U.S. DEPARTMENT OF AGRICULTURE
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TRANSPORT AND COMBUSTION
OF FIREBRANDS

FINAL REPORT OF GRANTS FG-SP-114 AND FG-SP-146. (VOL. II)

INSTITUTO NACIONAL DE TECNICA AEROESPACIAL
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U. S. DEPARTMENT OF AGRICULTURE
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TRANSPORT AND COMBUSTION
OF FIREBRANDS

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FOREWORD

This research program has been sponsored by the Forest Service of the United States Deoartment of Agriculture under *Grants* FG-Sp-114 and FG-Sp-1 4« , monitore.l by the European Regional Research Office in Rome of the Agricultural Research Service. The research work has been performed at the Propulsion Department of the Institute Nacional de Tecnica Aeroespacial Esteban Terradas. Madrid. Spain. The complete research program of both Grants comprised two different problems: The study of the basic laws controlling open fires and the study of the combustion properties and flight paths of burning embers of wood (firebrands). According to this the final Report of the Grants has been divided in two volumes: Open Fires and Transport and Combustion of Firebrands.

ACKNOWLEDGEMENT

It is aknowledged the valuable advice given by Professors I.Da Riva and A.Linan, and the valuable partial collaborations of Dr. J.M.Ortega, Mr. R.Elvira Pison and Mr.E. Mezquida. The authors are also indebted to the excellent work performed by the laboratory assistants C.Garcia Fernandez, M.Muhoz and F.Silva; draftsman E.Goni and calculists J.M.Vale_ ro and R.Almarza; photographer W.Pantoja and typist Miss F.Mo re da .

A B S T R A C T

A theoretical and experimental study has been carried out on the combustion properties and flight paths of firebrands when they are carried upwards by convective currents and then forwards bv the winds.

The study has shown that the flight paths of firebrands can be accurately calculated by assuming that they fly at their terminal velocity of fall. This velocity of fall decreases continuously as the firebrand burns.

Several types of wind tunnels have been developed espe_ cially designed to study combustion of firebrands at their final velocity of fall.

The study has also shown that combustion and flight paths of firebrands can also be calculated from data obtained on the combustion of firebrands at constant wind speed.

The influence of the initial size and initial shape of the firebrands, kind of wood and initial moisture content has been studied, as well as the influence of several types of convection columns configurations.

Results of these studies enable the calculation of the maximum range of possible fire spread by firebrands of given initial characteristics, once the convective currents above the fire are known as well as the horizontal wind conditions.

- I l l -

C O N T E N T S

1. <u>INTRODUCTION</u>

In high-intensity forest fires the dominating fire propagation mechanism is the transport of burning embers or firebrands ahead of the fire front. Burning pieces of wood are carried aloft by the convective air currents and then they are carried forward by the winds.

Showers of thousands of burning embers ignite large areas ahead of the fire. This phenomenon, called spotting, is one of the worst characteristics of major fires, increasing their intensity and making fire suppresion much more diffi-cult [1,2].

Firebrands spread fire over firebreaks, rivers, land areas without vegetation and over other natural fire-barriers. In extreme adverse conditions large firebrands can be carried up to very high altitudes, and then if picked up by strong ho-rizontal winds they may ignite secondary fires at great dis-tance, even at several miles, from the main fire front. These secondary fires are very dangerous and they are very difficult to prevent and suppress.

The problem of fire spread by firebrands depends, es-sentially,on two factors: the aerodynamic field around the fire, and the flight and combustion properties of the firebrands when transported by convective currents and by the winds.

There is some information of the first problem, espe-cially in connection with convection plumes, such as the works listed in references [3,4] and [5]. On the contrary, there exists practically no information whatsoever on the firebrand problem.

Little is known on the flight characteristics of firebrands and on the burning and ignition properties of them, neither exists any data on the influence of size, shape, kind of wood, moisture content etc, on the aerodynamic and combustion proper ties of firebrands.

In order to study the principal aspects of the problem of firebrands, the Forest Service of the U.S. Department of Agriculture has sponsored a research program which has been carried out at the Instituto Nacional de Tecnica Aeroespacial of Madrid under Grants FG-Sp-llU- and FG-Sp-146.

The research program has been directed to the study of the flight characteristics and combustion properties of fire- brands, including flight paths calculations, distances travel- led and state of burning of the firebrands when falling on the ground in order to asses the potential danger of fire spread.

The study of the influence on these processes of the initial size and shape of the firebrands, kind of wood and moisture content has been also included. Some studies on the general laws governing combustion of wood with forced convec- tion have also been carried out. They were not specifically included in the research program, but they have been conduct- ed in order to deduce from them the basic laws controlling combustion of firebrands when they fly at variable relative wind speed.

Results will be given in form of general dimension- less expressions including all variables and parameters,from which scaling laws may be immediately derived.

The study of the aerodynamic field associated to a

fire has not been included in the research program. There-
fore, the convective currents and winds will be considered as
data of the problem.

2. FUNDAMENTAL EQUATIONS AND MODEL OF THE PROCESS

The fundamental problem to be solved is the study of
flight paths and combustion processes of burning embers of
wood when they are carried by convective currents or by the
winds.

Therefore, it is necessary to calculate the flight
paths under given wind conditions, studying at the same time
how combustion of the firebrand progresses. This combustion
process is of the convective type and it is complicated by
the fact that the relative wind speed acting of the fire-
brand is not constant, but it decreases as the firebrand
burns.

Flight paths will be calculated under the following
assumptions (Fig.1):

1°) Bidimensional motion

2°) Rotational motion of the firebrands will not be consider-
ed. Therefore, equations of the motion will be referred
to that of the center of gravity.

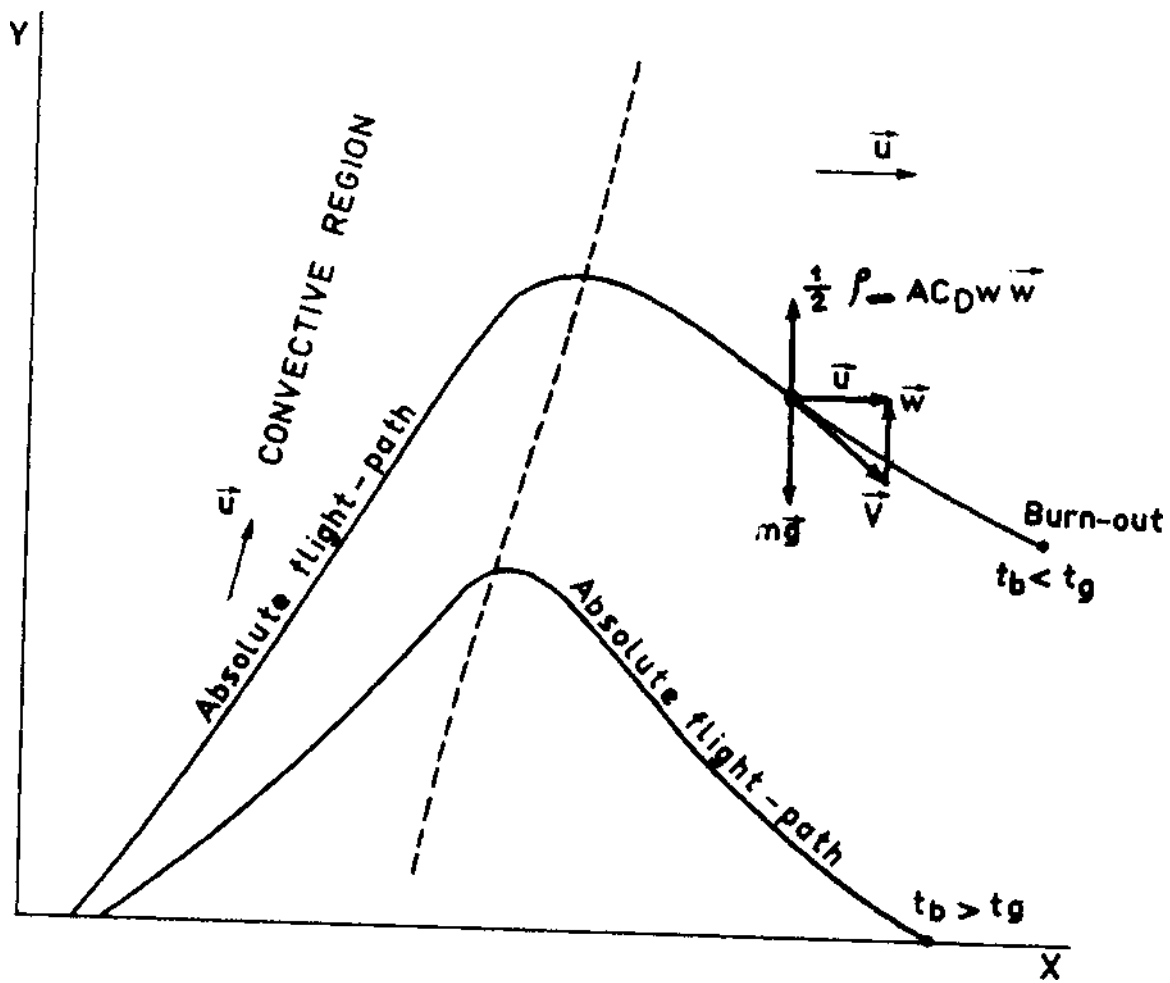3°) The aerodynamic drag will be assumed to be given by an
expression of the form:

Fig.1 - Model of the Process

$$D = -P_a - {}^{AC}D^{w\,w} \qquad (1)$$

in which $P_{a,\infty}$ is the air density at the infinity, C_D is the aerodynamic drag coefficient, A the cross-section area of the firebrand and,

$$\vec{w} = \vec{u} - \vec{V}$$

is the relative velocity of the wind with respect to the fire-brand. In this last expression u is the velocity of the wind and $\vec{V}$ is the absolute velocity of the center of gravity of the firebrand.

Motion of a firebrand of variable mass m will be governed by the following vectorial equation:

$$\frac{d}{dt}\vec{M} = -\frac{1}{2}\rho_{a,\infty}AC_D w\vec{w} + m\vec{g} \qquad (3)$$

The rate of change of momentum M will be calculated by selecting a control surface coinciding at time t with the surface of the solid part of the firebrand and by applying the momentum equation to the solid part and gases ejected, separately, it results:

$$\frac{d}{dt}\vec{M} = m\frac{d\vec{V}}{dt} + \vec{V}\frac{dm}{dt} + \vec{V}\int_\Sigma \rho_g\,(\vec{w}_e\vec{n})\,d\sigma +$$

$$+ \int_\Sigma \rho_g\,\vec{w}_e\,(\vec{w}_e\,\vec{n})\,d\sigma , \qquad (4)$$

in which m is the mass of the <—.olid part of the **firebrand,**
p is t-he density of tl,(^ases ejected through **the firebrand**
surface _T_, and w   it, t^e ejection velocity of these **gases**
measured with respect t > the ^ent«r of gravity.

Since:

$$\vec{V} \ \frac{dm}{dt} + \vec{V} \int_{\Sigma} \rho_g \ (\vec{w}_e \vec{n}) \ d\sigma = 0 \tag{5}$$

it results

$$\frac{d}{dt} \ \vec{M} = m \ \frac{d\vec{V}}{dt} + \int_{\Sigma} \rho_g \ \vec{w}_e \ (\vec{w}_e \vec{n}) \ d\sigma \tag{6}$$

The term:

$$\vec{F}_p = \int_{\Sigma} \rho_g \ \vec{w}_e \ (\vec{w}_e \vec{n}) \ d\sigma \tag{7}$$

represents the self-propulsion force of the firebrand origi-
nated by the combustion process. This force will normally be
zero or very small. Gas density p   resulting from the com-
bustion process will be practically constant all over the fire_
brand surface and ejection velocities w   if they are not
                                        J   e   J
constant over that surface are₅ in all cases, very small. Only
in some exceptional cases and for very short periods of time
self propulsion processes have been observed in **firebrands,as**
in some pine cones.
      Therefore, term F   will be taken equal to zero and
                        P
the equation of motion will reduce to the expression:

$$m \frac{d\vec{V}}{dt} = - \frac{1}{2} \rho_{a,\infty} A w \vec{w} + m\vec{g} \qquad (8)$$

which is similar to the equation of motion of a particle of constant mass.

Taking a coordinate system in which x is the horizontal axis and y the vertical direction, it results:

$$m \frac{dV_x}{dt} = m \frac{du_x}{dt} - m \frac{dw_x}{dt} = - \frac{1}{2} \rho_{a,\infty} C_D A w^2 \frac{w_x}{w} \qquad (9)$$

$$m \frac{dV_y}{dt} = m \frac{du_y}{dt} - m \frac{dw_y}{dt} = \frac{1}{2} \rho_{a,\infty} C_D A w^2 \frac{w_x}{w} - mg \qquad (10)$$

Assuming a constant wind speed, or that it changes slowly as compared with the rate of change of w , it results:

$$\frac{dw_x}{dt} + \frac{1}{2} \frac{\rho_{a,\infty} C_D A}{m} w w_x = 0 \qquad (11)$$

$$\frac{dw_y}{dt} + \frac{1}{2} \frac{\rho_{a,\infty} C_D A}{m} w w_y - g = 0 \qquad (12)$$

The mass, cross-section area A and drag coefficient C_n are changing, since the particle is burning, and this combustion process depends on w . Therefore, parameter:

$$\alpha \simeq \frac{\rho_{a,\infty} C_D A}{2m} \qquad (13)$$

is a function of w and t .

The problem lies in the integration of system (11) and (12), in order to obtain the flight paths of the firebrands by means of the expressions:

$$X = \int_0^t (u_x - w_x) \, dt \qquad (14)$$

$$Y = \int_0^t (u_y - w_y) \, dt \qquad (15)$$

Another important variable of the process is the burning-out time t, (w,t) of the firebrand. This burning-out time may be longer or shorter than the time t_o spent by the firebrand in flight till it falls on the ground.

In the first case, the firebrand reaches the ground while still burning, and in the second case the firebrand burns out in the air. When t, = t_g the maximum horizontal range of possible fire spread is reached.

EXPERIMENTAL TECHNIQUE AND RESEARCH FACILITIES

Very little information is available on combustion of wood with forced convection, and no analytical studies of any
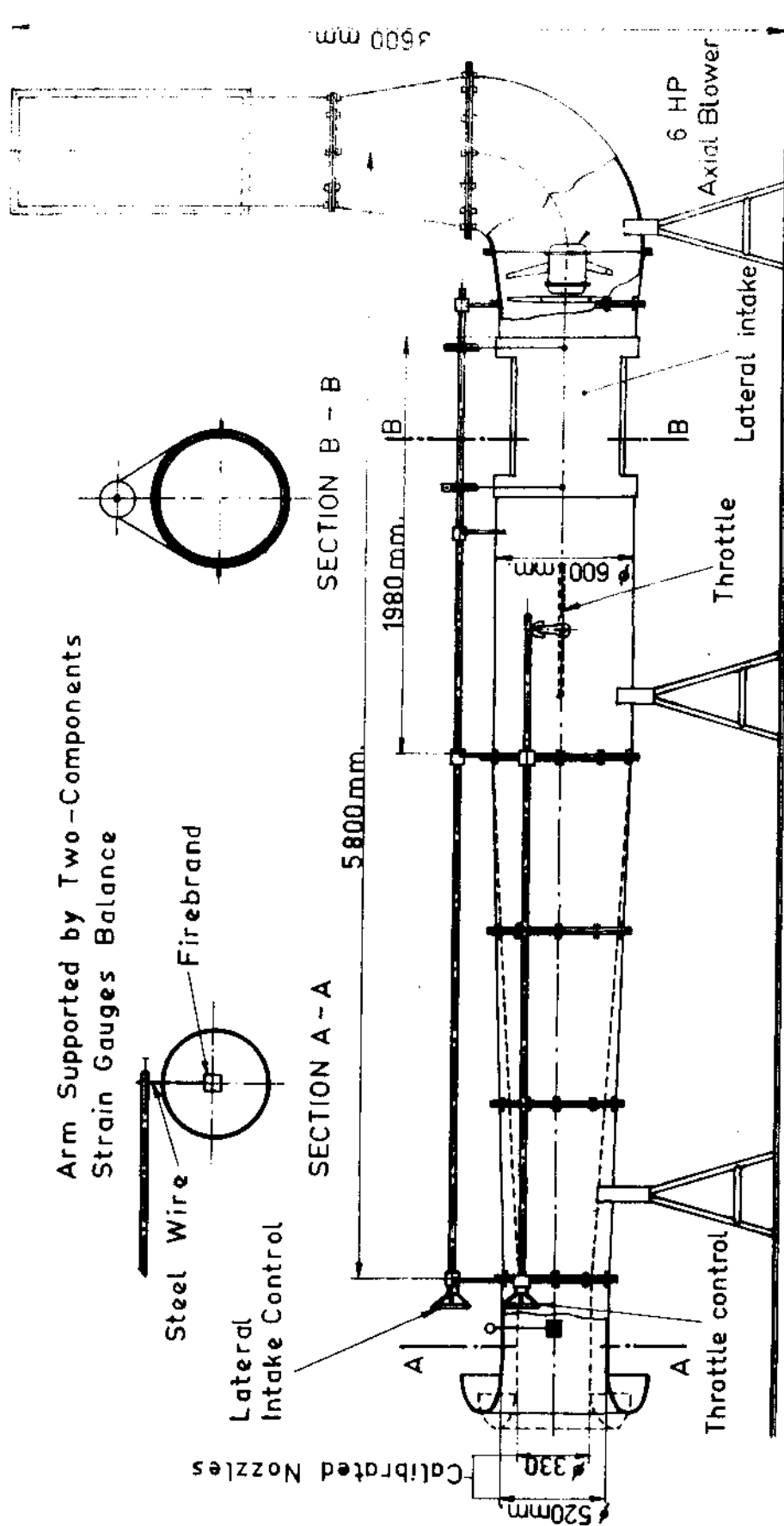
Arm Supported by Two-Components
Strain Gauges Balance

Firebrand

Steel Wire

SECTION A - A

SECTION B - B

Lateral
Intake Control

Calibrated Nozzles

Ø 330

Ø 520 mm

5800 mm

1980 mm

Ø 600 mm

Throttle

Throttle control

Lateral intake

6 HP
Axial Blower

≥600 mm

Fig.2 - Horizontal Wind-Tunnel

kind exits on this problem. Therefore, function a (w,t) as well as the burning time 1, will be determined experimental ly.

It was selected the experimental procedure of meas- uring the weight and the aerodynamic drag of burning parti- cles of wood in a wind tunnel.

The aerodynamic drag of a burning particle on which a constant air speed acts is a function of time mainly because its size decreases as it burns. Furthermore, the aerodynamic drag coefficient C_n may vary because of shape changes and due to the combustion process. It is possible to determine the aerodynamic drag coefficient C~ by measuring the aerod^ namic drag and by determining the variable cross-section area A of the firebrand by means of photographs. However, it was decided not to determine systematically the drag coefficient C_n . For the purposes of the research program it was suffi- cient to measure the over-all aerodynamic drag, and the study of the interesting problem of the influence of a combustion process on the aerodynamic drag is difficult to be carried with wood, because of the changes in size and shape of the burning particles and because of the heterogeneous nature of this substance.

In the first place, two wind tunnels of the suction type were designed and constructed. This type of tunnel was selected because by placing the firebrand at the inlet sec- tion of.the tunnel, it was very easy to control the wind speed acting on the firebrand by means of lateral intakes of variable area.
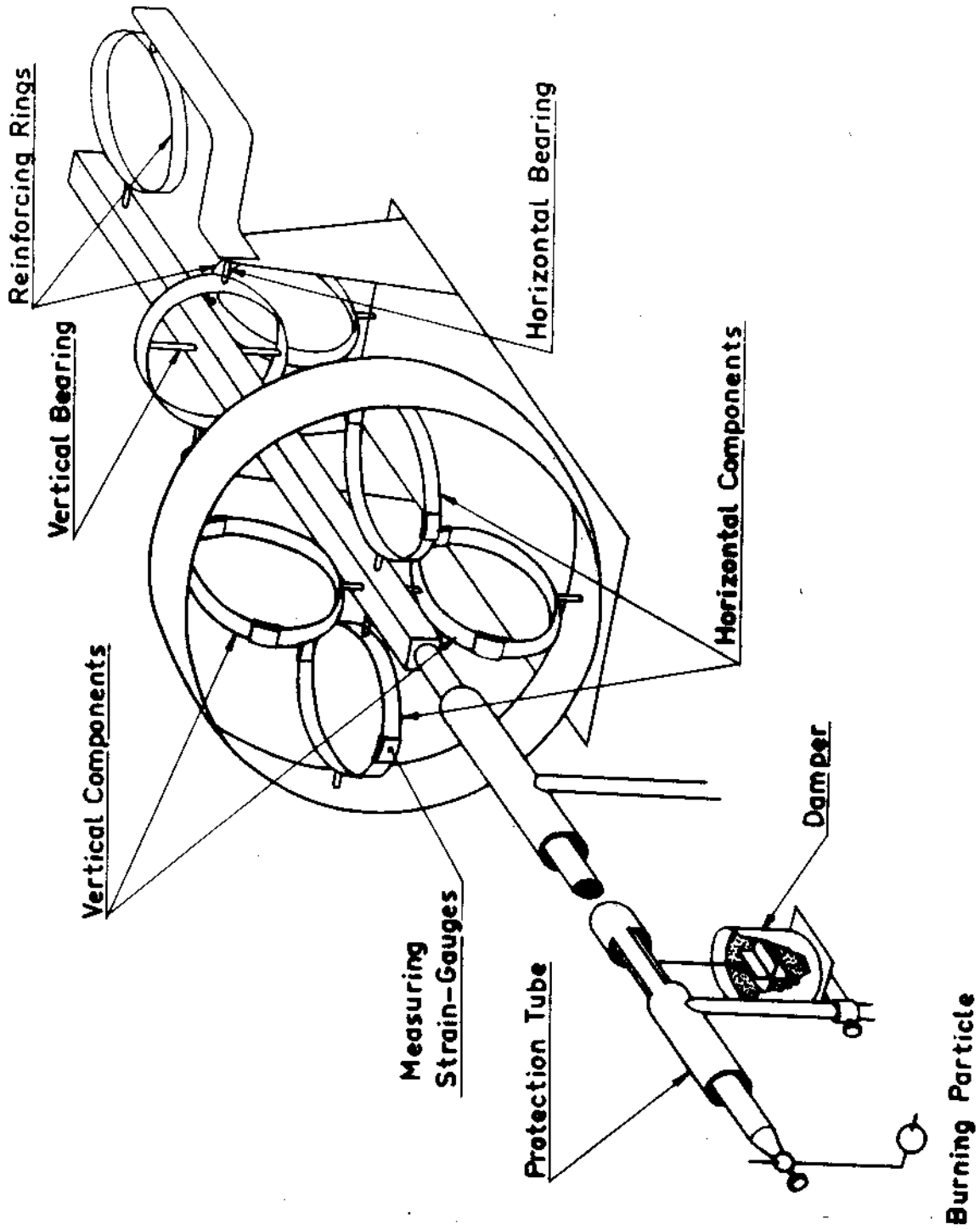
Fig.3 - Two-Components Strain-gauges Balance.

Fig.2 shows the horizontal wind tunnel. Air is drawn into the tunnel by means of an axial blower entrained by a 6HP AC electric motor. Wind speed is controlled with the two lateral intakes shown in the figure and with a lenticular throttle. Wind speed can be varied continuously from zero up to 40 m/sec. Firebrands up to 10 cm in diameter can be tested.

The inlet nozzle is a calibrated jet engine intake. Wind velocity is determined by measuring the static pressure with micromanometers at four points located around the periphe_ ry of the test section. In order to have a higher range of velocities two intake nozzles were used, one of 32 cm and the other one of 52 cm in diameter. The firebrand is supported by means of a thin steel wire protected with a cowling. Ignition is achieved with a butane torch and the weight and the aerody- namic drag are continuously measured with a two-components strain-gauge balance as the firebrand burns.

The balance was designed and constructed at the INTA. It is of the ring type (Fig.3), in which the strain gauges are placed on rings of high-duty steel. Two rings are used for each component (vertical component for weight and horizontal component for the aerodynamic drag) and the other two branches of a Wheatstone bridge are formed with a box of small bars with strain-gauges attached as variable resistences.

The balance has a long arm supporting the firebrand, **which** multiplies the measured forces by a factor of about forty. The ring layout, the strain-gauges arrangement and the electri cal circuits have been designed in a way that the effects of temperature and lateral stresses are automatically compensated. Only forces which produce deformations of opposite sign are

Electrical micromotor

Connecting arm

Primary gear box

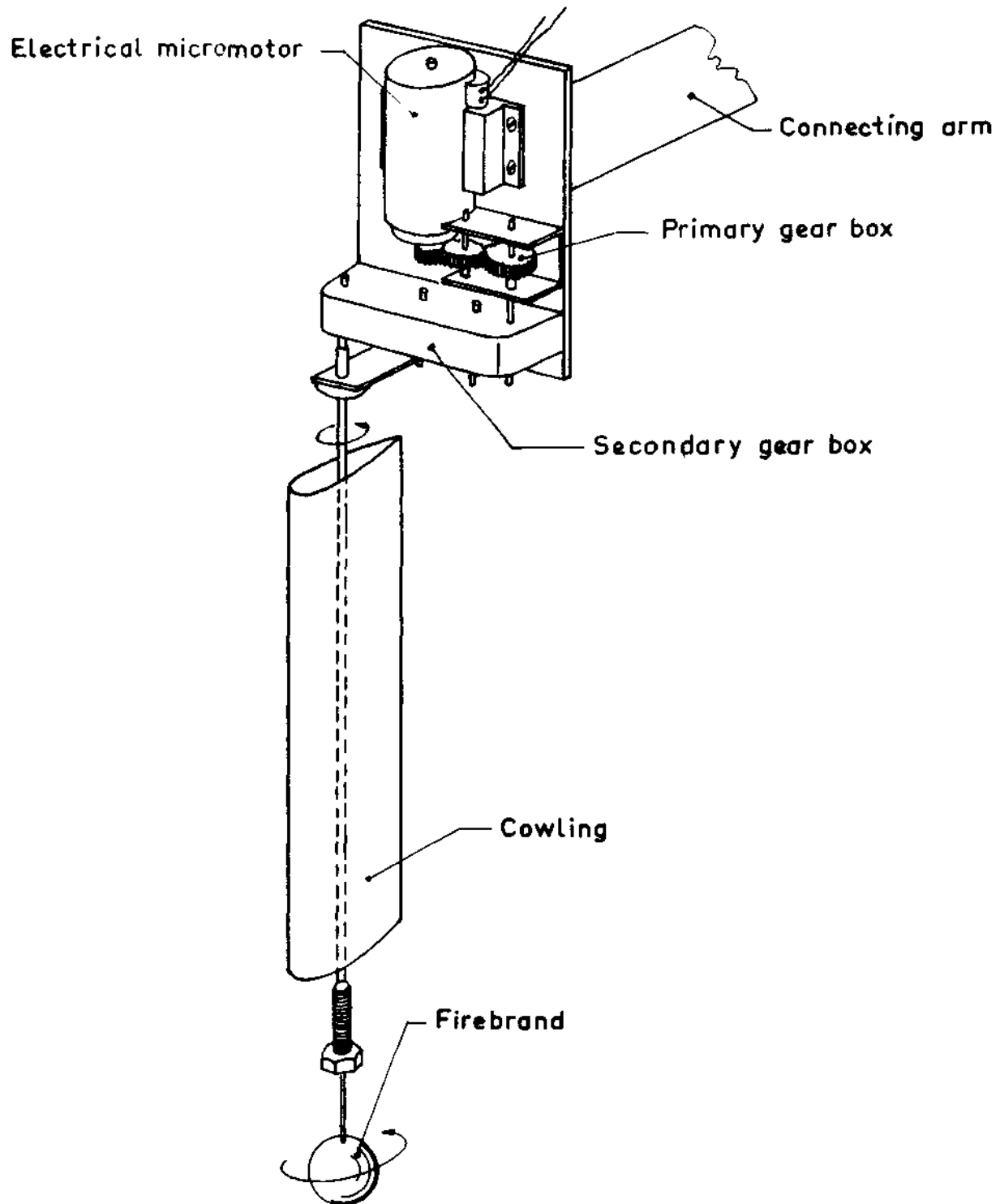Secondary gear box

Cowling

Firebrand

Fig.4 - Rotating Device of Firebrands

recorded.

The signals from the balance are recorded by means of a four channels Kipp and Zonen micrograph of high sensibility.

As the research program progressed it was decided to incorporate a rotating device of the firebrand. It consists of a micro-electric motor incorporated in the arm, as shown in Fig.4.

From the first experimental and theoretical studies it was concluded, as shown in paragraph 4, that the firebrands fly practically all their trajectories at a velocity constantly equal to their final velocity of fall, that is to say, at a velocity for which the aerodynamic drag and the weight are equal.

Therefore, a great number of experiments were carried out for which the tunnel wind speed is decreased continuously as the firebrand burns, in order to keep its weight equal to the aerodynamic drag throughout the combustion process.

To carry out rapidly these experiments a small wind tunnel of the suction type was placed vertically* . (Fig.5). It also has a calibrated intake nozzle, lateral intakes and a lenticular throttle in order to have an easy and rapid control of the wind speed.

The firebrand is held with a thin steel wire provided with a counter-weight. Wind speed is continuously reduced as the firebrand burns keeping the wire in a horizontal position.

With this tunnel placed horizontally and with a scale the first experimental results were obtained (Ref.9)

Suction blower

Lateral intake

Throttle

Micromanometer

Throttle control

Lateral intake control

Counter-weight

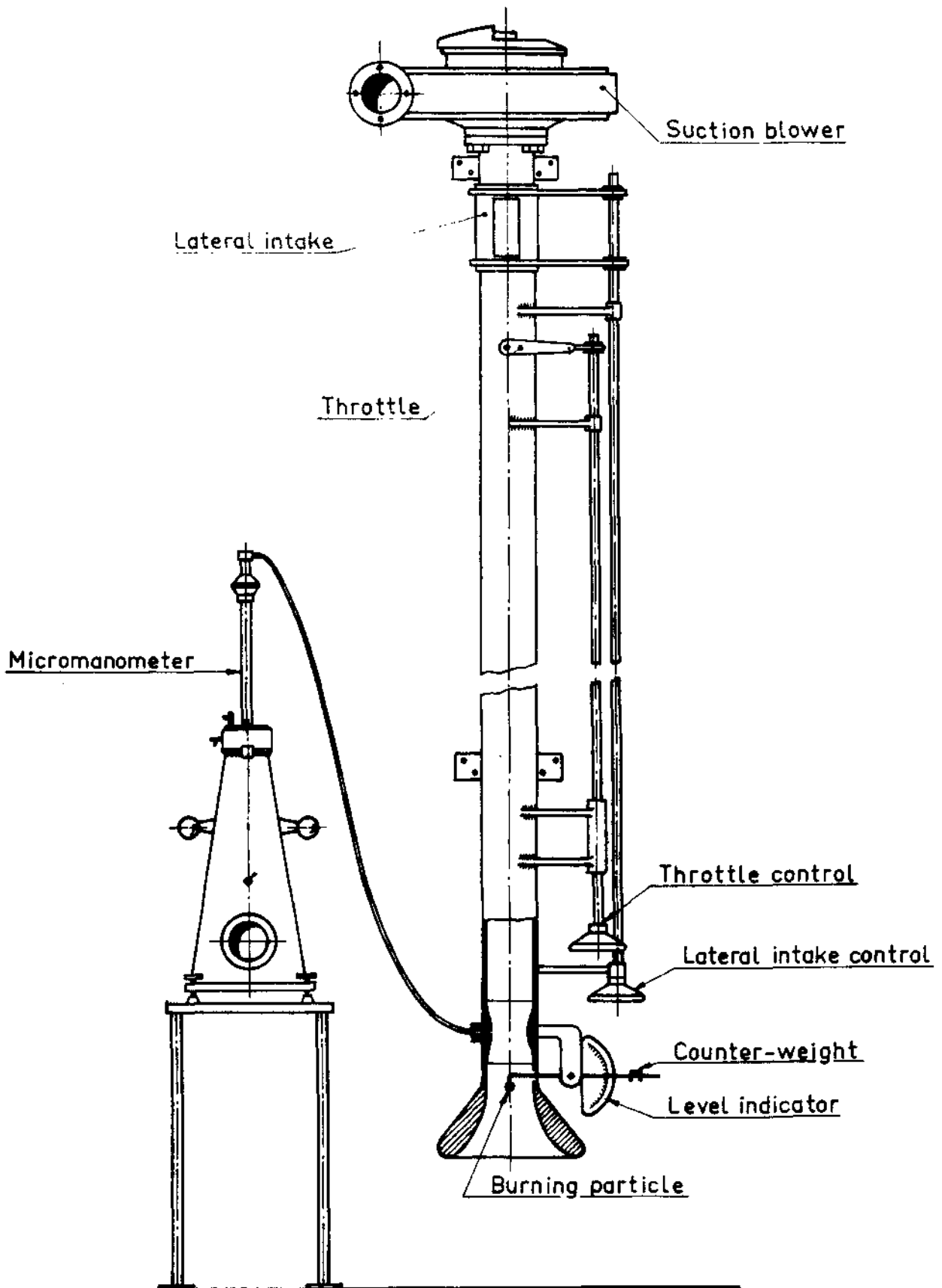Level indicator

Burning particle

Fig.5 - Vertical Wind-Tunnel

In this way curves of the final velocity of fall as function of time as well as burning out times are rapidly obtained.

In the horizontal large tunnel a simple device was incorporated in order to be able to carry out easily these type of experiments. It consists (Fig.6) of a wire with a counter weight provided with a damping mechanism of the oscillations and with an aerodynamic cowling (not shown in the figure) covering the device and the wire up to the vicinity of the firebrand.

Since the air velocity is horizontal, the firebrand is kept during the combustion process at its final velocity of fall if the wire is constantly mantained at an angle of 45° with respect to that horizontal direction. This is achieved by properly reducing continuously the wind speed throughout the combustion process.

In the final part of the research program another test facility was designed and constructed. It was decided to verify the possible influence of the free motion of the firebrand on the combustion process and, therefore, a new wind tunnel was designed and constructed in which the firebrands move free ly within an air current as they burn.

The wind tunnel is shown in Fig.7. It consists of a vertical cone of 3000 mm in length of transparent plastic mate rial provided with an intake nozzle. The cone is attached to a cylindrical section of 1400 mm in length on top of which another smaller cone is placed supporting the suction centrifu gal blower.

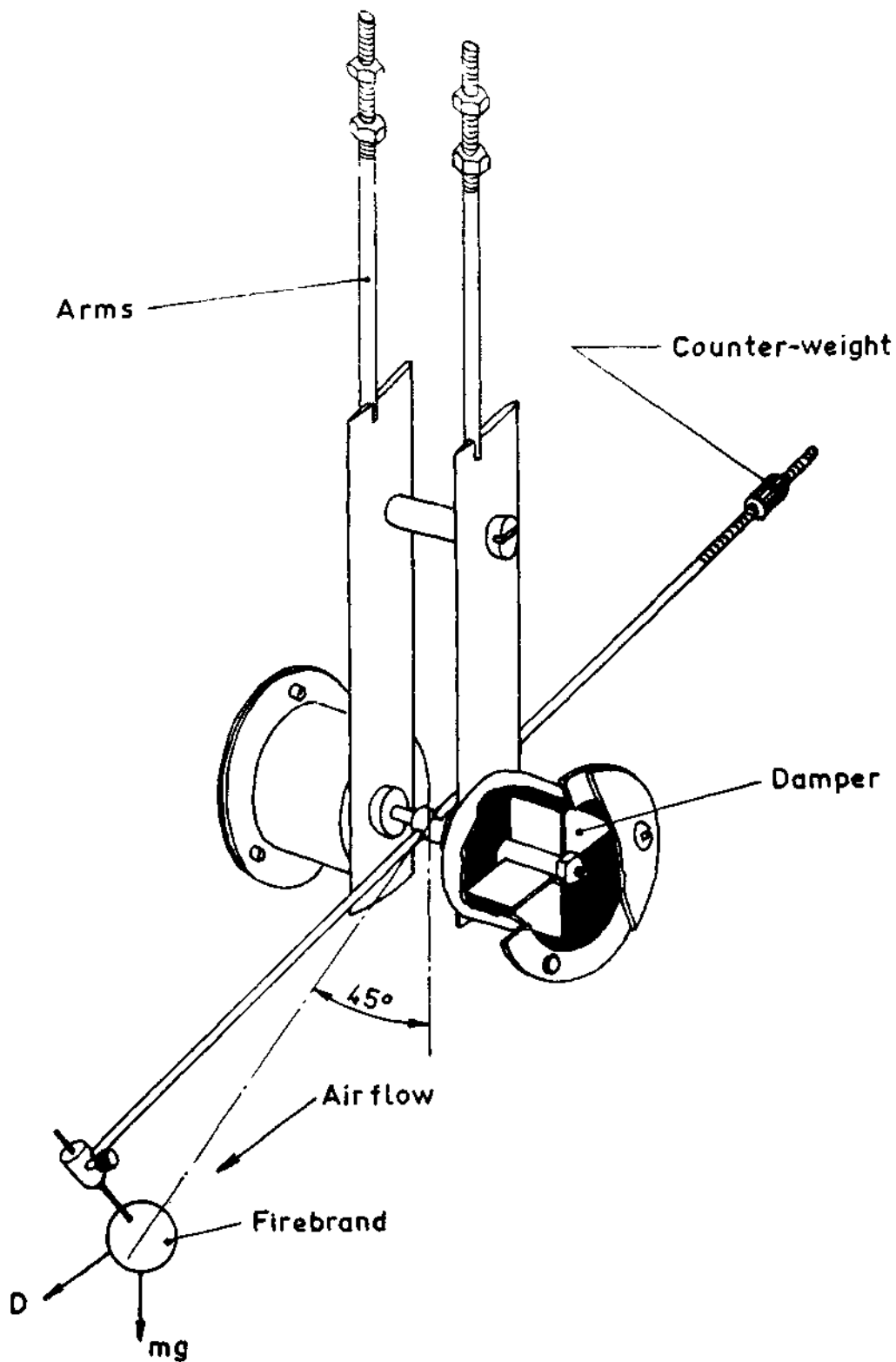The wind tunnel is calibrated by introducing in it

Fig.6 - Device for Burning Firebrands at Final Velocity
of Fall in the Horizontal Wind Tunnel

several wood spheres of different size. Their final veloci-
ties of fall are known, and the spheres become distributed
along the cone according to size, giving an indication of the
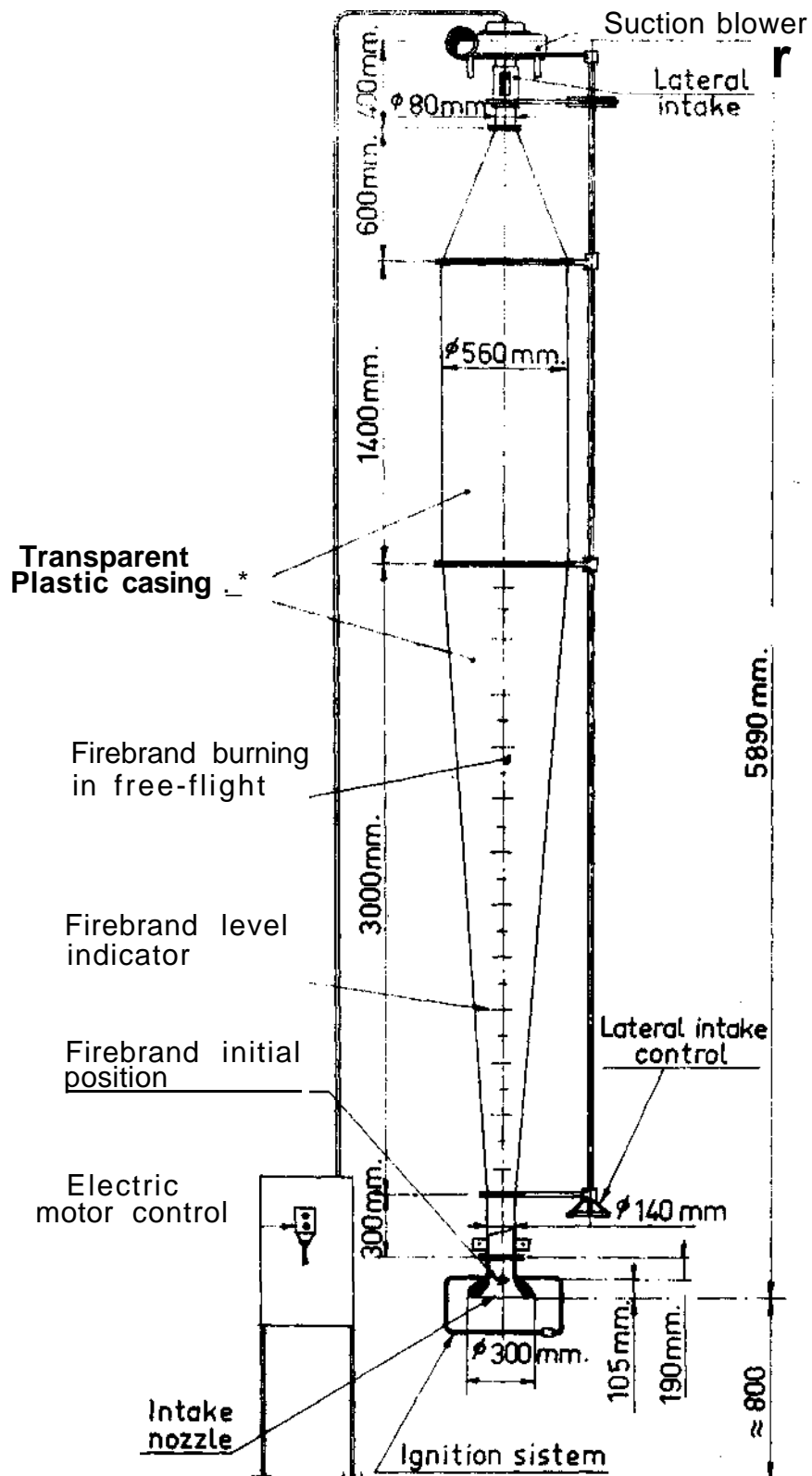average value of the air velocity at each location.

When a firebrand is introduced through the lower in-
take it climbs up as it 1 irns, and its final velocity of fall
is recorded by comparison with that of the sphere with the
same average location or by taking photographs.

At first, the wind tunnel had a high degree of vorti-
city and the firebrands had a strong tumbling motion. This ef
feet was reduced to tolerable limits after several modifica-
tions.

By taking long exposure time photographs, the effect
of tumbling can be avoided, since these photographs give the
average location of firebrands as function of time.

In this way it is possible to measure terminal veloci-
ties of fall and results agree well with those obtained with
the vertical or horizontal wind tunnels in which the fire-
brands were kept attached at a fixed position.

However, with this tunnel measurements of terminal ve-
locities of fall are lenghty and somewhat difficult due of
the unavoidable tumbling motion of firebrands. On the other
hand, the tunnel is extremely useful for measuring burning-
out times of firebrands. Measurements simply consist in
checking the elapsed time since the firebrand is introduced
through the lower intake till it is consumed, usually at the
cylindrical section in which air speed is very low.

Suction blower

Lateral intake

r

φ80mm.

600 mm. 20mm.

φ560 mm.

1400 mm.

Transparent Plastic casing .ᵀ*

5890 mm.

Firebrand burning in free-flight

3000mm.

Firebrand level indicator

Firebrand initial position

Lateral intake control

Electric motor control

300mm.

φ140 mm

φ300 mm.

105 mm.

190 mm.

800

Intake nozzle

Ignition sistem

7 - Vertical Wind Tunnel for Burning Firebrands in Fr
Flight Conditions

Figs . 8 and 9 show some examples of typical experimental results obtained at the beginning of the research program by burning firebrands at constant wind speed. In Fig.8 the laws of variation of the weight and aerodynamic drag of a spherical firebrand are shown as function of time. Fig. 9 shows the variation of the weight of a firebrand as function of time for several wind speeds. The weight changes rapidly at first and then it decreases slowly.

Finally, the photograph of Fig.10 shows a firebrand burning in the small wind tunnel. When the air speed is low, a flame exists in the first part of the combustion process and afterwards it extinguishes and combustion continues as a glowing process. At high air speeds there is no flaming and all combustion occurs as a glowing process.

<+.   SOLUTION OF THE SYSTEM

Solution of system (11), (12) is very involved because parameter a is a complicated function of both w and t .

If an average value of parameter a is taken an analytical solution is easily obtained, and in Ref.[10] it is shown that these non-burning particles approach very rapidly their final velocities of fall given by conditions:
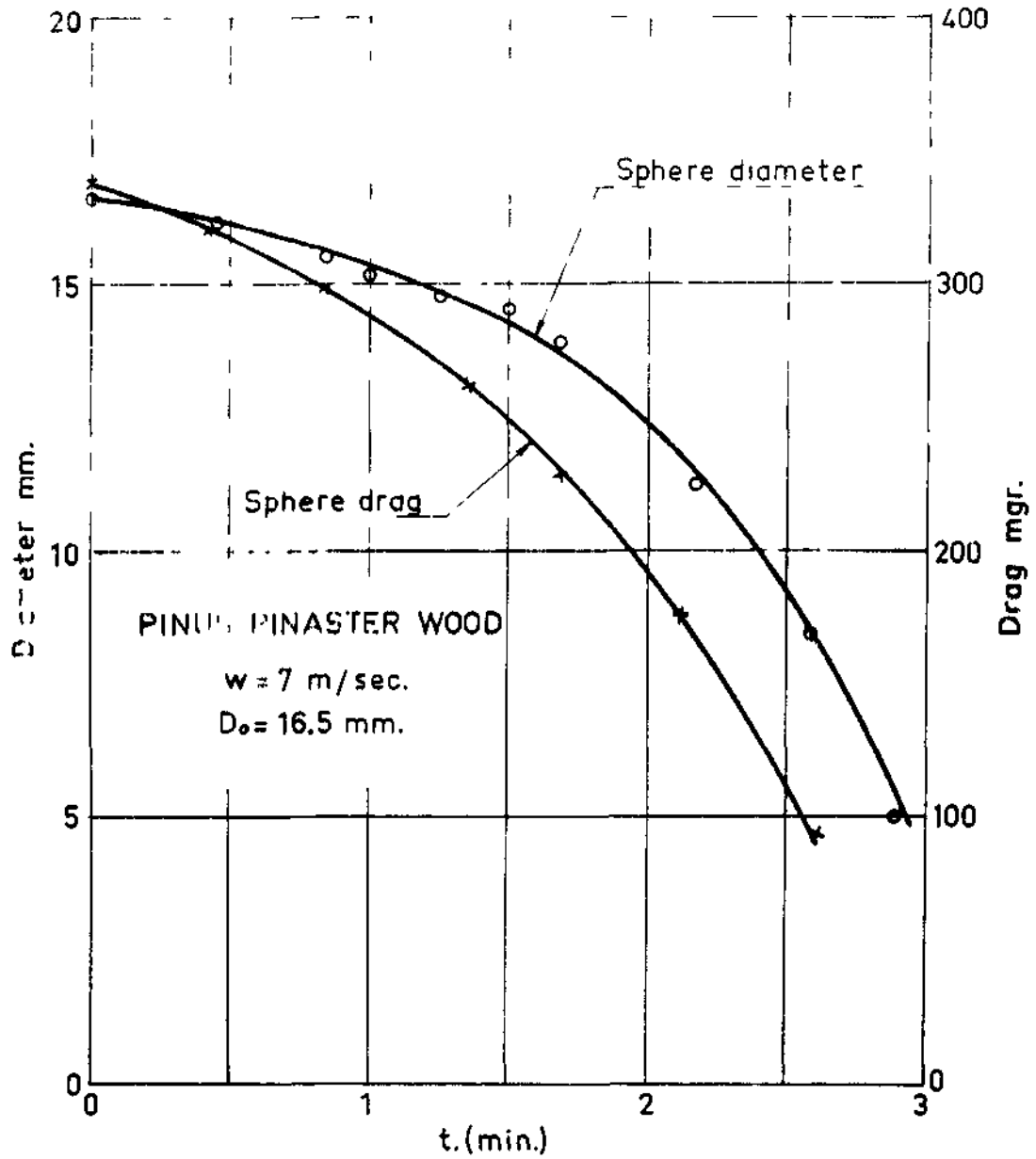
$$w_x = 0 \tag{16}$$

$$w_y = w_f = \left(\frac{f-M}{a}\right)^{1/2} \tag{17}$$

Fig.8 - Aerodynamic Drag of a Burning Sphere of Pine-Wood,

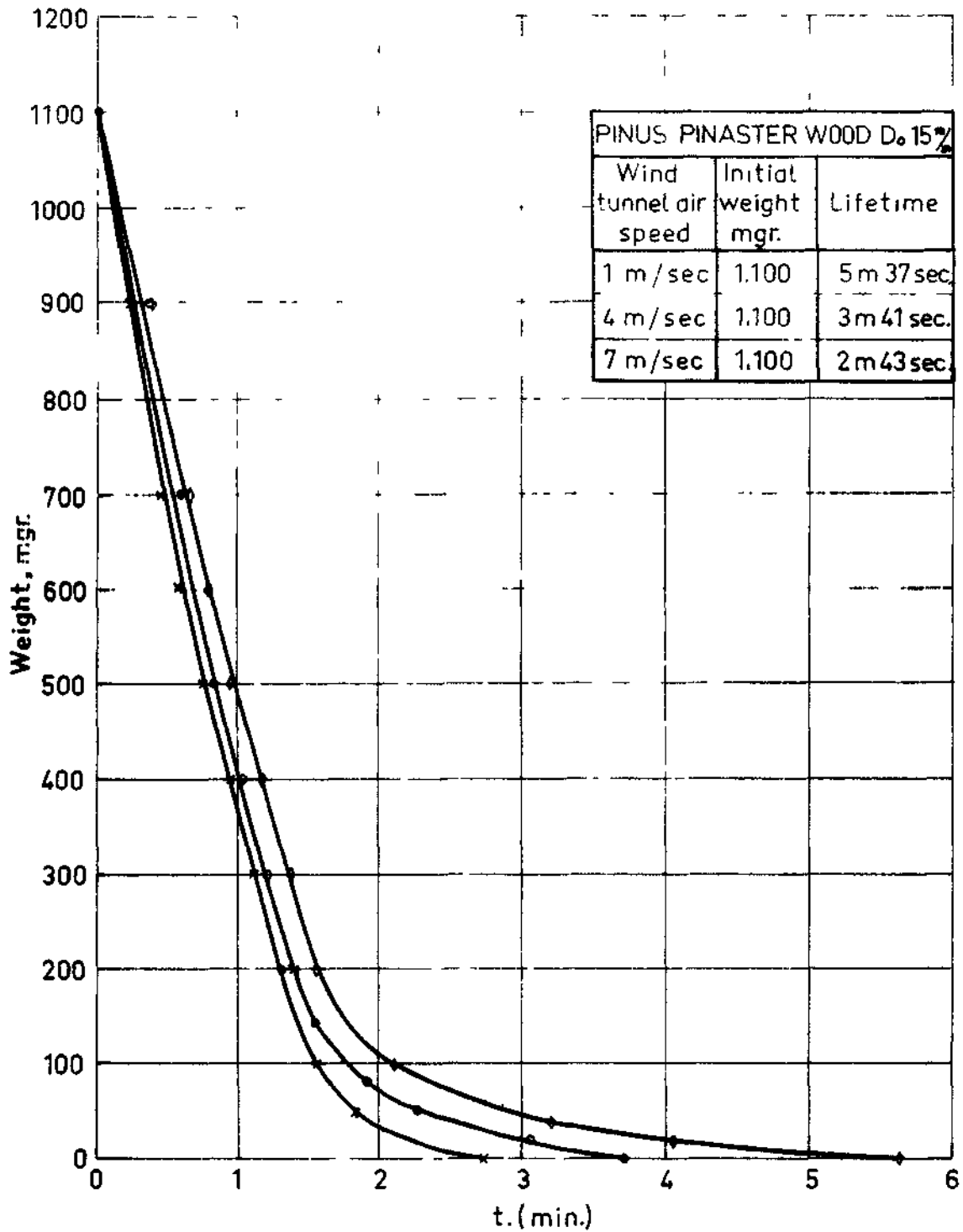| PINUS PINASTER WOOD D₀ 15%		
Wind tunnel air speed	Initial weight mgr.	Lifetime
1 m/sec	1.100	5 m 37 sec.
4 m/sec	1.100	3 m 41 sec.
7 m/sec	1.100	2 m 43 sec.

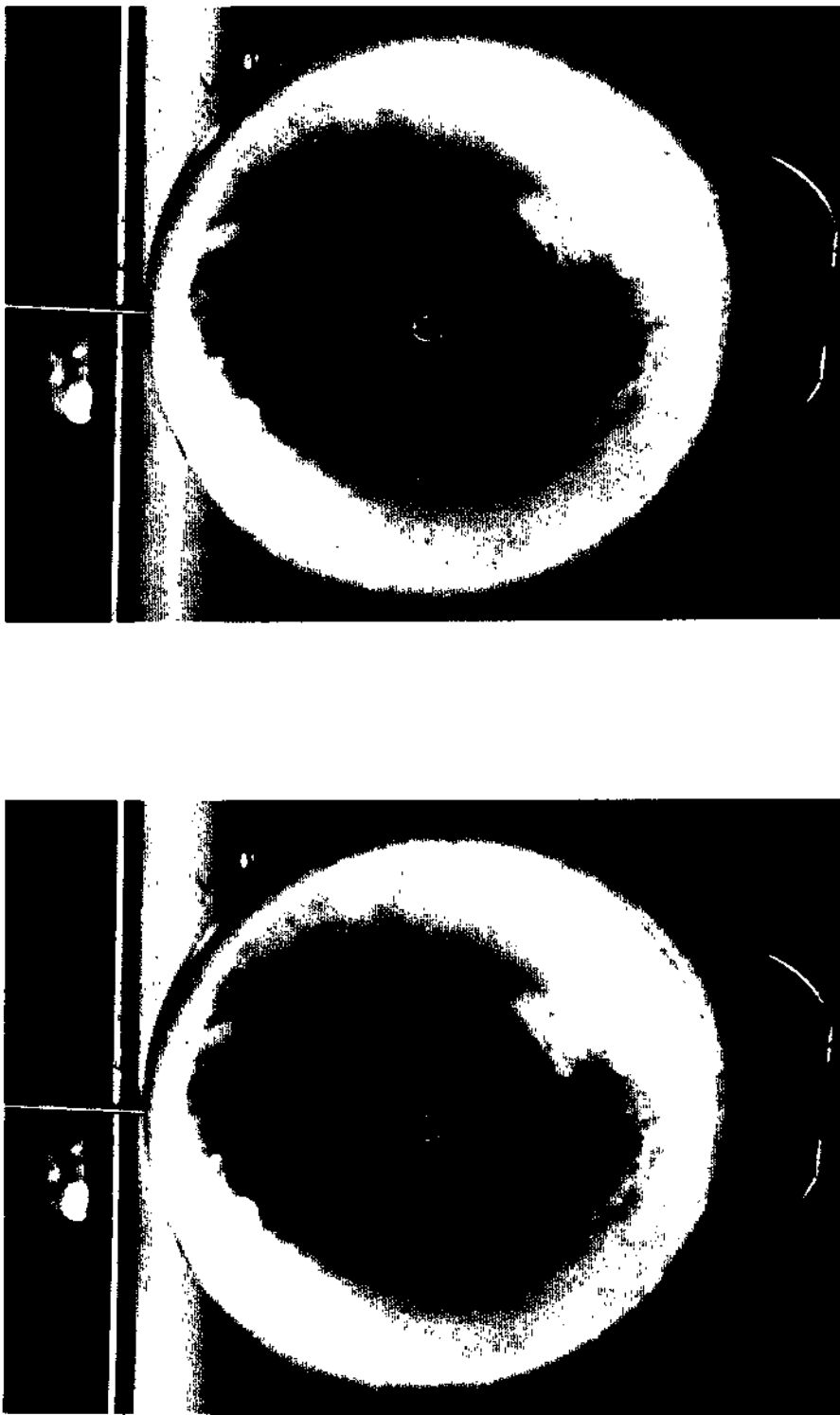Fig.9 - Weight-Time Curves of Burning Spheres of Pine-Wood

Fig.10. Photographs of firebrands burning in the small wind tunnel.
a): flaming, b): glowing.

Parameter a increases with time and it depends weakly on relative wind speed w . Therefore, the asymptotic solution of eq.(11) when a is variable is also w = 0 . For this condi- tions it is easily shown that the asymptotic solution of eq. (12) is also given by:

$$w_y \longrightarrow w_f = \left(\frac{g}{\alpha(w,t)}\right)^{1/2} \qquad (18)$$

By means of numerical integration of system (11)-(12), which may be carried out readily with the experimental values of a , it can be verified that velocities w_x and w_y tend very rapidly towards their asymptotic values.

In Figs. 11 and 12 two representative cases are shown. The firebrands are of "pinus pinaster" wood with initial diame_ ters of 17 mm and 25 mm. An initial value of $w_{x,o} = 20$ m/sec has been taken and for the vertical component of velocity two cases have been considered: $w_{y,o} = 20$ m/sec and $w_{y,o} = 0$. The first case would correspond to the initial flight condi- tions of a firebrand carried upwards by the convection column produced by the fire. The second case would correspond to a firebrand leaving the convection column at a certain height and being thrown into a horizontal wind at a zero vertical com ponent of its velocity.

The experimental values of the terminal velocities of fall are also shown in the figures. It may be seen that in all cases in a matter of seconds both components of the veloci ty, w and w , tend very rapidly towards zero and towards w.p respectively.
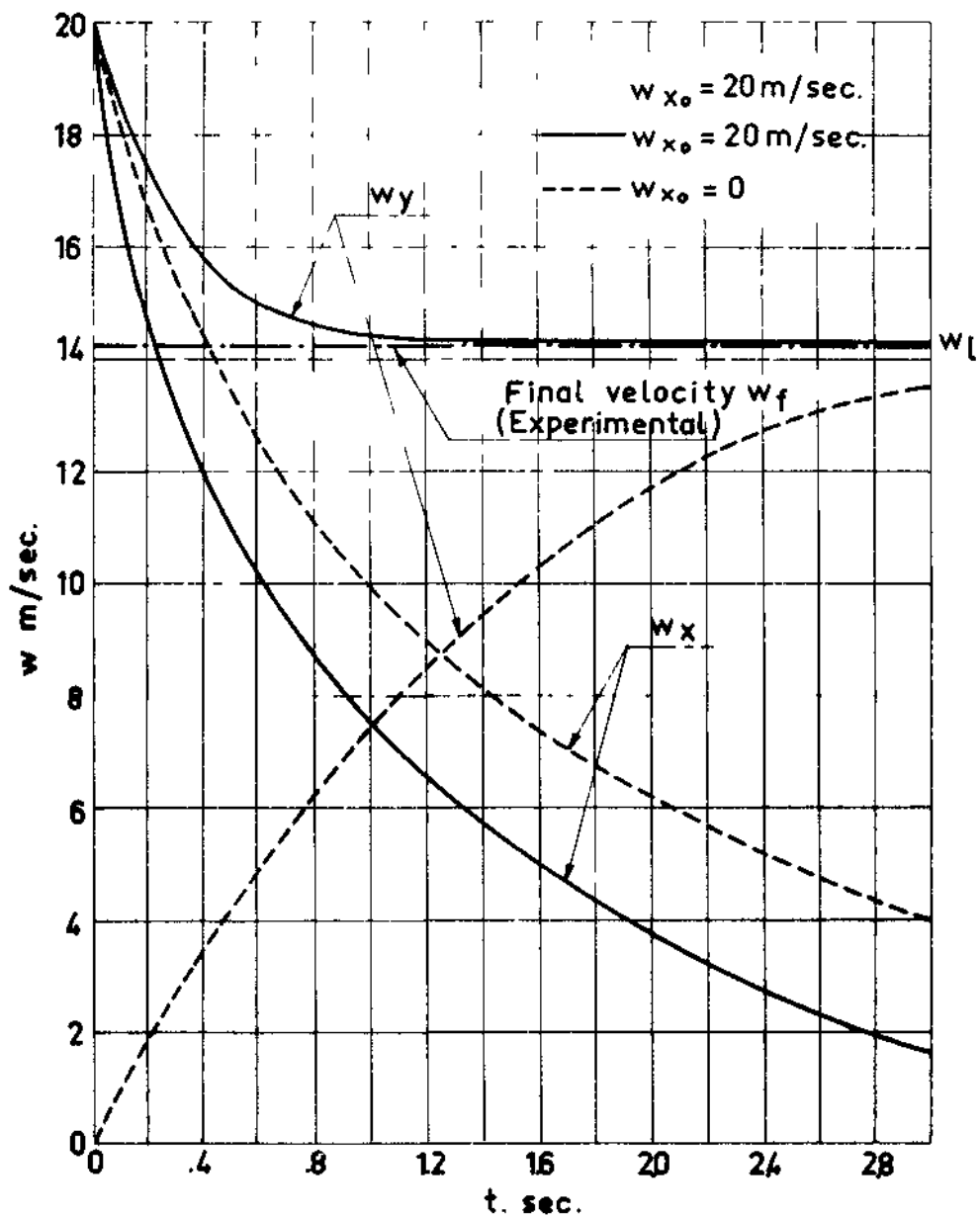
These times are compared in Fig.13 with the burning-

Fie.11 - Calculated Velocity **Components** w   and   w   and **Ex-**
perimental Final **Velocity of Fall** w_ .' **Spherical**
Firebrand of Pine **Wood.** D =1 7 mm, t, = 140 sec.

out times, which are two orders of magnitude greater than the time required for the firebrand to approach the asymptotic ve locity values.

Therefore, in order to calculate the flight paths it will be admitted the assumption that the firebrands fly all the trajectory at the final velocity of fall.

In order to estimate the possible errors introduced b this simplifying as sumptions, upper bounding or majorant expre sions W_x and W_y for w_x and w_y were obtained,

They were derived considering that:

$$- \frac{dw_x}{dt} = \alpha w w_x \geq \alpha_o w w_x \qquad (19)$$

$$- \frac{dw_y}{dt} = \alpha w w_y - g \geq \alpha_o w w_y - g \qquad (20)$$

$$\left(\text{for} \quad w_{y,o} > \left(\frac{g}{\alpha_o} \right)^{1/2} \right) \quad ,$$

and integrating analytically equations (11) and (12) for $a = a_o$ (Ref.[10]). It is obtained:

$w_{xo} = 20 \, m/sec.$

$wy_o = 20 \, m/sec.$

$wy_o = 0$

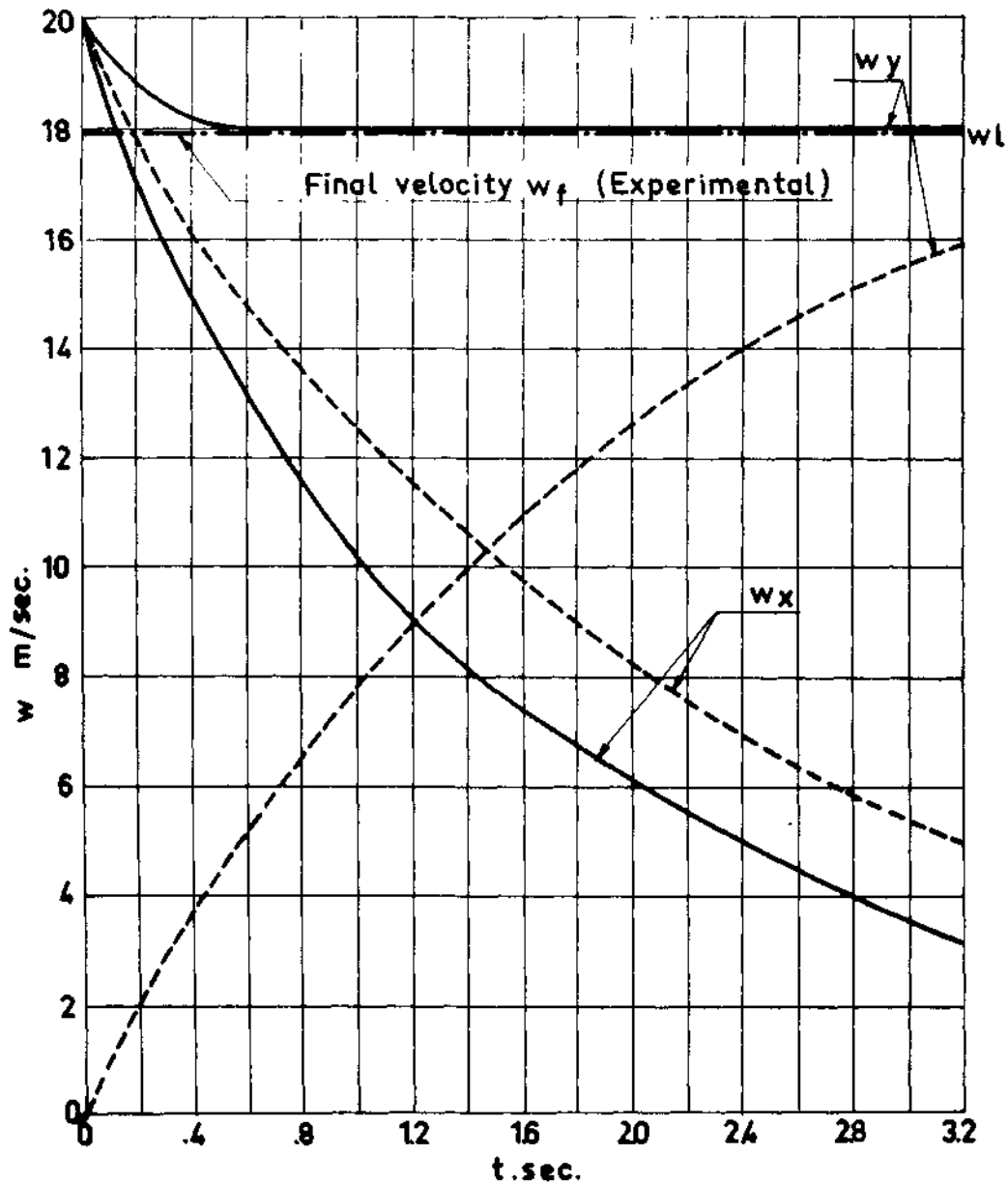**Fig. 12 - Calculated 'Velocity Components** w_x **and** w_y **and Ex-peridental Final Velocity of Fall** w_f **. Spherical Firebrand of Pine Wood.** $D_o = 22$ mm, $t_D = 195$ sec.

$$w_x \lessgtr W_x = \frac{2(g/\alpha_o)^{1/2}\,\exp\left[-(g\alpha_o)^{1/2}\,t\right]}{(g/\alpha_o)^{1/2} + w_{y,o} - \left[w_{y,o} - (g/\alpha_o)^{1/2}\right]\exp\left[-2(g\alpha_o)^{1/2}\,t\right]}$$

$$(21)$$

$$w_y - (g/\alpha)^{1/2} \lessgtr W_y - (g/\alpha_o)^{1/2} =$$

$$= \frac{2(g/\alpha_o)^{1/2}\left[w_{y,o} - (g/\alpha_o)^{1/2}\right]\exp\left[-2(g\alpha_o)^{1/2}t\right]}{(g/\alpha_o)^{1/2} + w_{y,o} - \left[w_{y,o} - (g/\alpha_o)^{1/2}\right]\exp\left[-2(g\alpha_o)^{1/2}t\right]}$$

$$(22)$$

With these expressions it can be verified that the time re-
quired by the firebrands to reach velocities very close to
their asymptotic values is always very small in all cases of
practical interest.

The errors introduced in the calculations of the flight
paths by this simplificatory assumption are even smaller.

The errors of the horizontal and vertical paths may be
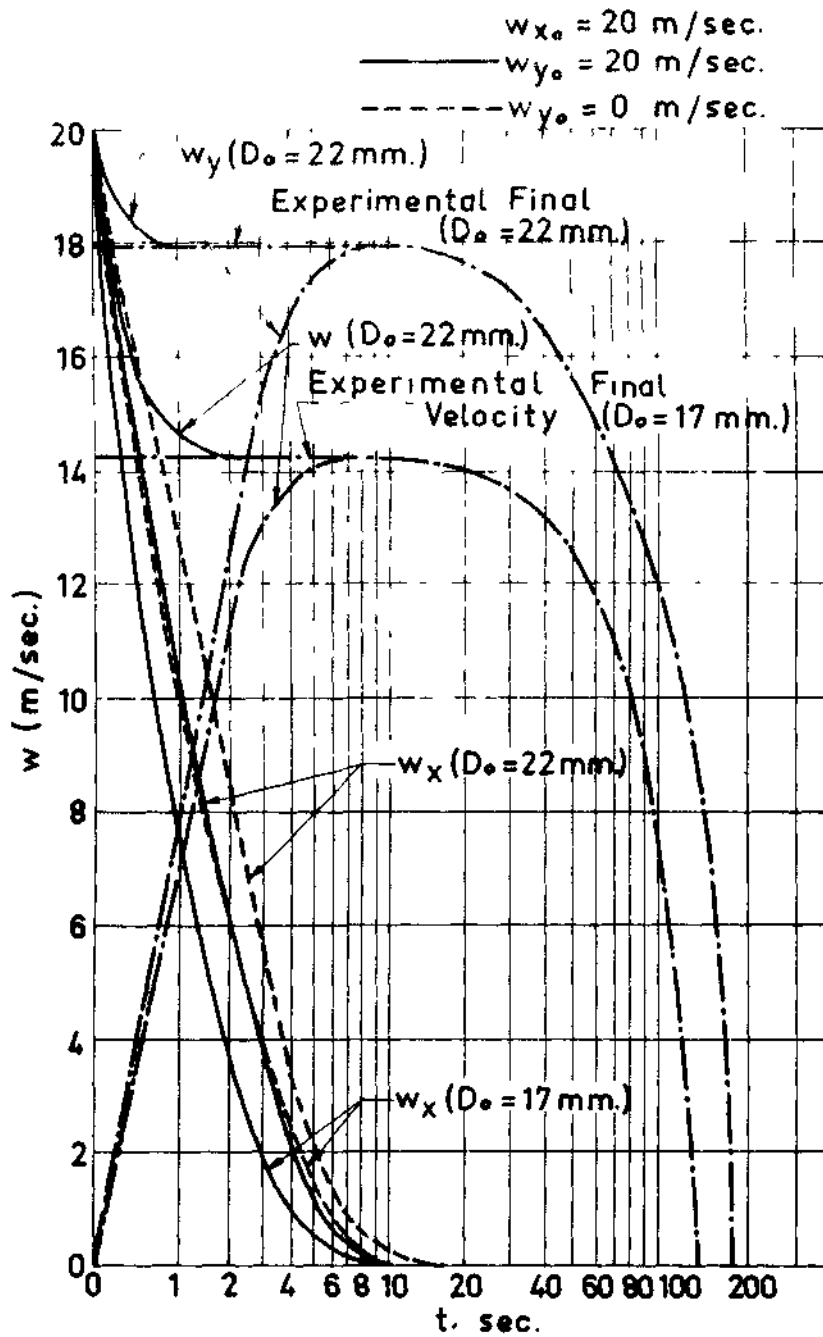defined in the form :

$w_{x_0} = 20$ m/sec.

$w_{y_0} = 20$ m/sec.

$w_{y_0} = 0$ m/sec.

$w_y (D_o = 22$ mm.)

Experimental Final
($D_o = 22$ mm.)

$w (D_o = 22$ mm.)

Experimental
Velocity

Final
($D_o = 17$ mm.)

$w_x (D_o = 22$ mm.)

$w_x (D_o = 17$ mm.)

w (m/sec.)

t. sec.

Fig.13 - Comparison of Numerically Integrated Values of w
and w and Experimental Final Velocities of Fall.
y

$$\epsilon_x = \frac{\int_0^{t_f} w_x \, dt}{\int_0^{t_f} (u_x - w_x) \, dt} \simeq \frac{\int_0^{t_f} w_x \, dt}{u_x \, t_f} \qquad (23)$$

$$\epsilon_y = \frac{\int_0^{t_f} (w_y - w_f) \, dt}{\int_0^{t_f} (u_y - w_y) \, dt} \simeq \frac{\int_0^{t_f} (w_y - w_f) \, dt}{u_y t_f - \int_0^{t_f} w_f \, dt} \, . \qquad (24)$$

Taking the expressions of w_x and w_y given by (2 and (22) into the above formulas, it can be verified that these errors are extremaly small provided that the wind i not too low or the final time t_f not too small, but these cases are of no practical interest

By admitting this fundamental simplification that t firebrands fly all the time at their final velocities of fa the flight paths are given by the expressions:

$$X = \int_0^t u_x \, dt \qquad (25)$$

$$Y = \int_0^t (u_y - w_f) \, dt \qquad (26)$$

Therefore, the problem consists in determining the final

velocities w   as function of time with the experimental procedures discussed in paragraph 3 .

EXPERIMENTAL RESULTS

5 .1   Results Obtained in the Horizontal and Vertical Wind Tunnels

The research program comprised the study of different types of firebrands.   Their initial size and shape, kind of wood and moisture content are the parameters of the process.

Three geometrical configurations were selected: spherical, cylindrical and square plated firebrands, with initial sizes ranging from 5 to 50 mm in diameter or length.

Five kinds of wood were studied: pine wood ("pinus pinaster"), oak ("quercus rubra"), spruce ("picea excelsa"), aspen ("populus tremuloides") and balsa ("ochroma lagopus"). In addition, spherical, cylindrical and square-plates firebrands, of charcoal were also studied.

Moisture content of firebrands ranged from 2% (very dry) to 25% (very humid).

Finally, a number of experiments were also carried out with natural firebrands, especially with pine cones and pine brackets.

The largest part of the experiments consisted in the
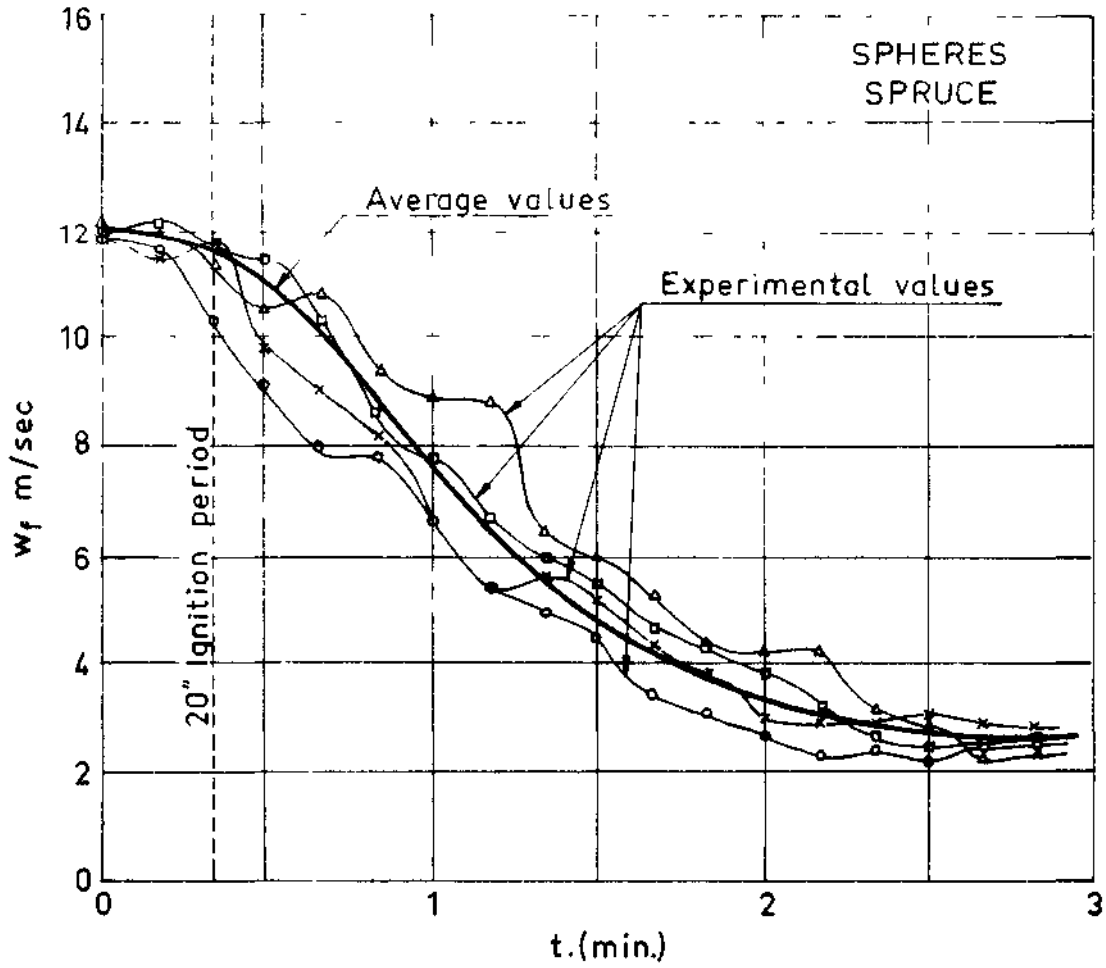
Fig.14 - Experimental and Average Values of Final **Velocities**
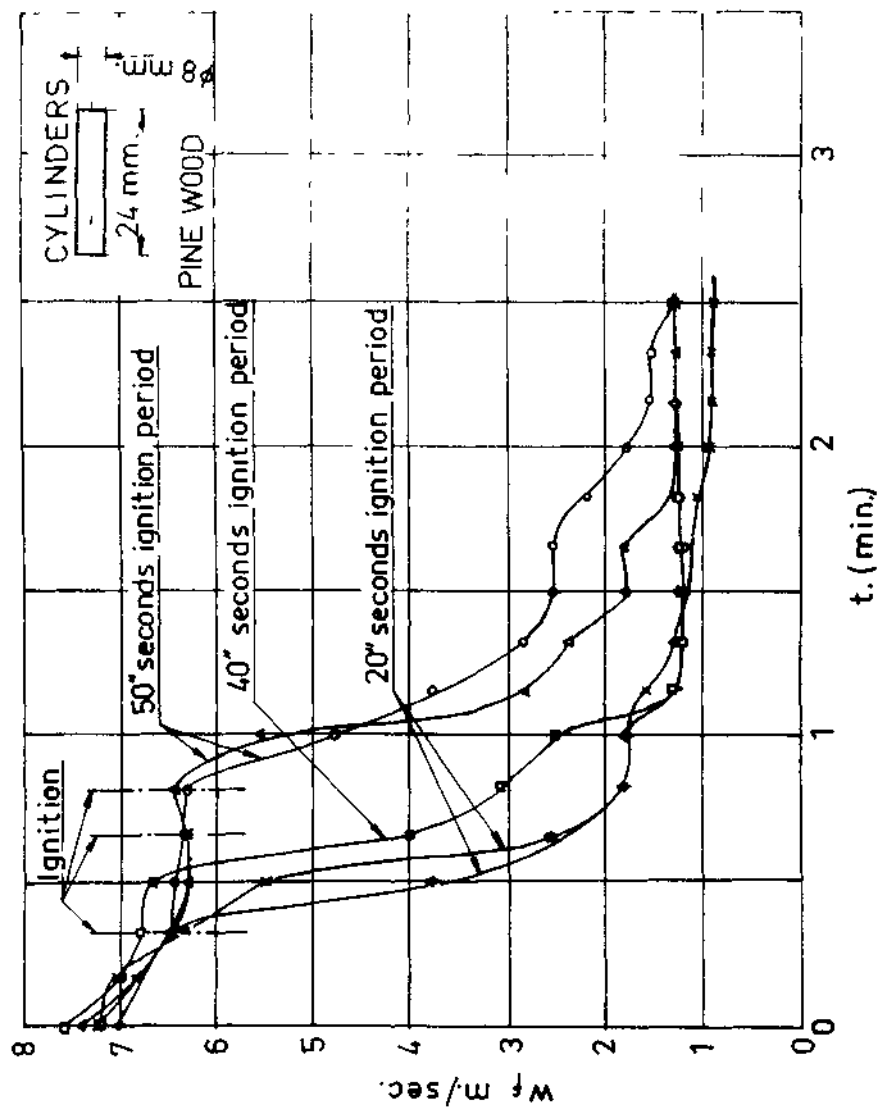of Fall as Functions of Time

Fig.15 - Influence of Ignition Time on Curves of Final
Velocities of Fall as Function of Time

determination of the terminal velocities of fall w,. as function of time as described in paragraph 4.

Due to the heterogeneous nature of wood results showed a certain scattering,and,therefore,it was necessary to repeat the experiments in order to obtain average values,as shown in Fig.14.

The initial shape of curves w,. = f(t) depends appreciably on the ignition process, since the gases of the ignition torch have a lower density than that of the ambient air. There **fore, when** the flame is taken out the final velocity of fall decreases suddenly. (Figs.14 and 15). Burning-out times depend also,to a certain extent, on ignition times.

The ignition of the firebrand introduces a subjective factor into the process. In order to reduce the effect of this subjective factor ignition times were made as short as possible, and identical ignition-times values were assigned to identical firebrands. In this way the influence of the ignition process on the flight paths and burning-out times of the firebrands could be avoided.

A very extense research program on final velocities of fall has been carried out, Results are shown in full in referen ces through 9 13 and will be included in dimensionless form in paragraph 8.

Some typical representative examples are shown in Figs. 16,17,18 and 19. Final velocities of fall are given for all kinds of wood, and for different sized cylindrical, spherical and square-plates firebrands; and for initial moisture contents of 2% and 25%.

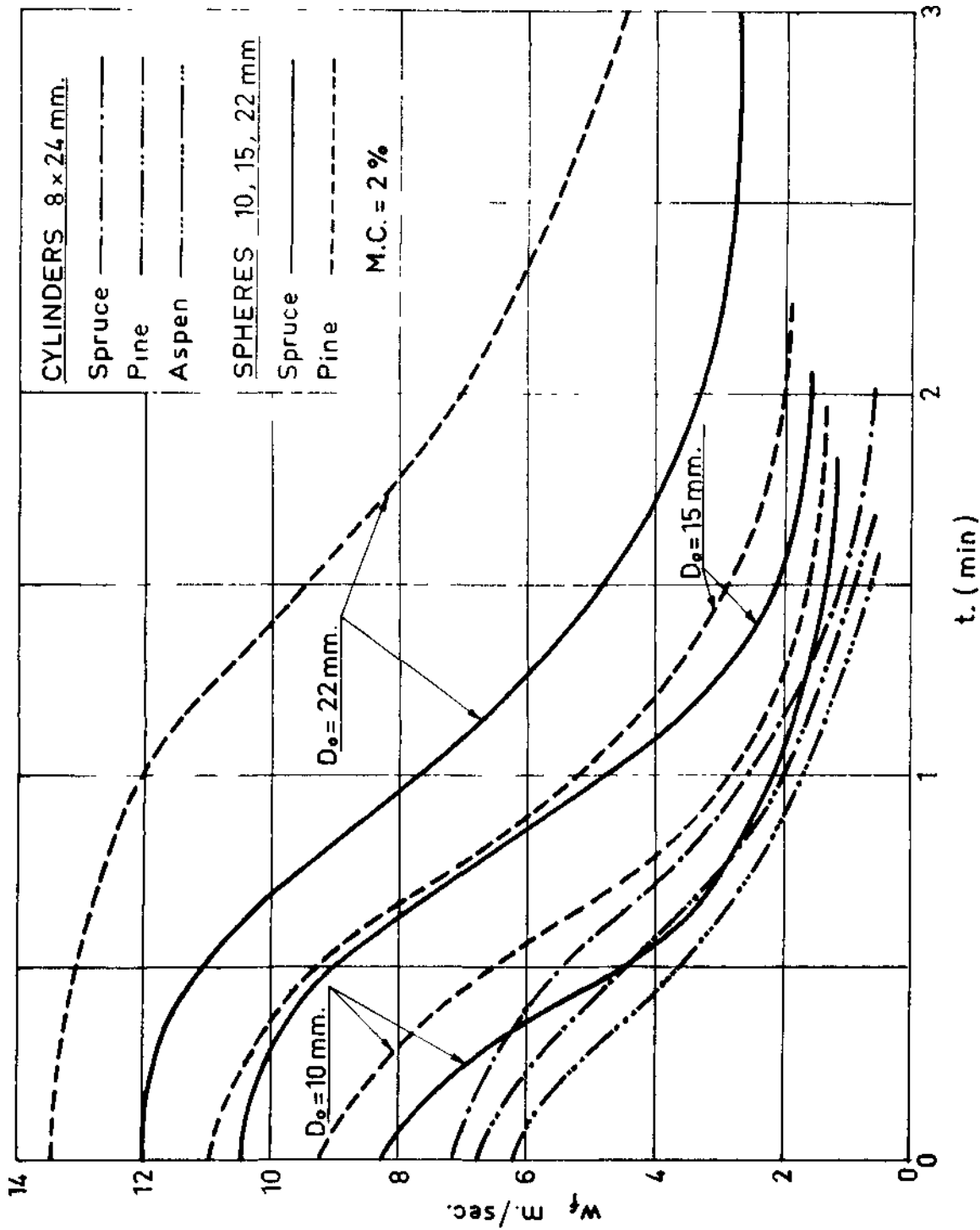Fig.20 shows similar results obtained with charcoal

Fig. 16 - Final Velocities of Fall, Cylindrical and Spherical Firebrands of Spruce, Aspen and Pine Woods.
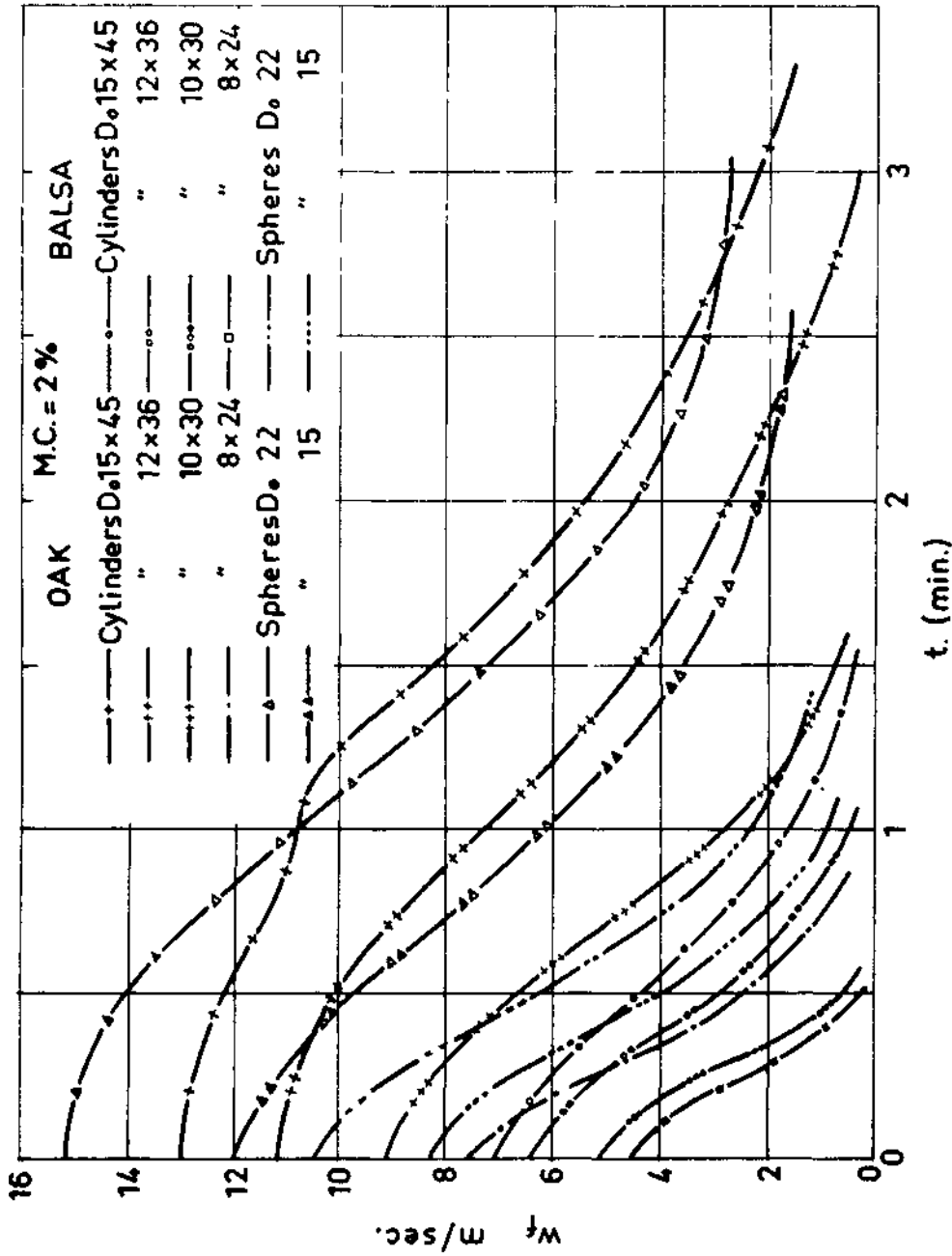
Fig.17 - Final Velocities of Fall. Cylindrical and Spherical Fire-
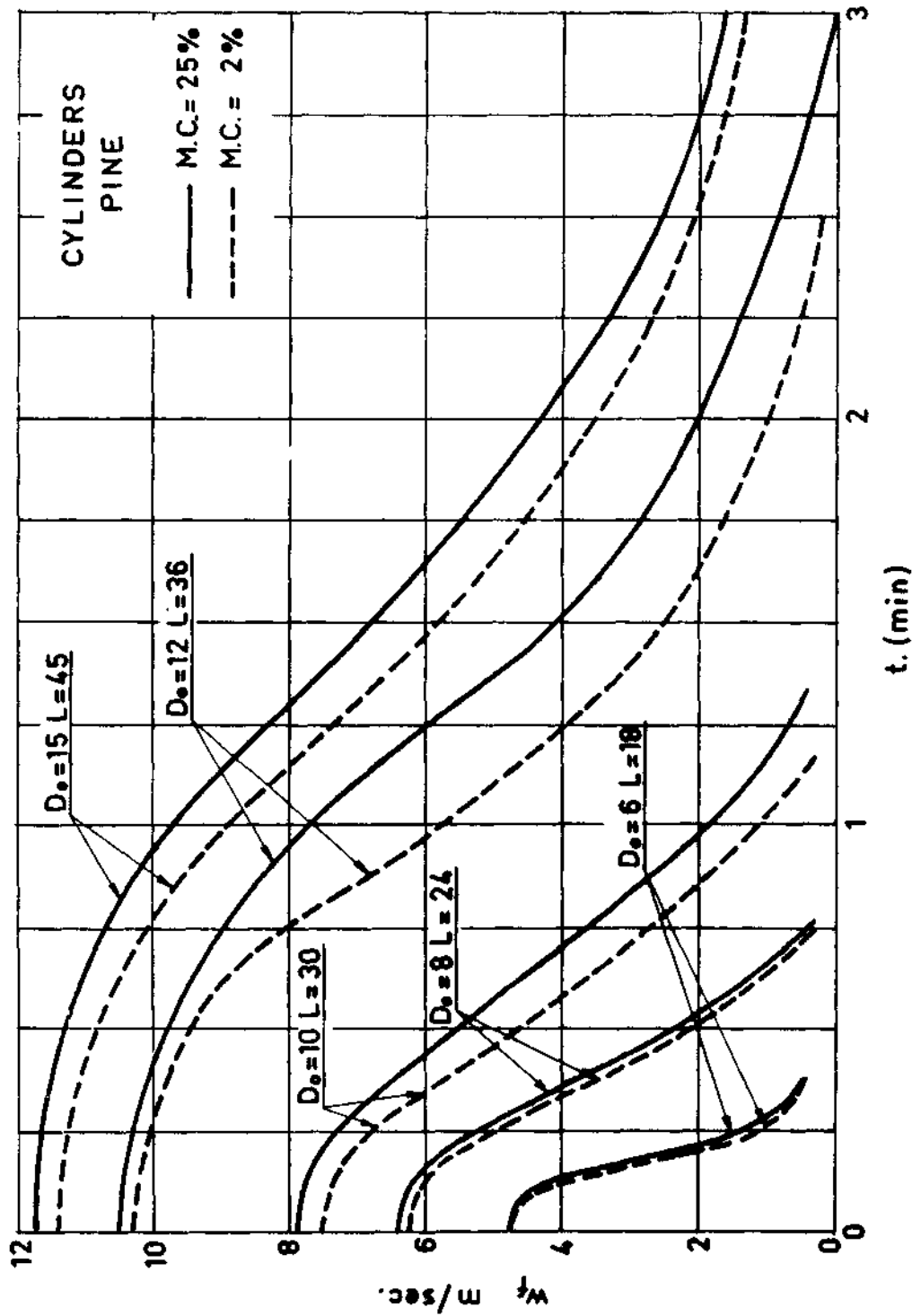brands of Balsa and Oak Woods.

Fig.18 - Final Velocities of Fall. Cylindrical Firebrands. Pine Wood.
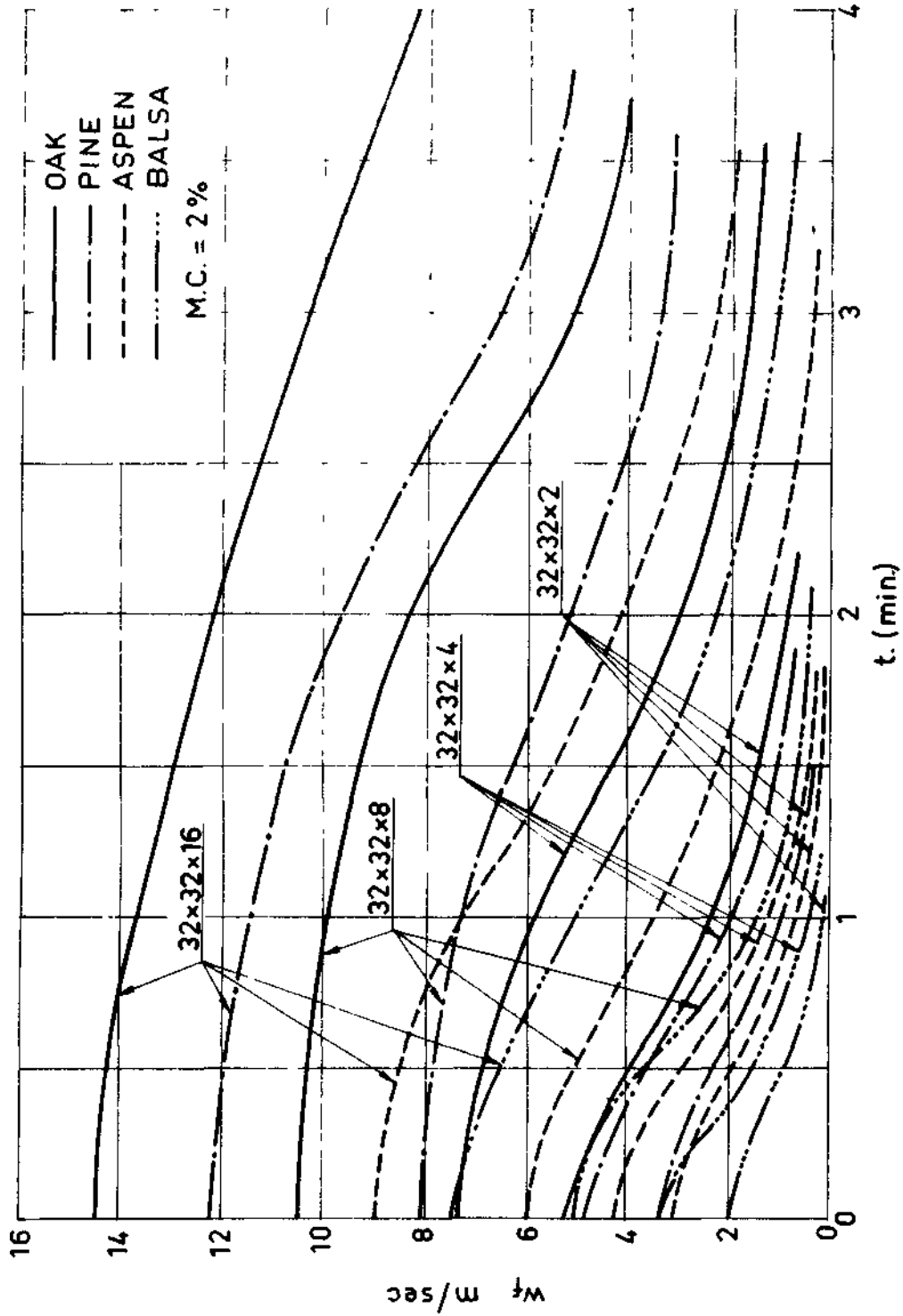Moisture Contents of 2% and 25%.

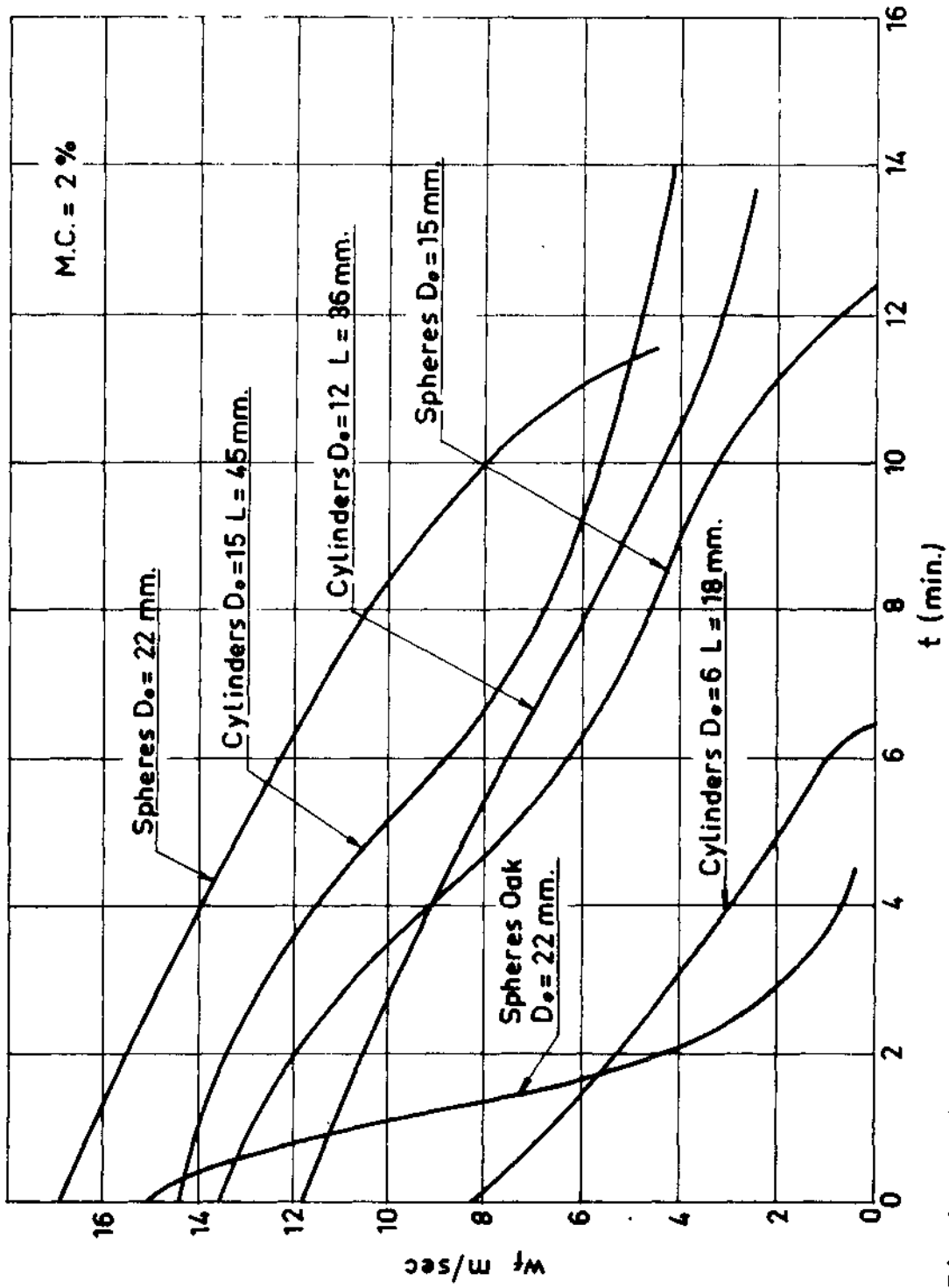Fig.19 – Final Velocities of Fall. Square Plates Firebrands of Oak, Aspen, Balsa and Pine Woods.

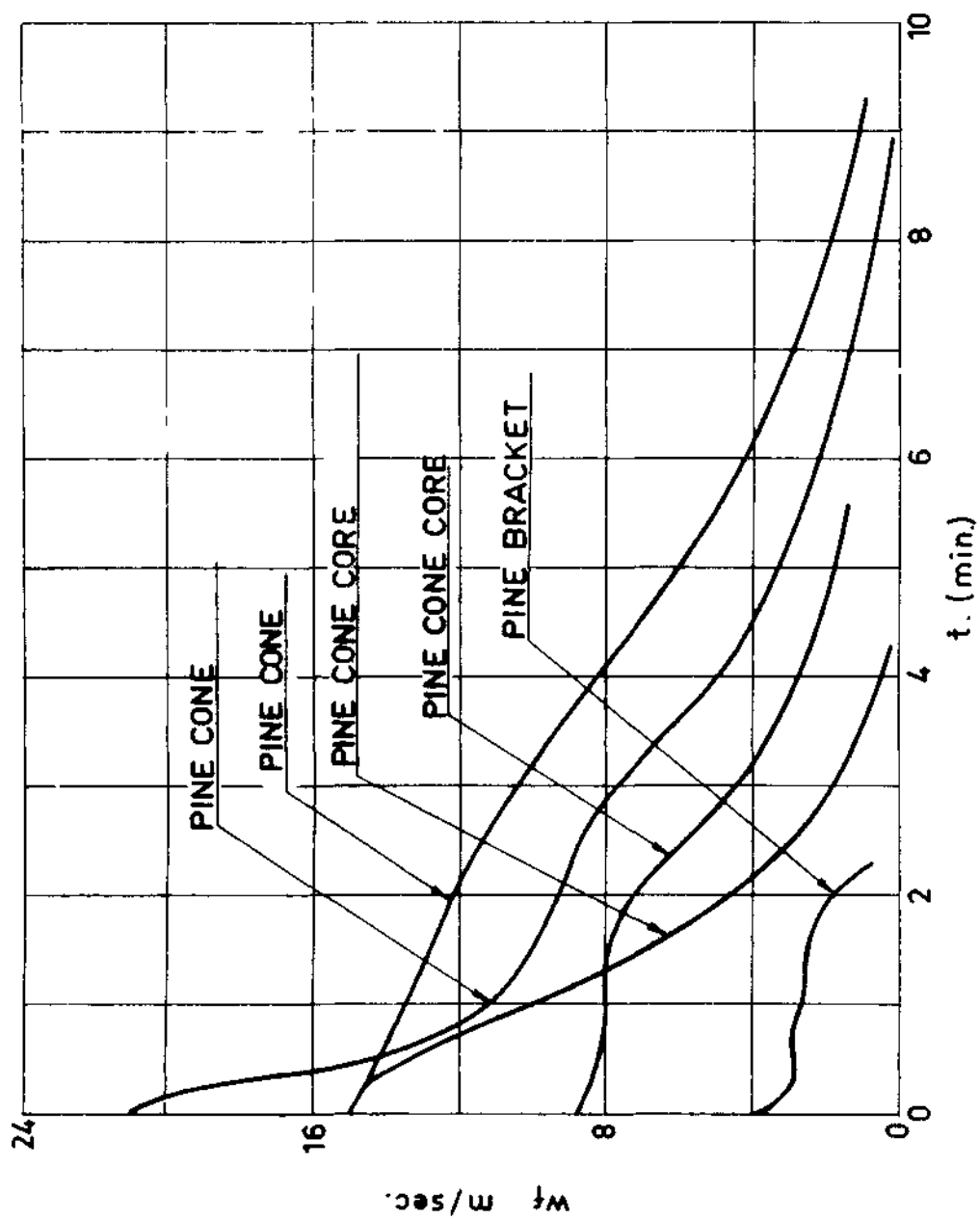Fig.20 – Final Velocities of Fall, Spherical and Cylindrical Charcoal
Firebrands

Fig. 1 - Fall ing velocities of Fall of Natural Firebrands.

Axis labels: Wf m/sec. (vertical), t. (min.) (horizontal)

Curve labels: PINE CONE, PINE CONE, PINE CONE CORE, PINE CONE CORE, PINE BRACKET
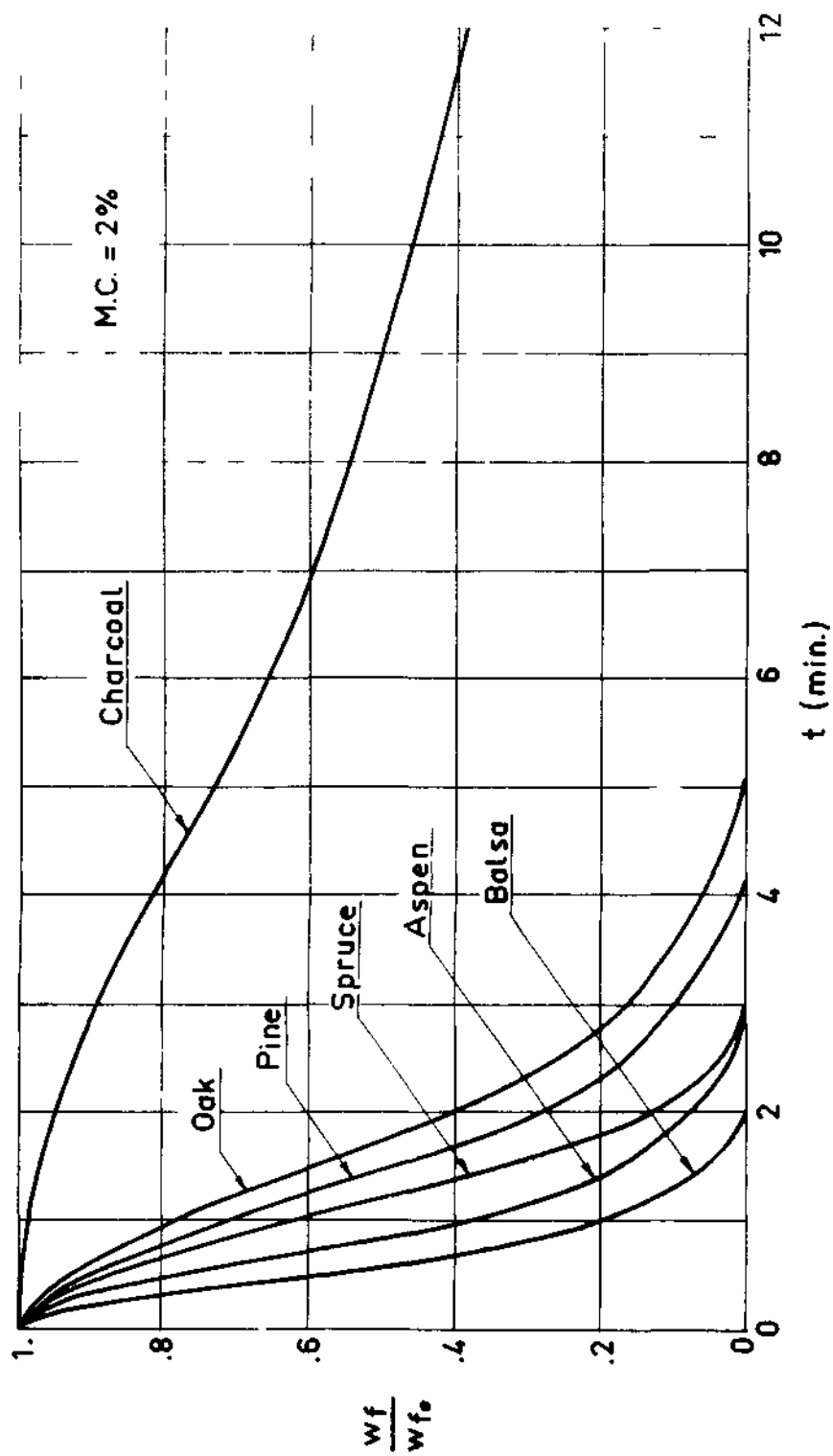
Fig. 22 - Final Velocities of Fall. Cylindrical Firebrands of Equal Size :
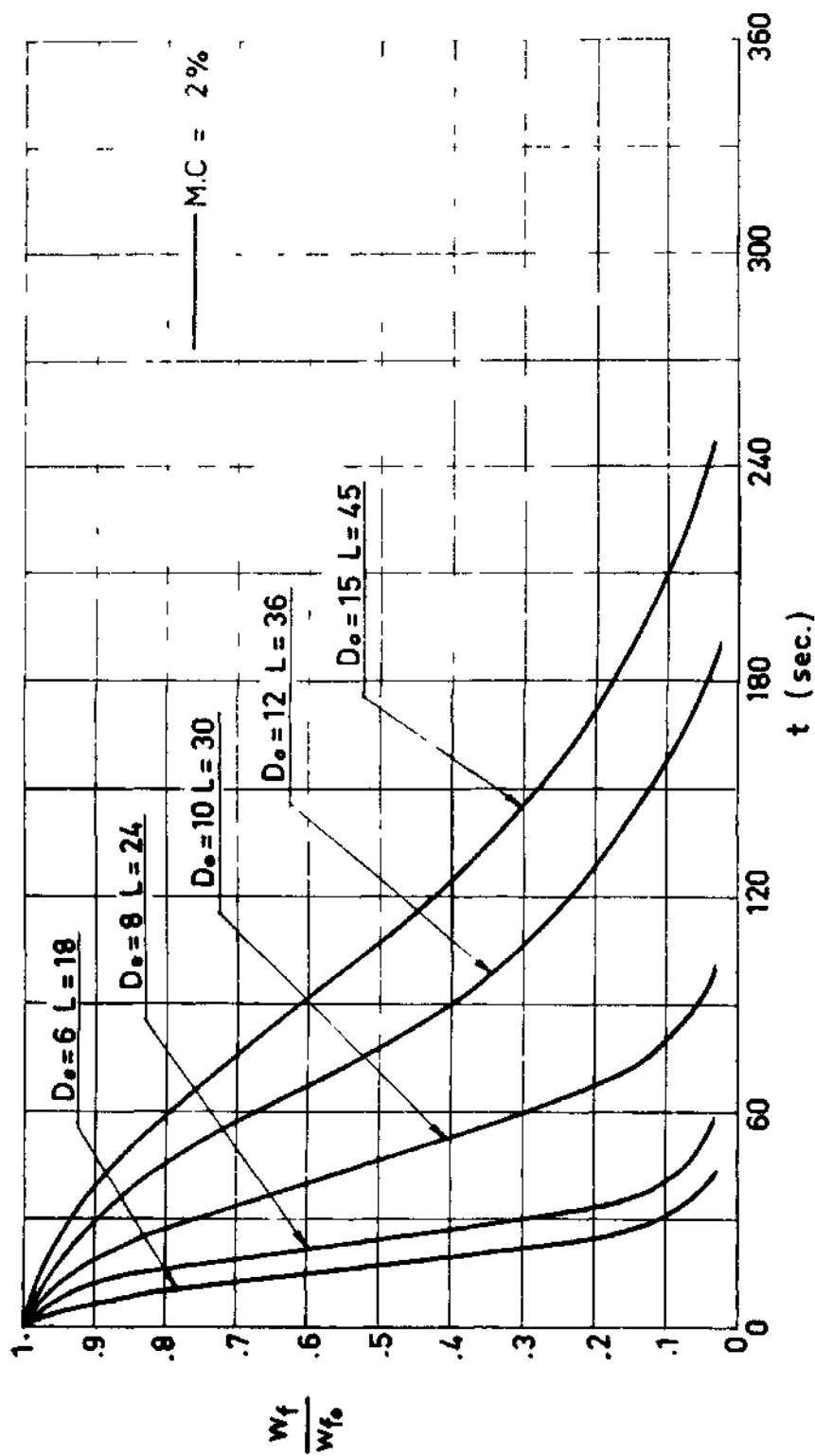Balsa, Aspen, Spruce, Pine and Oak Woods and Charcoal.

Fig.23 - Final Velocities of Fall, Cylindrical Firebrands.
Oak Wood. Influence of Size

firebrands, which were studied because of their very long burn
ing time, and in Fig.21 some results obtained with pine cones
and pine brackets are included. It may be mentioned that
brackets separate from burning pine cones after a short time,
and then they burned-out very rapidly. The remainder pine
cone core behaves very much like wood.

Comparison of results will be mainly carried out on the
basis of the maximum horizontal distance that a firebrand may
reach while still burning. However, some preliminary conclu-
sions can be derived. For example, it may be observed that
moisture content lengthens considerably the ignition process,
but after ignition it does not influence very much the combus-
tion process, at least for small and medium sized firebrands.

Fig.22 compares results with respect to size and Fig.
23 shows a comparison of results with respect to kind of wood.
There are some differences among the woods tested, but the more
significant result is the extremely long burning-out times of
charcoal firebrands.

5.2 Influence of the Free Motion of the Firebrands

All results reported in the preceeding paragraphs were
obtained in either the horizontal or the vertical wind tun-
nels, with the firebrands being held in a fixed position as
they burn.

Cylindrical firebrands were held with their axis per-
pendicular to the wind and plate-shaped firebrands with their
largest surface perpendicular also to the wind tunnel longitu-
dinal axis. These are the positions of maximum drag and they
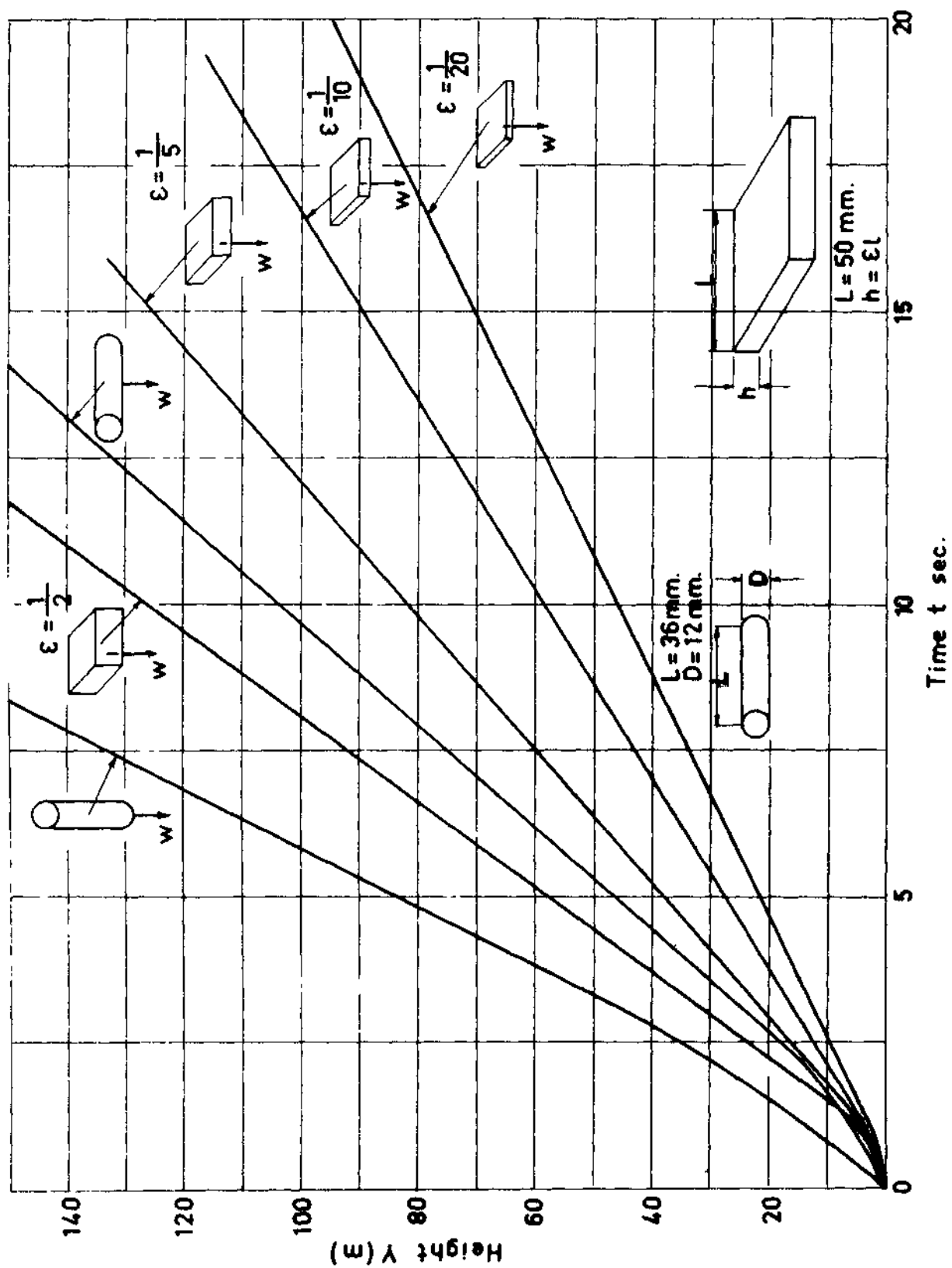
Fig.24 - Calculated Free-Fall Times of Different Shaped Pieces of Pine Wood.

also are the positions of maximum stability in a free-fall.

However, it was considered the possibility that the aerodynamic drag of firebrands moving freely in the air might differ appreciably from the measured aerodynamic drag when thev are held at rest in a wind tunnel.

Therefore, a study was made on this possible source of error. The free fall times in still air of cylinders and square plates of wood of several sizes were calculated for the positions of maximum and minimum aerodynamic drag (Fig.24).

At the same time drop tests were performed of the cyl inders and plates by using a meteorological balloon. In the first place, free fall times of 12 x 36 mm cylinders of pine wood were measured at heights of 100 and 200 meters, first droping the cylinders one by one and afterwards droping 100 cylinders at the same time from a metallic box attached to be balloon*. (See Fig.25).

The following results were obtained:

a)   The cylinders always fell tumbling.

b)   The measured falling times of the cylinders were of the same order of magnitude than those calculated for the posi tion of maximum drag. The errors were smaller than a 10%.

c)   When the 100 cylinders were dropped there were an impor- tant horizontal dispersion but they fell in times difer- ring less than a 10%.

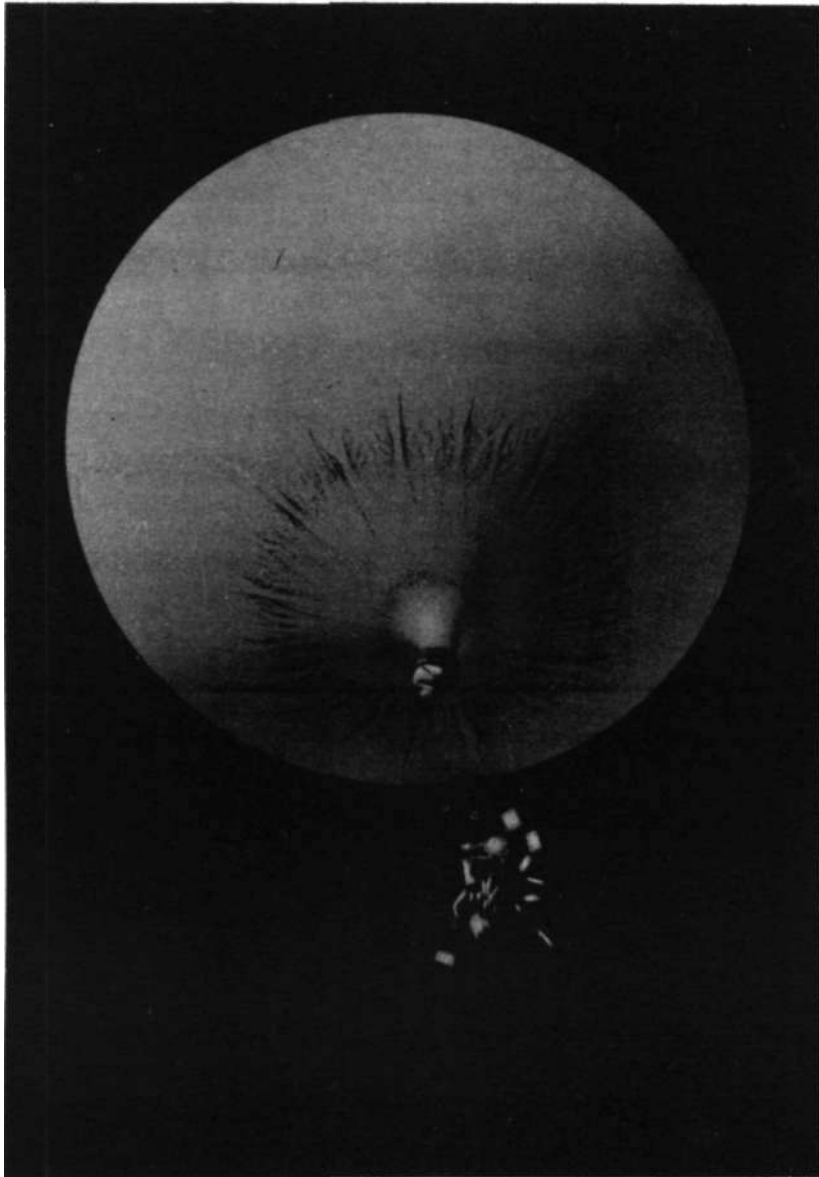* The actual weight of the cylinders was kept within +_ 1% of the weight taken for the calculations.

Fig.25. Cylindrical and plate-shaped pieces of wood were loosened from a balloon in order to study free-fall times.

Some complementary drop tests were carried out with square plates and similar conclusions were obtained. Therefore, it was concluded that the experimental procedure of keeping the firebrands at rest did not introduce any important errors in the results as far as the aerodynamic drag is concerned.

With respect to the combustion process, when the firebrands burn in a fixed position the forced convection originated by the air stream produces an asymmetrical combustion process, and then, the firebrands do not keep their original shape as they burn. In order to overcome this effect the rotating device of firebrands shown in Fig.4- was designed and installed in the horizontal wind tunnel.

However, not very significant differences were found among the results obtained for fixed and for rotating or free-moving firebrands. These differences were, in many cases, of the same order of magnitude than those originated by the natural scattering of results produced by the heterogeneous properties of wood, which by itself modifies in many cases the original shape of the firebrands as combustion progresses.

6. FLIGHT PATHS

Once the expressions of the final velocities of fall w have been determined as function of time, the flight paths and distances travelled by the firebrands while still burning are readily calculated if the convective currents and winds are known.
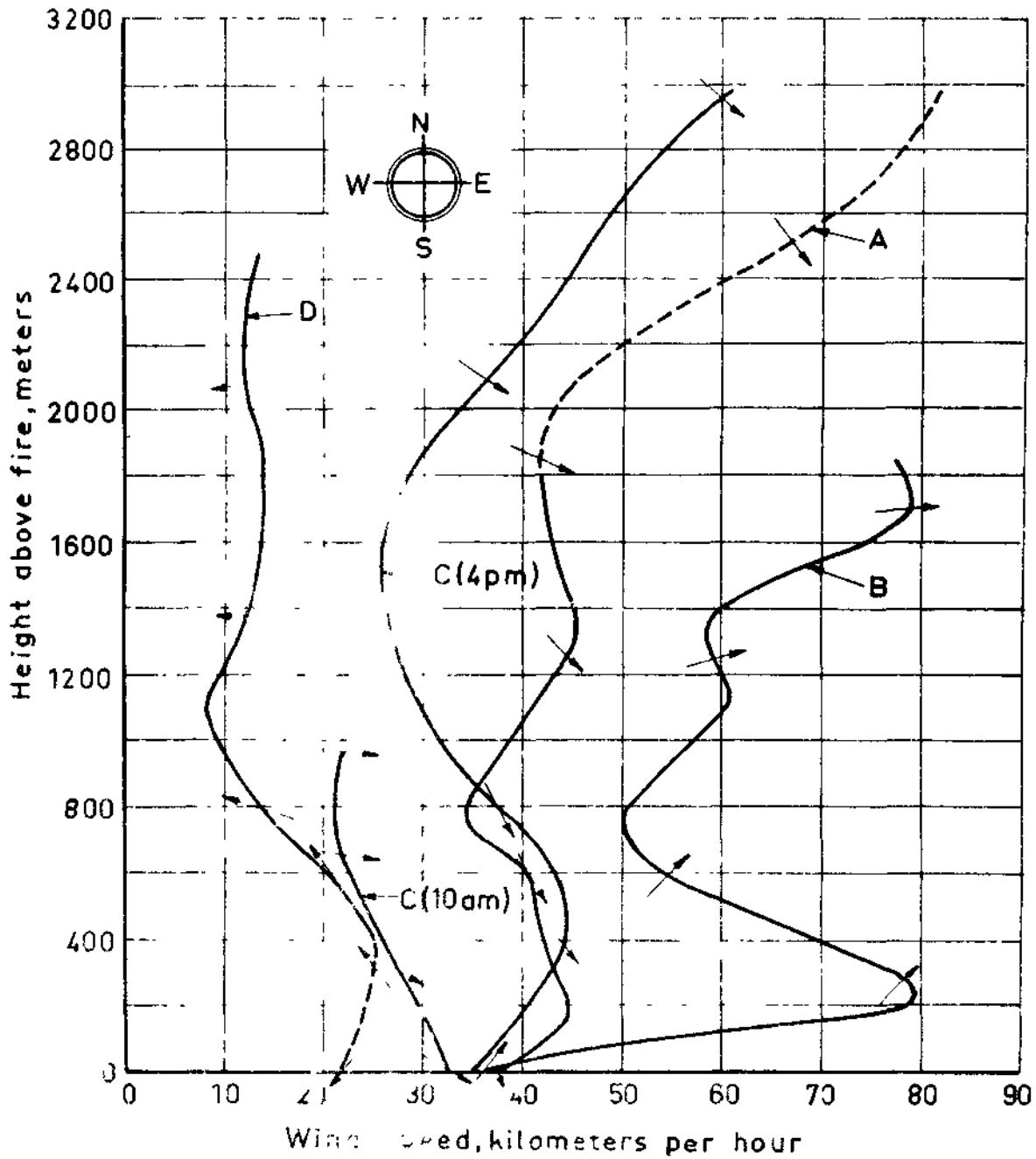
Fig.26   Wind iD'ilf ; above some major forest **fires.**
A: Wood River Valley fire, May 2, **1951;**
B: Chatsworth **fire, July 14, 1954; C: Fort Lewis**
fire, October **23, 1953;** D: **Jamison fire, August 31,**
1954. (*Taken from Ref.l)

Wind conditions above a forest fire can be very differ
ent, as shown m Fig.26. However, it has been observed that
in most major fires a low-level jet wind exists for which the
maximum intensity of wind occurs at or near the ground, as
shown in several wind profiles of that Fig.26.

Convection columns always exist above a well-developed
forest fire. They are of different types, which are deter-
mined by the prevailing wind conditions.

When there is a jet wind, and the wind decreases or has
a small value aloft, a vertical or almost vertical convection
column appears which is called a tower convection column.[1] If
the wind aloft increases, the convection column curves gradual
ly towards the direction of the wind.

When a strong wind-gradient exists aloft the convection
column bends sharply, originating what is called a "fractured
convection column."

There almost no data on the values of the convective
speeds within the convection columns, although vertical veloci-
ties up to 110-130 km/hour have been observed in some high-
intensity fires.

A number of theoretical studies have been carried out
on the variation of the air velocities within fire plumes or
convection columns, such as those of Refs. [3], [4], and [5].

Countryman[g], made very interesting observations on the
behaviour of convection columns on large-scale test fires. It
seems that theoretical models calculated for thermal plumes do
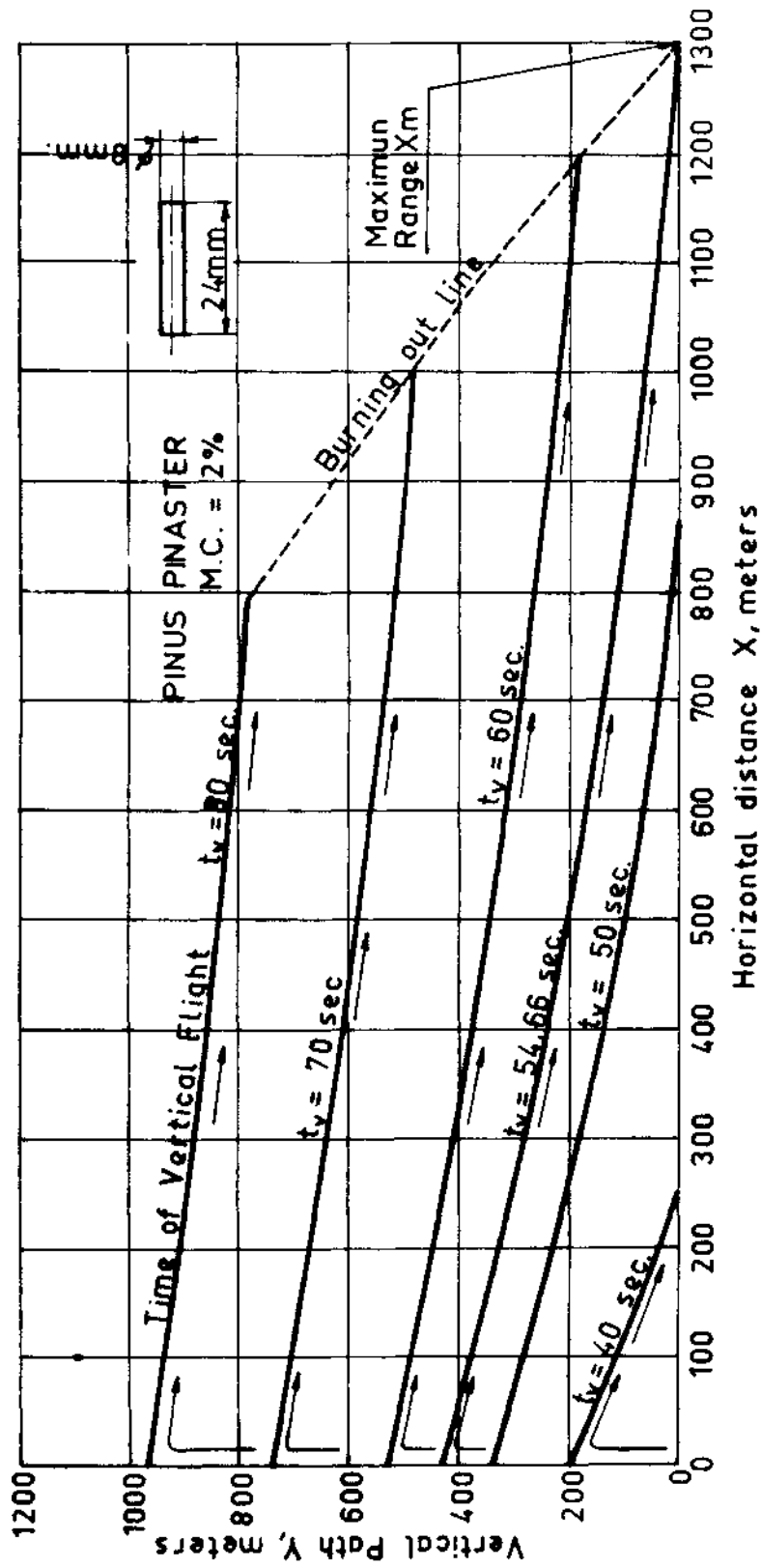not apply for these huge convection columns, that may reach

Fig.27 - Flight Paths. Vertical Convection Column. Cylindrical Firebrands
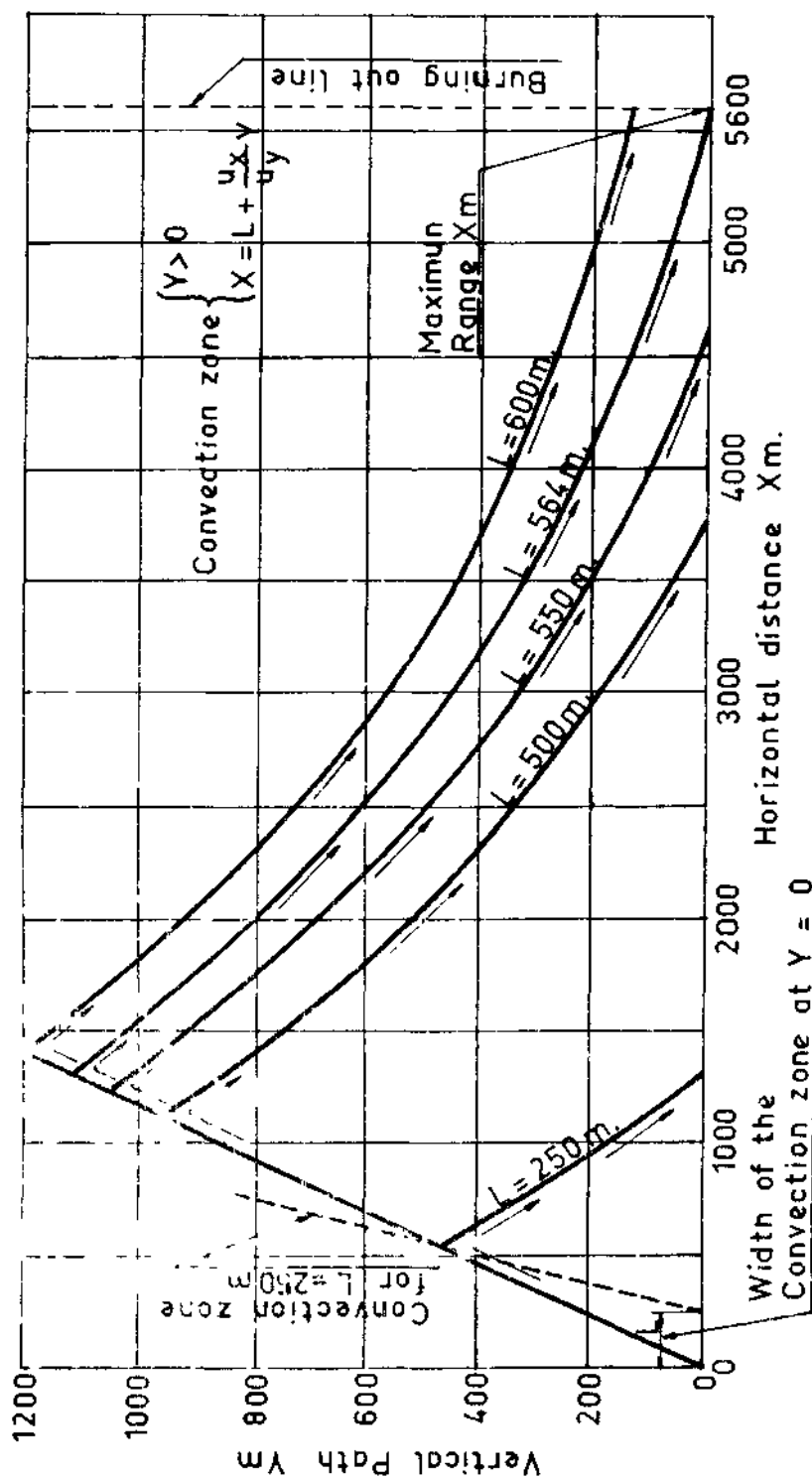
Fig.28 - Flight Paths. Inclined Convection Column. Spherical Firebrands.

L = Initial Distance from the Firebrand to the Convection Column Border Line.

till 8000 or 9000 m in height, and that little is known on the values and laws of variation of the air currents within these large convection columns.

Once the curves w = f(t) are obtained, flight paths and burning-out distances reached by the firebrands can be calculated immediately for any type of convection column. However, for simplicity, and because of the lack of actual data, two simplified models of convection columns were in the first place considered:

The first model considers a vertical convection column of constant speed. The firebrands leave the convection column at random, thrown out by turbulence, and then they are picked up by a constant horizontal wind. An example of the resulting flight paths for cylindrical firebrands are shown in Fig.27.

In the second model, an inclined convection column of a given width was assumed. The velocity within the convection column was constant and was the product of a constant horizontal wind and of a constant vertical convective velocity.

The firebrands are picked up from the ground and they leave the convection column at a point determined by the initial position of the firebrand. Flight paths calculated with this model of convection column for spherical firebrands are given in Fig.28.

These two models of convection columns are oversimplified. However, they give an actual order of magnitude of the distances reached by the firebrands, and they are especially useful for the calculations of comparative results, which
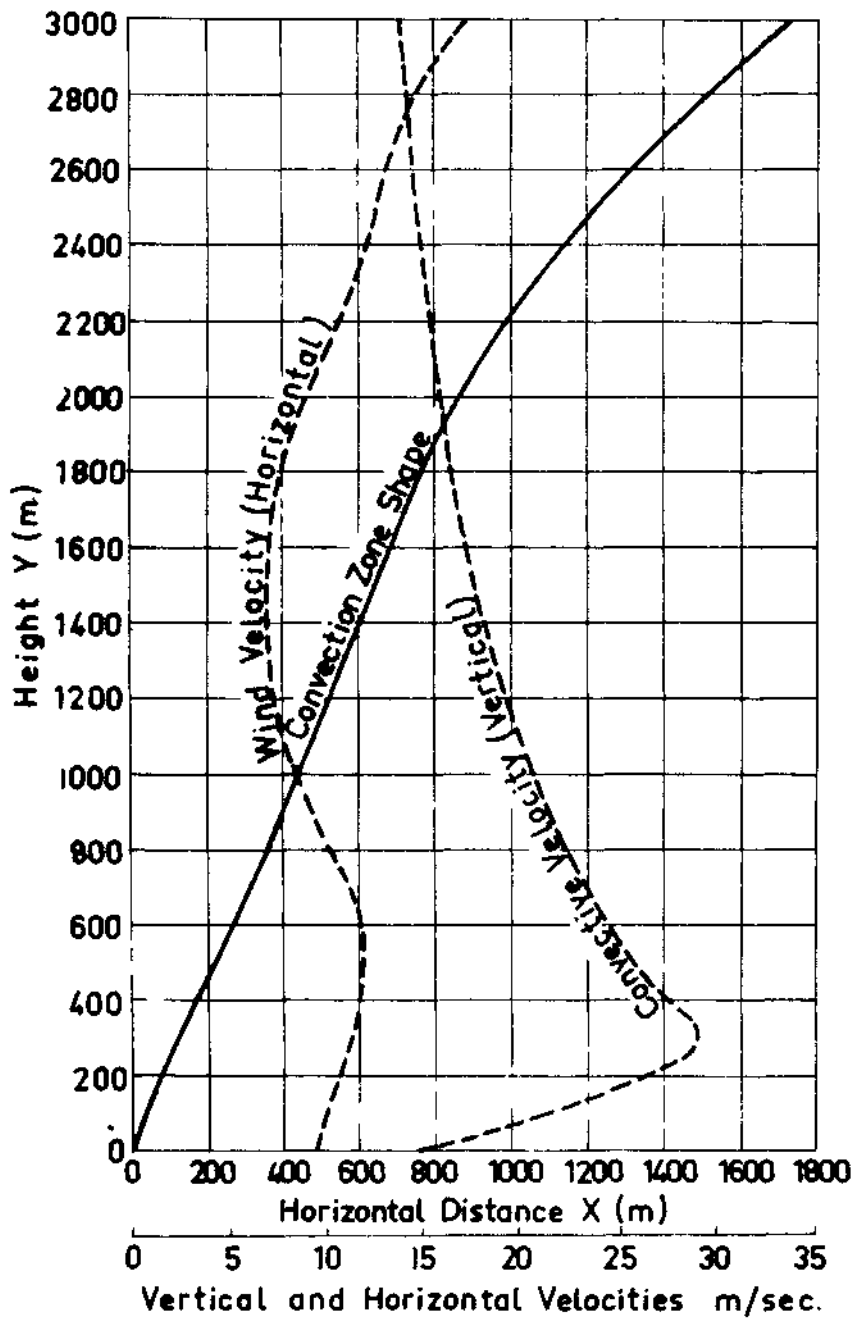
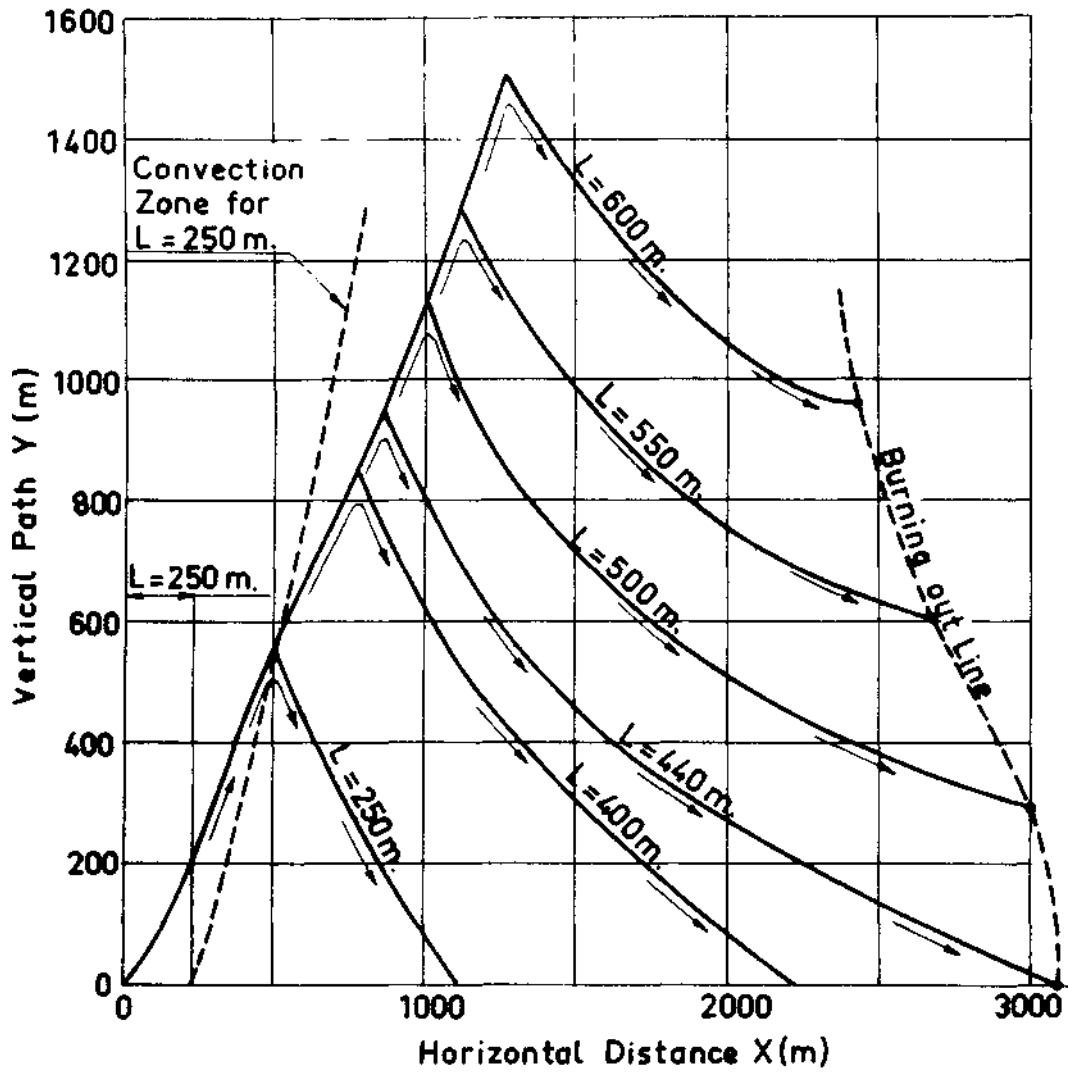Fig.29 - Wind Profile, Convective Velocity and
Convection Zone.

Fig.30 - Flight Paths.(Wind and Convective **Conditions** of **Fig.29).Spherical Firebrands**

would be extremely lengthy using more realistic models.

However, two examples will be given of flight paths calculations using actual wind conditions and more realistic convection column models. These models are shown in Figs. 29 and 31,in which the convective velocities are similar to those theoretically calculated[3, 4]. The resulting flights paths for spherical and cylindrical firebrands are included in Figs. 30 and 32, showing that the model developed for studying the flight paths of firebrands can be applied without difficulty for any kind of convection models or wind conditions.

Comparative results of the flight paths and distances travelled by the firebrands have been carried out, including cylindrical, spherical and square-plates firebrands of five kinds wood and charcoal with 2% and 25% of moisture content. These comparative results are shown in full in Refs.[11] and[12] These results show the existence of a critical height, defined by condition that if the firebrand leaves the convection column at this critical height Y_m, it reaches a maximum horizontal distance X_m while still burning. This horizontal distance X_m is the maximum range of fire propagation, which depends on the firebrands characteristics and on the convective and horizontal wind conditions.

Figs. 33 through 38 show some examples of the critical height Y_m as function of the vertical wind component u_y and as function of the initial size of the firebrands, for several kinds of wood, moisture contents and for vertical and inclined convection columns. For vertical convection columns the value of $t_r - t_f$, time of flight out of the convection column is also included, which is proportional to the horizon-
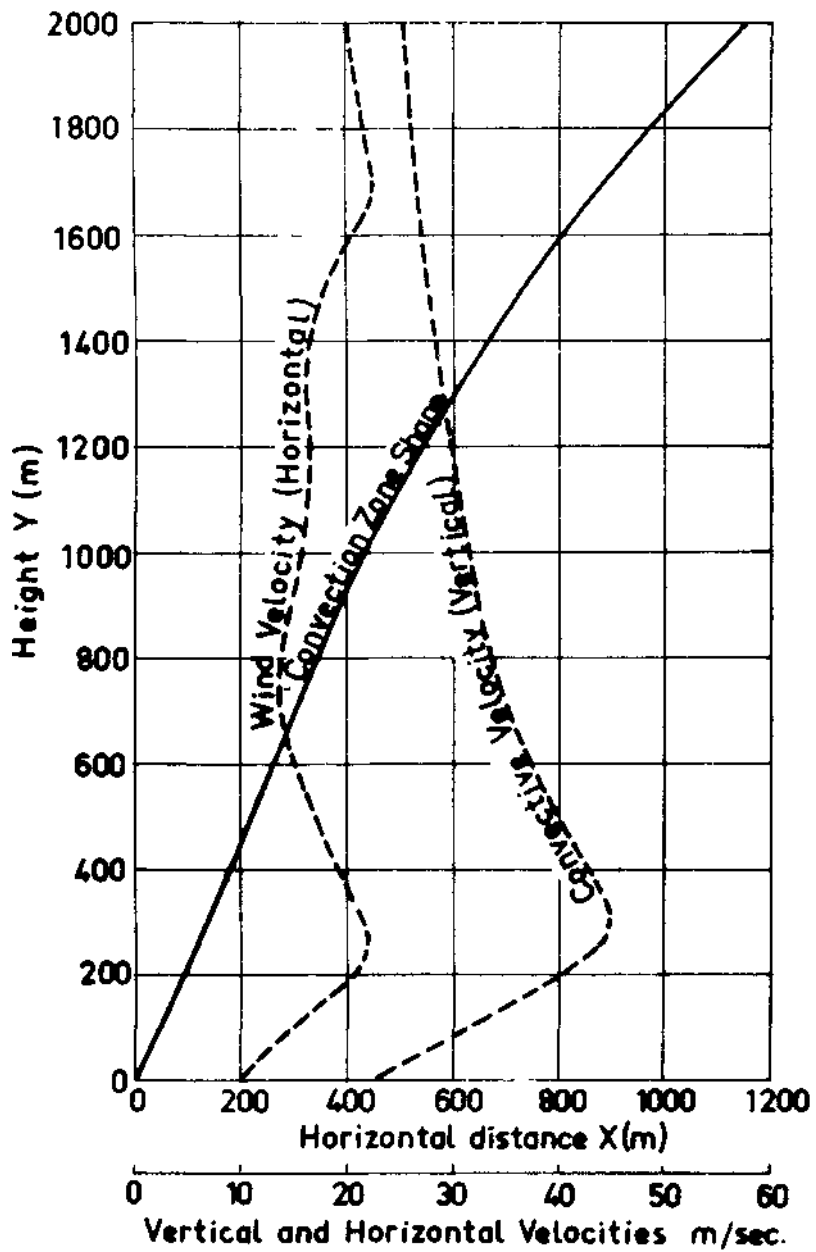
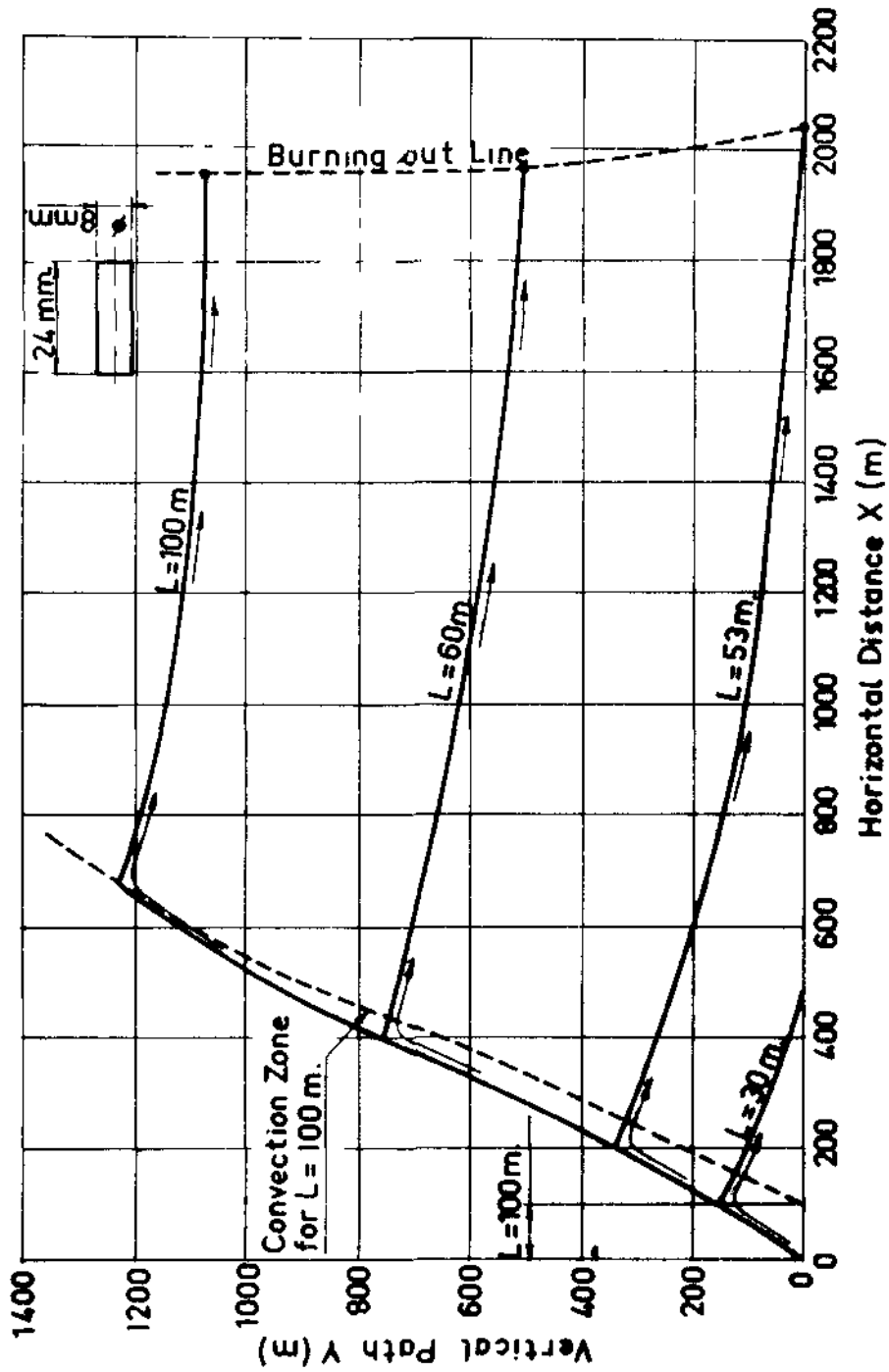Fig.31 - Wind Profile, Connective Velocity and Convection Zone.

Fig. 32 - Flight Paths. (Wind and Convective Conditions of Fig. 31).

Cylindrical Firebrands

tal distance reached by the firebrand. For inclined convection columns, instead of $t_r - t_v$ total flight times t_f have been included.

The principal conclusions which .have been derived are as follows:

1°.- There exists a critical height Y_m at which if the fire-
brand leaves the convection column it reaches a maximum
horizontal distance X_m while still burning.

2°.- The maximum horizontal range X_m of fire spread depends
on the firebrands characteristics and on the wind condi-
tions, existing an interdependence between these two
factors.

3°.- For adverse conditions X_m may reach values of the order
of several miles, even for small firebrands and for mod-
erate wind conditions.

4-°.- The zone of potential danger of fire propagation depends,
to a considerable extent, on the size of the firebrands;
the critical or more dangerous size depends, especially,
on the value of the convective velocity.

5°.- The kind of wood has a sizable influence on the process.
Wood density appears to be the most important parameter
as far as the maximum possible range of fire propagation
is concerned. Roughly, both Y_m and X_m are proportion
al to wood density for firebrands of equal initial size
and shape .

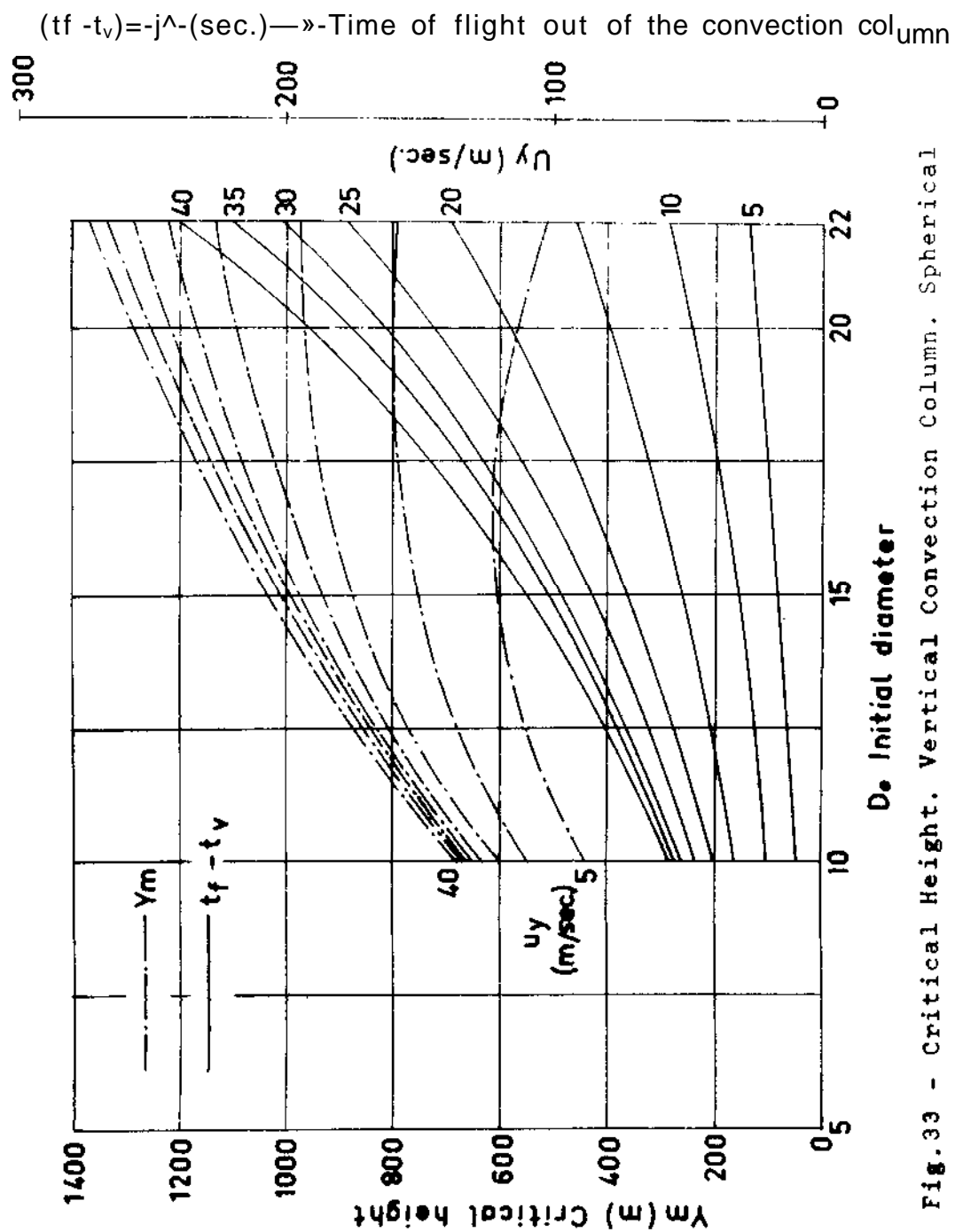6°.- Charcoal firebrands are, by far, the most dangerous type

Fig.33 - Critical Height. Vertical Convection Column. Spherical Firebrands of Pine Wood. M.C.25%.
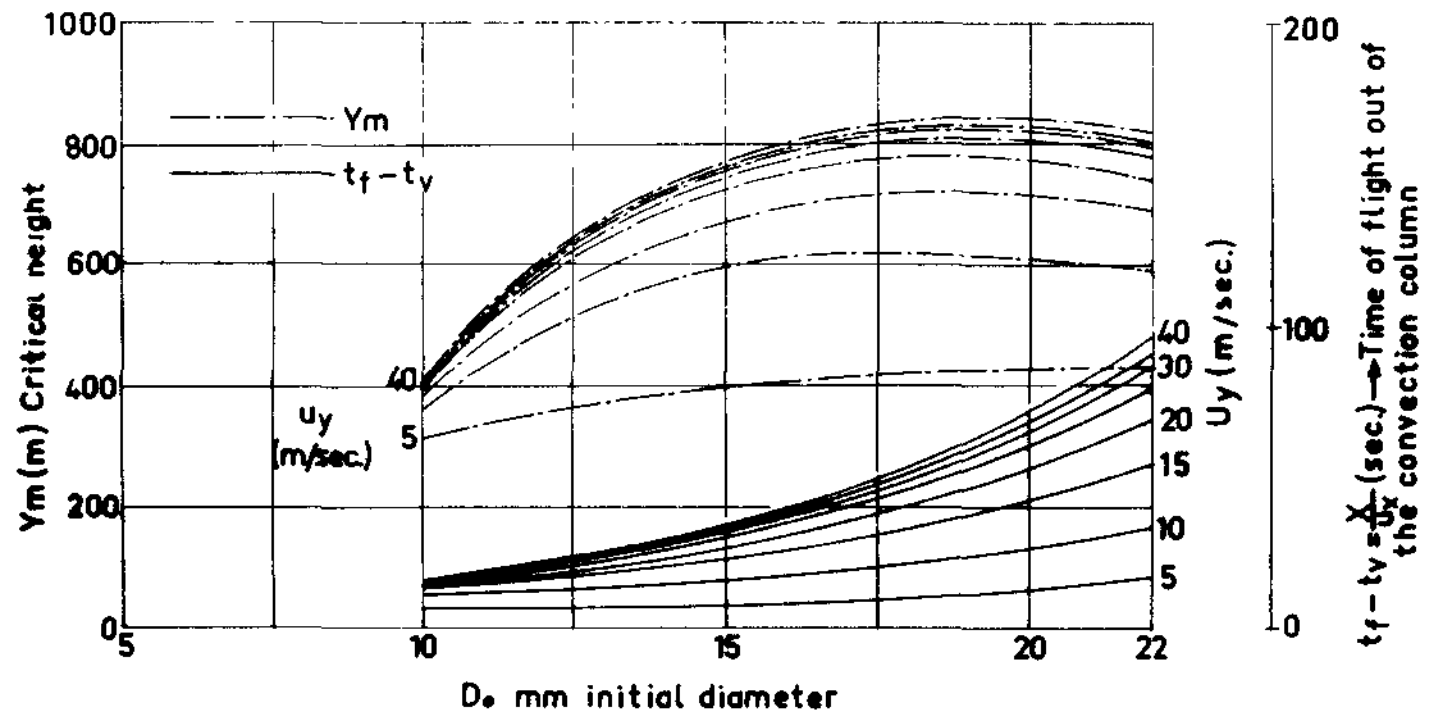
Fig.34 - Critical Height. Vertical Convection Column. Spherical Firebrands of Balsa Wood. K.C. 25%.
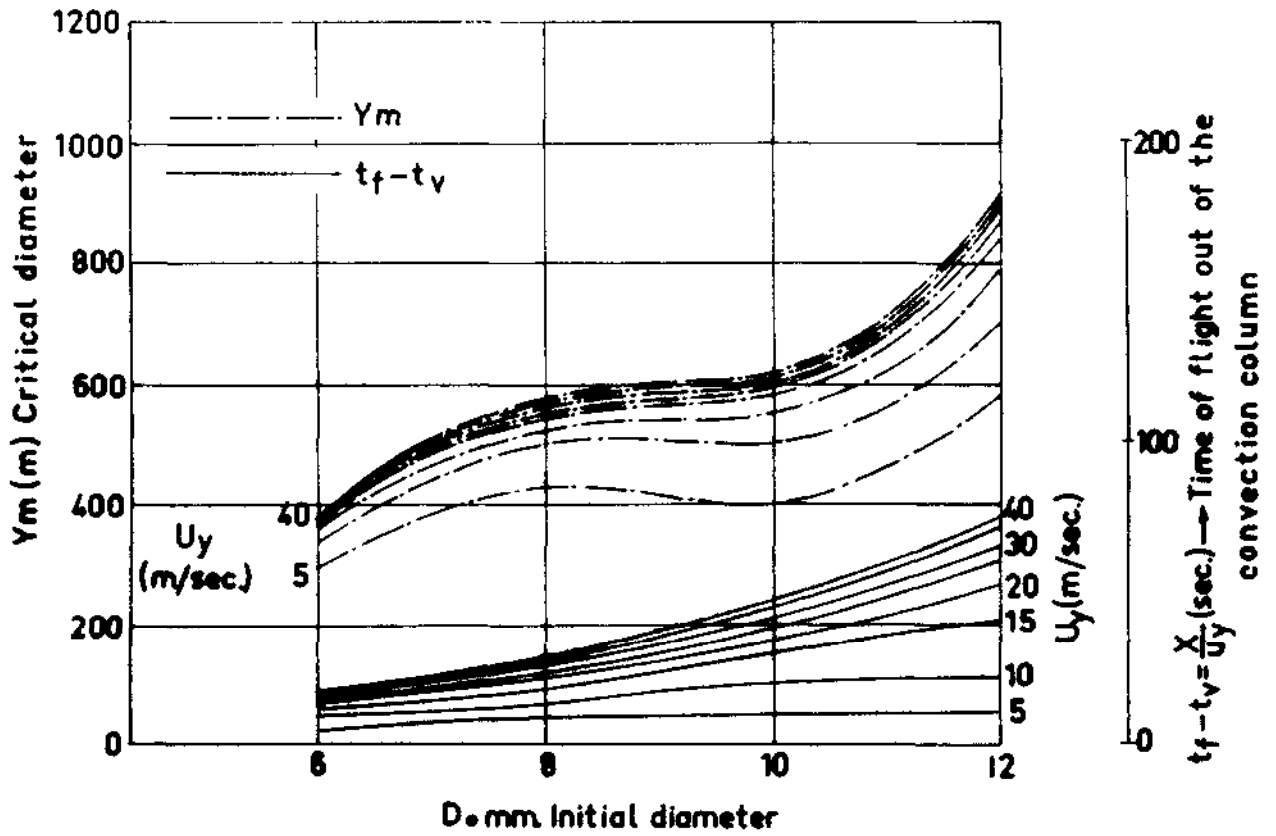
Pig.35 - Critical Height. Vertical Convection Column.
Cylindrical Firebrands of Aspen Hood. M.C.25%
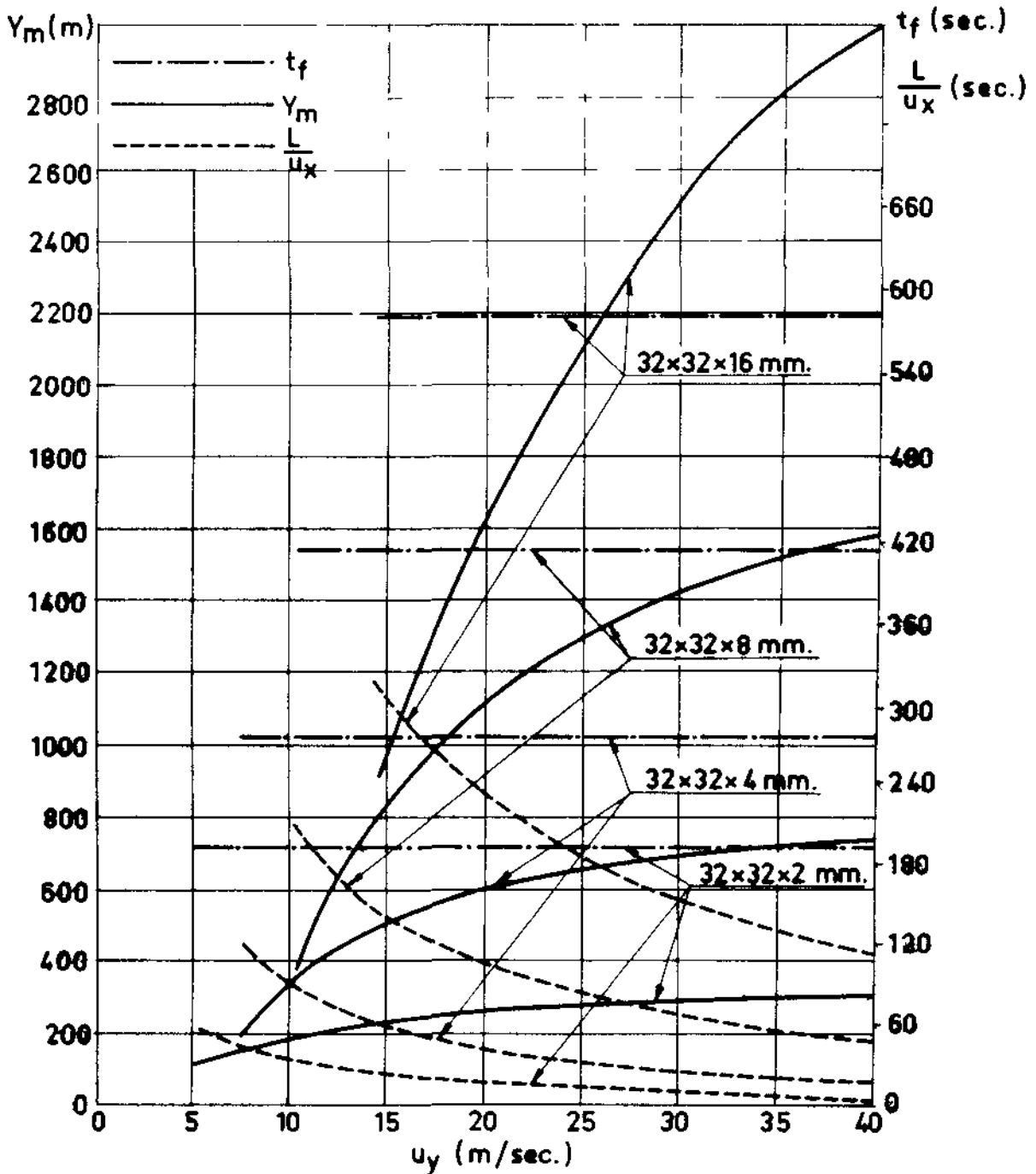
Fig.36 - Critical Height Y$_{\circ IB}$, Total Flight Time t$_f$ and Ratio
L/u$_x$ of Distance L of Firebrand to Convection Column
Border to Wind Velocity u$_x$ for Maximum Range. Inclined*
Convection Column. **Square** Plates Firebrands of Pine **Wood**

Fig. 37 - Y_m , t_f and L/u_x for Charcoal Cylindrical Firebrands.

Fig.38 - Y , tf and L/u_x for Pine Cones and Pin« Brackets .

of firebrands as far as possible maximum range of fire spread is concerned.

7°.- Initial shape of the firebrands also exerts a sizeable but not striking influence on the process. Different shapes would be more or less dangerous depending on the type of firebrands and wind conditions.

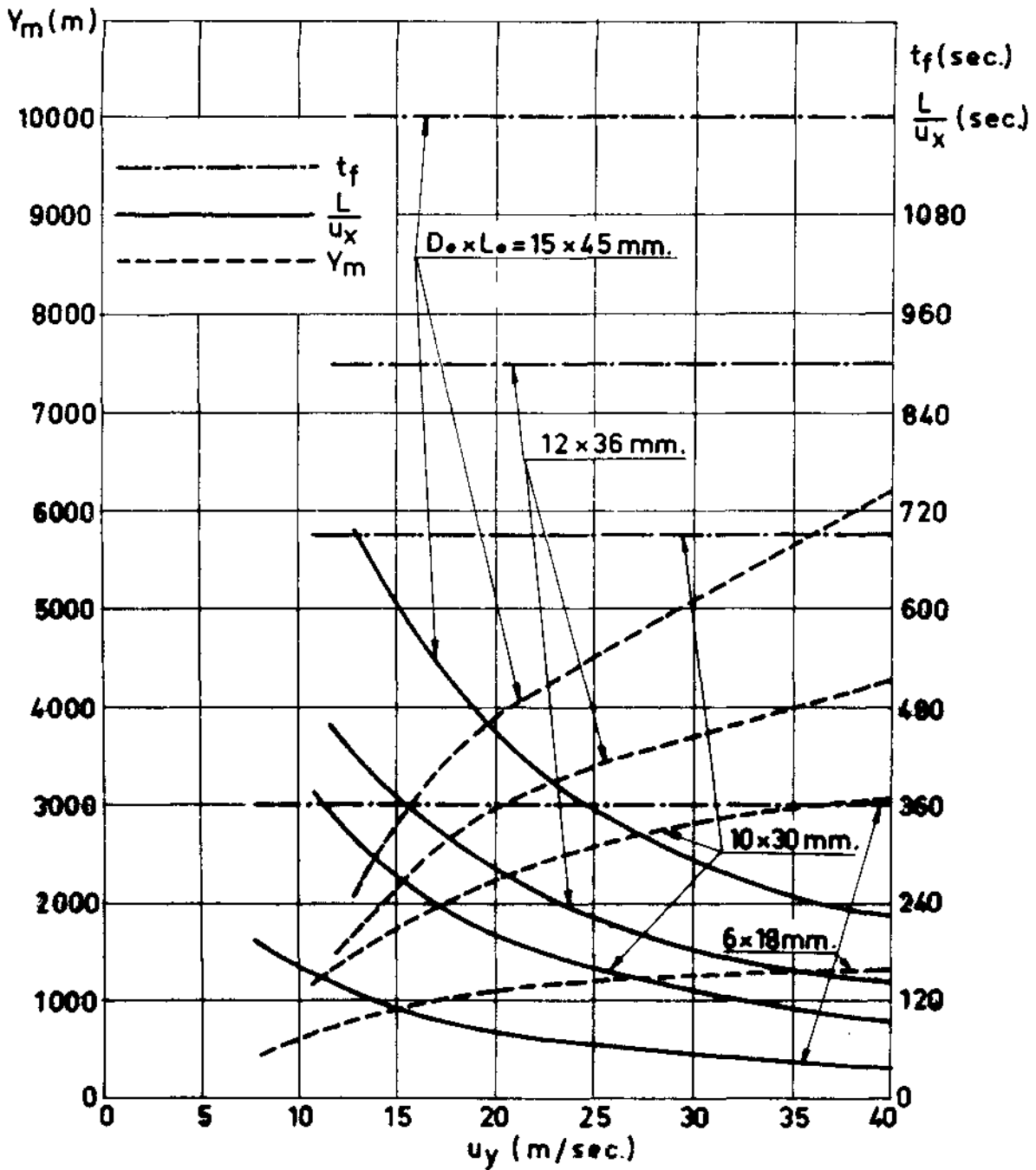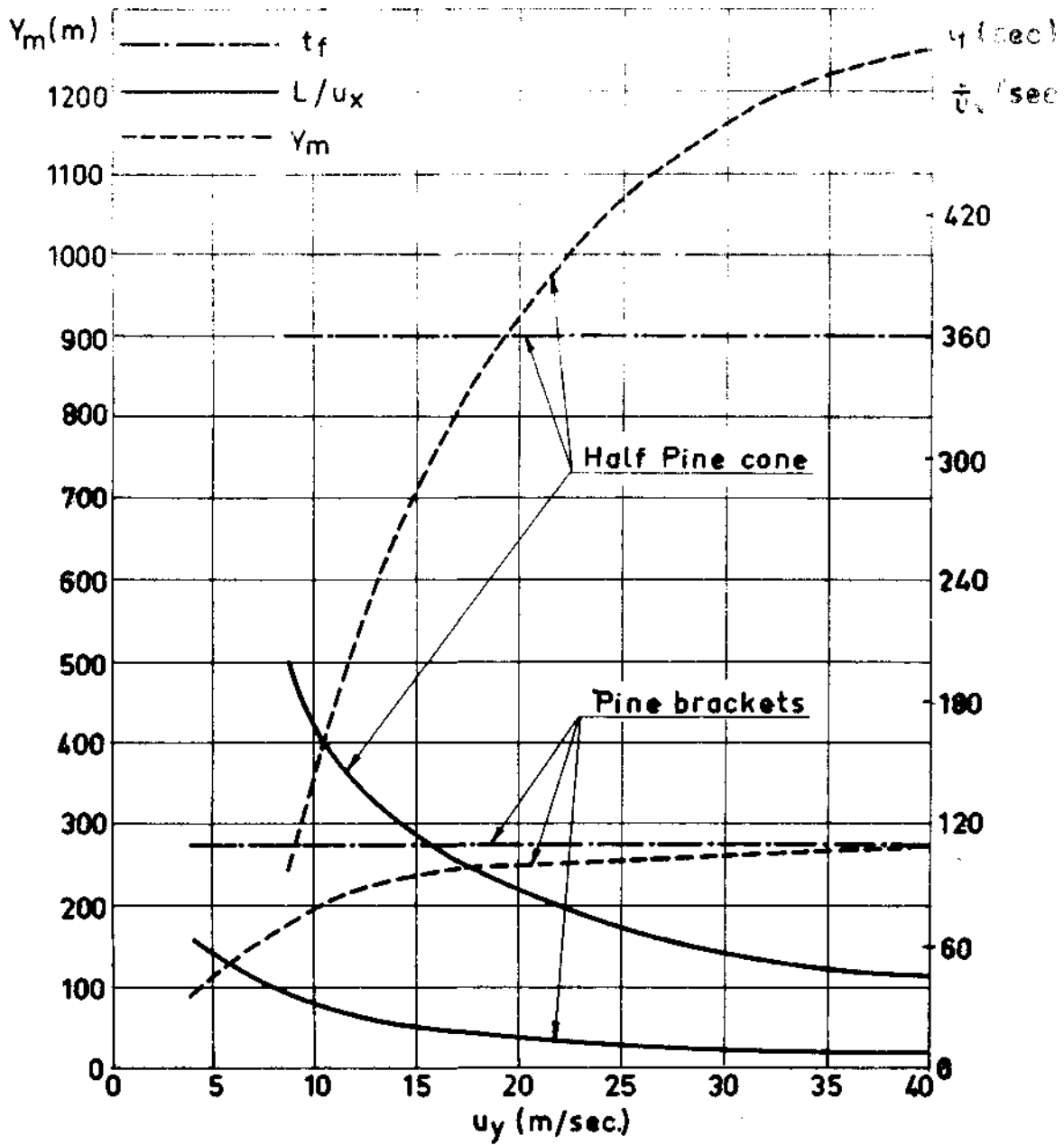8°.- Moisture content exerts a very strong influence on the ig_ nition process of the firebrands, but after ignition its influence is not very important, at least for not very large firebrands.

9°.- Natural firebrands tested have shown no remarkable dif- ferences with geometrical shaped firebrands of similar size.

7. COMBUSTION OF WOOD WITH FORCED CONVECTION

A study has been conducted on combustion of wood with forced convection. This study has been carried out by burning a great number of firebrands at constant wind speed in the horiz.ontal wind tunnel shown in Fig.2. The weight and the aero- dynamic drag of the burning firebrands were recorded as func- tion of time with the strain-gauges balance shown in Fig.6. At the same time, the volume and surface of firebrands were detei? mined by means of photographs.

Some results are given in Figs. 39, 40 and 41. They show typical laws of variation of weight, surface and volume

Fig.39 - Combustion of Firebrands at Constant Wind Speed. Weight-
Time Curves. Spherical Firebrands of Oak Wood.
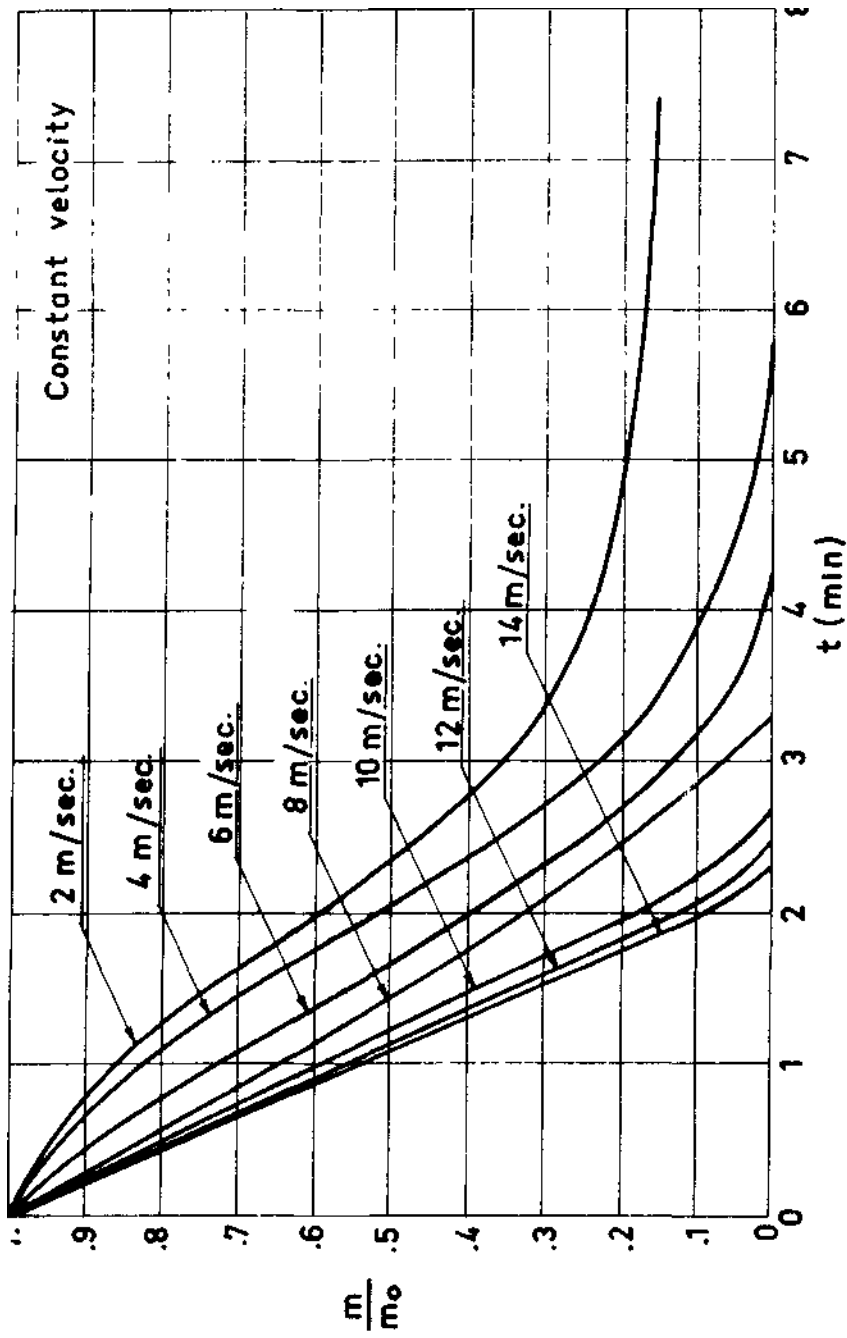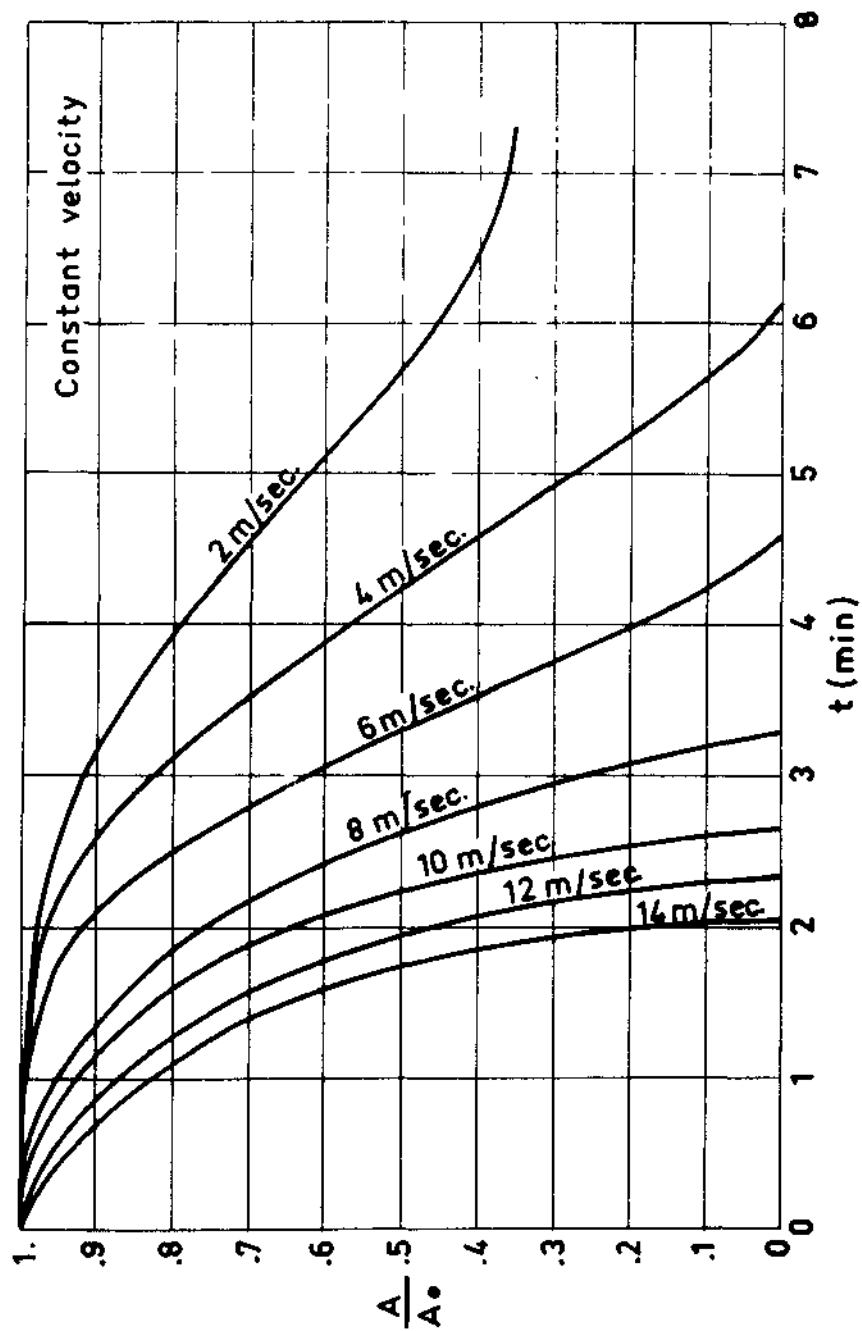
$D_o = 22$ mm. M.C.$=2\%$.

Fig. 40 - Combustion of Firebrands at Constant Wind Speed. Surface-Time Curves. Spherical Firebrands of Oak Wood.
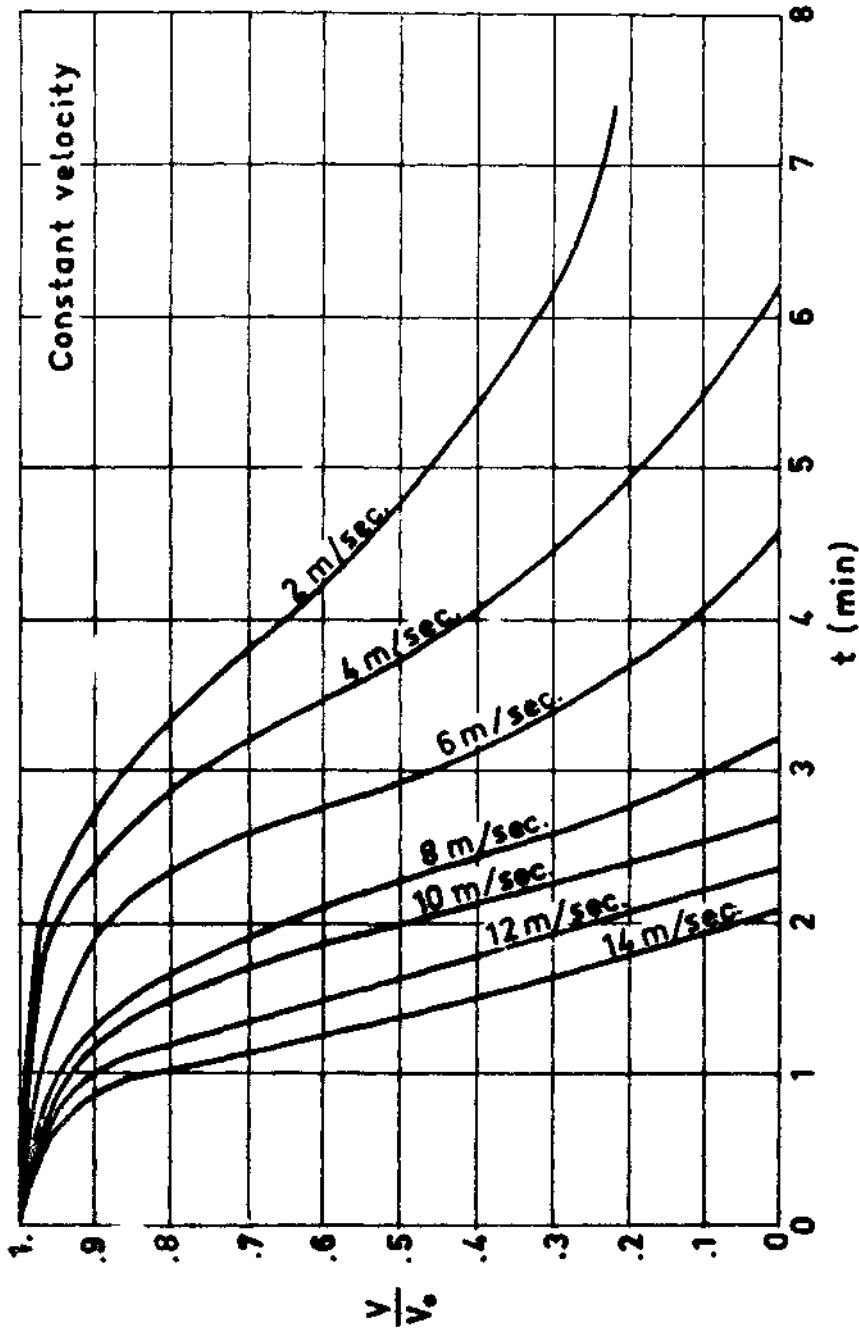
$D_o = 22$ mm.   M.C. $= 2\%$.

Fig.41 - Combustion of Firebrands at Constant Wind Speed. Volume-
Time Curves. Spherical Firebrands of Oak Wood.

$D_0 = 22$ mm.   M.C.= 2%.

as function of time. Results are shown in full in Ref.[12]

From these results final velocities of fall w,. at constant wind speed are immediately determined.

The principal objective of this study was the attainment of some basic laws of the combustion of wood with forced convection in order to deduce from then the combustion properties and flight paths of the firebrands when they fly at their final velocity of fall.

In the first place, it was shown the feasibility of deriving analytical expressions of the final velocities of fall w , starting from empirical laws giving approximately the density and surface area (or a lineal dimension) of the firebrand as function of time.

An example of this type of calculation is given in Ref.[7] , from which Figs.42 and 43 have been taken. Fig.42 shows the final velocities of fall experimentally obtained and those calculated from the laws of variation of the radius and density of spherical firebrands when burning at constant wind speed.

Fig.43 gives the flight paths calculated with the two final velocities of fall. It may be observed that the approximation given by the theoretical curves is fairly good. However, the burning out time or final point or curve $w_f = f(t)$, obtained theoretically, is considerable longer than the experimental value. This is due to the fact that the wood particles never burn out down to a zero diameter in the wind tunnel, but they always break off from the wire when they have burned down to a very small size, and, therefore, theoretical
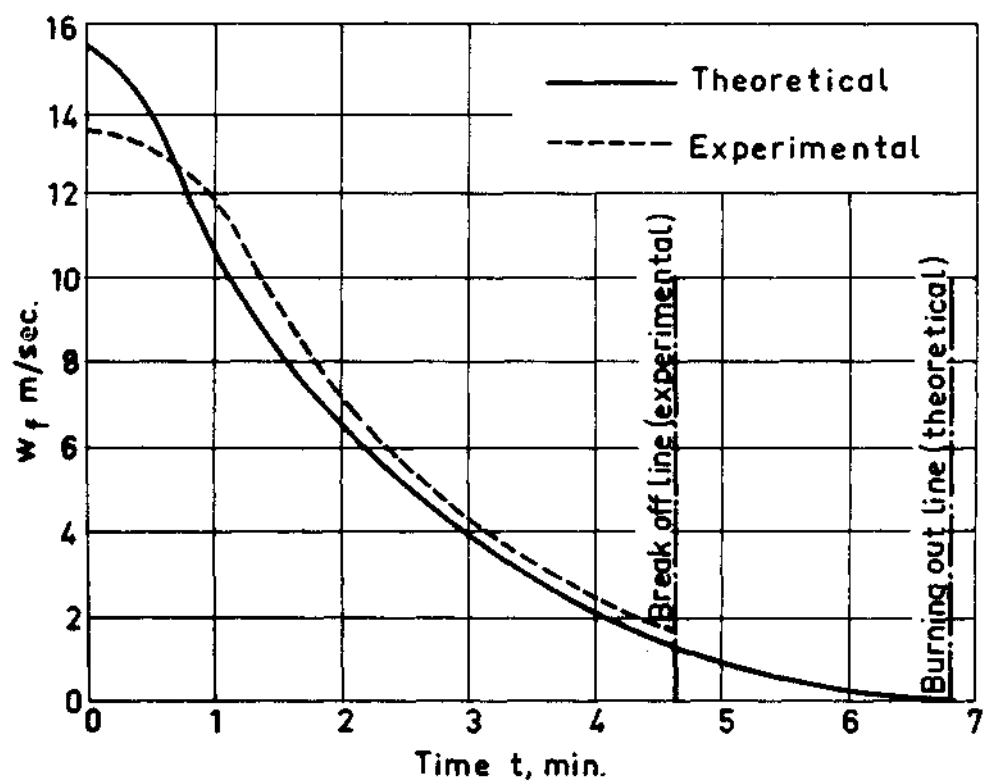
Fig.42 - Experimental and Theoretical Final Velocity of Fall. (Ref.[7])
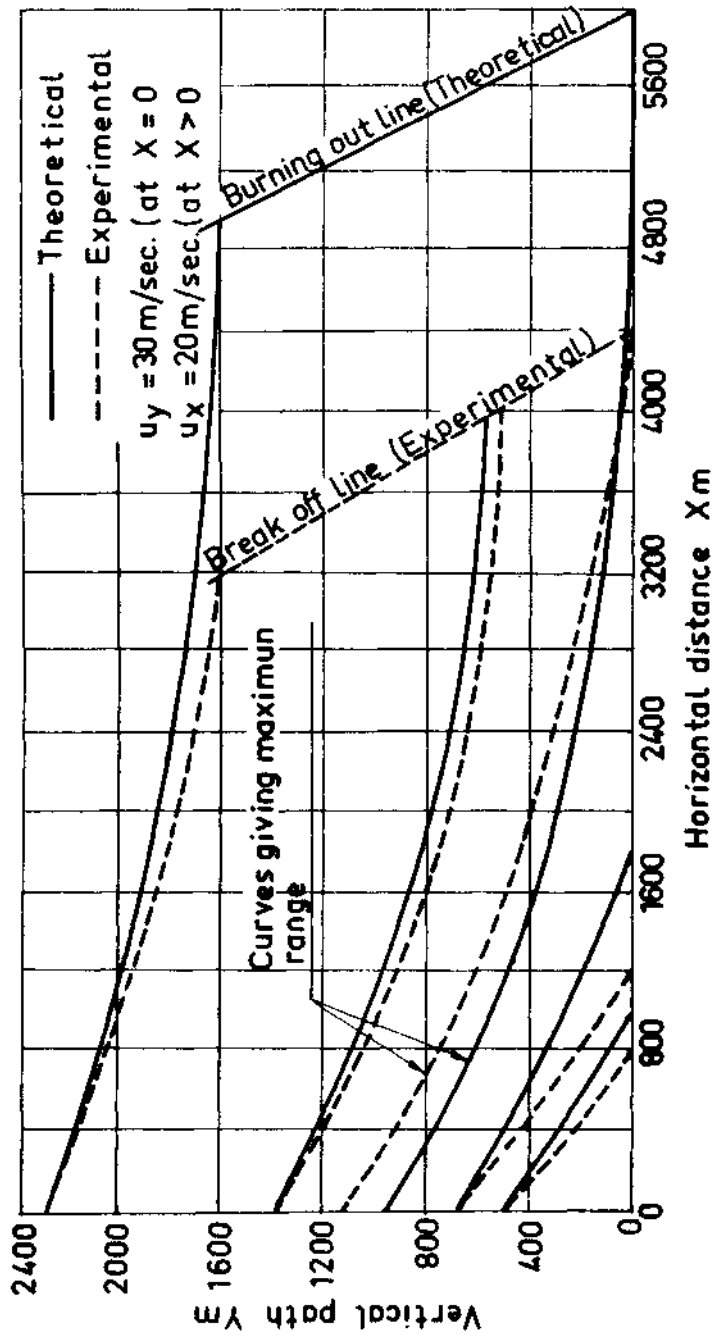
Fig. 43 - Flight Paths Calculated from Theoretical and from Experimental Values of the Final Velocities of Fall (Ref. 7).

results are probably more accurate in this case. However, this discrepancy is not important, because the ignition potential of very small firebrands is very small also.

In the second place, more general calculations have been carried out by using expressions derived from dimensional analysis.

DIMENSIONAL ANALYSIS

8.1 Results for Combustion at Constant Wind Speed

All theoretical and experimental results will be expres_ sed in dimensionless form. In the first place ,this study will be applied to the case of combustion of wood with forced con- vection at constant wind speed, and then to the case of combus tion of firebrands when flying at their final velocities of fall.

A firebrand will be characterized by its initial den- sity $p_{w,o}$ and by three characteristic lengths D_o , L_o , and 1^*_o . On the other hand, air will be characterized by its den- sity $p_{a,\infty}$ and viscosity $u_{a,\infty}$ at the infinity,

D is the diameter for spherical and cylindrical fire-
brands and the height (vertical dimension perpendicular to
the wind) for plate-shaped firebrands. L_Q is the longitu-
dinal axis for cylindrical firebrands and the width (hori^
zontal dimension perpendicular to the wind) for plate-
shaped firebrands. Finally, 1 is the thickness (paral-
lel to the wind) of plate-shaped firebrands.
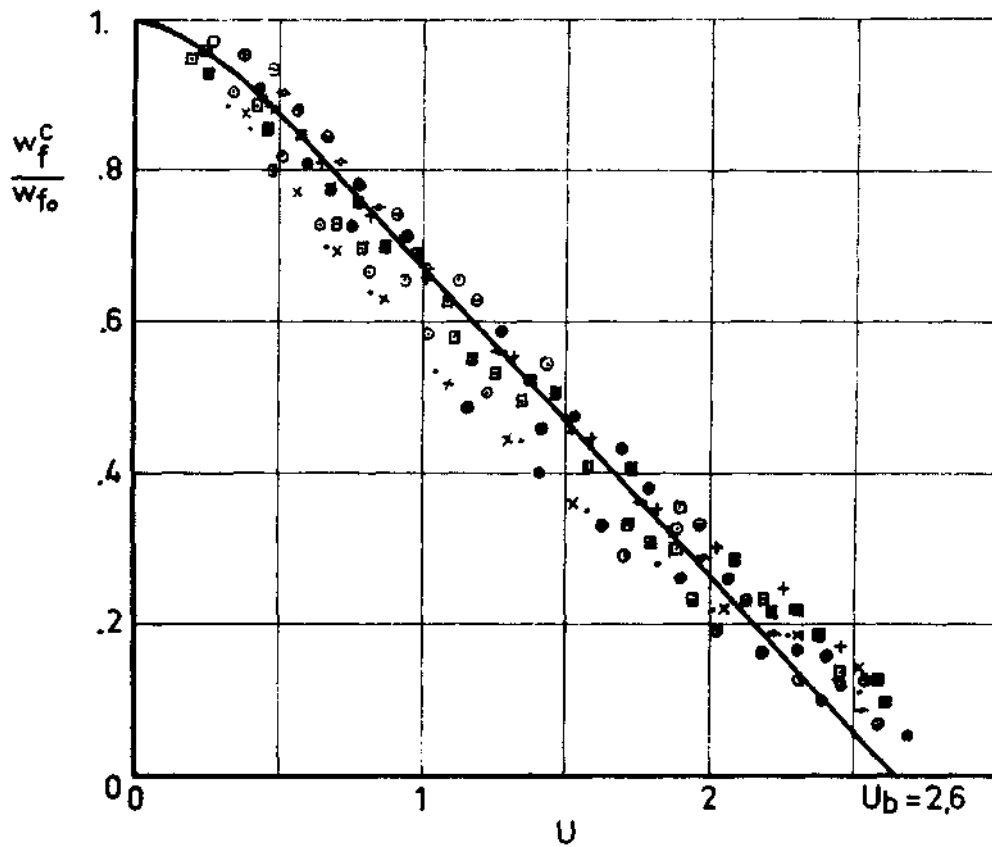
Fig.[1^] - Dimensionless Correlation of Experimental
Results for the Combustion of Fireb.rands at
Constant Wind Speed.

According to dimensional analysis, any property £ of the firebrand referred to its initial value £$_o$, will be given by an expression of the form:

$$\frac{\xi}{\xi_0} = \phi \left[\left(\frac{wt}{D_o}\right)^\alpha , \left(\frac{wD_o \rho_{a,\infty}}{\mu_{a,\infty}}\right)^\beta , \left(\frac{\rho_{a,\infty}}{\rho_{w,o}}\right)^\gamma , \left(\frac{L_o}{D_o}\right)^\delta , \left(\frac{l_o}{D_o}\right)^\epsilon \right]$$

(27)

or:

$$\frac{\xi}{\xi_0} = \phi \left[\chi^\alpha , Re^\gamma , \zeta^\gamma , \lambda_1^\delta , \lambda_2^\epsilon \right]$$

(28)

In this expression, $x = wt/D_o$ is a characteristics parameter of this non-stationary combustion process; $Re = wD_o \rho_{a,\infty}/\mu_{a,\infty}$ in the Reynolds number; $£ = \rho_{a,\infty}/\rho_{w,o}$ is a parameter character-izing the kind of wood, and parameters $\lambda_1 = L_o/D_o$ and $\lambda_2 = l_o/D_o$ represent the firebrand's geometrical configuration*.

For cylindrical firebrands, is $\lambda_2 = 1$ and for spheri cal firebrands is $\lambda_1 = \lambda_2 = 1$.

Variable ξ can be the mass, volume, density, aerodyna mic drag of the firebrand or final velocity of fall.

In particular, all experimental values of the final ve_ locities of fall** w^c obtained for spherical and cylindrical firebrands and for the three kinds of wood investigated have been correlated with the following expressions:

: In all these expressions subscript o denotes initial value.

'•* Superscript c will be used to denote final velocities of fall of firebrands burning at constant wind speed.

$$\frac{w_f^c}{w_{f,o}} = F\ (U) \tag{29}$$

in   which

$$U = \chi \, Re^{-0.4} \, \zeta^{1.3} \, \lambda_1^{-0.4} \tag{30}$$

In Fig.M-4 expression (29) is represented and it may be seen that the correlation obtained is very reasonable.

Considering that each experimental value is the average of 5-6 measurements, in Fig.M-4 a total of more than 300 experiments are represented, which shows the very important saving in time and space resulting from this dimensionless representation of results.

The burning-out value U_r, which corresponds to $w_f/w_{f,o} = 0$, is practically the same for all cases investigated and it is given by:

$$U_b = \frac{wt_b^c}{D_o} \, Re^{-0.4} \, \zeta^{-1.3} \, \lambda_1^{-0.4} \tag{31}$$

from which, the burnmg-out time t_b is obtained.

8.2   Results for Combustion of Firebrands Flying at their Final Velocity of Fall

A similar dimensional analysis has been carried out for firebrands when burning within an air current with velocity constantly equal to their final velocity of fall.

Any firebrand property n , such as weight, density, aerodynamic drag, final velocity of fall, etc. is expressed in the form:

$$\frac{\eta}{\eta_o} = \phi \left\{ \chi_f^{\alpha} , R_{ef}^{\beta} , \zeta^{\gamma} , \lambda_1^{\delta} , \lambda_2^{\epsilon} \right\} \tag{32}$$

Variables t, , A. and X were defined in the prece ing paragraph, and Xf $^{an<}3$ R ^ are:

$$\chi_f = \frac{w_{f,o} t}{D_o} \tag{33}$$

$$R_{ef} = \frac{w_{f,o} D_o \rho_{a,\infty}}{\mu_{a,\infty}} \tag{34}$$

All experimental results obtained for the final veloc ities of fall w   for spherical, cylindrical and square plates firebrands and for all kinds of wood studied* were cor related with the following expression:

$$\frac{w_f}{w_{f,o}} = \phi \ (Z) \tag{35}$$

being:

$$Z = \chi_f \ R_{ef}^{-0.4} \ \zeta^{1.3} \ \lambda_1^{-0.4} \ K\lambda_2 \tag{36}$$

* Pine wood, spruce, aspen, oak and balsa Charcoal fire-
  brands were not included.

For square plates firebrands is X = 1 and dimensionless
constant K is equal to 0.62. For spherical and cylindrical
firebrand A_2 is equal to unity and constant K is also
equal to one.

All experimental results are shown in Fig.45. They
include a total of over 500 experimental values and it may be
seen that, considering the heterogeneous properties of wood,
the correlation obtained may be considered as very satisfac-
tory.

9 .   CALCULATIONS OF FINAL VELOCITIES OF FALL STARTING FROM
     DATA ON COMBUSTION OF FIREBRANDS AT CONSTANT WIND SPEED

Finally, final velocities of fall w,. of firebrands
flying and burning at a relative wind velocity constantly
equal to this final velocity of fall will be calculated
starting from the values of the final velocities of fall $w^\wedge$
obtained by burning firebrands at constant wind speed.

Under actual flight and burning conditions, mass,
aerodynamic drag, density,etc. of a firebrand have a function
al dependency on time, since they depend on the complete time-
history of the wind velocity and then, on the complete combus-
tion process.

This functional dependency implies that in order to
calculate actual flight paths of firebrands when flying and
burning at their final velocity of fall starting from combus-
tion data obtained at constant wind speed, a complementary
assumption has to be introduced.
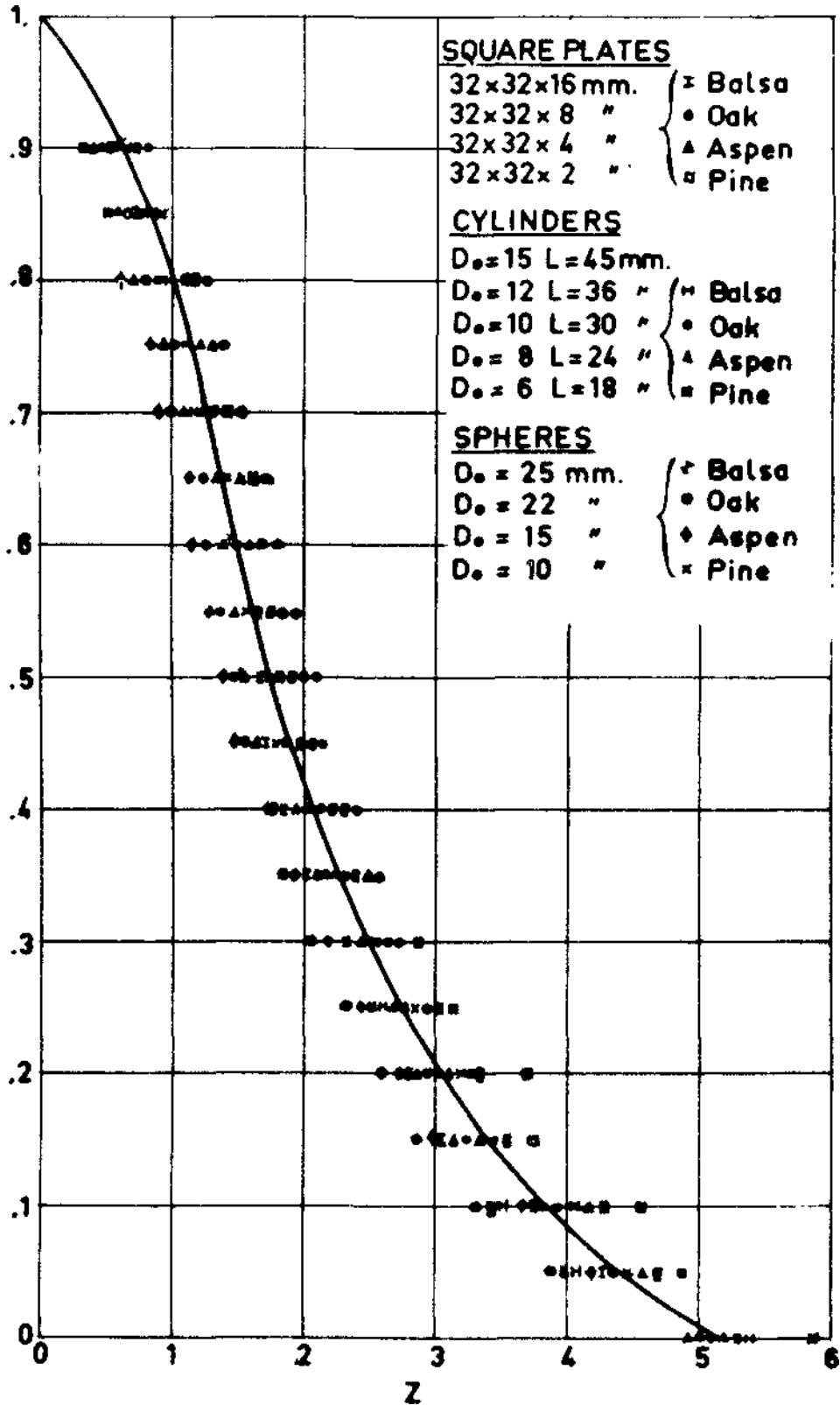
ig.45 - Dimensionless Correlation of Experimental
Results for the Combustion of Firebrands
at Final Velocity of Fall.

This complementary assumption is needed because the basic laws of wood combustion under non-stationary conditions are not known, lack of knowledge which is mainly due to the heterogeneous properties of wood.

A reasonable assumption which will give a satisfactory approximation in practice is to assume that the elementary variation of the final velocity of fall w, of the firebrand when it burns at the final velocity of fall, is equal to the elementary variation of final velocity w_f when the firebrand burns at constant wind speed w , when this velocity is equal to w_f. • That is to say:

$$\frac{dw_f}{dt} = \left(\frac{dw_f^c}{dt}\right)_{w=w_f} \tag{37}$$

Therefore, once an analytical expression is found for function

$$\frac{w_f^c}{w_{f,o}} = F\left(\chi \, , \, Re \, , \, \zeta \, , \, \lambda_1 \, , \, \lambda_2\right) \tag{38}$$

the expression of w   as function of time is obtained by inte_grating the differential equation:

$$\frac{d}{dt}\left(\frac{w_f}{w_{f,o}}\right) = \frac{d}{dt}\left(\frac{w_f^c}{w_{f,o}}\right) = \left(\frac{\partial F}{\partial t}\right)_{w=w_f} \tag{39}$$

Expression w_f/w_f represented in Fig.44 was approximated by

means of a straight line:

$$\frac{w_f^c}{w_{f,o}} = 1 - \frac{U}{U_b} \qquad \left(U_b \geq U \geq \frac{U_b}{5} \right) \qquad (40)$$

and with a parabolic expression

$$\frac{w_f^c}{w_{f,o}} = 1 - \frac{5}{2} \frac{U^2}{U_b^2} \qquad \left(\frac{U_b}{5} \geq U \geq 0 \right) \qquad (41)$$

tangent to the straight line at $U = \dfrac{U_b}{5}$.

    With the expression of U **given** by (30), it results

$$\frac{d}{dt} \left(\frac{w_f^c}{w_{f,o}} \right) = - \frac{A}{U_b} w^{0.6} \qquad \left(U_b \geq U \geq \frac{U_b}{5} \right) \qquad (42)$$

and

$$\frac{d}{dt} \left(\frac{w_f^c}{w_{f,o}} \right) = - \frac{5 A^2}{U_b^2} w^{1.2} t \qquad \left(\frac{U_b}{5} \geq U \geq 0 \right) \qquad (43)$$

where

$$A = \frac{1}{D_o} \left(\frac{D_o \rho_{a,\infty}}{\mu_{a,\infty}} \right)^{-0.4} \left(\frac{\rho_{a,\infty}}{\rho_{w,o}} \right)^{1.3} \left(\frac{L_o}{D_o} \right)^{-0.4} \qquad (44)$$

and U, is a diraensionless constant given by (31) and equal

to 2 .6

Taking $w = w$ and $w = w_f$ in (42) and (43), integrating with boundary condition:

$$t \approx 0 \qquad\qquad w_f = w_{f,0} \qquad\qquad (45)$$

and matching the two solutions at $U = U/5$, it is finally-obtained:

$$\frac{w_f}{w_{f,0}} = \left(1 - 0.4 \frac{V}{U_b}\right)^{2.5} \qquad (0 \le w_f \le 0.9\ w_{f,0}) \quad (46)$$

$$\frac{w_f}{w_{f,0}} = \left[1 + \frac{1}{2}\ \frac{V}{U_b}^2\right]^{-5} \simeq 1 - \frac{5}{2}\ \left(\frac{V}{U_b}\right)^2$$

$$\left(0.9\ w_{f,0} \le w_f \le w_{f,0}\right) \quad (47)$$

where

$$V = \frac{w_{f,0}\ t}{D_0}\ \left(\frac{w_{f,0}\ D_0\ \rho_{a,\infty}}{\mu_{a,\infty}}\right)^{-0.4} \left(\frac{\rho_{a,\infty}}{\rho_{w,0}}\right)^{1.3} \left(\frac{L_0}{D_0}\right)^{-0.4} \quad (48)$$

that is, V is the expression of Z for spherical and cylindrical firebrands for which this calculation applies[5,5] .

In Fig.46 theoretical curve $\dfrac{w_f}{w_{f,0}} = F\ (V)$ given by

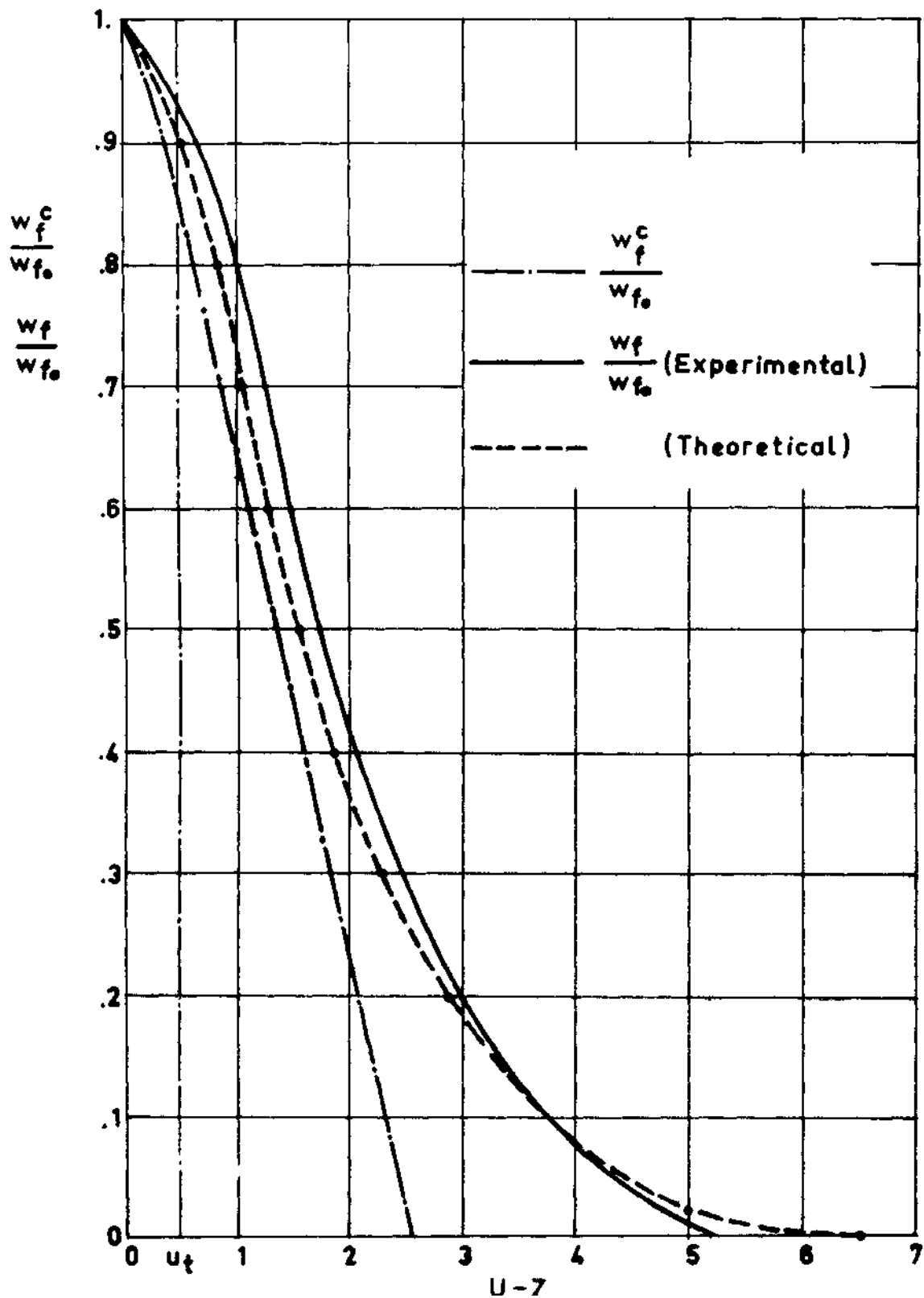This is because no experimental values were available of w for plate-shaped firebrands.

Fig.46 - Comparison of the Experimental Final Velocities
of Fall and the Theoretical Curve $w_f = F(Z)$
Derived from Curve $w^\wedge = F(U)$

expressions (46) and (47) is represented and compared with the
curve experimentally obtained. Function $w_f/w_{f,o} = F(U)$,

from which the theoretical curve has been derived, is also
shown.

It can be seen that the theoretical and experimental
curves agree very well, which shows that results corresponding
to actual conditions when firebrand fly and burn at their fi-
nal velocity of all can be deduced from results obtained by
burning firebrands at constant wind speed.

It can also be seen that the theoretical curve gives a
burning-out value of V , and then of time, longer than the
experimental value. This result is similar to that included
in paragraph 7, in which it was explained why the theoretical
results give longer combustion times than the experimental re-
sults obtained by burning firebrands suspended from a wire.
In this experimental way the final part of the combustion proc
ess, when the firebrands are very small, cannot be reproduced
and these tiny firebrands keep burning and flying for quite a
long time because their final velocity of fall is also extreme
ly small and therefore, they fall down and burn at very low
speed.

Finally, Fig.'+7 shows, for a particular case (cylindri_
cal firebrands of oak-wood) curves $w_f/w_{f,o} = f(t)$ calculated

from experimental data obtained by burning the firebrands at
constant wind speed and the experimental curves directly ob-
tained burning the firebrands at their final velocities of
fall. According to what it could be expected from the gener-
al comparison of Fig.46, experimental and calculated results
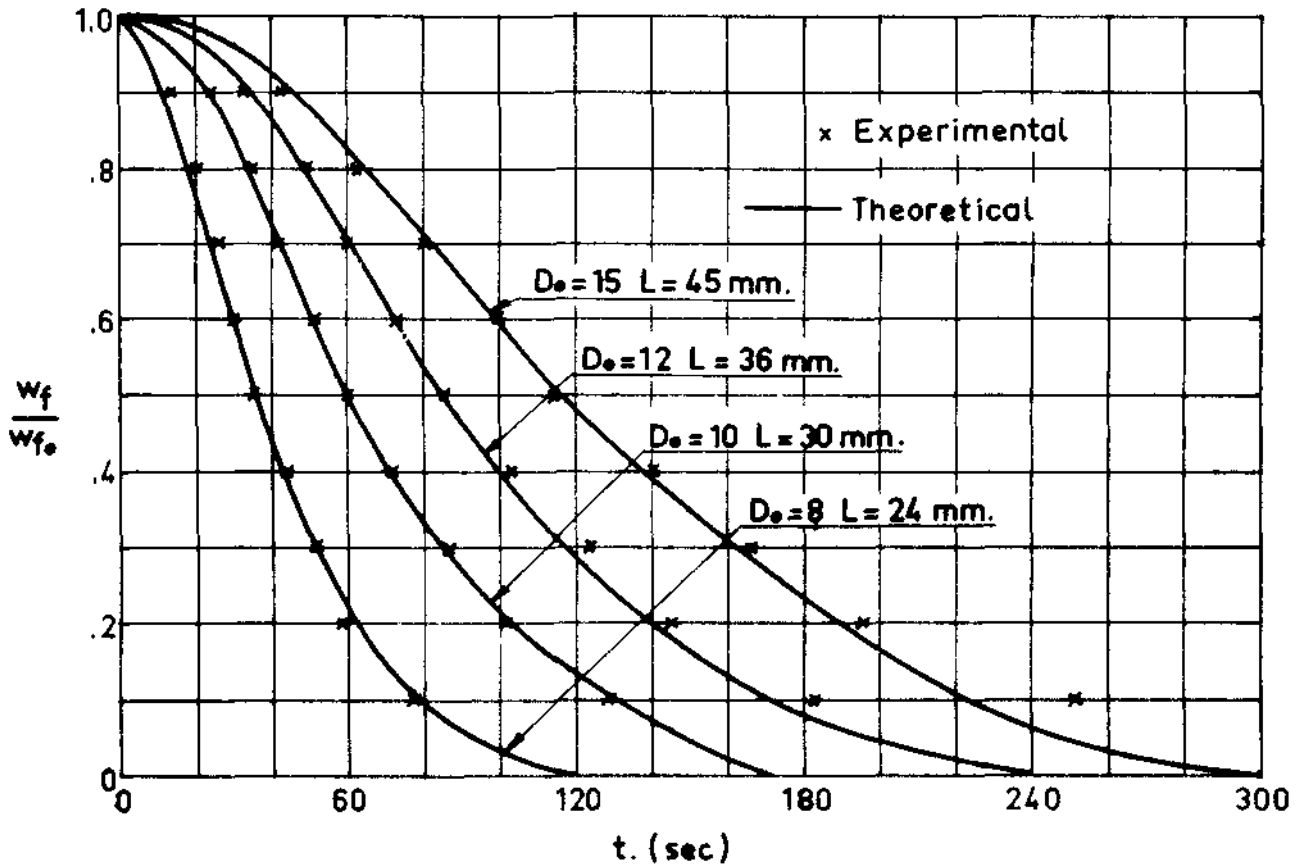are in an excellent agreement.

Fig.47 - Experimental Final Velocities of Fall w_f of Cylindrical
Firebrands of Oak Wood and Theoretical Values Derived
from Values of w   Obtained at Constant Wind Speed.

10 . <u>CONCLUDING REMARKS</u>

In the present study methods have been developed to
calculate the areas of possible fire spread by firebrands as
function of the wind conditions and convective currents and as
function of the initial characteristics of the firebrands.

The study has shown that flight paths can be accurate-
ly calculated by assuming that the firebrands fly at their fi-
nal velocity of fall, velocity which decreases continuously as
the firebrand burns. Therefore, testing facilities have been
developed to study combustion of firebrands at this variable
final velocity of fall. In addition, it has been shown that
these studies can also be performed starting from data obtain-
ed on the combustion of firebrands at constant wind speed.

The influence of the firebrand initial size and shape,
kind of wood and moisture content has been thoroughly investi-
gated, as well as the influence of the configurations of the
convection columns above the fire.

From the results of these studies it is possible to
calculate the maximum range of possible fire spread by fire-
brands of given initial characteristics, if the convection col
umn configuration and wind conditions are known.

Fire spread by firebrands depends essentially on the
convective currents and wind conditions in forest fires.There-
fore , an accurate knowledge of these phenomena is absolutely
required in order to apply correctly the information obtained
from the basic studies on firebrands. Information is especial

ly needed on the internal structures of convection columns in order to study the probability that firebrands may reach certain heights when carried upwards by the convective currents and being thrown away by turbulence. If this probability function were known, as well as the horizontal winds, statistical studies on firebrands could be carried out, which would give the probability of firebrands of given initial character istic falling at certain distance from the fire. Some of these statistical studies were carried out in the present research program, but in order to have realistic answers it is absolutely necessary to have more information on the complete aerodynamic field around a forest fire.

Another important area for which these studies could be applied is the problem of fire ignition by firebrands. This problem of ignition, depending on firebrand's properties when falling on the ground and on forest environment, is perhaps, the most promising area for a direct application of the basic studies on firebrands, especially in connection with prevention of ignition.

It is hoped that the studies included in the present Report will have contributed to the knowledge and solution of the fundamental problem of the prevention and suppression of forest fires.

Madrid, May 1967.

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PRINCIPAL SYMBOLS

A   Maximum cross sectional area of a firebrand

c   Values corresponding to combustion at constant wind sp-eed (superscript)

Cp   Aerodynamic drag coefficient

J)   Diameter of a spherical or cylindrical firebrand

g   Gravitational acceleration

1   Characteristic thickness of a plate-shaped firebrand

L   Axial length of a cylindrical firebrand or width of a plate-shaped firebrand. Also, initial distance from a firebrand to the convection column border line

m   Firebrand mass

o   Initial value (subscript)

r   Radius

Re   Reynold's number

t   Time

t^   Burning-out time

tf   Final time, equal to t^ or t

t,,   Ground time or flight time until the firebrand falls on the ground

u   Wind velocity

V   Absolute velocity of a firebrand. Also, volume of a fire brand

w   Relative velocity of the wind with respect to the fire-brand

Wf   Final or terminal velocity of fall

X   Horizontal axis; also subscript: x component.

X   Maximum horizontal range reached by a firebrand whiJe still burning

Y   Vertical axis; also subscript: y component

Y_m Critical height reached by a firebrand within a convection column for which maximum range X_m is reached.

a $= C_D A / 2m$

e_x, e_y Errors in length of the flight paths

x_I $= L_O / D_O$

A_2 $= V^D O$

$u_{a,OO}$ Air viscosity

X $= wt / D_Q$

$p_{a,OO}$ Air density

p_w Density of firebrand

? $= p_{a,OO} / p_{w,O}$