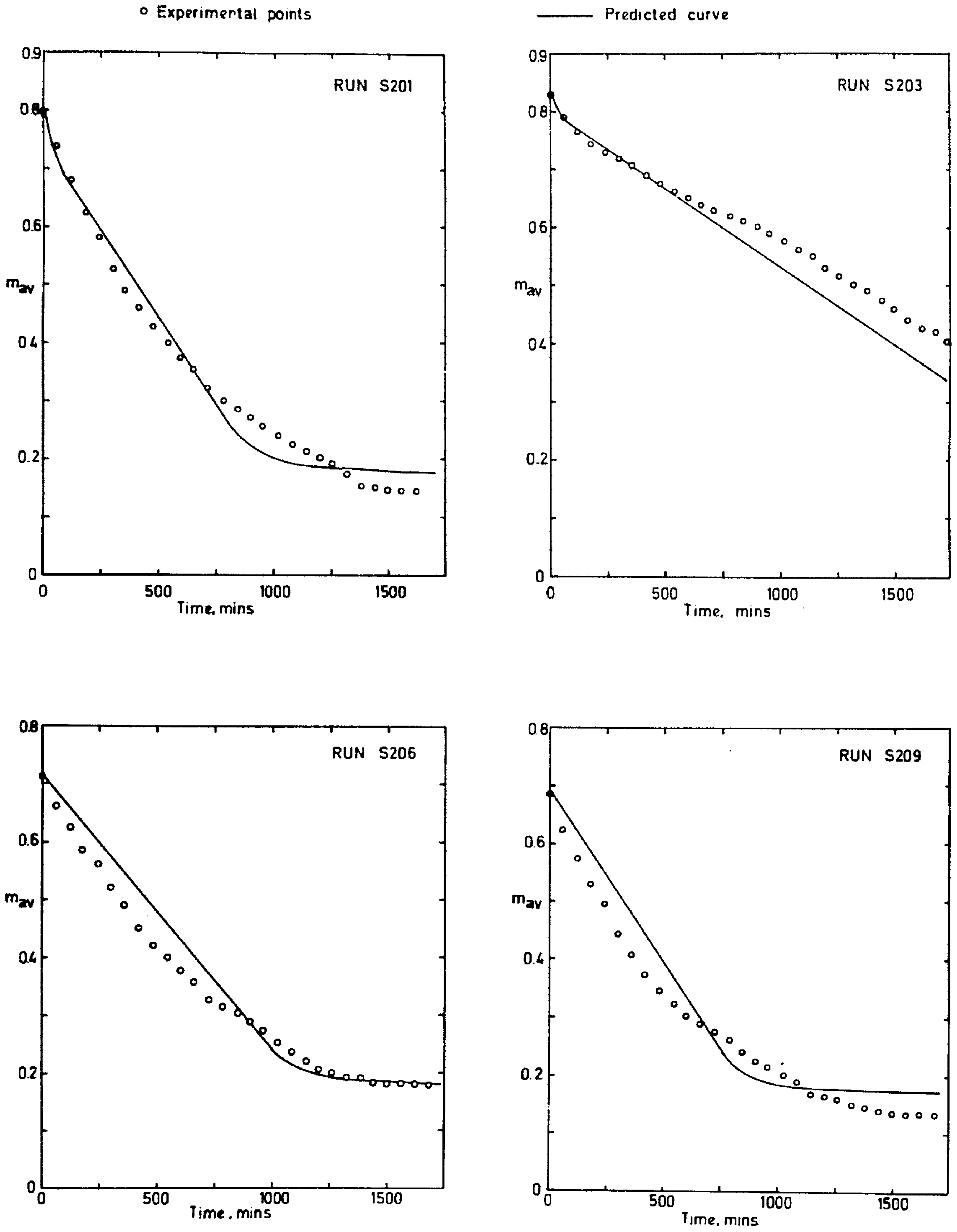


FIG.7.9.

DRYING CURVES FOR DEEP BEDS OF HAY



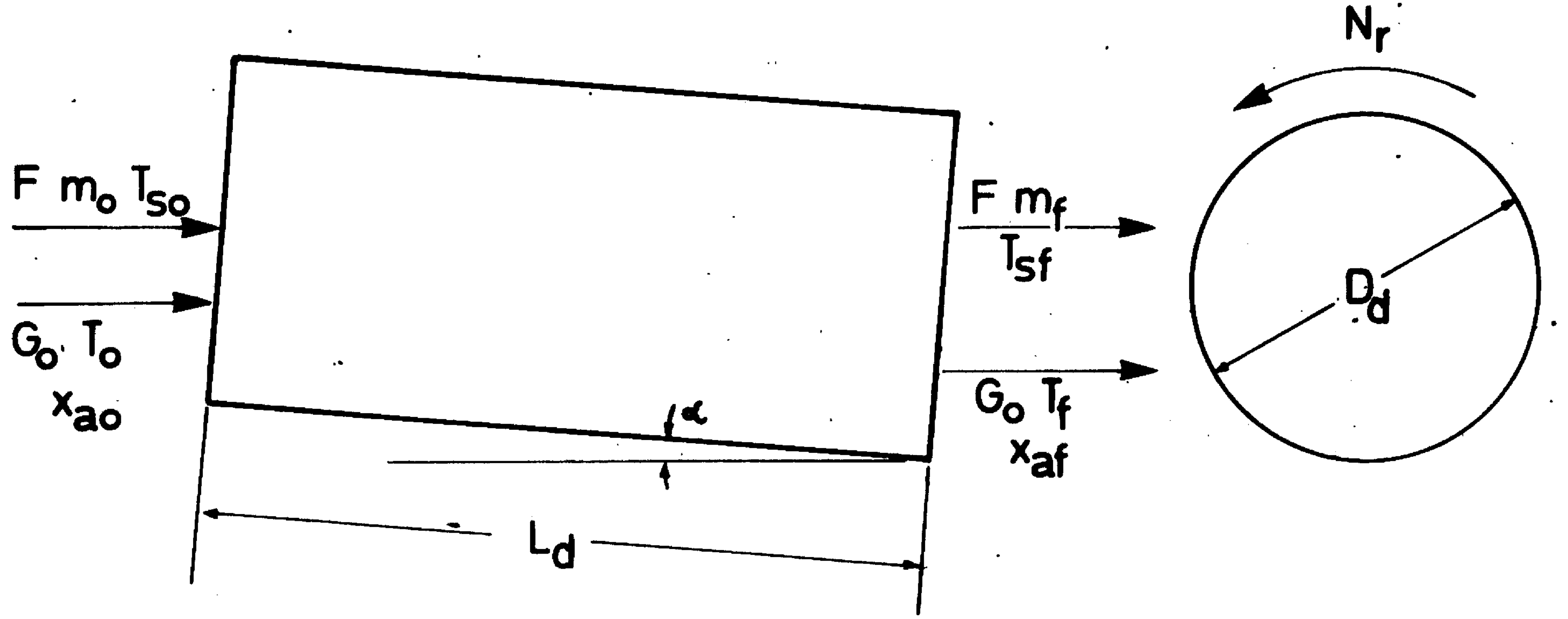


FIG. 8.1 SCHEMATIC DIAGRAM OF A ROTARY DRIER

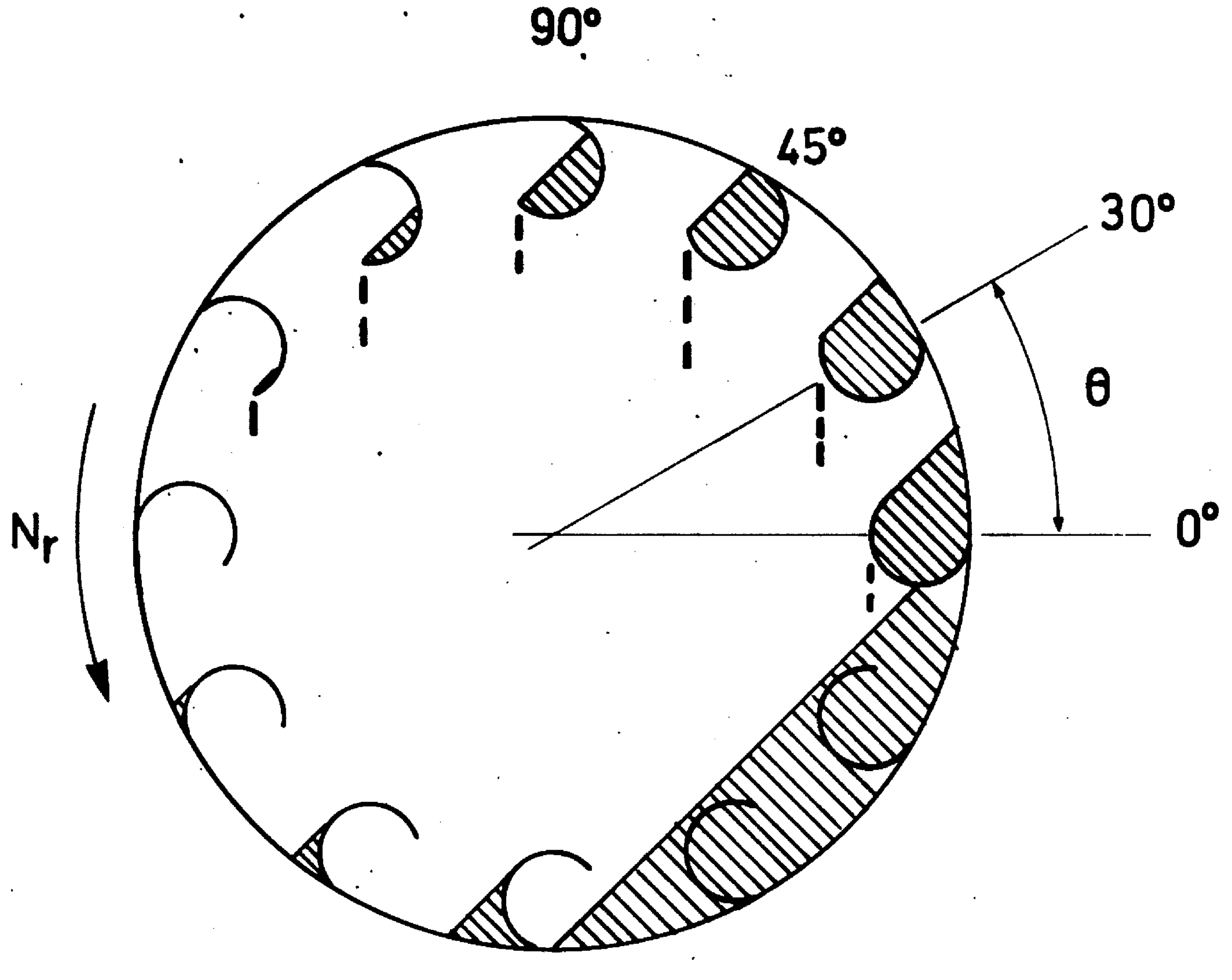


FIG. 8.2

CASCADING SOLIDS IN A ROTARY DRIER

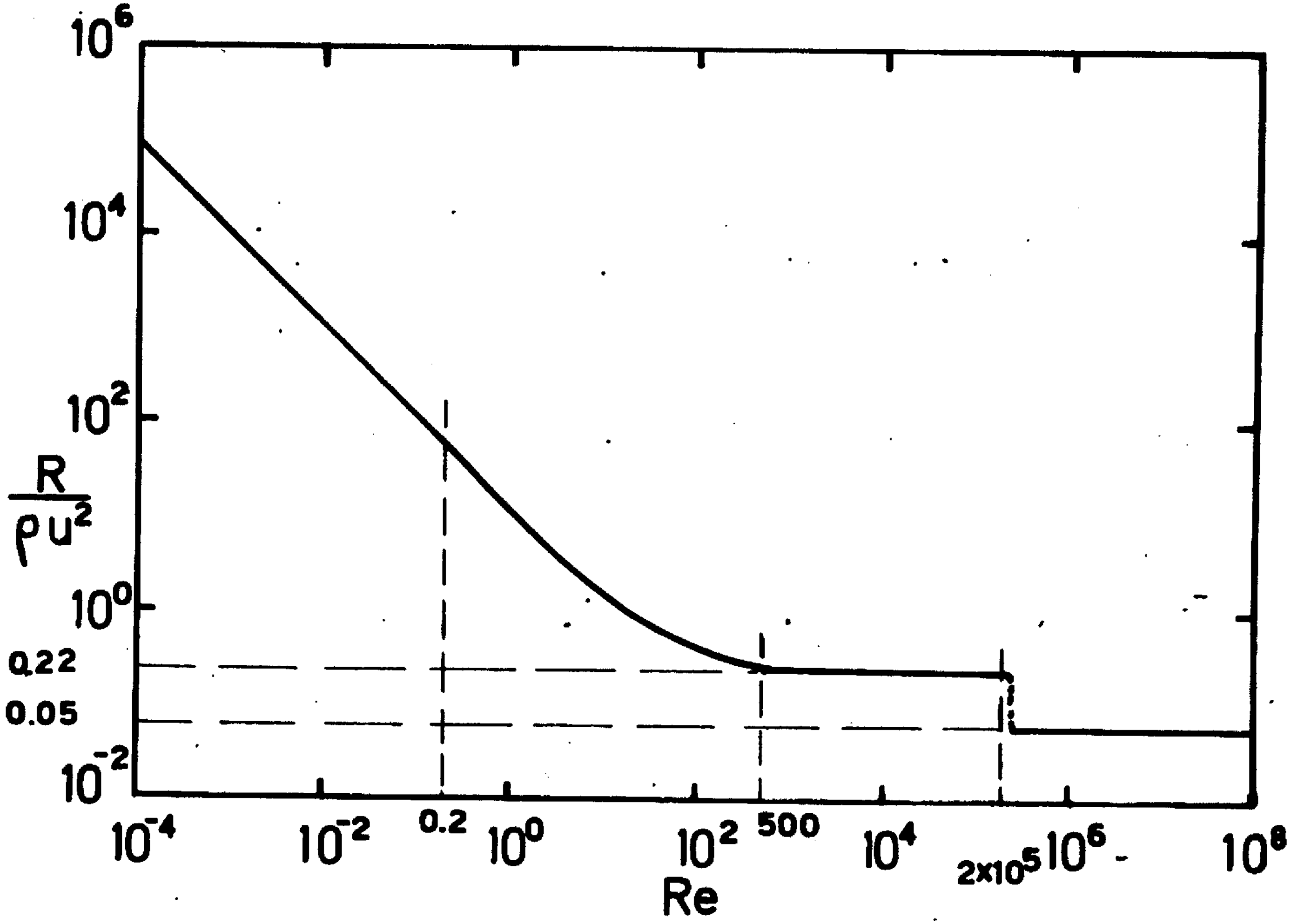
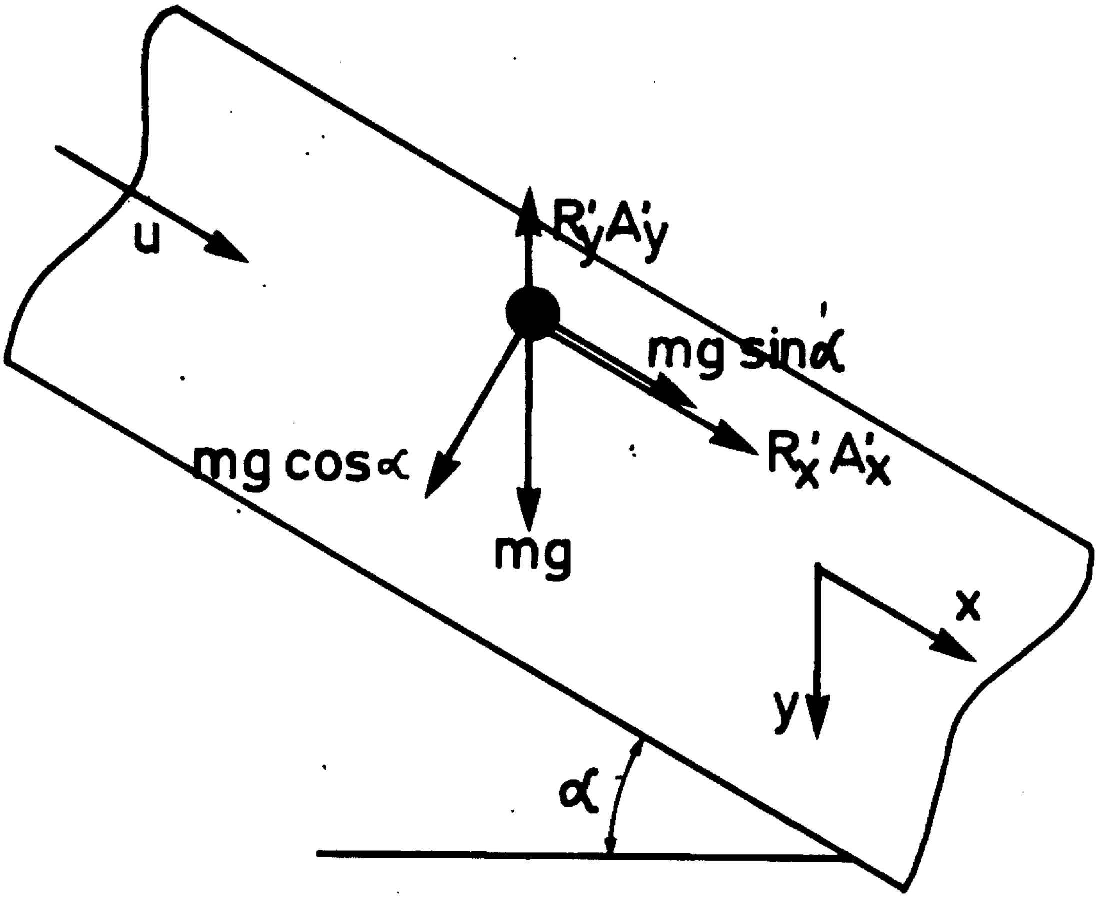


FIG.8.3

PLOT OF $\frac{R'}{\rho u^2}$ VS. Re

FOR SPHERES

FIG. 8.4.
FORCES ACTING ON A PARTICLE IN A ROTARY DRIER



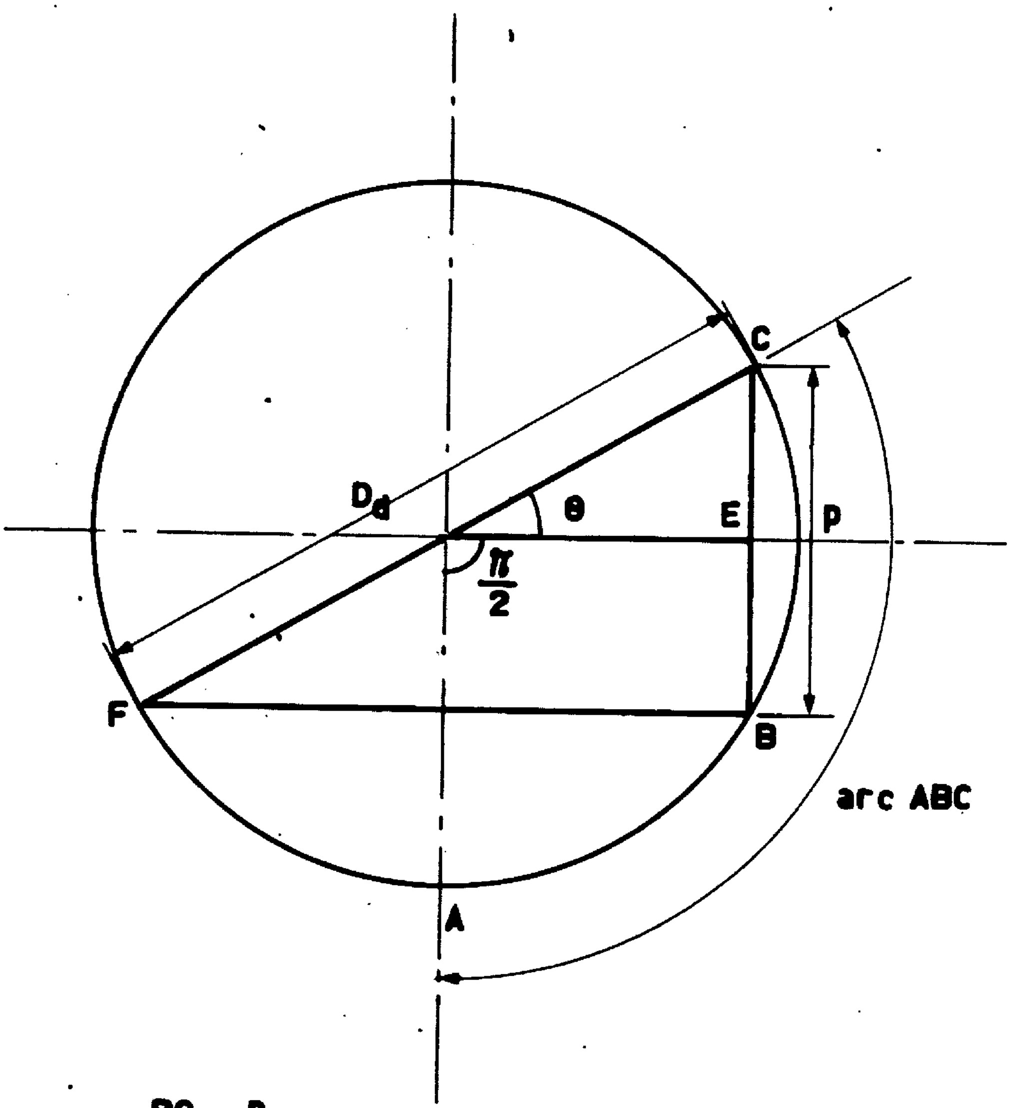
$$m\ddot{x} = mg\sin\alpha + R'_xA'_x$$

$$m\ddot{y} = mg - R'_yA'_y$$

m = mass of particle
g = acceleration due to gravity
u = velocity of air
α = angle of inclination of drier
R' = resistance per unit projected area
A' = projected area of particle

FIG. 8.5

RELATIONSHIP BETWEEN ω AND δ



$$\frac{BC}{CF} = \frac{p}{D_d} = \sin\theta$$

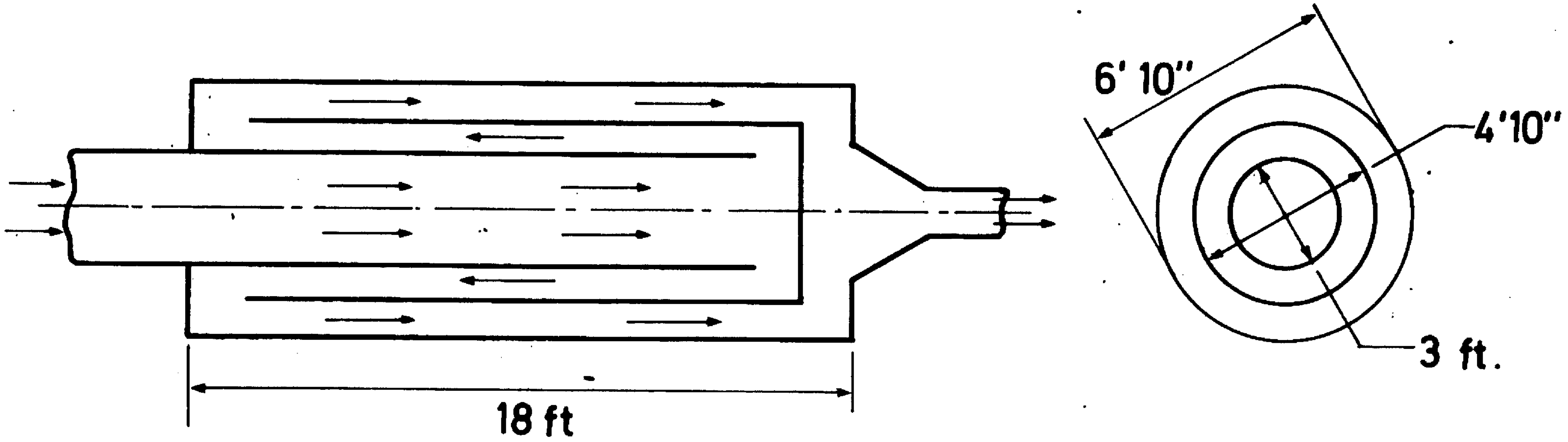
$$\delta = \frac{\pi D_d}{\text{arc } ABC} = \frac{2\pi}{\frac{\pi}{2} + \theta}$$

Hence $\theta = 2\pi/\delta - \pi/2$

$$p = \omega D_d = D_d \sin\theta$$

$$\omega = \sin(2\pi/\delta - \pi/2)$$

FIG.8.6.
COCKLE PARK DRIER



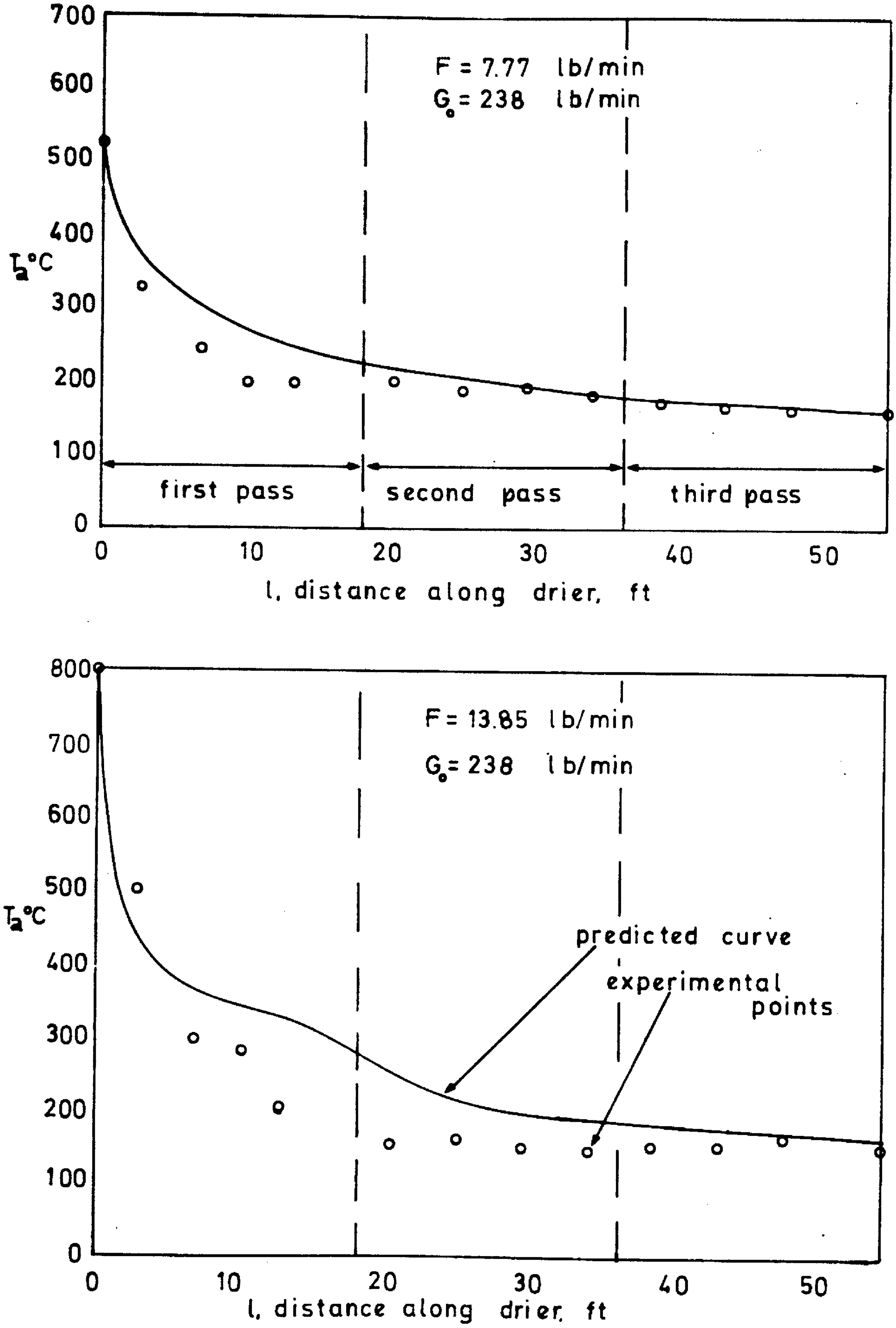


FIG.8.7. EXPERIMENTAL AND PREDICTED TEMPERATURE PROFILES IN ROTARY DRIER

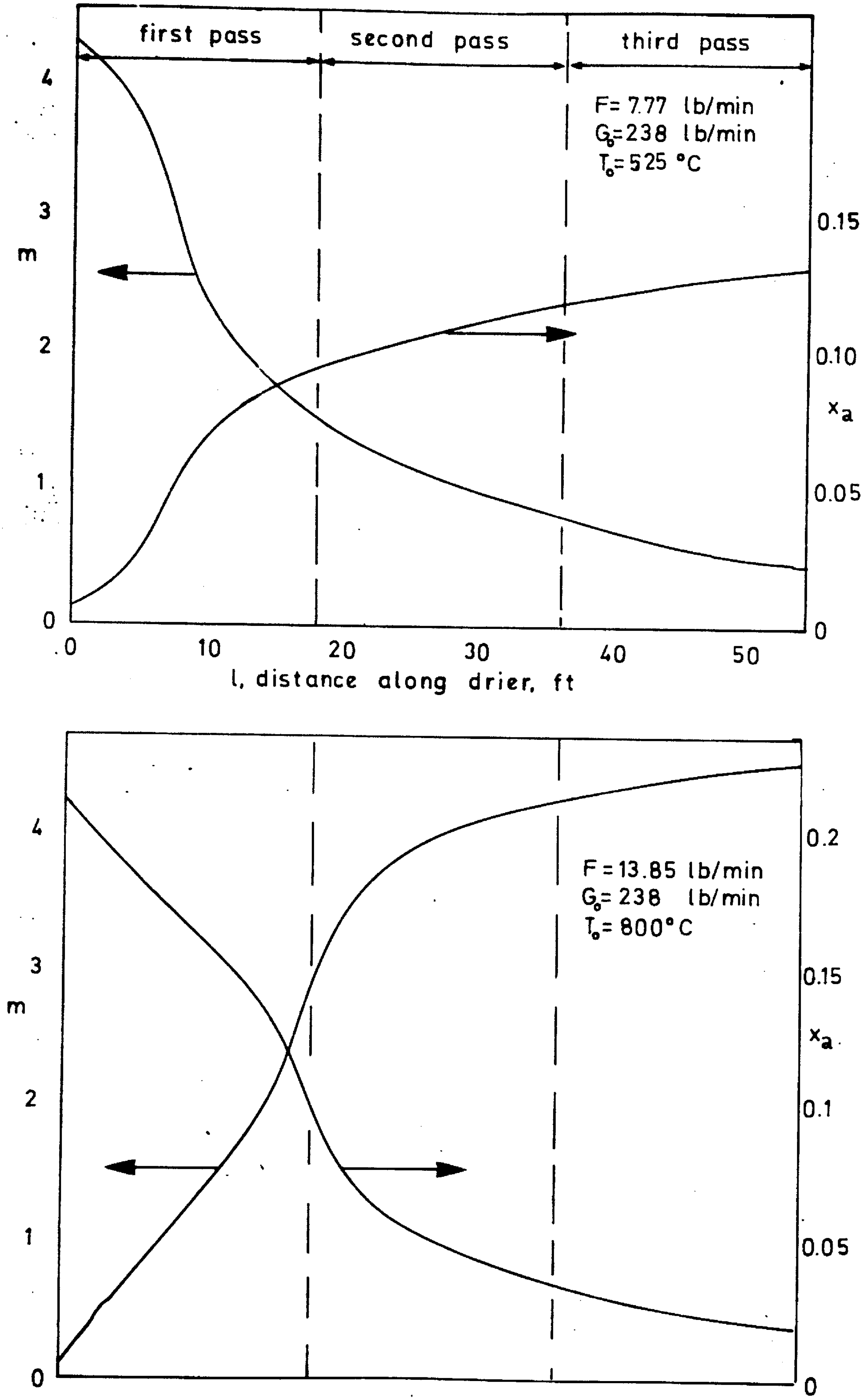


FIG. 8.8. PREDICTED MOISTURE PROFILES IN ROTARY DRIER

FIG. 8.9: PLOT OF m_f, τ, T_f vs. T_o F=7.94 lb/min

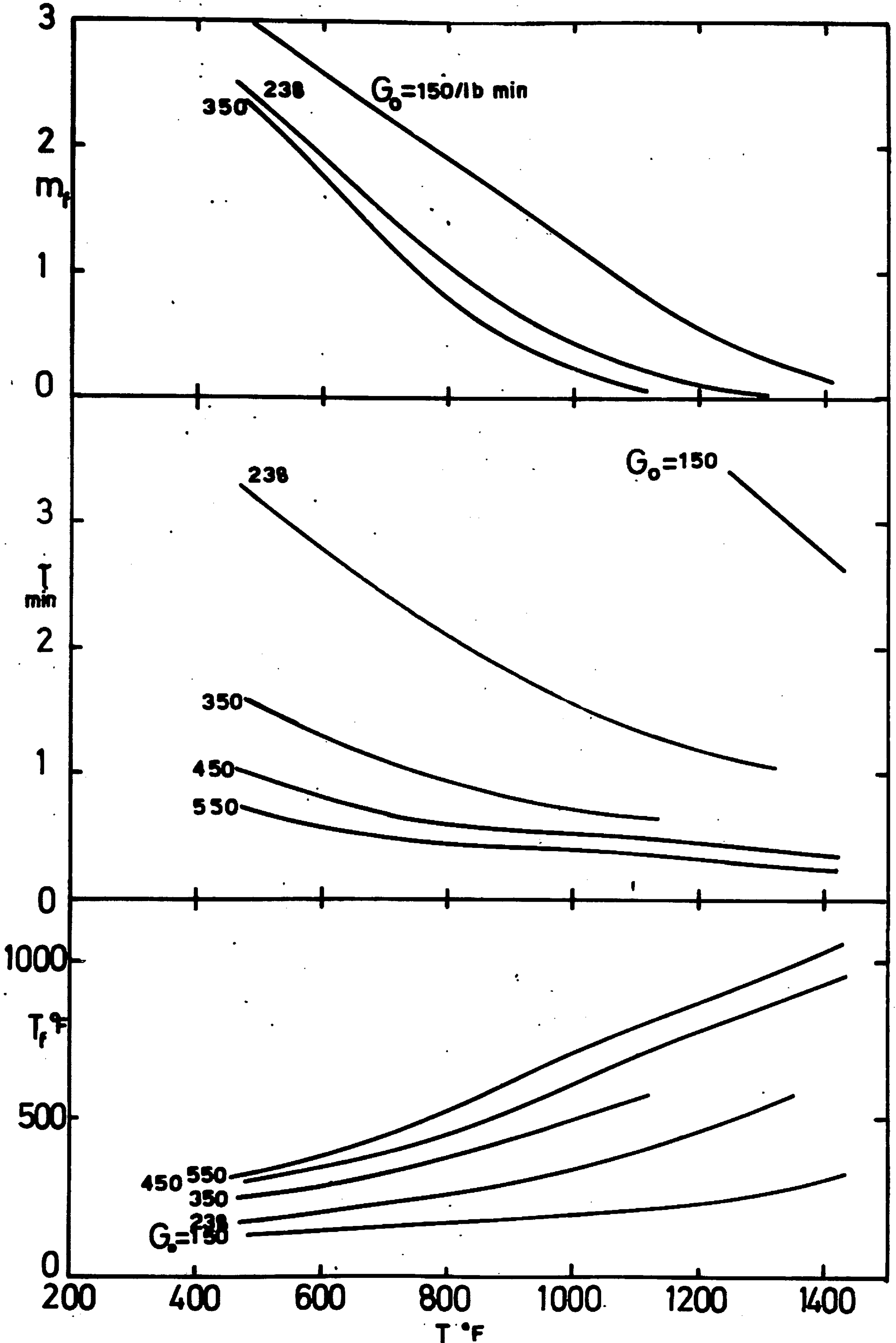


FIG.8.10 PLOT OF m_f, τ, T_f vs. T_o $G_o = 238$ lb/min

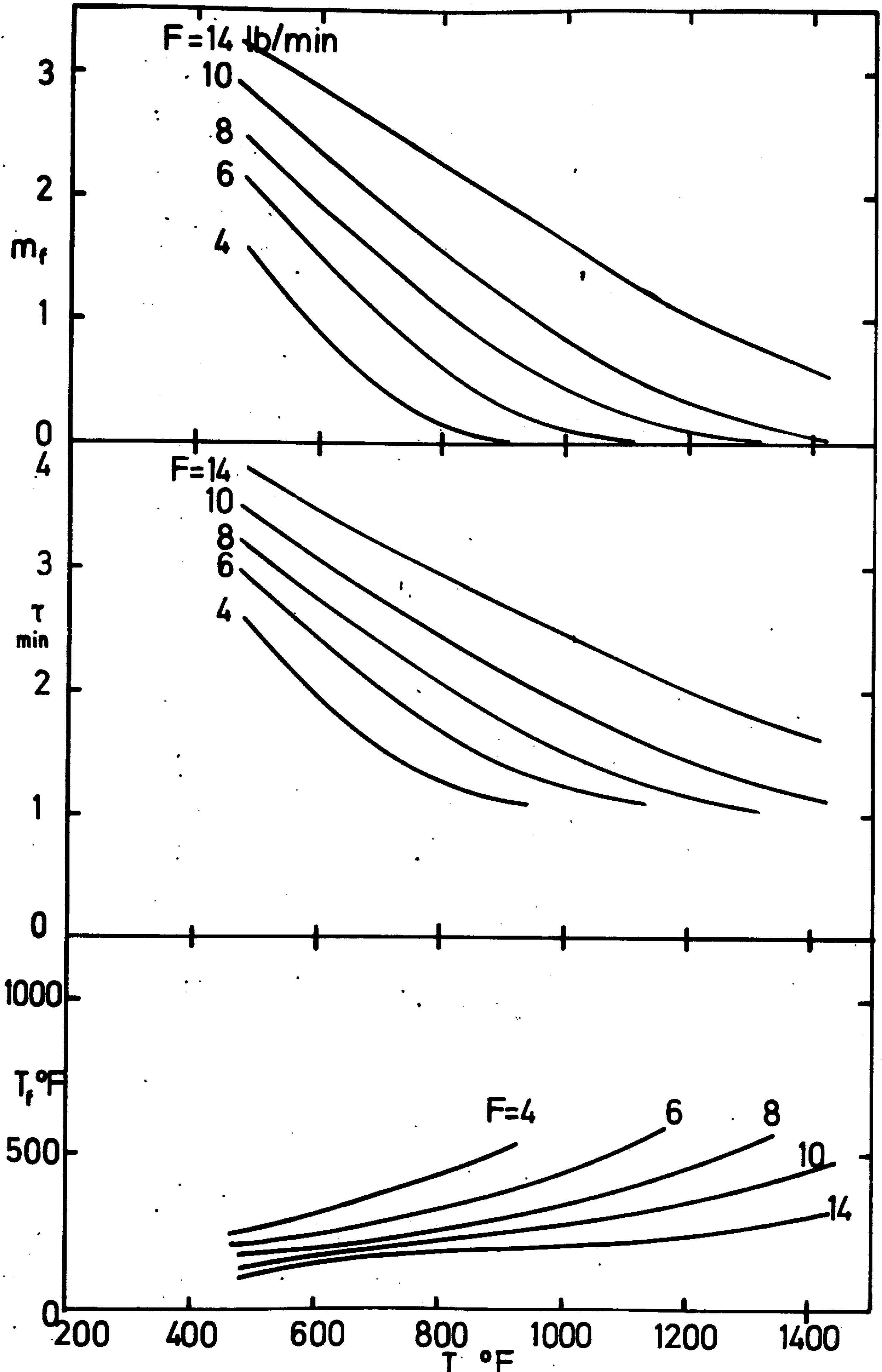


FIG. 8.11. PLOT OF m_f, τ, T_f vs. G_o $F = 7.94$ lb/min

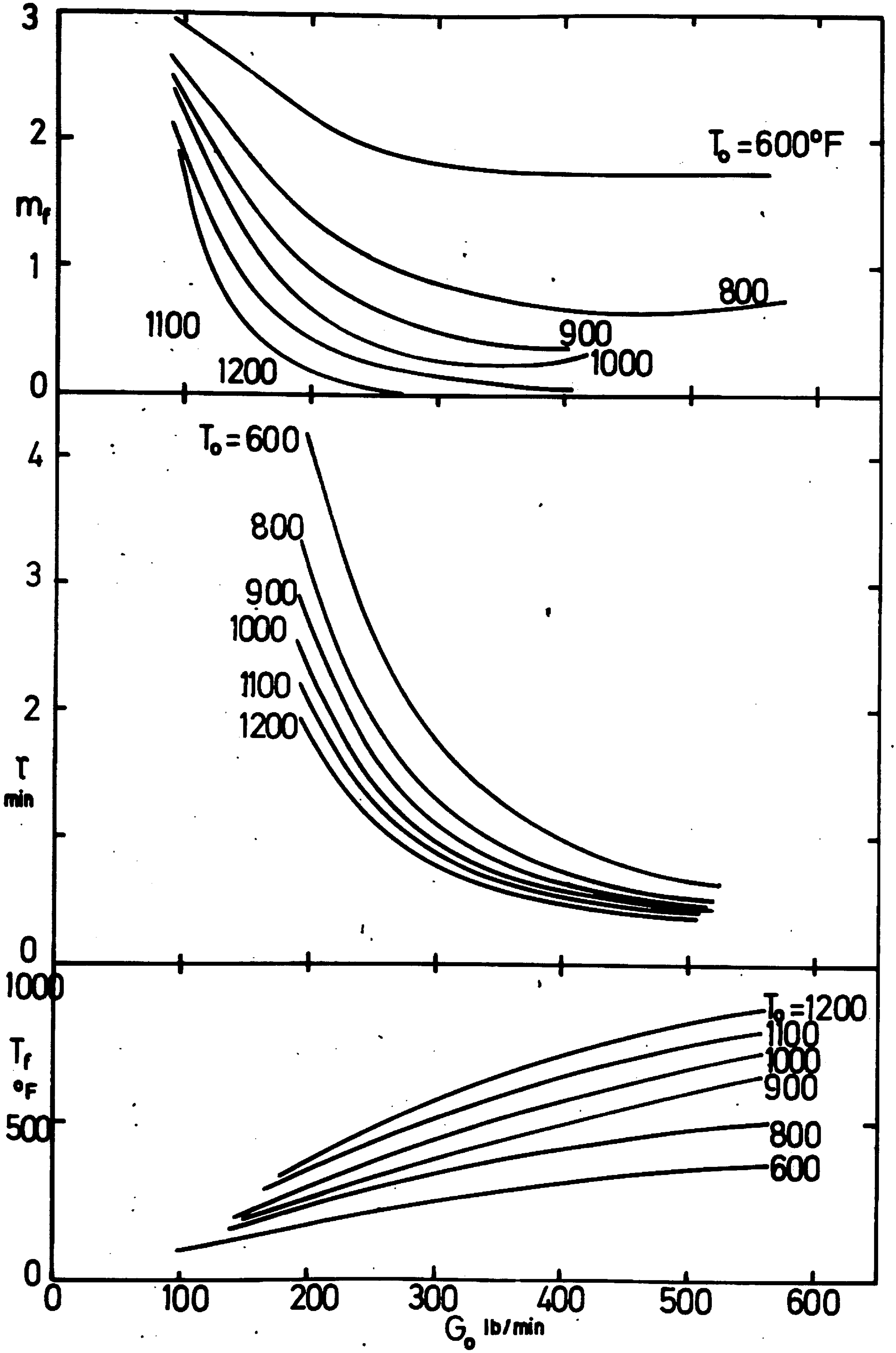


FIG.8.12. PLOT OF m_f, T, T_f vs. F G_0=238 lb/min

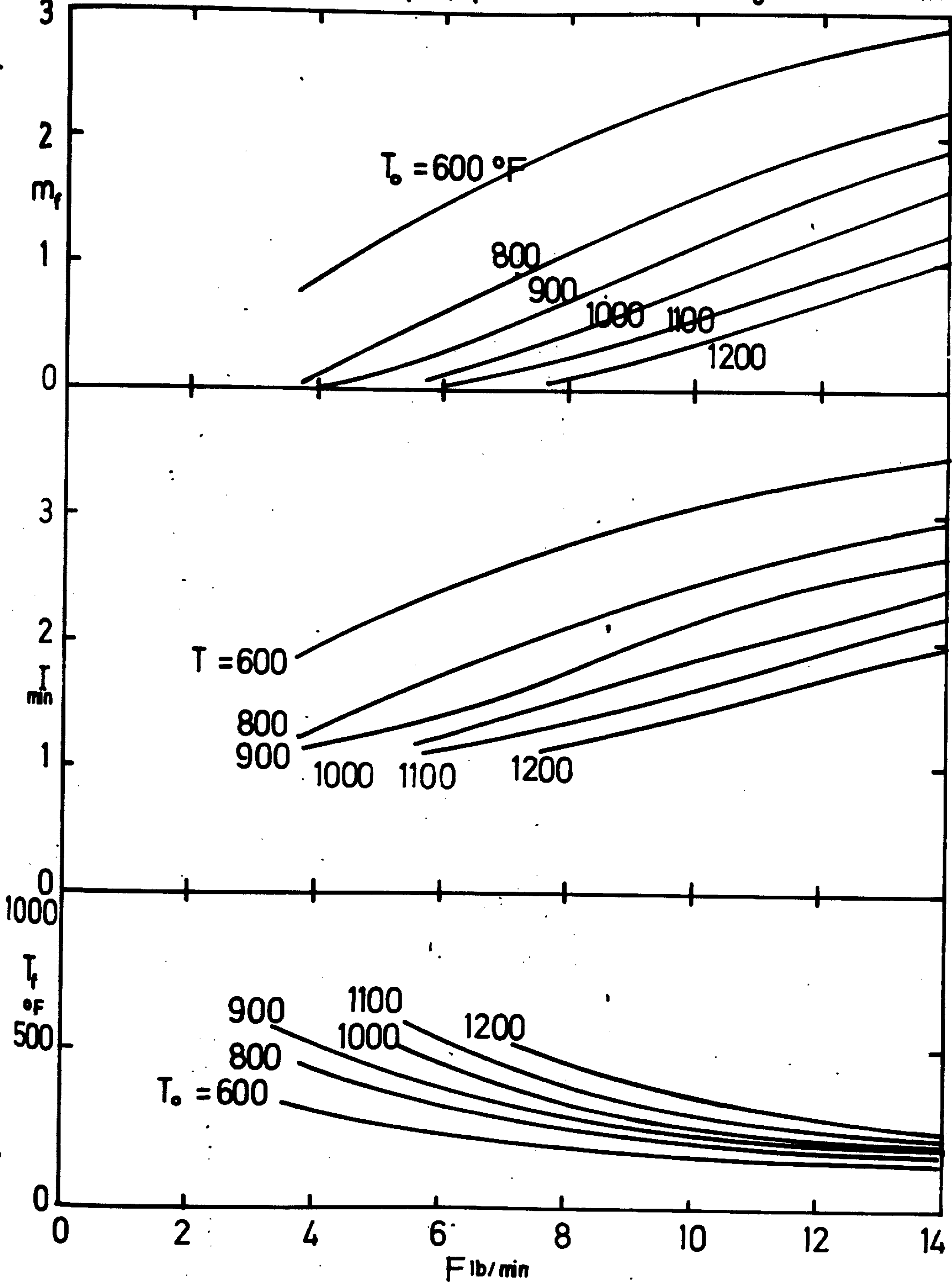
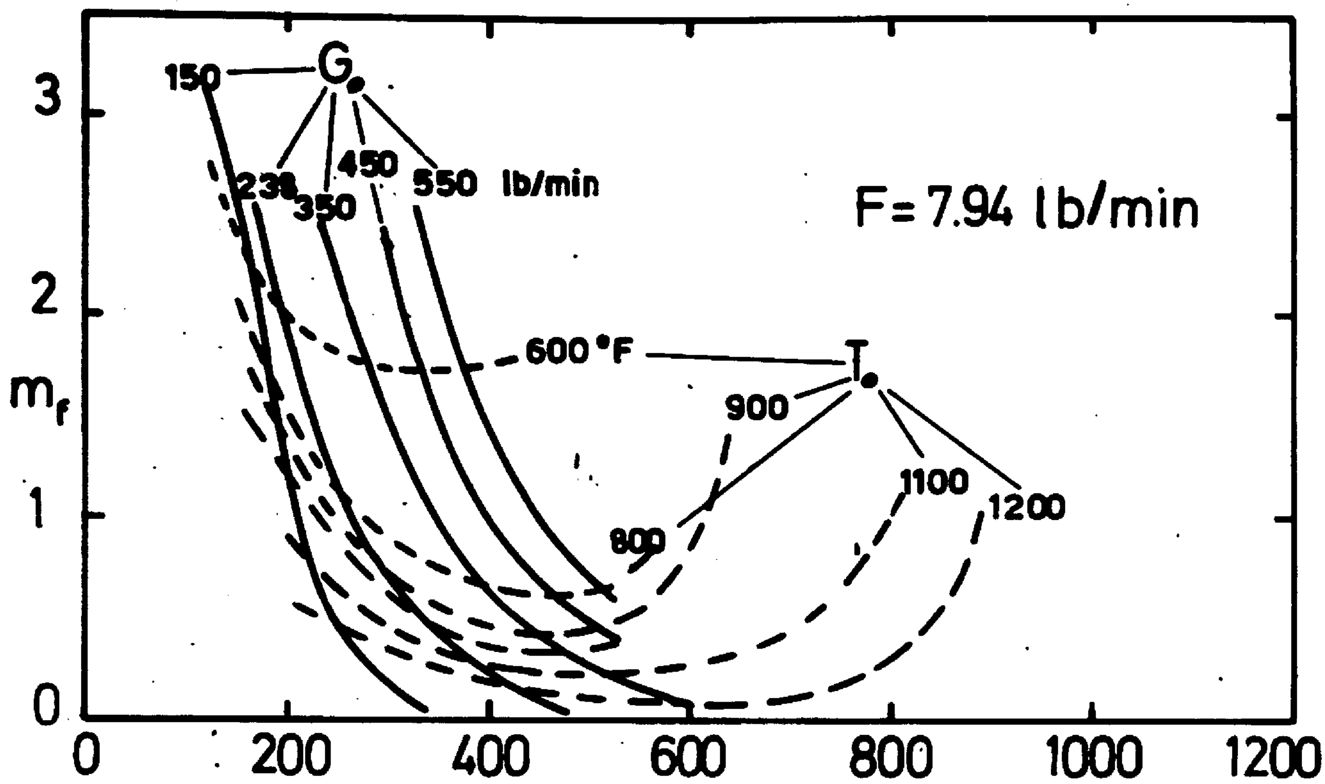


FIG.8.13 PLOT OF m_f vs. T_f



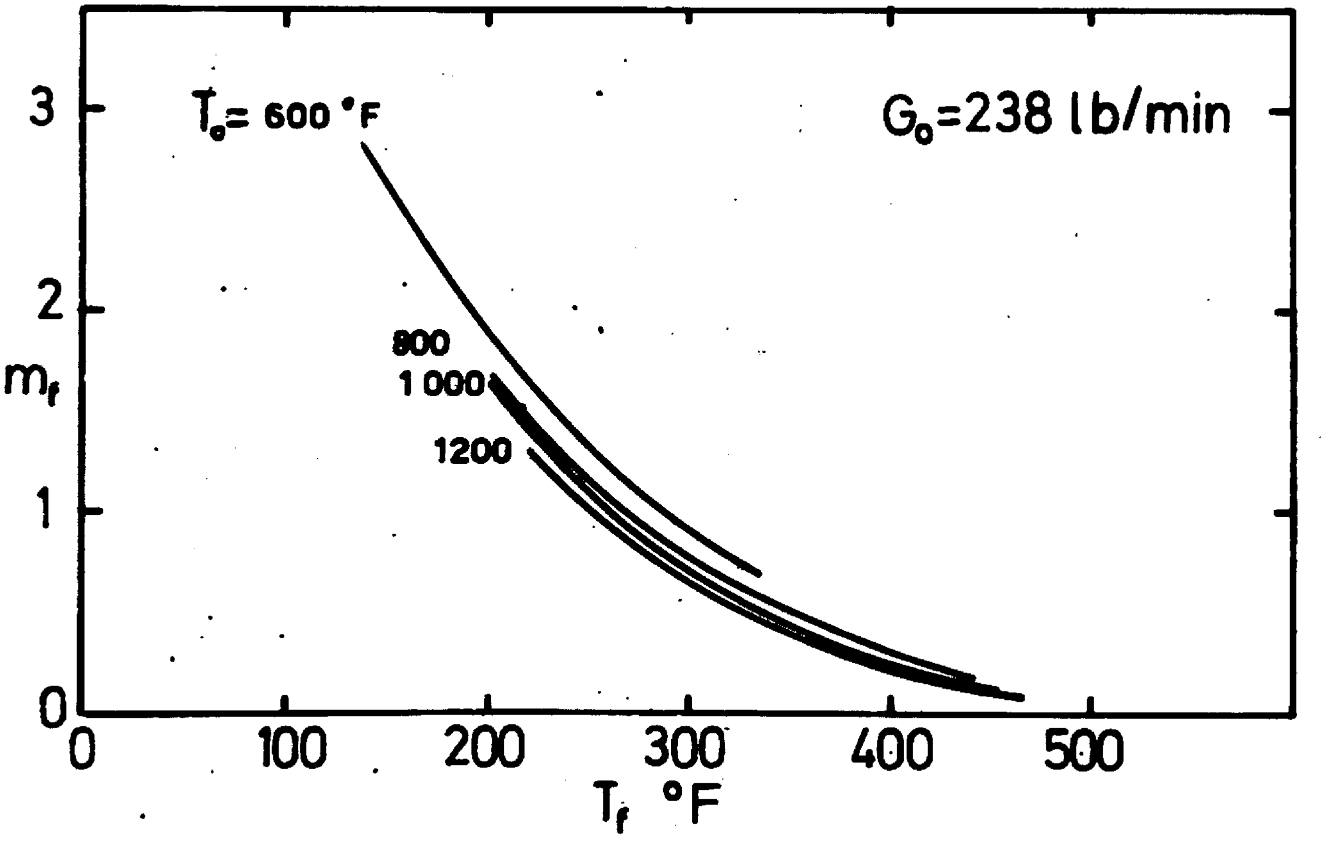
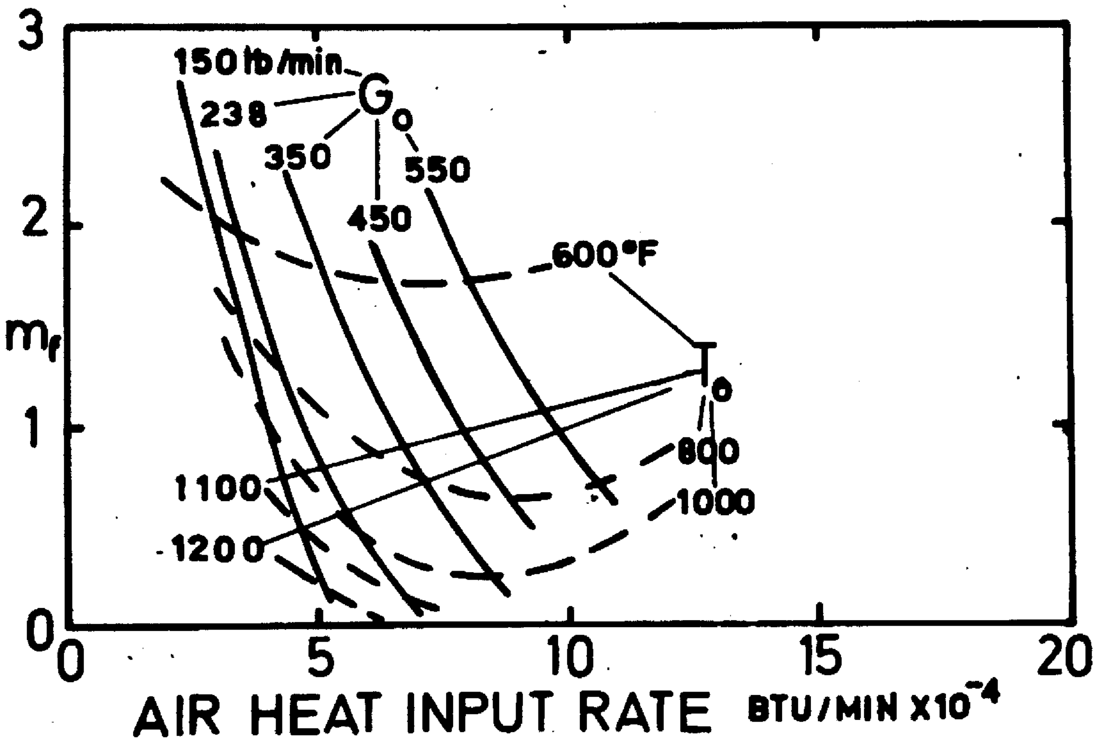


FIG.8.14 PLOT OF m_f vs. T_f

FIG.8.15.

PLOT OF m_f versus AIR HEAT INPUT RATE

F=7.94 lb/min



XII

APPENDICES

APPENDIX 12.1

DERIVATION OF BALANCE RESPONSE EQUATIONS

1. Response to Step input.

(a) First Order System:

The transfer function of a first order system is

$$G(s) = \frac{1}{\tau s + 1}$$

where τ = time constant of system.

Consider a step input of size a:

$$x(t \leq 0) = 0$$

$$x(t > 0) = a$$

The transform of this input is

$$X[s] = \frac{a}{s}$$

Thus, the response from the system is given by

$$Y[s] = G(s)\,X[s]$$

$$= \frac{a}{s}\,\frac{1}{\tau s + 1}$$

Using the method of partial fractions:

$$Y[s] = \frac{A}{s} + \frac{B}{\tau s + 1}$$

Equating the numerators:

$$A(\tau s + 1) + Bs = a$$

$$(A\tau + B)s + A = a$$

Hence $A = a$

and $A\tau + B = 0, \quad B = -A\tau = -a\tau$

Thus $Y[s] = \frac{a}{s} - \frac{a\tau}{\tau s + 1} = \frac{a}{s} - \frac{a}{s + 1/\tau}$

By Inverse Laplace Transform

$$y(t) = a - a\exp(-t/\tau)$$

$$= a(1 - \exp(-t/\tau))$$

(b) Second Order System:

The transform function of a second order system is

$$G(s) = \frac{1}{\tau^2 s^2 + 2\Lambda\tau s + 1}$$

where τ = time constant of system

and Λ = Damping ratio = 1 for critical damping

Let $\Delta = 1$, then

$$G(s) = \frac{1}{(\tau s + 1)^2}$$

For a step input, $X[s] = \frac{a}{s}$, the response of a critically damped second order system is

$$Y[s] = \frac{a}{s} \frac{1}{(\tau s + 1)^2}$$

Using partial fractions:

$$Y[s] = \frac{A}{s} + \frac{B}{\tau s + 1} + \frac{C}{(\tau s + 1)^2}$$

Equating the numerators:

$$A(\tau s + 1)^2 + Bs(\tau s + 1) + Cs = a$$

$$A(\tau^2 s^2 + 2s\tau + 1) + B(\tau s^2 + s) + Cs = a$$

Hence $A = a$

$A\tau^2 + B\tau = 0$

$2A\tau + B + C = 0$

Thus $A = a, \quad B = -a\tau, \quad C = -a\tau$

Thus

$$Y[s] = \frac{a}{s} - \frac{a\tau}{\tau s + 1} - \frac{a\tau}{(\tau s + 1)^2}$$

$$= \frac{a}{s} - \frac{a}{s + 1/\tau} - \frac{a}{\tau(s + 1/\tau)^2}$$

By Inverse Laplace Transform:

$$y(t) = a - a\exp(-t/\tau) - a\frac{t}{\tau}\exp(-t/\tau)$$

$$= a(1 - (1 + t/\tau)\exp(-t/\tau))$$

2. Response to Exponential Input.

For a second order critically damped system, the transfer function is

$$G(s) = \frac{1}{(\tau s + 1)^2}$$

The transform of an exponential input of the form

$$x(t \leq 0) = 0$$

$$x(t > 0) = a(1 - \exp(-k't))$$

is

$$X[s] = \frac{ak'}{s(s + k')}$$

Thus the response is

$$Y[s] = \frac{ak'}{s(s + k')(\tau s + 1)^2}$$

Using partial fractions:

$$Y[s] = \frac{A}{s} + \frac{B}{s + k'} + \frac{C}{\tau s + 1} + \frac{D}{(\tau s + 1)^2}$$

Equating the numerators:

$$A(s + k')(\tau s + 1)^2 + Bs(\tau s + 1)^2 + Cs(s + k')(\tau s + 1) + Ds(s + k') = ak'$$

whence:

$$a = a$$

$$B = -\frac{a}{(k'\tau - 1)^2}$$

$$C = -a\tau\left(1 - \frac{1}{(k'\tau - 1)^2}\right)$$

$$D = -a\tau\left(1 + \frac{1}{(k'\tau - 1)}\right)$$

Thus

$$Y[s] = \frac{a}{s} - \frac{a}{(k'\tau - 1)^2}\,\frac{1}{s + k'}$$

$$- a\left(1 - \frac{1}{(k'\tau - 1)^2}\right)\frac{1}{s + 1/\tau}$$

$$- \frac{a}{\tau}\left(1 + \frac{1}{k'\tau - 1}\right)\frac{1}{(s + 1/\tau)^2}$$

Hence

$$y(t) = a - \frac{a}{(k'\tau - 1)^2}\exp(-k't) - a(1 - \frac{1}{(k'\tau - 1)^2})\exp(-t/\tau)$$

$$- \frac{a}{\tau}(1 + \frac{1}{k'\tau - 1})t\exp(-t/\tau)$$

$$= a\left[1 - \frac{\exp(-k't)}{(\quad\quad)^2} - (1 + \frac{1}{k'\tau - 1})(1 - \frac{1}{k'\tau - 1} + \frac{t}{\tau})\exp(-t/\tau)\right]$$

APPENDIX 12.2

CALCULATION OF AIR FLOW RATE FROM ORIFICE PLATE READINGS

ACCORDING TO B.S.1042 PART 1.

The density of air is given by

$$\rho_a = \frac{(14.7)(144)(28.84)}{1545(T_a + 460)}$$

where T_a is the temperature of the air

The term E is defined as

$$E = \frac{1}{\sqrt{1 - (od/id)^4}}$$

where od = diameter of orifice, inches

id = internal diameter of pipe, inches

The term Q_a is defined as

$$Q_a = 0.608\ E\left(\frac{od^2/4}{144}\right)\sqrt{2g\rho_a(5.2)}\ \frac{60}{\rho_a}$$

where g is the acceleration due to gravity

The flow rate of the air is then given by

$$\text{Flow rate} = Q_a\sqrt{\Delta P}\quad ft^3/min$$

where ΔP is the pressure drop across the orifice plate, inches w.g.

Example:

Let $T_a = 60^\circ F$, od = $1\frac{1}{4}$" and id = 2"

then

$$\rho_a = 0.076\ lb/ft^3$$

$$(od/id)^4 = (0.625)^4 = 0.152$$

$$E = 1/\sqrt{0.848} = 1.087$$

$$Q_a = (0.608)(1.087)\ \frac{1.7}{576}\sqrt{2(32.174)(0.076)(5.2)}\ \frac{60}{0.076}$$

$$= 24.4$$

Hence, for a pressure drop of 4 ins w.g., the flow rate of air is

$$24.4\sqrt{4} = 48.8\ ft^3/min$$

APPENDIX 12.3

DERIVATION OF MOISTURE CONTENT FORMULAE

Moisture content on a dry basis is defined by

$$m = \frac{\text{weight of water}}{\text{weight of dry-matter}} = w_w/w_d$$

Let the total weight be w, then

$$m = (w - w_d)/w_d = \frac{w}{w_d} - 1 \qquad \text{........(A)}$$

Let the moisture content at time 0 be m_o, then

$$m_o = (w_o/w_d) - 1$$

whence

$$w_d = w_o/(m_o + 1)$$

Similarly, if the moisture content at the end of drying is m_f, then

$$w_d = w_f/(m_f + 1)$$

Substituting for w_d in equation (A) above

$$m = \frac{w}{w_o}(m_o + 1) - 1 \qquad \text{........(5.1)}$$

and

$$m = \frac{w}{w_f}(m_f + 1) - 1 \qquad \text{........(5.2)}$$

APPENDIX 12.4

SAMPLE CALCULATION

(1) Calculation of Moisture Contents:

The experimental readings of time, weight and temperature for run number 89 are shown in table A. The time is given in integer minutes, i.e. parts of a minute are ignored. The weight is given in tenths of a gram, and the temperatures in tenths of a degree Centigrade.

The tare weight is 8.1 gm, hence the final weight is

$$19.0 - 8.1 = 10.9 \text{ gm}$$

The final moisture content, dry basis, is 0.0273 gm/gm, thus from equation (5.2), the moisture content at time t is given by

$$m = (\text{weight at time } t) \frac{1 + 0.0273}{10.9} - 1$$
$$= 0.0942\ w_t - 1$$

At time = 1 minute, the weight is 59.8 - 8.1 = 51.7 gm, and thus the moisture content is

$$0.0942(51.7) - 1 = 3.8728$$

The moisture content of the sample at other times can be calculated similarly

The exact value of the time for each reading can be calculated from the number of readings which are the same. For example, there are six readings of time = 2 minutes, and the real times are, therefore,

$$2 + \frac{0}{6} \quad ; \quad 2 + \frac{1}{6} \quad ; \quad 2 + \frac{2}{6} \quad ; \quad 2 + \frac{3}{6} \quad ; \quad 2 + \frac{4}{6} \quad ; \quad 2 + \frac{5}{6}$$

i.e. 2.0; 2.1667; 2.3333; 2.5; 2.6667; 2.8333

The values of the moisture content of the sample, and the times of the readings are shown in table B.

(2) Calculation of Drying Rates:

(a) Polynomial Approximation.

The coefficients of an eighth-order polynomial, fitted to the moisture content - time points, are given in table C. The moisture content is therefore expressed as a function of time by

$$m = 4.7012 - 0.9208\ t + 0.08030\ t^2 - 0.000587\ t^3 - 0.0007237\ t^4$$
$$+ 0.00008341\ t^5 - 0.000004375\ t^6 + 0.0000001136\ t^7$$

By differentiation,

$$-\frac{dm}{dt} = 0.9208 - 0.1606\ t + 0.001761\ t^2 + 0.002895\ t^3 - 0.0004171\ t^4 + 0.00002625\ t^5 - 0.0000007952\ t^6 + 0.000000009424\ t^7$$

At time = 10 minutes,

$$-\frac{dm}{dt} = 0.1393\ \text{min}^{-1}$$

The drying rate at other times can be calculated similarly, and the values are shown in table B. The plot of drying rate against moisture content for this method is shown in fig.5.9.

(b) Segmentation Method.

At time = 0.1667, the moisture content = 4.5137

At time = 0.3333, the moisture content = 4.4100

Thus, over the interval of time 0.1667 minutes to 0.3333 minutes, the average rate of drying is

$$\frac{4.5137 - 4.4100}{0.3333 - 0.1667} \doteq 0.6221\ \text{min}^{-1}$$

The average moisture content over this time interval is

$$\frac{4.5137 + 4.4100}{2} = 4.4618$$

The average moisture contents and average drying rates over all the other time intervals can be calculated similarly. The results are shown in table D. The plot of drying rate against moisture content for this method is given in fig.5.4

(c) Segmentation Method with Grouping.

The average of the first six moisture content readings is

$$\frac{4.5137 + 4.4100 + 4.2636 + 4.1367 + 4.0141 + 3.8728}{6} = 4.2026$$

The average of the first six time readings is

$$\frac{0.1667 + 0.3333 + 0.5000 + 0.6667 + 0.8333 + 1.0000}{6} = 0.5833\ \text{min}$$

Thus, a "smoothed" point has been calculated. Similarly, the second six readings of moisture content and time can be averaged to give 3.4423 and 1.5833 respectively.

Thus, the average drying rate over the time interval 0.5833 to 1.5833 is

$$\frac{4.2026 - 3.4423}{1.5833 - 0.5833} = 0.7603$$

and the average moisture content is

$$\frac{4.2026 + 3.4423}{2} = 3.8225$$

Similarly, by taking successive groups of six values of time and moisture content, and averaging them, table E can be obtained. The plot of drying rate against moisture content for this method is shown in fig.5.7.

(d) Fitting of Equations.

The straight lines shown in figs.5.4, 5.7 and 5.9 are those fitted by the method of least squares to the respective plots of drying rate against moisture content.

Table A - (i)

Run Factor Tare

8;89;10 ;8.1 ;

Time	**Weight**	T_1	T_2	T_3	T_4
0000;	+0666;	+0187;	+0175;	+0152;	+1280;
0000;	+0655;	+0187;	+0175;	+0152;	+1281;
0000;	+0640;	+0186;	+0177;	+0152;	+1281;
0000;	+0626;	+0187;	+0176;	+0152;	+1281;
0000;	+0613;	+0187;	+0175;	+0152;	+1281;
0001;	+0598;	+0187;	+0175;	+0152;	+1282;
0001;	+0585;	+0187;	+0175;	+0153;	+1283;
0001;	+0570;	+0187;	+0175;	+0153;	+1284;
0001;	+0557;	+0186;	+0175;	+0153;	+1283;
0001;	+0545;	+0186;	+0175;	+0154;	+1284;
0001;	+0534;	+0187;	+0176;	+0152;	+1284;
0002;	+0523;	+0187;	+0175;	+0152;	+1285;
0002;	+0511;	+0187;	+0176;	+0153;	+1285;
0002;	+0500;	+0187;	+0175;	+0152;	+1285;
0002;	+0491;	+0187;	+0177;	+0154;	+1285;
0002;	+0481;	+0187;	+0176;	+0151;	+1285;
0002;	+0472;	+0187;	+0175;	+0153;	+1285;
0003;	+0463;	+0187;	+0176;	+0152;	+1286;
0003;	+0455;	+0187;	+0175;	+0152;	+1286;
0003;	+0447;	+0187;	+0174;	+0152;	+1287;
0003;	+0438;	+0187;	+0174;	+0153;	+1287;
0003;	+0430;	+0187;	+0176;	+0153;	+1287;
0003;	+0422;	+0187;	+0175;	+0153;	+1287;
0004;	+0415;	+0187;	+0175;	+0152;	+1287;
0004;	+0408;	+0187;	+0175;	+0152;	+1287;
0004;	+0402;	+0187;	+0175;	+0154;	+1289;
0004;	+0395;	+0186;	+0176;	+0153;	+1289;
0004;	+0388;	+0186;	+0175;	+0153;	+1289;
0004;	+0382;	+0187;	+0175;	+0152;	+1289;
0005;	+0377;	+0187;	+0175;	+0151;	+1289;
0005;	+0370;	+0186;	+0176;	+0152;	+1289;
0005;	+0366;	+0187;	+0177;	+0154;	+1289;
0005;	+0360;	+0187;	+0177;	+0154;	+1289;
0005;	+0354;	+0187;	+0177;	+0153;	+1289;
0005;	+0349;	+0187;	+0176;	+0154;	+1289;
0006;	+0344;	+0187;	+0175;	+0152;	+1289;
0006;	+0339;	+0187;	+0176;	+0153;	+1289;
0006;	+0335;	+0187;	+0177;	+0154;	+1290;
0006;	+0331;	+0187;	+0177;	+0154;	+1290;
0006;	+0325;	+0187;	+0177;	+0155;	+1290;
0006;	+0321;	+0187;	+0177;	+0155;	+1290;
0007;	+0316;	+0188;	+0177;	+0154;	+1290;
0007;	+0313;	+0188;	+0177;	+0155;	+1290;
0007;	+0308;	+0188;	+0176;	+0153;	+1289;
0007;	+0305;	+0188;	+0177;	+0154;	+1290;
0007;	+0301;	+0187;	+0179;	+0153;	+1290;
0007;	+0297;	+0187;	+0178;	+0155;	+1290;
0008;	+0294;	+0188;	+0177;	+0153;	+1290;
0008;	+0291;	+0188;	+0178;	+0152;	+1290;
0008;	+0289;	+0187;	+0177;	+0154;	+1291;
0008;	+0284;	+0187;	+0177;	+0154;	+1291;
0008;	+0282;	+0187;	+0178;	+0153;	+1292;
0008;	+0280;	+0187;	+0177;	+0153;	+1292;
0009;	+0276;	+0188;	+0177;	+0154;	+1292;
0009;	+0272;	+0188;	+0177;	+0153;	+1293;
0009;	+0270;	+0189;	+0177;	+0154;	+1293;
0009;	+0267;	+0188;	+0177;	+0153;	+1293;
0009;	+0264;	+0188;	+0178;	+0152;	+1293;
0009;	+0262;	+0188;	+0177;	+0154;	+1292;
0010;	+0260;	+0188;	+0177;	+0153;	+1291;
0010;	+0257;	+0188;	+0177;	+0153;	+1290;
0010;	+0255;	+0188;	+0176;	+0152;	+1291;
0010;	+0253;	+0188;	+0177;	+0153;	+1291;
0010;	+0250;	+0187;	+0178;	+0154;	+1291;
0010;	+0248;	+0188;	+0178;	+0153;	+1292;
0011;	+0246;	+0189;	+0177;	+0152;	+1291;
0011;	+0244;	+0188;	+0177;	+0153;	+1291;
0011;	+0242;	+0189;	+0177;	+0153;	+1291;
0011;	+0241;	+0188;	+0178;	+0153;	+1291;
0011;	+0238;	+0188;	+0179;	+0154;	+1291;
0011;	+0237;	+0188;	+0179;	+0153;	+1292;
0012;	+0234;	+0189;	+0179;	+0153;	+1290;
0012;	+0233;	+0189;	+0177;	+0154;	+1290;
0012;	+0231;	+0190;	+0177;	+0154;	+1290;
0012;	+0230;	+0189;	+0178;	+0154;	+1290;
0012;	+0228;	+0189;	+0179;	+0155;	+1290;
0012;	+0228;	+0190;	+0179;	+0154;	+1291;
0013;	+0226;	+0189;	+0178;	+0154;	+1290;
0013;	+0224;	+0190;	+0179;	+0154;	+1290;
0013;	+0222;	+0189;	+0178;	+0154;	+1290;
0013;	+0222;	+0190;	+0178;	+0154;	+1291;
0013;	+0221;	+0189;	+0180;	+0154;	+1290;
0013;	+0219;	+0190;	+0179;	+0154;	+1291;
0014;	+0219;	+0189;	+0179;	+0154;	+1290;
0014;	+0216;	+0189;	+0178;	+0154;	+1291;
0014;	+0216;	+0190;	+0177;	+0153;	+1291;
0014;	+0215;	+0190;	+0178;	+0154;	+1291;
0014;	+0213;	+0190;	+0179;	+0154;	+1292;
0014;	+0213;	+0190;	+0179;	+0153;	+1293;
0015;	+0211;	+0189;	+0179;	+0155;	+1293;
0015;	+0211;	+0189;	+0179;	+0155;	+1292;
0015;	+0210;	+0190;	+0178;	+0154;	+1292;
0015;	+0209;	+0190;	+0178;	+0154;	+1292;
0015;	+0209;	+0190;	+0179;	+0155;	+1293;
0015;	+0208;	+0191;	+0180;	+0157;	+1293;
0016;	+0206;	+0190;	+0179;	+0156;	+1293;
0016;	+0205;	+0190;	+0180;	+0155;	+1292;
0016;	+0205;	+0191;	+0180;	+0155;	+1292;
0016;	+0204;	+0191;	+0180;	+0156;	+1292;
0016;	+0204;	+0191;	+0180;	+0157;	+1292;
0016;	+0204;	+0191;	+0182;	+0156;	+1293;
0017;	+0202;	+0190;	+0181;	+0157;	+1294;
0017;	+0203;	+0190;	+0181;	+0156;	+1294;
0017;	+0201;	+0191;	+0181;	+0156;	+1294;
0017;	+0201;	+0191;	+0180;	+0155;	+1294;
0017;	+0201;	+0191;	+0180;	+0157;	+1294;
0017;	+0200;	+0192;	+0179;	+0157;	+1295;

Table A - (ii)

```
0018; +0199; +0191; +0180; +0157; +1295;
0018; +0198; +0191; +0181; +0156; +1295;
0018; +0199; +0192; +0182; +0157; +1295;
0018; +0198; +0192; +0180; +0157; +1295;
0019; +0197; +0191; +0182; +0157; +1296;
0019; +0195; +0192; +0181; +0157; +1296;
0019; +0194; +0192; +0182; +0157; +1297;
0020; +0194; +0191; +0181; +0157; +1297;
0020; +0194; +0192; +0182; +0158; +1298;
0020; +0193; +0192; +0182; +0158; +1298;
0021; +0193; +0192; +0182; +0158; +1298;
0021; +0192; +0193; +0182; +0158; +1299;
0021; +0193; +0193; +0180; +0158; +1299;
0022; +0191; +0192; +0182; +0158; +1300;
0023; +0190; +0192; +0183; +0158; +1301;
0024; +0190; +0193; +0183; +0158; +1302;
```

Termination Codes

```
-1;+6;+2;
```

Figures for Moisture content Determination

```
538.7904; 486.3217; 474.3366;
249.6903;249.4297;  239.8950;
```

Termination Code

```
-50000;
```

Table B

```
                                                      RUN NO    89

          CALCULATED MOISTURE CONTENTS AND DRYING RATES CALCULATED FROM

   TIME        MCDB       P-RATE            TIME       MCDB       P-RATE            TIME

   0.1667     4.5137     0.8941            0.3333     4.4100     0.8676            0.5000
   0.6667     4.1367     0.8153            0.8333     4.0141     0.7897            1.0000
   1.1667     3.7502     0.7397            1.3333     3.6089     0.7155            1.5000
   1.6667     3.3732     0.6686            1.8333     3.2696     0.6459            2.0000
   2.1667     3.0528     0.6025            2.3333     2.9491     0.5818            2.5000
   2.6667     2.7700     0.5421            2.8333     2.6852     0.5233            3.0000
   3.1667     2.5250     0.4875            3.3333     2.4496     0.4705            3.5000
   3.6667     2.2893     0.4385            3.8333     2.2139     0.4234            4.0000
   4.1667     2.0820     0.3949            4.3333     2.0254     0.3815            4.5000
   4.6667     1.8935     0.3564            4.8333     1.8369     0.3446            5.0000
   5.1667     1.7238     0.3226            5.3333     1.6861     0.3122            5.5000
   5.6667     1.5730     0.2928            5.8333     1.5259     0.2837            6.0000
   6.1667     1.4317     0.2667            6.3333     1.3940     0.2587            6.5000
   6.6667     1.2997     0.2437            6.8333     1.2620     0.2366            7.0000
   7.1667     1.1866     0.2233            7.3333     1.1395     0.2170            7.5000
   7.6667     1.0735     0.2052            7.8333     1.0358     0.1995            8.0000
   8.1667     0.9793     0.1888            8.3333     0.9604     0.1837            8.5000
   8.6667     0.8944     0.1739            8.8333     0.8756     0.1692            9.0000
   9.1667     0.8002     0.1601            9.3333     0.7813     0.1558            9.5000
   9.6667     0.7248     0.1474            9.8333     0.7059     0.1433           10.0000
  10.1667     0.6588     0.1354           10.3333     0.6400     0.1315           10.5000
  10.6667     0.5928     0.1240           10.8333     0.5740     0.1204           11.0000
  11.1667     0.5363     0.1133           11.3333     0.5174     0.1099           11.5000
  11.6667     0.4797     0.1032           11.8333     0.4703     0.0999           12.0000
  12.1667     0.4326     0.0936           12.3333     0.4138     0.0905           12.5000
  12.6667     0.3855     0.0846           12.8333     0.3855     0.0817           13.0000
  13.1667     0.3478     0.0762           13.3333     0.3289     0.0736           13.5000
  13.6667     0.3195     0.0686           13.8333     0.3007     0.0662           14.0000
  14.1667     0.2724     0.0616           14.3333     0.2724     0.0594           14.5000
  14.6667     0.2441     0.0554           14.8333     0.2441     0.0534           15.0000
  15.1667     0.2253     0.0499           15.3333     0.2158     0.0482           15.5000
  15.6667     0.2064     0.0451           15.8333     0.1970     0.0436           16.0000
  16.1667     0.1687     0.0409           16.3333     0.1687     0.0396           16.5000
  16.6667     0.1593     0.0373           16.8333     0.1593     0.0362           17.0000
  17.1667     0.1499     0.0342           17.3333     0.1310     0.0332           17.5000
  17.6667     0.1310     0.0314           17.8333     0.1216     0.0305           18.0000
  18.1667     0.1027     0.0288           18.3333     0.1122     0.0279           18.6667
  19.0000     0.0933     0.0244           19.3333     0.0745     0.0226           19.6667
  20.0000     0.0650     0.0186           20.3333     0.0650     0.0164           20.6667
  21.0000     0.0556     0.0119           21.3333     0.0462     0.0098           21.6667
  22.0000     0.0368     0.0063           23.0000     0.0273     0.0067           24.0000
```

Table B

```
                         RUN NO    89
E CONTENTS AND DRYING RATES CALCULATED FROM FITTED POLYNOMIAL
E
            TIME      MCDB      P-RATE         TIME      MCDB      P-RATE

           0.3333    4.4100    0.8676         0.5000    4.2686    0.8413
           0.8333    4.0141    0.7897         1.0000    3.8728    0.7645
           1.3333    3.6089    0.7155         1.5000    3.4863    0.6917
           1.8333    3.2696    0.6459         2.0000    3.1659    0.6239
           2.3333    2.9491    0.5818         2.5000    2.8643    0.5616
           2.8333    2.6852    0.5233         3.0000    2.6004    0.5051
           3.3333    2.4496    0.4705         3.5000    2.3647    0.4542
           3.8333    2.2139    0.4234         4.0000    2.1480    0.4089
           4.3333    2.0254    0.3815         4.5000    1.9595    0.3687
           4.8333    1.8369    0.3446         5.0000    1.7898    0.3334
           5.3333    1.6861    0.3122         5.5000    1.6296    0.3023
           5.8333    1.5259    0.2837         6.0000    1.4788    0.2750
           6.3333    1.3940    0.2587         6.5000    1.3563    0.2510
           6.8333    1.2620    0.2366         7.0000    1.2149    0.2298
           7.3333    1.1395    0.2170         7.5000    1.1112    0.2110
           7.8333    1.0358    0.1995         8.0000    1.0075    0.1941
           8.3333    0.9604    0.1837         8.5000    0.9133    0.1787
           8.8333    0.8756    0.1692         9.0000    0.8379    0.1646
           9.3333    0.7813    0.1558         9.5000    0.7531    0.1515
           9.8333    0.7059    0.1433        10.0000    0.6871    0.1393
          10.3333    0.6400    0.1315        10.5000    0.6211    0.1277
          10.8333    0.5740    0.1204        11.0000    0.5551    0.1168
          11.3333    0.5174    0.1099        11.5000    0.5080    0.1065
          11.8333    0.4703    0.0999        12.0000    0.4420    0.0967
          12.3333    0.4138    0.0905        12.5000    0.4043    0.0875
          12.8333    0.3855    0.0817        13.0000    0.3666    0.0790
          13.3333    0.3289    0.0736        13.5000    0.3289    0.0711
          13.8333    0.3007    0.0662        14.0000    0.3007    0.0638
          14.3333    0.2724    0.0594        14.5000    0.2630    0.0574
          14.8333    0.2441    0.0534        15.0000    0.2253    0.0516
          15.3333    0.2158    0.0482        15.5000    0.2064    0.0466
          15.8333    0.1970    0.0436        16.0000    0.1781    0.0422
          16.3333    0.1687    0.0396        16.5000    0.1593    0.0385
          16.8333    0.1593    0.0362        17.0000    0.1404    0.0352
          17.3333    0.1310    0.0332        17.5000    0.1310    0.0323
          17.8333    0.1216    0.0305        18.0000    0.1122    0.0296
          18.3333    0.1122    0.0279        18.6667    0.1027    0.0262
          19.3333    0.0745    0.0226        19.6667    0.0650    0.0206
          20.3333    0.0650    0.0164        20.6667    0.0556    0.0142
          21.3333    0.0462    0.0098        21.6667    0.0556    0.0078
          23.0000    0.0273    0.0067        24.0000    0.0273    0.0232
```

Table C

```
COEFFICIENTS OF POLYNOMIAL

     A0 =   4.701155*  +0
     A1 =  -9.208325*  -1
     A2 =   8.030319*  -2
     A3 =  -5.870030*  -4
     A4 =  -7.236859*  -4
     A5 =   8.340886*  -5
     A6 =  -4.374996*  -6
     A7 =   1.135904*  -7
     A8 =  -1.178043*  -9
```

Table D

```
              RUN NO    89            SEGMENTATION METHOD  -  NO GROUPING

  AVMC      AVRATE          AVMC      AVRATE          AVMC      AVRATE          AVMC      AVRATE

 4.4618     0.6221         4.3393     0.8483         4.2026     0.7917         4.0754     0.7352
 3.9434     0.8483         3.8115     0.7352         3.6795     0.8483         3.5476     0.7352
 3.4298     0.6786         3.3214     0.6221         3.2177     0.6221         3.1093     0.6786
 3.0009     0.6221         2.9067     0.5090         2.8172     0.5655         2.7276     0.5090
 2.6428     0.5090         2.5627     0.4524         2.4873     0.4524         2.4072     0.5090
 2.3270     0.4524         2.2516     0.4524         2.1810     0.3959         2.1150     0.3959
 2.0537     0.3393         1.9925     0.3959         1.9265     0.3959         1.8652     0.3393
 1.8134     0.2828         1.7568     0.3959         1.7050     0.2262         1.6579     0.3393
 1.6013     0.3393         1.5495     0.2828         1.5024     0.2828         1.4552     0.2828
 1.4128     0.2262         1.3751     0.2262         1.3280     0.3393         1.2809     0.2262
 1.2385     0.2828         1.2008     0.1697         1.1631     0.2828         1.1254     0.1697
 1.0924     0.2262         1.0547     0.2262         1.0217     0.1697         0.9934     0.1697
 0.9698     0.1131         0.9369     0.2828         0.9039     0.1131         0.8850     0.1131
 0.8567     0.2262         0.8190     0.2262         0.7908     0.1131         0.7672     0.1697
 0.7389     0.1697         0.7154     0.1131         0.6965     0.1131         0.6729     0.1697
 0.6494     0.1131         0.6305     0.1131         0.6070     0.1697         0.5834     0.1131
 0.5646     0.1131         0.5457     0.1131         0.5269     0.1131         0.5127     0.0566
 0.4939     0.1697         0.4750     0.0566         0.4562     0.1697         0.4373     0.0566
 0.4232     0.1131         0.4090     0.0566         0.3949     0.1131         0.3855     0.0000
 0.3761     0.1131         0.3572     0.1131         0.3384     0.1131         0.3289     0.0000
 0.3242     0.0566         0.3101     0.1131         0.3007     0.0000         0.2865     0.1697
 0.2724     0.0000         0.2677     0.0566         0.2535     0.1131         0.2441     0.0000
 0.2347     0.1131         0.2253     0.0000         0.2205     0.0566         0.2111     0.0566
 0.2064     0.0000         0.2017     0.0566         0.1876     0.1131         0.1734     0.0566
 0.1687     0.0000         0.1640     0.0566         0.1593     0.0000         0.1593     0.0000
 0.1499     0.1131         0.1451    -0.0566         0.1404     0.1131         0.1310     0.0000
 0.1310     0.0000         0.1263     0.0566         0.1169     0.0566         0.1074     0.0566
 0.1074    -0.0566         0.1074     0.0283         0.0980     0.0283         0.0839     0.0566
 0.0697     0.0283         0.0650     0.0000         0.0650     0.0000         0.0603     0.0283
 0.0556     0.0000         0.0509     0.0283         0.0509    -0.0283         0.0462     0.0566
 0.0320     0.0094         0.0273     0.0000
```

Table E

```
RUN NO    89            SEGMENTATION METHOD
   AVERAGING POINTS IN GROUPS OF     6

    TIME        MCDB        AVMC       AVRATE

   0.5833      4.2026      3.8225      0.7603
   1.5833      3.4423      3.1313      0.6221
   2.5833      2.8203      2.5760      0.4885
   3.5833      2.3318      2.1315      0.4006
   4.5833      1.9312      1.7670      0.3283
   5.5833      1.6029      1.4647      0.2765
   6.5833      1.3264      1.2094      0.2341
   7.5833      1.0924      1.0013      0.1822
   8.5833      0.9101      0.8261      0.1681
   9.5833      0.7421      0.6745      0.1351
  10.5833      0.6070      0.5496      0.1147
  11.5833      0.4923      0.4452      0.0943
  12.5833      0.3981      0.3596      0.0770
  13.5833      0.3211      0.2873      0.0675
  14.5833      0.2535      0.2292      0.0487
  15.5833      0.2048      0.1821      0.0456
  16.5833      0.1593      0.1444      0.0298
  17.5833      0.1294      0.1106      0.0295
  18.8611      0.0917      0.0745      0.0175
  20.8333      0.0572
```

APPENDIX 12.5.

INTEGRATION OF THE DRYING EQUATIONS

(a) The Constant Rate Equation:

$$-\frac{dm}{dt} = k_o$$

$$dm = -k_o\,dt$$

$$\int dm = \int -k_o\,dt$$

$$m = -k_o t + \text{constant}$$

At $t = 0$, $m = m_o$, thus constant $= m_o$

hence $$m = m_o - k_o t$$

(b) The Falling Rate Equation:

$$-\frac{dm}{dt} = k(m - m_e)$$

$$\frac{dm}{m - m_e} = -k\,dt$$

$$\int \frac{d(m - m_e)}{m - m_e} = \int -k\,dt$$

$$\log_e(m - m_e) = -kt + \text{constant}$$

At $t = 0$, $m = m_o$, thus constant $= \log_e(m_o - m_e)$

hence
$$\log_e(m - m_e) = -kt + \log_e(m_o - m_e)$$

$$\log_e \frac{m - m_e}{m_o - m_e} = -kt$$

$$\frac{m - m_e}{m_o - m_e} = e^{-kt}$$

(c) Multiple Falling Rate Equation:

Period 1:

The integration is the same as in (b) except that k is replaced by k_1 and m_e by m_{e1} giving

$$\frac{m - m_{e1}}{m_o - m_{e1}} = \exp(-k_1 t)$$

Period 2:

From (b)

$$\log_e(m - m_{e2}) = -k_2 t + \text{constant}$$

At $t = t_{c1}$, $m = m_{c1}$, thus constant $= \log_e(m_{c1} - m_{e2}) + k_2 t_{c1}$

hence $$\log_e(m - m_{e2}) = -k_2 t + \log_e(m_{c1} - m_{e2}) + k_2 t_{c1}$$

$$\frac{m - m_{e2}}{m_{c1} - m_{e2}} = \exp(-k_2(t - t_{c1}))$$

Period 3:

By a similar procedure it can be shown that

$$\frac{m - m_{e3}}{m_{c2} - m_{e3}} = \exp(-k_3(t - t_{c2}))$$

The time to reach the first and second critical moisture contents can be calculated if the critical moisture contents are known, and vice-versa. From the equations above:

$$t_{c1} = -\frac{1}{k_1} \log_e \frac{k_2(m_{e1} - m_{e2})}{(k_1 - k_2)(m_o - m_{e1})}$$

$$t_{c2} = -\frac{1}{k_2} \log_e \frac{(k_1 - k_2)k_3(m_{e2} - m_{e3})}{(k_2 - k_3)k_1(m_{e1} - m_{e2}}$$

The critical moisture contents are related to the other drying parameters by

$$m_{c1} = \frac{k_1 m_{e1} - k_2 m_{e2}}{k_1 - k_2} \quad ; \quad m_{c2} = \frac{k_2 m_{e2} - k_3 m_{e3}}{k_2 - k_3}$$

APPENDIX 12.6

MATHEMATICAL ANALYSIS OF THREE-PERIOD DRYING CURVE

Let the subscripts x, y and z refer to the three states of water, and the subscript o to conditions at time = 0. The moisture content of the grass, m, is given by

$$m = \frac{w}{d}$$

where w is the weight of water and d is the weight of drymatter.

Hence

$$m = \frac{w_x + w_y + w_z}{d}$$

$$= \frac{w_x}{d} + \frac{w_y}{d} + \frac{w_z}{d}$$

Let α, β and γ be the proportions of dry-matter in each of the three states, i.e.

$$d_x = \alpha d$$

$$d_y = \beta d$$

$$d_z = \gamma d$$

Hence

$$m = \alpha\frac{w_x}{d_x} + \beta\frac{w_y}{d_y} + \gamma\frac{w_z}{d_z}$$

$$= \alpha m_x + \beta m_y + \gamma m_z$$

Hence, the drying rate is

$$-\frac{dm}{dt} = -\alpha\frac{d}{dt}(m_x) - \beta\frac{d}{dt}(m_y) - \gamma\frac{d}{dt}(m_z)$$

In period 1, $-\frac{dm}{dt} = k_1(m - m_{e1}) \qquad m \geq m_{c1}$

In period 2 $-\frac{dm}{dt} = k_2(m - m_{e2}) \qquad m_{c2} \leq m \leq m_{c1}$

In period 3 $-\frac{dm}{dt} = k_3(m - m_{e3}) \qquad m \leq m_{c2}$

where $k_1 > k_2 > k_3 \qquad m_{e1} > m_{e2} > m_{e3} \qquad m_{c1} > m_{c2}$

In the first period, water is being lost from state x only. The drying of this state is given by the equation

$$-\frac{dm}{dt} = -\alpha\frac{d}{dt}(m_x) = \alpha k_x(m_x - m_{ex})$$

A moisture gradient is set up within the state, and drying proceeds until the moisture content reaches the equilibrium moisture content, m_e. Then the second state y also starts to lose moisture, and the drying is described by

$$-\frac{dm}{dt} = -\beta\frac{d}{dt}(m_y) = \beta k_y(m_y - m_{ey})$$

The resistance to removal of water from this state, however, is higher so that the value of k is lower. When the moisture content in the second state reaches the equilibrium moisture content, the third state starts to lose moisture, and the drying is described by

$$-\frac{dm}{dt} = -\gamma\frac{d}{dt}(m_z) = \gamma k_z(m_z - m_{ez})$$

Once again, the resistance to removal of water is greater, resulting in a lower k.

The critical points mark the movement of the drying front from one state to another

APPENDIX 12.7

DERIVATION OF THE RESIDENCE TIME FORMULA

(1) Consider the motion of a particle in a fluid:

The fluid exerts a force on the particle, which can be expressed by

$$P = R'A'$$

where R' is the resistance force per unit projected area

and A' is the area of the particle projected in the direction of flow

Let u be the vlocity of the fluid relative to the particle, and the density of the fluid, then

$$P = \frac{R'}{\rho u^2} \rho u^2 A'$$

It has been found that the term $R'/\rho u^2$ depends on the Reynold's Number of flow. Letting $R'/\rho u^2 = \phi(Re)$,

$$P = \phi(Re)\ \rho u^2\ A'$$

(2) Motion in a vertical direction (y direction) - see fig.8.4.

The equation of motion in a vertical direction is

$$m\ddot{y} = -P + mg(1 - \rho/\rho_p)$$

$$= -\phi(Re_y)\ \dot{y}^2\ A' + mg(1 - \rho/\rho_p)$$

$$\ddot{y} = -\phi(Re_y)(A'/m)\dot{y}^2 + g(1 - \rho/\rho_p)$$

where m is the mass of the particle

g is the acceleration due to gravity

ρ_p is the density of the particle

For a spherical particle,

$$A'/m = \frac{\pi}{4} d_p^{\,2} \Big/ \frac{\pi}{6} d_p^{\,3} \rho_p = 1.5/\rho_p d_p$$

where d_p is the particle diameter

For a cylinder of length l and diameter d_p,

$$A'/m = dl \Big/ \frac{\pi}{4} d_p^{\,2} l \rho_p = \frac{4}{\pi} \Big/ \rho_p d_p$$

Let

$$\ddot{y} = -K_y \dot{y}^2 + b$$

where $K_y = \dfrac{J\,\rho\,m(Re_y)}{\rho_p d_p}$

$J = 1.5$ for a sphere

$= 4/\pi$ for a cylinder

$b = g(1 - \rho/\rho_p)$

Hence

$$\frac{d\dot{y}}{dt} = b - K_y \dot{y}^2$$

$$\frac{d\dot{y}}{\frac{b}{K_y} - \dot{y}^2} = K_y dt$$

Letting $f = \dfrac{g}{K_y}(1 - \rho/\rho_p)$ and integrating

$$\frac{1}{2f} \log_e \frac{f + \dot{y}}{f - \dot{y}} = K_y t + \text{constant}$$

At $t = 0$, $\dot{y} = u_i$, thus constant $= \dfrac{1}{2f} \log_e \dfrac{f + u_i}{f - u_i}$

thus $$\frac{1}{2f} \log_e \frac{f + \dot{y}}{f - \dot{y}} \cdot \frac{f - u_i}{f - u_i} = K_y t$$

whence $$\dot{y} = \frac{q - 1}{q + 1} f$$

where $$q = r \exp(2fK_y t)$$

and $$r = (f + u_i)/(f - u_i)$$

thus $$\frac{dy}{dt} = f \frac{r \exp(2fK_y t)}{r \exp(2fK_y t) + 1} - \frac{f}{r \exp(2fK_y t) + 1}$$

Separating and Integrating:

$$y = \frac{1}{2K_y} \log_e \frac{(r \exp(2fK_y t) + 1)^2}{r \exp(2fK_y t)} + \text{constant}$$

At $t = 0$, $y = 0$,

thus constant $= -\dfrac{1}{2K_y} \log_e \dfrac{(r + 1)^2}{r}$

hence

$$y = ft + \frac{1}{K_y} \log_e \frac{1}{2f} (f + u_i + (f - u_i) \exp(-2fK_y t))$$

(3) **Motion of a Particle along the Drying Cylinder (x direction):**

Let u be the velocity of the particle relative to the cylinder, in the x-direction (along the axis), and $\dot{x}$ be the velocity of the particle relative to the cylinder, so that $(u - \dot{x})$ is the velocity of the fluid relative to the particle.

The equation of motion is (see fig.8.4):

$$m\ddot{x} = mg \sin\alpha + \varphi(Re_x)\,\rho A'(u - \dot{x})^2$$

whence
$$\ddot{x} = g \sin\alpha + K_x(u - \dot{x})^2$$

If $\alpha = 0$, then

$$\frac{d\dot{x}}{dt} = K_x(u - \dot{x})^2$$

Separating the variables:

$$\frac{d\dot{x}}{(u - \dot{x})^2} = K_x dt$$

Integrating:

$$\frac{dx}{dt} = \dot{x} = u - \frac{1}{K_x t + 1/u} + \text{constant}$$

At $t = 0$, $\dot{x} = 0$, thus constant $= 0$

Again, separating and integrating:

$$x = ut - \frac{1}{K_x}\log_e(K_x t + 1/u) + \text{constant}$$

At $t = 0$, $x = 0$, thus constant $= -(\log_e u)/K_x$

hence

$$x = ut - \frac{1}{K_x}\log_e(uK_x t + 1)$$

APPENDIX 12.8

CALCULATION OF PARTICLE DENSITY

Let the density of a particle be ρ_{po} at moisture content (dry basis) m_o, and ρ_p at moisture content m. Let the volume of the particle be V_p and assume that no shrinkage occurs as it dries. Let the weight of the particle at moisture content m_o be w_o and its weight at moisture content m be w. Let w_d be the weight of dry-matter in the particle.

Then: $$w_o = V_p \rho_{po}$$

Now $$m_o = \frac{\text{weight of water}}{\text{weight of dry-matter}}$$

$$= \frac{w_o - w_d}{w_d} = \frac{w_o}{w_d} - 1$$

therefore $$w_d = w_o/(m_o + 1)$$

Similarly $$m = \frac{w - w_d}{w_d} = \frac{w}{w_d} - 1 = \frac{w}{w_o}(m_o + 1) - 1$$

therefore $$w = \frac{m + 1}{m_o + 1} w_o$$

The particle density is

$$\rho_p = w/V_p$$

$$= \frac{w_o}{V_p} \frac{m + 1}{m_o + 1}$$

$$= \rho_{po} \frac{m + 1}{m_o + 1}$$

APPENDIX 12.9

CALCULATION OF CASCADE DENSITY

(i) Weight of dry-matter in flights + Weight of dry-matter in cascade = Total weight of dry-matter

$$W_f \quad + \quad W_c \quad = \quad W_x$$

(ii) Volume of cascade + Volume of flights = Total drier volume

$$V_c \quad + \quad V_f \quad = \quad V_d$$

If the density of dry-matter in the flights, in the cascades and in the whole drier is ρ_f, ρ_c and ρ_x respectively, then

$$V_f = W_f/\rho_f \quad ; \quad V_c = W_c/\rho_c \quad ; \quad V_d = W_x/\rho_x$$

Substituting:

$$W_f/\rho_f + W_c/\rho_c = W_x/\rho_x = (W_f + W_c)/\rho_x$$

The residence time in the drier is given by

$$= N_c(t_c + t_f) = \tau_c + \tau_f$$

Let $t_f/t_c = \tau_f/\tau_c = R_t$

thus $\tau_f = R_t\tau_c$

and $\tau = (R_t + 1)\tau_c$

Now, the rate of flow of dry-matter through each phase is the same,

i.e. $F = W_x/\tau = W_f/\tau_f = W_c/\tau_c$

thus

$$\frac{W_f + W_c}{(R_t + 1)\tau_c} = \frac{W_f}{R_t\tau_c} = \frac{W_c}{\tau_c}$$

therefore

$$R_t(W_f + W_c) = (R_t + 1)\,W_f = R_t(R_t + 1)W_c$$

thus

$$W_c = \frac{1}{R_t}W_f$$

$$\frac{W_f}{\rho_f} + \frac{W_f}{R_t\rho_c} = \frac{W_f(1 + 1/R_t)}{\rho_x}$$

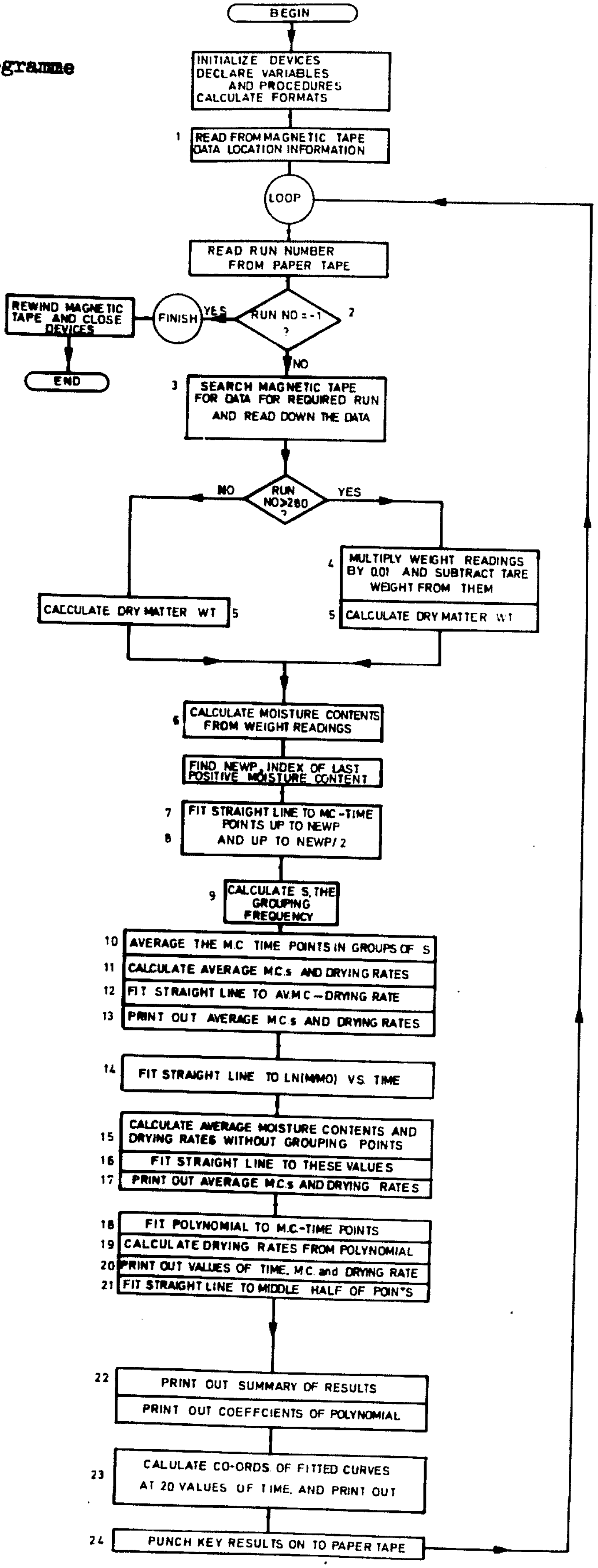
whence

$$c = \frac{\rho_x\rho_f}{(R_t + 1)\rho_f - R_t\rho_x}$$

XIII

COMPUTER PROGRAMMES

Block Diagram of Data Analysis Programme



Data Analysis Programme - (i)

```
AG22MDB→

begin library A0,A6,A7,A8,A12,A13;
      comment Prog to read from <DONSDATA> and execute;
      open(10);  open(20);  open(30);  find(100,[DONSDATA]);
begin real mcdbin,mcwbin,mcwbout,drymatterwt,mcdbout,
      anseo,ansud,chop,dp,od,id,roomtemp,initialweight,
      finalweight,ta,rhum,pv,x,tw,td,mva,mvd,mvw,sartorin,sartorout,mc
      inter,tt,tdp,cfm,lbps,area,maxt,minmc,
      ra,rb,rc,rd,rg,ls,load,re,xr,xt;
integer nextblock,blockno,i,j,k,runno,number,p,np,s,newp,
      date,batch,codea,codeb,ap,kk,
      fa,fb,fc,fd,fe,fg,fh,fi,fj,fk,fl,fm,fn,variety,state;
real array control,size[1:600],ba,bb,bc,bd,be,bg[1:2],
      avtemp,standev[1:4],ca[1:10];
procedure UNIFIT(x,y,p,a,r);
real r;  integer p;  array x,y,a;
begin real sx,sxs,sy,sys,syx;
      integer i;
      sx:=sxs:=sy:=sys:=syx:=0;
      for i:=1 step 1 until p do
      begin sx:=sx+x[i];  sxs:=sxs+x[i]×x[i];
            sy:=sy+y[i];  sys:=sys+y[i]×y[i];
            syx:=syx+y[i]×x[i];
      end;
      a[2]:=(p×syx-sy×sx)/(p×sxs-sx×sx);
      a[1]:=(sy×sxs-sx×syx)/(p×sxs-sx×sx);
      r:=(p×syx-sx×sy)/(sqrt((p×sxs-sx×sx)×(p×sys-sy×sy)));
end;

procedure FORCEFIT(x,y,p,a,r);
real r,a;  integer p;  array x,y;
begin real sx,sxs,sy,sys,syx;
      integer i;
      sx:=sxs:=sy:=sys:=syx:=0;
      for i:=1 step 1 until p do
      begin sx:=sx+x[i];  sxs:=sxs+x[i]×x[i];
            sy:=sy+y[i];  sys:=sys+y[i]×y[i];
            syx:=syx+y[i]×x[i];
      end;
      a:=sy/sx;
      r:=(p×syx-sx×sy)/(sqrt((p×sxs-sx×sx)×(p×sys-sy×sy)));
end;
```

Data Analysis Programme - (ii)

```
procedure CURVFIT(x,y,p,d,b);
value p,d;      array x,y,b;    integer p,d;
begin real t,c,f,sigy,sigysq;   integer g,k,i,n,m,j,l;
    n:=d+1;  l:=n+1;
    begin realarray a[1:n,1:l], sigxn[1:2×d], sigyxn[1:d];
        sigy:=0;  sigysq:=0;
        for g:=1 step 1 until d do sigyxn[g]:=0;
        for g:=1 step 1 until 2×d do sigxn[g]:=0;
        for k:=1 step 1 until p do
        begin sigy:=sigy+y[k];
            sigysq:=sigysq+y[k]↑2;
            for g:=1 step 1 until 2×d do sigxn[g]:=sigxn[g]
                                        +x[k]↑g;
            for g:=1 step 1 until d do sigyxn[g]:=sigyxn[g]
                                        +y[k]×x[k]↑g;
        end;
        for i:=1 step 1 until n do
        begin for j:=1 step 1 until l do
            begin if i=1 and j=1 then a[i,j]:=p else
                if i=1 and j=l then a[i,j]:=sigy else
                if j=l then a[i,j]:=sigyxn[i-1] else
                        a[i,j]:=sigxn[i+j-2];
            end;
        end;
        for m:=1 step 1 until n do
        begin t:=a[m,m];
            if t=0 then for i:=m step 1 until n do
            begin t:=a[i,m];
                if t≠0 then
                begin for j:=1 step 1 until l do
                    begin c:=a[m,j]; a[m,j]:=a[i,j];
                        a[i,j]:=c;
                    end;
                    goto next;
                end;
            end;
next:       c:=a[m,m];
            for j:=m step 1 until l do a[m,j]:=a[m,j]/c;
            for i:=1 step 1 until n do
            begin if m≠i then
                begin f:=a[i,m];
                    for j:=m step 1 until l do
                        a[i,j]:=a[m,j]×(-1)×f+a[i,j];
                end;
            end;
        end;
        for i:=1 step 1 until n do b[i]:=a[i,l];
    end;
end;
```

```
procedure CALC3(mo,me,k,maxt,n,nm);  real mo,me,k,maxt;  integer n;
                                 array nm;
begin real t;
      for t:=0 step entier(maxt+1.0)/20 until entier(maxt+1.0)×1.0001
                                                               do
      nm[t/(entier(maxt+1.0)/20)+1,n]:=me+(mo-me)×exp(-k×t);
end;

procedure SUMPRINT;
begin write text(30,[[p10c28s]D.J.MENZIES[7s]AJ22DMY****1970[cc34s]
                                          results*of*run*no*]);
      write(30,fh,runno);
      write text(30,[[cc20s]air*temp*=*]);  write(30,fa,avtemp[1]);
      write text(30,[*deg*c****log(airtemp)*=*]);
      write(30,fc,ln(avtemp[1]));
      if avtemp[1]<100 then
      begin write text(30,[[c20s]dew*point*=*]);  write(30,fa,tdp);
            write text(30,[*deg*c[4s]relative*humidity*=*]);
            write(30,fa,rhum×100);  charout(30,6);
            write text(30,[[c20s]pv*=*]);  write(30,fc,pv);
            write text(30,[*lb/sq*in[4s]absolute*humidity*=*]);
            write(30,fn,x);  write text(30,[*lb/lb]);
      end;
      write text(30,[[c20s]airflow*=*]);  write(30,fa,cfm);
      write text(30,[*cfm** =** ]);
      write(30,fe,lbps/area);  write text(30,[*lb/sec-sqft[c20s]
            grass*batch*no*:*]);  write(30,fj,batch);
      write text(30,[[7s]length*of*chop*=*]);  write(30,fm,chop);
      write text(30,[*ins[c20s]grass*state*:*]);
      if state=4 then write text(30,[** whole***])
      else if state=5 then write text(30,[leaves*only])
      else write text(30,[stems*only*]);
      write text(30,[* *variety*:]);
      if variety=1 then write text(30,[*italian*rye**])
      else if variety=2 then write text(30,[perennial*rye*]);
      write text(30,[[c20s]number*of*points*recorded*=*]);
      write(30,fh,p);
      write text(30,[[c20s]initial*mcdb*=*]);  write(30,fe,mcdbin);
      write text(30,[*gm/gm[4s]final*mcdb*=*]);  write(30,fe,mcdbout);
      write text(30,[*gm/gm[c20s]drymatter weight*calcd.*from*final
                                                        *mcdb
            [cc20s]fitting**m*=*mo*+*ct***to*first*]);  write(30,fh,newp)
      write text(30,[*points[c20s]correlation*=*]);  write(30,fn,ra);
      write text(30,[[c20s]c*=]);  write(30,fd,ba[2]);
      write text(30,[[5s]mo*=*]);  write(30,fe,ba[1]);
      write text(30,[[5s]log(-c)*=*]);
      if -ba[2]>0 then write(30,fd,ln(-ba[2])) else
                        write text(30,[----]);
      write text(30,[[cc20s]fitting**m*=*mo*+*ct**to*first*]);
      write(30,fh,newp÷2);
      write text(30,[*points[c20s]correlation*=*]);  write(30,fn,rb);
      write text(30,[[c20s]c*=*]);  write(30,fd,bb[2]);
      write text(30,[[5s]mo*=*]);  write(30,fe,bb[1]);
      write text(30,[[5s]log(-c)*=*]);
      if -bb[2]>0 then write(30,fd,ln(-bb[2])) else w
                        write text(30,[-----]);
      write text(30,[[cc20s]fitting* m/mo*=* exp(-kt)* to*first*]);
      write(30,fh,ap);
```

```
     write text(30,[*points[c20s]correlation*=*]);  write(30,fn,rd);
     write text(30,[[5s]k*=*]); write(30,fd,-bd[2]);
     write text(30,[[5s]log*k*=*]);
     if -bd[2]>0 then write(30,fd,ln(-bd[2]))
                 else write text(30,[-----]);
     write text(30,[[cc20s]fitting*polynomial*to*first*]);
     write(30,fh,newp);
     write text(30,[*points*and*differentiating[c20s]-dm/dt*=*k(m*-*me)
          **fitted*to*middle*half*of*points
          [c20s]correlation*=*]);  write(30,fn,rg);
     write text(30,[[c20s]k*=*]);  write(30,fd,bg[2]);
     write text(30,[[5s]me*=*]);  write(30,fc,-bg[1]/bg[2]);
     write text(30,[[5s]log*k*=*]);
     if bg[2]>0 then write(30,fe,ln(bg[2])) else w
                write text(30,[---- ]);
     write text(30,[[cc20s]segmentation*method**-**-DM/DT=k(m-me)
          **fitted[c20s]correlation*=*]);
     write(30,fn,re);  write text(30,[[c20s]k*=*]);  write(30,fd,be[2])
     write text(30,[[5s]me*=*]);  write(30,fc,-be[1]/be[2]);
     write text(30,[[5s]log*k*=*]);
     if be[2]>0 then write(30,fe,ln(be[2]))
          else write text(30,[-----]);
     write text(30,[[cc20s]averaging*points*in*groups*of*]);
     write(30,fh,s);
     write text(30,[[5s]and*fitting*-dm/dt*=*k(m*-*me)[c20s]
          correlation*=*]);
     write(30,fn,rc);  write text(30,[[c20s]k*=*]);  write(30,fd,bc[2])
     write text(30,[[5s]me*=*]);  write(30,fc,-bc[1]/bc[2]);
     write text(30,[[5s]no*of*points*=*]);  write(30,fh,entier(p/s));
     write text(30,[[5s]log*k*=*]);
     if bc[2]>0 then write(30,fd,ln(bc[2])) else
          write text(30,[-----]);
end;


procedure PUNCH;
begin integer fa,fb,fc,fd,fe,ff,fg,fh,fi,fj;
fa:=format([ss-nddddd;]);        fb:=format([ss-nddd;]);
fc:=format([ss-nd;]);            fd:=format([ss-d.dddddd₁₀+nd;]);
fe:=format([ss-d.ddd₁₀+nd;]);    ff:=format([ss-ndd.dddd;]);
fg:=format([ss-ndddd.dd;]);      fh:=format([ss-nd.dd;]);
fi:=format([ss-nddd.dd;]);       fj:=format([ss-d.dddddd;]);
write(10,fb,runno);    write(10,fb,newp);
write(10,fj,ra);  write(10,fd,ba[1]);
write(10,fd,ba[2]);    write(10,fj,rb);  newline(10,1);
write(10,fd,bb[1]);    write(10,fd,bb[2]);
write(10,fb,ap);  write(10,fj,rd);
write(10,fd,exp(bd[1]));    write(10,fd,-bd[2]);
write(10,fj,rg);  write(10,fd,bg[2]);
newline(10,1);
write(10,fd,-bg[1]/bg[2]);
write(10,fj,re);  write(10,fd,be[2]);
write(10,fd,-be[1]/be[2]);
newline(10,1);
write(10,fb,s);   write(10,fj,rc);
write(10,fd,bc[2]);    write(10,fd,-bc[1]/bc[2]);
newline(10,1);
gap(10,20);
end;
```

Data Analysis Programme - (v)

```
          fb:=format([-ndd.dddd]);
          fa:=format([-nddd.dd]);          fc:=format([-nd.dddd]);
          fd:=format([ss-nd.dddddd]);      fe:=format([ss-ndd.dddd]);
          fg:=format([-d.ddd₁₀+nd]);       fh:=format([nddd]);
          fi:=format([-d.dddsdddsddd₁₀+nd]);
          fj:=format([nd]);                fk:=format([d]);
          fl:=format([-d.dddddd₁₀+nd]);    fm:=format([-nd.dd]);
          fn:=format([-d.dddddd]);

          readbinary(100,control,[xcontrol]);
          readbinary(100,size,[blocksiz]);
          blockno:=10;
loop:           number:=read(20);  if number=-1 then goto finish;
          for i:=11 step 1 until control[1]+10 do
                if control[i]=number then goto found;
          write text(30,[[p]run*no*]);  write(30,fh,number);
          write text(30,[*not*found]);
          goto loop;
found:          if i=blockno then goto loop;
          if i=nextblock then goto ready;
          skip(100,i-blockno-1);
ready:          blockno:=i;

begin real array time[1:1000];
          begin real array weight[1:1000];
          begin realarray element[1:size[i]];
                readbinary(100,element,[datafile]);
                runno:=element[1];          date:=element[2];
                batch:=element[3];          variety:=element[4];
                chop:=element[5];           od:=element[8];
                id:=element[9];       state:=element[6];
                dp:=element[7];       roomtemp:=element[10];
                mcdbin:=element[11];        mcdbout:=element[12];
                mcwbin:=mcdbin/(1+mcdbin);     mcwbout:=mcdbout/(1+mcdbout);
                initialweight:=element[13];
                finalweight:=element[14];
                sartorin:=element[15];      sartorout:=element[16];
                codeb:=element[17];         codea:=element[18];
                s:=element[19];       mvd:=element[20];
                mvw:=element[21];           mva:=element[22];
                for i:=1,2,3,4 do avtemp[i]:=element[i+22];
                avtemp[1]:=element[23];  ta:=avtemp[1];
                area:=element[35];          p:=element[36];
                for i:=1,2,3,4 do standev[i]:=element[i+43];
                td:=element[27];      tw:=element[28];
                pv:=element[29];      x:=element[30];
                tdp:=element[31];           rhum:=element[32];
                cfm:=element[33];           lbps:=element[34];
                ls:=element[40];      load:=element[41];
                for i:=1 step 1 until p do
                begin time[i]:=element[400+(i×2)-1];
                      weight[i]:=element[400+i×2];
                end;
         end;
         begin real array mc[1:1000];
                minmc:=0.3;   maxt:=time[p];
                if runno>280 then
                begin for i:=1 step 1 until p do weight[i]:=finalweight
                            +(weight[i]-sartorout)×0.01;
                      drymatterwt:=finalweight/(1+mcdbout);
                end else drymatterwt:=weight[p]/(1+mcdbout);
```

```
                    for i:=1 step 1 until p do mc[i]:=weight[i]/drymatterwt-1;
                    for i:=1 step 1 until p do if mc[i]<0 then
                    begin newp:=i-1;  goto IRA;
                    end;
                    newp:=p;
IRA:                UNIFIT(time,mc,newp,ba,ra);   UNIFIT(time,mc,newp+2,bb,rb);
                    mc1:=mc[1];
                    for s:=newp÷20 do
                    begin real array at,am,aavm,ar[1:250];
                          i:=0;
                          if s<1 then s:=1;
aaa:                      anseo:=ansud:=0;  i:=i+1;
                          for k:=1 step 1 until s do
                          begin anseo:=anseo+time[(i-1)×s+k];
                                ansud:=ansud+mc[(i-1)×s+k];
                          end;
                          at[i]:=anseo/s;  am[i]:=ansud/s;
                          if (i+1)×s≤newp then goto aaa;
                          np:=i;
                          for k:=1 step 1 until np-1 do
                          begin ar[k]:=(-1)×(am[k+1]-am[k])/(at[k+1]-at[k]);
                                aavm[k]:=(am[k]+am[k+1])/2;
                          end;
                          UNIFIT(aavm,ar,np-1,bc,rc);
                          for i:=1 step 1 until np-1 do
                          begin if i=1 or (i-1)÷50×50=i-1 then
                                begin write text(30,[[p10c40s]run*no*]);
                                      write(30,fh,runno);
                                      write text(30,[[10s]segmentation*method
                                            [c43s]
                                      averaging*points*in*groups*of*]);
                                      write(30,fh,s);  newline(30,2);
                                      write text(30,[[41s]***time******mcdb
                                      ******avmc*****avrate*]);
                                      newline(30,2);
                                end;
                                space(30,40);
                                write(30,fb,at[i]);  space(30,1);
                                write(30,fb,am[i]);
                                space(30,1);  write(30,fb,aavm[i]);
                                space(30,1);
                                write(30,fb,ar[i]);
                                newline(30,1);
                          end;
                          space(30,40);  write(30,fb,at[np]);  space(30,1);
                          write(30,fb,am[np]);
            end;
            begin real array xx[1:1000];
UVF:              for i:=1 step 1 until newp do xx[i]:=ln(mc[i]/mcdbin);
                  FORCEFIT(time,xx,newp,bd[2],rd);
            end;
            begin real array xm,xr[1:500];
                  i:=0;
                  for k:=1 step 1 until newp-1 do
                  begin xm[k]:=(mc[k]+mc[k+1])/2;
                        xr[k]:=(-1)×(mc[k+1]-mc[k])/(time[k+1]-time[k]);
                  end;
                  UNIFIT(xm,xr,newp-1,be,re);
```

```
        write text(30,[[p10c32s]run*no*]);  write(30,fh,runno);
        write text(30,[[10s]segmentation*method**-**no*grouping
                                                  [cc20s]
        ****avmc****avrate********avmc****avrate********avmc**
        **avrate********avmc****avrate[cc20s]]);
        for k:=1 step 1 until newp-1 do
        begin write(30,fb,xm[k]);  write(30,fb,xr[k]);
            if k÷4×4=k then
            begin newline(30,1);  space(30,20);
            end else space(30,4);
        end;
    end;
    begin real array rate[1:1000];
        CURVFIT(time,mc,newp,8,ca);
        for i:=1 step 1 until newp do
        begin rate[i]:=ca[2];
            if time[i]>0 then for j:=1 step 1 until 7 do
                rate[i]:=rate[i]+(j+1)×ca[j+2]×time[i]↑j;
            rate[i]:=rate[i]×(-1);
        end;
        write text(30,[[p10c55s]run*no*]);  write(30,fh,runno);
        write text(30,[[cc29s]****time******mcdb******rate[9s]
        time******mcdb*****rate[cc29s]]);
        if time[newp]>3 then inter:=0.5
        else if time[newp]>1.6 then inter:=0.25
        else if time[newp]>0.8 then inter:=0.1
        else inter:=0.05;
        kk:=0;  j:=1;
        for tt:=0 step inter until time[newp]×1.0001 do
        begin for i:=j step 1 until newp do
            begin if tt≠0 then
            begin if abs((time[i]-tt)/tt)<0.001 then
                begin kk:=kk+1; j:=i;
                    write(30,fb,time[i]);  space(30,1);
                    write(30,fb,mc[i]);  space(30,1);
                    write(30,fb,rate[i]);
                    if kk÷2×2=kk then
                    begin newline(30,1);  space(30,29);
                    end else space(30,4);
                    goto also;
                end;
                goto djm;
            end
            else if i=1 then
            begin kk:=kk+1;
                write(30,fb,time[i]);  space(30,1);
                write(30,fb,mc[i]);  space(30,1);
                write(30,fb,rate[i]);  space(30,4);
                goto also;
            end;
djm:
            end;
        also:
        end;
        UNIFIT(mc,rate,newp÷2-1,bg,rg);
        write text(30,[[p10c55s]run*no*]);' write(30,fh,runno);
        write text(30,[[cc20s]calculated*moisture*contents
        *and*drying*rates*calculated*
        from*fitted*polynomial[cc12s]****time
        * ** mcdb*** p-rate** *   time**  *mcdb** *p-rate*
```

```
            *******time******mcdb
            ****p-rate[cc12s]]);
            for i:=1 step 1 until newp do
            begin write(30,fb,time[i]); write(30,fb,mc[i]);
                  write(30,fb,rate[i]);
                  if i+3×3=i then begin newline(30,1);  space(30,12);
                                  end else space(30,4);
            end;
            for i:=1 step 1 until newp+2 do
            begin mc[i]:=mc[i+newp+4];
                  rate[i]:=rate[i+newp+4];
            end;
      end;
      begin real array nm[1:50,1:4];
            SUMPRINT;

            write text(30,[[p20c36s]coefficients*of*polynomial[cc]]);
            for j:=1 step 1 until 9 do
            begin write text(30,[[40s]a]);  write(30,fk,j-1);
                  write text(30,[*=*]);
                  write(30,fl,ca[j]);  newline(30,1);
            end;
            CALC3(mc1,-bg[1]/bg[2],bg[2],time[newp],1,nm);
            CALC3(mc1,-be[1]/be[2],be[2],time[newp],2,nm);
            CALC3(mc1,-bc[1]/bc[2],bc[2],time[newp],3,nm);
            CALC3(mc1,0,-bd[2],time[newp],4,nm);
            write text(30,[[p10c55s]run*no*]);  write(30,fh,runno);
            write text(30,[[cc41s]
            curves*derived*from*various*fittings*:*[cc36s]time
            *****poly*****poly*****segm***grouping***me=0[c55s]exp
            ******exp******exp******exp[cc]]);
            for i:=1 step 1 until 20 do
            begin xt:=(i-1)×entier(maxt+1)/20;
                  space(30,32);
                  xr:=ca[1];
                  for j:=2 step 1 until 9 do xr:=xr+ca[j]×xt↑(j-1);
                  write(30,fb,xt);  write(30,fb,xr);
                  for j:=1,2,3,4 do write(30,fb,nm[i,j]);
                  newline(30,1);
            end;
            PUNCH;
      end;
      nextblock:=blockno+1;
      goto loop;
end;
end;
end;
finish:
end;
write text(30,[[p]]);
rewind(100);  close(20);  close(30);  close(10);  close(100);
end→
```

Data Analysis Programme - Sample Results (ix)

```
        D.J.MENZIES        AG22DMY     1970

                 RESULTS OF RUN NO   89

AIR TEMP =     18.87 DEG C    LOG(AIRTEMP) =    2.9374
DEW POINT =    516.84 DEG C    RELATIVE HUMIDITY =    73.23%
PV =   0.2311 LB/SQ IN    ABSOLUTE HUMIDITY =  0.009937 LB/LB
AIRFLOW =    34.00 CFM    =        0.0831 LB/SEC-SQFT
GRASS BATCH NO : 13        LENGTH OF CHOP =   0.00 INS
GRASS STATE :     WHOLE        VARIETY : ITALIAN RYE
NUMBER OF POINTS RECORDED =  123
INITIAL MCDB =        4.3778 GM/GM     FINAL MCDB =       0.0273 GM/GM
DRYMATTERWEIGHT CALCD. FROM FINAL MCDB

FITTING  M = MO + CT  TO FIRST  123 POINTS
CORRELATION = -0.889744
C =    -0.170698     MO =       2.9161      LOG(-C) =     -1.767861

FITTING  M = MO + CT  TO FIRST   61 POINTS
CORRELATION = -0.968777
C =     -0.364327     MO =       3.8999      LOG(-C) =     -1.009704

FITTING  M/MO =  EXP(-KT)  TO FIRST    0 POINTS
CORRELATION = -0.997763      K =      0.194548      LOG K =     -1.637078

FITTING POLYNOMIAL TO FIRST  123 POINTS AND DIFFERENTIATING
-DM/DT = K(M - ME)  FITTED TO MIDDLE HALF OF POINTS
CORRELATION =  0.999406
K =       0.199069     ME =    0.0544      LOG K =      -1.6141

SEGMENTATION METHOD  -  -DM/DT=K(M-ME)  FITTED
CORRELATION =  0.974518
K =       0.189202     ME =   -0.0353      LOG K =      -1.6649

AVERAGING POINTS IN GROUPS OF    6     AND FITTING -DM/DT = K(M - ME)
CORRELATION =  0.998954
K =       0.193308     ME =   -0.0172      NO OF POINTS =   20      LOG K =     -1.643472
```

Data Analysis Programme - Sample Results (x)

```
                              RUN NO    89

   TIME        MCDB        RATE            TIME        MCDB        RATE

   0.1667      4.5137      0.8941          0.5000      4.2686      0.8413
   1.0000      3.8728      0.7645          1.5000      3.4863      0.6917
   2.0000      3.1659      0.6239          2.5000      2.8643      0.5616
   3.0000      2.6004      0.5051          3.5000      2.3647      0.4542
   4.0000      2.1480      0.4089          4.5000      1.9595      0.3687
   5.0000      1.7898      0.3334          5.5000      1.6296      0.3023
   6.0000      1.4788      0.2750          6.5000      1.3563      0.2510
   7.0000      1.2149      0.2298          7.5000      1.1112      0.2110
   8.0000      1.0075      0.1941          8.5000      0.9133      0.1787
   9.0000      0.8379      0.1646          9.5000      0.7531      0.1515
  10.0000      0.6871      0.1393         10.5000      0.6211      0.1277
  11.0000      0.5551      0.1168         11.5000      0.5080      0.1065
  12.0000      0.4420      0.0967         12.5000      0.4043      0.0875
  13.0000      0.3666      0.0790         13.5000      0.3289      0.0711
  14.0000      0.3007      0.0638         14.5000      0.2630      0.0574
  15.0000      0.2253      0.0516         15.5000      0.2064      0.0466
  16.0000      0.1781      0.0422         16.5000      0.1593      0.0385
  17.0000      0.1404      0.0352         17.5000      0.1310      0.0323
  18.0000      0.1122      0.0296         19.0000      0.0933      0.0244
  20.0000      0.0650      0.0186         21.0000      0.0556      0.0119
  22.0000      0.0368      0.0063         23.0000      0.0273      0.0067
  24.0000      0.0273      0.0232
```

Data Analysis Programme - Sample Results (xi)

```
                    RUN NO    89

      CURVES DERIVED FROM VARIOUS FITTINGS :

  TIME      POLY      POLY      SEGM    GROUPING    ME=0
                       EXP       EXP       EXP       EXP

 0.0000    4.7012    4.5137    4.5137    4.5137    4.5137
 1.2500    3.6729    3.5313    3.5556    3.5411    3.5393
 2.5000    2.8707    2.7654    2.7993    2.7773    2.7752
 3.7500    2.2541    2.1682    2.2023    2.1774    2.1761
 5.0000    1.7796    1.7025    1.7310    1.7063    1.7064
 6.2500    1.4095    1.3395    1.3590    1.3363    1.3380
 7.5000    1.1150    1.0564    1.0653    1.0458    1.0492
 8.7500    0.8769    0.8357    0.8335    0.8176    0.8227
10.0000    0.6833    0.6636    0.6505    0.6384    0.6451
11.2500    0.5269    0.5294    0.5061    0.4976    0.5058
12.5000    0.4028    0.4248    0.3921    0.3871    0.3966
13.7500    0.3065    0.3432    0.3021    0.3003    0.3110
15.0000    0.2326    0.2796    0.2310    0.2322    0.2439
16.2500    0.1756    0.2300    0.1749    0.1786    0.1912
17.5000    0.1305    0.1913    0.1306    0.1366    0.1499
18.7500    0.0942    0.1612    0.0957    0.1036    0.1176
20.0000    0.0664    0.1376    0.0681    0.0776    0.0922
21.2500    0.0483    0.1193    0.0463    0.0573    0.0723
22.5000    0.0394    0.1050    0.0291    0.0413    0.0567
23.7500    0.0285    0.0939    0.0156    0.0287    0.0444
```

LIST OF IDENTIFIERS

DATA ANALYSIS PROGRAMME

Identifier		Meaning
anseo		Summation term
ansud		Summation Term
ap		Not used
area		Cross-sectional area of sample
avtemp	**A	Average of temperatures recorded on channels 1, 2, 3 and 4 of data logger; $avtemp_1$ = air temperature
ba	A	Intercept and slope of straight line fitted to m - t points up to "newp"
batch		Grass batch number
bb	A	Intercept and slope of straight line fitted to m - t points up to "newp"/2
bc	A	Intercept and slope of straight line fitted to plot of drying rate against average moisture content (Segmentation and Grouping Method)
bd	A	Intercept and slope of straight line fitted to plot of $\log_e(m/m_o)$ against time, but forced to pass through origin.
be	A	Intercept and slope of straight line fitted to plot of drying rate against moisture content (Segmentation Method)
bg	A	Intercept and slope of straight line fitted to plot of drying rate against moisture content (Polynomial Method)
ca	A	Coefficients of polynomial fitted to plot of moisture content against time
cfm		Air flow rate in ft^3/min
chop		Length of chop of grass, inches
codea		Code number = 1 for data recorded in single scan mode = 2 for data recorded in single channel mode
codeb		Code number = 1 for data recorded on high and medium temperature rigs; = 2 for data recorded on low temperature rig

IDENTIFIERS IN DATA ANALYSIS PROGRAMME - CONTD.

control	A	An array containing the run numbers in the order in which they were recorded on magnetic tape
date		Date on which the run was carried out.
dp		Pressure drop across the orifice plate, inches w.g.
drymatterwt		Weight of dry-matter in the sample, gram
element	A	A temporary storage array for data from magnetic tape blocks
fa, fb, fc, fd, fe, ff, fg, fh, fi, fj, fl, fm, fn		formats
finalweight		Final weight of sample, gram
i		Counter
id		Internal diameter of pipe holding orifice plate
initialweight		Initial weight of sample, gram
j		Counter
k, kk		Counters
lbps		Air flow rate in $lb/sec\ ft^2$
load		Weight of sample, initially, in runs earlier than 240
ls		Leaf to stem ratio of sample, by weight
maxt		Maximum time for recalculation of drying curves from constants
mc	A	Moisture contents calculated from sample weights
mcdbin		Initial moisture content of sample, dry basis
mcdbout		Final moisture content of sample, dry basis
mcwbin		Initial moisture content of sample, wet basis
mcwbout		Final moisture content of sample, wet basis
mc1		Calculated moisture content at time = 0
minmc		Moisture content below which certain calculations are not to be done
mva		Millivolt reading for air temperature
mvd		Millivolt reading for dry bulb temperature of inlet air
mvw		Millivolt reading for wet bulb temperature of inlet air

IDENTIFIERS IN DATA ANALYSIS PROGRAMME - CONTD.

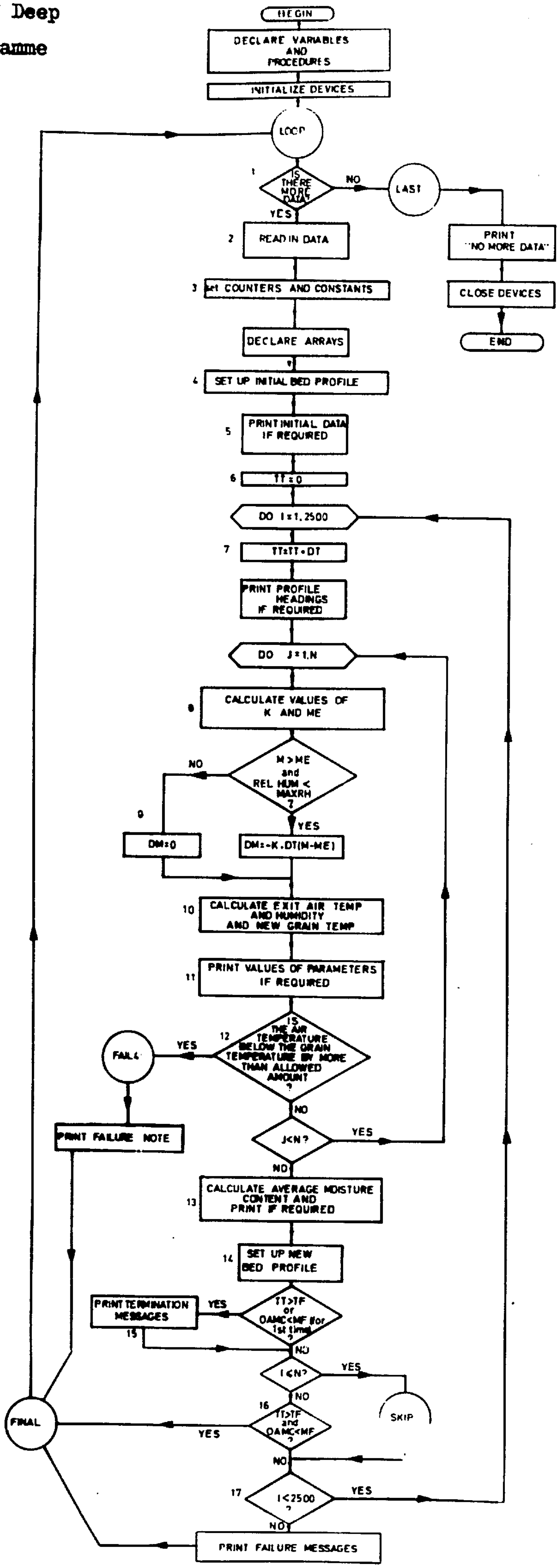
newp		Number of points recorded until moisture content fell below 0
nm	A	Array holding values of recalculated moisture contents by various equations
np		Number of points obtained by grouping original points
number		Not used
od		Diameter of orifice, inches
p		Number of points recorded
pv		Vapour pressure of water in inlet air, lb/in^2
ra, rb, rc, rd, re, rg		Correlation coefficients corresponding to straight lines fitted, ba, bb, etc.
rate	A	Drying rates calculated from differentiated polynomial
rhum		Relative humidity of drying air
roomtemp		Temperature of inlet (ambient) air, ^oF
runno		Experimental run number
s		Number of points taken in a group
sartorin		Initial reading on data logger channel 0
sartorout		Final reading on data logger channel 0
size	A	Array containing the sizes of the blocks on the magnetic tape, in the order recorded
standev	A	Standard deviations of temperatures on channels 1, 2, 3 and 4 of data logger
state		Code number = 4 for whole grass, = 5 for leaves only, = 6 for stems only
ta		Temperature of drying air, ^oC
td		Temperature of inlet air, ^oC
tdp		Dew point temperature of inlet air, ^oC
time	A	Experimental time readings
tt		Not used
tw		Wet-bulb temperature of inlet air, ^oC

IDENTIFIERS IN DATA ANALYSIS PROGRAMME - CONTD.

variety		Code number = 1 for Italian Rye Grass = 2 for Perennial Ryegrass
weight	A	Experimental weight readings
x		Absolute humidity of inlet air
xm	A	Average moisture contents for segmentation method
xr		Evaluation term
	&	Average drying rates by segmentation method
xt		Evaluation term
xx	A	An array containing the values of $\log_e(m/m_o)$

**A indicates that the identifier is an array

Block Diagram of Deep Bed Drying Programme



```
'BEGIN' SYSACT(1,6,120);  SYSACT(1,8,60);
     SYSACT(0,12,1);  SYSACT(1,12,1);
'BEGIN' 'REAL' A,MC,G,TC,HC,DT,BC,DZ,DM,TT,Y,TGO,
          X,AREA,RHOD,WTWATER,K,ME,HC,CPG,
ALPHA,BETA,GAMMA,DELTA,EPSILON,ZETA,ETA,IOTA,
KAPPA,LAMBDA,MU,NU,PI,SIGMA,DAMC,ENTH,
F,TF,MF,RELH,MAXRH,RHOA,CCA,FAT,PR,
SSA,THCON,AIRVIS,CPA,DP,VOIDAGE,
C1,C2,L1,L2,L3,L4,L5,DIFF,D,CA,CB,CC,CD,CE,CF;
'INTEGER' I,J,N,MM,NN,CODE,TIMECOUNT,MCCOUNT,DATASET;
'PROCEDURE' SPACE(DV,N);  'INTEGER' DV,N;
'BEGIN' 'INTEGER' V;  SYSACT(DV,1,V);
      SYSACT(DV,2,V+N);
'END';
     'REAL' 'PROCEDURE' RELHUM(T,X);  'VALUE' T,X;  'REAL' T,X;
     'BEGIN' 'REAL' PV,PS;
          PV:=14.696*X/(X+0.6219);
PS:=EXP(54.6329-12301.69/(T+459.69)-5.16923*LN(T+459.69));
          RELHUM:=PV/PS;
     'END';
'REAL' 'PROCEDURE' ENTHALPY(T,X);  'VALUE' T,X;  'REAL' T,X;
'BEGIN' ENTHALPY:=0.2405*T+X*(0.448*(T-32)+1075.9);
     'END';
'COMMENT'
12345678901234567890123456789012345678901234567890123456789012345678901234567890
         1         2         3         4         5         6         7         8
;
LOOP:
ININTEGER(0,DATASET);  'IF' DATASET=-1 'THEN' 'GOTO' LAST;
ININTEGER(0,N);
INREAL(0,TF);  INREAL(0,MF);  INREAL(0,MC);
     INREAL(0,G);  INREAL(0,HC);  INREAL(0,TC);  INREAL(0,TGO);
INREAL(0,AREA);  INREAL(0,RHOD);  INREAL(0,BC);  INREAL(0,A);
INREAL(0,C1);  INREAL(0,C2);  INREAL(0,L1);  INREAL(0,L2);
INREAL(0,L3);  INREAL(0,L4);  INREAL(0,L5);  INREAL(0,CA);
INREAL(0,CB);  INREAL(0,CC);  INREAL(0,CD);  INREAL(0,CE);
INREAL(0,CF);  ININTEGER(0,MM);  ININTEGER(0,NN);
INREAL(0,DIFF);  ININTEGER(0,CODE);
INREAL(0,MAXRH);
```

```
'IF' CCDE=1 'THEN' INREAL(C,HC);
TIMECCUNT:=0;  MCCCUNT:=0;
'BEGIN' 'REAL' 'ARRAY' H,T,NH,NT(/1:N+1/),M,TGR(/1:N/);
NH(/1/):=H(/1/):=HO;  NT(/1/):=T(/1/):=TO;
'FCR' I:=2 'STEP' 1 'UNTIL' N+1 'CO'
'BEGIN' T(/I/):=TGC;  H(/I/):=HC; 'END';
'FOR' J:=1 'STEP' 1 'UNTIL' N 'DO' 'BEGIN' TGR(/J/):=TGO;
M(/J/):=MO;  'ENC';
      ENTH:=ENTHALPY(T(/1/),H(/1/));
            DZ:=BD/N;
PAT:=14.7;  GCA:=53.34;  RHOA:=PAT*144/(GCA*(TO+46C));
DP:=0.01158;  SSA:=306;  THCCN:=0.0156;  AIRVIS:=0.046;  CPA:=C.24;
VOIDAGE:=0.4; PR:=C.71;
CT:=0.5;
'IF' CCDE=2 'THEN' HC:=CE*G**CF;
'IF' CODE=3 'THEN' HC:=0.5738*((G*(TC+460))/PAT)**0.6011;
'IF' CODE=4 'THEN' HC:=(SSA*CE*(G*60*DP/AIRVIS)**CF)*THCON*(PR**0.33)
/(60*CP);
X:=CZ*AREA*RHCC;
'IF' A=1C0 'THEN' 'GOTO' NOHEAD;
SYSACT(1,15,1);
CUTSTRING(1,'('CEEP BEC CRYING CF AGRICULTURAL PRODUCE')');
SYSACT(1,14,3);
OUTSTRING(1,'('DATA SET NO ')');  OUTINTEGER(1,DATASET);
SYSACT(1,14,2);
OUTSTRING(1,'('INITIAL MCISTURE CONTENT = ')');
OUTREAL(1,MO);
CUTSTRING(1,'(' LB/LB')');  SYSACT(1,14,1);
CUTSTRING(1,'('TARGET MCISTURE CCNTENT = ')');  OUTREAL(1,MF);
SYSACT(1,14,1);
CUTSTRING(1,'('TARGET CRYING TIME = ')');  OLTREAL(1,TF);
SYSACT(1,14,1);
OUTSTRING(1,'('BULK DENSITY CF CRYMATTER IN MATL = ')');
OUTREAL(1,RHOD);  OUTSTRING(1,'(' LB/CU FT')');
SYSACT(1,14,1);
OUTSTRING(1,'('INITIAL MATERIAL TEMPERATURE = ')');
OUTREAL(1,TGO);
CUTSTRING(1,'(' CEG F')');  SYSACT(1,14,1);
CUTSTRING(1,'('GAS FLOW RATE = ')');
OUTREAL(1,G);  CUTSTRING(1,'(' LB/MIN SQFT')');
```

```
SYSACT(1,14,1);
CUTSTRING(1,'('INITIAL GAS TEMPERATURE = ')');
OUTREAL(1,TC);
OUTSTRING(1,'(' DEG F')');  SYSACT(1,14,1);
CUTSTRING(1,'('INITIAL GAS HUMICITY = ')');
OUTREAL(1,HO);
OUTSTRING(1,'(' LB WATER/LB CRY GAS')');
SYSACT(1,14,1);
OUTSTRING(1,'('ASSUMPTICNS : K(MIN-1) = ')');
OUTREAL(1,CA);  OUTSTRING(1,'(' EXP(')');  CUTREAL(1,CB);
CUTSTRING(1,'('/ABSTEMP)')');  SYSACT(1,14,1);
CUTSTRING(1,'('      ME = ')');
OUTREAL(1,CC);  OUTSTRING(1,'('(SQRT(HUMIDITY)/ABSTEMPSQ) + ')');
            OUTREAL(1,CD);  SYSACT(1,14,1);
CUTSTRING(1,'('ASSUMPTICN : CPG = ')');
OUTREAL(1,C1);  OUTSTRING(1,'(' + ')');  OUTREAL(1,C2);
OUTSTRING(1,'(' * MOISTURE CCNTENT')');  SYSACT(1,14,1);
CUTSTRING(1,'('HEAT TRANSFER CCEFFICIENT FOR INITIAL CONDITIONS = ')');
OUTREAL(1,HC);  CUTSTRING(1,'(' BTU/MIN CUFT DEG F')');  SYSACT(1,14,1);
OUTSTRING(1,'('HC EVALLATED BY METHOD ')');  CUTINTEGER(1,CODE);
SYSACT(1,14,1);
'IF' CODE=1 'THEN'
OUTSTRING(1,'('VALUE OF HC FED IN IN DATA')');
'IF' CCDE=2 'THEN'
'BEGIN' OUTSTRING(1,'('HC = ')');  CUTREAL(1,CE);
OUTSTRING(1,'(' * G ** ')');  CUTREAL(1,CF);
'END';
'IF' CCDE=3 'THEN'
'BEGIN'             OLTSTRING(1,'('HC = 0.5738 * ((G* ABSTEMP')');
CUTSTRING(1,'(' )/ATM PRESSURE) ** 0.6011')');
'END';
'IF' CODE=4 'THEN' 'BEGIN'
OUTSTRING(1,'('HC = (SP SURF AREA * ')');  OLTREAL(1,CE);
CUTSTRING(1,'(' * (REYNCLCS BASEC ON PARTICLE DIAM) ** ')');
CUTREAL(1,CF);  CUTSTRING(1,'(' )/60')');
'END';
SYSACT(1,14,1);
CUTSTRING(1,'('BEC CEPTH = ')');
OUTREAL(1,BD);
OUTSTRING(1,'(' FT    =    ')');
```

```
Y:=BC*12;  CLTREAL(1,Y);  CUTSTRING(1,'(' IN')');
SYSACT(1,14,1);
CUTSTRING(1,'('NUMBER OF THIN LAYERS = ')');  OUTINTEGER(1,N);
SYSACT(1,14,1);  CLTSTRING(1,'('TFICKNESS CF ELEMENT = ')');
OUTREAL(1,DZ);  OUTSTRING(1,'(' FT    =    ')');
Y:=CZ*12;  CUTREAL(1,Y);  OUTSTRING(1,'(' IN')');  SYSACT(1,14,1);
CUTSTRING(1,'('WEIGHT CF CRYMATTER IN ELEMENT = ')');  OUTREAL(1,X);
OUTSTRING(1,'(' LB')');  SYSACT(1,14,1);
OUTSTRING(1,'('CROSS-SECTIONAL AREA = ')');  OUTREAL(1,A);
CUTSTRING(1,'('SC FT')');
SYSACT(1,14,1);
OUTSTRING(1,'('TIME INTERVAL = ')');
CUTREAL(1,CT);
CUTSTRING(1,'(' MIN')');  SYSACT(1,14,1);
OUTSTRING(1,'('MAXM VALLE OF (T MATL - T GAS) ALLCWEC = ')');
CUTREAL(1,DIFF);  OUTSTRING(1,'(' DEG F')');  SYSACT(1,14,1);
CUTSTRING(1,'('REL HUM ABCVE WFICF NC CRYING OCCURS = ')');
Y:=MAXRH*10C;  OUTREAL(1,Y);  CUTSTRING(1,'(' PER CENT')');
SYSACT(1,14,1);
CUTSTRING(1,'('CCNCITICNS PRINTEC OUT EVERY ')');  OUTINTEGER(1,MM);
OUTSTRING(1,'(' ITERATICNS')');  SYSACT(1,14,1);
OUTSTRING(1,'('AND EVERY ')');  OLTINTEGER(1,NN);
CUTSTRING(1,'(' LAYERS')');  SYSACT(1,14,1);
NOHEAD:
TT:=0;
'FCR' I:=1 'STEP' 1 'UNTIL' 25CC 'DO'
'BEGIN'
TT:=TT+DT;
'IF' I'/'MM*MM=I 'THEN'
'BEGIN' SYSACT(1,15,1);
CUTSTRING(1,'('PROFILE CF BEC AFTER A TIME OF ')');
OUTREAL(1,TT);  SYSACT(1,14,1);
CUTSTRING(1,'('ITERATICN NC ')');  OUTINTEGER(1,I);
SYSACT(1,14,2);
OUTSTRING(1,'('                    MCDBOUT        X OUT          TGR CUT')');
CUTSTRING(1,'('        TAIR CUT      ENTF AIR CUT        REL HUM')');
SYSACT(1,14,2);
'END';
               'FOR' J:=1 'STEP' 1 'UNTIL' N 'DO'
'BEGIN'
```

```
        K:=CA*EXP(CB/(T(/J/)+459.69));
ME:=CC*SQRT(H(/J/))/((T(/J/))*T(/J/))+CD;
RELH:=RELHUM(T(/J/),H(/J/));
'IF' M(/J/)>ME 'AND' RELH<MAXRH 'THEN'
DM:=-K*DT*(M(/J/)-ME)/(1+0.5*K*DT) 'ELSE' DM:=0;
NH(/J+1/):=H(/J/)-DM*RHOD*DZ/(G*DT);
                          CPG:=C1+C2*M(/J/);
'IF' CODE=3 'THEN' HC:=0.5738*((G*(T(/J/)+460))/PAT)**0.6011;
D:=RHOD*2/(HC*DT);  F:=-DZ*RHOD/(G*DT);
ALPHA:=1+D*DM*0.448;
BETA:=D*(CPG+M(/J/)+DM)+1;
GAMMA:=1-D*(CPG+M(/J/));
DELTA:=-1;
EPSILON:=-D*DM*(1061.54*(L3+L4*EXP(L5*M(/J/)))+32);
ZETA:=0.2405+0.448*NH(/J+1/);
ETA:=F*(CPG+M(/J/)+DM);
IOTA:=-F*(CPG+M(/J/));
KAPPA:=0.2405+0.448*H(/J/);
LAMBDA:=1061.54*(H(/J/)-NH(/J+1/))-F*DM*32;
MU:=BETA/ALPHA;
NU:=(GAMMA*TGR(/J/)+DELTA*T(/J/)+EPSILON)/ALPHA;
PI:=ETA/ZETA;
SIGMA:=(IOTA*TGR(/J/)+KAPPA*T(/J/)+LAMBDA)/ZETA;
TGR(/J/):=(NU-SIGMA)/(PI-MU);
NT(/J+1/):=MU*TGR(/J/)+NU;
ENTH:=ENTHALPY(NT(/J+1/),NH(/J+1/));
M(/J/):=M(/J/)+DM;
'IF' I'/'MM*MM=I 'AND' (J'/'NN*NN=J 'OR' J=1) 'THEN'
'BEGIN'
OUTINTEGER(1,J);
Y:=M(/J/);  OUTREAL(1,Y);
Y:=NH(/J+1/);  OUTREAL(1,Y);
Y:=TGR(/J/);
OUTREAL(1,Y);
Y:=NT(/J+1/);  OUTREAL(1,Y);
OUTREAL(1,ENTH);
Y:=RELHUM(NT(/J+1/),NH(/J+1/))*100;
OUTREAL(1,Y);           OUTINTEGER(1,J);
SYSACT(1,14,1);
'END' LAYER PRINT;
```

```
'IF' TGR(/J/)-T(/J/)>DIFF 'THEN' 'GOTO' FAIL4;
'END' TOP OF BED REACHED;
     CONTINUE:    WTWATER:=0;
'FOR' J:=1 'STEP' 1 'UNTIL' N 'DO' WTWATER:=WTWATER+M(/J/);
OAMC:=WTWATER/N;
'IF' I'/'MM*MM=I 'THEN'
'BEGIN' SYSACT(1,14,1);
OUTSTRING(1,'('OVERALL MOISTURE CONTENT = ')');
OUTREAL(1,OAMC);
SYSACT(1,14,2);
'END';
JUMP:
'FOR' J:=2 'STEP' 1 'UNTIL' N+1 'DO'
'BEGIN' H(/J/):=NH(/J/);  T(/J/):=NT(/J/);
'END';
NOCHANGE:
'IF' ((TT>TF 'AND' TIMECOUNT=0) 'OR' (OAMC<MF 'AND' MCCOUNT=0)) 'AND'
I>N 'THEN'
'BEGIN' SYSACT(1,15,1);
OUTSTRING(1,'('ITERATION NO ')');  OUTINTEGER(1,I);  SYSACT(1,14,1);
OUTSTRING(1,'('TOTAL DRYING TIME = ')');
OUTREAL(1,TT);  SYSACT(1,14,1);
OUTSTRING(1,'('TARGET DRYING TIME = ')');  OUTREAL(1,TF);
SYSACT(1,14,1);
OUTSTRING(1,'('FINAL MOISTURE CONTENT = ')');
OUTREAL(1,OAMC);  SYSACT(1,14,1);
OUTSTRING(1,'('TARGET MOISTURE CONTENT = ')');  OUTREAL(1,MF);
SYSACT(1,14,2);
OUTSTRING(1,'('FINAL BED PROFILE :')');
SYSACT(1,14,2);
OUTSTRING(1,'('  MATL TEMP         M.C.D.B.')');
SYSACT(1,14,2);
'FOR' J:=1 'STEP' 1 'UNTIL' N 'DO'
'BEGIN' Y:=TGR(/J/);  OUTREAL(1,Y);  SPACE(1,2);
Y:=M(/J/);  OUTREAL(1,Y);  SYSACT(1,14,1);
'END';
'END';
'IF' I<=N 'THEN' 'GOTO' SKIP;
'IF' TT>TF 'THEN' TIMECOUNT:=1;
'IF' OAMC<MF 'THEN' MCCOUNT:=1;
```

```
'IF' TT>TF 'AND' OAMC<MF 'THEN' 'GOTC' FINAL;
SKIP:
'ENC' OF TIME ITERATION LCOP;
SYSACT(1,15,1);
CUTSTRING(1,'('SCLLTICN NCT REACFEC IN 2500 ITERATIONS')');
SYSACT(1,14,2);
CUTSTRING(1,'('FINAL CRYING TIME = ')');  OUTREAL(1,TT);
SYSACT(1,14,2);
OUTSTRING(1,'('FINAL MOISTURE CCNTENT = ')');
OUTREAL(1,OAMC);
SYSACT(1,15,1);
'GCTC' FINAL;
FAIL4:
OUTSTRING(1,'('FAILURE DUE TC EXCESSIVE COOLING OF GAS')');
SYSACT(1,14,1);  CUTSTRING(1,'('ITERATION NO ')');
OUTINTEGER(1,I);  SYSACT(1,14,1);
OUTSTRING(1,'('LAYER NO ')');  OUTINTEGER(1,J);
SYSACT(1,14,2);
'GCTC' FINAL;
'END' OF ARRAY DECLARATICN BLOCK;
FINAL:'GOTO' LOOP;
LAST:
SYSACT(1,15,1);
OUTSTRING(1,'('NO MORE DATA')');
SYSACT(0,12,0);  SYSACT(1,12,C);
'END';
'END'
```

```
DEEP BED DRYING CF AGRICULTURAL PRODUCE
CATA SET NO        +134
INITIAL MOISTURE CONTENT = +3.421999'-01   LB/LB
TARGET MCISTURE CCNTENT = +1.399999'-01
TARGET DRYING TIME = +2.6CCCCO'+C2
BULK CENSITY OF CRYMATTER IN MATL = +4.144999'+01   LB/CU FT
INITIAL MATERIAL TEMPERATURE = +6.700000'+01   DEG F
GAS FLOW RATE = +2.180999'+CC   LB/MIN SCFT
INITIAL GAS TEMPERATURE = +1.55CCCO'+02   DEG F
INITIAL GAS HUMICITY = +6.999998'-03   LB WATER/LB DRY GAS
ASSUMPTICNS : K(MIN-1) = +8.358000'+03   EXP(-7.967000'+03  /ABSTEMP)
     ME = +7.C4CCCC'+C3  (SQRT(HLMIDITY)/ABSTEMPSC) + +6.015000'-02
ASSUMPTICN : CPG = +3.100000'-01   +  0                * MOISTURE CONTENT
HEAT TRANSFER CCEFFICIENT FCR INITIAL CONDITIONS = +8.650568'+C0   BTU/MIN CUFT DEG F
HC EVALUATED BY METHOD            +3
HC = 0.5738 * ((G* ABSTEMP )/ATM PRESSURE) ** 0.6011
BED DEPTH = +1.000000'+00    FT   =    +1.200000'+01   IN
NUMBER OF THIN LAYERS =           +60
THICKNESS OF ELEMENT = +1.666666'-02   FT   =   +1.999999'-01   IN
WEIGHT CF CRYMATTER IN ELEMENT = +6.908332'-C1   LB
CRCSS-SECTICNAL AREA = +1.CC0000'+00  SC FT
TIME INTERVAL = +5.CCCCCC'-C1   MIN
MAXM VALUE CF (T MATL - T GAS) ALLOWED = +2.C00000'+C1   DEG F
REL HUM ABCVE WHICH NC DRYING CCCURS = +9.800000'+01   PER CENT
CONDITICNS PRINTED OLT EVERY          +20   ITERATIONS
ANC EVERY           +5   LAYERS
```

Deep Bed Drying Programme - Sample Results (ix)

```
PROFILE CF BEC AFTER A TIME CF +1.000CCO'+01
ITERATION NO         +20

          MCCBOUT        X OUT         TGR OLT        TAIR OUT     ENTH AIR OUT      REL HUM
  +1  +2.962702'-01  +8.323084'-03  +1.267277'+02  +1.481523'+02  +4.501852'+01  +5.503610'+00
  +5  +3.309639'-C1  +1.205443'-C2  +9.759149'+01  +1.168892'+02  +4.153962'+01  +1.807116'+01
 +10  +3.387442'-01  +1.103220'-C2  +6.825817'+C1  +7.534643'+01  +3.020457'+01  +5.899089'+01
 +15  +3.39C800'-01  +8.149370'-03  +6.419914'+C1  +6.510522'+01  +2.454656'+01  +6.204379'+01
 +2C  +3.39C801'-C1  +8.032575'-03  +6.417274'+01  +6.499536'+01  +2.439234'+01  +6.140063'+01
 +25  +3.39C801'-01  +8.032571'-03  +6.417272'+01  +6.499511'+01  +2.439228'+01  +6.140060'+01
 +30  +3.390801'-C1  +8.032571'-03  +6.417272'+C1  +6.499511'+01  +2.439228'+01  +6.140060'+01
 +35  +3.390801'-01  +8.032571'-03  +6.417272'+C1  +6.499511'+01  +2.439228'+01  +6.140060'+01
 +40  +3.39C801'-01  +8.032571'-03  +6.417272'+01  +6.499511'+01  +2.439228'+01  +6.140060'+01
 +45  +3.39C8C1'-C1  +8.032571'-03  +6.417272'+01  +6.499511'+01  +2.439228'+01  +6.140060'+01
 +50  +3.390801'-01  +8.032571'-03  +6.417272'+C1  +6.499511'+01  +2.439228'+01  +6.140060'+01
 +55  +3.39C801'-01  +8.032571'-03  +6.417272'+01  +6.499511'+C1  +2.439228'+01  +6.140060'+01
 +6C  +3.39C801'-01  +8.032571'-03  +6.417272'+01  +6.499511'+01  +2.439228'+01  +6.140060'+01

OVERALL MOISTURE CONTENT = +3.370358'-C1
```

LIST OF IDENTIFIERS

DEEP BED DRYING PROGRAMME

Identifier	Meaning
A	Code number, = 100 for omitting printout of initial conditions
AIRVIS	Viscosity of air, lb/ft hr
ALPHA	Evaluation term
AREA	Cross-sectional area of bed, = 1 ft^2
BD	Depth of bed, ft
BETA	Evaluation term
C1, C2	Constants for evaluating CPG
CA, CB	Constants for evaluating K
CC, CD	Constants for evaluating ME
CE, CF	Constants for evaluating HC
CODE	Code number for choosing the formula to calculate HC
CPA	Specific heat of air, Btu/lb ^{o}F
CPG	Specific heat of dry-matter in grass, Btu/lb^{o}F
D	Evaluation term
DATASET	Index number of set of data, = -1 to terminate programme
DELTA	Evaluation term
DIFF	Tolerance to determine severity of temperature overshoot, F^{o}
DM	Change in moisture content
DP	Particle diameter, ft
DT	Time interval, ft
DZ	Thickness of layer, ft
ENTH	Enthalpy of air, Btu/lb
EPSILON, ETA, F	Evaluation terms
G	Air flow rate, lb dry-matter/min ft^2
GAMMA	Evaluation term
GCA	Gas constant for air
HC	Volumetric heat transfer coefficient, Btu/min ft^3 ^{o}F
HO	Initial humidity of air, lb/lb
I	Counter

IDENTIFIERS IN DEEP BED DRYING PROGRAMME - CONTD.

IOTA	Evaluation term
J	Counter
K	Drying constant, min^{-1}
KAPPA	Evaluation term
L1, L2	Read in, but not used
L3, L4, L5	Constants to correct latent heat for moisture content effect
LAMBDA	Evaluation term
MAXRH	Relative humidity above which no drying takes place, decimal
MCCOUNT	Counter to indicate whether condition OAMC MF has been reached
ME	Equilibrium moisture content
MF	Target (experimental) moisture content
MM	Printout of bed profile given every MM time iterations
MO	Initial moisture content of material
MU	Evaluation term
N	Number of layers
NN	Bed profile printed out every NN layers
NU	Evaluation term
OAMC	Average bed moisture content
PAT	Atmospheric pressure, lb/in^2
PI	Evaluation term
PR	Prandtl number
RELH	Relative humidity, decimal
REP	Reynold's number based on particle diameter
RHOA	Density of air, lb/ft^3
RHOD	Density of dry-matter in bed, lb/ft^3
SIGMA	Evaluation term
SSA	Specific surface of material, ft^{-1}
TF	Target (experimental) drying time, min
TGO	Initial temperature of material, ^{o}F

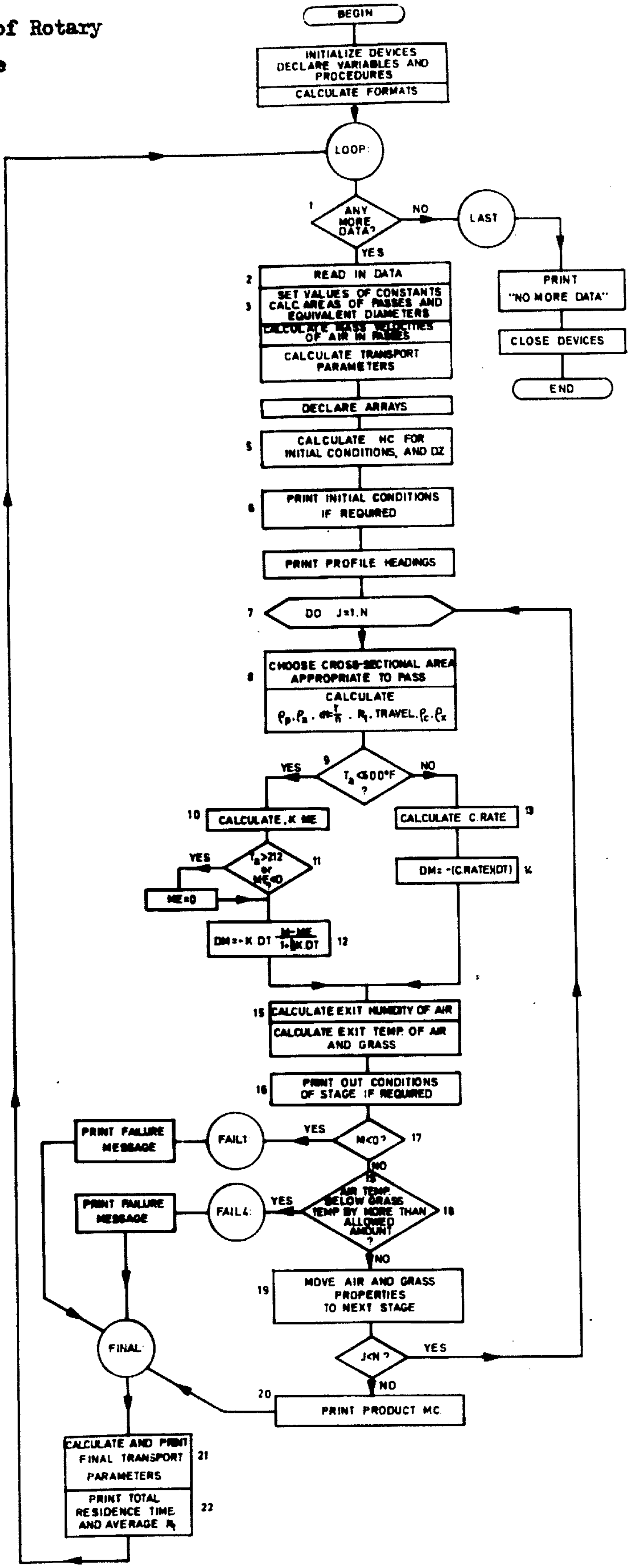
IDENTIFIERS IN DEEP BED DRYING PROGRAMME - CONTD.

THCON	Thermal conductivity of air, Btu/hr ft °F
TIMECOUNT	Counter to indicate whether condition TT TF has been reached
TO	Temperature of drying air, °F
TT	Total drying time, min
VOIDAGE	Porosity of bed
WTWATER	Summation term
X	Weight of dry-matter in a layer
Y	Holding term
ZETA	Evaluation term

Arrays:

H	Humidity of the air entering the layers
NH	Humidity of the air leaving the layers
T	Temperature of the air entering the layers, °F
NT	Temperature of the air leaving the layers, °F
M	Moisture content of the material in the layers
TGR	Temperature of the material in the layers

Block Diagram of Rotary Drier Programme



```
'BEGIN' SYSACT(1,6,120);  SYSACT(1,8,60);
     SYSACT(0,12,1);  SYSACT(1,12,1);
'BEGIN' 'REAL'   MO,G,TO,HO,DT,BD,DZ,DM,TT,TGO,
          X,AREA,RHOD,K,ME,HC,CPG,GOG,
M,TGR,T,H,NT,NH,
ALPHA,BETA,GAMMA,DELTA,EPSILON,ZETA,ETA,IOTA,PHIRE,TRT,TRAVEL,
KAPPA,LAMBDA,MU,NU,PI,SIGMA,TLAMBDA,TDELTA,RPM,
F,RHOA,GCA,PAT,PR,FTIME,STIME,TK,
SSA,THCON,AIRVIS,CPA,DP,REP,VOIDAGE,RHOX,RESTIME,RATIO,
DDIAM1,DDIAM2,DDIAM3,AREA1,AREA2,AREA3,GOG1,GOG2,GOG3,STRT,SRAT,
DDIAMB,DDIAMC,
GRASSRATE,RHOC,DDIAM,CX,CY,CRATE,RHOP,XC,RHOPO,
          C1,C2,L3,L4,L5,DIFF,D,CA,CB,CC,CD,CE,CF;
'INTEGER' I,J,N,MM,NN,CODE,DATASET,
NOLAYERS,A,B,FA,FB,FC,FD,FE,FF;
'PROCEDURE'WRITE(DV,F,Q);'VALUE'DV,F,Q;'INTEGER'DV,F;'REAL'Q;'CODE';
'INTEGER''PROCEDURE'FORMAT(S);'STRING'S;'CODE';
'PROCEDURE' SPACE(DV,N);  'INTEGER' DV,N;
'BEGIN' 'INTEGER' V;  SYSACT(DV,1,V);
      SYSACT(DV,2,V+N);
'END';
'COMMENT'
12345678901234567890123456789012345678901234567890123456789012345678901234567890
        1         2         3         4         5         6         7         8
;
FA:=FORMAT('('-NDD.DD')');  FB:=FORMAT('('-NDDDD')');
FC:=FORMAT('('-D.DDDDDD')');  FD:=FORMAT('('NDD')');
FE:=FORMAT('('-ND.DDDD')');   FF:=FORMAT('('-NDDD.DD')');
LOOP:
ININTEGER(0,DATASET);  'IF' DATASET=-1 'THEN' 'GOTO' LAST;
ININTEGER(0,N);
INREAL(0,MO);
     INREAL(0,G);  INREAL(0,HO);  INREAL(0,TO);  INREAL(0,TGO);
INREAL(0,GRASSRATE);
INREAL(0,DDIAM1);  INREAL(0,DDIAM2);  INREAL(0,DDIAM3);
INREAL(0,RHOD);  INREAL(0,BD);  INREAL(0,C1);  INREAL(0,C2);
     INREAL(0,L3);  INREAL(0,L4);  INREAL(0,L5);  INREAL(0,CA);
     INREAL(0,CB);  INREAL(0,CC);  INREAL(0,CD);  INREAL(0,CE);
INREAL(0,CF);  INREAL(0,CX);  INREAL(0,CY);
```

```
ININTEGER(0,MM);  ININTEGER(0,NN);
INREAL(0,DIFF);  ININTEGER(0,CODE);
INREAL(0,RESTIME);
ININTEGER(0,A);  ININTEGER(0,B);
INREAL(0,RHOPO); INREAL(0,RPM);  INREAL(0,PHIRE);  INREAL(0,TDELTA);
     'IF' CODE=1 'THEN' INREAL(0,HC);
DP:=0.00833;  SSA:=306;  THCON:=0.0156;  AIRVIS:=0.046;  CPA:=0.24;
VOIDAGE:=0.4; PR:=0.71;  STRT:=SRAT:=0;
AREA1:=3.14159*DDIAM1*DDIAM1/4;
AREA2:=3.14159*DDIAM2*DDIAM2/4-AREA1;
AREA3:=3.14159*DDIAM3*DDIAM3/4-AREA2-AREA1;
DDIAMB:=SQRT(4*AREA2/3.14159);
DDIAMC:=SQRT(4*AREA3/3.14159);
AREA:=(AREA1+AREA2+AREA3)/3;
PAT:=14.7;  GCA:=53.34;
GOG:=G/AREA1;  RHOA:=PAT*144/(GCA*(TO+460));
GOG1:=G/AREA1;  GOG2:=G/AREA2;  GOG3:=G/AREA3;
TK:=1.5*PHIRE*RHOA/(DP*RHOPO);
F:=60*60*SQRT(32.2/TK);
TLAMBDA:=SIN(3.14159*(2/TDELTA-0.5));
FTIME:=60*(TLAMBDA*DDIAM1/F-LN(0.5)/(TK*F));
STIME:=1/(TDELTA*RPM);
TRT:=BD*(FTIME+STIME)/(GOG*FTIME/RHOA-LN(GOG*FTIME*TK/RHOA+1)/TK);
RATIO:=STIME/FTIME;
T:=TC;  H:=HO;  TGR:=TGO;  M:=MO;
          DZ:=BD/N;
RHOX:=(GRASSRATE*RESTIME)/(BD*AREA);
RHOC:=RHOX*RHOD/((RATIO+1)*RHOD-RATIO*RHOX);
X:=GRASSRATE*RESTIME/N;   XC:=DZ*RHOC*AREA;
TRY:
NOLAYERS:=1;
'IF' NOLAYERS/N>0.05 'THEN'
'BEGIN' N:=N*2;  X:=X/2;  XC:=XC/2;  DZ:=DZ/2;  'GOTO' TRY;
'END';
CARRYON:
'IF' CODE=2 'THEN' HC:=CE*GOG**CF;
'IF' CODE=3 'THEN' HC:=0.5738*((GOG*(TC+460))/PAT)**0.6011;
'IF' CODE=4 'THEN' HC:=(SSA*CE*(GOG*60*DP/AIRVIS)**CF)*THCON*(PR**0.33)
/(60*CP);
'IF' CODE=5 'THEN' HC:=0.374*(GOG/RHOA)**0.46;
```

```
'IF' CODE=6 'THEN' HC:=CE*(GCG**CF)/DDIAM1;
'IF' A=100 'THEN' 'GOTO' NOHEAD;
SYSACT(1,15,1);
OUTSTRING(1,'('SIMULATION OF A ROTARY GRASS DRIER ')');
SYSACT(1,14,2);
OUTSTRING(1,'('DATA SET NO ')');  WRITE(30,FC,DATASET);
SYSACT(1,14,2);
OUTSTRING(1,'('GRASS PROPERTIES :')');  SYSACT(1,14,2);
OUTSTRING(1,'('GRASS FEED RATE = ')');
WRITE(30,FE,GRASSRATE);  OUTSTRING(1,'(' LB/MIN')');  SYSACT(1,14,1);
OUTSTRING(1,'('INITIAL MOISTURE CONTENT = ')');
WRITE(30,FE,MO); OUTSTRING(1,'(' LB/LB')');  SYSACT(1,14,1);
OUTSTRING(1,'('INITIAL GRASS TEMPERATURE = ')');
WRITE(30,FE,TGO);  OUTSTRING(1,'(' DEG F')');  SYSACT(1,14,1);
OUTSTRING(1,'('BULK DENSITY OF DRYMATTER IN FLIGHTS = ')');
WRITE(30,FA,RHCC);OUTSTRING(1,'(' LB/CU FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('BULK DENSITY OF GRASS DRYMATTER IN CASCADE = ')');
WRITE(30,FC,RHCC);OUTSTRING(1,'(' LB/CU FT')');SYSACT(1,14,1);
OUTSTRING(1,'('AVERAGE BULK DENSITY OF GRASS IN DRIER = ')');
WRITE(30,FC,RHOX);OUTSTRING(1,'(' LB/CU FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('DENSITY OF GRASS PARTICLE = ')');
WRITE(30,FA,RHOPC);OUTSTRING(1,'(' LB/CU FT')'); SYSACT(1,14,1);
SYSACT(1,14,1);
OUTSTRING(1,'('AIR PROPERTIES :')');  SYSACT(1,14,2);
OUTSTRING(1,'('AIR FLOW RATE = ')');
WRITE(30,FA,G);  OUTSTRING(1,'(' LB/MIN  =  ')');
WRITE(30,FA,GOG);  OUTSTRING(1,'(' LB/MIN-SQ FT')');  SYSACT(1,14,1);
OUTSTRING(1,'('INITIAL AIR TEMPERATURE = ')');
WRITE(30,FF,TO); OUTSTRING(1,'(' DEG F')'); SYSACT(1,14,1);
OUTSTRING(1,'('INITIAL AIR HUMIDITY = ')');
WRITE(30,FC,HO); OUTSTRING(1,'(' LB/LB')'); SYSACT(1,14,1);
SYSACT(1,14,1);
OUTSTRING(1,'('DRYING PARAMETERS : ')');  SYSACT(1,14,2);
OUTSTRING(1,'('TEMP < 600 DEG F :  -DM/DT = K(M - ME)')');
SYSACT(1,14,1);
OUTSTRING(1,'('                        K (MIN)-1 = ')');
WRITE(30,FC,CA);OUTSTRING(1,'(' EXP(')');
WRITE(30,FC,CB);  OUTSTRING(1,'(' * TEMP)')'); SYSACT(1,14,1);
OUTSTRING(1,'('                         ME = ')');
WRITE(30,FB,CC); OUTSTRING(1,'(' (SQ RT HUMIDITY / TEMPSQ) +')');
```

```
WRITE(30,FC,CD);  SYSACT(1,14,1);
OUTSTRING(1,'('TEMP > 600 DEG F :  -DM/DT = CONST = C ')');
SYSACT(1,14,1);
OUTSTRING(1,'('                    C = ')');
WRITE(30,FC,CX); OUTSTRING(1,'(' + ')');
WRITE(30,FC,CY); OUTSTRING(1,'(' *TEMP ')'); SYSACT(1,14,1);
OUTSTRING(1,'('       CPG = ')');
WRITE(30,FA,C1); OUTSTRING(1,'(' + ')');
WRITE(30,FC,C2); OUTSTRING(1,'(' * M.C.')');  SYSACT(1,14,1);
OUTSTRING(1,'('HEAT TRANSFER COEFFICIENT FOR INITIAL CONDITIONS = ')');
WRITE(30,FA,HC); OUTSTRING(1,'(' BTU/MIN CUFT DEG F')'); SYSACT(1,14,1);
OUTSTRING(1,'('HC EVALUATED BY METHOD ')');
WRITE(30,FC,CODE);  SYSACT(1,14,1);
'IF' CODE=1 'THEN'
OUTSTRING(1,'('VALUE OF HC FED IN IN DATA')');
'IF' CODE=2 'THEN'
'BEGIN' OUTSTRING(1,'('HC = ')');  OUTREAL(1,CE);
OUTSTRING(1,'(' * G ** ')');  OUTREAL(1,CF);
'END';
'IF' CODE=3 'THEN'
'BEGIN'              OUTSTRING(1,'('HC = 0.5738 * ((G* ABSTEMP')');
OUTSTRING(1,'(' )/ATM PRESSURE) ** 0.6011')');
'END';
'IF' CODE=4 'THEN' 'BEGIN'
OUTSTRING(1,'('HC = (SP SURF AREA * ')');  OUTREAL(1,CE);
OUTSTRING(1,'(' * (REYNOLDS BASED ON PARTICLE DIAM) ** ')');
OUTREAL(1,CF);  OUTSTRING(1,'(' )/60')');
'END';
'IF' CODE=5 'THEN' OUTSTRING(1,'('HC = 0.374*AIRVEL**0.46')');
'IF' CODE=6 'THEN'
'BEGIN' OUTSTRING(1,'('HC = ')'); OUTREAL(1,CE);
OUTSTRING(1,'(' * G ** ')'); OUTREAL(1,CF);
OUTSTRING(1,'(' / DRIER DIAMETER')');
'END';
SYSACT(1,14,1);
OUTSTRING(1,'('MAXIMUM VALUE OF (T GRASS - T AIR) ALLOWED = ')');
WRITE(30,FA,DIFF); OUTSTRING(1,'(' DEG F')'); SYSACT(1,14,1);
SYSACT(1,14,1);
OUTSTRING(1,'('DRIER DIMENSIONS :')');  SYSACT(1,14,2);
OUTSTRING(1,'('DRIER LENGTH = ')');
```

```
WRITE(30,FF,BD); OUTSTRING(1,'(' FT  =  ')');
WRITE(30,FF,BD*12); OUTSTRING(1,'(' IN')'); SYSACT(1,14,1);
OUTSTRING(1,'('DIAMETER OF FIRST PASS OF DRIER = ')');
WRITE(30,FA,DDIAM1); OUTSTRING(1,'(' FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('DIAMETER OF SECOND PASS = ')');
WRITE(30,FA,DDIAM2); OUTSTRING(1,'(' FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('DIAMETER OF THIRD PASS = ')');
WRITE(30,FA,DDIAM3); OUTSTRING(1,'(' FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('CROSS-SECTIONAL AREA OF FIRST PASS = ')');
WRITE(30,FA,AREA1); OUTSTRING(1,'(' SQ FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('CROSS-SECTIONAL AREA OF SECOND PASS = ')');
WRITE(30,FA,AREA2); OUTSTRING(1,'(' SQ FT')');  SYSACT(1,14,1);
OUTSTRING(1,'('CROSS-SECTIONAL AREA OF THIRD PASS = ')');
WRITE(30,FA,AREA3); OUTSTRING(1,'(' SQ FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('NUMBER OF STAGES = ')');
WRITE(30,FD,N);  SYSACT(1,14,1);
OUTSTRING(1,'('LENGTH OF STAGE = ')');
WRITE(30,FC,DZ);  OUTSTRING(1,'(' FT  =  ')');
WRITE(30,FE,DZ*12); OUTSTRING(1,'(' INS')'); SYSACT(1,14,1);
OUTSTRING(1,'('ROTATION SPEED = ')');
WRITE(30,FA,RPM); OUTSTRING(1,'(' REV/MIN')'); SYSACT(1,14,1);
OUTSTRING(1,'('AVERAGE WEIGHT OF DRYMATTER PER STAGE = ')');
WRITE(30,FC,X); OUTSTRING(1,'(' LB')'); SYSACT(1,14,1);
OUTSTRING(1,'('AVERAGE WEIGHT OF DRYMATTER PER STAGE IN CASCADE = ')');
WRITE(30,FC,XC); OUTSTRING(1,'(' LB/CU FT')');  SYSACT(1,14,1);
OUTSTRING(1,'('NUMBER OF STAGES DROPPED PER ITERATION = ')');
WRITE(30,FD,NOLAYERS); SYSACT(1,14,1);
OUTSTRING(1,'('DELTA = ')');
WRITE(30,FE,TDELTA); SYSACT(1,14,1);
OUTSTRING(1,'('LAMBDA = ')');
WRITE(30,FC,TLAMBDA); SYSACT(1,14,1);
OUTSTRING(1,'('PHI(RE) = ')');
WRITE(30,FE,PHIRE); SYSACT(1,14,1);
SYSACT(1,14,1);
OUTSTRING(1,'('VALUES OF PARAMETERS AT INITIAL CONDITIONS :')');
 SYSACT(1,14,2);
OUTSTRING(1,'('CASCADE TIME = ')');
WRITE(30,FC,FTIME); OUTSTRING(1,'(' MINS')'); SYSACT(1,14,1);
OUTSTRING(1,'('SOAK TIME = ')');
WRITE(30,FC,STIME); OUTSTRING(1,'(' MINS')'); SYSACT(1,14,1);
```

```
CUTSTRING(1,'('SCAK TIME/CASCACE TIME RATIO = ')');
WRITE(30,FE,RATIC); SYSACT(1,14,1);
OUTSTRING(1,'('CALCULATED RESIDENCE TIME = ')');
WRITE(30,FE,TRT); OUTSTRING(1,'(' MINS')'); SYSACT(1,14,1);
SYSACT(1,14,1);
OUTSTRING(1,'('CCNDITICNS PRINTEC OUT EVERY ')');
WRITE(30,FD,NN); OUTSTRING(1,'(' STAGES')'); SYSACT(1,14,1);
NCHEAC:
SYSACT(1,15,1);
OUTSTRING(1,'('PROFILE OF DRIER AFTER STEADY STATE REACHEC')');
SYSACT(1,14,2);
CUTSTRING(1,'('          MCDB       HUM      ')');
OUTSTRING(1,'('  T GR      T AIR     RES TIME     RATIC     TRAVEL  ')');
SYSACT(1,14,2);
                 'FCR' J:=1 'STEP' 1 'UNTIL' N 'DO'

'BEGIN'
'IF' J>N*2/3 'THEN' 'BEGIN' AREA:=AREA3;  GOG:=GOG3;  'END' 'ELSE'
'IF' J>N'/'3 'THEN' 'BEGIN' AREA:=AREA2; GOG:=GOG2; 'END' 'ELSE'
'BEGIN' AREA:=AREA1;   GCG:=GCG1;  'ENC';
'IF' J>N*2/3 'THEN' DDIAM:=CCIAMC 'ELSE'
'IF' J>N'/'3 'THEN' CCIAM:=CCIAMB 'ELSE' DCIAM:=DDIAM1;
RHOP:=RHCPO*(M+1)/(MC+1);
RHOA:=PAT*144/(GCA*(T+460));
TK:=1.5*PHIRE*RHCA/(CP*RHOP);
F:=6C*6C*SQRT(32.2/TK);
FTIME:=6C*(TLAMBDA*CCIAM/F-LN(0.5)/(TK*F));
TRAVEL:=GCG*FTIME/RHOA-LN(GOG*FTIME*TK/RHOA+1)/TK;
TRT:=BD*(FTIME+STIME)/TRAVEL;
RATIO:=STIME/FTIME;
STRT:=STRT+TRT;   SRAT:=SRAT+RATIC;
RHCX:=(GRASSRATE*TRT    )/(BC*AREA);
RHCC:=RHCX*RHOC/((RATIC+1)*RHCC-RATIC*RHCX);
DT:=TRT/N;
XC:=CZ*RHOC*AREA;
'IF' T<600 'THEN'
'BEGIN' K:=CA*EXP(CB*(T-32)*5/9);
ME:=CC*SQRT(H)/(((T-32)*5/9)**2)+CD;
'IF' T>212 'CR' ME<0  'THEN' ME:=0;
'IF' M>ME 'THEN'
DM:=-K*DT*(M-ME)/(1+C.5*K*CT) 'ELSE' DM:=0;
```

```
'END' 'ELSE'
'BEGIN' CRATE:=CX+CY*(T-32)*5/9;
DM:=-CRATE*DT;
'END';
NH:=H-DM*RHOX*DZ/(GOG*DT);
                    CPG:=C1+C2*M;
'IF' CODE=2 'THEN' HC:=CE*GOG**CF;
'IF' CODE=3 'THEN' HC:=0.5738*((GOG*(T+460))/PAT)**0.6011;
'IF' CODE=4 'THEN' HC:=(SSA*CE*(GOG*60*DP/AIRVIS)**CF)*THCON*(PR**0.33)
/(60*DP);
'IF' CODE=5 'THEN' HC:=0.374*(GOG/RHOA)**0.46;
'IF' CODE=6 'THEN' HC:=CE*(GOG**CF)/DDIAM;
D:=RHOX*2/(HC*DT/(RATIO+1));  F:=-DZ*RHOX/(GOG*DT);
ALPHA:=1+D*DM*0.448;
BETA:=D*(CPG+M+DM)+1;
GAMMA:=1-D*(CPG+M);
DELTA:=-1;
EPSILON:=-D*DM*(1061.54*(L3+L4*EXP(L5*M))+32);
ZETA:=0.2405+0.448*NH;
ETA:=F*(CPG+M+DM);
IOTA:=-F*(CPG+M);
KAPPA:=0.2405+0.448*H;
LAMBDA:=1061.54*(H-NH)-F*DM*32;
MU:=BETA/ALPHA;
NU:=(GAMMA*TGR+DELTA*T+EPSILON)/ALPHA;
PI:=ETA/ZETA;
SIGMA:=(IOTA*TGR+KAPPA*T+LAMBDA)/ZETA;
TGR:=(NU-SIGMA)/(PI-MU);
NT:=MU*TGR+NU;
M:=M+DM;
'IF' J'/'NN*NN=J 'OR' J=1 'THEN'
'BEGIN'
WRITE(30,FD,J);  SPACE(1,2);
WRITE(30,FE,M); SPACE(1,2); WRITE(30,FE,NH); SPACE(1,2);
WRITE(30,FF,TGR); SPACE(1,2); WRITE(30,FF,NT); SPACE(1,2);
'IF' B=100 'THEN' 'GOTO' BYPASS;
WRITE(30,FE,TRT); SPACE(1,2); WRITE(30,FE,RATIO); SPACE(1,2);
WRITE(30,FE,TRAVEL); SPACE(1,2);
WRITE(30,FD,J);
BYPASS:
```

```
SYSACT(1,14,1);
'END' STAGE PRINT;
'IF' M<C 'THEN' 'GCTC' FAIL1;
                         'IF' TGR-T>DIFF 'THEN' 'GOTO' FAIL4;
'IF' (J+1)<=N 'THEN'
'BEGIN' T:=NT;  H:=NH;
'ENC';
'ENC' STEADY STATE REACHEC;
SYSACT(1,14,1);
OUTSTRING(1,'('PRCDUCT MCISTURE CCNTENT = ')');
OUTREAL(1,M);  SYSACT(1,14,2);
     'GCTO' FINAL;
FAIL1:  SYSACT(1,15,1); CUTSTRING(1,'('FAILURE - M.C. <0')');
SYSACT(1,14,1);
CUTSTRING(1,'('LAYER NO ')');  OUTINTEGER(1,J);
SYSACT(1,14,2);
          'GCTC' FINAL;
FAIL4: SYSACT(1,15,1);
CUTSTRING(1,'('FAILURE CUE TC EXCESSIVE COOLING OF AIR')');
SYSACT(1,14,1);
OUTSTRING(1,'('LAYER NO ')');  CUTINTEGER(1,J);
SYSACT(1,14,2);
     'GCTC' FINAL;
FINAL:
SYSACT(1,15,1);
'IF' A=100 'THEN' 'GCTC' WANG;
OUTSTRING(1,'('FINAL VALUES CF PARAMETERS  :')');  SYSACT(1,14,2);
OUTSTRING(1,'('CASCADE TIME = ')');
WRITE(30,FC,FTIME); CUTSTRING(1,'(' MINS')'); SYSACT(1,14,1);
OUTSTRING(1,'('SCAK TIME/CASCADE TIME RATIC = ')');
WRITE(3C,FE,RATIO); SYSACT(1,14,1);
CUTSTRING(1,'('CALCULATEC RESIDENCE TIME = ')');
WRITE(3C,FE,TRT); CUTSTRING(1,'(' MINS')'); SYSACT(1,14,1);
OUTSTRING(1,'('WEIGHT OF CRYMATTER PER STAGE IN CASCADE = ')');
WRITE(30,FC,XC); OUTSTRING(1,'(' LB/CU FT')');  SYSACT(1,14,1);
CUTSTRING(1,'('CENSITY CF GRASS PARTICLE = ')');
WRITE(3C,FA,RHOP); CUTSTRING(1,'(' LB/CU FT')'); SYSACT(1,14,1);
OUTSTRING(1,'('BULK DENSITY CF GRASS DRYMATTER IN CASCADE = ')');
WRITE(30,FC,RHOC);OUTSTRING(1,'(' LB/CU FT')');SYSACT(1,14,1);
SYSACT(1,14,5);
```

```
CUTSTRING(1,'('CALCULATEC MEAN VALUES OF PARAMETERS :')');
SYSACT(1,14,2);
WANG:
OUTSTRING(1,'('MEAN RESIDENCE TIME  =  ')');
WRITE(30,FE,STRT/J); OUTSTRING(1,'(' MINS')'); SYSACT(1,14,1);
CUTSTRING(1,'('MEAN SCAK/CASCACE RATIC = ')');
WRITE(3C,FE,SRAT/J); SYSACT(1,14,1);
SYSACT(1,14,5);
'GCTC' LCCP;
LAST:
SYSACT(1,15,1);
CUTSTRING(1,'('NO MORE CATA')');
SYSACT(C,12,C);  SYSACT(1,12,0);
'END';
'ENC'
```

Rotary Drier Programme - Sample Results (x)

```
SIMULATION OF A ROTARY GRASS DRIER
DATA SET NO   1
GRASS PROPERTIES :
GRASS FEED RATE =   7.9400 LB/MIN
INITIAL MOISTURE CONTENT =   4.2600 LB/LB
INITIAL GRASS TEMPERATURE =  50.0000 DEG F
BULK DENSITY OF DRYMATTER IN FLIGHTS =    7.00 LB/CU FT
BULK DENSITY OF GRASS DRYMATTER IN CASCADE =  0.003007 LB/CU FT
AVERAGE BULK DENSITY OF GRASS IN DRIER =  0.012028 LB/CU FT
DENSITY OF GRASS PARTICLE =   55.00 LB/CU FT
AIR PROPERTIES :
AIR FLOW RATE =  233.00 LB/MIN  =    32.96 LB/MIN-SQ FT
INITIAL AIR TEMPERATURE =   500.00 DEG F
INITIAL AIR HUMIDITY =  0.007000 LB/LB
DRYING PARAMETERS :
TEMP < 600 DEG F :  -DM/DT = K(M - ME)
                    K (MIN)-1 =  0.020400 EXP( 0.020280 * TEMP)
                    ME =  32924 (SQ RT HUMIDITY / TEMPSQ) +-0.224550
TEMP > 600 DEG F :  -DM/DT = CONST = C
                    C = -1.839600 +  0.024680 *TEMP
      CPG =    0.30 +  0          * M.C.
HEAT TRANSFER COEFFICIENT FOR INITIAL CONDITIONS =    8.08 BTU/MIN CUFT DEG
HC EVALUATED BY METHOD   5
HC = 0.374*AIRVEL**0.46
MAXIMUM VALUE OF (T GRASS - T AIR) ALLOWED =   50.00 DEG F
DRIER DIMENSIONS :
DRIER LENGTH =    54.00 FT  =   648.00 IN
DIAMETER OF FIRST PASS OF DRIER =    3.00 FT
DIAMETER OF SECOND PASS =    4.83 FT
DIAMETER OF THIRD PASS =    6.83 FT
CROSS-SECTIONAL AREA OF FIRST PASS =    7.07 SQ FT
CROSS-SECTIONAL AREA OF SECOND PASS =   11.28 SQ FT
CROSS-SECTIONAL AREA OF THIRD PASS =   18.33 SQ FT
NUMBER OF STAGES = 540
LENGTH OF STAGE =  0.100000 FT  =    1.2000 INS
ROTATION SPEED =   15.50 REV/MIN
AVERAGE WEIGHT OF DRYMATTER PER STAGE =  0.014704 LB
AVERAGE WEIGHT OF DRYMATTER PER STAGE IN CASCADE =  0.003675 LB/CU FT
NUMBER OF STAGES DROPPED PER ITERATION =   1
DELTA =   3.0000
LAMBDA =  0.499999
PHI(RE) =   1.0000
VALUES OF PARAMETERS AT INITIAL CONDITIONS :
CASCADE TIME =  0.007155 MINS
SOAK TIME =  0.021505 MINS
SOAK TIME/CASCADE TIME RATIO =   3.0058
CALCULATED RESIDENCE TIME =   1.0476 MINS
```

Rotary Drier Programme - Sample Results (xi)

```
PROFILE OF DRIER AFTER STEADY STATE REACHED

        MCDB      HUM       T GR      T AIR     RES TIME   RATIO     TRAVEL

  1     4.2273    0.0081     58.34    488.93    1.0476     3.0058    1.4774     1
 25     3.9052    0.0191    210.61    345.98    1.2938     3.1925    1.1787    25
 50     3.7770    0.0235    256.03    302.71    1.3823     3.2526    1.0984    50
 75     3.6828    0.0267    263.53    286.06    1.4130     3.2816    1.0723    75
100     3.6017    0.0294    261.17    276.65    1.4269     3.3016    1.0604   100
125     3.5288    0.0319    256.52    269.50    1.4359     3.3181    1.0525   125
150     3.4620    0.0342    251.57    263.40    1.4427     3.3328    1.0465   150
175     3.4004    0.0363    246.80    257.81    1.4488     3.3461    1.0411   175
200     3.3008    0.0397    236.42    250.05    2.8573     3.0999    0.5375   200
225     3.2031    0.0430    228.26    241.31    2.8617     3.1128    0.5362   225
250     3.1166    0.0460    221.40    233.31    2.8659     3.1237    0.5349   250
275     3.0392    0.0486    215.22    226.11    2.8687     3.1331    0.5340   275
300     2.9692    0.0510    209.56    219.58    2.8705     3.1411    0.5334   300
325     2.9054    0.0532    204.33    213.59    2.8716     3.1480    0.5329   325
350     2.8544    0.0549    201.04    208.41    2.8737     3.1535    0.5322   350
375     2.7871    0.0572    194.19    202.56    5.6920     2.8285    0.2762   375
400     2.7147    0.0597    188.10    195.68    5.6676     2.8293    0.2773   400
425     2.6529    0.0618    183.11    189.69    5.6459     2.8295    0.2784   425
450     2.5996    0.0636    178.77    184.52    5.6259     2.8292    0.2794   450
475     2.5534    0.0651    174.97    180.02    5.6074     2.8287    0.2803   475
500     2.5129    0.0665    171.64    176.13    5.5899     2.8281    0.2812   500
525     2.4773    0.0677    168.71    172.70    5.5738     2.8273    0.2820   525

PRODUCT MOISTURE CONTENT = +2.457906'+00


FINAL VALUES OF PARAMETERS  :
CASCADE TIME =  0.007608 MINS
SOAK TIME/CASCADE TIME RATIO =    2.8268
CALCULATED RESIDENCE TIME =    5.5648 MINS
WEIGHT OF DRYMATTER PER STAGE IN CASCADE =  0.021483 LB/CU FT
DENSITY OF GRASS PARTICLE =   36.17 LB/CU FT
BULK DENSITY OF GRASS DRYMATTER IN CASCADE =  0.011723 LB/CU FT
CALCULATED MEAN VALUES OF PARAMETERS :
MEAN RESIDENCE TIME  =    3.2870 MINS
MEAN SOAK/CASCADE RATIO =   3.0704
```

LIST OF IDENTIFIERS

ROTARY DRIER PROGRAMME

A	Code number = 100 for omitting printout of input data, etc.
AIRVIS	Viscosity of air, lb/ft hr
ALPHA	Evaluation term
AREA	Local cross-sectional area of drier, ft^2
AREA1	Cross-sectional area of 1st pass of drier, ft^2
AREA2	Cross-sectional area of 2nd pass of drier, ft^2
AREA3	Cross-sectional area of 3rd pass of drier, ft^2
B	Code number = 100 for omitting some of the profile printout
BD	Length of drier, ft
BETA	Evaluation term
C1, C2	Constants for evaluating CPG
CA, CB	Constants for evaluating K
CC, CD	Constants for evaluating ME
CE, CF	Constants for evaluating HC
CODE	Indicates which formula is to be used to calculate HC
CPA	Specific heat of air, Btu/lb °F
CPG	Specific heat of dry-matter in grass, Btu/lb °F
CRATE	Constant drying rate, min^{-1}
CX, CY	Constants for evaluating CRATE
D	Evaluation term
DATASET	Index number of set of data, = -1 to terminate programme
DDIAM	Local equivalent drier diameter, ft
DDIAM1	Diameter of first pass, ft
DDIAM2	Diameter of second pass, ft
DDIAM3	Diameter of third pass, ft
DDIAMB	Equivalent diameter of second pass, ft
DDIAMC	Equivalent diameter of third pass, ft
DELTA	Evaluation term
DIFF	Tolerance for calculating severity of temperature overshoot, F°

IDENTIFIERS IN ROTARY DRIER PROGRAMME - CONTD.

DM	Change in moisture content of grass after passing through a stage
DP	Diameter of grass particle, ft
DT	Residence time of grass in a stage, min
DZ	Length of a stage, ft
EPSILON	Evaluation term
ETA	Evaluation term
F	Evaluation term
FA, FB, FC, FD, FE, FF	Formats
FTIME	Cascade time, min
G	Air flow rate, lb/min
GAMMA	Evaluation term
GCA	Gas constant for air
GOG	Local air velocity, lb/min ft^2
GOG1	Mass velocity of air in first pass, lb/min ft^2
GOG2	Mass velocity of air in second pass, lb/min ft^2
GOG3	Mass velocity of air in third pass, lb/min ft^2
GRASSRATE	Grass feed rate, lb/min
H	Humidity of air entering a layer, lb/lb
HC	Heat transfer coefficient, Btu/min ft^3 °F
HO	Humidity of inlet air, lb/lb
I	Counter
IOTA	Evaluation term
J	Counter
K	Drying constant, min^{-1}
KAPPA	Evaluation term
L3, L4, L5	Constants for correcting the latent heat for effect of moisture content

IDENTIFIERS IN ROTARY DRIER PROGRAMME - CONTD.

LAMBDA	Evaluation term
M	Moisture content of grass in a stage, dry basis
MAXRH	Maximum relative humidity at which drying takes place (Not used)
ME	Equilibrium moisture content, lb/lb
MM	Not used, but read in
MO	Initial moisture content of grass, lb/lb, dry basis
MU	Evaluation term
N	Number of stages
NH	Humidity of air leaving a stage, lb/lb
NN	Printout of conditions in stage every NN stages
NOLAYERS	Number of stages advanced for a time interval, = 1
NT	Temperature of air leaving a stage, ^{o}F
NU	Evaluation term
PAT	Atmospheric pressure, lb/in^2
PHIRE	Resistance coefficient
PI	Evaluation term
PR	Prandtl number
RATIO	Ratio of soak time to cascade time
REP	Reynold's Number based on particle diameter
RESTIME	Overall residence time, min (Fed in but not used)
RHOA	Density of air. lb/ft^3
RHOC	Density of dry-matter in cascade, lb/ft^3
RHOD	Density of dry-matter in flights, lb/ft^3
RHOP	Local density of grass particle, lb/ft^3
RHOPO	Density of grass particle initially, lb/ft^3
RHOX	Average density of dry-matter in a stage, lb/ft^3
RPM	Speed of rotation of drier, rev/min
SIGMA	Evaluation term
SRAT	Summation term

IDENTIFIERS IN ROTARY DRIER PROGRAMME - CONTD.

SSA	Specific surface of grass in flights, ft^{-1}
STIME	Soak time, min
STRT	Summation term
T	Temperature of air entering a stage, °F
TDELTA	Travel ratio
TGO	Initial temperature of grass, °F
TGR	Temperature of grass in stage, °F
THCON	Thermal conductivity of air, Btu/hr ft °F
TK	Evaluation term
TLAMBDA	Ratio of distance of fall to diameter of pass
TO	Initial temperature of air, °F
TRAVEL	Distance along drier travelled by grass in cascading, ft
TRT	Residence time based on local conditions, min
VOIDAGE	Voidage of grass in flights
X	Weight of dry-matter in a stage, lb
XC	Weight of dry-matter in cascade in a stage, lb
ZETA	Evaluation term