

**U.S. DEPARTMENT OF AGRICULTURE  
FOREST SERVICE**

**TRANSPORT AND COMBUSTION  
OF FIREBRANDS**

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

**INSTITUTO NACIONAL DE TECNICA AEROSPACIAL  
MADRID-SPAIN**

U. S. DEPARTMENT OF AGRICULTURE  
FOREST SERVICE

**TRANSPORT AND COMBUSTION  
OF FIREBRANDS**

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## F O R E W O R D

This research program has been sponsored by the Forest Service of the United States Department of Agriculture under *Grants* FG-Sp-114 and FG-Sp-146, monitored 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 Instituto Nacional de Técnica 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.

## A C K N O W L E D G E M E N T

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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 by 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 especially 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.

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## 1. INTRODUCTION

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 suppression much more difficult<sup>1,2</sup>.

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 horizontal winds they may ignite secondary fires at great distance, 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, essentially, 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, especially in connection with convection plumes, such as the works listed in references<sup>3, 4</sup> and<sup>5</sup>. 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 properties 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-11U- and FG-Sp-146.

The research program has been directed to the study of the flight characteristics and combustion properties of firebrands, including flight paths calculations, distances travelled 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 convection have also been carried out. They were not specifically included in the research program, but they have been conducted 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 dimensionless 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. Therefore, 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 firebrand 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 considered. 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:



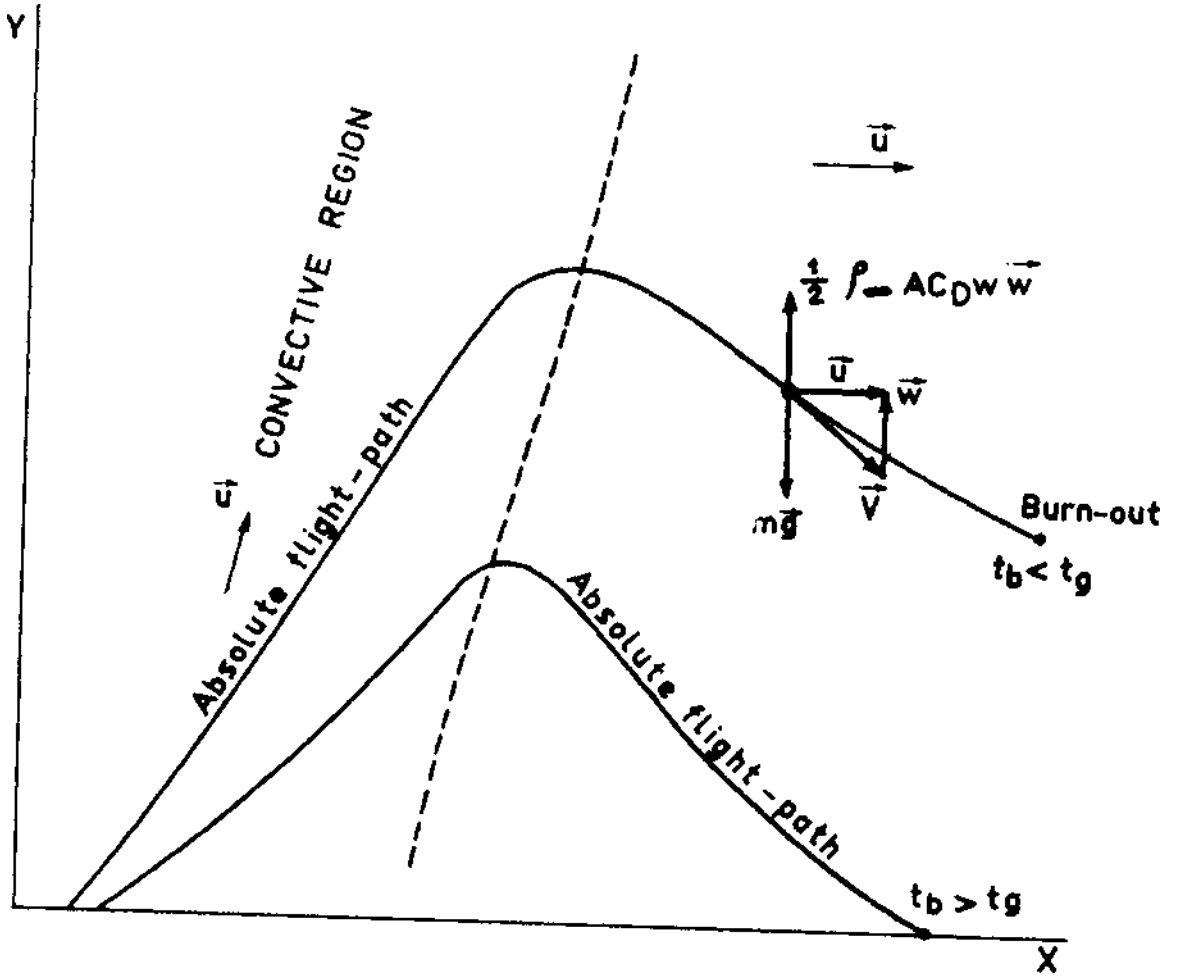


Fig.1 - Model of the Process

$$\vec{D} = -\rho_a - AC_D \vec{w} \vec{w} \quad (1)$$

in which  $\rho_{a,\infty}$  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 firebrand. In this last expression  $u$  is the velocity of the wind and  $V$  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:

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

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:

$$\begin{aligned} \frac{d}{dt} \vec{M} = m \frac{d\vec{V}}{dt} + \vec{V} \frac{dm}{dt} + \vec{V} \int_{\Sigma} \rho_g (\vec{w}_e \vec{n}) d\sigma + \\ + \int_{\Sigma} \rho_g \vec{w}_e (\vec{w}_e \vec{n}) d\sigma, \quad (4) \end{aligned}$$

in which  $m$  is the mass of the solid part of the firebrand,  $\rho$  is the density of the gases ejected through the firebrand surface  $T$ , and  $w_e$  is the ejection velocity of these gases measured with respect to the center of gravity.

Since:

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

it results

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

The term:

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

represents the self-propulsion force of the firebrand originated by the combustion process. This force will normally be zero or very small. Gas density  $\rho$  resulting from the combustion process will be practically constant all over the firebrand surface and ejection velocities  $w_e$  if they are not

constant over that surface are, 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  $F_p$  will be taken equal to zero and the equation of motion will reduce to the expression:

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

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:

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

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

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

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

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

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:

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

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:

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

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

Another important variable of the process is the burning-out time  $t_b$  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  $t_b = t_o$  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

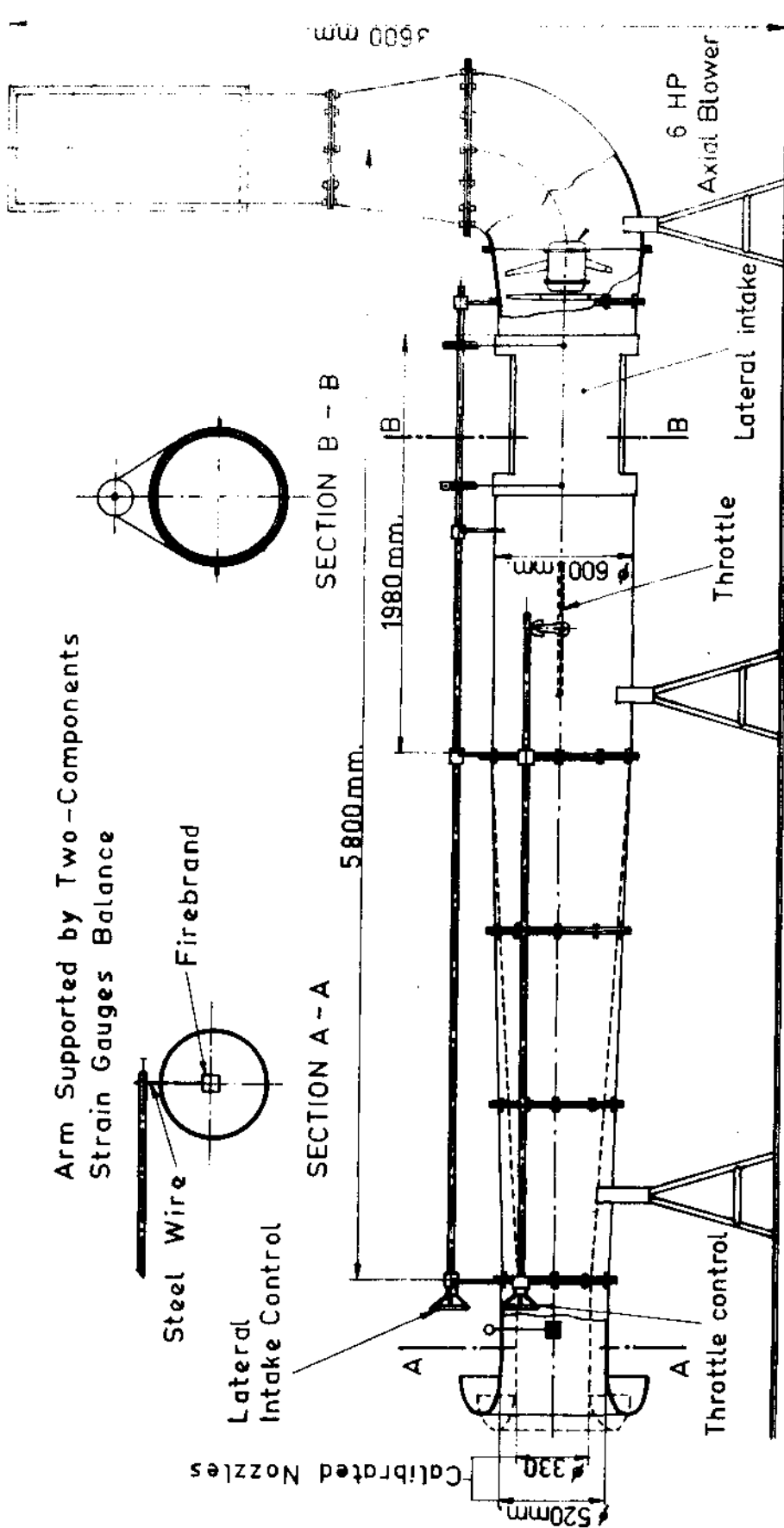


Fig.2 - Horizontal Wind-Tunnel

kind exists on this problem. Therefore, function  $a(w,t)$  as well as the burning time  $t_1$ , will be determined experimentally.

It was selected the experimental procedure of measuring the weight and the aerodynamic drag of burning particles 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  $C_n$  by measuring the aerodynamic 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 sufficient 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 section of the tunnel, it was very easy to control the wind speed acting on the firebrand by means of lateral intakes of variable area.

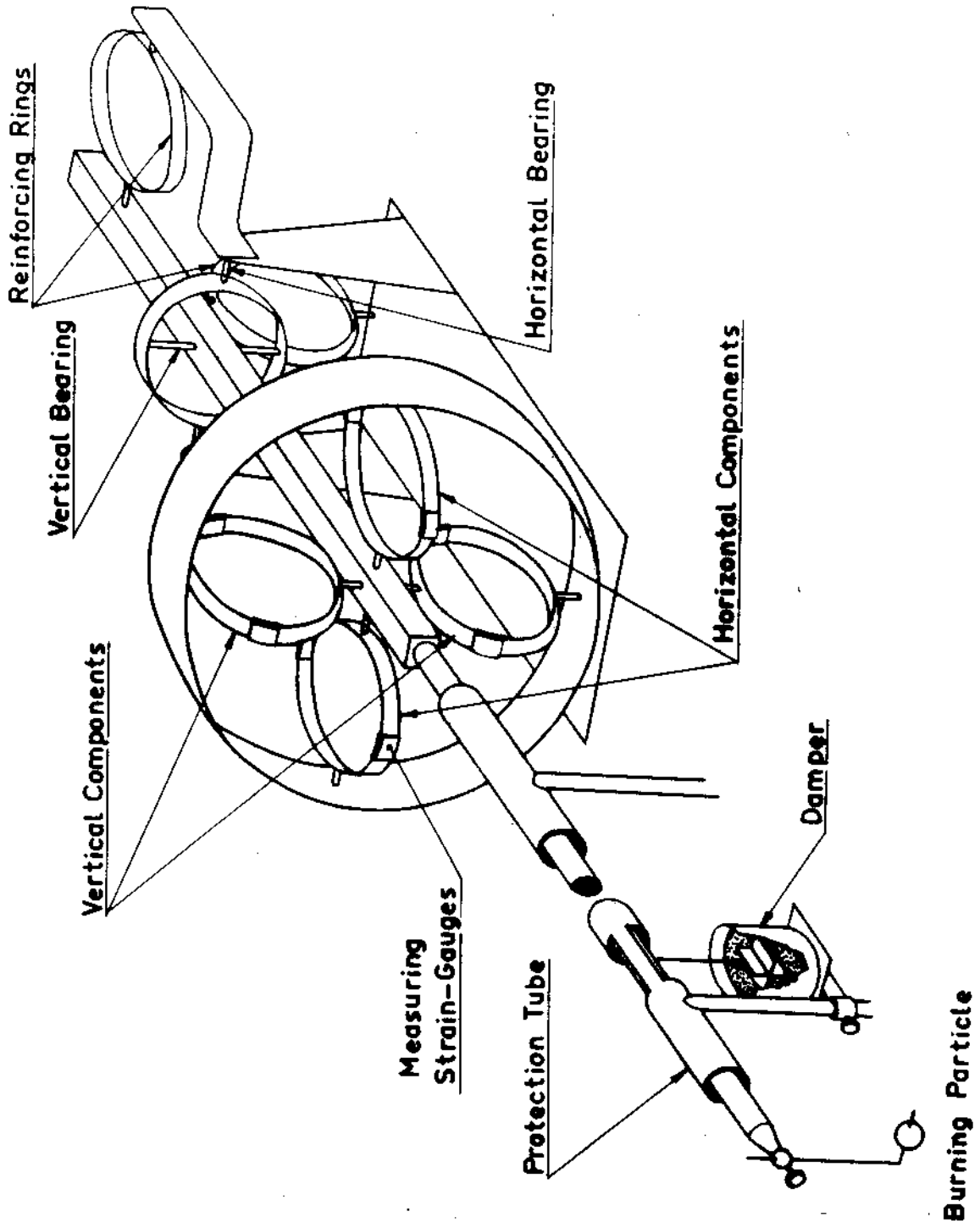


Fig.3 - Two-Components Strain-gauges Balance.



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 periphery 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 aerodynamic 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 resistances.

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 electrical 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

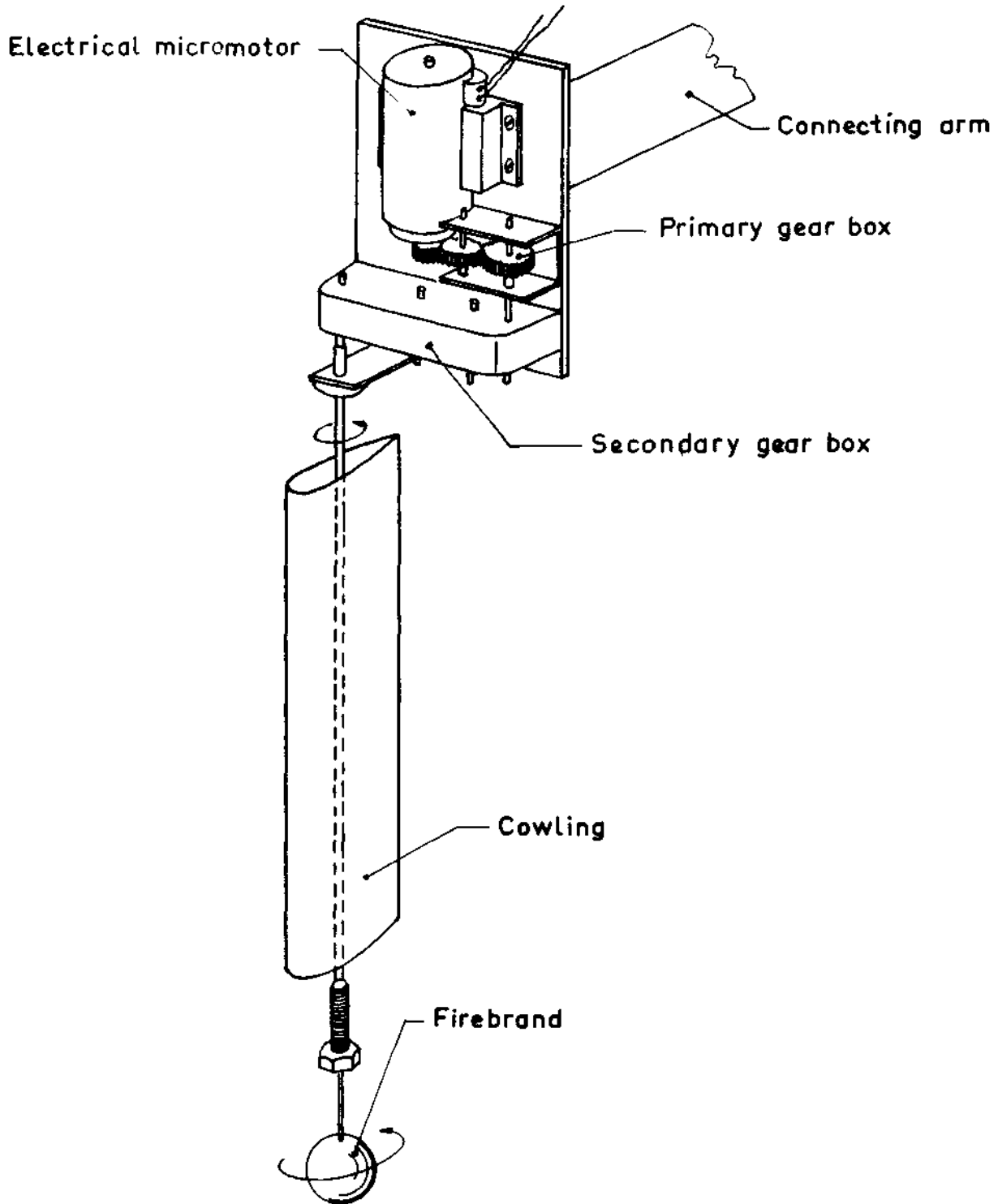


Fig.4 - Rotating Device of Firebrands

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)

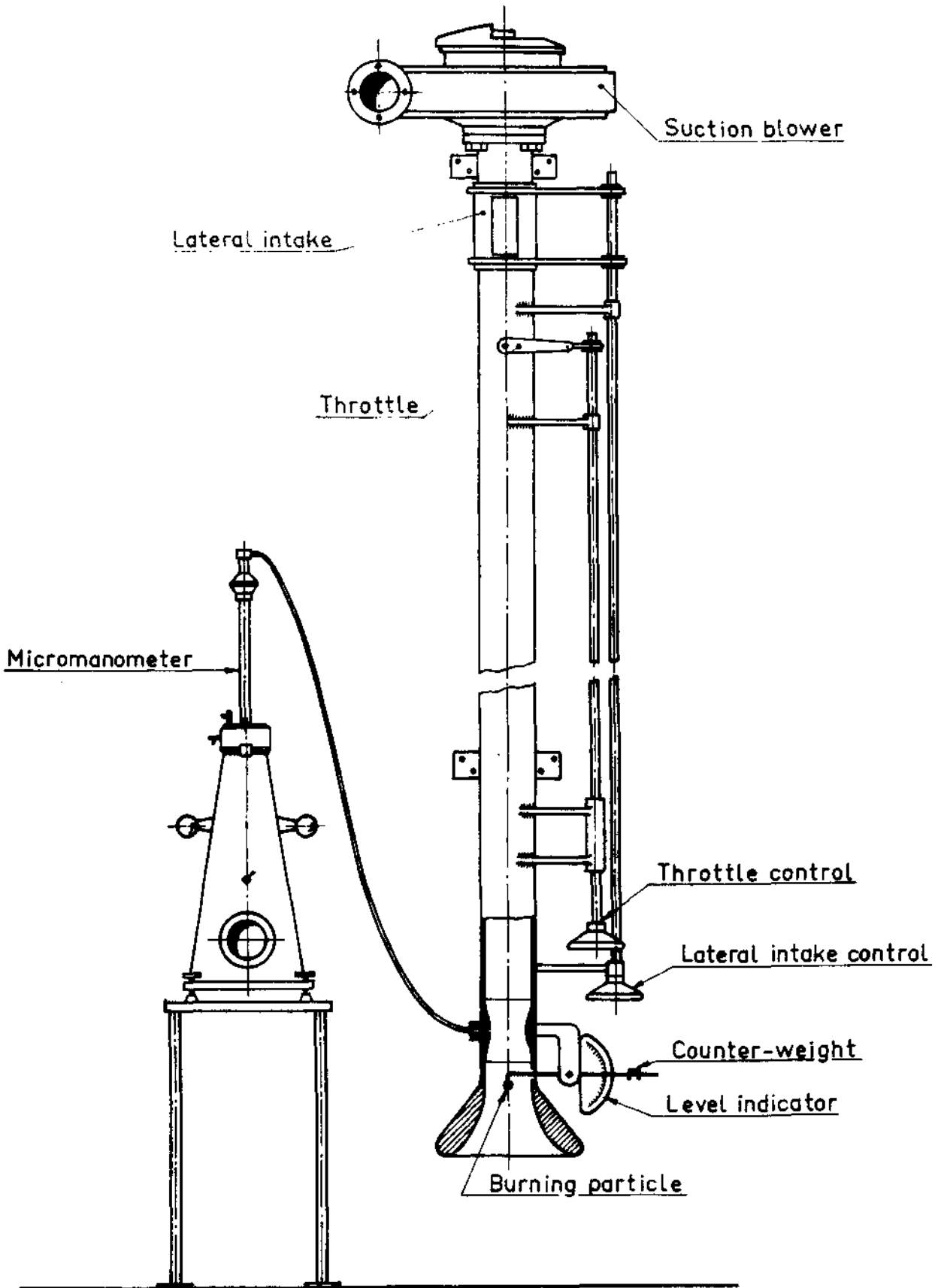


Fig.5 - Vertical Wind-Tunnel

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 maintained at an angle of  $45^\circ$  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 freely 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 material 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 centrifugal blower.

The wind tunnel is calibrated by introducing in it

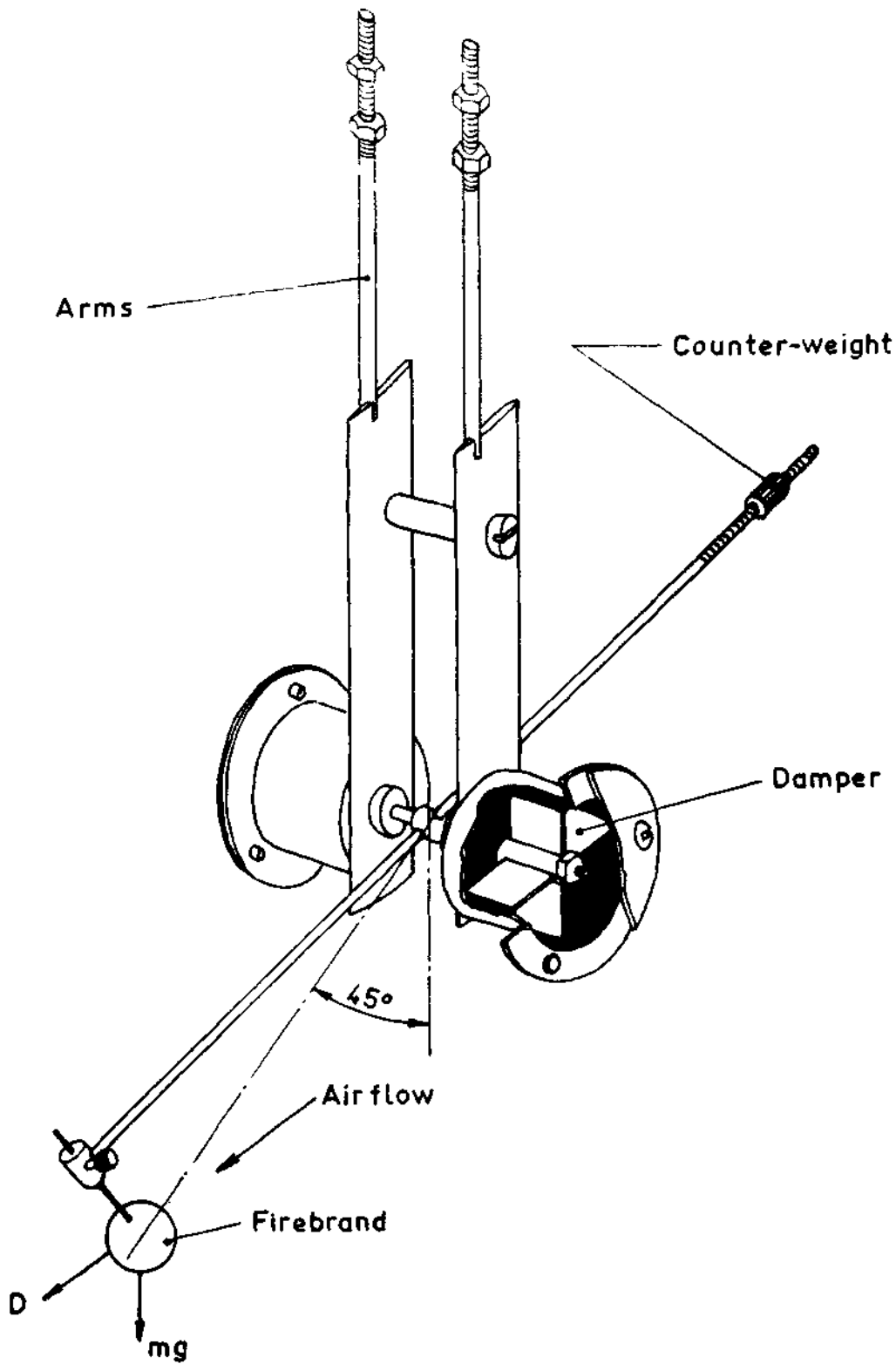


Fig.6 - Device for Burning Firebrands at Final Velocity of Fall in the Horizontal Wind Tunnel

several wood spheres of different size. Their final velocities 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.

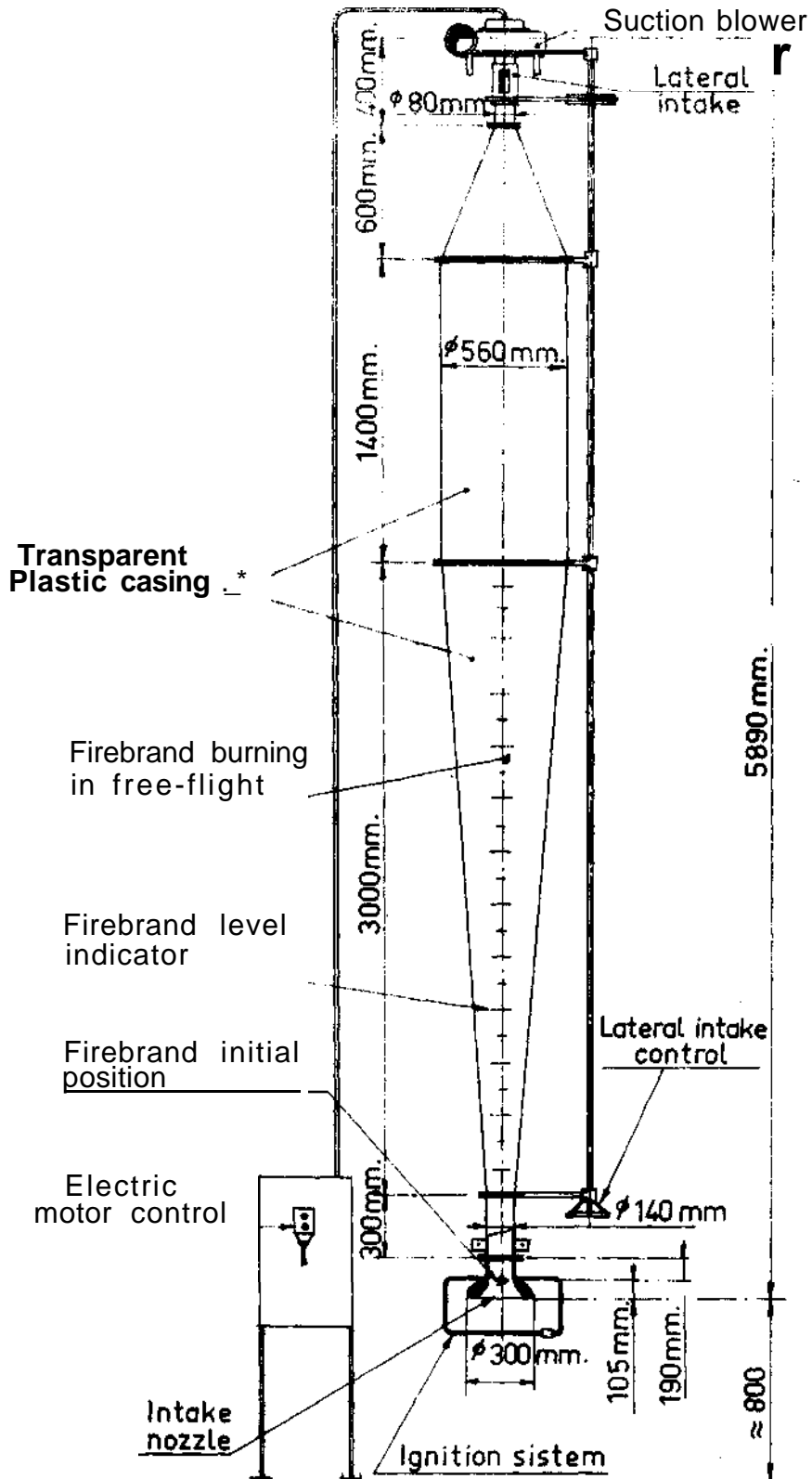
When a firebrand is introduced through the lower intake it climbs up as it turns, and its final velocity of fall is recorded by comparison with that of the sphere with the same average location or by taking photographs.

At first, the wind tunnel had a high degree of vorticity and the firebrands had a strong tumbling motion. This effect was reduced to tolerable limits after several modifications.

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 velocities of fall and results agree well with those obtained with the vertical or horizontal wind tunnels in which the firebrands were kept attached at a fixed position.

However, with this tunnel measurements of terminal velocities of fall are lengthy and somewhat difficult due to 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.



7 - Vertical Wind Tunnel for Burning Firebrands in Free 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. <sup>10</sup> it is shown that these non-burning particles approach very rapidly their final velocities of fall given by conditions:

$$w_x = 0 \quad (16)$$

$$w_y = w_f = f - M a^{1/2} \quad (17)$$

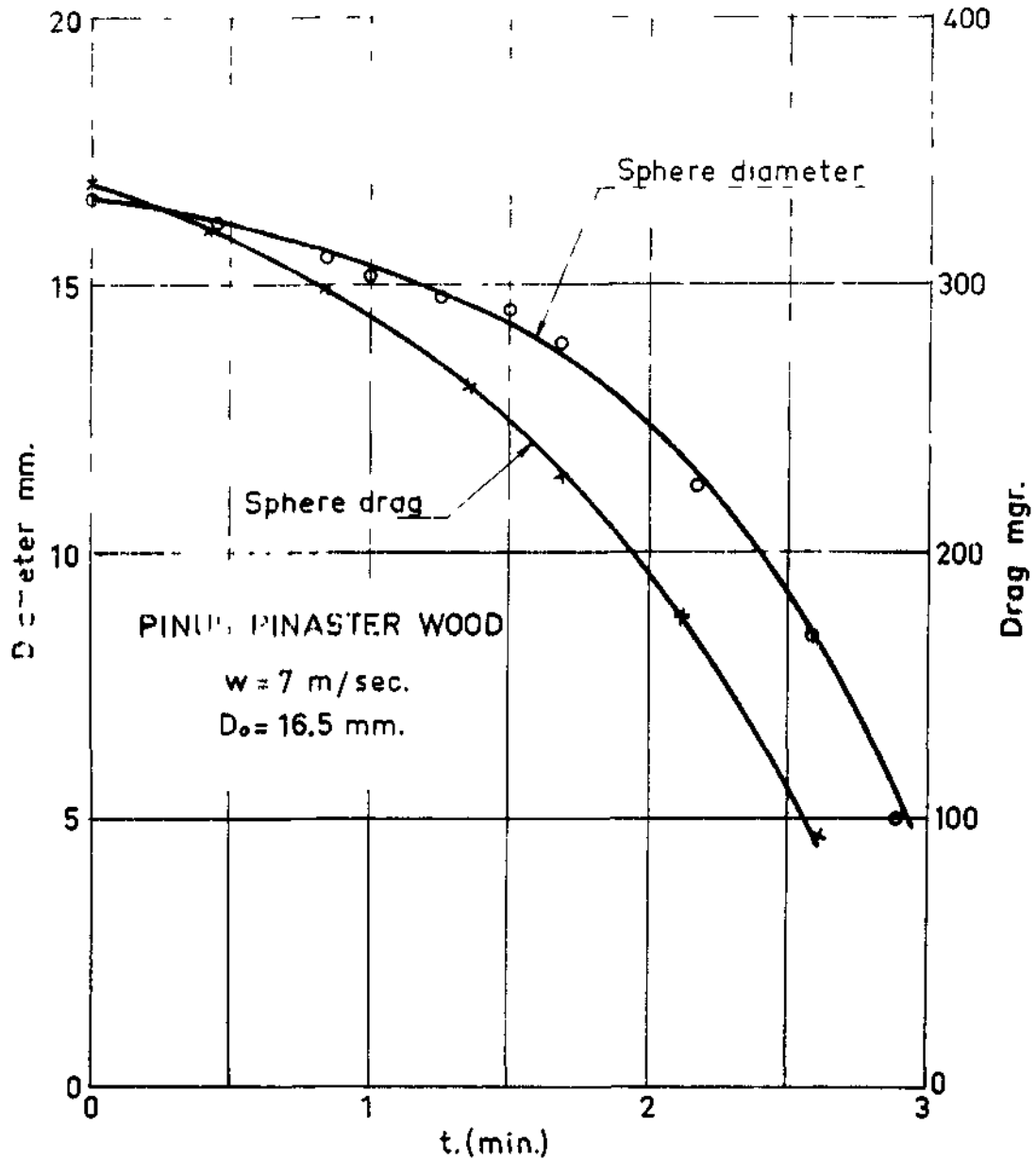


Fig.8 - Aerodynamic Drag of a Burning Sphere of Pine-Wood,

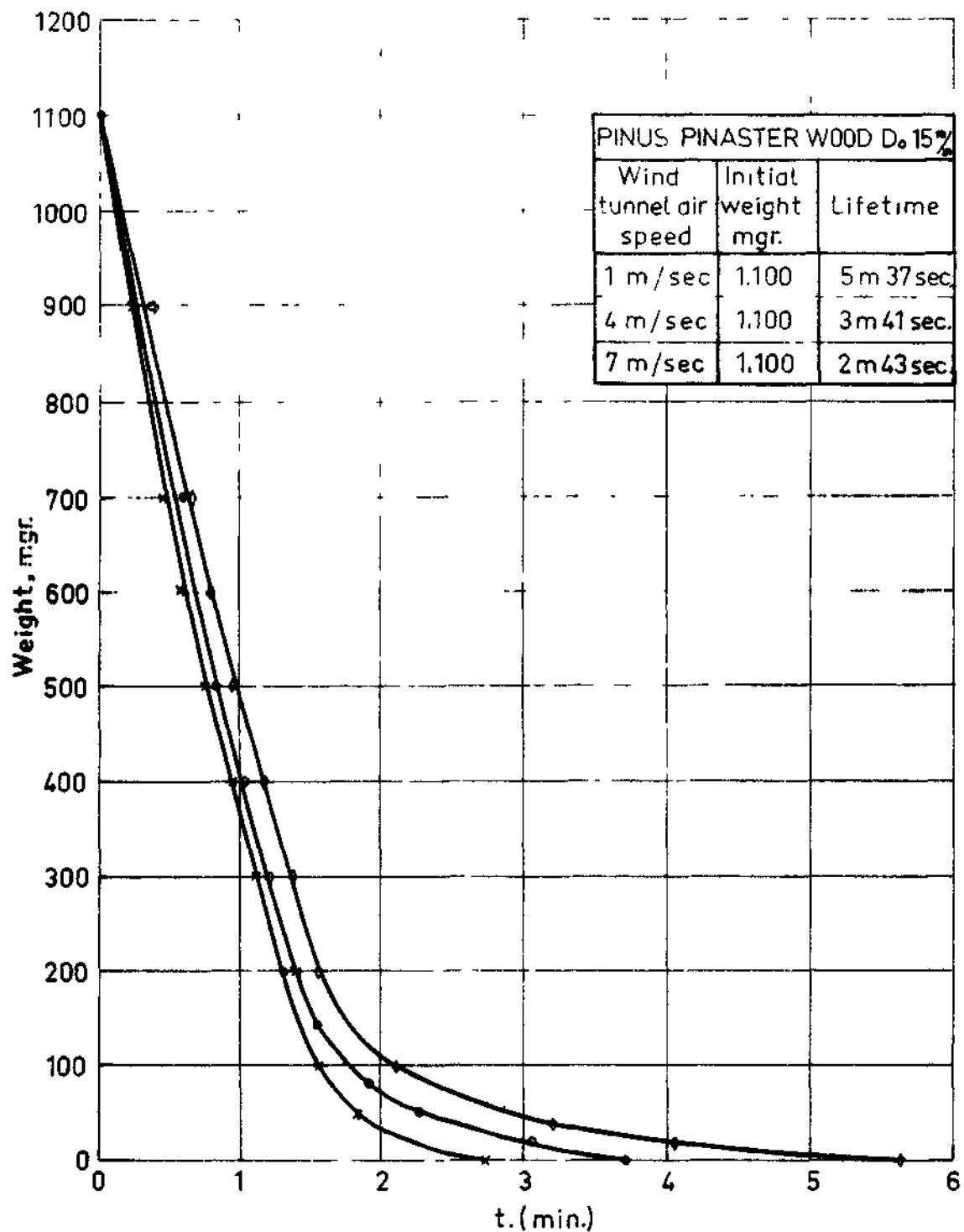


Fig.9 - Weight-Time Curves of Burning Spheres of Pine-Wood

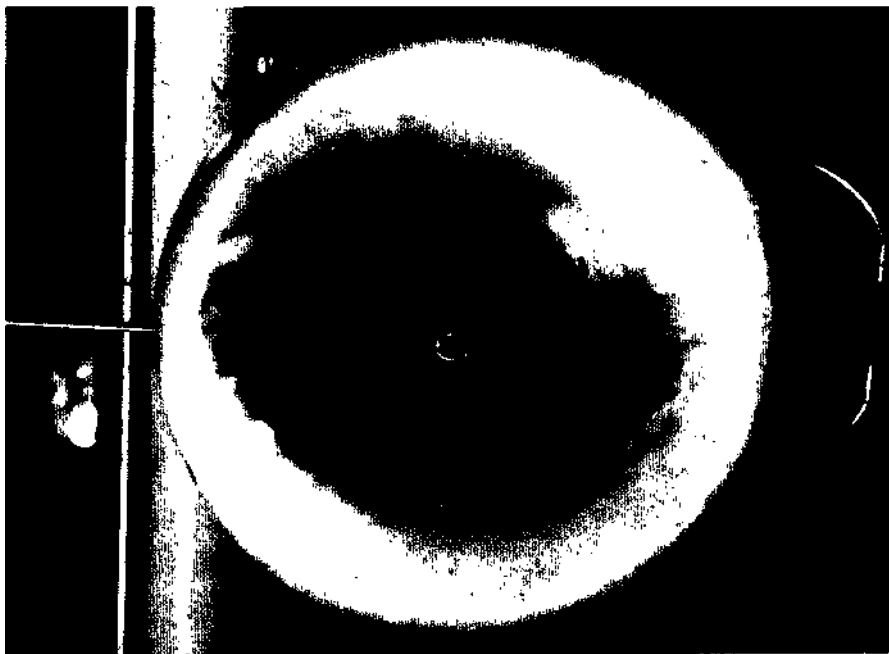


Fig.10. Photographs of firebrands burning in the small wind tunnel.

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 conditions it is easily shown that the asymptotic solution of eq. (12) is also given by:

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

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 diameters of 17 mm and 25 mm. An initial value of  $w_{x,0} = 20$  m/sec has been taken and for the vertical component of velocity two cases have been considered:  $w_{y,0} = 20$  m/sec and  $w_{y,0} = 0$ .

The first case would correspond to the initial flight conditions 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 component 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 velocity,  $w_x$  and  $w_y$ , tend very rapidly towards zero and towards  $w_p$  respectively.

These times are compared in Fig.13 with the burning-

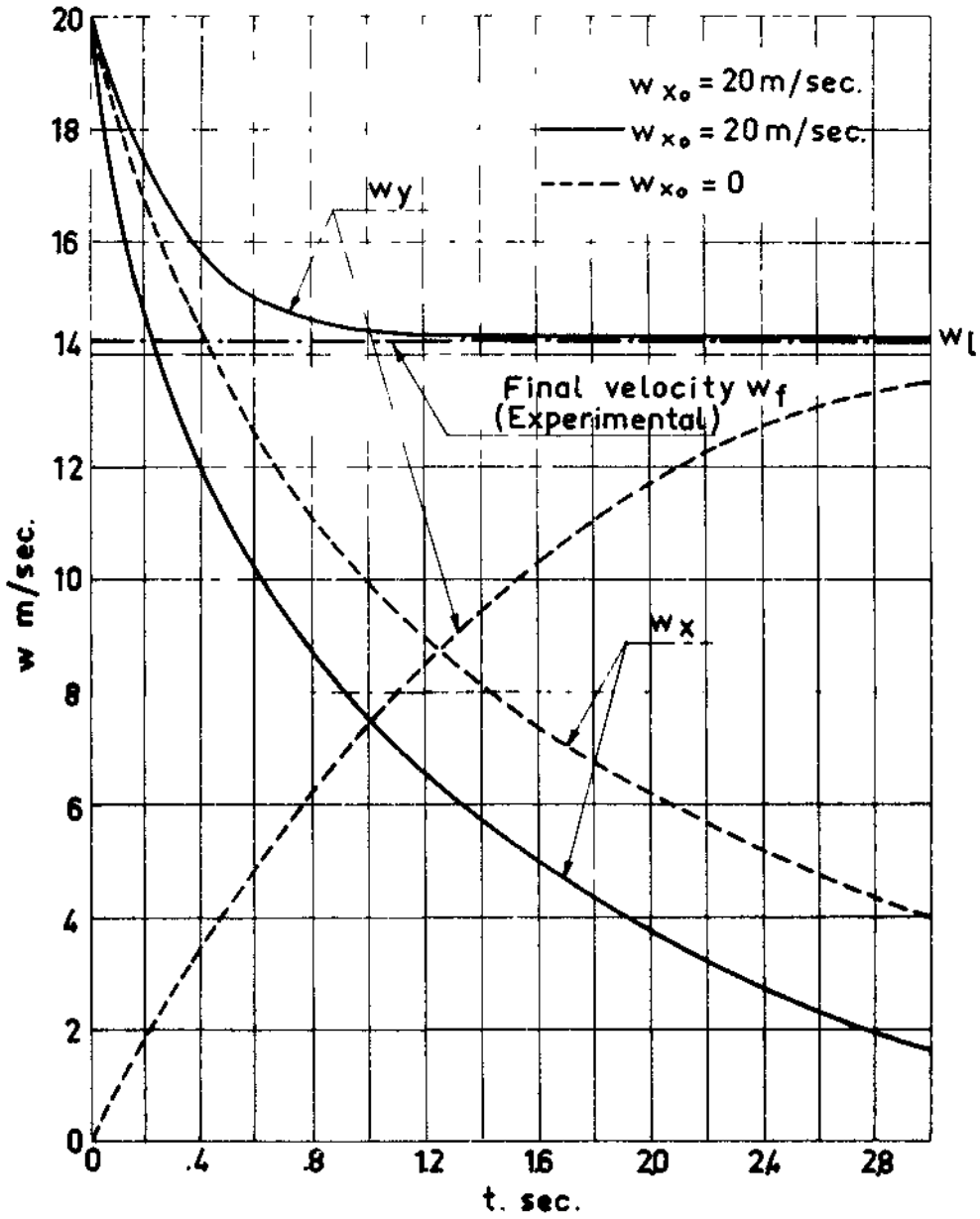


Fig.11 - Calculated Velocity Components  $w_x$  and  $w_y$  and Experimental Final Velocity of Fall  $w_z$  of Spherical Firebrand of Pine Wood.  $D = 17$  mm,  $t_f = 140$  sec.

out times, which are two orders of magnitude greater than the time required for the firebrand to approach the asymptotic velocity 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 by this simplifying assumptions, upper bounding or majorant expressions  $W_x$  and  $W_y$  for  $w_x$  and  $w_y$  were obtained,

They were derived considering that:

$$- \frac{dw_x}{dt} = \alpha w w_x \geq \alpha_0 w w_x \quad (19)$$

$$- \frac{dw_y}{dt} = \alpha w w_y - g \geq \alpha_0 w w_y - g \quad (20)$$

$$\left\{ \text{for } w_{y,0} > \left( \frac{g}{\alpha_0} \right)^{1/2} \right\} ,$$

and integrating analytically equations (11) and (12) for  $a = a_0$  (Ref.<sup>10</sup>). It is obtained:

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

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

$$w_{z_0} = 0$$

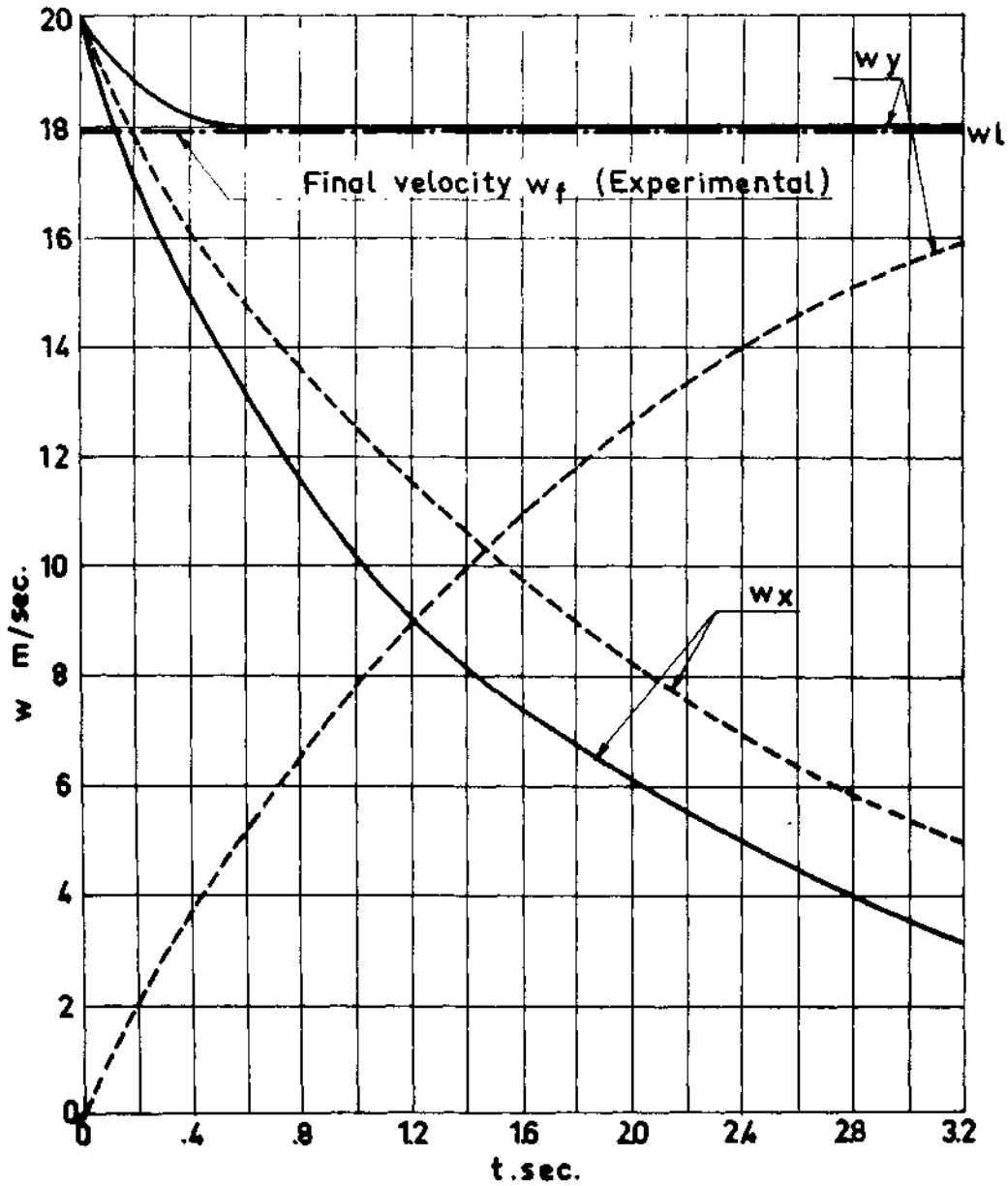


Fig. 12 - Calculated Velocity Components  $w_x$  and  $w_y$  and Experimental Final Velocity of Fall  $w_f$ . Spherical Firebrand of Pine Wood.  $D = 22 \text{ mm}$ ,  $t_D = 195 \text{ sec.}$



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

(21)

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

(22)

With these expressions it can be verified that the time required 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 :

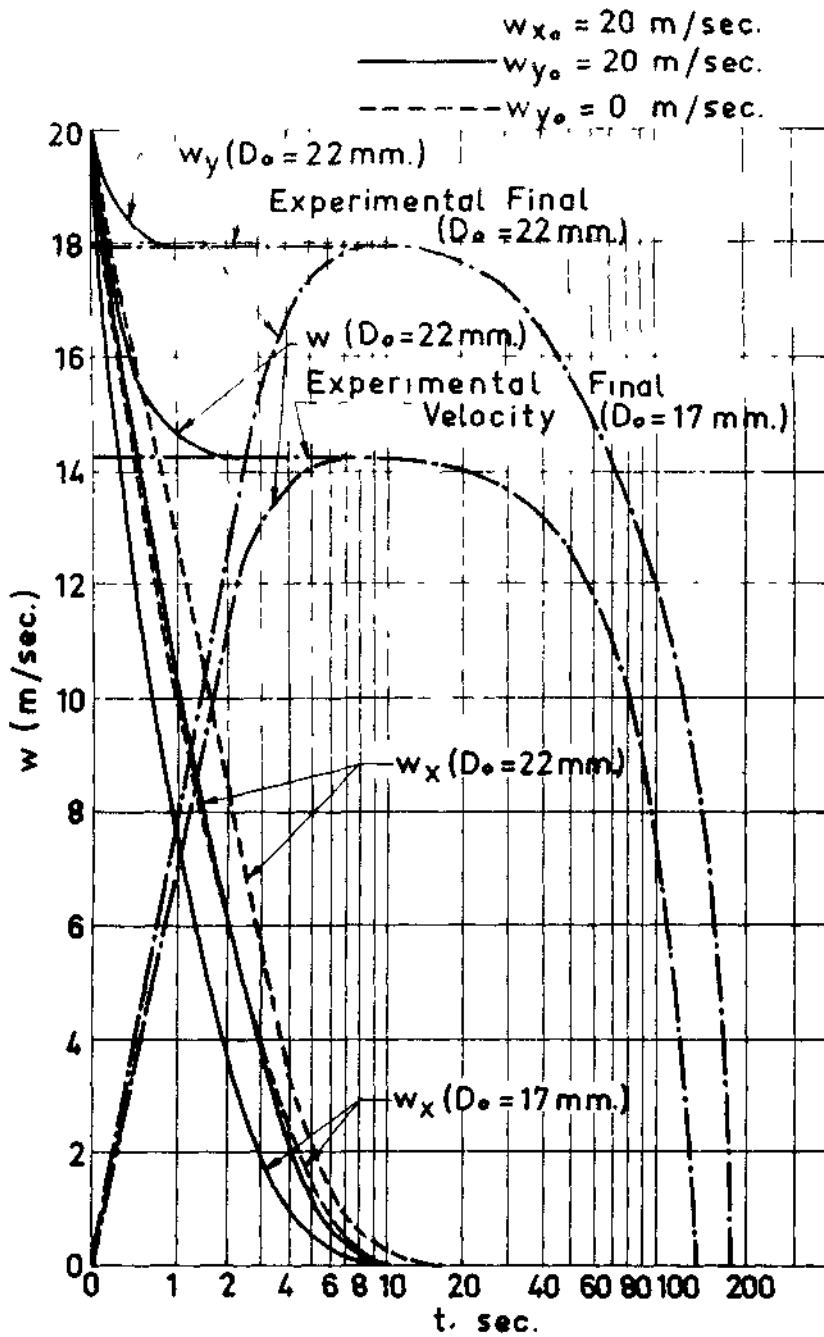


Fig.13 - Comparison of Numerically Integrated Values of  $w$  and  $w$  and Experimental Final Velocities of Fall.  
y

$$\epsilon_x = \frac{\int_0^{t_f} w_x dt}{\int_0^{t_f} (u_x - w_x) dt} \approx \frac{\int_0^{t_f} w_x dt}{u_x t_f} \quad (23)$$

$$\epsilon_y = \frac{\int_0^{t_f} (w_y - w_f) dt}{\int_0^{t_f} (u_y - w_y) dt} \approx \frac{\int_0^{t_f} (w_y - w_f) dt}{u_y t_f - \int_0^{t_f} w_f dt} \quad (24)$$

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 extremely small provided that the wind is 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 the firebrands fly all the time at their final velocities of the flight paths are given by the expressions:

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

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

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

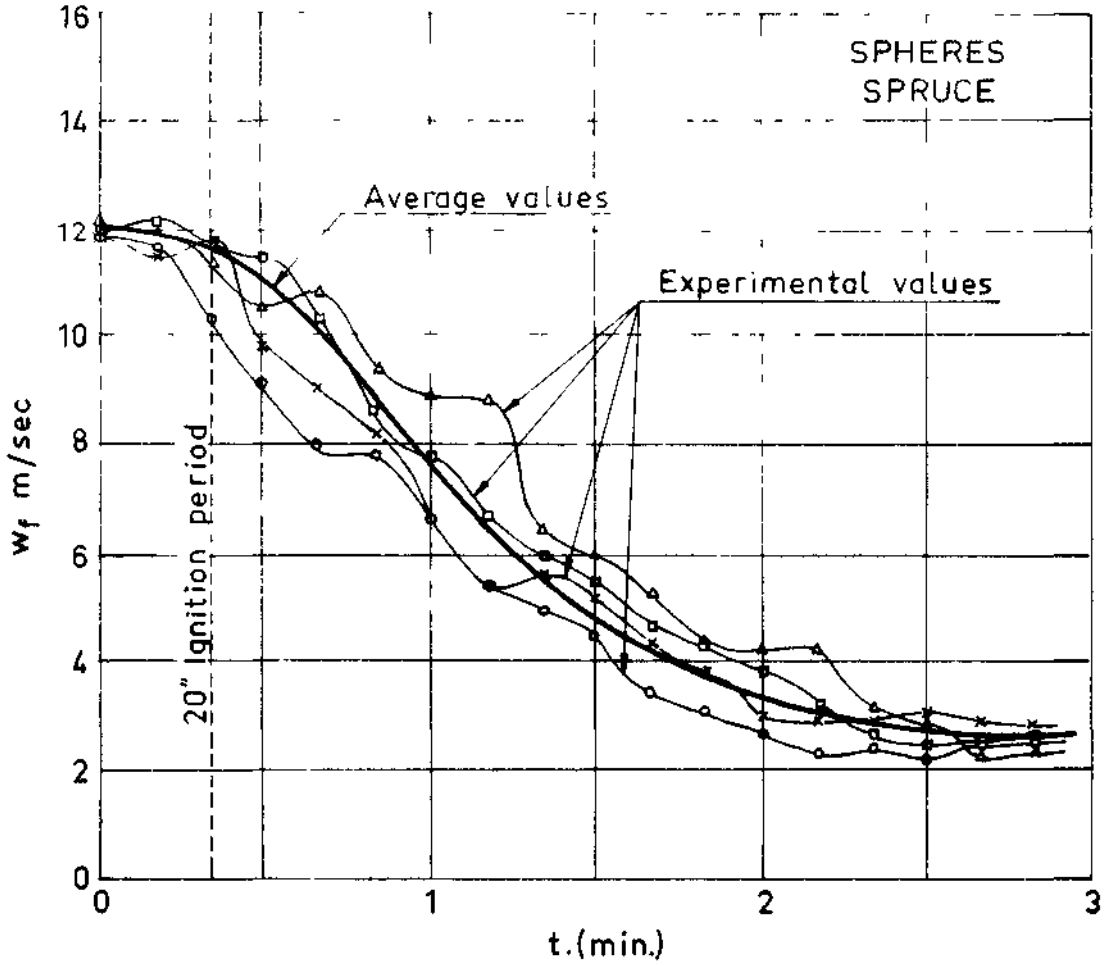


Fig.14 - Experimental and Average Values of Final Velocities of Fall as Functions of Time

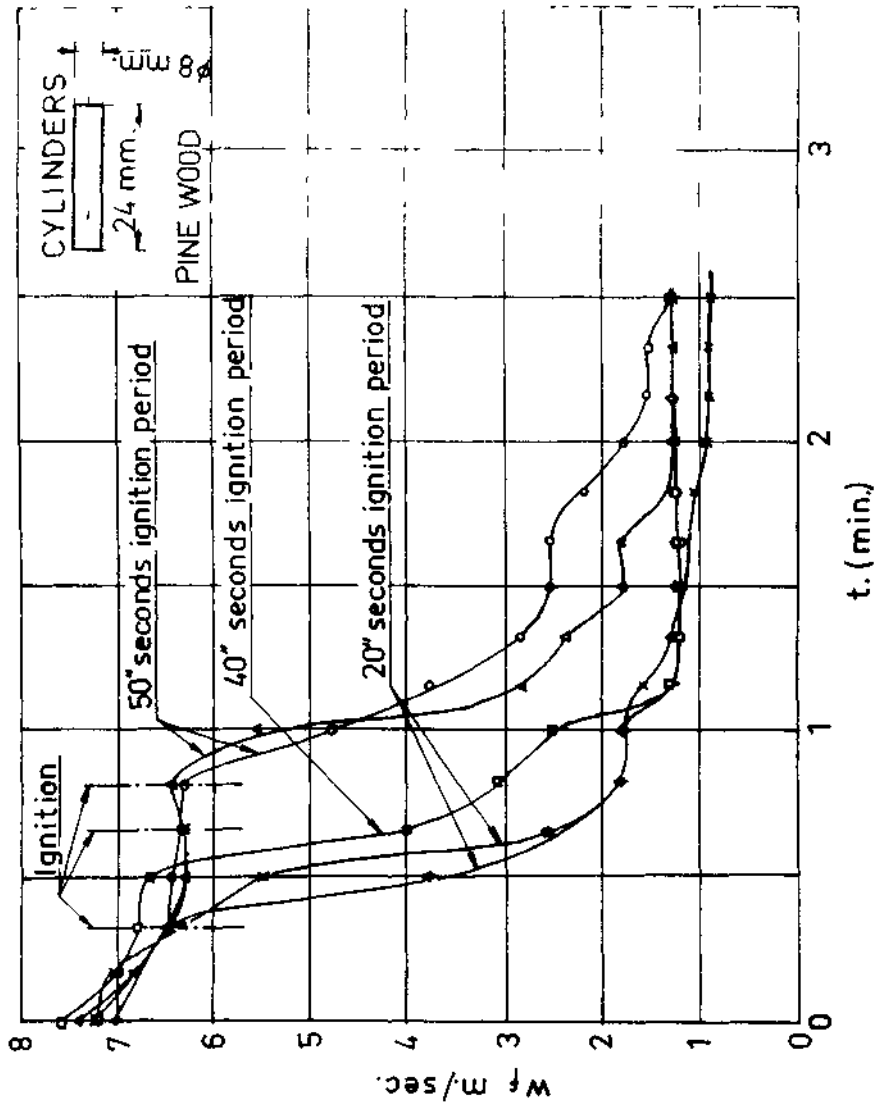


Fig.15 - Influence of Ignition Time on Curves of Final Velocities of Fall as Function of Time

determination of the terminal velocities of fall  $w_{\infty}$  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  $w_{\infty} = f(t)$  depends appreciably on the ignition process, since the gases of the ignition torch have a lower density than that of the ambient air. Therefore, **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 extensive research program on final velocities of fall has been carried out, Results are shown in full in references through <sup>9</sup> and <sup>13</sup> 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

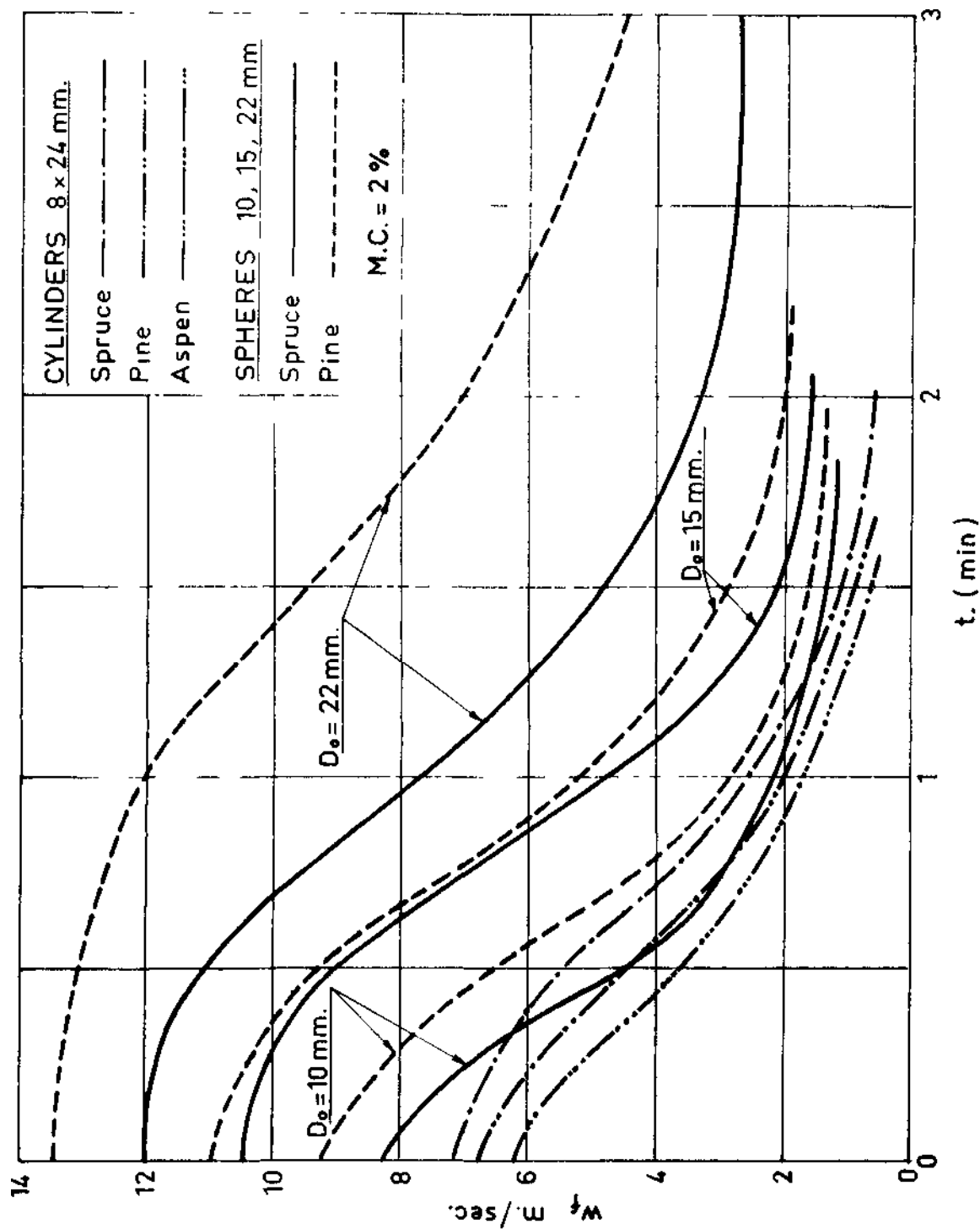


Fig.16 - Final Velocities of Fall. Cylindrical and Spherical Firebrands of Spruce, Aspen and Pine Woods.



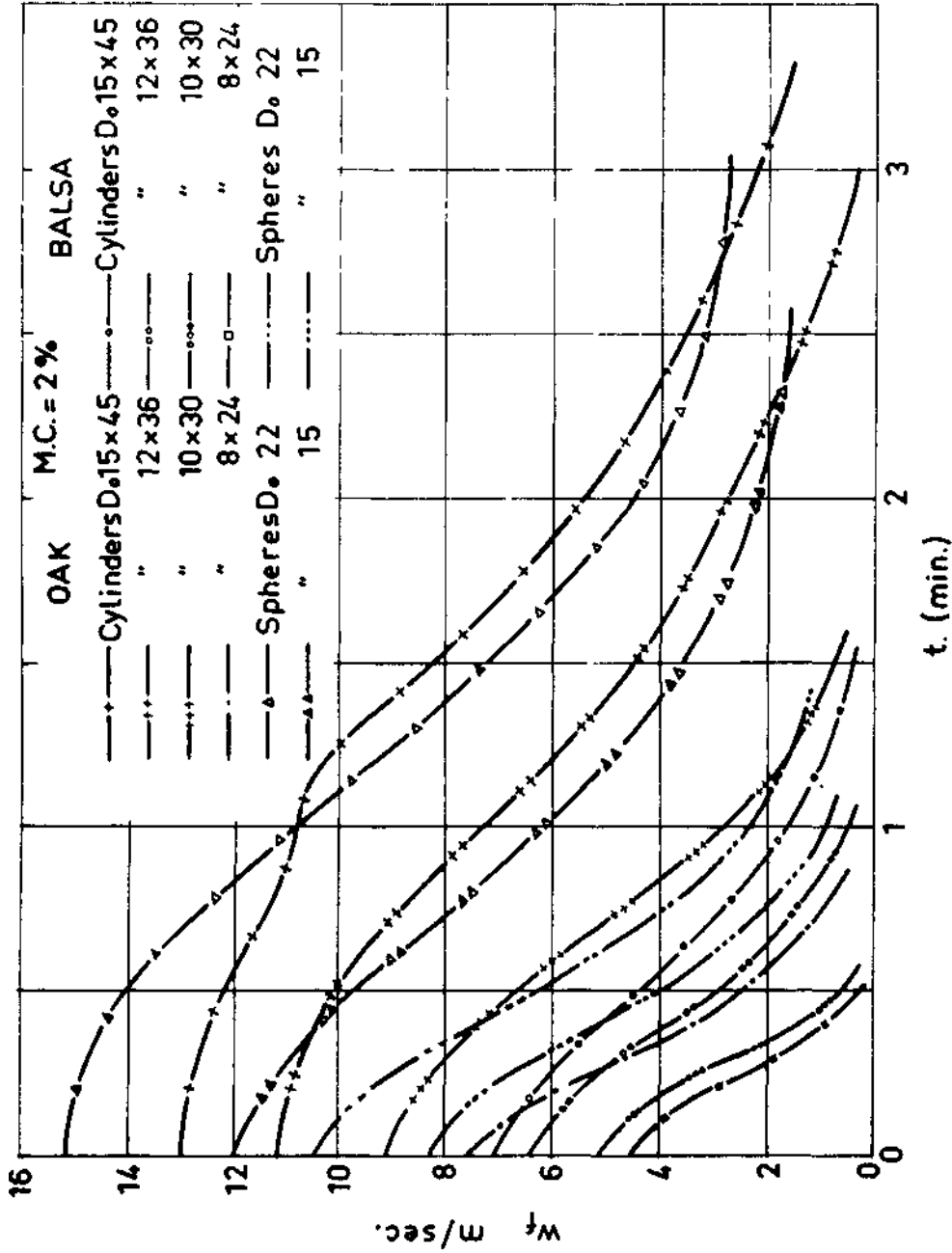


Fig.17 - Final Velocities of Fall. Cylindrical and Spherical Fire-brands of Balsa and Oak Woods.

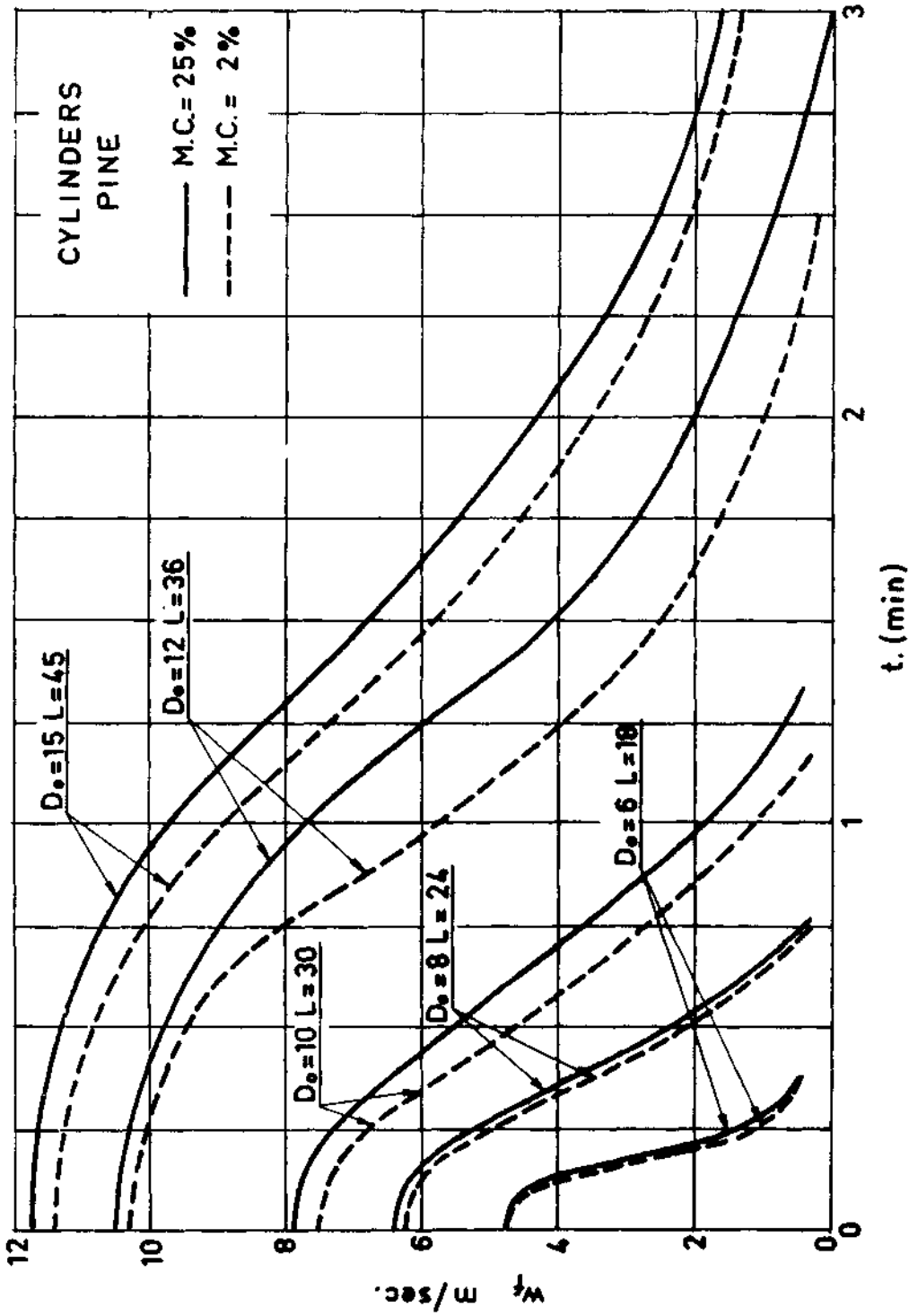


Fig.18 - Final Velocities of Fall. Cylindrical Firebrands. Pine Wood. Moisture Contents of 2% and 25%.

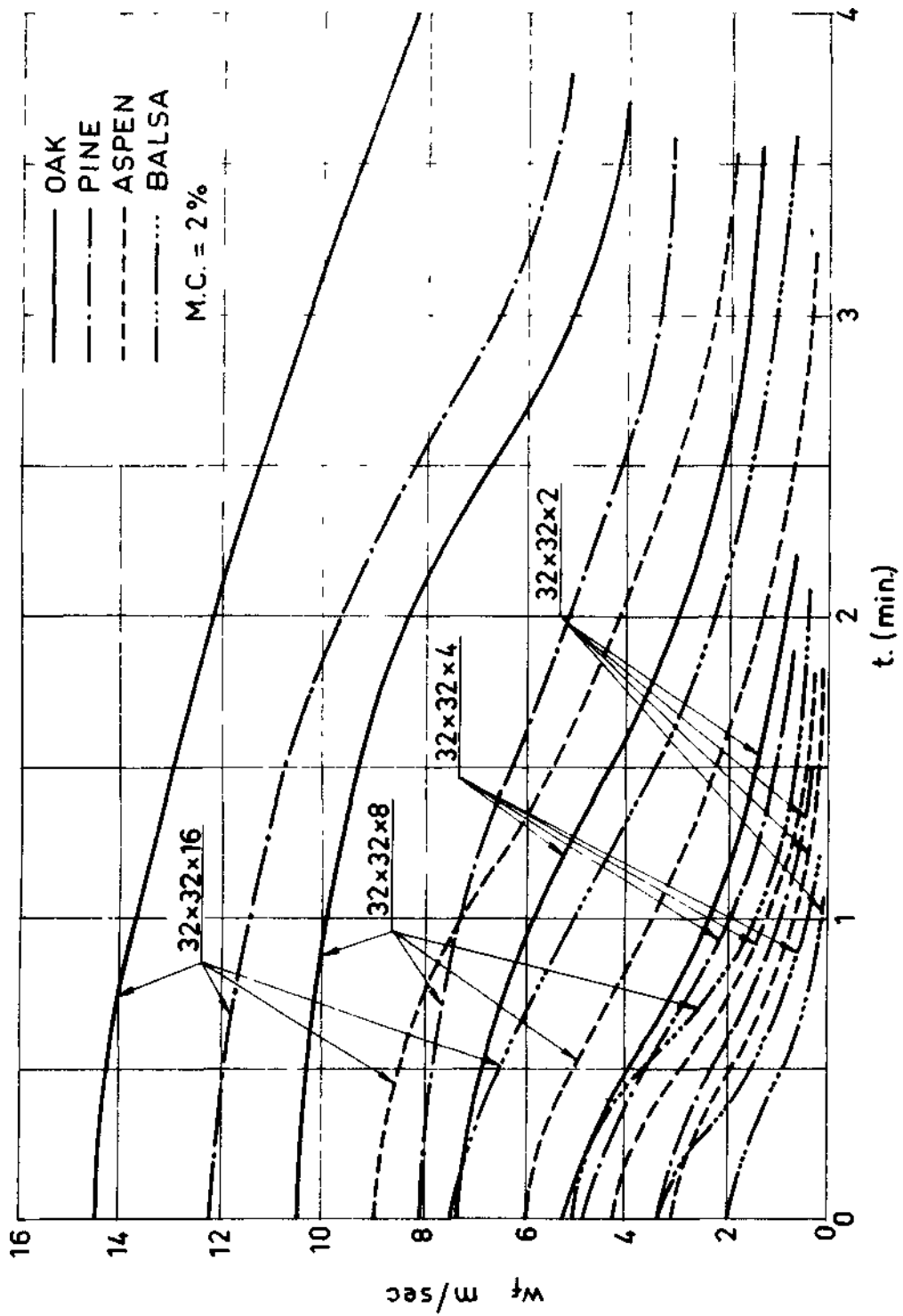


Fig.19 - Final Velocities of Fall. Square Plates Firebrands of Oak, Aspen, Balsa and Pine Woods.

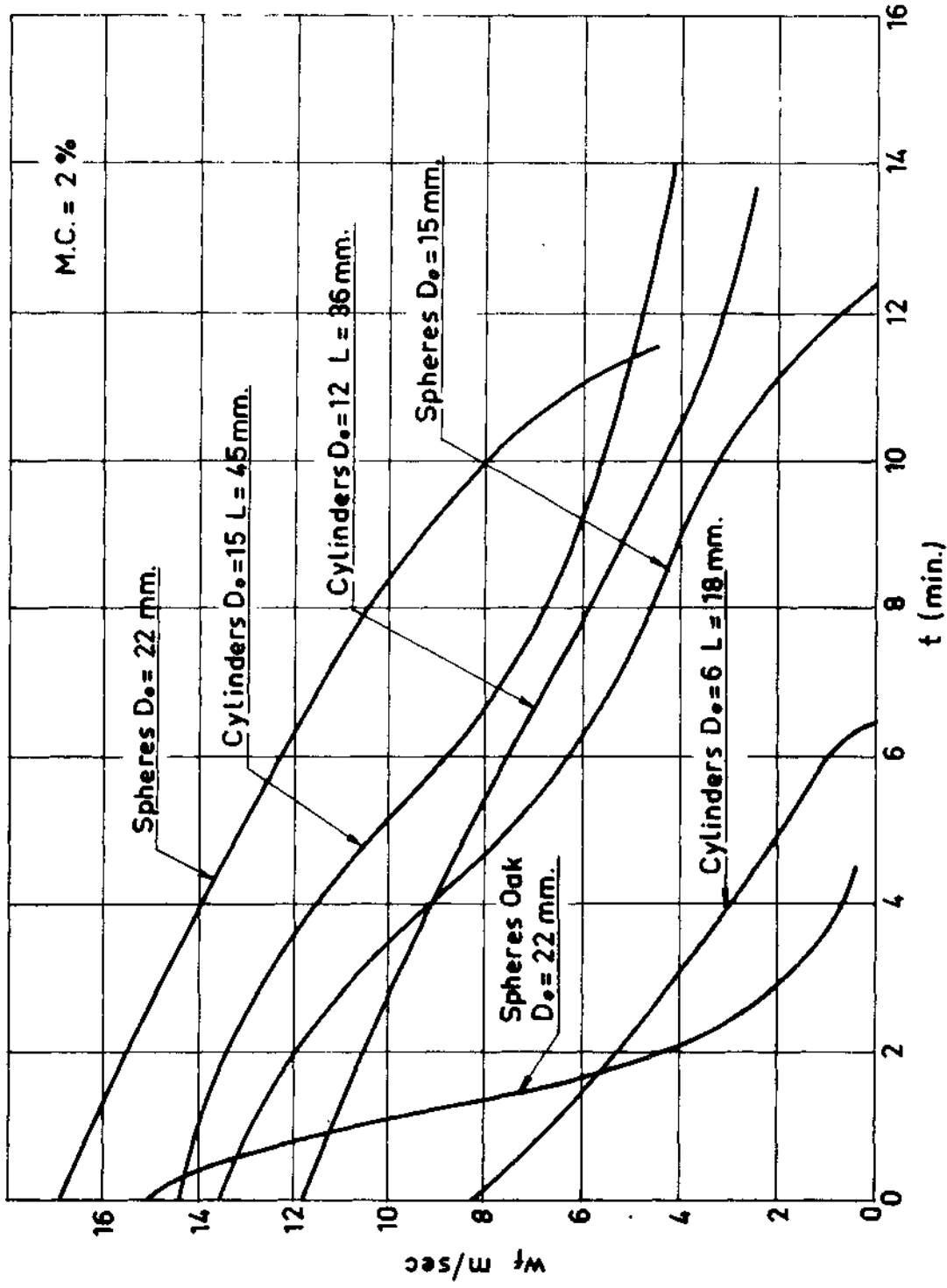


Fig.20 - Final Velocities of Fall. Spherical and Cylindrical Charcoal Firebrands

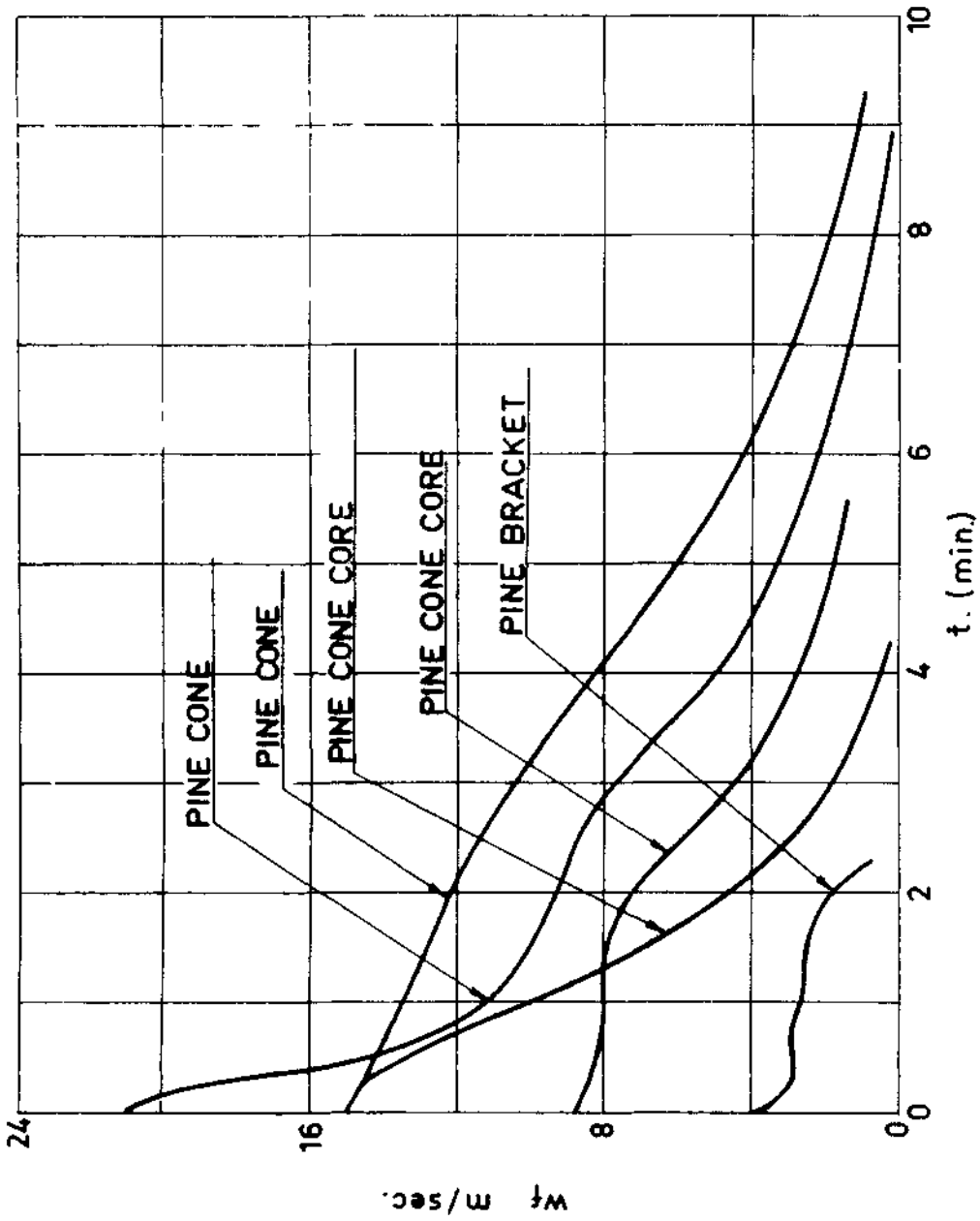


Fig. 1 - Velocity Curves of Fall of Natural Fir-Cones.

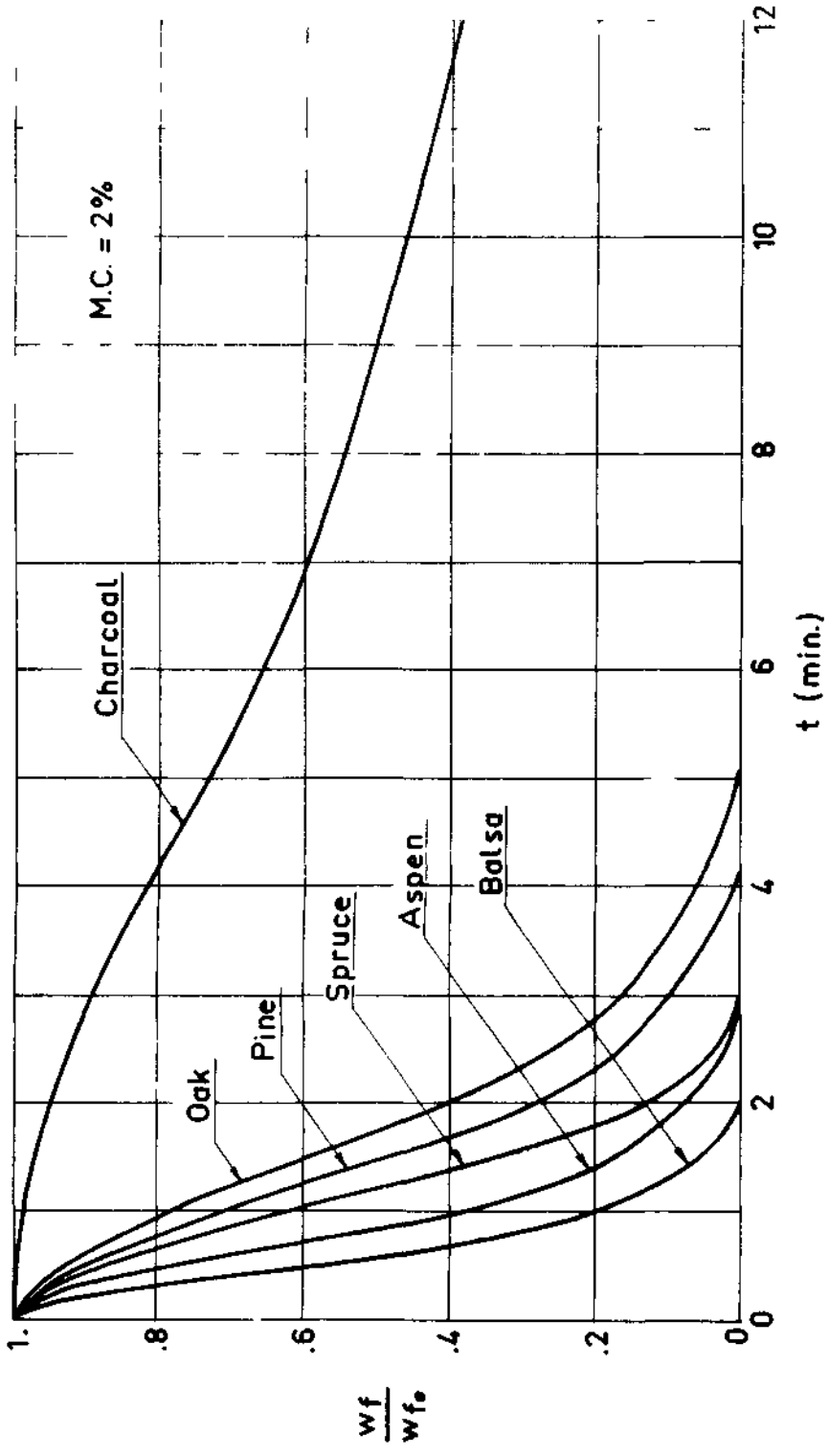


Fig.22 - Final Velocities of Fall. Cylindrical Firebrands of Equal Size ;  
 Balsa, Aspen, Spruce, Pine and Oak Woods and Charcoal.

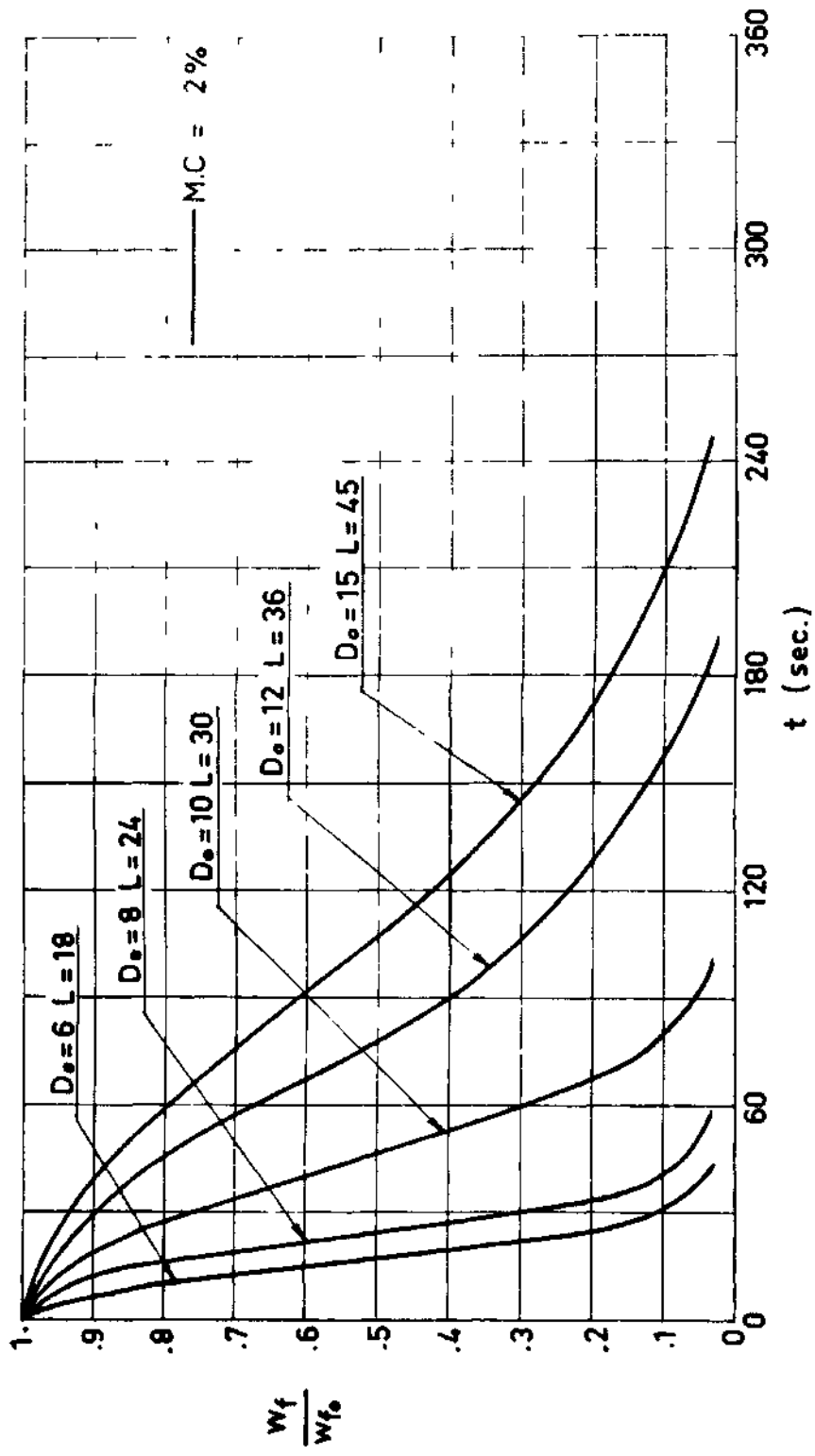


Fig.23 - Final Velocities of Fall. Cylindrical Firebrands.  
Oak Wood. Influence of Size

firebrands, which were studied because of their very long burning 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 conclusions 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 combustion 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 preceding paragraphs were obtained in either the horizontal or the vertical wind tunnels, with the firebrands being held in a fixed position as they burn.

Cylindrical firebrands were held with their axis perpendicular to the wind and plate-shaped firebrands with their largest surface perpendicular also to the wind tunnel longitudinal axis. These are the positions of maximum drag and they



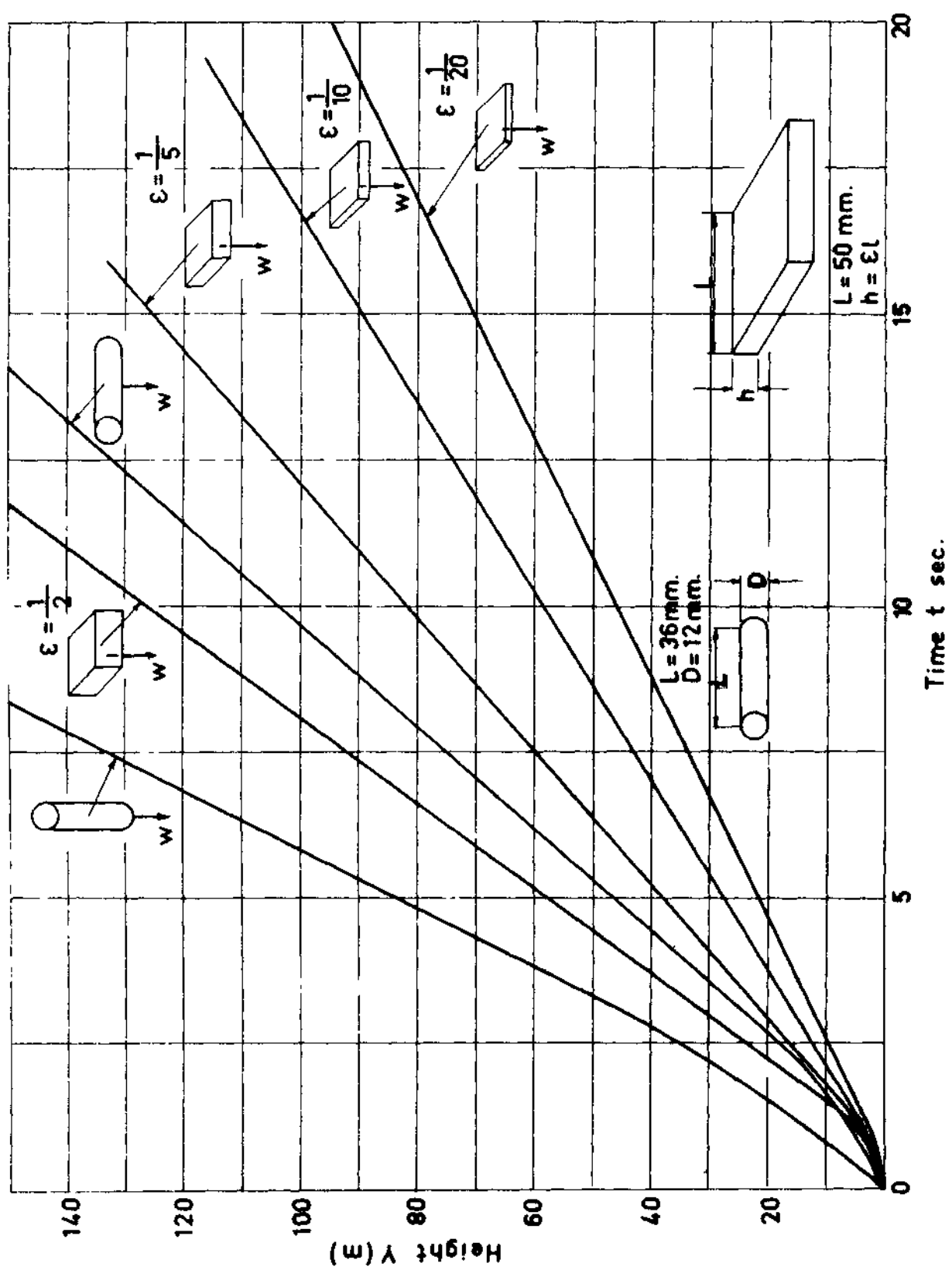


Fig.24 - Calculated Free-Fall Times of Different Shaped Pieces of Pine Wood.

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 they 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 cylinders 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 dropping the cylinders one by one and afterwards dropping 100 cylinders at the same time from a metallic box attached to the 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 position of maximum drag. The errors were smaller than a 10%.
- c) When the 100 cylinders were dropped there were an important horizontal dispersion but they fell in times differing less than a 10%.

\* The actual weight of the cylinders was kept within  $\pm 1\%$  of the weight taken for the calculations.

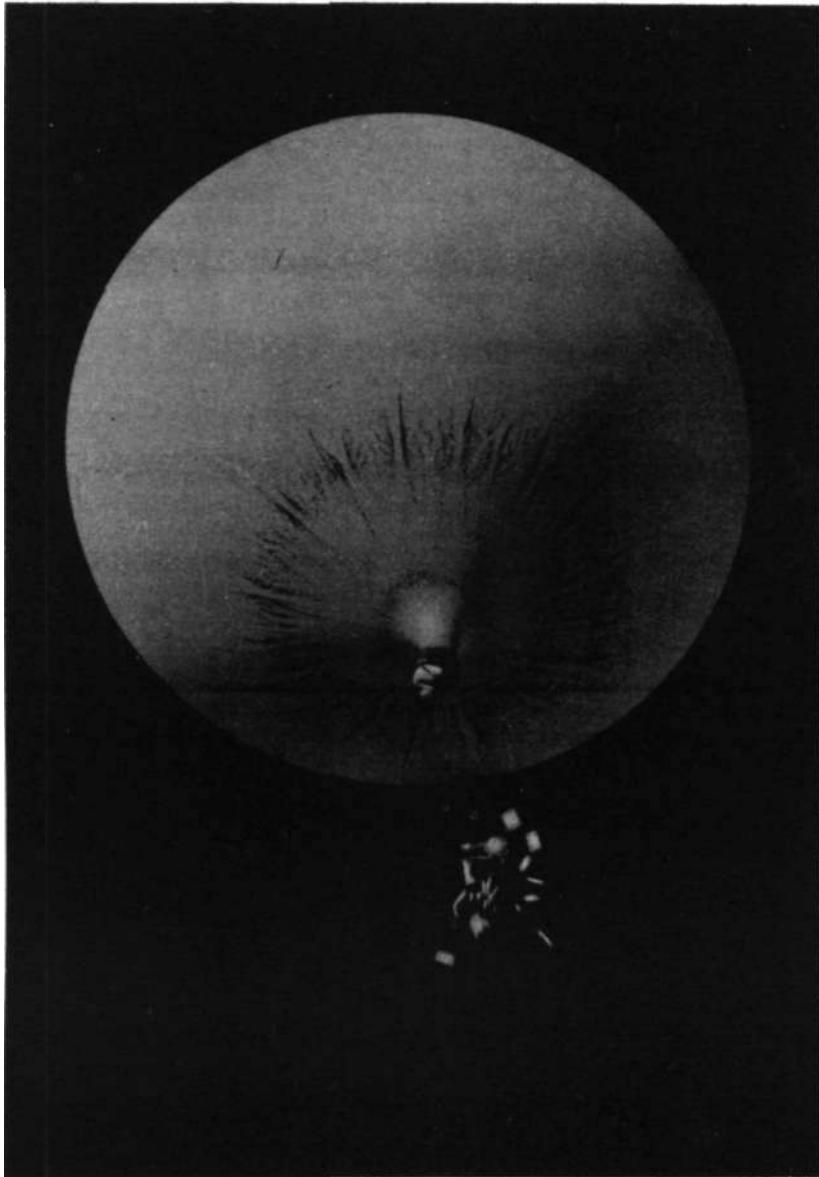


Fig.25. Cylindrical and plate-shaped pieces of wood were loosened from a balloon in order to study free-fall times.

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.

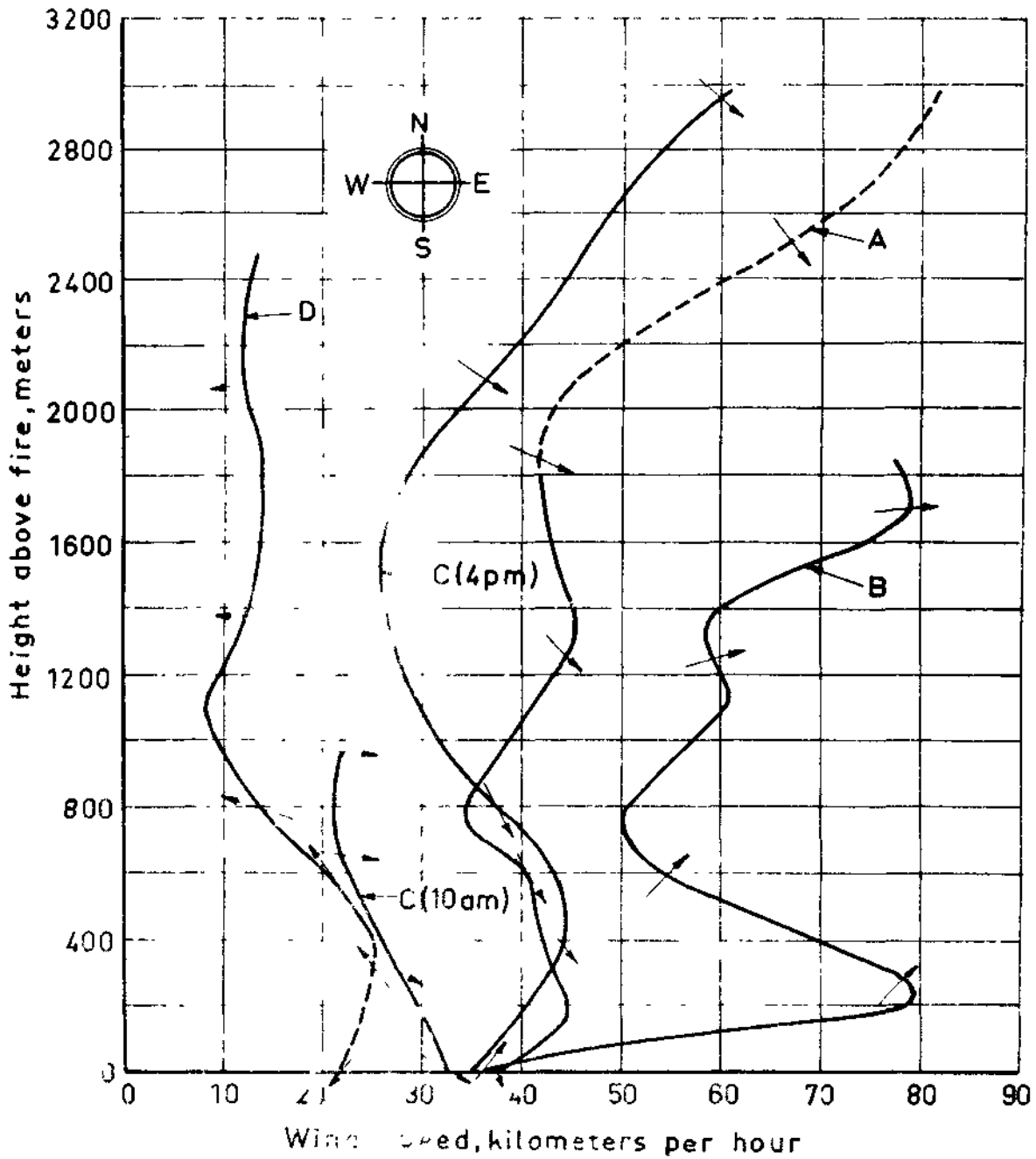


Fig.26 Wind profile; above some major forest fires.  
A: Wood River Valley fire, May 2, 1951;  
B: Chatsworth fire, July 14, 1954; C: Fort Lewis  
fire, October 23, 1953; D: Jamison fire, August 31,  
1954. (\*Taken from Ref.1)

Wind conditions above a forest fire can be very different, as shown in 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 determined 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.<sup>1</sup> If the wind aloft increases, the convection column curves gradually 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 is almost no data on the values of the convective speeds within the convection columns, although vertical velocities 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. <sup>3</sup>, <sup>4</sup>, and <sup>5</sup>.

Countryman<sup>g</sup>, 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

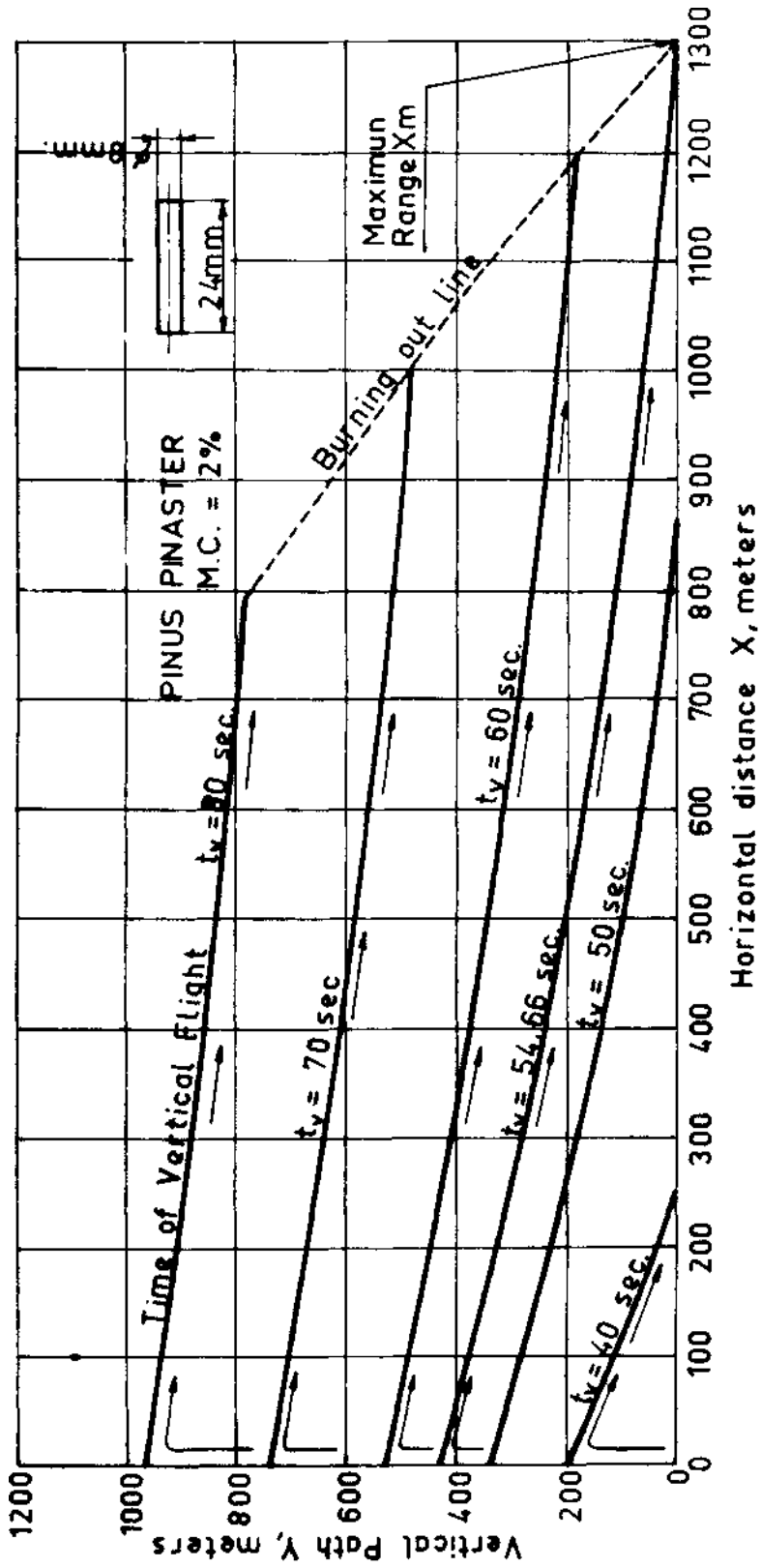


Fig.27 - Flight Paths. Vertical Convection Column. Cylindrical Firebrands

PINUS PINASTER D. = 22mm.  
M.C. = 2%

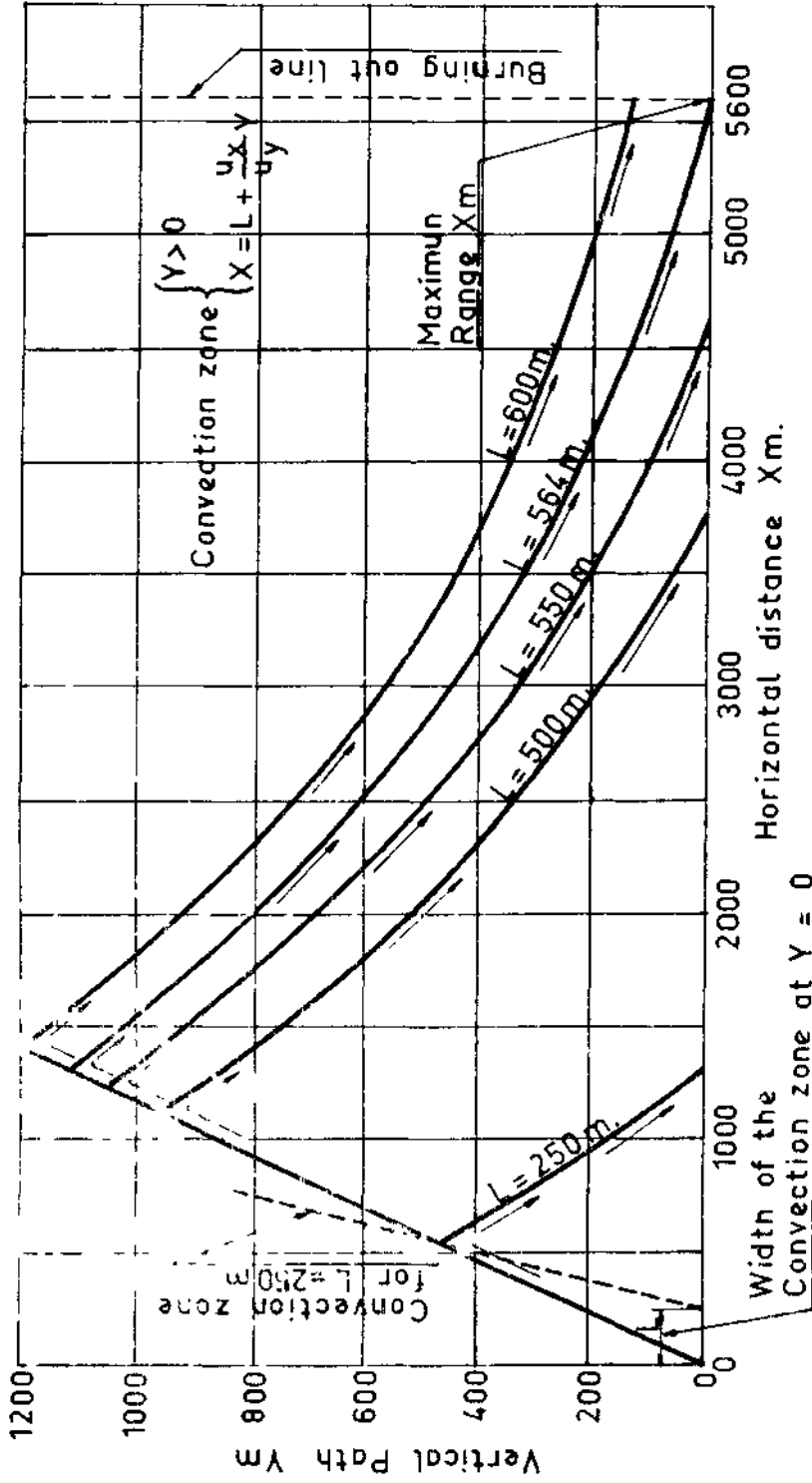


Fig.28 - Flight Paths. Inclined Convection Column. Spherical Firebrands.  
L = Initial Distance from the Firebrand to the Convection Column Border Line.



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

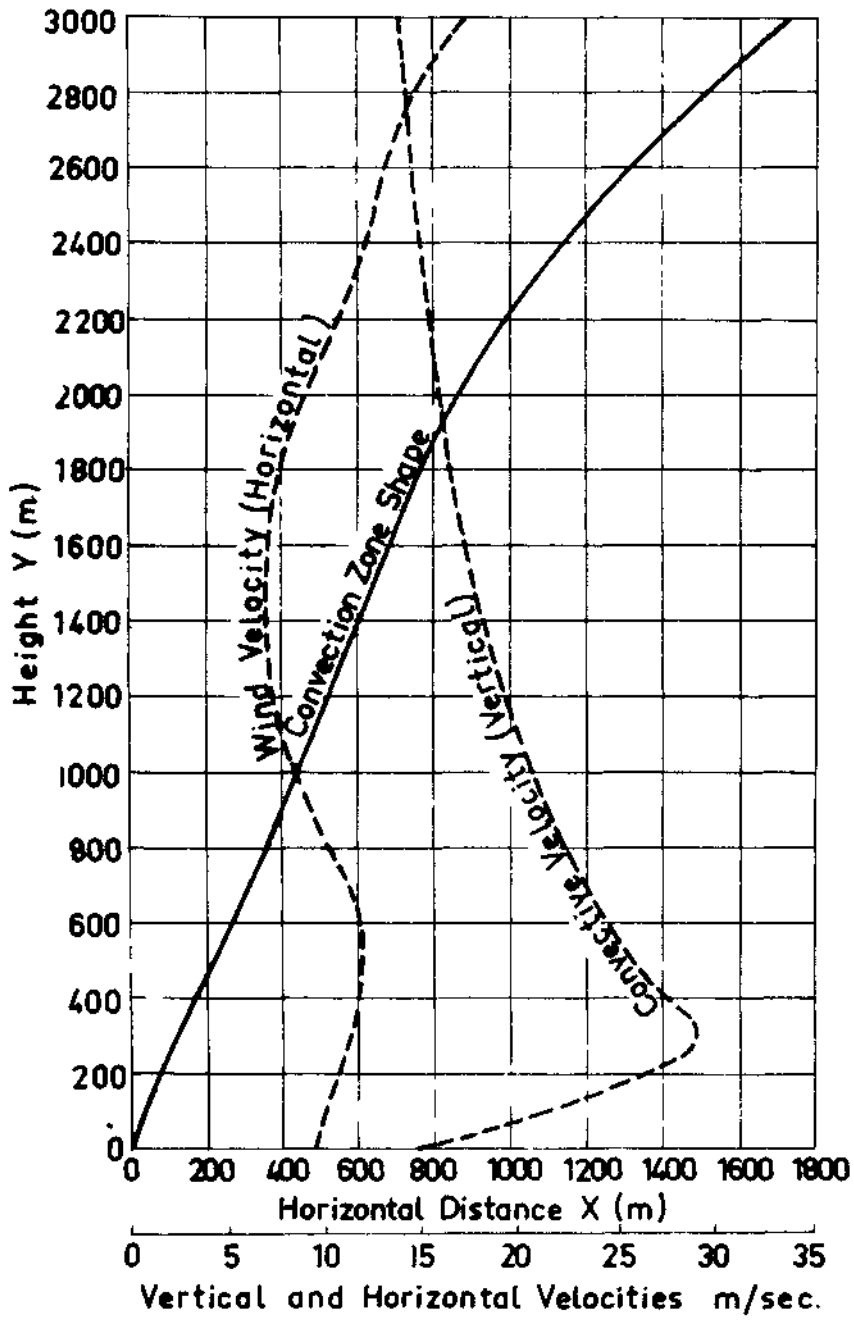


Fig.29 - Wind Profile, Convective Velocity and Convection Zone.

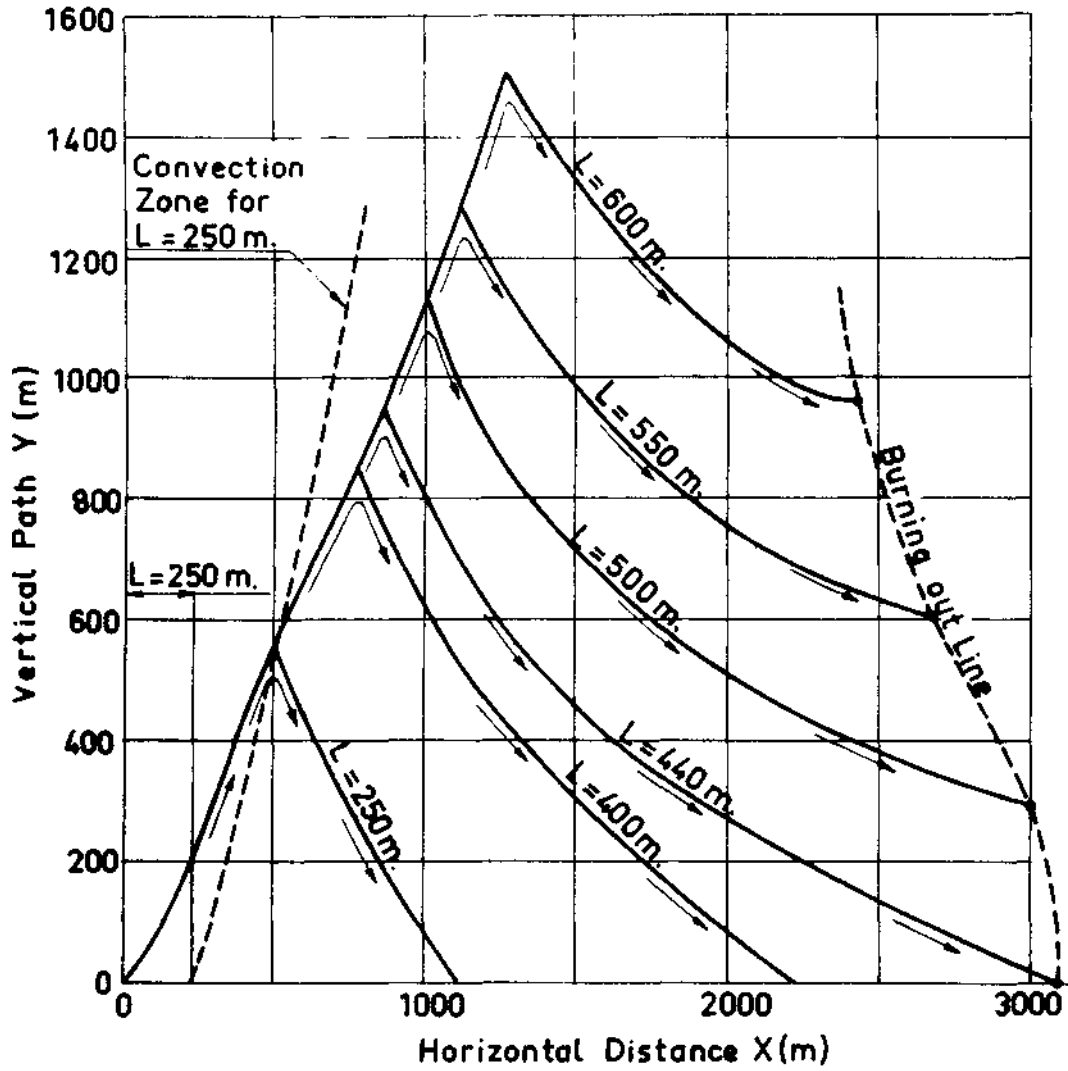


Fig.30 - Flight Paths.(Wind and Convective Conditions of Fig.29).Spherical Firebrands

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<sup>3, 4</sup>. The resulting flight 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.<sup>11</sup> and<sup>12</sup>. 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-

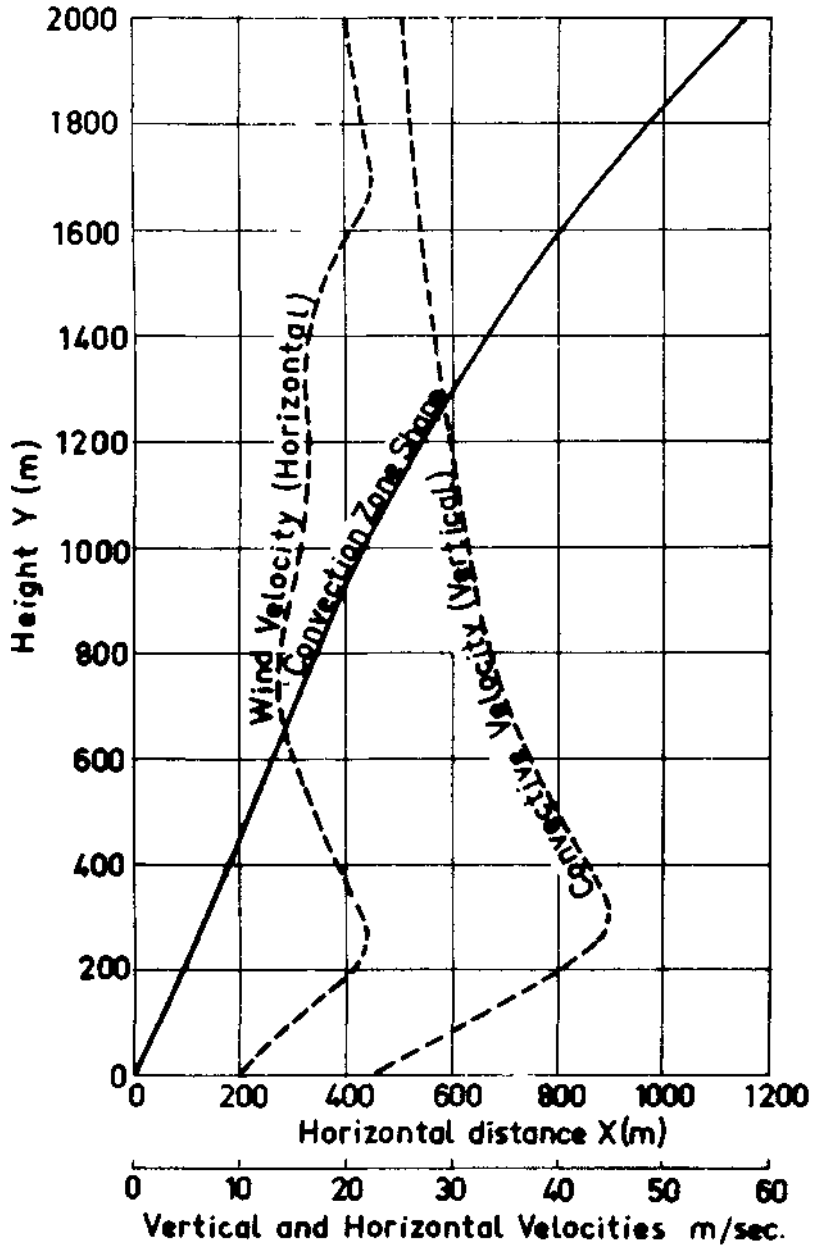


Fig.31 - Wind Profile, Convective Velocity and Convection Zone.

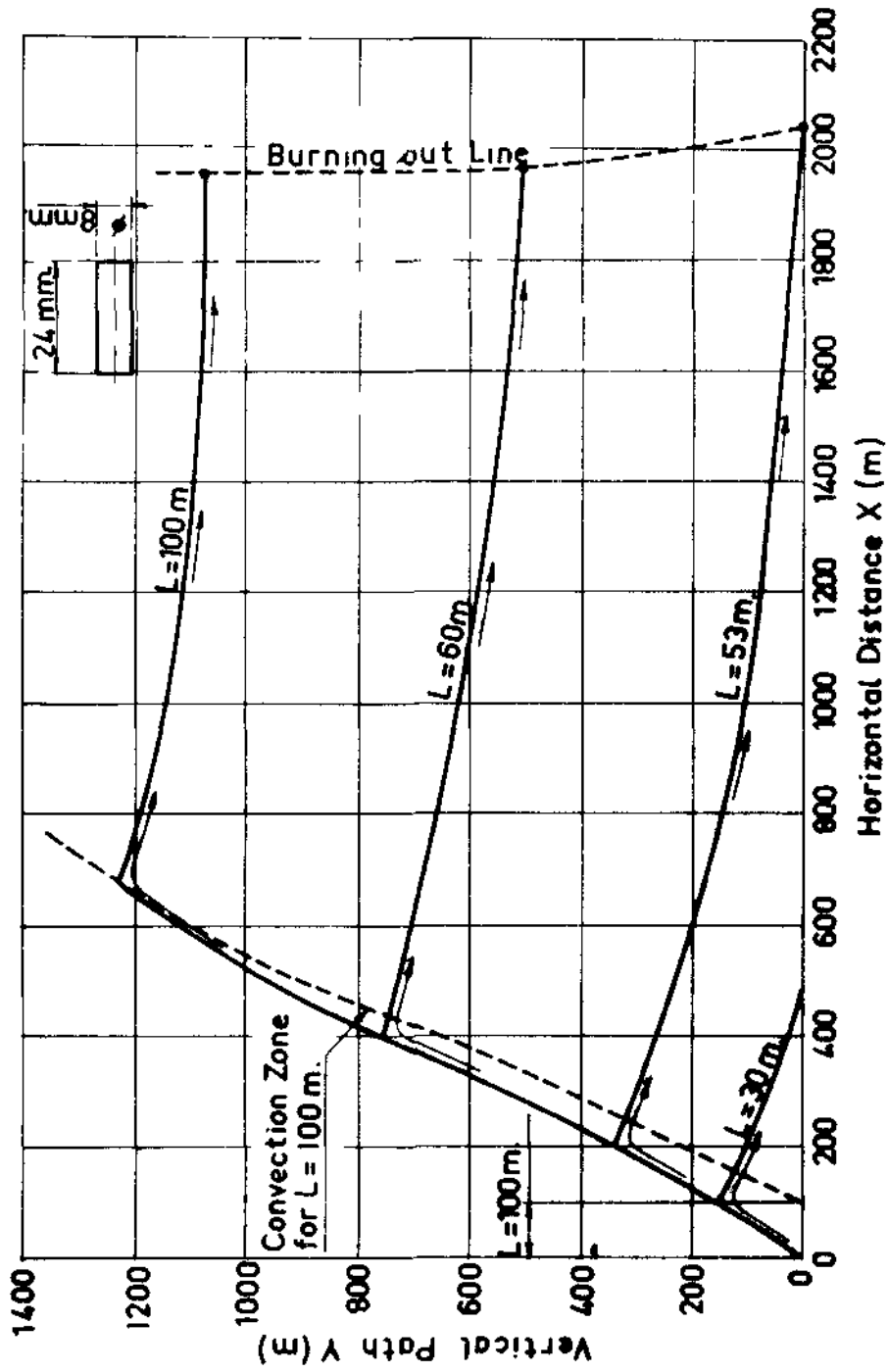


Fig. 32 - Flight Paths. (Wind and Convective Conditions of Fig. 31).  
Cylindrical Firebrands

tal distance reached by the firebrand. For inclined convection columns, instead of  $t_r - t_f$  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 firebrand 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 conditions, 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 moderate 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 proportional to wood density for firebrands of equal initial size and shape.
- 6°.- Charcoal firebrands are, by far, the most dangerous type

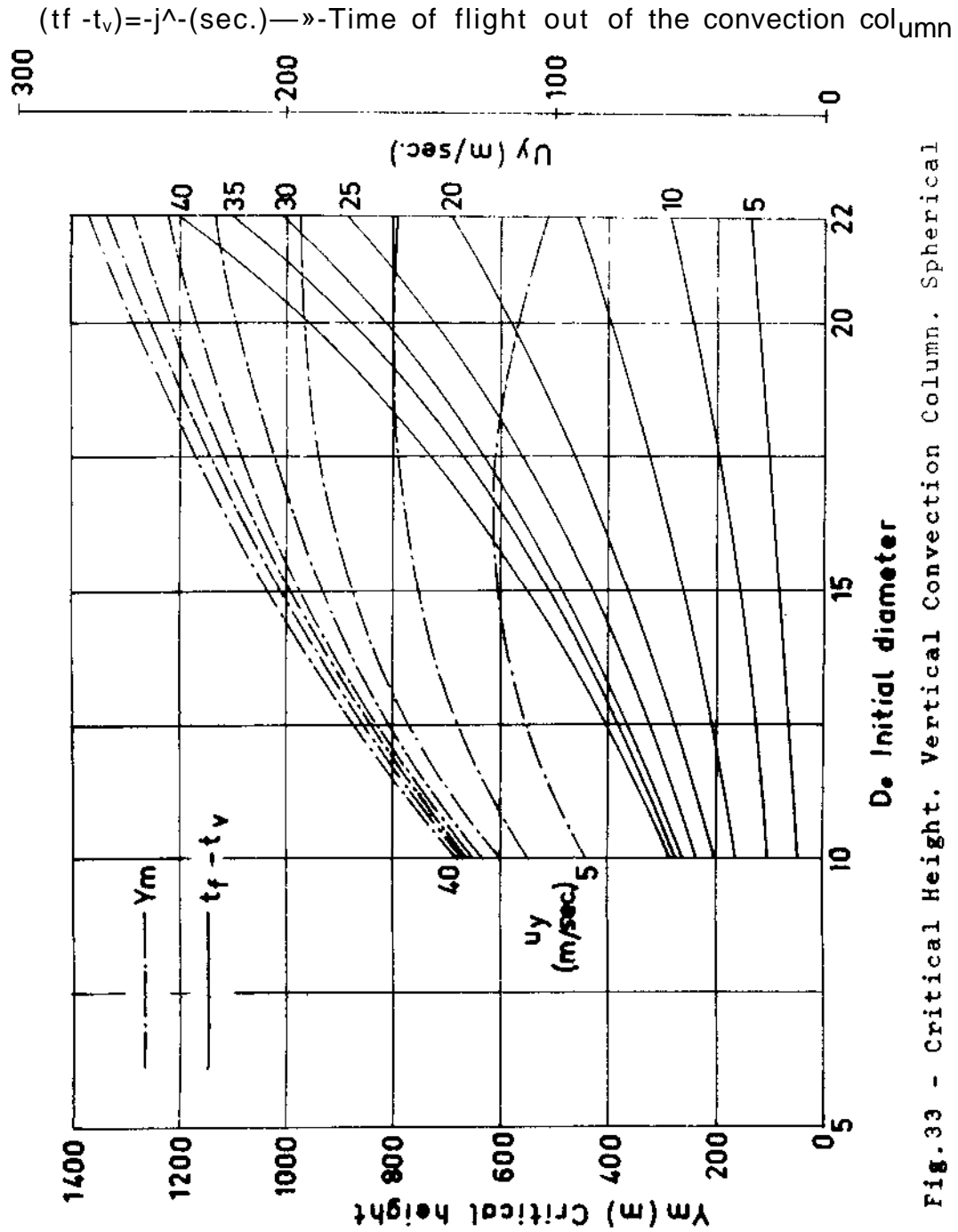


Fig.33 - Critical Height. Vertical Convection Column. Spherical Firebrands of Pine Wood. M.C.25%.



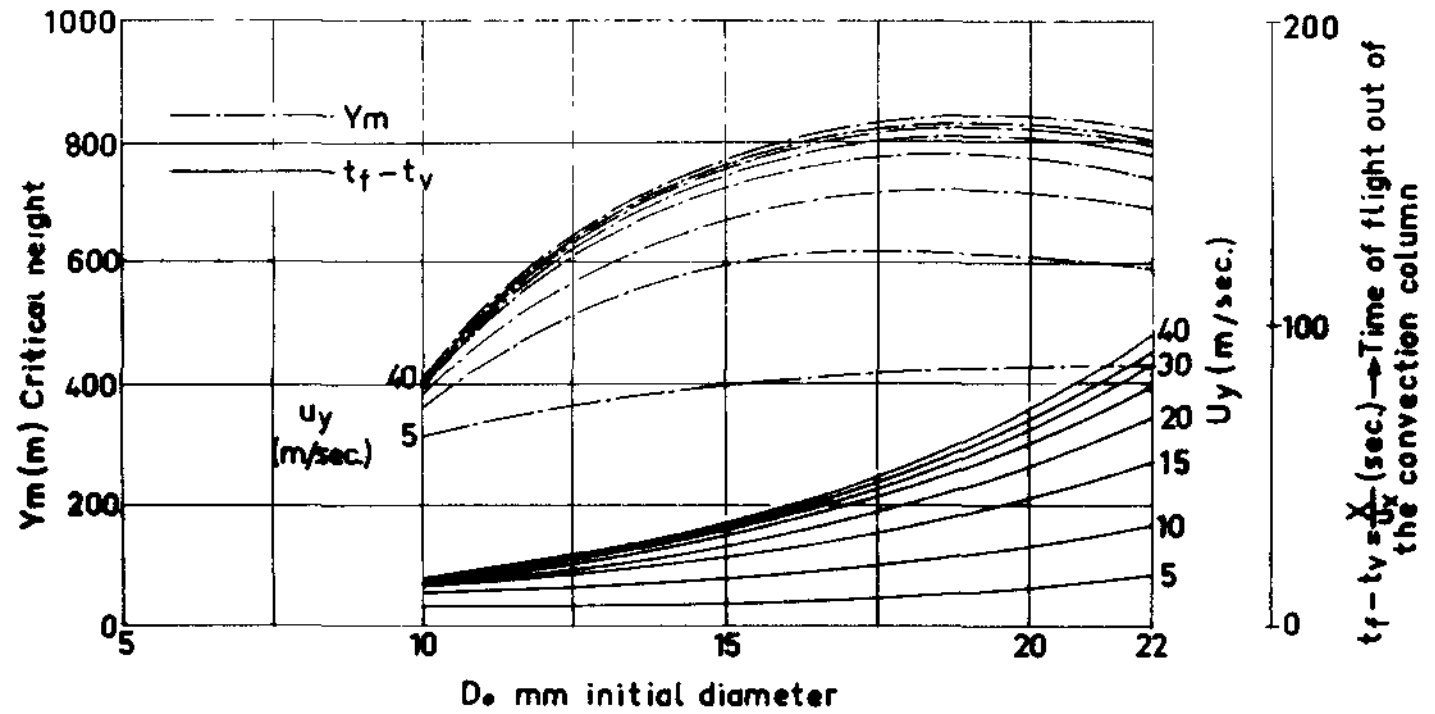


Fig.34 - Critical Height. Vertical Convection Column. Spherical Firebrands of Balsa Wood. K. C. 25%.

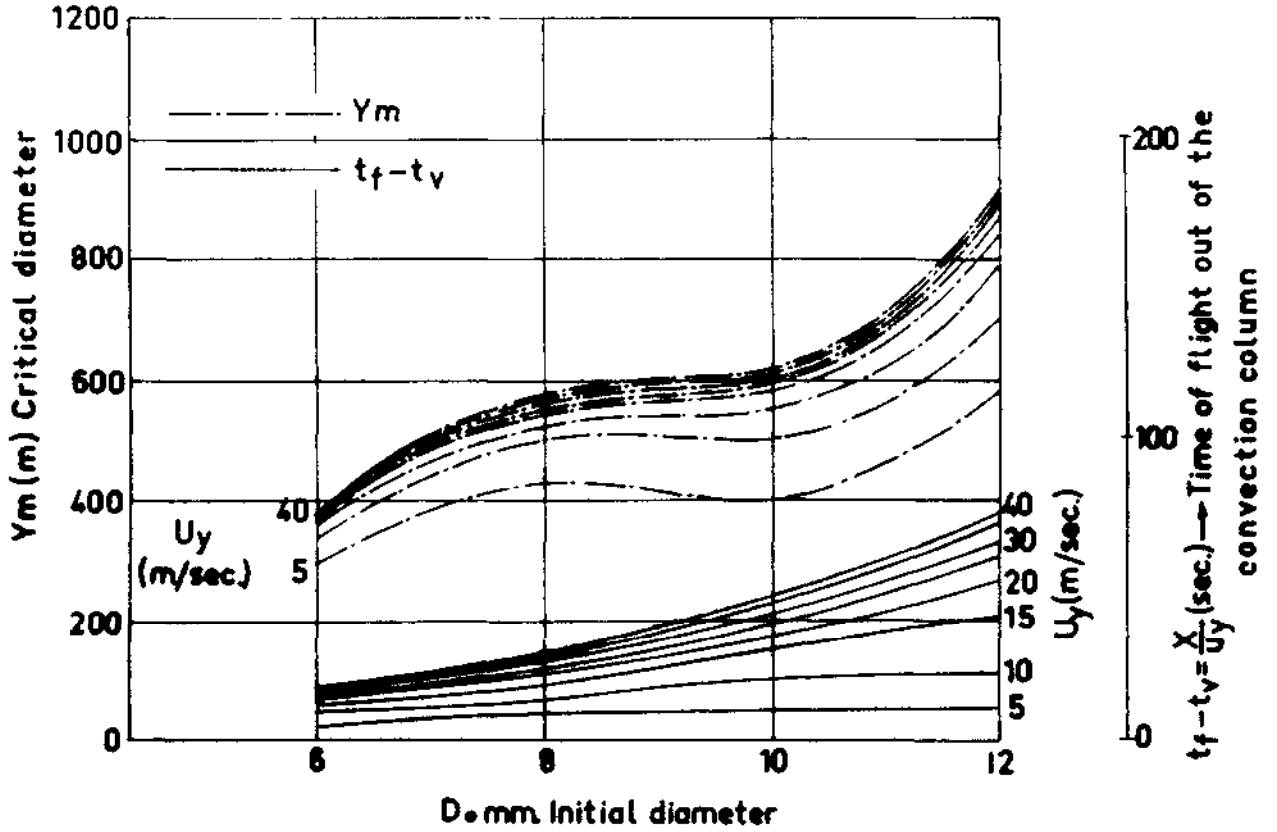


Fig.35 - Critical Height. Vertical Convection Column.  
Cylindrical Firebrands of Aspen Hood. M.C.25%

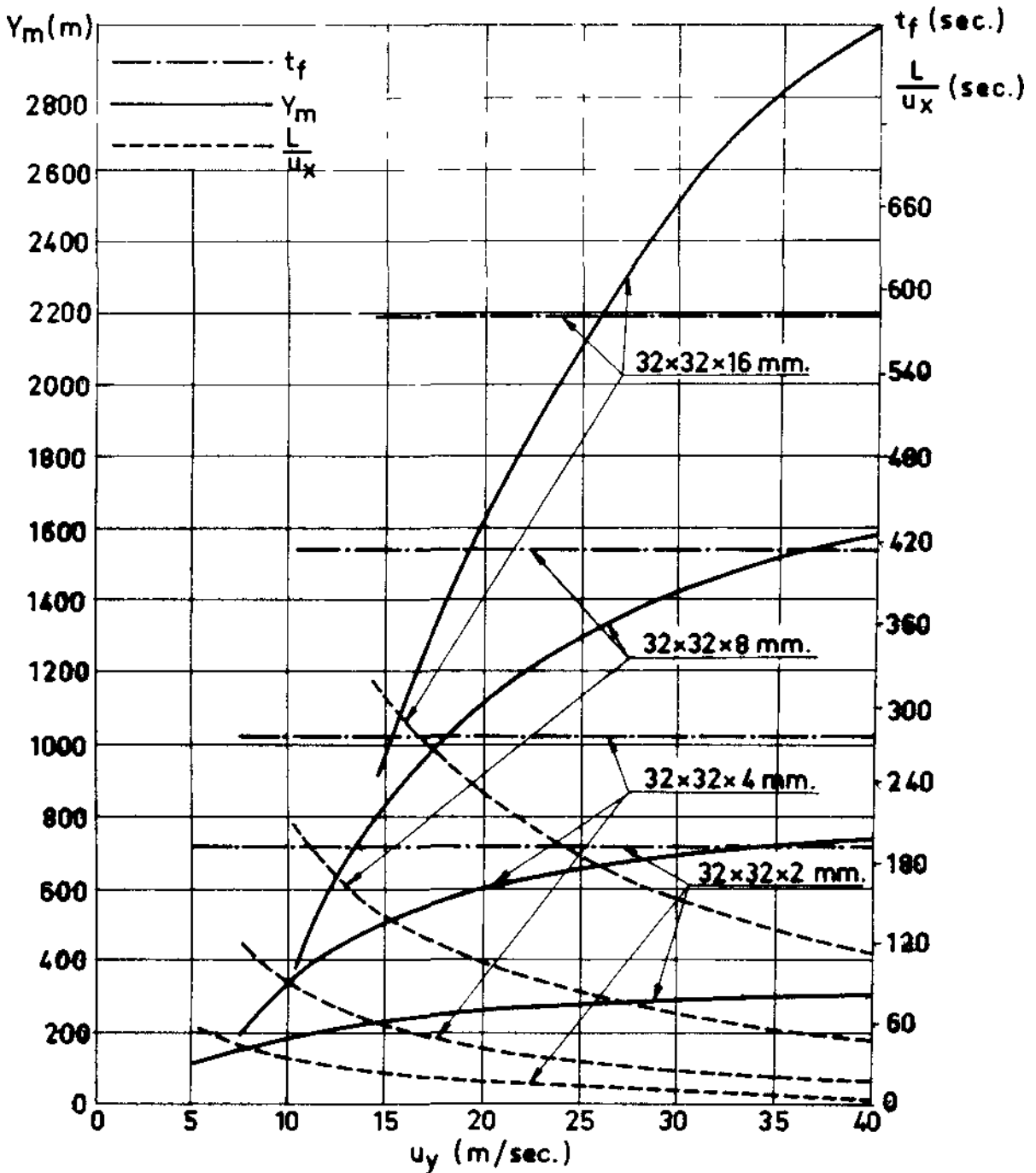


Fig.36 - Critical Height  $Y_m$ , Total Flight Time  $t_f$  and Ratio  $\frac{L}{u_x}$  of Distance  $L$  of Firebrand to Convection Column Border to Wind Velocity  $u_x$  for Maximum Range. Inclined\* Convection Column. Square Plates Firebrands of Pine Wood

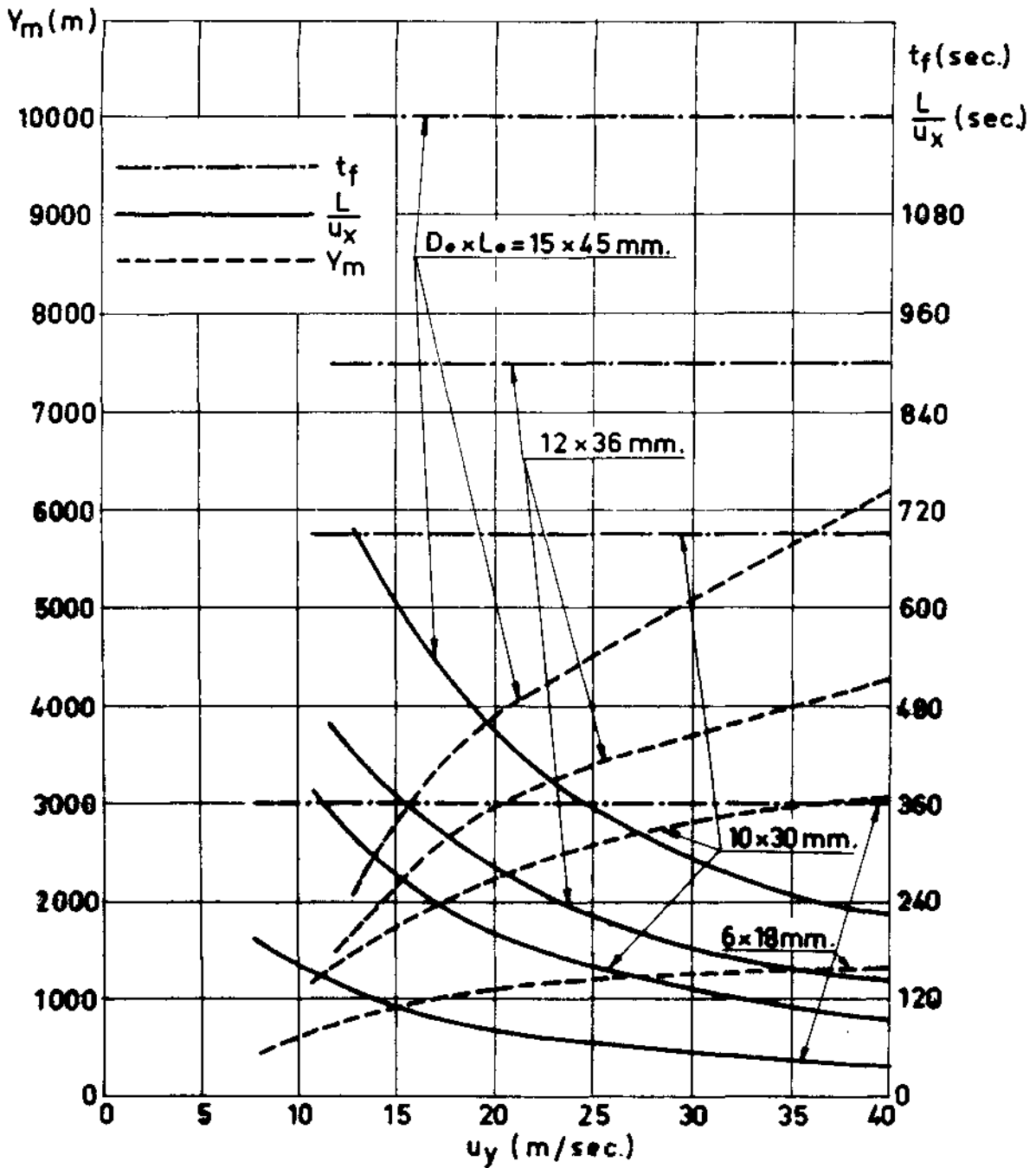


Fig.37 -  $Y_m$ ,  $t_f$  and  $L/u_x$  for Charcoal Cylindrical Firebrands.

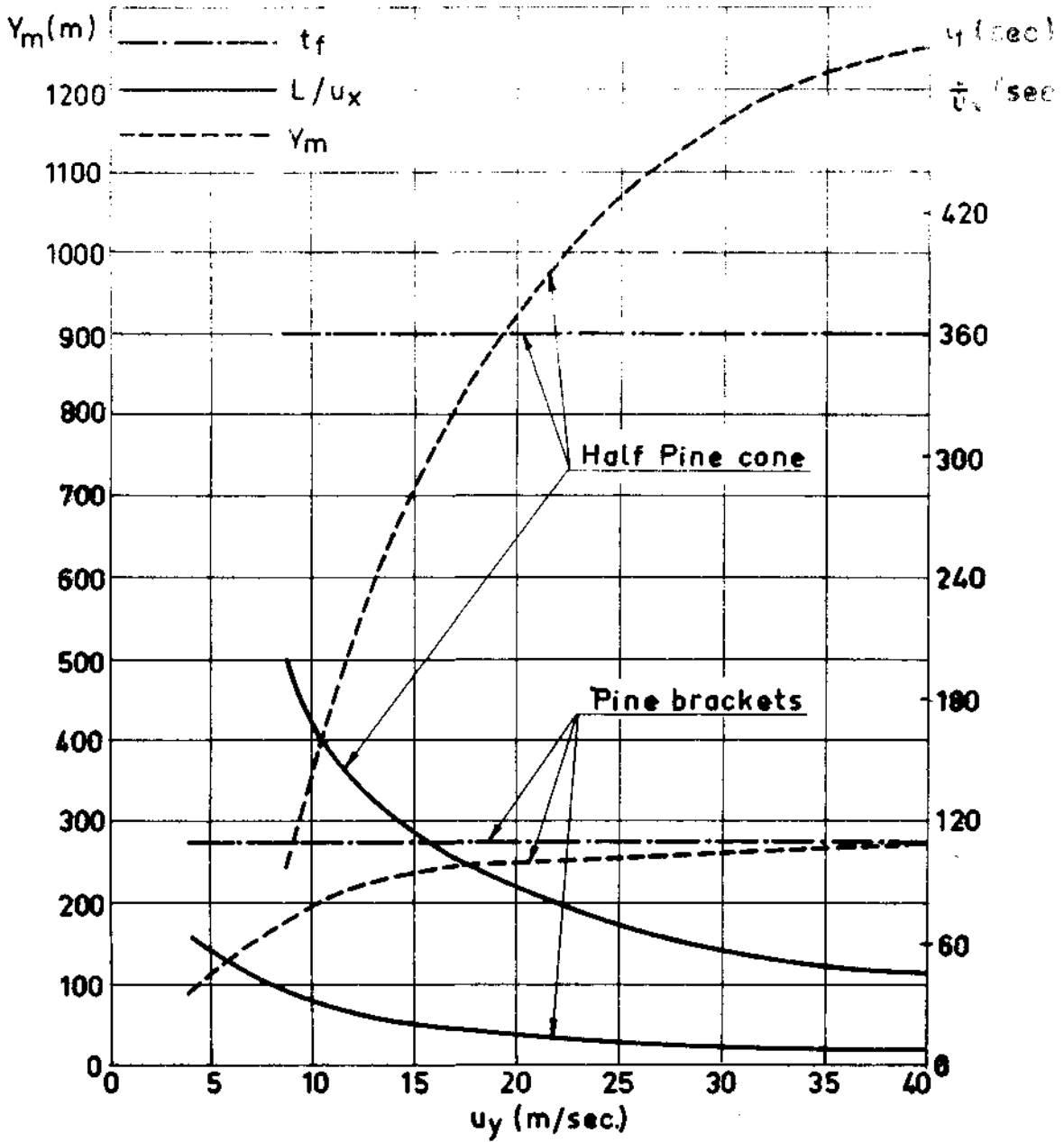


Fig.38 - Y<sub>m</sub>, t<sub>f</sub> and L/u<sub>x</sub> for Pine Cones and Pine Brackets.

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 ignition 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 differences 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 horizontal wind tunnel shown in Fig.2. The weight and the aerodynamic drag of the burning firebrands were recorded as function of time with the strain-gauges balance shown in Fig.6. At the same time, the volume and surface of firebrands were determined 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

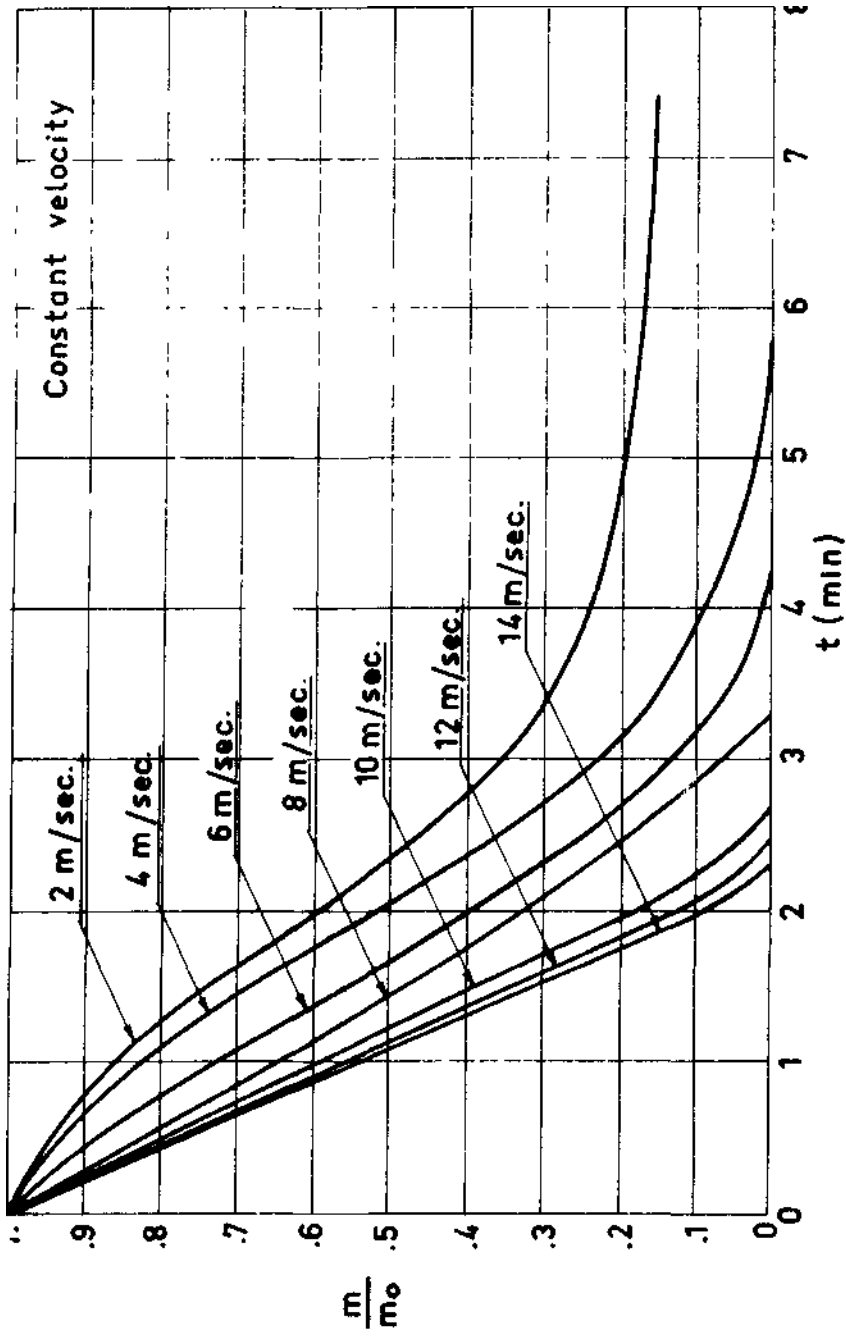


Fig.39 - Combustion of Firebrands at Constant Wind Speed. Weight-Time Curves. Spherical Firebrands of Oak Wood.

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

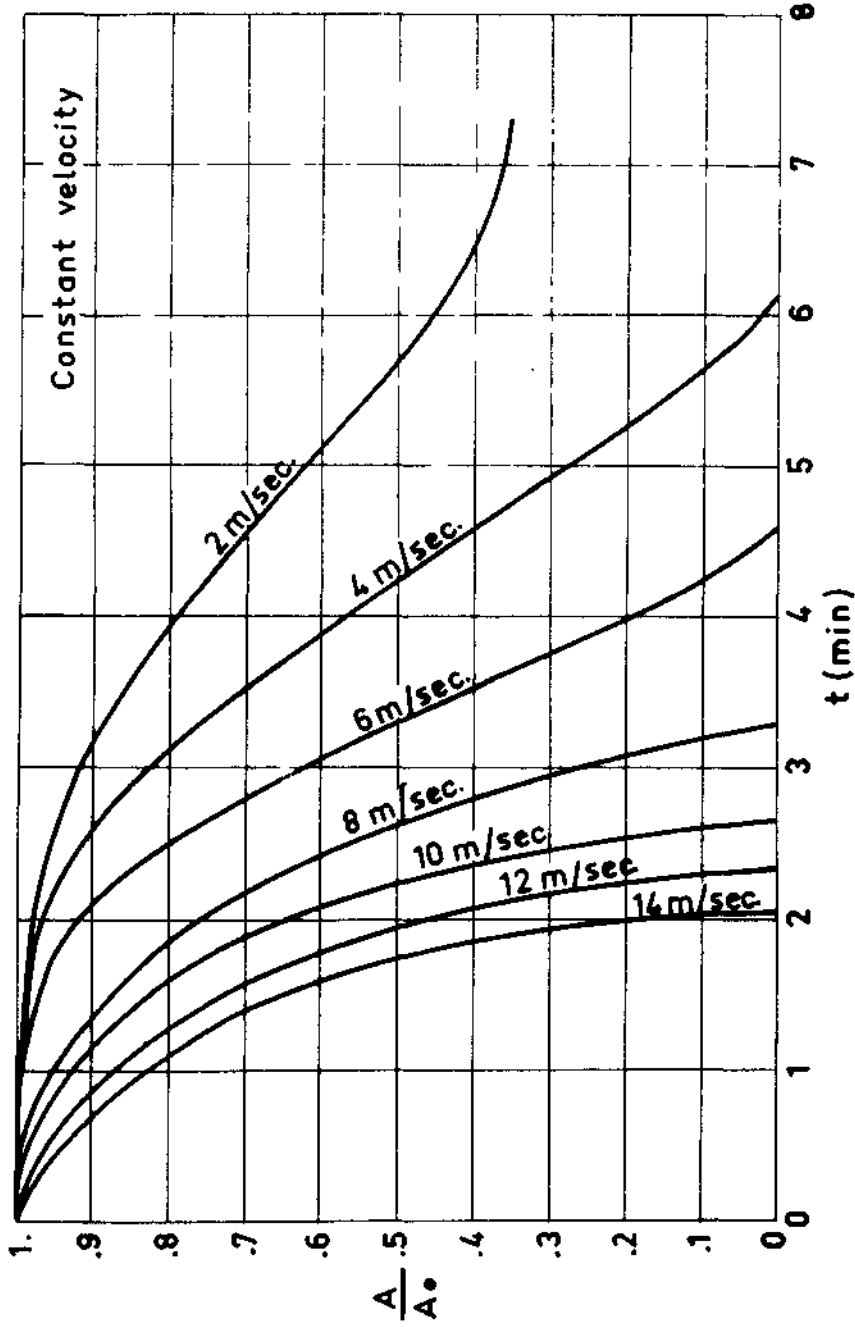


Fig.40 - Combustion of Firebrands at Constant Wind Speed. Surface-Time Curves. Spherical Firebrands of Oak Wood.

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



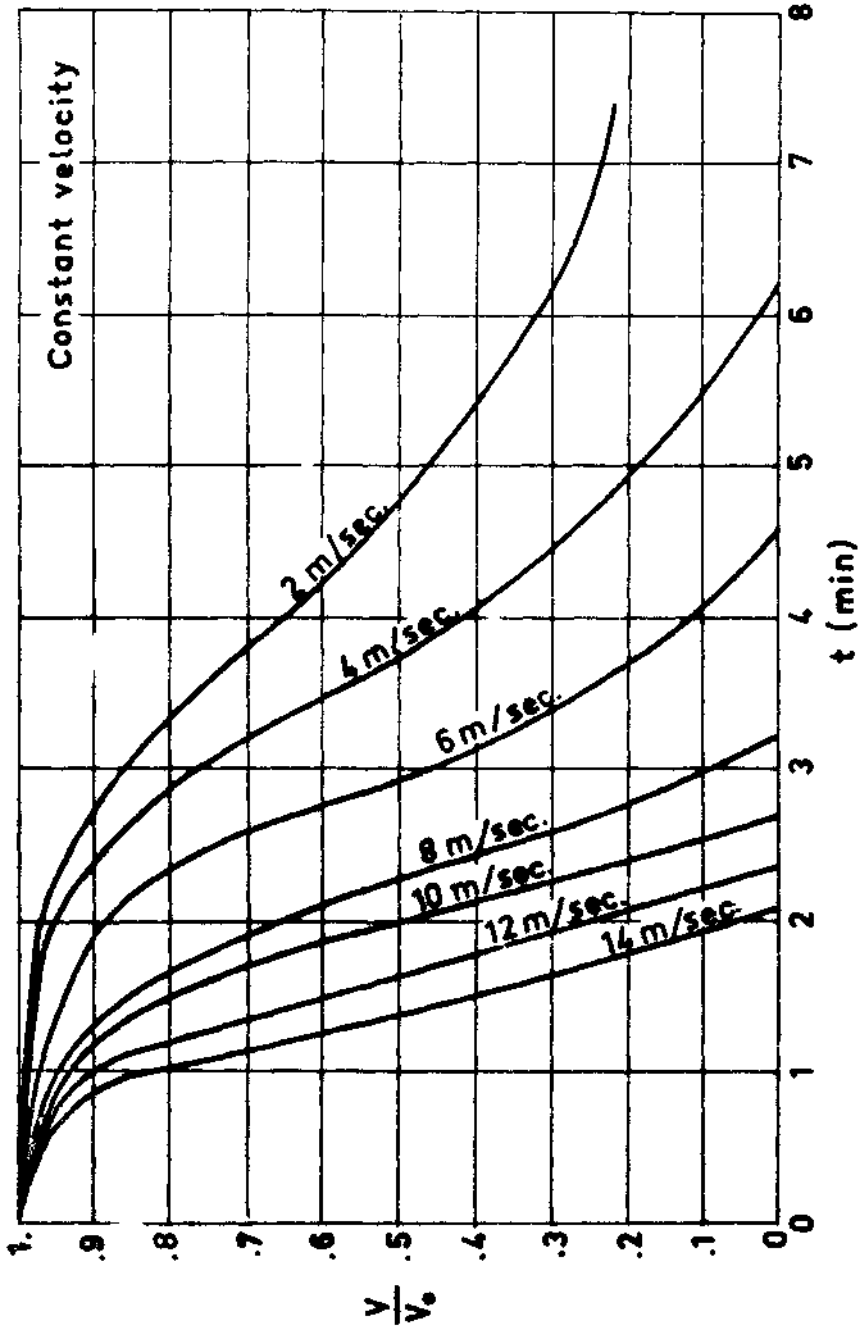


Fig. 41 - Combustion of Firebrands at Constant Wind Speed. Volume-Time Curves. Spherical Firebrands of Oak Wood.

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

as function of time. Results are shown in full in Ref.<sup>12</sup>

From these results final velocities of fall  $w_f$  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 them 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  $w_f$ , 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.<sup>7</sup>, 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

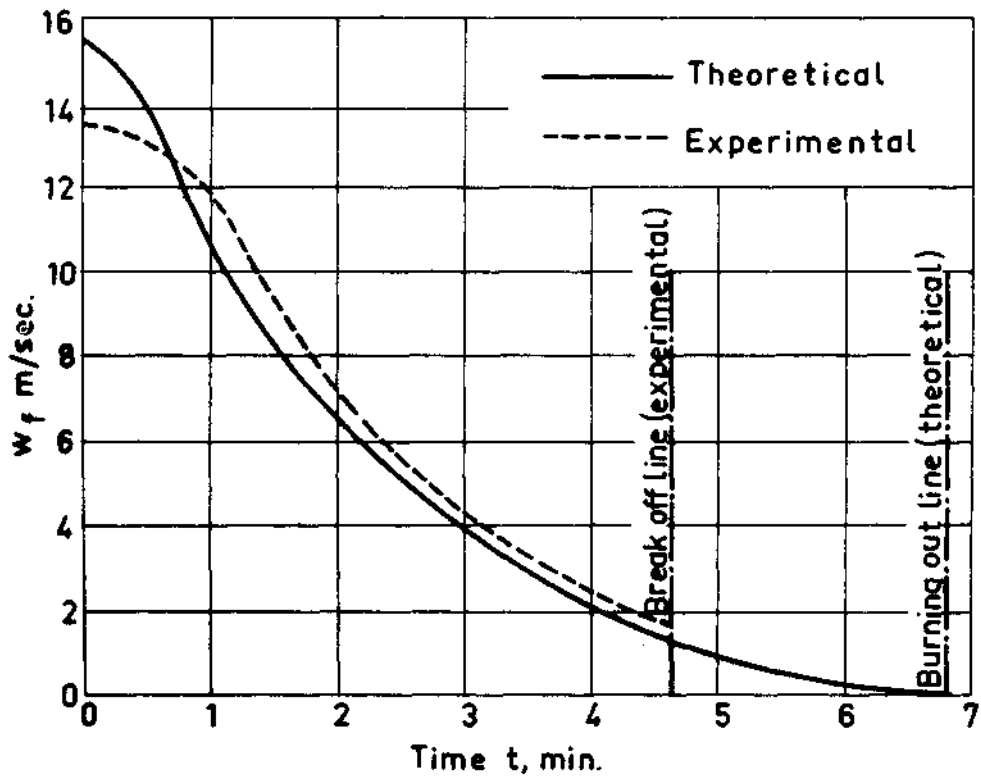


Fig.42 - Experimental and Theoretical Final Velocity of Fall. (Ref.<sup>7</sup>)

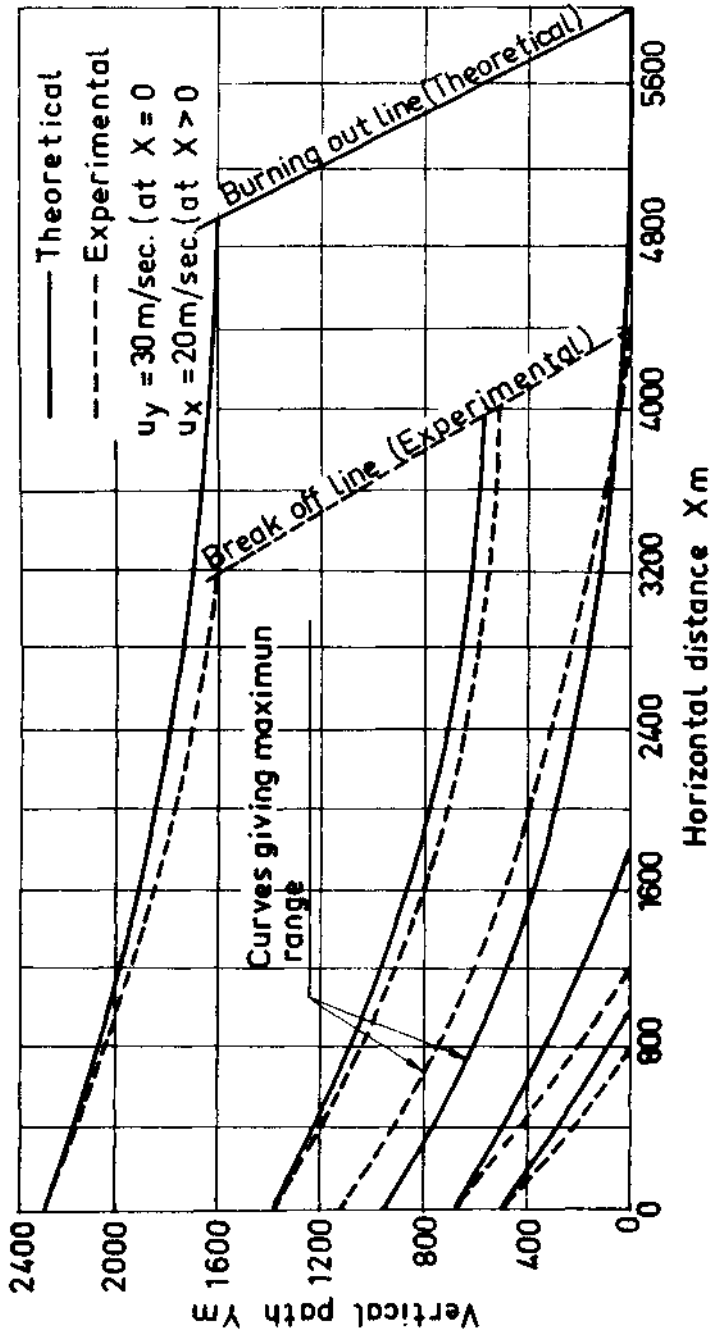


Fig. 43 - Flight Paths Calculated from Theoretical and from Experimental Values of the Final Velocities of Fall (pof. 7).

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 expressed in dimensionless form. In the first place, this study will be applied to the case of combustion of wood with forced convection at constant wind speed, and then to the case of combustion of firebrands when flying at their final velocities of fall.

A firebrand will be characterized by its initial density  $\rho_j$  and by three characteristic lengths  $D_j$ ,  $L_j$ , and  $l_j^*$ . On the other hand, air will be characterized by its density  $\rho_{a,\infty}$  and viscosity  $\mu_{a,\infty}$  at the infinity,

$D_j$  is the diameter for spherical and cylindrical firebrands and the height (vertical dimension perpendicular to the wind) for plate-shaped firebrands.  $L_j$  is the longitudinal axis for cylindrical firebrands and the width (horizontal dimension perpendicular to the wind) for plate-shaped firebrands. Finally,  $l_j^*$  is the thickness (parallel to the wind) of plate-shaped firebrands.

	ASPEN	OAK	PINE	
SPHERES	x	•	■	22 mm.
	.	⊙	□	15 mm.
CYLINDERS	+	•	■	15 x 45
	•	•	□	18 x 36

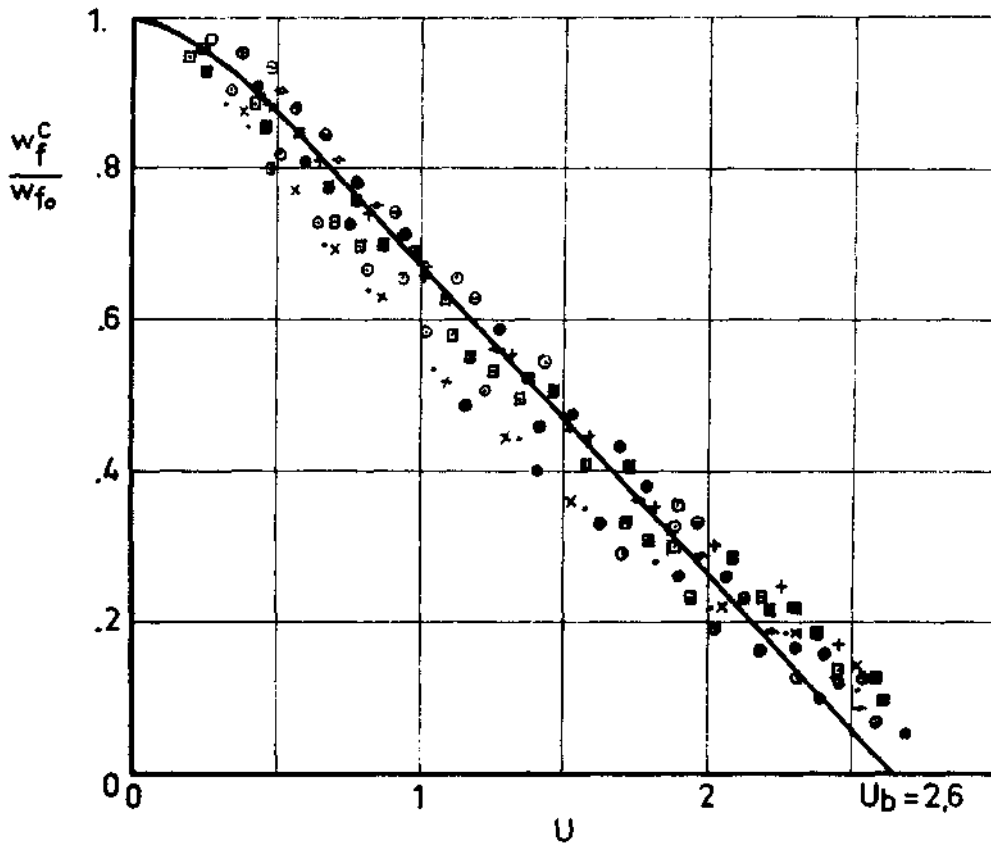


Fig. 1^ - Dimensionless Correlation of Experimental Results for the Combustion of Firebrands at Constant Wind Speed.

According to dimensional analysis, any property  $\xi$  of the firebrand referred to its initial value  $\xi_0$ , will be given by an expression of the form:

$$\frac{\xi}{\xi_0} = \phi \left[ \left( \frac{wt}{D_0} \right)^\alpha, \left( \frac{wD_0 \rho_{a,\infty}}{\mu_{a,\infty}} \right)^\beta, \left( \frac{\rho_{a,\infty}}{\rho_{w,0}} \right)^\gamma, \left( \frac{L_0}{D_0} \right)^\delta, \left( \frac{l_0}{D_0} \right)^\epsilon \right] \quad (27)$$

or:

$$\frac{\xi}{\xi_0} = \phi \left[ \chi^\alpha, Re^\gamma, \zeta^\gamma, \lambda_1^\delta, \lambda_2^\epsilon \right] \quad (28)$$

In this expression,  $\chi = wt/D$  is a characteristics parameter of this non-stationary combustion process;  $Re = wD \rho_{a,\infty} / \mu_{a,\infty}$  in the Reynolds number;  $\zeta = \rho_{a,\infty} / \rho_{w,0}$  is a parameter characterizing the kind of wood, and parameters  $A_{r1} = L_0/D_0$  and  $A_{r2} = l_0/D_0$  represent the firebrand's geometrical configuration\*.

For cylindrical firebrands, is  $A_{r1} = 1$  and for spherical firebrands is  $A_{r1} = A_{r2} = 1$ .

Variable  $\xi$  can be the mass, volume, density, aerodynamic drag of the firebrand or final velocity of fall.

In particular, all experimental values of the final velocities 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.

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

in which

$$U = \chi Re^{-0.4} \zeta^{1.3} \lambda_1^{-0.4} \quad (30)$$

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  $U$ , which corresponds to  $w_f/w_{f,o} = 0$ , is practically the same for all cases investigated and it is given by:

$$U_b = \frac{wt_b^c}{D_o} Re^{-0.4} \zeta^{-1.3} \lambda_1^{-0.4} \quad (31)$$

from which, the burning-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:

$$\frac{n}{n_0} = \phi \left( \chi_f^\alpha, R_{ef}^\beta, \zeta^\gamma, \lambda_1^\delta, \lambda_2^\epsilon \right) \quad (32)$$

Variables  $t$ ,  $A$ , and  $X$  were defined in the preceding paragraph, and  $\chi_f$ ,  $R_{ef}$ ,  $\zeta$ ,  $\lambda_1$ ,  $\lambda_2$  are:

$$\chi_f = \frac{w_{f,0} t}{D_0} \quad (33)$$

$$R_{ef} = \frac{w_{f,0} D_0 \rho_{a,\infty}}{\mu_{a,\infty}} \quad (34)$$

All experimental results obtained for the final velocities of fall  $w_f$  for spherical, cylindrical and square plates firebrands and for all kinds of wood studied\* were correlated with the following expression:

$$\frac{w_f}{w_{f,0}} = \phi(Z) \quad (35)$$

being:

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

\* Pine wood, spruce, aspen, oak and balsa Charcoal firebrands 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.

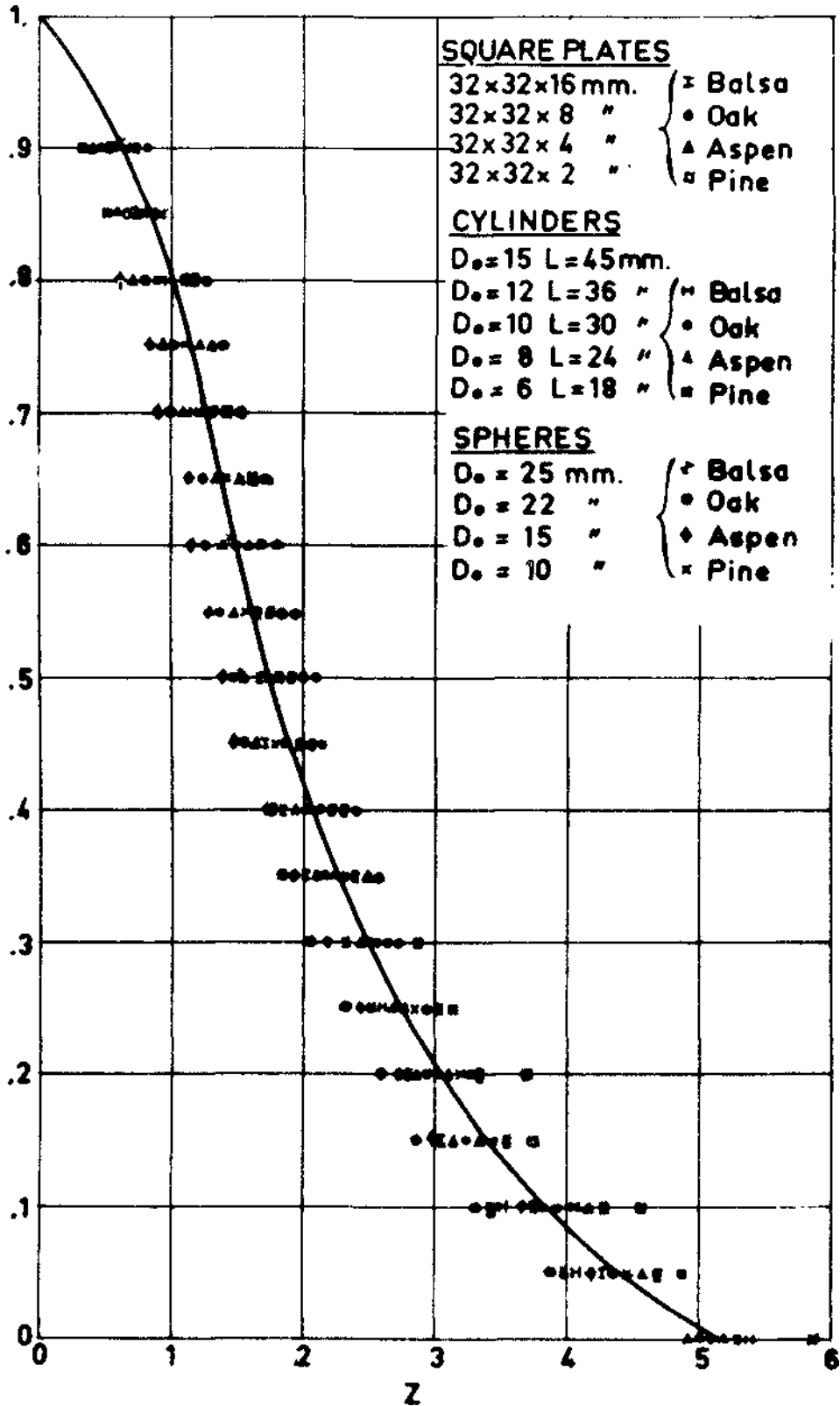
All experimental results are shown in Fig.45. They include a total of over 500 experimental values and it may be seen that, considering the heterogeneous properties of wood, the correlation obtained may be considered as very satisfactory.

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

Finally, final velocities of fall  $w_f$  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  $w_f^*$  obtained by burning firebrands at constant wind speed.

Under actual flight and burning conditions, mass, aerodynamic drag, density, etc. of a firebrand have a functional dependency on time, since they depend on the complete time-history of the wind velocity and then, on the complete combustion 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 combustion 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:

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

Therefore, once an analytical expression is found for function

$$\frac{w_f^c}{w_{f,0}} = F(\chi, Re, \zeta, \lambda_1, \lambda_2) \quad (38)$$

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

$$\frac{d}{dt} \left( \frac{w_f}{w_{f,0}} \right) = \frac{d}{dt} \left( \frac{w_f^c}{w_{f,0}} \right) = \left( \frac{\partial F}{\partial t} \right)_{w=w_f} \quad (39)$$

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

means of a straight line:

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

and with a parabolic expression

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

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

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

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

and

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

where

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

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

to 2.6

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

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

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

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

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

$$(0.9 w_{f,0} \leq w_f \leq w_{f,0}) \qquad (47)$$

where

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

that is,  $V$  is the expression of  $Z$  for spherical and cylindrical firebrands for which this calculation applies<sup>5,5</sup>.

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

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

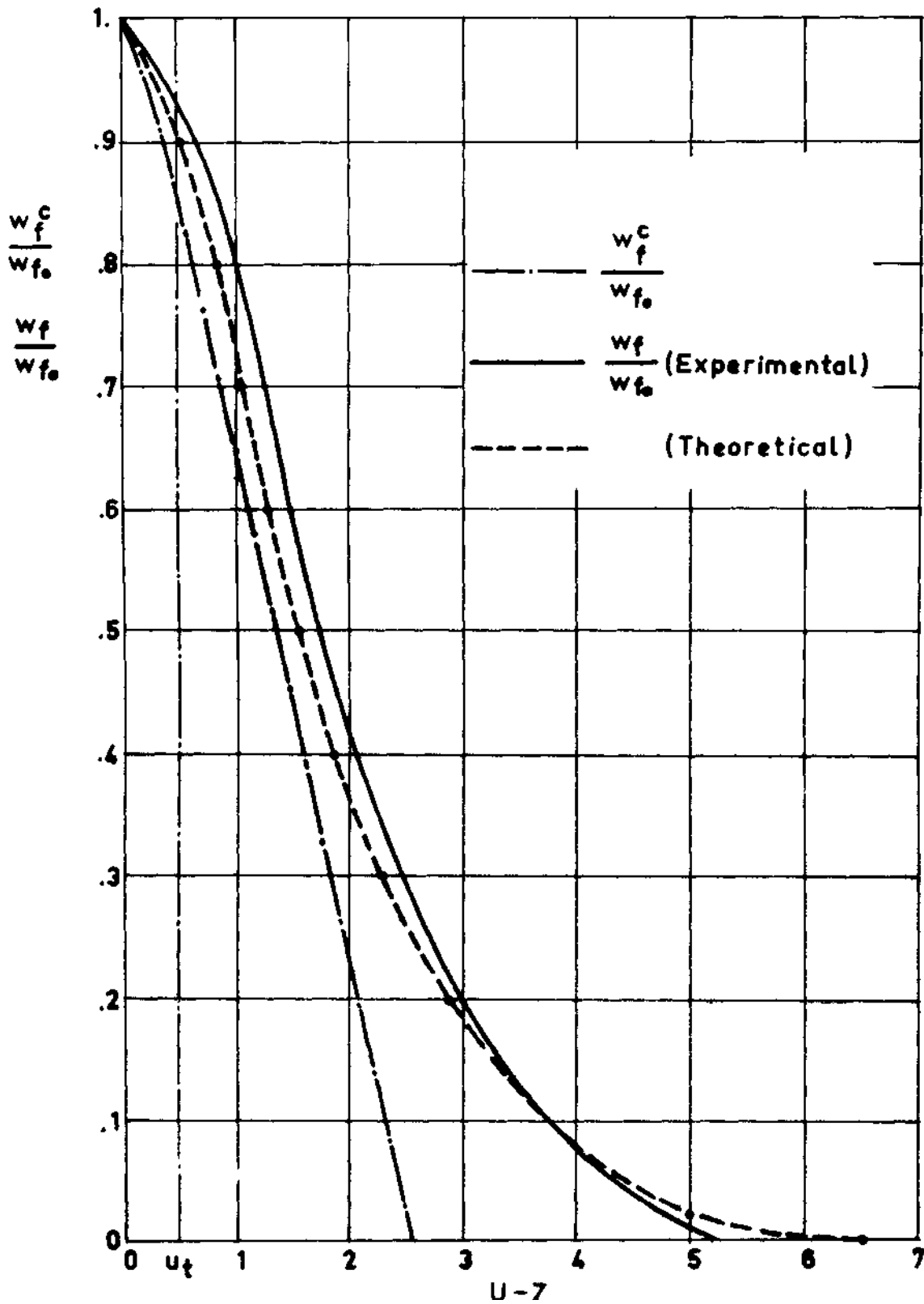


Fig.46 - Comparison of the Experimental Final Velocities of Fall and the Theoretical Curve  $w_f = F(Z)$  Derived from Curve  $w^{\wedge} = F(U)$

expressions (46) and (47) is represented and compared with the curve experimentally obtained. Function  $w_f/w_{f,0} = F(U)$ , 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 final velocity of fall 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 results obtained by burning firebrands suspended from a wire. In this experimental way the final part of the combustion process, 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 extremely small and therefore, they fall down and burn at very low speed.

Finally, Fig. 7 shows, for a particular case (cylindrical firebrands of oak-wood) curves  $w_f/w_{f,0} = f(t)$  calculated from experimental data obtained by burning the firebrands at constant wind speed and the experimental curves directly obtained burning the firebrands at their final velocities of fall. According to what it could be expected from the general comparison of Fig. 46, experimental and calculated results are in an excellent agreement.



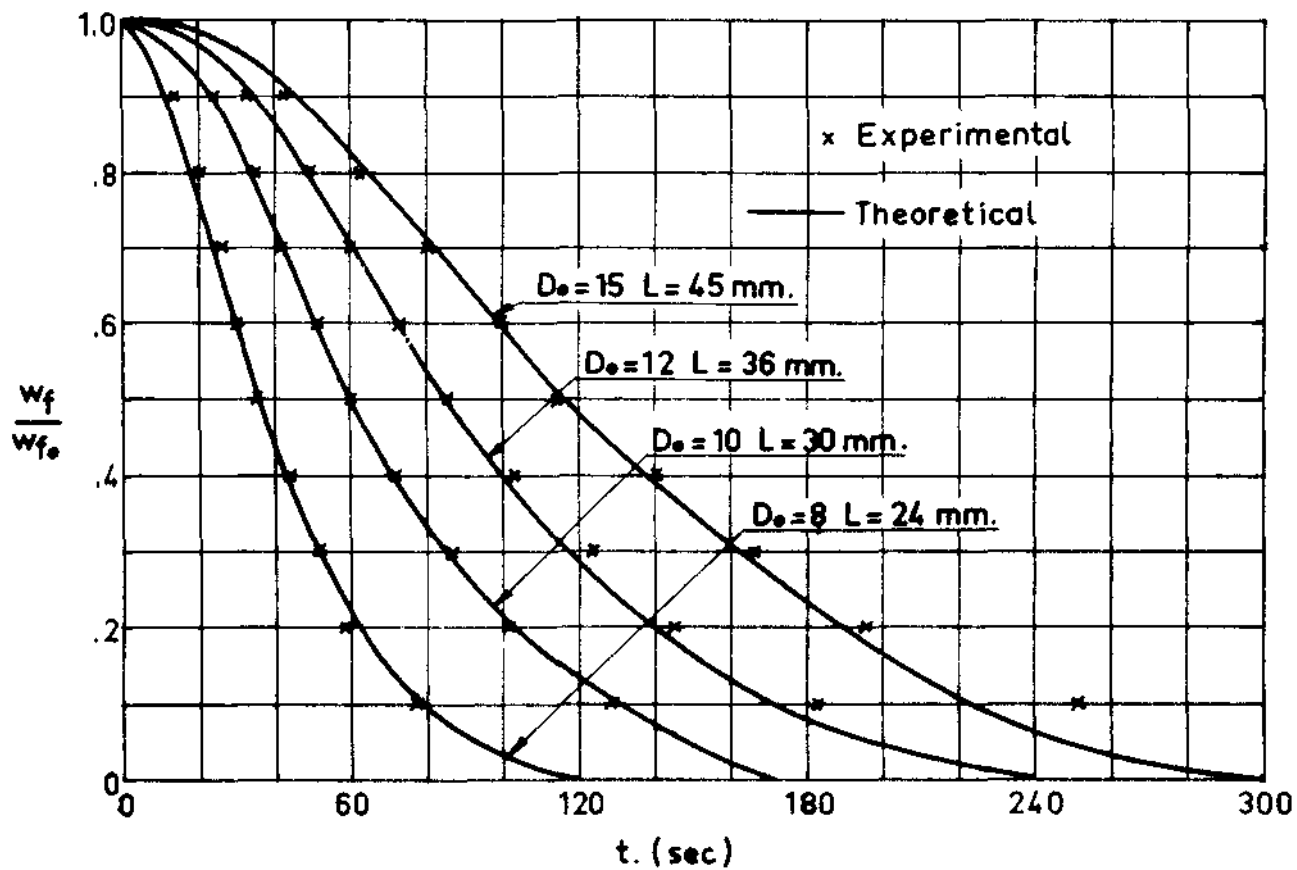


Fig.47 - Experimental Final Velocities of Fall  $w_f$  of Cylindrical Firebrands of Oak Wood and Theoretical Values Derived from Values of  $w$  Obtained at Constant Wind Speed.

## 10 . CONCLUDING REMARKS

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 accurately calculated by assuming that the firebrands fly at their final 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 obtained 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 investigated, 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 firebrands of given initial characteristics, if the convection column configuration and wind conditions are known.

Fire spread by firebrands depends essentially on the convective currents and wind conditions in forest fires. Therefore, 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 characteristic 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 speed (superscript)
Cp	Aerodynamic drag coefficient
J)	Diameter of a spherical or cylindrical firebrand
g	Gravitational acceleration
<i>l</i>	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 <sup>^</sup>	Burning-out time
t <sub>f</sub>	Final time, equal to t <sup>^</sup> or t
t <sub>g</sub>	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 firebrand
W <sub>f</sub>	Final or terminal velocity of fall
X	Horizontal axis; also subscript: x component.

- X Maximum horizontal range reached by a firebrand while 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
- $X_I = L_0 / D_0$
- $A_2 = V^D_0$
- $u_{a,00}$  Air viscosity
- X =  $wt / D_0$
- p Air density
- $a, \omega$
- $p_j$  Density of firebrand
- $w$
- ? =  $p_{a,00} / p_{w,0}$