PHYSICO-CHEMICAL STUDIES ON DUSTS OF SMALL PARTICLE SIZE.

by

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SUMMARY.

A brief description is given of the respiratory system and the way in which it deals with inhaled dusts; of the methods employed for sampling and analysing airborne dusts; of the methods employed in mines to suppress the fine dust particles; and of the mechanism of atomisation of aqueous media applied in dust suppression.

An apparatus has been developed for the examination of the settling characteristics of fine dust clouds. This consists of a chamber fitted with a pair of photoelectric cells and connected to a recording instrument for the continuous measurement of the dust concentration. Dust present in the chamber intercepts some of the light reaching one of the cells and produces a differential current which is measured by the recorder. A thermal precipitator is incorporated in the apparatus for the calibration of the photoelectric cell system and also to enable samples of the dust clouds to be withdrawn for microscopic examination.

Sedimentation studies have been carried out using various dusts. The results show that the dusts sediment rapidly over the first few hours, after which the rate of disappearance is less rapid until only the very small particles remain, when sedimentation is very slow.

A compressed-air spray has been developed and calibrated, and the effects of alterations to the variables studied. The results indicate that the nozzle/

/nozzle dimensions have no effect on atomisation, but atomisation increases as the air rate and the velocity differential between air and water are increased. Atomisation decreases slightly as the sampling distance from the nozzle is increased. The distribution of the droplets in the spray has been found to follow the relationship:-

$$\frac{dn}{dx} = ax^2 \text{ exp. } (-bx^{2/3})$$

It has been found that the empirical formula:-

$$Do = \frac{585\sqrt{6}}{V\sqrt{\rho}} + 597\left(\frac{U}{\sqrt{6\rho}}\right)^{0.45}\left(1000\,\frac{Qw}{Qa}\right)^{1.5}$$

gives a good approximation to the Sauter Mean Diameter of the spray droplets.

The effects of the air blast used for atomisation on the sedimenting dust cloud, have been studied and two theories have been put forward to account for them. The results show that more dust is removed than is predicted by theory.

The effect of the water spray on the sedimenting dust cloud has been studied. The results indicate that a proportion of the dust cloud is removed. The amount of dust removed is increased as the atomisation, droplet velocity and duration of spraying are increased.

The effect of the compressed-air spray on the size distribution of the dust in the suspended cloud has been investigated. The results show that the air blasts have little effect on the size distribution of the dust cloud, but the water sprays remove a proportion of all sizes of particles. A greater percentage of the/

/the $>$ 0.83μ particles is removed as the droplet diameter is decreased. The percentage of $<$0.83μ particles removed decreases as the droplet diameter is decreased. The results also show that as the duration of spraying is increased, the percentage of $>$0.83μ particles removed is increased whereas the percentage of $<$0.83μ particles removed is decreased.

An instrument has been designed and made (the H-J sampler) which enables fairly large samples of airborne mine dusts to be collected from the atmosphere of the pit. Trials carried out underground have given good results. A comparison has been made with another manufactured sampler (the Hexhlet, designed by Wright) and it has been found that the H-J sampler gives larger samples and that this outweighs the advantage of the elutriater on the Hexhlet.

INTRODUCTION.

The work of this Thesis is part of a programme carried out at this College for the National Coal Board and is related to the pneumoconiosis problem in the coal mining industry.

Pneumoconiosis is a general term employed to describe the common types of respiratory diseases caused by dust. It implies both the inhalation of excessive amounts of dust and the deposition of fine particles in the pulmonary tissue. Silicosis is a form of pneumoconiosis and at the International Silicosis Conference, held in South Africa, it was given the following definition:- "Silicosis is a pathological condition of the lungs due to inhalation of silicon dioxide. It can be produced experimentally in animals..". Thus silicosis is caused only by silica dust, asbestosis by asbestos dust, etc.

The lung as described by Gardner (1) is an organ that permits interchange of gas between the blood and the inhaled air. As it is in free communication with the external atmosphere it is more or less exposed to the gaseous or particulate impurities in it. The lung has certain mechanisms which protect it from the accumulation of such foreign particles. First there is the nose through which the respiratory tract opens to the rest of the body and this is guarded by a coarse filter of hair. Behind the nose there is a series of moist-walled, tortuous passages where many of the smaller particles are trapped. In addition there are/

/are the nasal cavities, the remaining portion of the upper respiratory tract, the pharynx, the trachea and the bronchi and these are lined by cells covered with minute vibratory hairs and cilia. The wavelike vibration of these hairs tends to carry any particles lodging on their surface away from the lungs back towards the external atmosphere.

Particles that succeed in passing these barriers and which penetrate to the terminal air spaces of the lungs are ingested by wandering scavenger cells. These cells move independently and tend to carry the foreign particles out of the air spaces into a special drainage system known as the lymphatics. The lymphatics are minute vessels which drain into sedimenting basins known as lymph nodes. They are situated along the course of the vessels and bronchi and at the root of the lungs where the trachea divides into the two main bronchi.

For ordinary amounts of atmospheric pollution, these protective mechanisms are adequate to prevent significant accumulation of foreign particles in the functional part of the lungs. If a person continues to work in a very dusty atmosphere for long periods his protective devices cannot cope with the situation, the mechanisms themselves are damaged and the dust particles collect where air should be.

The relationship between the amount of dust deposited in the lungs during inhalation and the amount in the air is determined by the behaviour of particulate matter/

/matter in the respiratory system. It has been known for a long time that only a fraction of inhaled dust is retained and that the percentage retention varies with particle size.

The size of airborne dust particles which are likely to be harmful is not definitely known. Some authors claim that particles less than five microns are dangerous, others, particles less than three microns. From mathematical and physical considerations it is seen that there must be an "optimum" size of particle having the greatest probability of penetrating to and being retained in the alveoli. Larger particles will be relatively scarce in the alveoli because of earlier deposition in the upper respiratory tract and finer particles will decrease in number because of lower retention. This relationship has been predicted (2) and derived indirectly from measurements of total retention. It has also been confirmed in human lungs (3,4). Bedford and Warner (5) recognised under the optical microscope that 98% of all particles occurring in silicotic tissue were below 1.2 micron in size, whereas Cartwright and Nagelschmidt (6) found 0.4 micron to be the predominant size in lung tissue of coal miners. Hatch has shown (7) that in the microscopic range, particles about 1 micron in size must be regarded as significant contributors. It seems reasonable to assume that any dust particle will be dangerous if, when drawn up into the nostrils and other protective air passages in large amounts, it clogs the protective systems, and allows the smaller dust to enter the lungs much more/

/more easily.

Dust Formation.

The formation of dust in a coal mine depends on a number of factors:-

(i) The hardness of the coal - it has been found that a hard coal generally gives off more dust than a soft one.

(ii) The height from which the coal falls - more dust is produced the higher the distance the coal has to fall.

(iii) The direction in which the coal is cut - it has been found that less dust is produced when coal is drilled upwards and also that wet drilling produces finer dust than dry drilling (8).

(iv) The sharpness of the tools used - a dull bit has been found to produce more dust than a sharp one.

(v) Speed of operation - generally more dust is produced the faster the speed of cutting.

Owing to lack of information, it is difficult to define dangerous dust concentrations accurately. It is now accepted (9) that men can work safely in atmospheres containing not more than 850 coal or 650 anthracite, 1-5 micron particles per cubic centimetre or 450 rock, 0.5-5 micron particles per cubic centimetre of air.

Methods of Sampling and Analysing Airborne Dusts.

A number of instruments are available for measuring dust concentrations in mines and the following/

/following are in most common use.

(a) The Konimeter. This instrument consists of a spring operated pump by means of which a small sample of dusty air (2.5 cc or 5 cc) can be drawn through a small orifice and caused to impinge at high velocity upon a glass slide which is coated with a thin film of glycerine jelly. Thirty different samples may be taken on one slide. A microscope is incorporated so that each dust trace on the slide can be examined immediately. This instrument has the disadvantage that only about 20% of the dust sampled is caught on the slide (10). It has also been claimed that this impingement method forms aggregates on the slide and some of the dust particles are smashed by it.

(b) The Owens' Jet Dust Counter. This is also an impingement instrument. It was developed by Hatch and Thompson and is similar to the Konimeter. As the velocity of impingement is much higher than in the konimeter, no coating is used on the slide. This instrument allows the collection of eight samples on a single glass slide. The dust ribbons so formed are matched against a series of standard ribbons under a comparison microscope. The disadvantages of the konimeter also apply here.

(c) The Impinger. This instrument was developed at the United States Bureau of Mines by Greenburgh and Smith (11). The dust laden air is caused to impinge at high velocity through a nozzle on to a glass surface immersed in water. The impingement takes place on to a water free surface since the constant action of the air stream maintains the surface in a dry state. The liquid/

/liquid is then removed and a portion examined under a microscope. The chief disadvantage of the "impinger" is its low efficiency for collecting small particles.
(d) The P.R.U. Handpump. With this instrument, the air containing dust is drawn through a small filter on which the particles are deposited. A direct reading for dust concentration is then obtained from the stained filter paper by examining it with a light extinction type of instrument. The P.R.U. Handpump is used mainly for rough comparative work since it is not possible to distinguish between large and small particles on the sample obtained.
(e) The Thermal Precipitator. This is the instrument most commonly used by the National Coal Board. It was designed by Green and Watson (12) and consists of two parts, the head which carries a heated wire and the aspirator which draws the air past the heated wire. The wire is heated by an electric current and as the dust laden air is drawn slowly past the hot wire, the particles pass within the thermal gradient and are deposited on cover glasses suitably positioned in the head. This instrument has a sampling efficiency of 100% for dust particles in the range 0.2 - 2.0 microns. The cover glasses are removed, mounted on a glass slide and examined under a high powered microscope.

Dust Suppression in Coal Mines.

As no cure is as yet known for pneumoconiosis, prevention is the only effective remedy. There are two main lines of approach to the problem, firstly, through control of dust production and dissemination, and secondly, by control of the health of workers by examination/

/examination.

Dust suppression measures have been applied in an ever increasing scale in British Coal Mines, so that at present, over 90% of the coal faces requiring treatment are being dealt with. All these methods require the use of water and therefore it has become increasingly important to apply the water carefully and as efficiently as possible, if problems of roof control, etc., are to be avoided.

Dust suppression can be accomplished in two ways:-

(i) Prevention of dust formation at its source.

(ii) Removal of dusts which have already become airborne.

The main methods used for the suppression of dusts at the source are wet cutting, water infusion and the use of foam. Water sprays have been much used for the removal of airborne dusts. Such sprays can be produced either by forcing water under pressure through a restricted orifice, or by the action of compressed-air. Both methods have been used underground with success and results obtained have tended to indicate that compressed-air operated sprays are more effective.

The advantages of the compressed-air operated sprays are:-

(i) Smaller droplets and better control of droplet size can be obtained.

(ii) The chance of clogging the nozzle openings is less than with swirl type sprays.

(iii) The/

(iii) The air used for atomisation increases the ventilation.

(iv) Compressed-air is readily available in most mines.

The use of wetting agents for reducing the amount of water has been widely studied and it has been found that during coal cutting, sprays formed from dilute solutions of wetting agents reduced dust concentrations much better than those using water alone (13).

The water infusion method consists of injecting water under pressure into bore holes which have been driven into the coal face to a depth determined by existing conditions. The water pressure is also determined by the mining conditions and varies between 30 and 300 lbs. per sq. inch. This method (14) has been applied with beneficial results but does not remove the dust completely. Infusion of unlimited quantities of water into the coal face is dangerous (15).

The use of foam for effective suppression of dusts at the source has been suggested by Price (16). However, tests carried out in pits with carefully controlled dust conditions gave inconclusive results. This method has the advantage that the amount of water applied as foam is considerably less than that required by other techniques.

Although a great deal of work on dust suppression has been carried out in mines using water sprays, very little has been done on the laboratory scale, under controlled conditions.

Atomisation.

In the process of atomisation, a continuous liquid/

/liquid jet is broken up into a large number of droplets and the surface area of the liquid is greatly increased. This can be achieved in several ways:-

(a) Discharge at a high velocity through a restricted orifice, e.g. as in a swirl type atomiser.

(b) Atomisation of the liquid by means of a stream of gas, e.g. the compressed-air atomiser.

(c) Atomisation by mechanical means, e.g. spinning disc or centrifugal atomiser.

In each of the above, the main force causing the break up of the jet is produced in a different way and in each case atomisation can be contributed to several factors.

The disintegration of a liquid jet at low velocities is fairly well understood, but the process of sudden atomisation at high discharge velocities, which takes place in any injection system has never been clearly explained.

One of the first theories for the disintegration of a liquid jet was put forward by Rayleigh (17) who analysed mathematically the stability of a non viscous jet and derived conditions for the disruption of the jet. Although the conditions assumed by Rayleigh do not in fact exist in an atomiser, his conclusions were accepted and used by Weber (18), Castleman (19) and Haenlein (20).

In analysis of spray formation, the importance of turbulent flow was stressed by Schweitzer (21), and De Juhasz (22).

Mehlig (23) attributed spray formation to the/

/the radial components of liquid velocity existing in a turbulent flow, while Thieman (24) held that turbulence increased the relative velocity between the outer liquid layer and the air and caused sudden disruption of the jet. Oschatz (25) considered the effects of flow in the atomiser and of the properties of the liquid and surrounding gas. He concluded that the flow in the atomiser itself played a major part in the process of atomisation and created conditions for an earlier or later jet disruption.

Liquid jet disruption was studied using high speed spark photography, by Holfelder (26) and Haenlein (20). They followed the disruption of a liquid jet as the discharge velocity was increased. Haenlein's experiments for the initial stages of jet disruption were confirmed theoretically by Weber's calculations (18).

Nukiyama and Tanisawa (27), in their photographic studies of spray formation, distinguished three types of jet disintegration as the velocity of discharge was increased.

Ohnesorge (28) also found similar stages of jet disruption, with an additional zero stage when droplets form slowly under gravity. Ohnesorge concluded that the different stages occurred at different values of Reynold's number.

From the observations of Scheubel (29) and Sauter (30), who investigated the process of atomisation in carburettors, Castleman (19) put forward a theory of jet disruption which was later supported by the/

/the work of Nukiyama and Tanisawa (27). Castleman suggested that a combination of the effects of the air friction and the relative velocity between the outer jet layer and the air, caused irregularities on the previously smooth liquid surface. As a result of this, small ligaments were torn from the main jet. These quickly broke up into small droplets due to the surface tension forces. In this theory, Castleman assumed that the most important factor in atomisation was the effect of air friction, which caused the tearing of the ligaments from the main jet stream. According to Castleman, the size of the liquid drop reached a lower limit at high discharge velocities because the ligaments collapsed as soon as they were formed and further increase in velocity could not produce smaller droplets.

Summarising, it can be said that the disintegration of a liquid jet discharged from the orifice of an atomiser is affected by:-

(i) The turbulence in the flow of the liquid from the orifice.

(ii) The properties of the medium into which the jet is discharged.

(iii) The viscosity and surface tension forces in the liquid.

The turbulence of the liquid flow will depend on the atomiser design and on the velocity of flow.

In general, the liquid viscosity and surface tension forces oppose the disintegration of the jet. High viscosity decreases the rate of breaking up of distortions/

/distortions of the droplets formed initially and increases the final droplet size. The action of surface tension is two-fold (31). It acts (a) in the initial stages of the development of surface distortions into ligaments, and (b) in the deformation of droplets.

Surface tension opposes process (a) but assists in the final stages of disruption. Since the disruption process is important in atomisation, an increase in liquid surface tension should cause a deterioration in atomisation.

A high speed jet emerging from the orifice in a continuous stream is thus disrupted by the action of the forces mentioned. This creates some larger droplets and a large proportion of smaller ones. During further travel, these larger droplets are broken up. The process of atomisation is therefore not completed immediately after the jet has emerged from the orifice, but proceeds during the jet movement into the surrounding medium until the droplet velocity falls below a critical value, when further disintegration cannot take place.

The work described in this Thesis was a continuation of the work of Massie (32) and Glen (33). It was hoped to study in detail the compressed-air spray and its effect on artificially produced dust clouds. The dust concentrations in a suitable chamber were to be measured by light extinction methods and by the use of the thermal precipitator. The latter was also to be employed to determine the particle size analysis of each suspension.

The/

/The problem of dust suppression in mines has been in existence for many years. In recent years, with the advent of nuclear power, dust suppression in that field has also become a problem of great importance.

SECTION 1.

THE SEDIMENTATION AND AGGREGATION OF DUSTS.

An aerosol is a disperse system in which the suspension medium is a gas. Its outstanding difference from a true colloid is its relative instability. The ultramicroscopic particles in a gold sol, for example, remain in suspension for indefinite periods and sedimentation is difficult to detect. Further, the particles in such a sol, though in active Brownian movement, never approach close enough to collide, but are held apart by ionic forces. Coagulation only takes place on the addition of an electrolyte, whence the isoelectric point is approached and the sol precipitates.

Aerial disperse systems on the other hand, such as smokes, fogs, mists, dusts, etc., behave in a different manner. Firstly, because of the relatively low viscosity and specific gravity of gases, the solid or liquid particles of the disperse phase settle more readily from the system, under the influence of gravity. Secondly, gas molecules have greater freedom of movement with much longer free paths than liquid molecules, hence the motion of particles due to Brownian movement is very much greater in an aerosol than in other disperse systems. Finally, several workers have found (34)(35) that particles of this type of disperse system have electrical charges, some positive, some negative and some electrically neutral.

Whilst smokes are formed by condensation, dusts/

/dusts are produced invariably by disintegration or dispersion processes. Speaking generally, they consist of larger and denser particles and hence sediment more rapidly than smokes. The number concentration in dust systems is usually low. Moreover, dust particles tend to coagulate when they come in contact. This process, however, is relatively slow.

Movement of Suspended Particles.

Particles suspended in a gas move under the influence of any or all the following forces.

(a) Forces causing Brownian movement, which result from the molecular activity of the gas itself.
(b) Forces which are independent of the gas, e.g. gravitational and centrifugal forces.
(c) Forces producing macroscopic gas movement, caused by convection, diffusion and mechanical disturbance.

When a particle is suspended in a gas it is subjected to a general bombardment by the gas molecules. If the particle is large in comparison to the mean free path of the gas molecule, the molecular bombardment will take the form of a continuous, uniform pressure, exerted over the whole surface of the particle. Small particles suspended in a gas, exhibit random movements, since they no longer encounter this continuous pressure. The impact of the gas molecules do not now average out over their surface; the particles slip between the gas molecules and are driven to and fro.

As a result of this motion, the orientation of the particles is continually changing. According to/

/to the kinetic theory, the average kinetic energy of a particle in Brownian movement in a gas, is the same as the average kinetic energy of the molecules of the gas. Owing to the greater mass of the particle, the velocity of the particle is necessarily smaller than that of the gas molecule.

All suspended particles are normally exposed to a gravitational force proportional to the difference between the densities of particles and gas. When this gravitational force becomes exactly balanced by a resisting force due, say, to the drag of the gas, the particles tend to rise or fall at a constant speed known as the terminal velocity. The behaviour of the sedimenting particles depends upon the nature of the gas flow around it, due to its motion. This varies with the size of the particle, and is dependent on the inertia of the gas thrust aside by the advancing particle. Part of the resistance to motion is due to the viscosity of the gas and part due to the sum of all the products formed by the accelerations and inertias of the gas molecules.

The velocity (V) with which small spherical particles move through a uniform viscous fluid (liquid or gas) under the influence of an external force is given by the expression:-

$$V = F/K.$$

where F represents the force and K is the functional resistance of the particles in passing through the gas.

Stokes/

/Stokes has shown that $K = 6\pi\eta rV$

where η = viscosity coefficient of the gas,
r = radius of the particle,
V = velocity.

A particle in suspension will be pulled vertically downwards by gravitation with a force of:-

$$4\pi r^3 \rho g/3 \quad \text{dynes}$$

and in any fluid, this force (F) will be diminished by the buoyancy of the fluid and will be given by:-

$$F = 4\pi r^3(\rho_1 - \rho_2)g/3$$

where, ρ_1 = density of the particle,
ρ_2 = density of the fluid.

When the velocity with which the particle is falling is such that the resistance it encounters is just balanced by the weight of the particle, it will continue to fall at that velocity.

Then, $6\pi\eta rV = 4\pi r^3(\rho_1 - \rho_2)g/3.$

Hence V = the ultimate constant velocity of the particle

$$= 2r^2(\rho_1 - \rho_2)g/9\eta$$

$$= d^2(\rho_1 - \rho_2)g/18\eta$$

From this formula it is seen that for any given material $(\rho_1 - \rho_2)$ and η will be constant and the velocity of the particle will then be proportional to the square of the radius. Non spherical particles will fall in the position in which they encounter maximum resistance, e.g. cubic crystals will fall point downwards, a plate will fall in a horizontal position and fine crystals with their major axis horizontal (36).

In/

/In the above formula, it is assumed that all the particles are spherical. With dusts and smokes, however, the particles may consist of very irregular crystals and aggregates.

A particle smaller than 10^{-5} cms will be smaller than the mean free space between the gas molecules. The velocity with which it will travel through the gas will thus be greater than that given by Stokes' Law.

Cunningham (37) and Millikan (38) have shown that $V = V^1(1+K^{\lambda}/r)$

where V = true velocity

V^1 = Stokes' velocity

λ = the mean free path of the gas molecule

r = the radius of the particle

K = constant (approximately equal to 0.86)

Davies (39) has expressed Stokes' Law in the form $FV = d^2(\rho_1 - \rho_2)g/18\eta$

where V is the terminal velocity of the particle, and F is a constant which depends on d and allows for the effect of 'slip' in gases. The 'slip' effect occurs when the particles approach the size value for the mean free path of the gas molecules. Davies calculated the values for F given in table 1.

TABLE 1./

TABLE 1.

Diameter (μ)	F
0.02	11.554
0.04	6.106
0.10	2.894
0.20	1.884
0.40	1.422
1.0	1.164
2.0	1.082
4.0	1.042
10.0	1.016
20.0	1.008
40.0	1.004
100.0	1.002

The 'slip' correction is obviously inappreciable for spheres greater than 20μ diameter.

When the gas is quite free from movement, the upper edge of a region containing very small falling particles, is usually quite well defined. As soon, however, as the start of sedimentation causes a change in the concentration of particles of a given size in the cloud, diffusion of the particles tends to eliminate it, the upper edge of the sedimenting cloud becoming more or less diffuse. If the concentration is the same everywhere, this produces no visible effect, but if there is a local difference in concentration, particles drift from the zone of high concentration to the/

/the one of low concentration to an extent which depends on the numbers present in the two regions.

In most cases, however, there are bulk movements of gas occurring in a random manner, with the result that the falling upper edge becomes more blurred or completely disappears. Thus the particles remain fairly evenly distributed throughout the gas while their concentration steadily decreases due to sedimentation. Convection generally gives rise to irregular currents and a circulation, which keeps the bulk of the gas well mixed. There will, however, be a stagnant zone next to walls, floors and other solid surfaces, which will be a function of the viscosity of the gas and the shape of the vessel containing the gas. The particles in the bulk of the gas will be in motion and uniformly mixed until one happens to be carried into the stagnant zone above the floor of the containing vessel, where it will be trapped and will sink to the floor at its terminal velocity. Thus, only those particles very near the floor will fall out, the others being moved away by turbulence.

Davies (39) has derived a sedimentation equation based on the above argument as follows:-

Consider a cloud of particles uniformly distributed and sedimenting in an air chamber.

Suppose that in time δt, all particles within a distance $V\delta t$ of the floor settle out, where V = the terminal velocity.

If the concentration of particles in the fluid per unit volume = C particles per cubic centimetre (p.p.c.c.)

/The

/The number falling out per unit area on the floor = $CV\delta t$.

As a result, the mean concentration in the chamber is reduced from C to $(C-\delta C)$ per unit volume.
Let h be the height of the chamber.
Then the total diminution of particles = $Ah\delta C$
where A = area of horizontal section of fluid
= cross sectional area of air chamber.
This must equal the total which has fallen out

$$\therefore\ Ah\delta C = ACV\delta t.$$

The rate of change of concentration $\frac{\delta C}{\delta t} = \frac{CV}{h}$ ----- (1)

On integration $C = C_o \exp\left(\frac{-Vt}{h}\right)$ ---------- (2)

where C_o = initial number of particles per unit volume supposed evenly dispersed throughout the chamber.
C = average number of particles per unit volume at time 't'.

From equation (2), the number of particles in the chamber at time 't' was

$$CAh = C_oAh \exp\left(\frac{-Vt}{h}\right)$$

Hence the number reaching the floor up to time 't'

$$= C_oAh - CAh$$

$$= C_oAh - C_oAh \exp\left(\frac{-Vt}{h}\right)$$

$$= C_oAh\left[1 - \exp\left(\frac{-Vt}{h}\right)\right]$$

If/

/If N_t = number falling per cm^2 on the base of the chamber up to time 't' from the beginning of the experiment

$$N_t = C_o h \left[1 - \exp\left(\frac{-Vt}{h}\right)\right] \text{---------- (3)}$$

h = velocity x time = Vt

$$N_t = C_o Vt \left[1 - \exp\left(\frac{-Vt}{h}\right)\right] \text{---------- (4)}$$

$$\frac{dN_t}{dt} = C_o V \exp\left(\frac{-Vt}{h}\right)$$

when $t = 0$, $\frac{dN_t}{dt} = C_o V$.

If N_t is plotted against t, $C_o V$ is then the slope of the straight line through the origin obtained when turbulence is absent, and is the tangent to the curve at the origin when turbulence is present. When $t \longrightarrow \infty$ the curve becomes a horizontal line and $N_t = C_o h$ which is the value which would have been obtained in calm conditions.

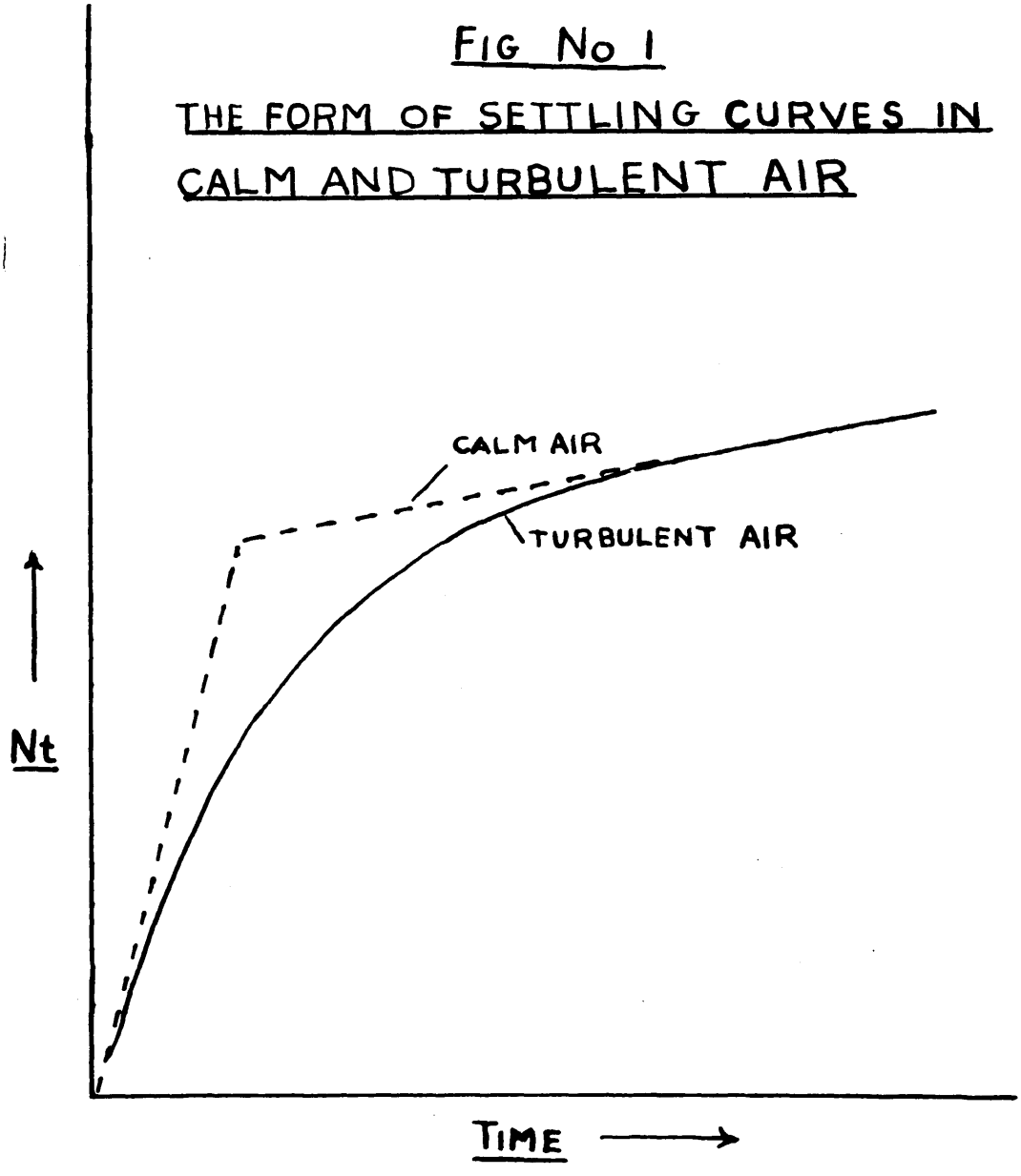
Therefore, in calm air, two intersecting straight lines should be obtained, while in turbulent air a curve results, which should approach the values obtained under calm conditions at $t = 0$ and again when t becomes large compared with h/V. The two types of relationship are shown in Fig. No. 1.

Experimental Dust Sedimentation Chamber.

The chamber to be used in this study of dust sedimentation was that employed by Glen (33) and was built/

FIG No 1

THE FORM OF SETTLING CURVES IN CALM AND TURBULENT AIR



/built in the form of a cylinder 60 inches high and 18 inches in diameter. This size and shape had been chosen for the following reasons:-

(i) The wall effect on dusts in suspension should be relatively small.

(ii) Samples of dust could be withdrawn by means of a thermal precipitator without causing any noticeable change in concentration.

(iii) Sprays with large throughputs and spray angles could be used without too many droplets striking the side of the chamber.

(iv) The amount of "dead space" was reduced by having a cylindrical chamber in preference to a cubical one.

The chamber which was suspended from a 'Dexion' metal stand by four lugs mid-way down its length, was fitted with a circular cover and had a conical base to assist drainage. The latter were attached to the chamber with butterfly nuts and bolts with rubber gaskets between to prevent leakage.

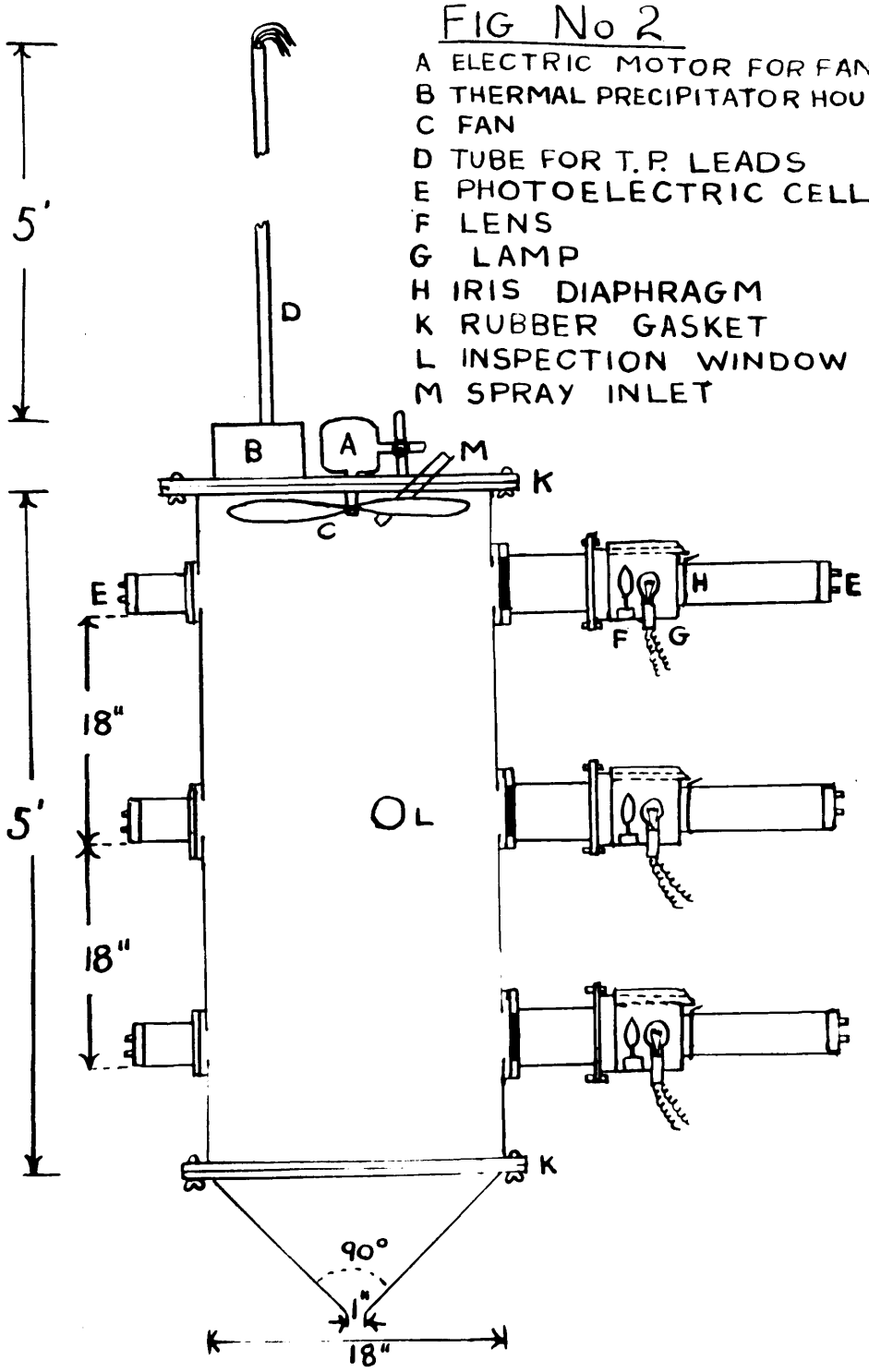
The chamber was painted internally with matt black paint to reduce light reflection. A three-bladed 10 inch fan, made from aluminium sheet, and driven by an electric motor, was fitted through a hole in the centre of the cover. The cover also had entrances for the spray nozzle and the thermal precipitator head. A drawing of the chamber is given in Fig. 2.

Dust Cloud Apparatus.

The apparatus employed to obtain a reproducible/

FIG No 2

A ELECTRIC MOTOR FOR FAN
B THERMAL PRECIPITATOR HOUSING
C FAN
D TUBE FOR T.P. LEADS
E PHOTOELECTRIC CELL
F LENS
G LAMP
H IRIS DIAPHRAGM
K RUBBER GASKET
L INSPECTION WINDOW
M SPRAY INLET



/reproducible dust cloud is shown in Fig. 3, and was a modification of the type used by Dautreband et al (41). Low pressure air from an electric blower entered the dust container through three small bore copper tubes and created a vortex which lifted the dust up through the elutriator chamber. It then passed through the cyclone separator and entered the dust chamber at the bottom. Only the smallest particles reached the chamber and gave a dust cloud which would remain in suspension for a sufficient length of time to enable readings to be made.

Photoelectric Cell Units.

Changes in dust concentration in the chamber were measured by a system of photoelectric cells. The system used was adopted from that employed by Smellie (41) and developed by Cumming, Rumford and Wright (42). The apparatus was further modified by Massie (43) to enable small concentrations to be measured. Three cell units were spaced at equal intervals down the length of the chamber to enable the dust concentration to be measured at different levels.

A typical photoelectric cell of the type used (44) is shown diagrammatically in Fig. 4. When light falls upon the sensitive surface a current is produced which can be measured with a suitable instrument.

The photoelectric cell unit (P.E.C.) is shown in Fig. 5. It consisted of a lamp housing (A) which contained a "Mazda" 12 volt, 24 watt, axial filament car bulb and was attached to a compartment (C) which/

FIG. No 3

DUST CLOUD APPARATUS

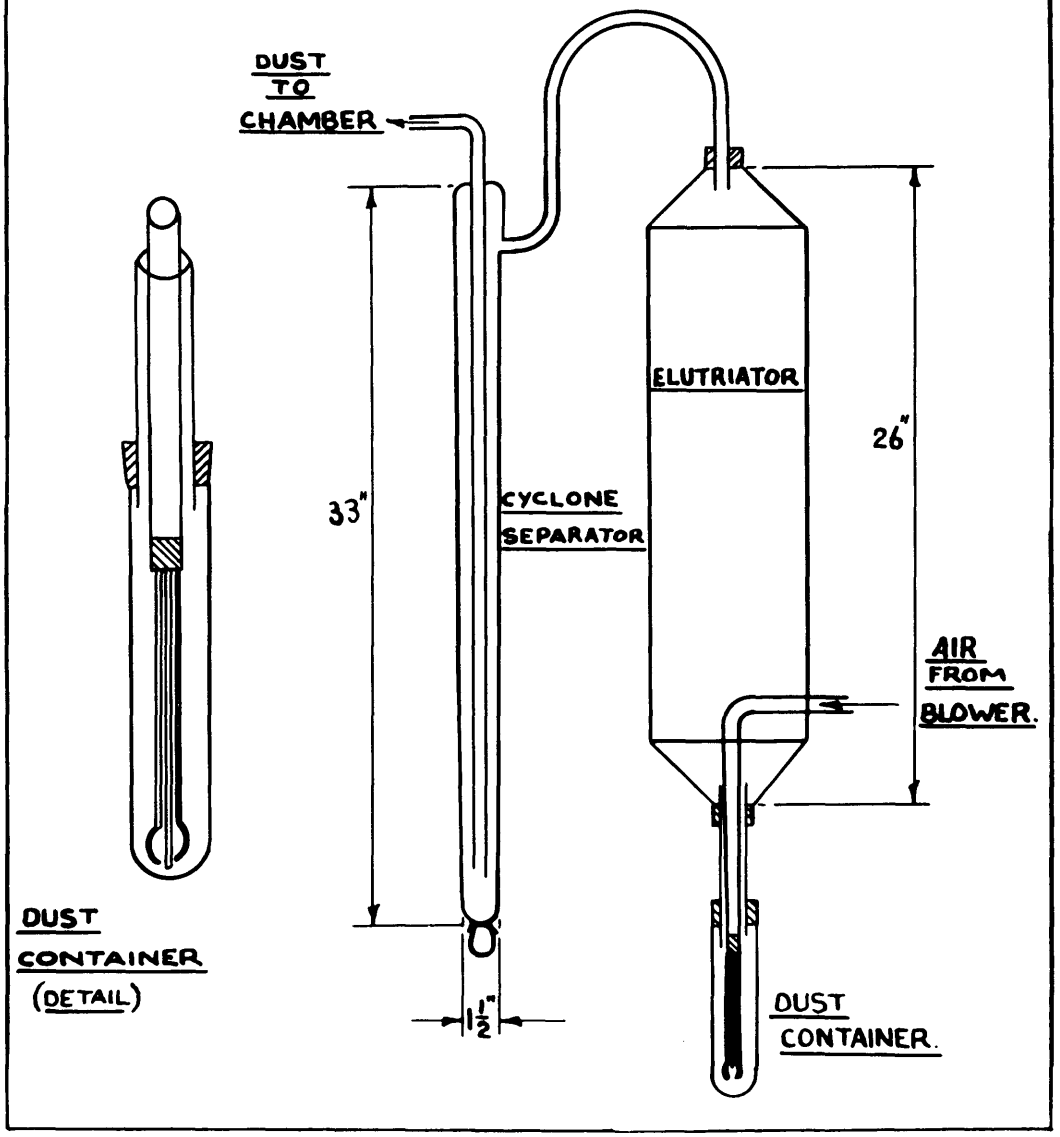
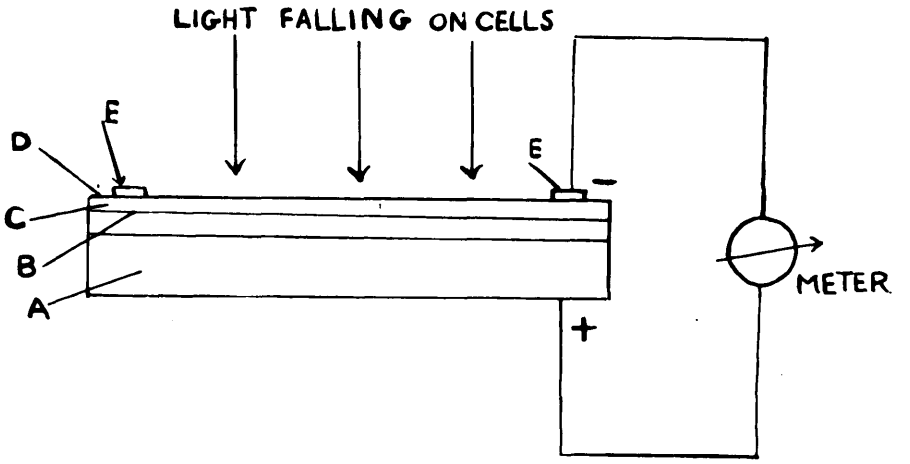


FIG No 4

SECTION OF PHOTOELECTRIC CELL

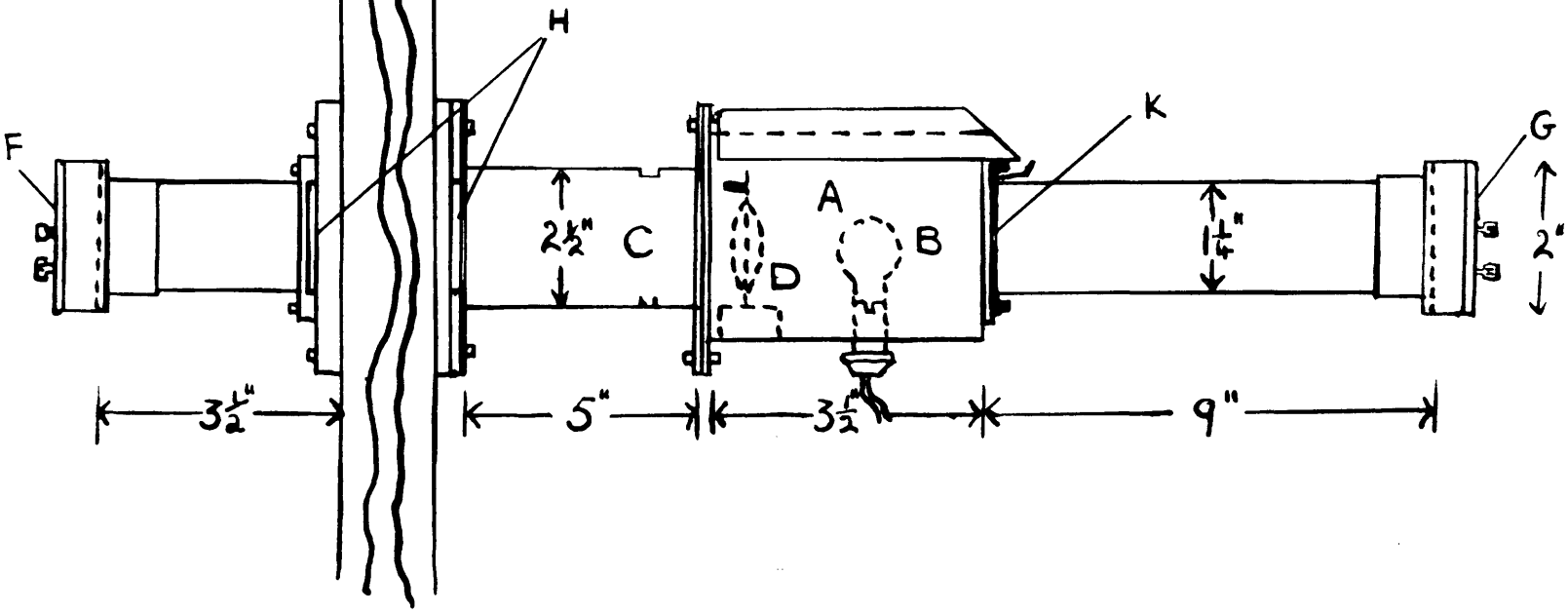


A - METAL BASE PLATE
B - SELENIUM LAYER
C - THEORETICAL BARRIER LAYER
D - TRANSPARENT METAL LAYER
E - COLLECTING RING

FIG No 5

PHOTOELECTRIC CELL UNIT

(NOT TO SCALE)



/which was in turn bolted to the dust chamber. This compartment, by separating the lens from the dust chamber, helped to prevent dust depositing on the lens.

The lamp current was supplied by a 12 volt car battery kept continuously charged by a trickle charger. The light from the lamp passed through a collimating lens (D) which made the beam parallel. After passing across the chamber the light beam fell on a photoelectric cell (F), the "reading" cell. On the other side of the lamp was a similar photo-electric cell (G). Between the latter compensating cell and the lamp housing was fitted an iris diaphragm (K) by means of which the amount of light reaching the compensating cell could be controlled. Transverse slots (H) were arranged at the point of entry and departure of the light beam to the chamber, into which suitably designed masking slides could be put, to reduce or cut off the light beam as required. A small observation window was cut in the front of the chamber and closed with transparent perspex. The window was so arranged that entering daylight could not fall on the P.E.C.'s.

The P.E.C.'s were connected in opposition across the terminals of a Kent multipoint recorder (45), thus enabling the readings from the three sets of cells to be read continuously on the same chart. The zero readings on the chart for the cells were obtained by adjustment of the iris diaphragms. If, when/

/when the iris diaphragm was reduced as far as possible, too much light still reached the compensating cell so that a zero line could not be obtained at a suitable position on the chart, a filter of suitable transparency was placed in front of the cell. The position of the zero line on the chart was then controlled by adjustment of the iris diaphragm. A diagram showing the circuit for the P.E.C. system is shown in Fig. 6.

Thermal Precipitator Unit.

A housing was bolted to the top cover of the chamber to accommodate a thermal precipitator (T.P.), as shown in Fig. 1. This consisted of a compartment (B) through which passed a light gauge copper tube 5 feet long and 1 inch diameter. Through this tube, electrical cable and rubber tubing were led and attached to the T.P. head.

The copper tube could be clamped at any part in its length and hence the T.P. head could be fixed at any depth in the chamber. When not in use the T.P. head was withdrawn into the compartment (B). This was fitted with a sliding door which closed against a rubber gasket and prevented the dust escaping into the atmosphere. The remainder of the T.P. unit was standard equipment operated according to the makers' instructions (46).

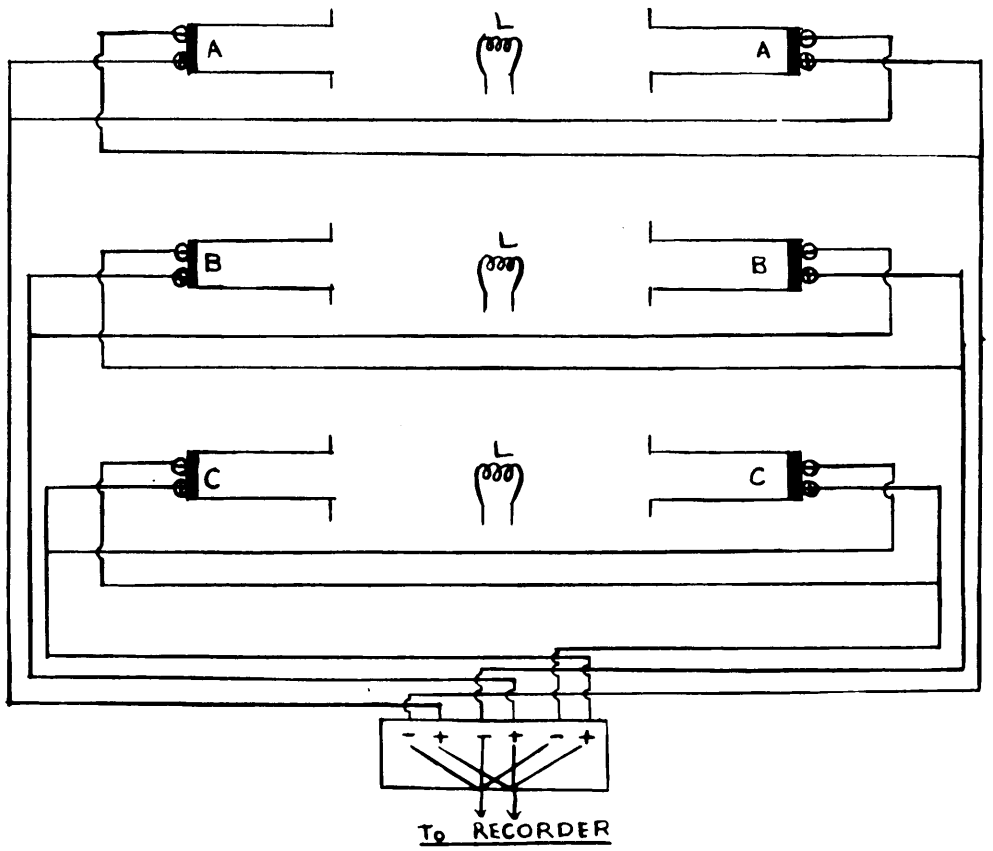
Experimental.

Calibration of Photoelectric Cell System and Recorder.

Glen (33) calibrated this photoelectric cell system/

FIG No.6

PHOTOELECTIC CELL CIRCUIT DIAGRAM.



A – PHOTOELECTRIC CELLS TOP SYSTEM
B – " " MIDDLE "
C – " " BOTTOM "
L – LAMPS

/system by means of Ilford gelatine neutral density filters of different known light transmissions. In the present work, however, the system was calibrated by means of the T.P.

The recorder and lights were switched on and the zero lines adjusted on the chart. The system was left for about two hours to settle down and this enabled the "zero drift" lines to be recorded on the chart. When the system had remained steady for half an hour, the slides on the chamber were closed to prevent dust reaching the lenses and cells. The fan was switched on and allowed to run for 15 seconds before the dust was introduced. The dust cloud was blown in for the desired time (depending on the type of dust being used) with the fan still running. The fan was left running for a further 15 seconds after the dust generator had been switched off. The slides were then removed and a T.P. sample taken immediately at the same level as one of the P.E.C. systems, but with the T.P. head so placed that it did not obscure the light beam. The chart reading was also marked at the corresponding point. T.P. samples were taken at the various P.E.C. system levels at noted times during the sedimentation of the dust. The T.P. cover glasses were removed, mounted on glass slides and examined later with a microscope and the dust concentrations estimated. In this calibration run with the three P.E.C. systems working, six T.P. samples were taken for each set of cells.

At the end of the run, the chart was removed, the/

/the zero line drawn and the galvanometer readings corresponding to the T.P. samples measured. A calibration curve of galvanometer units against dust concentration (p.p.c.c.) was then drawn up.

Ex U.S. army surplus photo-electron multipliers were tried to replace the P.E.C.'s, but were found to drift considerably and were thus unsatisfactory for this purpose.

Determination of concentration and size distribution of dust clouds using the T.P. samples.

A Vickers projection microscope equipped with a 2 mm oil immersion apochromatic lens and a x 10 compensating eyepiece was used. This gave a magnification of x 2400. Mercury vapour lighting was available giving very good resolution and enabling particles of size 0.2μ to be measured.

The particles were sized by comparing them with numbered circles on a previously calibrated graticule. Irregular particles were treated as an equivalent circle i.e. the cross sectional area of the particle was compared with the circle on the graticule. Over 400 particles were measured across the deposit on the cover slip. In the case of light deposit, more than one traverse was examined.

The particles were counted as the deposit was traversed horizontally across the field by means of a mechanical stage. Three traverses were measured on each strip, one 2 mm from each end and the third in the centre. Care was taken to focus in turn/

/turn on the underside of the cover glass and on the top of the slide, in case any of the larger particles had fallen from the cover glass, since there was usually a small air space between it and the slide.

Calculation of dust concentration from T.P. particle counts.

The dust in the air drawn through the T.P. is deposited on two cover glasses arranged on either side of the hot wire. The deposit on a cover glass takes the form shown in Fig. 7.

Suppose that on the two cover glasses the lengths of the T.P. deposits are L_1 and L_2 and the width of each counting traverse of the deposit is W. If the corresponding average counts across the deposits are N_1 and N_2 and V is the volume of air sampled, then:-

		Cover Glass 1.	Cover Glass 2.
Number of particles per deposit	=	$N_1 \times \frac{L_1}{W}$	$N_2 \times \frac{L_2}{W}$

$$\text{Dust concentration} = \left[\frac{N_1 \times L_1 + N_2 \times L_2}{W \times V}\right] \text{p.p.c.c.}$$

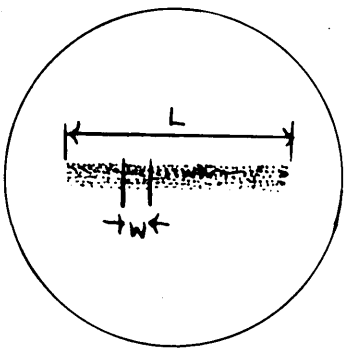
For an actual case where the volume sampled was 9.0 cc:-

Width of graticule i.e. counting traverse = 0.42 mm.

Length/

FIG No 7

DIAGRAM OF DUST DEPOSIT ON T.P. COVER GLASS



L = LENGTH OF DEPOSIT

W = WIDTH OF COUNTING TRAVERSE

	Cover Glass 1.	Cover Glass 2.
Length of strip =	9.70 mm.	9.74 mm.
Average number of particles per traverse =	238.7	389.7

$$\therefore \text{Dust concentration} = \frac{(9.7 \times 238.7 + 9.74 \times 389.7)}{0.42 \times 9.0} \text{ p.p.c.c.}$$

$$= 16{,}180 \text{ p.p.c.c.}$$

The homogeneity of the dust cloud.

After the calibration of each P.E.C. system as described above, a similar dust cloud was introduced and the dust allowed to sediment without movement of the T.P. head in the chamber. The dust concentrations were assessed by the recorder. The results are shown in the Table 2 and support the conclusion of Glen (33) that while sedimentation takes place, the dust cloud remains homogenious due to air movements. Davies sedimentation equation derived on page 25 would therefore appear to be applicable to the system.

This homogeneity makes only one set of P.E.C.'s necessary and therefore all the recorder points may be connected to, say, the middle set of cells enabling the record to be an almost continuous line.

TABLE 2./

TABLE 2.

The homogeneity of the dust cloud.

Time (hours)	Concentration (p.p.c.c.) in positions.		
	Top	Middle	Bottom
½	50,000	55,000	47,000
1	27,000	26,000	25,000
2	10,000	9,500	10,000
3	7,000	6,500	7,000
4	4,000	4,500	4,500
5	2,500	2,500	2,500

Dust sedimentation studies.

The sedimentation of a variety of dust types was studied, each being ground in a mechanical mortar and oven dried for 24 hours at 120°C. The dry dust samples were stored in desiccators and used as required.

The dusts studied were:-

(1) D.R.C. silica dust - supplied by Colin Stewart, Winsford, Cheshire.

(2) Ground silica dust - Loch Aline sand, a high grade silica sand mined at Loch Aline, Argyllshire. (It was ground for 8 hours in the mechanical mortar.)

(3) Ground coal dust - a mixture of shale and coal dust (approx. 50% of each).

(4) Ground fly ash - Fly ash received from a power station./

/station. (It was ground for 4 hours in the mechanical mortar.)

(5) Micron powder - Copper powder supplied by Powder Metallurgy Ltd., 58-62 High Holburn, London.

(6) Magnesium oxide dust)
(7) Sodium fluoride dust) Analar reagents.

These dusts were chosen as a typical cross-section of those found industrially. It was intended to study their mode of sedimentation under controlled conditions. From the results obtained suitable dust clouds would be selected for accelerated sedimentation studies employing water sprays.

The photoelectric cell system was altered so that the recorder gave only the readings from the middle set of cells. A calibration curve was drawn up for this new circuit using the procedure previously described.

When most of the dust had cleared from the chamber, the lights and recorder were again switched on, the zero line on the chart adjusted, and the system allowed to settle. Meanwhile, the dust holder of the generator was replenished with dust. A dust cloud was blown in and allowed to sediment over a period of 20 hours. This time, in order not to disturb the cloud, the T.P. sample was taken immediately on formation of the cloud and the T.P. head was left undisturbed in the chamber until the sedimentation run was almost completed. This T.P. sample not only provided a check on the/

/the P.E.C. calibration curve, but also gave a sample from which the size analysis of the original dust cloud could be obtained. At the end of the run a further T.P. sample was taken. The cover glasses were mounted on slides and later examined under the microscope when size analysis and dust counts were carried out.

When sedimentation had finished, the chart was removed from the recorder. The zero line was drawn along the length of the chart and a smooth curve drawn through the points of the sedimentation curve. The distances were then measured from the sedimentation curve to the zero drift line for times t = 0, $\frac{1}{2}$, 1, $1\frac{1}{2}$, 2, 3, 4 --- etc. hours, till the end of the run. The dust concentrations equivalent to these recorder readings were obtained from the calibration curve.

This procedure was repeated for each dust, the apparatus being thoroughly cleaned each time. New calibration curves were prepared for each dust.

Size distribution of dust cloud.

The size distribution of each of the dust clouds at the beginning of the sedimentation run was obtained by microscopic examination of the T.P. slides. A typical size frequency curve for D.R.C. silica dust is shown in Fig. 8. The average "projected" diameter of the dust particle (d_p) was obtained from this using $d_p = \frac{\Sigma d.n}{\Sigma n}$ where n is the number of particles of diameter "d".

The results were calculated for each dust used and/

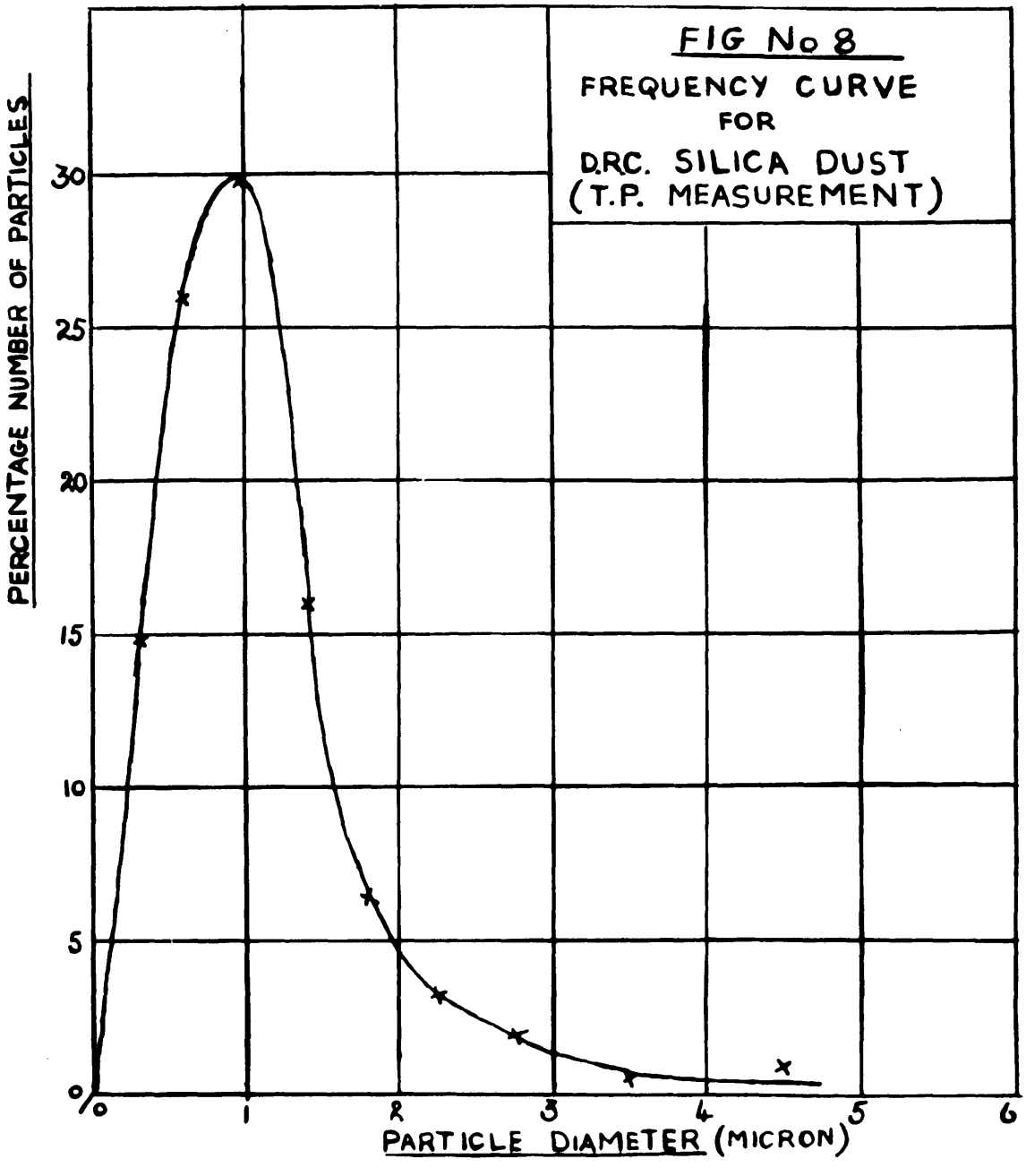


FIG No 8
FREQUENCY CURVE
FOR
D.R.C. SILICA DUST
(T.P. MEASUREMENT)
PERCENTAGE NUMBER OF PARTICLES
30
25
20
15
10
5
0
0
1
2
3
4
5
6
PARTICLE DIAMETER (MICRON)

/and are shown in Table 3.

TABLE 3.

Dust used.	Average projected diameter. (μ) d_p
D.R.C. silica dust.	1.09
Ground silica dust.	1.00
Ground coal dust.	1.84
Ground fly ash.	1.13
Copper dust.	1.41
Magnesium oxide powder.	2.55
Sodium fluoride powder.	1.7

Stokes Law Sedimentation.

Stokes Law may be written:-

$$t = \frac{18 \eta Fh \times 10^8}{(\rho - \rho_1)\, d^2 g}$$

where, d = particle diameter (μ)

η = viscosity of air = 1.8×10^{-4}

h = height of chamber = the height from the cone flange to the middle of the P.E.C. system

= 109.2 cms.

ρ = density of particle (gm/cc)

ρ_1 = density of air = .0012 gm/cc.

g = gravitational constant = 981 cms/sec^2.

t/

t = time in seconds.

F = constant with values on Table 1,

or $d^2 = \frac{18 \eta h F \times 10^8}{(\rho - \rho_l)\ t\ g}$

Substituting the values given above we get:-

$$d = 3.167 \sqrt{\frac{1}{t\ (\rho - .0012)}} \cdot \sqrt{F}$$

where t now is the time in hours.

The densities of the various dusts were found by means of a density bottle, using kerosene as the liquid. The results are given in Table 4.

TABLE 4.

Densities of dusts.

Dust used.	Density (gm/cc)
D.R.C. silica dust	2.5
Ground silica dust	2.5
Ground coal dust	1.5
Ground fly ash	2.9
Copper powder	6.35
Magnesium oxide powder	2.35
Sodium fluoride powder	2.67

Using the above formula and substituting values of t = $\frac{1}{2}$, 1, 1$\frac{1}{2}$, 2, 3 etc., and the value for the density of the material being used, the size which the sedimenting particle should be less than at time/

/time t was calculated. From the curve obtained from the sedimentation run the concentrations at known times were found. Table 5 is drawn up for D.R.C. silica dust incorporating these figures.

This decrease in concentration was taken as the number of particles of that size range. From these results, columns 2 and 3 of Table 6 were constructed and a percentage frequency composition obtained (column 4). An average particle size was then calculated using $d = \frac{\Sigma d.n}{\Sigma n}$

The results were calculated in a similar manner for the other dusts, using the sedimentation curves obtained for the various dusts. These results are given in Table 7, d_s signifies the average Stokes particle diameter.

Theoretical Stokes sedimentation curve.

A theoretical Stokes sedimentation curve was drawn up from the information obtained on the microscopic examination of the T.P. samples taken at the beginning of each sedimentation run.

The microscopic examination gave the dust concentration and size distribution of the cloud at the start of the sedimentation. Using the previously calculated sizes which the suspended particles should theoretically be less than at time 't', and percentage frequency curve of Fig. 9, the following table was drawn up for D.R.C. silica dust (Table 8).

The values in the fourth column are the dust/

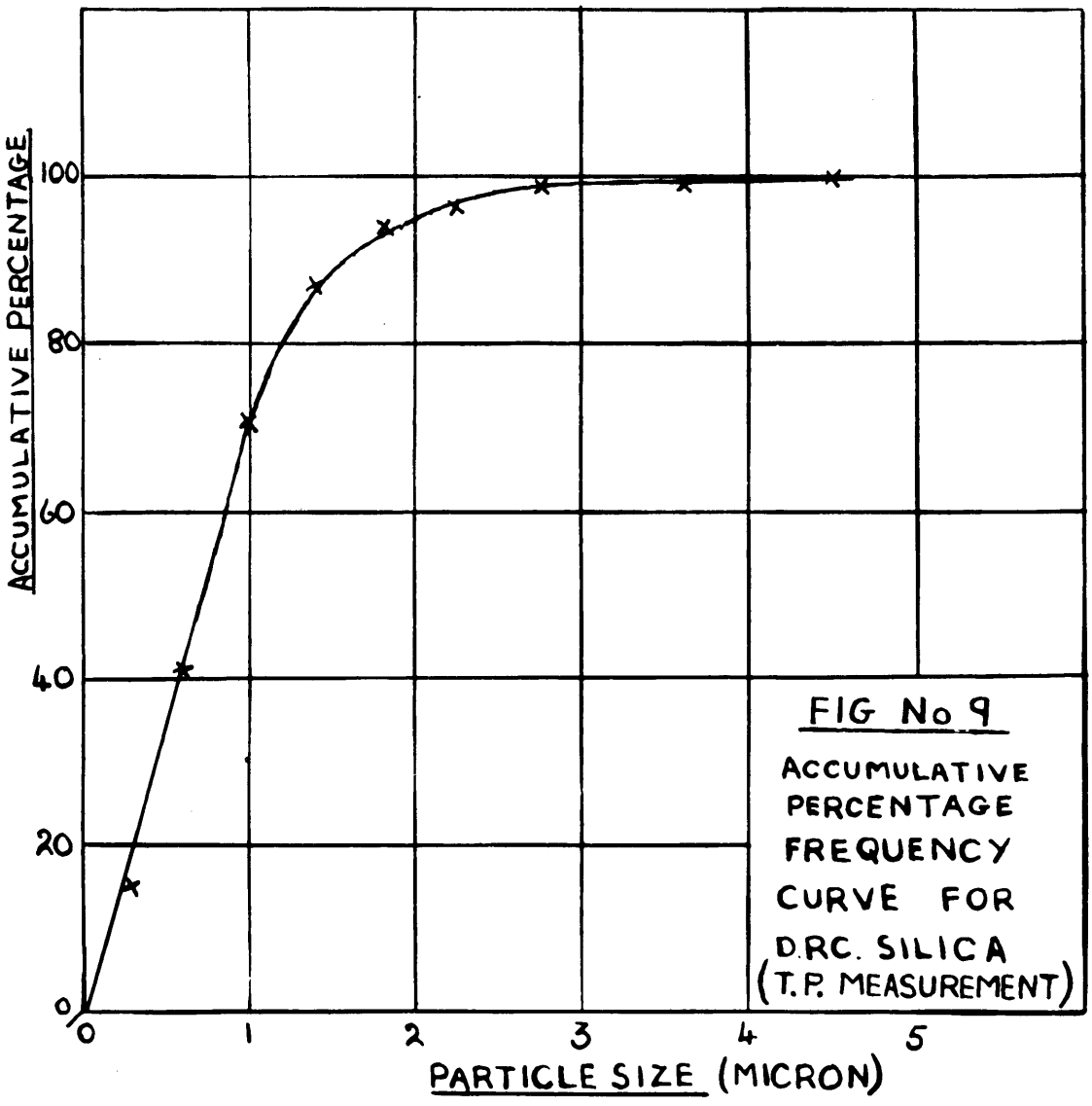


FIG No 9

ACCUMULATIVE PERCENTAGE FREQUENCY CURVE FOR D.R.C. SILICA (T.P. MEASUREMENT)

TABLE 5.

Sedimentation Time (t) (hours)	Particle size should be less than:- (μ)	Measured concentration of dust. (p.p.c.c.)	Decrease in concentration. (p.p.c.c.)
0	> 3.0	105,000	-
0.5	3.0	82,000	23,000
1.0	2.0	60,000	22,000
1.5	1.7	42,500	17,500
2.0	1.5	32,000	10,000
3.0	1.2	17,200	14,800
4.0	1.0	10,400	6,800
6.0	0.96	3,500	6,900
8.0	0.80	1,400	2,100
10.0	0.70	1,200	200
12.0	0.65	1,100	100
16.0	0.60	1,000	100
20.0	0.50	900	100

TABLE 6.

Particle Range (μ)	Average Size (μ) (d)	Number	% Number (n)	d x n.
> 3	4	23,000	21.9	65.7
2-3	2.5	22,000	20.9	52.25
1.7-2	1.9	17,500	16.7	31.73
1.5-1.7	1.6	10,500	10.0	16.00
1.2-1.5	1.4	14,800	14.1	19.74
1.0-1.2	1.1	6,800	6.5	7.15
0.9-1.0	0.95	6,900	6.6	6.27
0.8-0.9	0.85	2,100	2.0	1.70
0.7-0.8	0.75	200		
0.65-0.7	0.68 > 0.65	100 } 500	0.5	.33
0.6-0.65	0.62	100		
0.5-0.6	0.55	100		
< 0.5	0.25	900	0.8	.20
			100.0	201.07

∴ Average particle size (d_s) = $\frac{201.07}{100}$ = 2.01μ for silica dust.

TABLE 7.

Stokes diameters.

Dust used.	Average experimental Stokes diameter d_s (μ)
D.R.C. silica dust	2.01
Ground silica dust	2.23
Ground coal dust	1.6
Ground fly ash	2.59
Copper powder	1.43
Magnesium oxide powder	2.55
Sodium fluoride.	2.67

TABLE 8.

Theoretical Stokes Sedimentation Curve.

Sedimentation time (hours)	Particle size should be less than (μ)	Observed accumulative percentage undersize. %	Concentration (p.p.c.c.)
0	> 3.0	100	105,400
0.5	3.0	93.3	98,300
1.0	2.0	80.4	84,600
1.5	1.7	71.6	75,600
2.0	1.5	65.5	69,000
3.0	1.2	54.0	56,900
4.0	1.0	42.7	45,100
5.0	0.99	40.3	42,400
6.0	0.96	36.1	38,090
8.0	0.80	31.0	32,650
10.0	0.70	26.0	27,420
12.0	0.65	23.9	25,200
16.0	0.60	18.4	19,400
20.0	0.50	13.9	14,650

/dust concentrations equivalent to the cumulative undersize percentage values of column 3. This table was drawn up assuming that no aggregation of particles took place during sedimentation.

Davies Sedimentation.

From the Davies equation:-

$$Co\ A\ h - C\ A\ h = A\ Nt$$

$$\therefore\ Nt = (C - Co)\ h$$

where Co = dust concentration at the start of the run (t = o)

C = dust concentration at time, t, from the start of the run.

h = height of the chamber.

The height of the chamber was again taken as the height from the cone flange to the middle of the P.E.C. system (= 109.2 cms.).

A plot of Nt calculated in this way from the results in Table 5 is shown in Fig. 10 for D.R.C. silica dust, together with that obtained from the results of Table 8.

From the Davies equation (3) on page 25,

$$Nt = Coh\left[1 - \exp.\left(\frac{-Vt}{h}\right)\right]$$

$$\frac{Nt}{Coh} = 1 - \exp.\left(\frac{-Vt}{h}\right)$$

$$\text{or}\quad \exp.\left(\frac{-Vt}{h}\right) = 1 - \frac{Nt}{Coh}$$

$$\text{Taking logs}\quad \frac{Vt}{h} = \log e\left[1 - \frac{Nt}{Coh}\right]^{-1}$$

$$= 2.3 \log 10\left[\frac{1}{1 - \frac{Nt}{Coh}}\right]$$

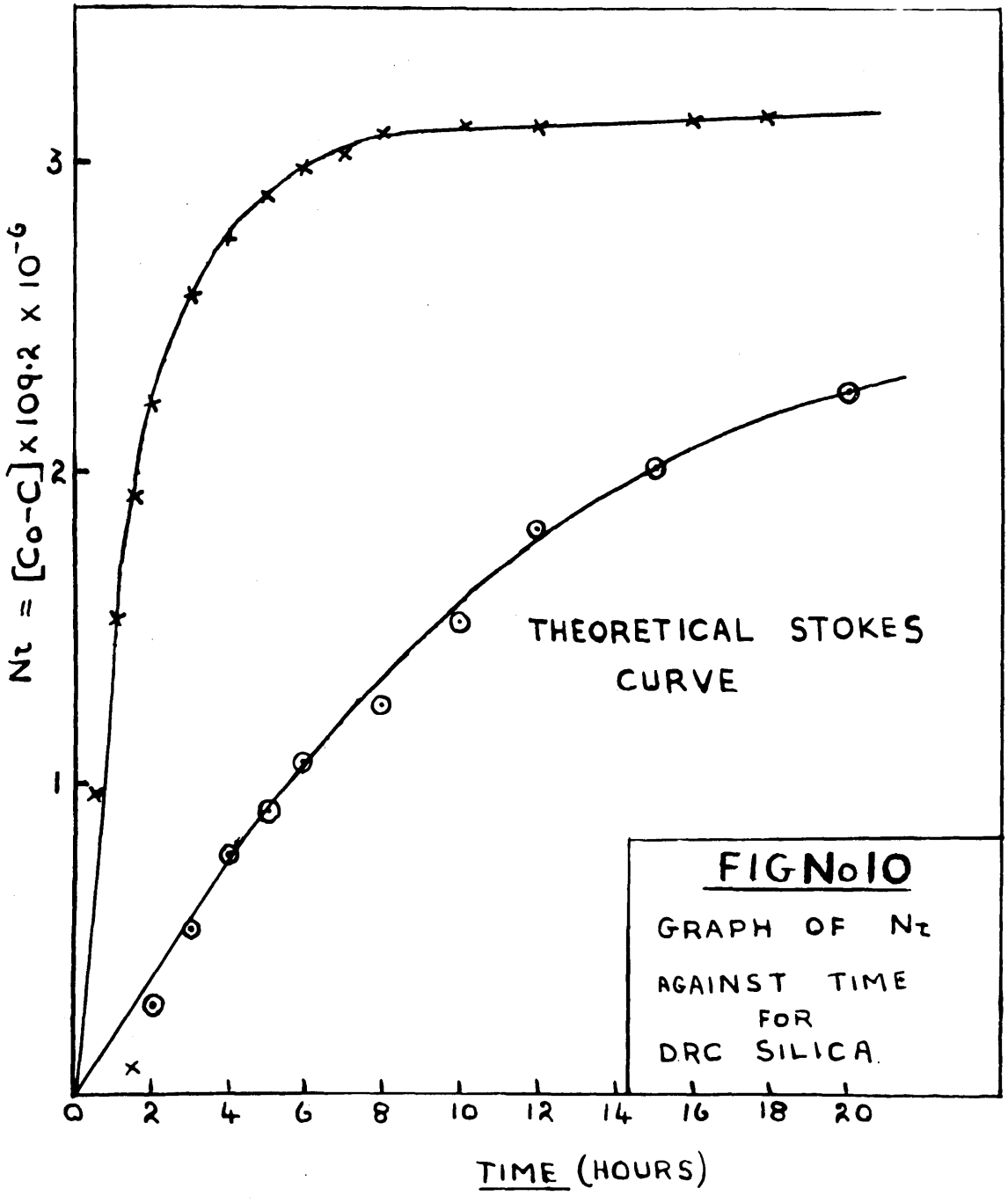


FIG No 10

GRAPH OF Nt AGAINST TIME FOR DRC SILICA

Fig. 11 shows a plot of the value of $2.3 \log 10 \frac{1}{1 - \frac{Nt}{Coh}}$ against time in hours for the curves of Fig. 10.

Now $$\frac{t}{2.3 \log 10 \left[\frac{1}{1 - \frac{Nt}{Coh}}\right]} = \frac{h}{v}$$

$$V = \left[\frac{2.3 \log 10 \left[\frac{1}{1 - \frac{Nt}{Coh}}\right]}{t}\right] h \text{ cms/hr.}$$

Thus the terminal velocity of the particles settling out at any given time during the sedimentation in this particular chamber is given by

$$V = \left[\frac{2.3 \log 10 \left[\frac{1}{1 - \frac{Nt}{Coh}}\right]}{3600t}\right] 109.2 \text{ cms/sec.}$$

As can be seen from Fig. 11 the relationship approaches linearity both at high and low values of t, enabling us to calculate a maximum and minimum terminal velocity from the constant values of the ratio,

$$\frac{2.3}{t} \log 10 \left[\frac{1}{1 - \frac{Nt}{Coh}}\right]$$

obtained at those values of t. From the velocities so obtained/

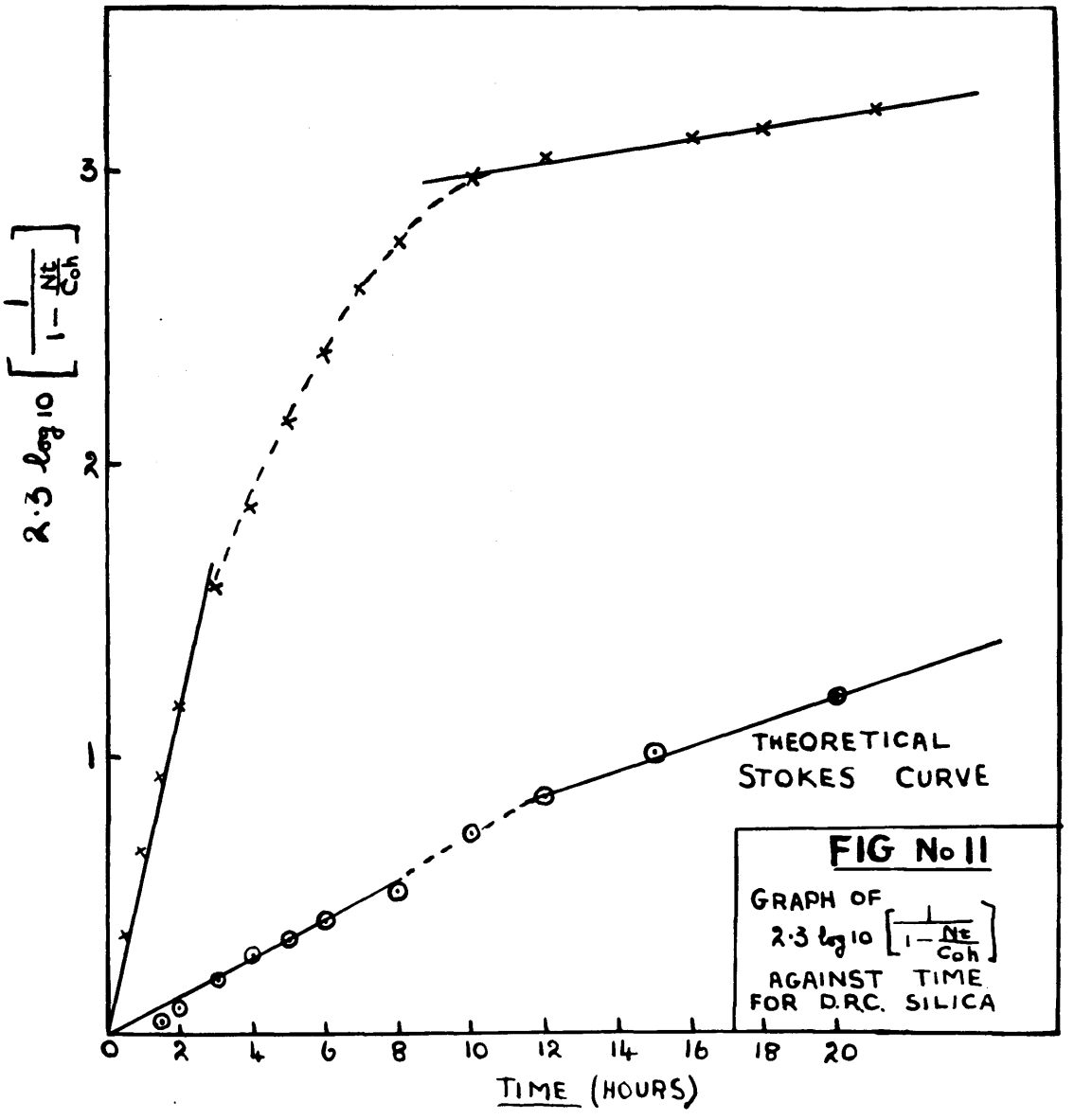


FIG No 11

GRAPH OF $2 \cdot 3 \log_{10} \left[\frac{1}{1 - \frac{Nt}{Coh}} \right]$ AGAINST TIME FOR D.R.C. SILICA

/obtained the related particle sizes can be calculated from the Stokes equation,

$$d^2 = \frac{F\ V\ 18 \times 10^8}{(\rho - \rho_1)\ g}$$

Substituting the appropriate values the equation becomes:-

$$d = 18.18 \sqrt{\frac{V}{(\rho - .0012)}} \quad \sqrt{F}$$

where F has the values shown in Table 1.

Table 9 gives the values of particle size calculated in this way from the sedimentation results measured by the photoelectric cells and recorder, while Table 10 gives the sizes obtained by a similar treatment of the theoretical Stokes sedimentation which was itself derived from the microscopic size measurements on the T.P. sample. The average values in Table 9 were designated the "Davies' diameters" (d_d) and those in Table 10, the "Davies-Stokes diameters" (d_t).

Comparison of the particle diameters found using the different methods.

The values for the average particle diameters calculated for the different methods are given in Table 11. Also given are the various ratios.

Portions of the dust deposits on some of the/

TABLE 9.

Particle sizes of dusts calculated from Davies' sedimentation method. (T.V. = terminal velocity)

Type of dust used.	MAXIMUM		MINIMUM		AVERAGE
	T.V. cm/sec.	Size (μ)	T.V. cm/sec.	Size (μ)	Dia. (μ) (d_d)
D.R.C. silica dust	.0247	1.89	.00137	.51	1.2
Ground silica dust	.01703	1.59	.0052	.92	1.21
Ground coal dust	.0187	2.11	.0046	1.09	1.55
Ground fly ash	.0339	2.05	.00039	.29	1.17
Copper powder	.0247	1.22	.004	.54	.83
Magnesium oxide powder.	.104	3.92	.00017	.24	2.08
Sodium fluoride powder.	.0206	1.90	.0027	.67	1.28

TABLE 10.

Particle sizes of dusts calculated from theoretical Stokes curves using Davies' method.

Type of dust used.	MAXIMUM		MINIMUM		AVERAGE
	T.V. cm/sec.	Size (μ)	T.V. cm/sec.	Size (μ)	Dia. (μ) (d_t)
D.R.C. silica dust	.0025	.67	.0016	.54	.61
Ground silica dust	.0041	.84	.0028	.71	.78
Ground coal dust	.0053	1.17	.00183	.73	.95
Ground fly ash	.0034	.71	.0012	.46	.59
Copper powder	.021	1.12	.007	.69	.91
Magnesium oxide powder	.016	1.87	.0046	1.08	1.48
Sodium fluoride powder	.009	1.13	.0014	.49	.81

TABLE 11.

Average particle sizes obtained by four different methods.

d_p = projected diameter measured by the microscope.

d_s = Stokes diameter calculated from sedimentation results.

d_d = Davies diameter.

d_t = Davies-Stokes diameter.

Type of dust used.	(d_p) (μ)	(d_s) (μ)	(d_d) (μ)	(d_t) (μ)	$\frac{d_s}{d_p}$	$\frac{d_d}{d_p}$	$\frac{d_d}{d_t}$
D.R.C. silica dust	1.09	2.0	1.2	.61	1.84	1.11	1.97
Ground silica dust	1.00	2.23	1.21	.78	2.23	1.21	1.56
Ground coal dust	1.84	1.6	1.09	.95	.87	.60	.52
Ground fly ash	1.13	2.59	1.17	.59	2.28	1.04	1.98
Copper powder	1.41	1.43	.83	.91	1.02	.59	.91
Magnesium oxide powder	2.55	2.66	2.08	1.48	1.05	.82	1.41
Sodium fluoride powder	1.7	2.67	1.28	.81	1.57	.75	1.58

/the T.P. slides were photographed and are shown in plates 1 - 8. Plates 1, 3, 5 and 7 are photographs of the deposits from D.R.C. silica, ground coal, ground fly ash and copper powder dust clouds on formation. The plates 2, 4, 6 and 8 are photographs of the deposits obtained from the same dust clouds at the end of the sedimentation period.

Discussion of results.

The ratios d_s/d_p found in this work agree favourably with those obtained by Timbrell (47) and Watson (48) who found that for sedimenting clouds, the value of d_s/d_p was in the range 0.8 - 2. The values of d_d/d_p lie much nearer 1.0 than do the values of d_s/d_p. This indicates the superiority of the Davies method of treating the sedimentation to the traditional Stokes method.

Comparison of Tables 5 and 8 indicates that the dust cloud sediments much more quickly than the rate demanded by the Stokes treatment of the measured size distribution. This is brought out more clearly by the ratio d_d/d_t obtained from the Davies treatment of both the actual and theoretical sedimentation.

The difference in value between d_d and d_t could be due to aggregation of particles giving larger particles with greater terminal velocities and hence "equivalent" particle diameters (i.e. the particle diameters equivalent to the terminal velocities).

The values for d_d/d_t lie in the range 1.5 - 2 in most cases. If the above statement is correct/

/correct this ratio will represent the average number of particles which have combined to form each aggregate.

The number of dust particles per aggregate were counted on the plates 1, 3, 5 and 7 and the following results obtained (Table 12). These figures are in reasonable agreement with those obtained from the sedimentation results (i.e. d_d/d_t) except in the case of coal dust and of copper powder, where perhaps the metal structure has an effect on the aggregation.

TABLE 12.

Number of dust particles per aggregate.

Plate No.	Type of dust used.	Average number of particles per aggregate.
1	D.R.C. silica dust	2.2
3	Ground coal dust	2.0
5	Ground fly ash	2.0
7	Copper powder	1.7

In studying the sedimentation of the various dusts, it was found that the particle concentration generally decreased rapidly over the first two or three hours (e.g. the upper curve of Fig. 10) when most of the aggregation would be likely/

/likely to take place. After about three hours the clouds sedimented progressively more slowly with perhaps a certain amount of aggregation still taking place. This second phase lasted about four hours. After nine hours only the smallest particles were left which sedimented slowly. It can be seen in Plates 1 - 8 that all the heavy aggregates are on the plates representing the samples taken at the beginning of sedimentation (i.e. 1, 3, 5 and 7). Plates 2, 4, 6 and 8 show the presence of small particles only.

The aggregates seen on plates 1, 3, 5 and 7 are, of course, aggregates of airborne dust and not particles which have come together on the slide since no aggregation takes place during the sampling (49). The sedimentation results described in this section will be compared in a later section with those obtained when water sprays are used.

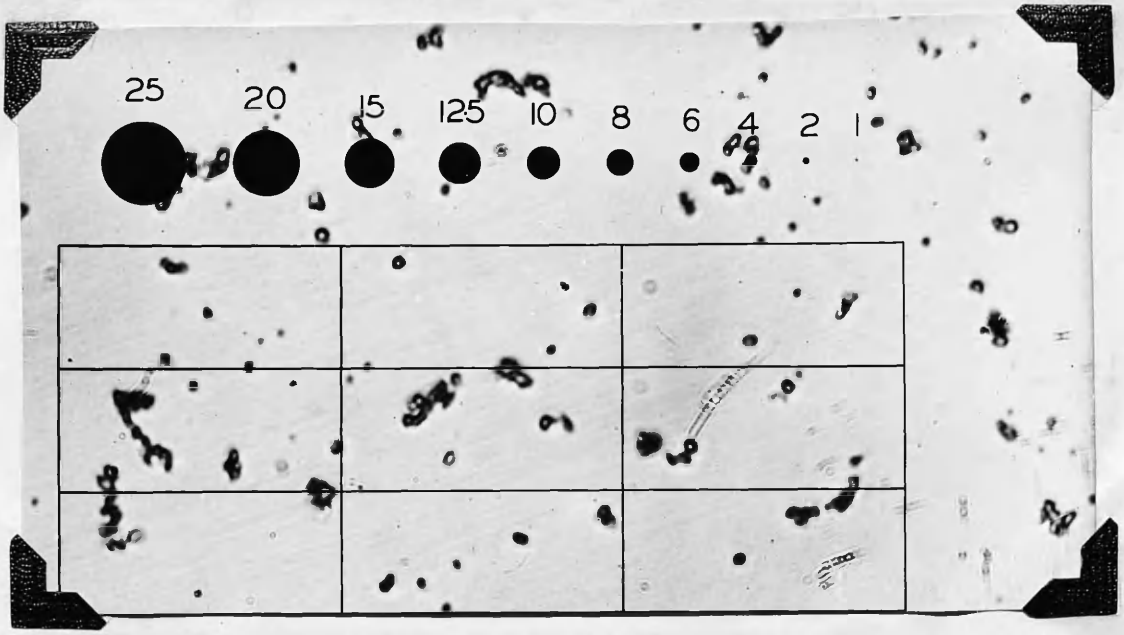


PLATE 1.

D.R.C. silica dust cloud on formation.

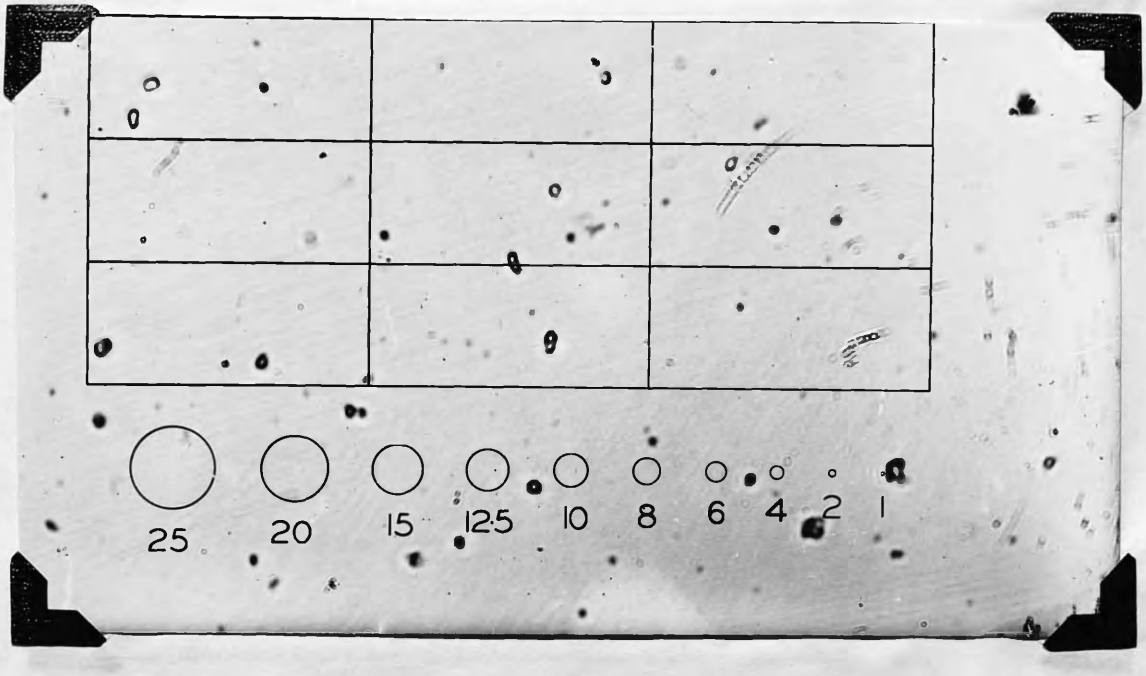


PLATE 2.

D.R.C. silica dust cloud after 18 hours sedimentation.

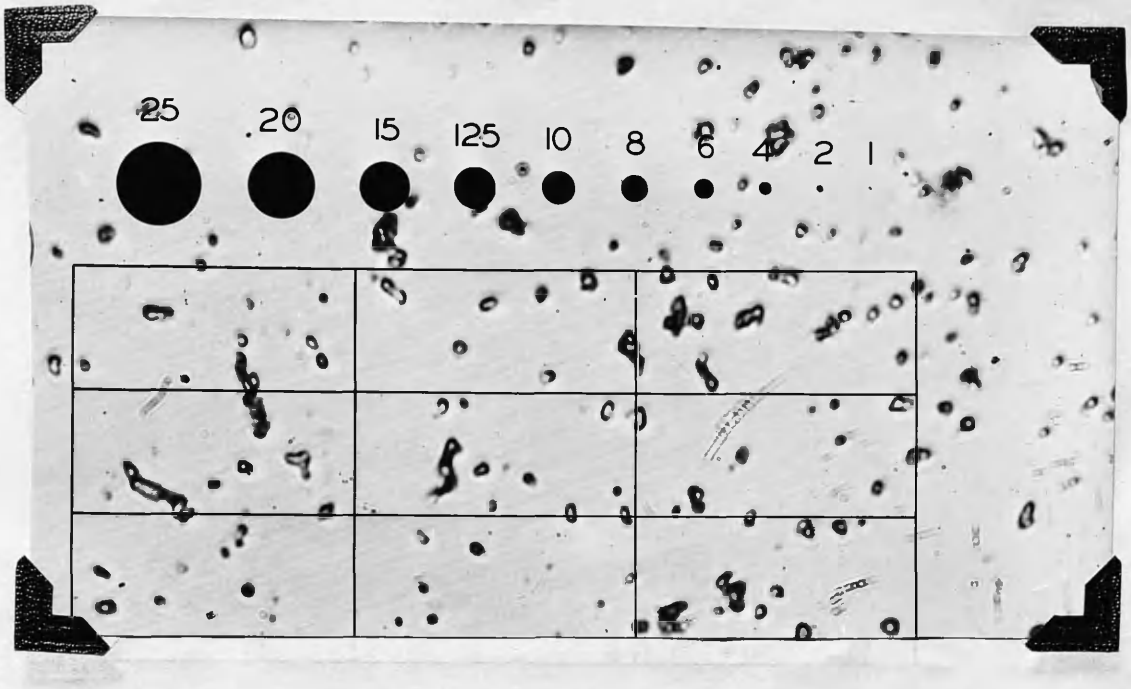


PLATE 3.

Ground coal dust cloud on formation.

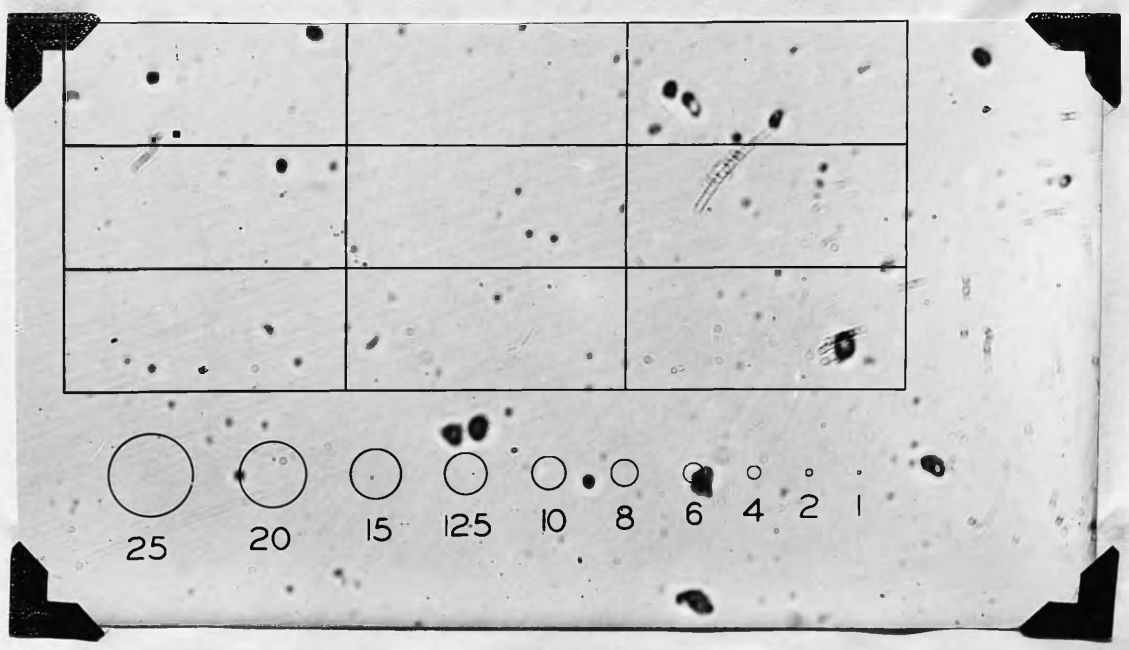


PLATE 4.

Ground coal dust cloud after 18 hours sedimentation.

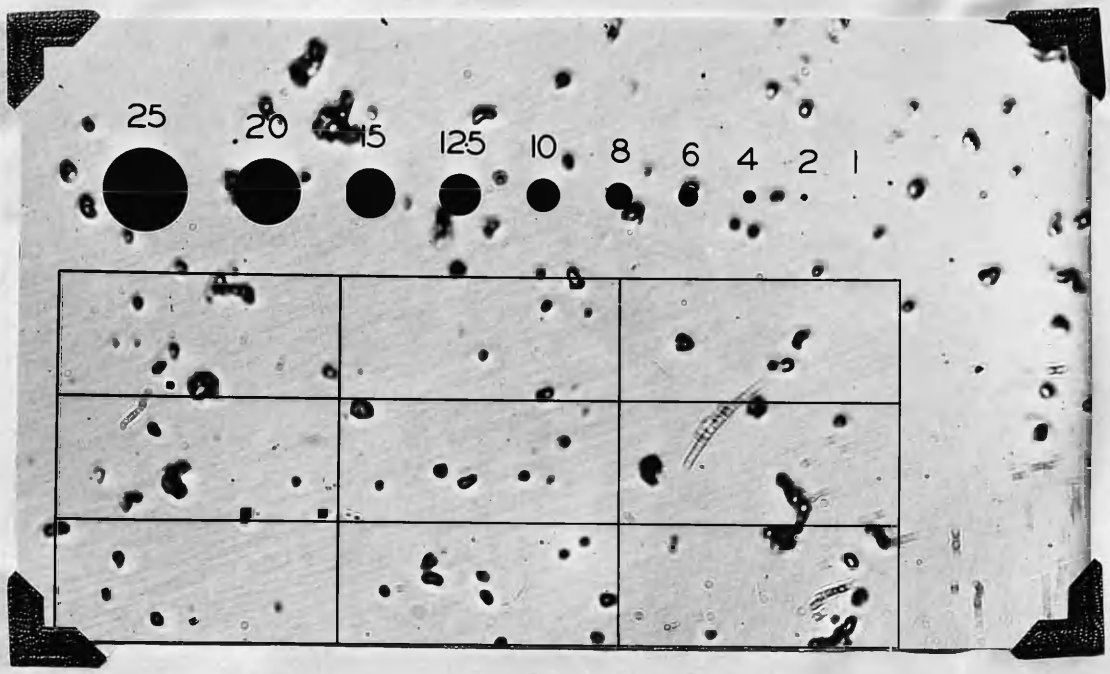


PLATE 5.

Ground fly ash dust cloud on formation.

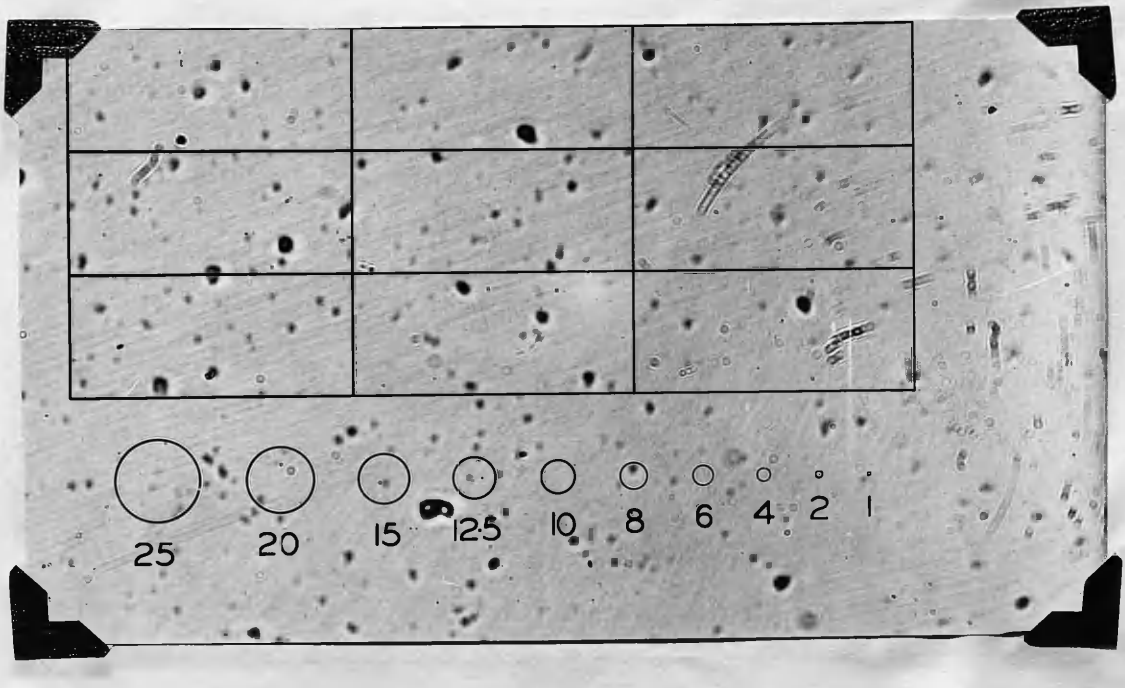


PLATE 6.

Ground fly ash dust cloud after 18 hours sedimentation.

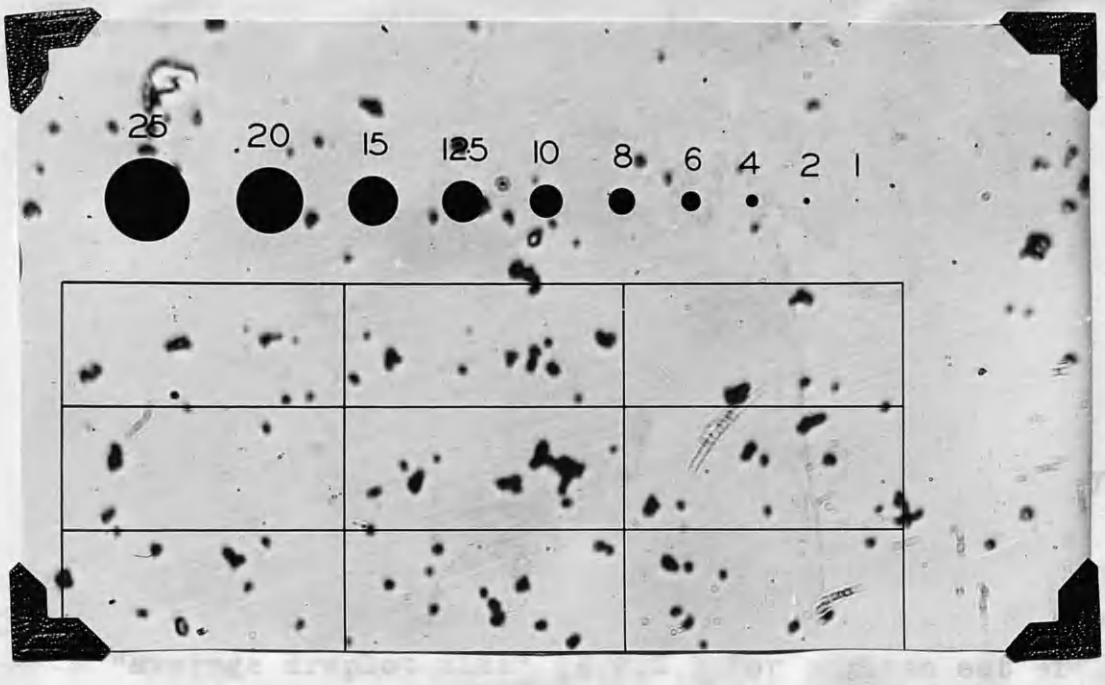


PLATE 7.

Copper powder cloud on formation.

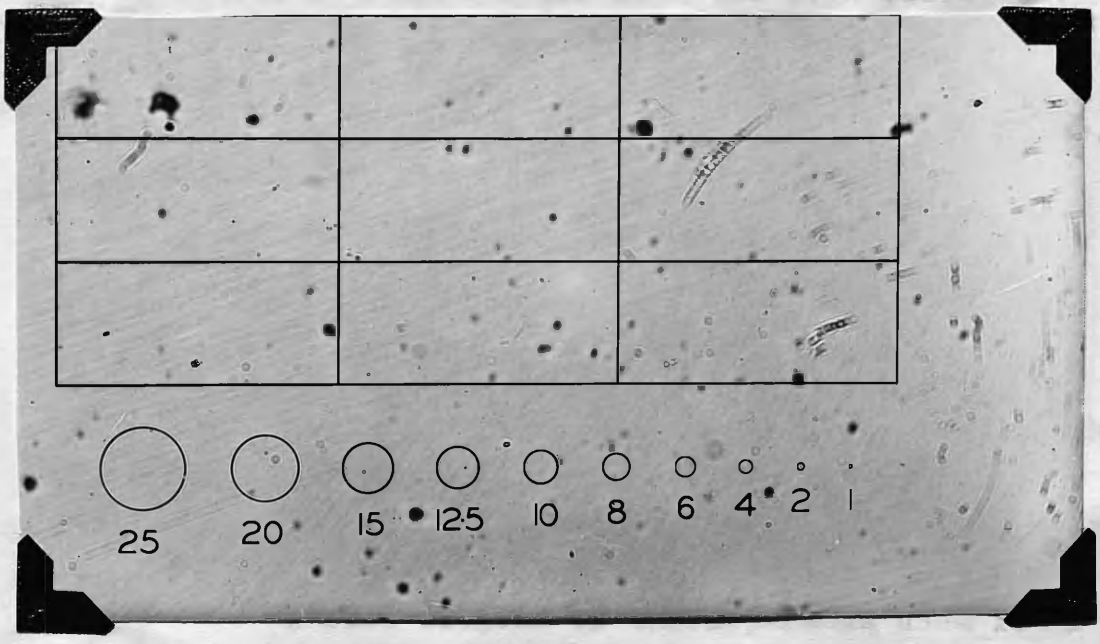


PLATE 8.

Copper powder cloud after 10 hours sedimentation.

SECTION 2.

THE COMPRESSED-AIR SPRAY.

A brief introduction on atomisation is given in the introduction of this thesis. In this section an investigation of the compressed-air spray has been carried out. This work was not intended as an exhaustive study on compressed-air atomisation. It was done merely as a means to an end, so that the "average droplet size" (A.D.S.) for a given set of conditions could be predicted, as also the effect of changes in the flows of air and water on the A.D.S.

The nozzle cups were of the same pattern as those used in Glen's swirl atomiser work (33). The dimensions of the nozzles were chosen so that they would give suitable throughputs and A.D.S.s for the concentrations of the dusts suspended in the chamber.

Spray Apparatus.

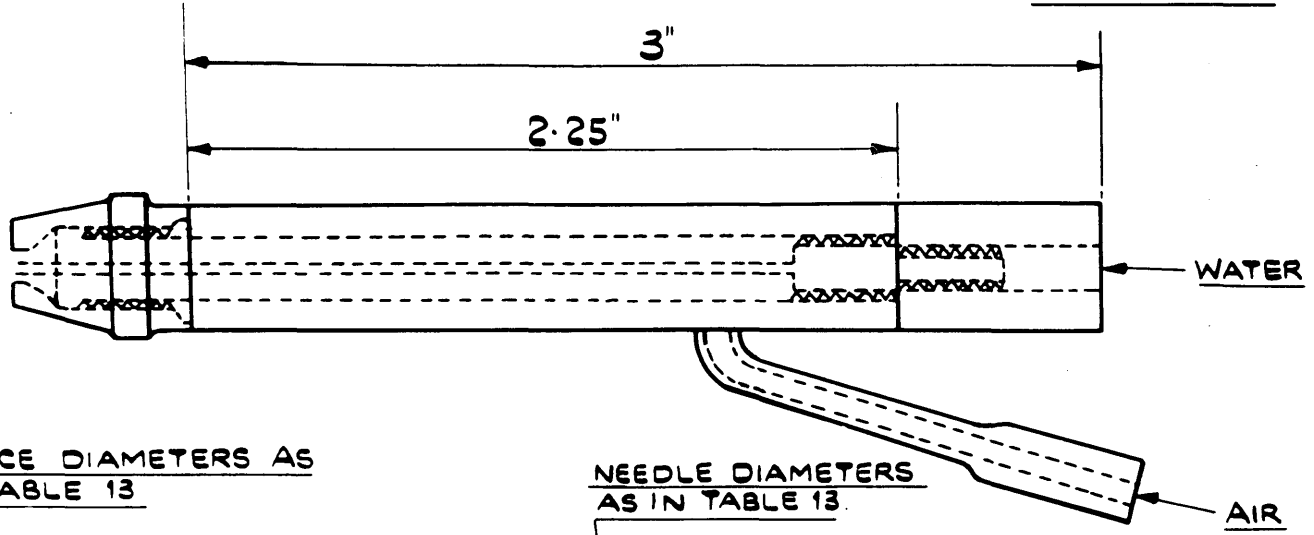
The compressed-air water spray employed in this work (Fig.12) was constructed from a stainless steel hypodermic needle, trimmed off square, which was screwed into a brass outer sheath. Varying sizes of nozzles could be screwed on to the end of the sheath and different sizes of needles could also be screwed on to the inner plug giving a range of nozzle diameters for both the air and water flows.

A flow diagram of the apparatus used is also given in Fig. 13. The compressed-air, supplied by/

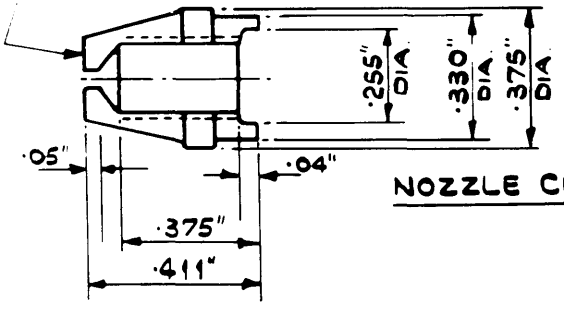
FIG. No. 12.

COMPRESSED - AIR SPRAY.

NOT TO SCALE

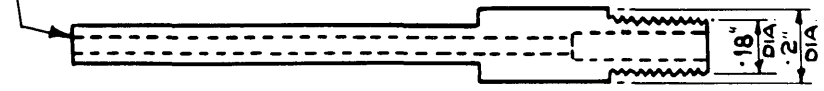


ORIFICE DIAMETERS AS IN TABLE 13



NOZZLE CUP.

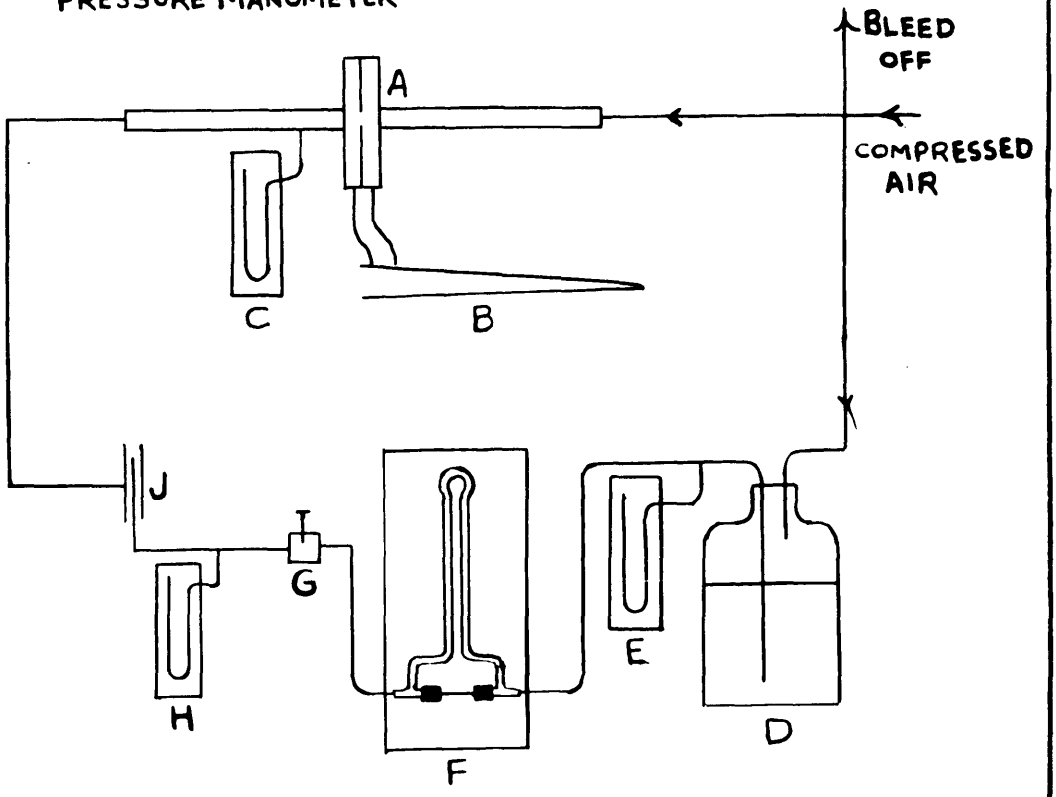
NEEDLE DIAMETERS AS IN TABLE 13.



NEEDLE.

FIG No 13

A - ORIFICE PLATE
B - MANOMETER
C - AIR PRESSURE MANOMETER
D - WATER HOLDER
E - AIR TO WATER PRESSURE MANOMETER
F - WATER METER
G - NEEDLE VALVE
H - WATER PRESSURE MANOMETER
J - SPRAY



/by a blower, was divided into two streams. One stream passed into the water supply vessel to provide the necessary pressure there. This pressure was adjusted by means of a screw clip. The other stream passed to an orifice plate, which had been previously calibrated and thence to the spray nozzle to atomise the water. This air flow was controlled at the bleed off point indicated in the figure. The air pressure was measured by a calibrated manometer fixed to the orifice plate.

The water from the supply vessel was maintained at a measured constant pressure and its throughput controlled by a needle valve, was measured by a calibrated water meter. Just prior to passing through the spray needle for atomisation, the pressure was measured on a manometer.

The sizes of the needles and nozzles used in this work are given in Table 13.

Experimental.

The orifice plate calibrated with a gas meter was used to measure the air throughput for each needle and nozzle combination.

The water throughputs were measured by spraying downwards into a measuring cylinder for a given time.

When the throughputs were plotted against the square root of the pressure ($\sqrt{P}$) straight lines were obtained for both water and air. Examples of the/

TABLE 13.

Needle Sizes.

Ref. No.	Internal Diameter (Ins.)	External Diameter (Ins.)	Internal Area $(Ins.)^2$	External Area $(Ins.)^2$
1	0.0709	0.0945	0.00386	0.00713
2	0.0447	0.0602	0.00153	0.00285
3	0.0424	0.0496	0.00117	0.00193
5	0.0162	0.0260	0.000505	0.000516

Nozzle Sizes.

Ref. Letter.	Internal Diameter (Ins.)	Internal Area $(Ins.)^2$
F	0.0563	0.0025
G	0.0897	0.0076
H	0.1295	0.0132
I	0.1608	0.0203
K	0.1074	0.0090

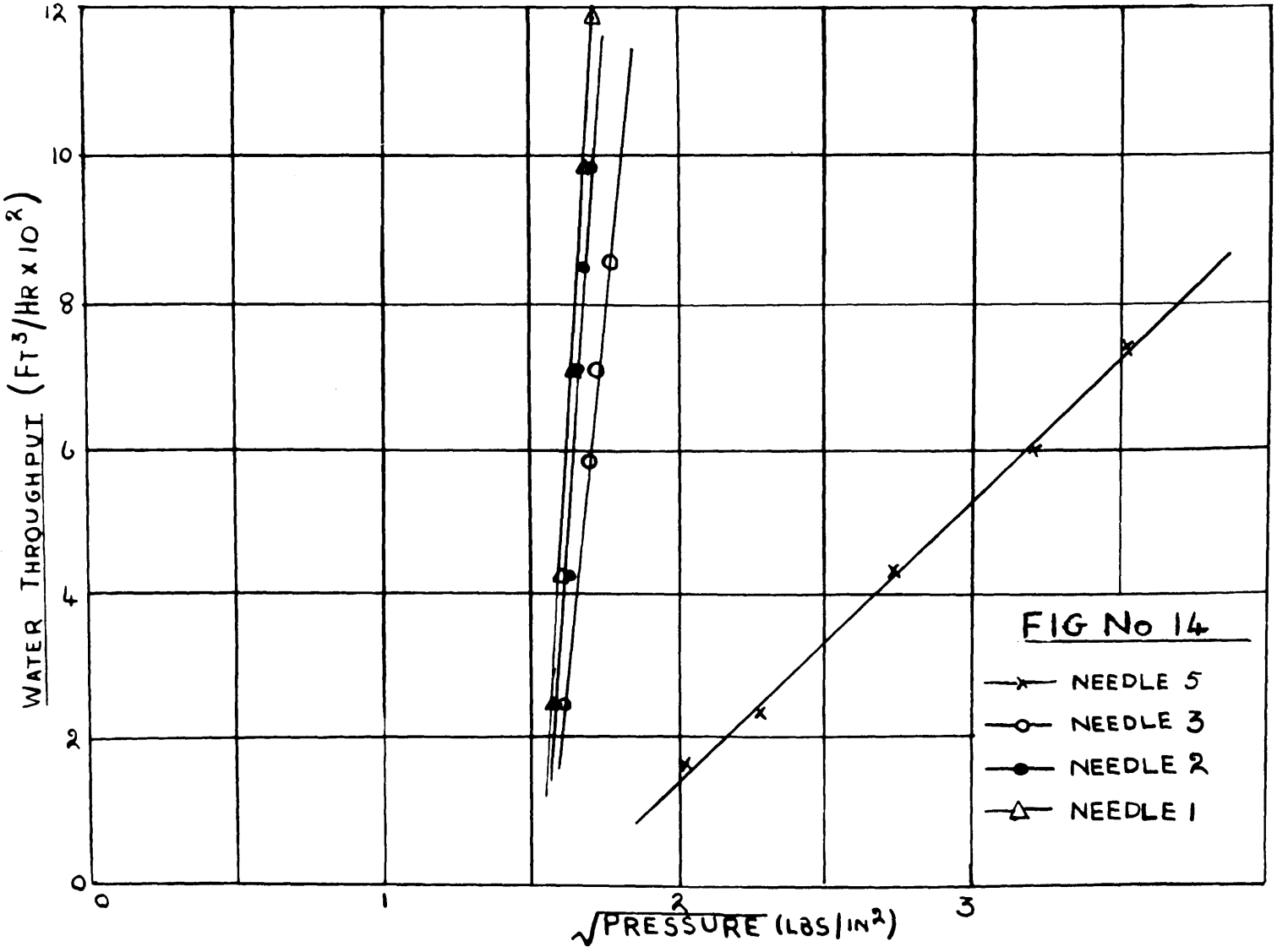
/the results obtained are shown in Fig. 14 for water and Fig. 15 for air.

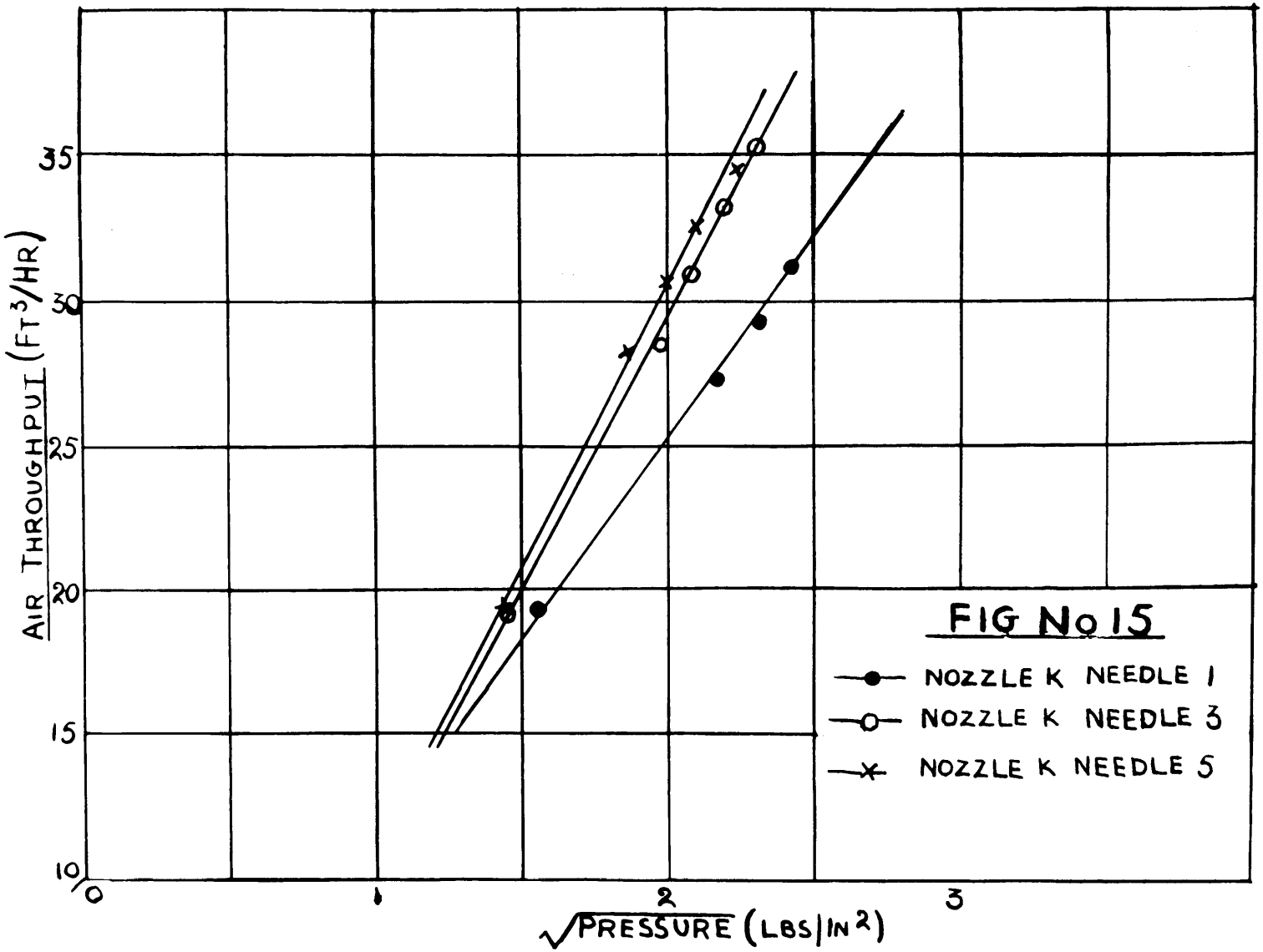
Droplet Size Measurements.

The direct method of droplet measurement was employed for measuring the average droplet size of the spray. By this method, the spray droplets are caught on a target from which they can be counted and measured. Glen (33) collected the droplets for measurement by the microscope on a glass slide coated with a silicone oil. However, by this method, it was found that the smaller droplets tended to disappear fairly rapidly due to evaporation and thus rapid counting was necessary.

The method employed was that suggested by Doble (50) and used later by Dimmock (51). In this method the spray droplets are collected in a shallow petri dish containing a suitable liquid. Doble used castor oil as the immersion liquid for the collection of water droplets. Nukiyama and Tanisawa (52) used various immersion liquids which included different types of oils, liquid paraffin, bakelite and rubber cement.

In this work, paraffin oil was used and the technique was as follows:- A clean petri dish was coated with vaseline. It was then gently heated and the vaseline allowed to melt to form a smooth surface (see plate 9), care being taken that all air bubbles were removed, as these appear similar to the water/


WATER THROUGHPUT (FT³/HR x 10²)
0
2
4
6
8
10
12
0
1
2
3
√PRESSURE (LBS/IN²)
FIG No 14
NEEDLE 5
NEEDLE 3
NEEDLE 2
NEEDLE 1


AIR THROUGHPUT (FT³/HR)
35
30
25
20
15
10
0
1
2
3
√PRESSURE (LBS/IN²)
FIG No 15
NOZZLE K NEEDLE 1
NOZZLE K NEEDLE 3
NOZZLE K NEEDLE 5

/water droplets when small. When the vaseline had solidified a layer of paraffin oil was poured on top of it. To collect a sample of the droplets the petri dish was passed under the spray at the desired height. The collected droplets were then examined under the microscope and their sizes measured using a calibrated linear graticule (see plates 10 and 11). Over 400 droplets were measured in each case.

Methods of Estimating Average Droplet Size (A.D.S.)

The fineness of a spray is generally found by comparing it with a similar ficticious spray composed of droplets of uniform size. Each of the following six formulae can be considered to give a mean diameter (A.D.S.)

(1) The normal one where, if the number of droplets (dn) in the real and ficticious sprays are equal, the sum of the diameters (x) is also regarded as equal.
Then A.D.S. = $\Sigma x.dn./\Sigma dn.$

(2) Where the number of droplets being equal, their total surface area is regarded as equal.
A.D.S. = $(\Sigma x^2.dn/\Sigma dn)^{\frac{1}{2}}$

(3) Where the number of droplets being equal, their total volume is regarded as equal.
A.D.S. = $(\Sigma x^3.dn/\Sigma dn)^{1/3}$

(4) Taking the sum of the diameters and that of the surface area to be equal.
A.D.S. = $\Sigma x^2.dn/\Sigma x.dn$

(5) Taking/

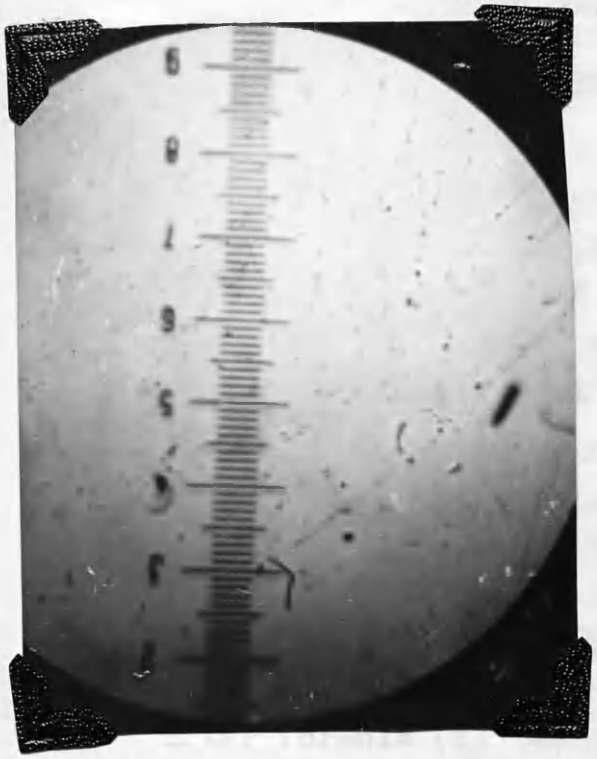


PLATE 9.

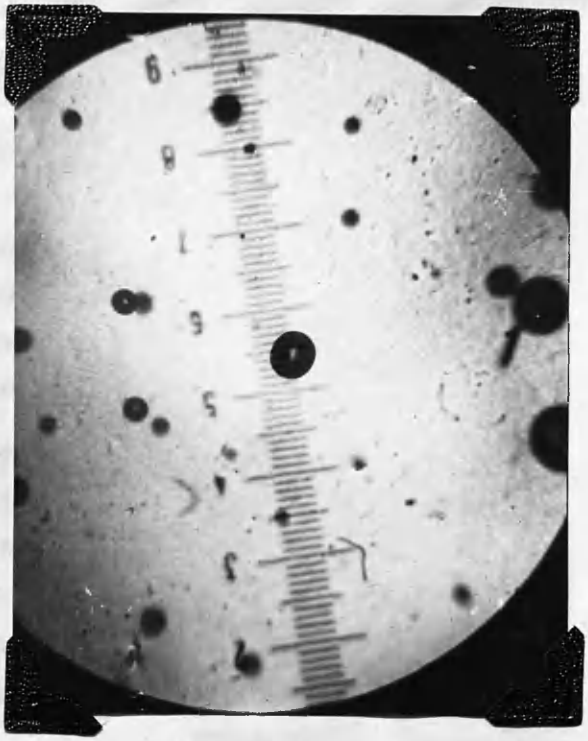


PLATE 10.

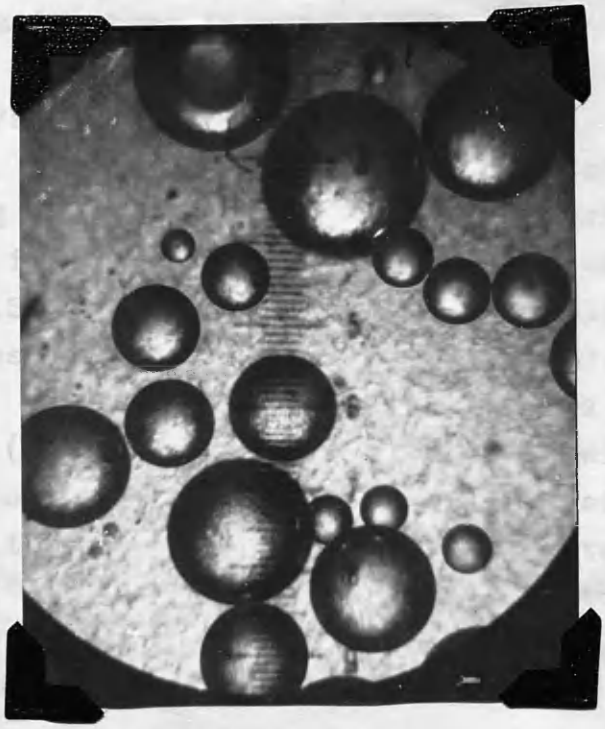


PLATE 11.

(5) Taking the sum of the diameters and that of the volume to be equal.

A.D.S. = $(\Sigma x^3.dn/\Sigma x.dn)^{\frac{1}{2}}$

(6) Taking the sum of the surface area and that of the volume to be equal.

A.D.S. = $\Sigma x^3.dn/\Sigma x^2.dn$

The choice of method to be used will depend on the object of atomisation, and which parameter of the droplet is deemed to be important in the process. The quality of atomisation is determined largely by the number of large droplets in the stream. The influence of the large droplets decreases progressively after formula (1) through (2), (3) and (6). Formula (6) is identical with the one used by Sauter (53) the resulting average droplet size being given the name "Sauter Mean Diameter" (S.M.D.).

The droplets were sampled from a selection of sprays, using the sampling technique described above. Table 14 shows the values obtained on calculating the A.D.S. by the above methods. From these results it can be seen that the value obtained for the A.D.S. depends on the method of calculation and increases from method (1) to method (6).

For the remainder of the work on atomisation formula (1) shall be used unless otherwise stated. The reasons for this are:- (i) it is simpler and quicker to use, (ii) comparative results only are required and this formula will be sufficiently accurate in most cases for this purpose, (iii) in the "knock-down"/

TABLE 14.

$x.dn/dn$	$(x^2.dn/dn)^{1/2}$	$(x^3.dn/dn)^{1/3}$	$x^2.dn/x.dn$	$(x^3.dn/x.dn)^{1/2}$	$x^3.dn/x^2.dn$
95.5	124.5	150.5	160.6	189.2	222
129.5	155.8	191.4	203.3	233.0	266
144.8	174.8	194.3	210.7	225.0	263.5
152.8	187.3	219.3	230.0	262.9	300.0
135.1	177.4	208.0	217.2	249.1	287.6
152.3	190.5	224.8	239.1	279.8	312.0

/"knock-down" of dust, the projected diameter of the water droplet is the important parameter.

The Effect of Atomiser Dimensions.

In the compressed-air spray the following variables may be considered to affect the atomisation:- water and air throughputs, pressures, velocities and the diameter of the needle and nozzle.
Spray runs were carried out with a number of needle and nozzle combinations keeping the above variables constant. The results are given in Table 15.
Column 3 gives the relative velocity V = Va - Vw,
where $Va = \frac{Qa}{\frac{\pi}{4} Da^2}$ and $Vw = \frac{Qw}{\frac{\pi}{4} Dw^2}$

Here, Qa and Qw are the volumes of air and water used. Da and Dw are the diameters of air and water vents. In this case Da = (Nozzle internal diameter - Needle external diameter).

From these results, it can be seen that the dimensions have little effect on the atomisation performance of the spray. However, they have an effect on the cone angle as can be seen from Table 16.

The Effect of the Volume Flow Ratio of Air to Water.

Since the effect of the diameters of the needles and nozzles was found to be negligible, the effect of the ratio of air volume flow (Qa) to water volume flow (Qw) was studied using various combinations of needles and nozzles. The results are shown in Fig.16/

TABLE 15.

Nozzle	Needle	V = Va-Vw (ft/hr)	$\frac{Qw}{Qa} \times 10^5$	A.D.S. (μ)
H	3	397,000	77	120
H	2	395,000	85	120
H	1	731,000	133.7	94
K	2	727,700	133.2	92
I	1	374,700	119.5	118.6
H	3	369,600	120.0	115.0
G	5	356,000	120.0	118.0
K	3	580,000	277.6	149.0
H	1	597,000	276.5	144.0

TABLE 16.

Effect of the Dimensions of Spray on Cone Angle.

Nozzle.	Needle.	Cone Angle.
G	5	70°
G	3	80°
G	2	90°
H	3	100°
H	2	110°
H	1	110°
I	1	110°
K	5	80°
K	3	100°
K	2	110°
K	1	110°

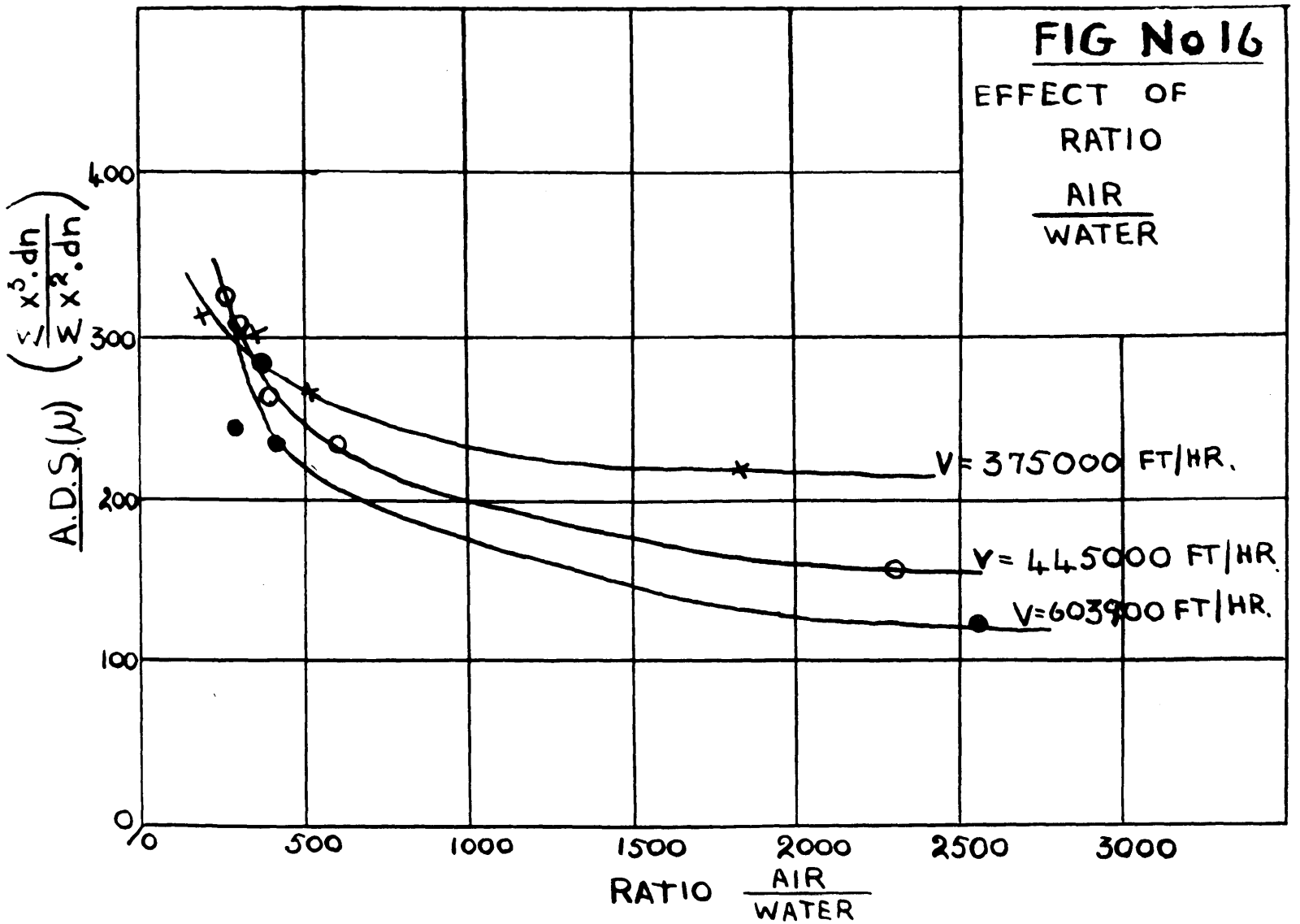


FIG No 16
EFFECT OF
RATIO
AIR / WATER
A.D.S.(μ) (Σ x³.dn / Σ x².dn)
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
RATIO AIR / WATER
V = 375000 FT/HR.
V = 445000 FT/HR.
V = 603900 FT/HR.

/Fig. 16 and it can be seen that as the amount of air is increased, i.e. the ratio Qa/Qw is increased, the A.D.S. of the spray decreases and the higher the air velocity, the smaller is the A.D.S. This graph also confirms the conclusion of the previous paragraph since the points obtained for different needle and nozzle sizes fit the same curve.

The same conclusions were reached by Nukiyama and Tanasawa (52) who found that if the ratio Qa/Qw was greater than 5,000, atomisation was not increased. In the present work, however, the ratio Qa/Qw was always less than 5,000.

The Effect of Air and Water Velocities.

Spray runs were carried out in which the relative velocity (Va - Vw) was altered, as were the needles and nozzles, the ratio Qa/Qw being kept constant throughout. The results are shown in Fig. 17. As the points fit smooth curves, this also agrees with the conclusions obtained previously on the effect of the dimensions. From the graph it can also be seen that as the relative velocity is increased, atomisation is increased and that an increase in the ratio Qw/Qa causes an increase in the A.D.S.

The Effect of the Sampling Distance from the Nozzle.

In this series, the same conditions for the spray system were used throughout but the distance of the point of sampling from the spray nozzle was varied./

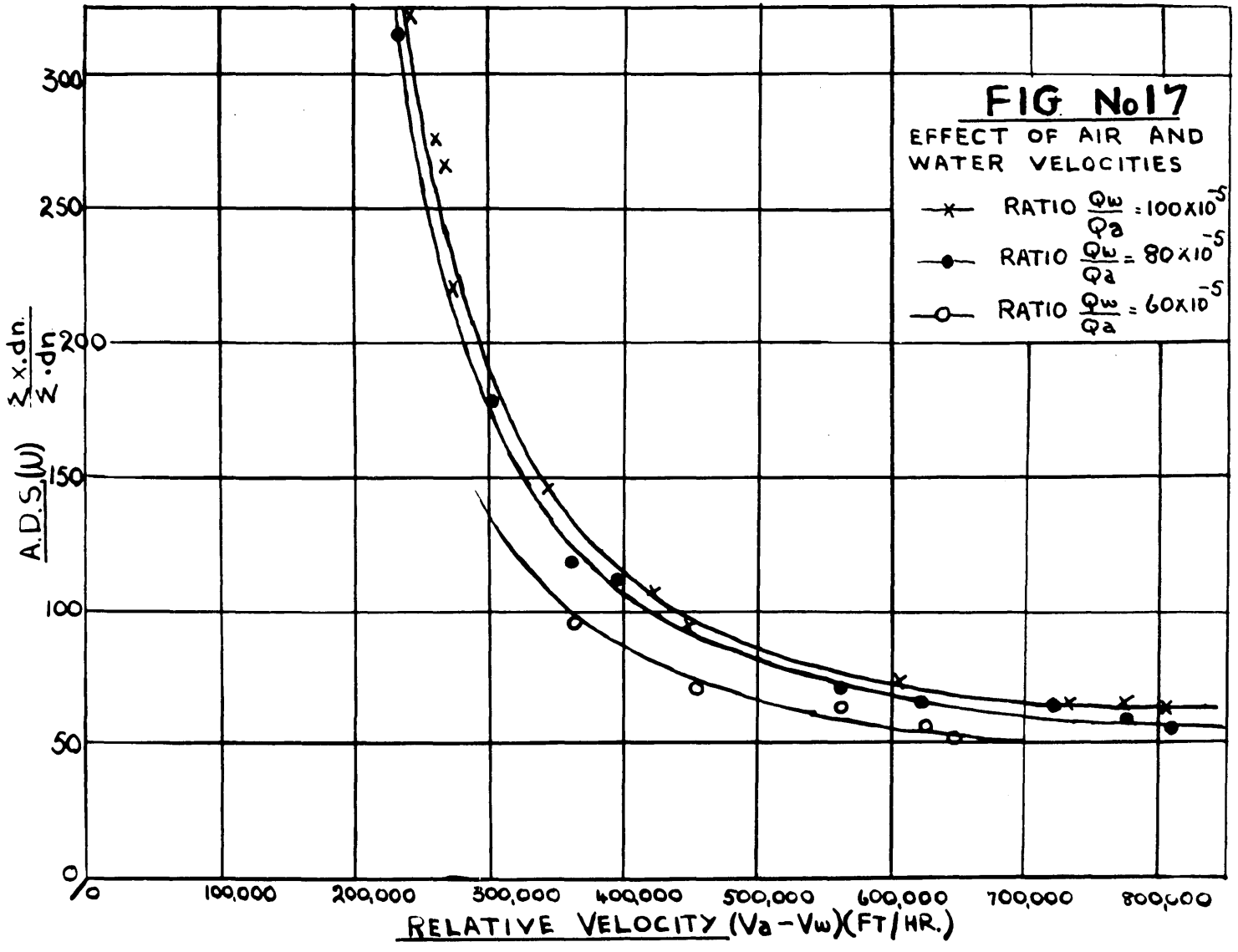


FIG No17
EFFECT OF AIR AND WATER VELOCITIES
RATIO $\frac{Qw}{Qa} = 100 \times 10^{-5}$
RATIO $\frac{Qw}{Qa} = 80 \times 10^{-5}$
RATIO $\frac{Qw}{Qa} = 60 \times 10^{-5}$
$\frac{\Sigma x.dn.}{\Sigma .dn}$ A.D.S.(W)
0
50
100
150
200
250
300
0/0
100,000
200,000
300,000
400,000
500,000
600,000
700,000
800,000
RELATIVE VELOCITY (Va - Vw)(FT/HR.)

/varied. The results are given in Table 17. These show that the A.D.S. of the spray increases slightly as the sampling point is moved further from the nozzle.

TABLE 17.

The effect of sampling distance.

Distance of Sampling. (inches)	A.D.S. (μ)
12	54.2
18	58.9
24	61.0
36	70.0
42	74.0

Energy Requirements of Compressed-Air Atomisation.

Applying the methods of Giffen and Muraszew (54), the energy supplied for atomisation and the energy needed for atomisation can be calculated as follows:-

(a) The Energy Supplied for Atomisation.

If Ww lbs. of water at a pressure Pw lbs/in.^{2} are injected into Wa lbs. air at Pa lbs/in.^{2} pressure,/

/pressure, the energy released is isothermal

$Ei = mRT \ln Pw/Pa$

where m = mass of air per lb. of water

R = gas constant = 96.6 ft.lbs/lb/°C

T = 17°C = 290°C Abs.

$m = Wa/Ww = Va\,\rho a/Vw\,\rho w$

where Va = volume of air

Vw = volume of water

$$Ei = (0.081 \times 96.6 \times 290 \times Va/62.5 \times Vw) 2.3 \log_{10}(Pw/Pa)$$

$$= 83.51\ Va/Vw \log_{10}(Pw/Pa) \text{ ft.lbs./lb.}$$

There is also the pressure energy due to the pressure of the liquid.

Ef = energy in the liquid

$= (Pw - Pa)\ 144/\rho$

Here $\rho = 62.5$

$Ef = 2.304\ (Pw - Pa)$ ft.lbs./lb.

Et = Total energy available for atomisation,

$= Ei + Ef$

$= 83.51\ Va/Vw \log_{10}(Pw/Pa) + 2.304\ (Pw-Pa)$ ft.lbs./lb.

(b) <u>The Energy Required for Atomisation</u>.

Consider 1 cc of liquid with surface area A_1. If this is atomised to give droplets with radius r_2 and surface area A_2.

The energy required for atomisation (Ea) is the product of the liquid surface tension (γ) and the increase in surface area per unit weight.

This/

/This can be expressed as $Ea = \gamma(A_2-A_1)/\rho$

where ρ = density of liquid (gm/cc) = 1 for water.
A_1 and A_2 are surface area of 1 cc of liquid before and after atomisation.
γ = surface tension (dynes/cm)
Now 1 cc of water has a surface area of 4.8 $cm.^2$

$$Ea = \gamma(A_2 - 4.8)/\rho$$
$$= \gamma(3V/r_2 - 4.8)/\rho$$

When V = 1 cc , r_2 is in microns and γ = 73.5 dynes/cm.
$Ea = (30{,}000/r - 4.8)\ 73.5.$
This may be compared directly with Et by converting to suitable units.
$Ea = (30{,}000/r - 4.8)\ 73.5/31{,}000$ ft.lbs./lb.

The values of Et and Ea were calculated for the different sprays. The Figs. 18 and 19 show the results obtained for the system nozzle G, needle 2 for a series of air throughputs. Fig. 18 shows that Ea tends to a constant value and this is shown further by the linear relationship obtained in Fig. 19. These facts indicate that above a certain pressure, Ea becomes independent of Et. It implies, in fact, that above certain conditions, the droplet size reaches a steady minimum value.

The Size Distribution of Spray Droplets.

A typical frequency curve showing the distribution of droplet sizes obtained is given in Fig. 20. Although the form of this type of curve has/

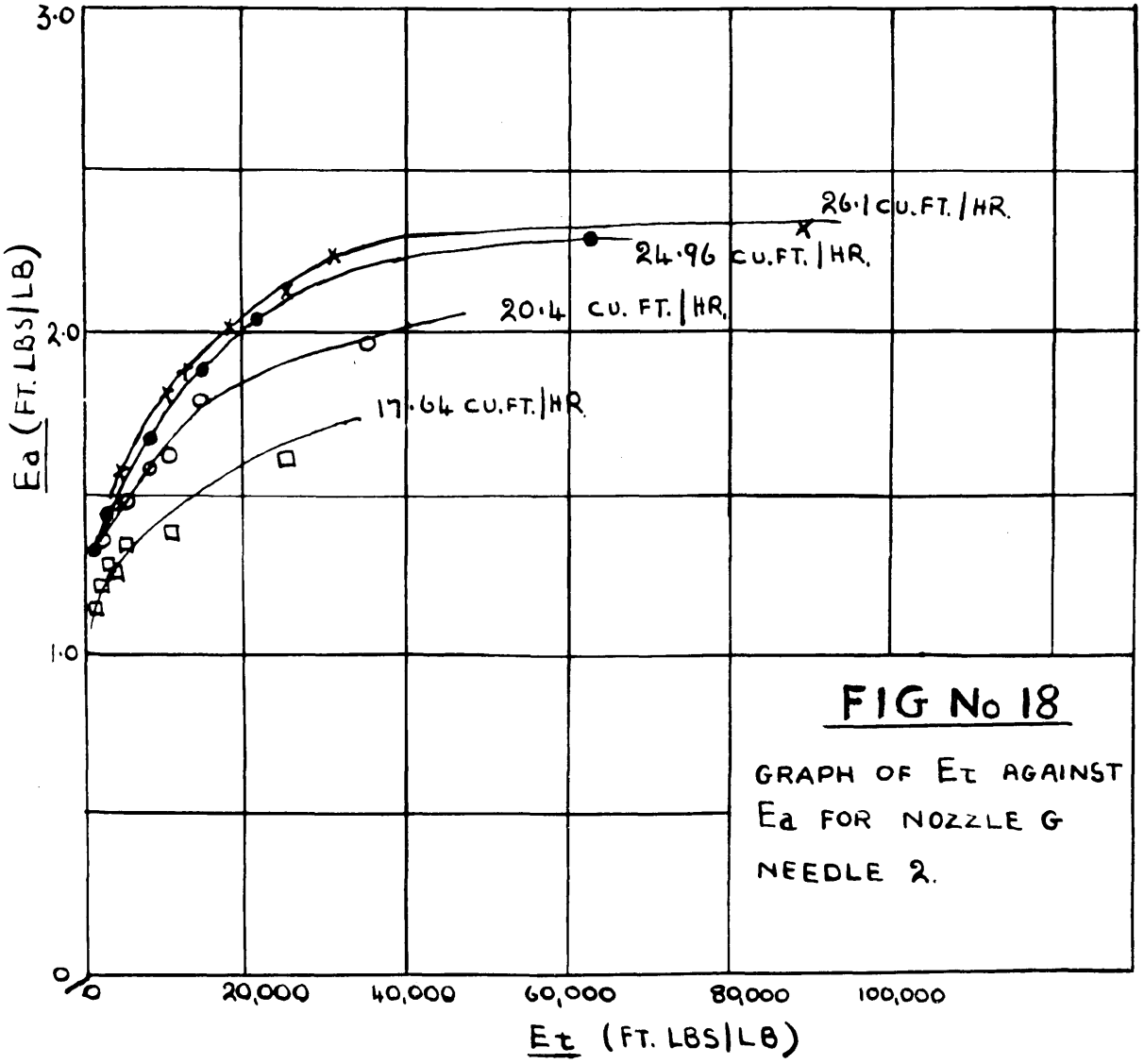


FIG No 18

GRAPH OF Et AGAINST Ea FOR NOZZLE G NEEDLE 2.

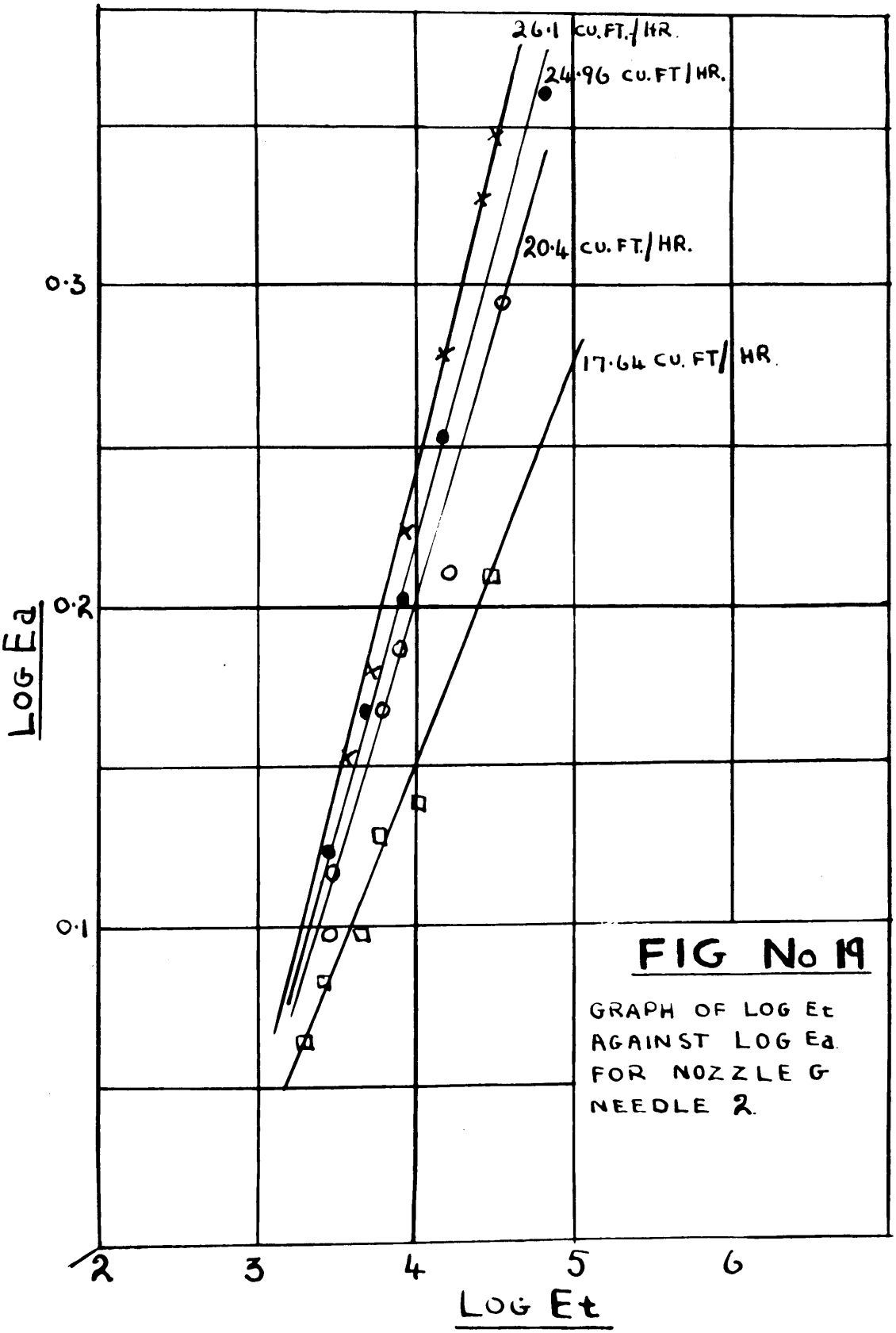


FIG No 19

GRAPH OF LOG Et AGAINST LOG Ea. FOR NOZZLE G NEEDLE 2.

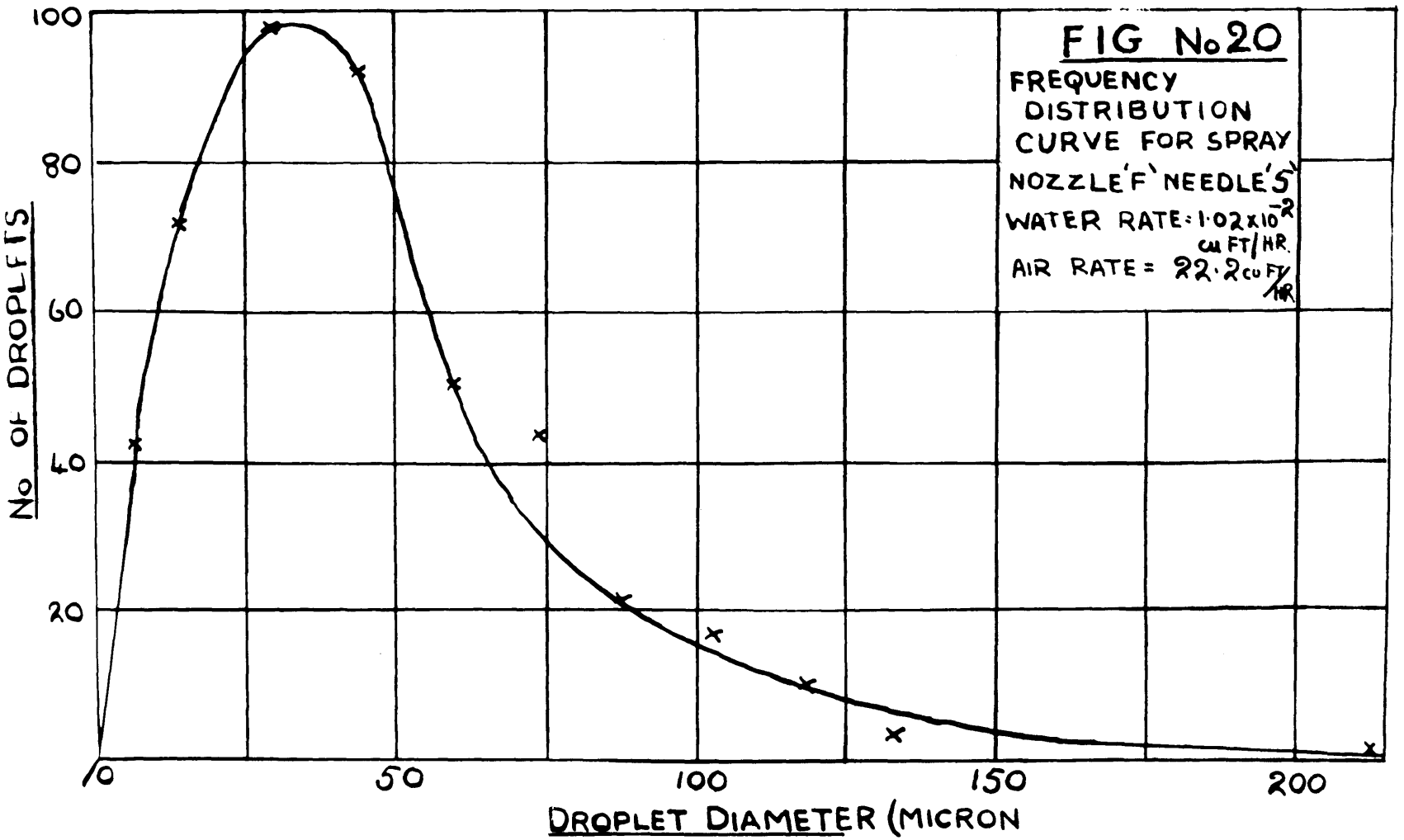


FIG No 20
FREQUENCY DISTRIBUTION CURVE FOR SPRAY NOZZLE 'F' NEEDLE '5'
WATER RATE: 1·02 x 10⁻² cu FT/HR.
AIR RATE = 22·2 cu FT/HR
No of DROPLETS
100
80
60
40
20
10
50
100
150
200
DROPLET DIAMETER (MICRON

/has been widely studied theoretically, its exact form is not yet definitely known.

In a spray system of this type, the large number of variables involved has prevented any great use of dimensional analysis. Nukiyama and Tanisawa have developed an empirical equation to represent their results with small air-atomising nozzles. In the development of this equation, they studied the results of other workers (55, 56) using different systems. Lewis et al (57) suggested the applicability of this equation to data for pressure nozzles, while Joyce (58) has applied the Rosin-Rammler equation (59) to spray size frequency data.

The Nukiyama and Tanisawa equation is given by $dn/dx = ax^p \exp.(-bx^q)$ ---------- (1)
Here a, b, p and q are test constants, dn/dx is the rate of variation of the number of droplets in relation to their diameter and is simply the number of droplets of diameter x.

Method of Determining Test Constants.

The formula (1) above may be written

$$\log 10 \left[\frac{1}{x^p} \frac{dn}{dx} \right] = (\log_{10} a) - \frac{bx^q}{2.3} \text{ ---------- (2)}$$

If $\log_{10} (1/x^p\ dn/dx)$ is plotted as ordinate against x^q as abscissa and the test points fit a straight line, the constant a will then have the value of $(1/x^p)\ (dn/dx)$ at x = o while b/2.3 will be the gradient/

/gradient of the line.

Values of p = 1, 2, 3 and q = $\frac{1}{4}$, $\frac{1}{2}$, 2/3, 4/5 and 9/10 were substituted in the equation and it was found that a straight line was only obtained using p = 2 and q = 2/3.

Curves similar to Fig. 21 were constructed as detailed above, using the results obtained from sprays with differing needle and nozzle sizes and the values for the constants p, q, a and b found. The results are given in Table 18 and from this it is seen that the drop size distribution conforms to a relationship,

$$\frac{dn}{dx} = ax^2 \exp\ (-bx^{2/3})$$

where a and b are test constants and depend on the spray system. This agrees with the results obtained by Nukiyama and Tanisawa. They found values of p = 2 and q = 1 were valid if Qa/Qw $>$ 5000, and, that the value of q decreased as the above ratio decreased.

The value of q is associated with the degree of uniformity of the droplet sizes in the spray. If the mass distribution of the drops is concentrated within a relatively narrow range of sizes the value of q is high, i.e. for a uniform atomisation. On the other hand, a low value of q represents a wide distribution of drop sizes.

The value of constant b has been found to vary with the relative velocity V while a is a constant/

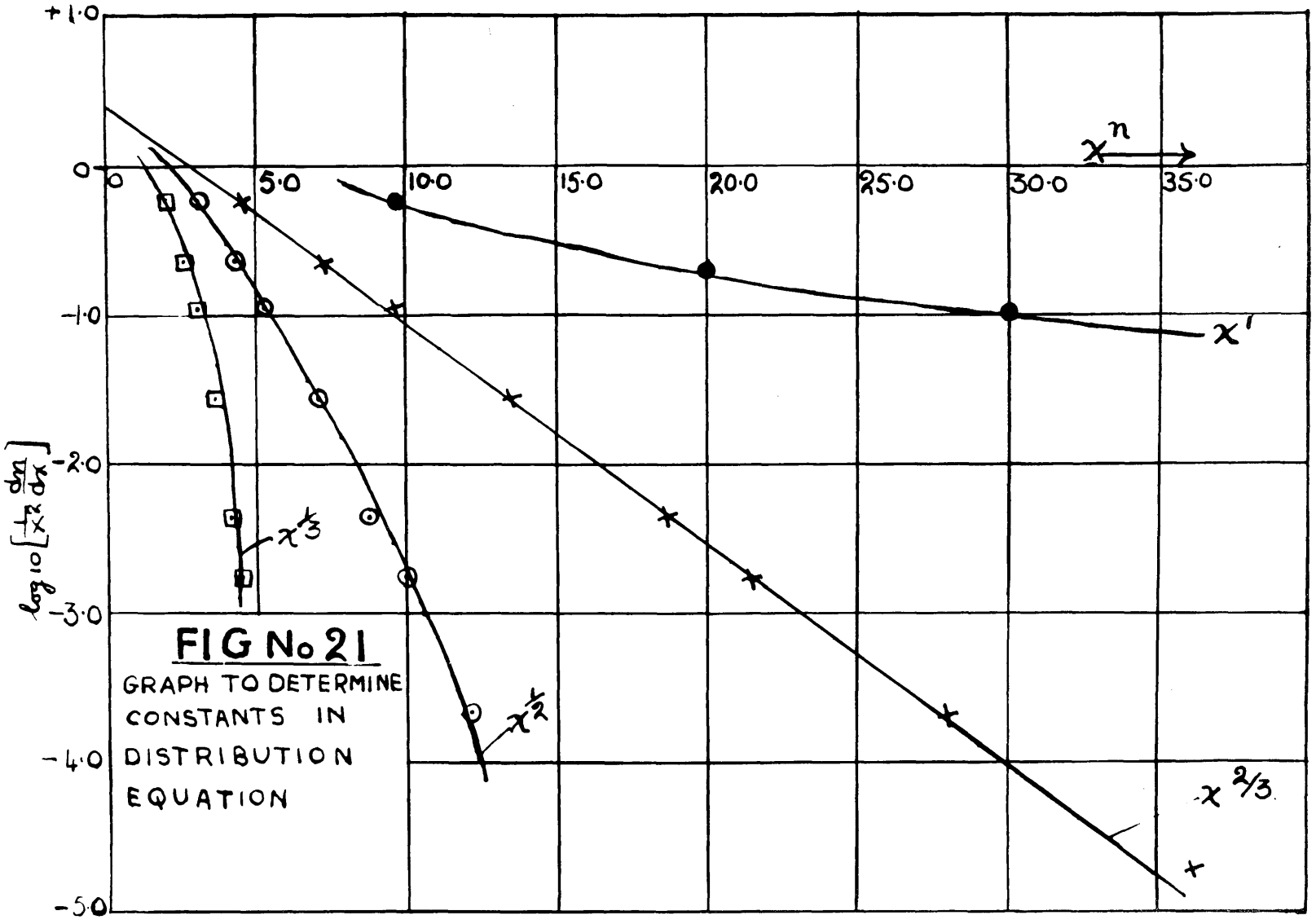


FIG No 21

GRAPH TO DETERMINE CONSTANTS IN DISTRIBUTION EQUATION

/constant which depends on the total number of droplets (n).

An A.D.S. Equation.

An equation giving the A.D.S. of the spray in terms of the operating variables and the properties of the liquid being sprayed has also been developed by Nukiyama and Tanisawa. It was decided to see whether it was applicable to the sprays used in this work.

The equation has been given as follows:-

$$Do = \frac{585\sqrt{6}}{V\sqrt{\rho}} + 597\left(\frac{\mu}{\sqrt{6\rho}}\right)^{0.45}\left(1000\,\frac{Qw}{Qa}\right)^{1.5}$$

Here, Do = Diameter of a single drop with the same ratio of surface to volume as the total sum of drops (μ)

i.e. $Do = \frac{\Sigma x^3.dn}{\Sigma x^2.dn}$

V = relative velocity between the air stream and the liquid stream (metres/sec.)

Qw/Qa = ratio of volume flow rate of liquid to volume flow rate of air.

ρ = liquid density (gm/cc)

μ = liquid viscosity (poises)

6 = liquid surface tension (dynes/cm).

For water $\rho = 1$; $\mu = 0.01$; $6 = 73$.

On substituting these values in formula (3) we get

$$Do = 28.64\left(1000\,\frac{Qw}{Qa}\right)^{1.5} + \frac{4999}{V} \quad \text{---------- (4)}$$

From/

TABLE 18.

Nozzle	Needle	p	q	a	b
F	5	2	⅔	2.8	15.5
G	5	2	⅔	0.5	19.3
G	3	2	⅔	0.13	28.0
H	2	2	⅔	0.33	23.6
K	1	2	⅔	0.35	25.2

TABLE 19.

Table showing values for Do obtained from experimental results and using formula.

$\frac{Qw}{Qa} \times 10^5$	Do from formula (4)	Do from experimental results	Nozzle Needle combination
30.1	165.0	250.0	Nozzle H Needle 5
60.2	182.7	222.0	" G " 5
194.9	238.8	266.0	" H " 3
244.8	260.7	263.5	" H " 2
279.0	305.5	300.2	" H " 2
406.0	300.3	287.6	" G " 3
43.3	136.0	154.2	" G " 5
170.5	204.0	239.0	" H " 3
206.0	212.0	216.8	" H " 2
221.0	230.5	197.5	" H " 2
328.0	307.2	311.5	" G " 3
368.0	337.9	327.5	" K " 2

/From equation (3) it appears that the size of the droplet in the spray is mainly governed by the term $\frac{\sigma}{V\sqrt{\rho}}$ when the ratio Qw/Qa is large, the viscosity being of minor importance under these conditions. When this ratio is small, Do is governed by the value

$$\left(\frac{\mu}{\sqrt{6\rho}}\right)^{0.45} \qquad \left(1000\ \frac{Qw}{Qa}\right)^{1.5}$$

and surface tension has only a small influence.

Table 19 gives values of Do calculated from experimental results using the method

$$Do = \frac{\Sigma x^3.dn}{\Sigma x^2.dn}$$

mentioned before, and also by using formula (4). It is found that a reasonable agreement is obtained in most cases.

In the following parts of this thesis, however, the practical results obtained for the A.D.S. of the given sprays will be used since they are readily available.

SECTION 3.

THE EFFECT OF AIR BLASTS ON SUSPENSIONS OF DUST IN THE CHAMBER.

Before the effect of the compressed air spray on the dust cloud could be determined, the effect of the air used for atomisation of the water had to be studied. It was obviously necessary to be able to separate the dilution effect of the compressed air from the knock-down achieved by the accompanying water droplets.

The dust chamber (Fig. 2) was now slightly altered. The middle photoelectric cell housing was removed on the side opposite to the lamp and the hole in that side of the chamber enlarged to enable the T.P. head to be inserted easily. The T.P. was used for measuring dust concentrations and from the same slides particle size analysis were carried out. Two of the dusts studied previously were used, viz. ground fly ash and ground coal dust. It had already been found that the dust concentration decreased rapidly during the first one and a half hours after the dust cloud had been first formed. The dust cloud was therefore left to sediment for at least this time before the air blast was started so that dust removed by normal sedimentation during the test would be negligible. The air blasts were applied in a down-

ward/

/ward direction in all cases.

The Theoretical Effect of the Air Added.

From a knowledge of the volume of the chamber and the volume of air added, one can predict the theoretical change in dust concentration that should take place. There are two limiting cases to be considered.

Case (a). Dust removed by displacement only. There is assumed to be no back-mixing of outgoing dust laden air with incoming dust free air.

Let the volume of the chamber = V cc.

Initial dust concentration = C_b p.p.c.c.

Volume of air added to the chamber = V_a cc.

$\therefore$ Volume of dust laden air leaving the chamber = V_a cc.

The number of particles initially in the chamber = $V_c C_b$

Number of particles displaced = $V_a C_b$

$\therefore$ Number of dust particles remaining = $C_b (V_c - V_a)$

$\therefore$ New dust concentration in the chamber = $\frac{C_b(V_c - V_a)}{V_c}$

$= C_{Di}$

$\therefore$ Concentration reduction by displacement = $\frac{V_a C_b}{V_c}$ p.p.c.c.

Percentage/

$\therefore$ Percentage of dust removed by displacement =

$$\frac{(C_b - C_{Di})\ 100}{C_b}$$

$$= 100\ \frac{V_a}{V_c}$$

Case (b). Dust removed by dilution and displacement. The mixing of the dust free air and dust laden air is assumed to be complete before the dust laden air leaves the chamber.

Initial dust concentration = C_b p.p.c.c.

Concentration after air is added and before dust is removed = $\frac{V_c\ C_b}{V_c+V_a}$

$\therefore$ Number of particles displaced = $\frac{V_a\ V_c\ C_b}{V_c + V_a}$

$\therefore$ Number of dust particles remaining = $V_c C_b - \frac{V_a V_c C_b}{V_c+V_a}$

$$= V_c\ \frac{C_b V_c}{V_c+V_a}$$

$\therefore$ New concentration in chamber = $\frac{C_b\ V_c}{V_c+V_a} = C_{Dm}$

$\therefore$ Concentration reduction by displacement and dilution = $\frac{V_a\ C_b}{V_c+V_a}$

$\therefore$ Percentage/

/Percentage of dust removed by displacement and dilution $= \frac{(C_b - C_{Dm})\ 100}{C_b}$

$$= \frac{100\ V_a}{V_c + V_a}$$

Since the air was added in a high velocity blast for a relatively short period of time, it is likely that the result will approximate more to case (a) than case (b).

It was considered that at least three factors would influence the effect produced by the air blasts. These were:-

(a) Initial dust concentration.
(b) Volume of air used.
(c) Velocity of air used.

Effect of Initial Dust Concentration.

A cloud of ground fly ash was blown into the chamber as described previously in Section 1 and was allowed to sediment for two hours. After the formation of the cloud, the stopper containing the dust delivery tube was removed from the bottom of the chamber. A T.P. sample was then taken and immediately afterwards a blast of 24,640 cc of air at a velocity of 214 ft/sec. was blown in through the top of the chamber over a period of two minutes. At the end of the two minutes another T.P. sample was taken/

/taken and immediately afterwards the same volume of air at the same velocity was blown in for a further two minutes when a further T.P. sample was taken. This procedure was carried out several times on the same dust cloud and the results obtained are shown in Table 20.

The number of particles removed by the air blast was obtained by subtracting the concentration of the dust cloud after blowing from the concentration before blowing.

It can be seen from Table 20 that the experimental reduction in concentration of ground fly ash is considerably greater than that expected from mere displacement and dilution. This greater reduction is probably the result of aggregation of dust particles due to the disturbance of the conditions existing in the dust chamber by the air blast.

Effect of Volume of Air Used.

Different volumes of air at the same pressure and velocity were blown in by increasing the time of the air blast. The results are shown in Table 21. It can be seen that for the shortest time of blowing, the dust removed is again more than could be expected from displacement and dilution but, as the time of blowing increases, the dust removed approaches the theoretical displacement value. In general/

TABLE 20.

Effect of initial dust concentration on dust removed by air blast.
Volume of chamber (V_c) = 248,000 cc. Dust used = ground fly ash.

Time of blast. (Mins.)	Volume of air used. (V_a)cc.	Measured dust concentrations. (p.p.c.c.)		Experimental Reductions.		Theoretical Reductions.			
						By displacement only.		By displacement and dilution.	
		Before blast (C_B)	After blast	Concentration (p.p.c.c.)	%	Concentration (p.p.c.c.) $\frac{V_a C_B}{V_c}$	% $100\ \frac{V_a}{V_c}$	Concentration (p.p.c.c.) $\frac{V_a C_B}{V_c+V_a}$	% $\frac{100\ V_a}{V_c+V_a}$
2	24,640	17,860	15,510	2,350	13.2	1,775	9.93	1,614	9.06
2	"	15,510	11,420	4,090	26.3	1,541	"	1,402	"
2	"	11,420	8,200	3,220	28.2	1,135	"	1,031	"
2	"	8,200	6,170	2,030	24.8	816	"	743	"
2	"	6,170	4,915	1,255	20.4	614	"	559	"

TABLE 21.

Effect of volume of air applied on dust removed.

Volume of chamber V_c = 248,000 cc. Dust used = Fly Ash.

Volume of air applied in blast. cc.	Measured dust concentration (p.p.c.c.)		Experimental Reductions.		Theoretical Reductions.			
					By displacement only.		By displacement and dilution.	
	Before blast.	After blast.	Concentration (p.p.c.c.)	%	Concentration (p.p.c.c.) $\frac{V_a C_B}{V_c}$	% $100\ \frac{V_a}{V_c}$	Concentration (p.p.c.c.) $\frac{V_a C_B}{V_c+V_a}$	% $\frac{100\ V_a}{V_c+V_a}$
25,140	24,720	16,180	8,540	34.5	2,502	10.1	2,738	9.2
75,420	23,600	14,240	9,360	39.6	7,170	30.4	5,500	23.3
125,700	16,270	8,580	7,690	47.3	8,260	50.8	5,470	33.7
188,500	12,870	5,520	7,350	57.2	9,760	76.1	5,560	43.3
Dust used = coal dust.								
25,140	20,700	17,200	3,500	16.9	2,095	10.1	1,905	9.2
75,420	34,500	28,400	6,100	17.7	10,500	30.4	8,040	23.3
100,560	18,160	12,470	5,690	31.4	7,380	40.7	5,250	28.9
125,700	29,400	14,400	15,000	51.1	14,920	50.8	9,920	33.7

/general it would seem that the final value lies midway between the "displacement only" and "displacement and dilution" values. The reason for this might be that as the time of blowing is increased and the dust concentration has decreased, the dust laden air in the chamber has a better opportunity of mixing with the dust free air blown in. Thus, both processes will be involved, giving results which will lie between the values expected if each process was acting by itself. For the short time run, aggregation will have a greater effect than with the longer runs since more aggregation takes place with higher dust concentrations.

Effect of Velocity of Air Used.

By using different needle and nozzle diameters, different velocities of air can be obtained. A diagram of the spray used is given in Fig. 7 of Section 2. The time was calculated for all the tests so that the same amount of air was blown in each time. The results are shown in Table 22 and indicate that over the range of velocities tested, the actual air velocity has no significant effect on the change in dust concentration. Two of the fly ash results approximate to "displacement only" and the other to "displacement and dilution" but the difference between the two limiting conditions is so small here that it is not significant. The reduction in concentration of the coal dust can not all be explained by "displacement and dilution". Much more dust/

TABLE 22.

Effect of velocity of air on dust removal.

Volume of chamber (V_c) = 248,000 cc. Dust used = Fly ash.

Volume of air applied Vacc.	Time of blast. Mins.	Initial Velocity of air. ft/sec.	Measured dust concentration (p.p.c.c.)		Experimental Reductions		Theoretical Reductions.			
							By displacement only.		By dilution & displacement.	
			Before blast	After blast	Concentration (p.p.c.c.)	%	Concentration (p.p.c.c.)	%	Concentration (p.p.c.c.)	%
27,840	2 mins.	66.3	15,100	13,400	1,700	11.3	1,753	11.6	1,520	10.1
"	2 mins. 15 secs.	82.7	4,250	3,700	550	12.9	493	11.6	428	10.1
"	2 mins. 17 secs.	97.2	5,950	5,380	570	9.6	690	11.6	600	10.1

Dust used = Coal dust.

27,840	2 mins.	66.3	32,700	25,400	7,300	22.3	3,790	11.6	3,300	10.1
"	2 mins. 15 secs.	82.7	22,360	14,220	8,140	36.5	2,490	11.6	2,250	10.1
"	2 mins. 17 secs.	97.2	30,540	18,720	11,820	38.8	3,540	11.6	3,080	10.1
"	2 mins. 38 secs.	132.0	15,250	11.650	3,600	23.6	1,765	11.6	1,533	10.1

/dust is removed than theory demands.

From the results obtained, it was decided that before finding the effect of the water spray on the sedimentation of the dust cloud, the effect of the air blast used for atomisation should be found first in every case.

SECTION 4.

THE EFFECT OF COMPRESSED-AIR SPRAYS ON SUSPENSIONS OF DUSTS IN THE CHAMBER.

According to Sell (60) the efficiency (η) of a water droplet in removing dust particles from air is given by

$$\eta = \frac{b^2}{D^2}$$

where D is the (projected) diameter of the droplet and b is the limiting diameter (of the streamlines) within which all particles travelling towards the droplet will collide with it and be captured by it.

This is shown diagrammatically in Fig. 22.

Sell has also shown that the efficiency is a function of the group

$$\frac{Mv}{RD}$$

where M = mass of particle = $\frac{\rho \pi d^3}{6}$

ρ = particle density

d = particle diameter

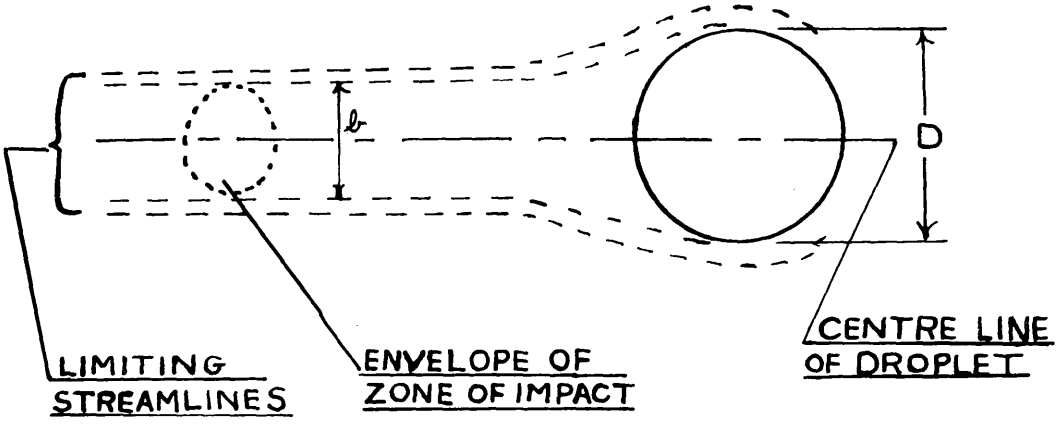
v = relative velocity (in the same straight line) of droplet and particle.

R = $3 \pi \mu d$ for particles within the Stokes law range.

μ = gas viscosity.

Then/

FIG No 22


b
D
LIMITING STREAMLINES
ENVELOPE OF ZONE OF IMPACT
CENTRE LINE OF DROPLET

Then $\frac{Mv}{RD} = \frac{1}{18} \frac{d^2 v \rho}{\mu D}$

The expression on the left hand side of this equation can be called the "impactability".

From Sell's calculations it would appear that a relationship of the type

$$\eta = \frac{k(d^2 v \rho)^p}{(u \ D)}$$ holds,

where k and p are constants, the latter being less than 1.0. Thus, in a dust suppression test of the type carried out in our dust chamber, the total number of dust particles knocked down during the duration of the spray run will be dependent on:-

(a) the efficiency,

(b) the number of particles per unit volume of gas space,

(c) the number of water droplets produced per second

$$\propto \frac{\text{water throughput}}{(\text{average droplet size})^3}$$

(d) the distance gone by a droplet in passing through the dust cloud (this assumes that a droplet collects many dust particles)

(e) the cone angle of the spray, and

(f) the time of spraying.

The rate of dust suppression should be related to the other variables in the following way:-

$$\frac{dn}{dt} = k^1 \left(\frac{d^2 v \rho}{\mu D}\right)^p (n_o - n) \frac{V}{D^3} L^q \propto^r$$

where/

/where n_o = initial dust concentration (particles per cc)

n = dust concentration at time t secs.

V = water throughput (cc's per sec.)

D = average droplet size (cm)

L = length of droplet path (cm)

α = cone angle of spray

k^1 p q r are constants.

In comparing sprays, therefore, where all other variables are kept steady, the efficiency of dust suppression should be proportional to the relative velocity between dust particles and droplet, and to the square of the average dust particle size, and vary inversely with the average droplet size of the spray.

It has been shown experimentally (60, 61) that the efficiency of removal of airborne dust particles varies with the size of the particle. This has also been found to be the case by Brown and Schrenk (62) who carried out their tests under actual mining conditions.

(a) Effect of water velocity on sedimentation.

Spray tests were carried out in a similar manner to those for the air blasts. The effect of the air used for the atomisation of the sprays was studied first in every case.

With the system in use the determination of even an average value of relative velocity in the same/

/same straight line of particle and droplet is virtually impossible. For the purposes of comparison it was assumed that in the vicinity of the spray nozzle the particles would be moving at the initial nozzle velocity of the air blast and the droplets were at the nozzle velocity of the water flow and thus the relative velocity was the difference between these. It was realised that this belief was a rather poor approximation to the truth but it was thought to be adequate for comparative results.

In these tests, therefore, the average droplet size and water throughput were kept constant while the water velocities were changed. This was achieved by using different needle and nozzle systems. The results are shown in the Tables 23 and 24. Here the percentage reduction in dust concentration due to the water droplets alone is obtained by subtracting the percentage reduction in concentration due to the air blast from the total percentage reduction obtained using the spray.

From these results, it can be seen that there is no apparent relationship between water velocity and the percentage dust removed. It is realised, of course, that the droplet velocity will be influenced by the gas velocity. The effects of the relative velocity of the spray can also be seen in the tables. It is apparent that, in general, the/

TABLE 23.

Effect of relative velocity (Va-Vw) of droplet on sedimentation of Fly Ash.

Volume Used.		Initial Velocities at orifice.		Relative Velocity Va-Vw (ft/sec)	A.D.S. of Spray (μ)	Concentrations (p.p.c.c.)			Reductions by					
									Air		Spray		Water Droplets	
Air c.c.	Water c.c.	Air Va (ft/sec)	Water Vw (ft/sec)			Before Air	After Air	After Spray	p.p.c.c.	%	p.p.c.c.	%	p.p.c.c.	%
42,200	57	651	0.4	650.6	67.0	55,300	45,900	22,000	9,400	17.0	23,900	52.2	14,500	35.2
49,100	57	215.5	1.1	214.4	66.8	8,060	6,460	3,610	1,600	19.9	2,850	44.0	1,250	24.1
58,900	57	204.4	0.6	203.8	66.7	9,850	7,500	3,890	2,350	23.8	3,610	48.0	1,260	24.2
53,000	57	201.1	0.8	200.3	67.4	22,380	17,600	9,560	4,780	21.4	8,040	45.6	3,260	23.2

TABLE 24.

Effect of relative velocity (Va-Vw) of droplet on sedimentation of Coal Dust.

Volume used.		Initial Velocities at orifice.		Relative Velocity Va - Vw (ft/sec)	A.D.S. of Spray. (μ)	Concentrations (p.p.c.c.)			Reductions by					
									Air		Spray		Water Droplets	
Air cc.	Water cc.	Air Va (ft/sec)	Water Vw (ft/sec.)			Before Air	After Air	After Spray	p.p.c.c.	%	p.p.c.c.	%	p.p.c.c.	%
42200	57	651	0.4	650.6	67.0	31,900	26,500	11,540	5,400	16.9	14,960	56.5	9,560	39.6
49100	57	215.5	1.1	214.4	66.8	17,970	14,300	5,160	3,670	20.4	9,140	63.9	5,470	43.5
58900	57	204.4	0.6	203.8	66.7	24,770	18,890	8,480	5,880	23.6	10,410	55.2	4,530	31.6
53000	57	201.1	0.8	200.3	67.4	17,470	13,720	5,530	3,750	21.5	8,190	59.5	4,440	38.0

/the percentage dust removed increases as the relative velocity of the spray increases. This is in agreement with the above theory.

(b) The effect of duration of spraying.

For this series of tests, the same needle and nozzle were used with the water and air velocities and throughputs the same. The time of spraying was increased for each run. The results obtained are given in Tables 25 and 26, from which it can be seen that no apparent increase in reduction of dust concentration is obtained, as the volume of water sprayed is increased. However, due to the difference between the concentrations of dust before spraying with air and water here, the previous assumptions that there will be the same reduction due to the effect of the air blast will not apply in all cases, i.e. when the time of spraying is 8 and 10 minutes. The results are shown in Figs. 23 and 24 where it is seen that as the time of spraying is increased the rate at which the dust is removed decreases. This may be due to the fact that the particle size of the dust cloud in the chamber is changed by spraying. As the time of spraying is increased, the average particle diameter of the dust suspended in the chamber may become smaller and the possibility of it coming into contact with a water droplet diminishes.

(c) The effect of degree of atomisation.

In order to increase atomisation, the needle,/

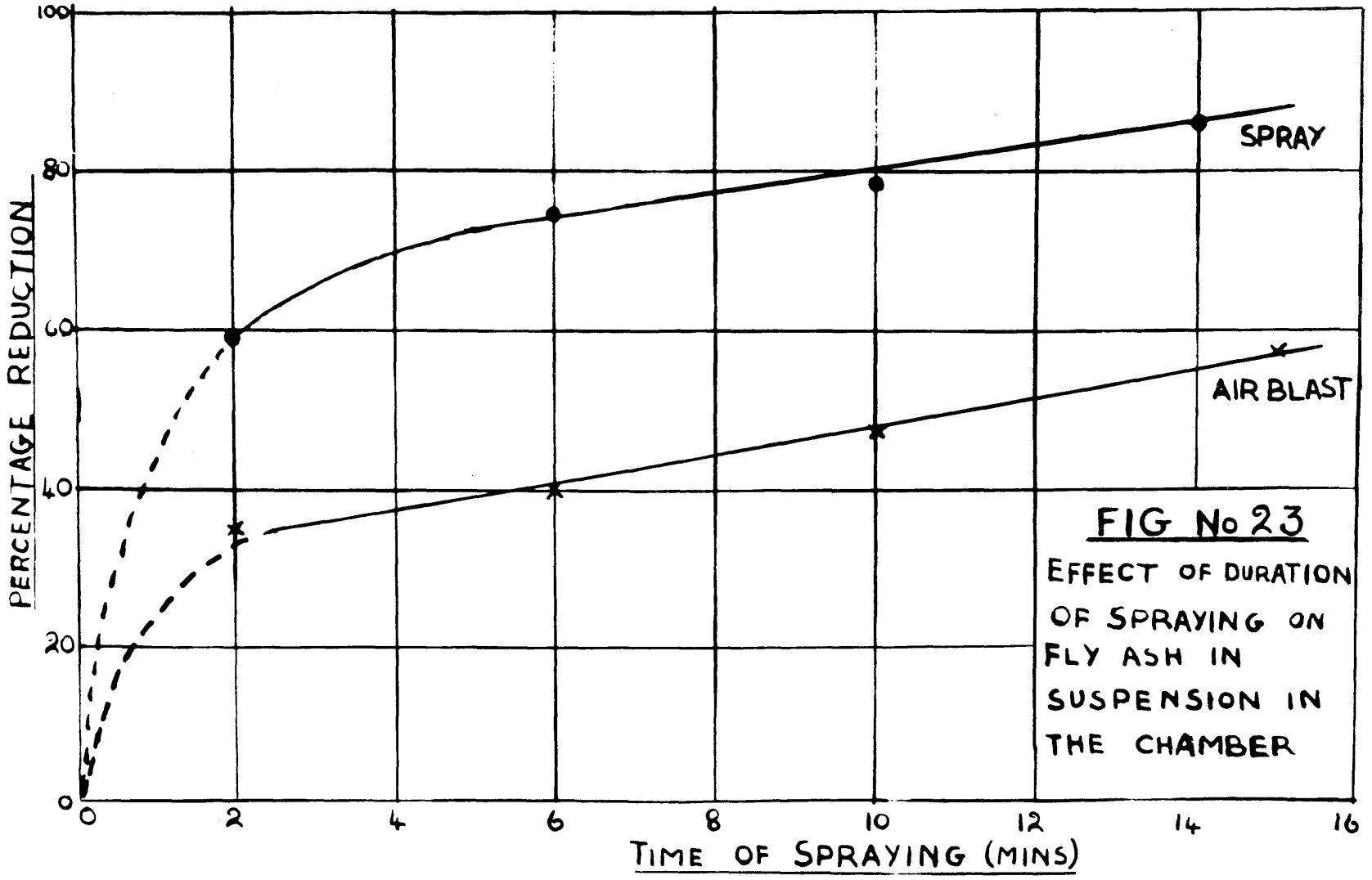


FIG No 23

EFFECT OF DURATION OF SPRAYING ON FLY ASH IN SUSPENSION IN THE CHAMBER

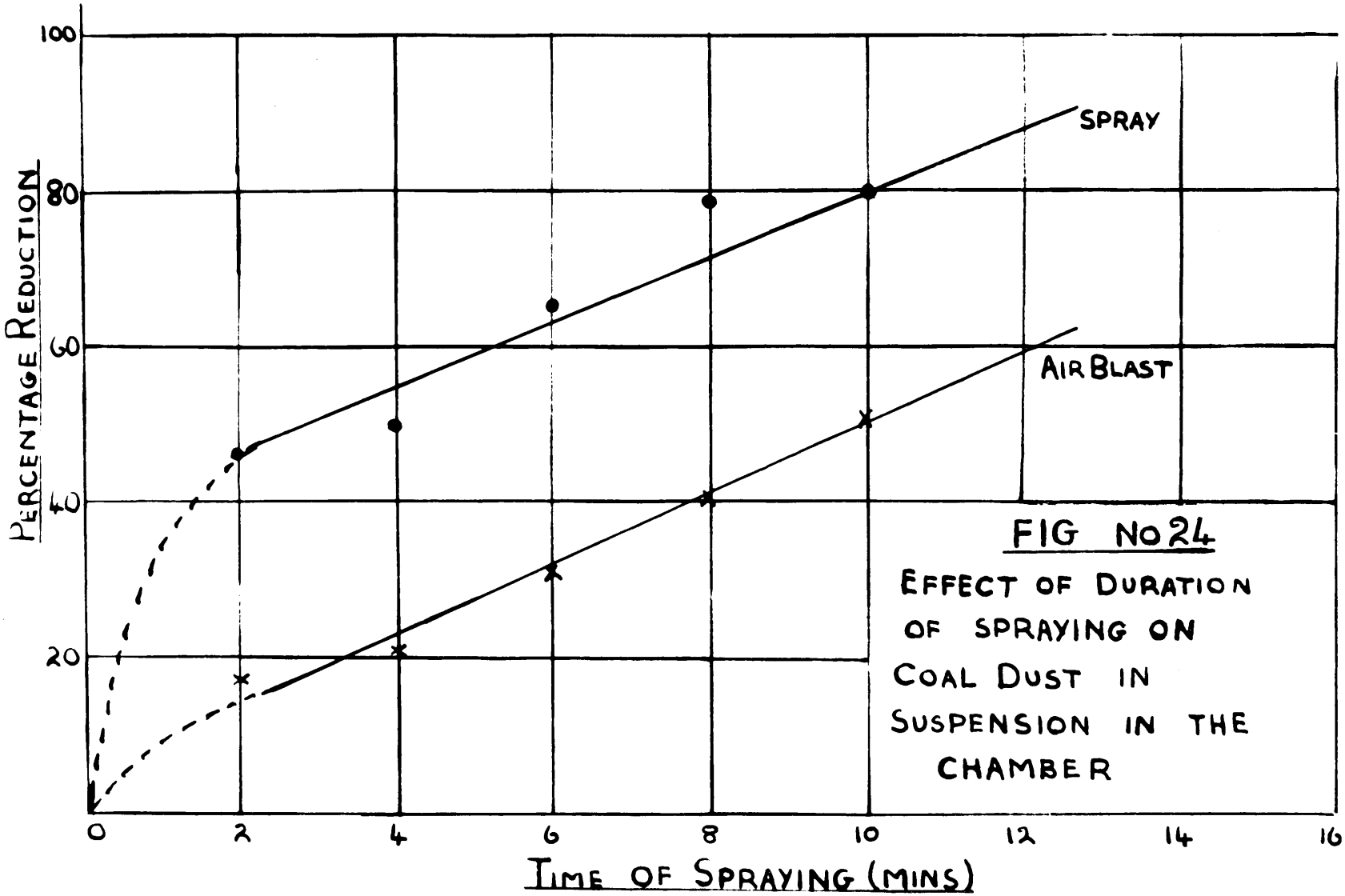


FIG NO 24

EFFECT OF DURATION OF SPRAYING ON COAL DUST IN SUSPENSION IN THE CHAMBER

TABLE 25.

Effect of Duration of Spraying.

Ground Fly Ash.

Time of Spraying (mins.)	Throughputs		Concentrations.			Reduction.				
	Air cc.	Water cc.	Before Air.	After Air.	After Spray.	- Air.		Spray.		Water
						p.p.c.c.	%	p.p.c.c.	%	%
2	25,140	67.6	24,720	16,180	6,651	8,540	34.5	9,530	59.0	24.5
6	75,420	202.8	23,600	14,240	3,590	9,360	39.7	10,650	74.8	33.0
10	125,700	338.0	16,270	8,580	1,850	7,690	47.3	6,730	78.4	31.0
15	188,500	507.0	12,870	5,520	783	7,350	57.2	4,737	86.0	28.8

TABLE 26.

Effect of Duration of Spraying.

Ground Coal Dust.

Time of Spraying.	Throughputs.		Concentrations.			Reductions.				
	Air cc's	Water cc's	Before Air	After Air	After Spray	Air		Spray		Water.
						p.p.c.c.	%	p.p.c.c.	%	%
2	25,140	67.6	20,700	17,200	9,320	3,500	16.9	7,880	46.0	29.1
4	50,280	135.2	16,460	13,120	6,640	3,340	20.3	6,480	49.4	29.1
6	75,420	202.8	34,500	24,000	8,210	6,100	30.4	15,790	65.7	48.0
8	100,560	270,4	18,160	10,800	5,690	7,360	40.5	8,530	79.0	38.5
10	125,700	338.0	29,400	14,400	2,900	15,000	51.0	11,500	80.0	29.0

/needle, nozzle, water rate and hence water velocity were kept constant, while the air throughput was changed each time. This gave a series of sprays each with a different average droplet diameter and also a different air throughput. The time of spraying was kept constant (4 minutes) so that the volume of water sprayed was the same each time. The results obtained are given in Tables 27 and 28 from which it can be seen that increased atomisation, i.e. a decrease in average droplet diameter of the spray, increases the percentage of dust removed from the chamber. This also agrees with the theory mentioned above.

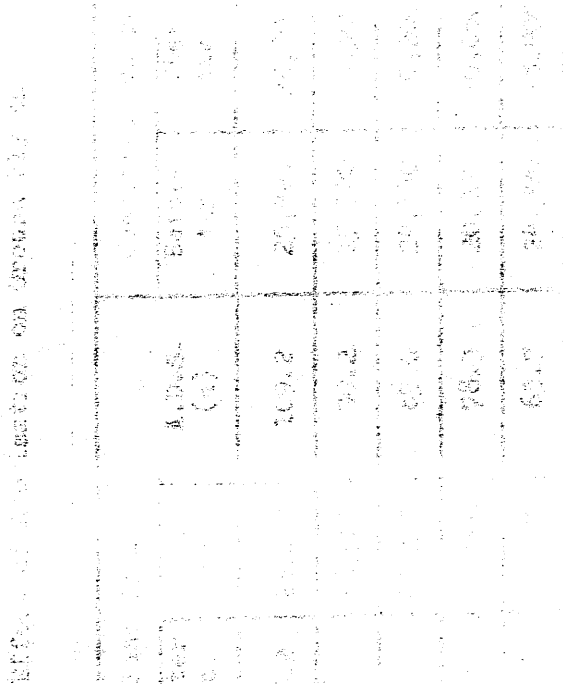


TABLE 27.

Effect of Atomisation on Ground Fly Ash.

Volume Used.		A.D.S. (μ)	Concentration p.p.c.c.			% Reduction.		
Water cc.	Air cc.		Before Air	After Air	After Spray	Air	Spray	Water
135.2	25,280	109.2	25,420	22,900	14,740	9.9	35.6	25.7
"	38,520	90.2	15,720	13,300	6,830	15.4	48.6	33.2
"	47,120	85.0	24,840	20,200	8,650	18.7	57.2	38.5
"	49,200	78.3	20,000	16,050	6,980	19.8	60.3	40.5
"	57,080	65.7	24,570	18,900	5,470	23.1	71.0	47.9

TABLE 28.

Effect of Atomisation of Ground Coal Dust.

Volume Used.		A.D.S. (μ)	Concentration p.p.c.c.			% Reduction.		
Water cc.	Air cc.		Before Air.	After Air.	After Spray.	Air.	Spray.	Water.
135.2	25,280	109.2	20,190	17,220	7, 270	14.7	57.8	33.1
"	38,520	90.2	19,100	16,100	9,580	15.7	40.5	24.8
"	47,120	85.0	16,880	13,680	6,260	19.0	54.4	35.4
"	49,200	78.3	16,460	14,480	6,640	12.1	54.2	42.1
"	57,080	65.7	20,100	15,500	4,870	22.9	68.6	45.7

SECTION 5.

THE EFFECT OF THE COMPRESSED-AIR SPRAY ON THE SIZE DISTRIBUTION OF THE DUST CLOUD IN SUSPENSION.

From the photographs on Plates 12, 13, 14 and 15, taken from T.P. slides obtained during a sedimentation run, it can be seen that as the duration of sedimentation is increased, the average particle diameter of the dust in the chamber decreases, due to the larger particles falling out of suspension.

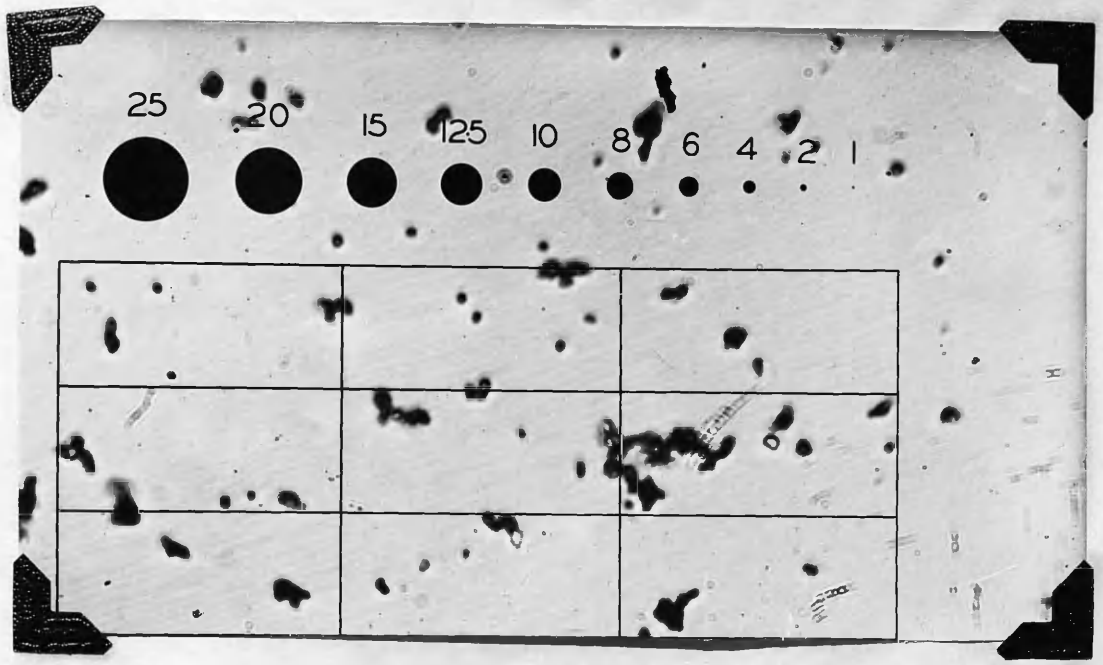
In the examination of the T.P. samples used to measure the concentration of the dust clouds before and after spraying, it was observed that the sprays had an effect on the size frequency as well as the concentration of the dust in suspension in the chamber.

(a) Effect of air blast.

The histogram in Fig. 25 shows the effect of the air blast on a suspended coal dust cloud. The air blast lasted four minutes and the volume of air used was 23,280 cc. From the figure it can be seen that the size distributions before and after the air blast are almost the same. This supports the conclusion reached in the previous section, that the effect of the air blast is merely to displace a volume of dust laden air.

(b) Effect of Average Droplet Size of Spray.

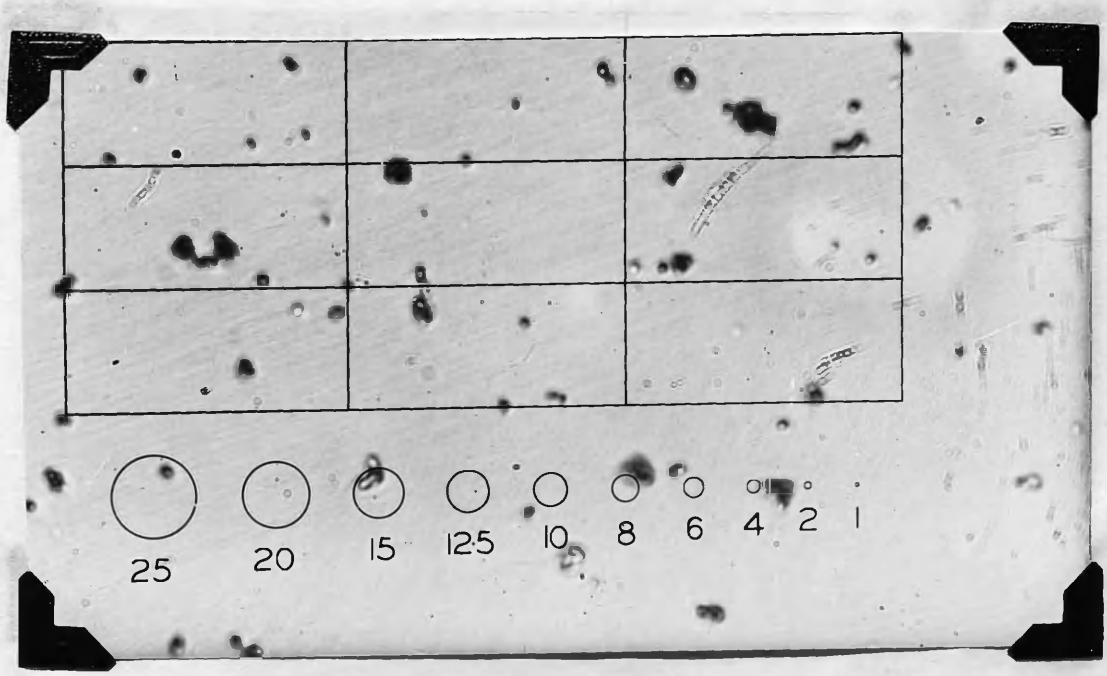
The effect of the average droplet size of the spray on the size distribution of a coal dust cloud/



X 2400

PLATE 12.

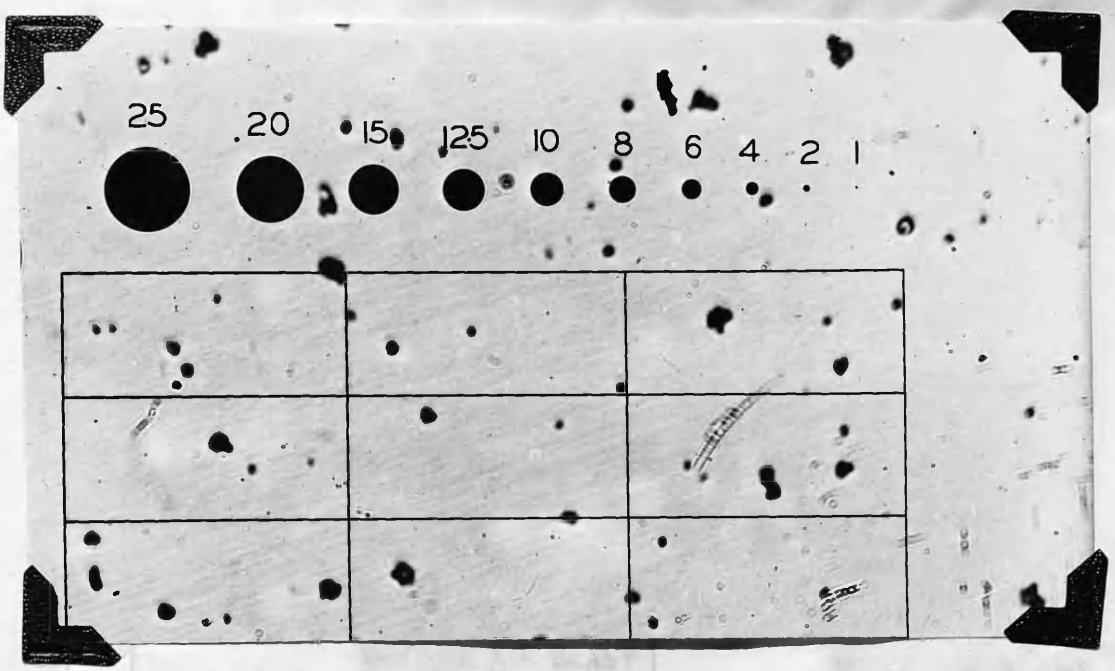
Coal dust cloud before spraying.



X 2400

PLATE 13.

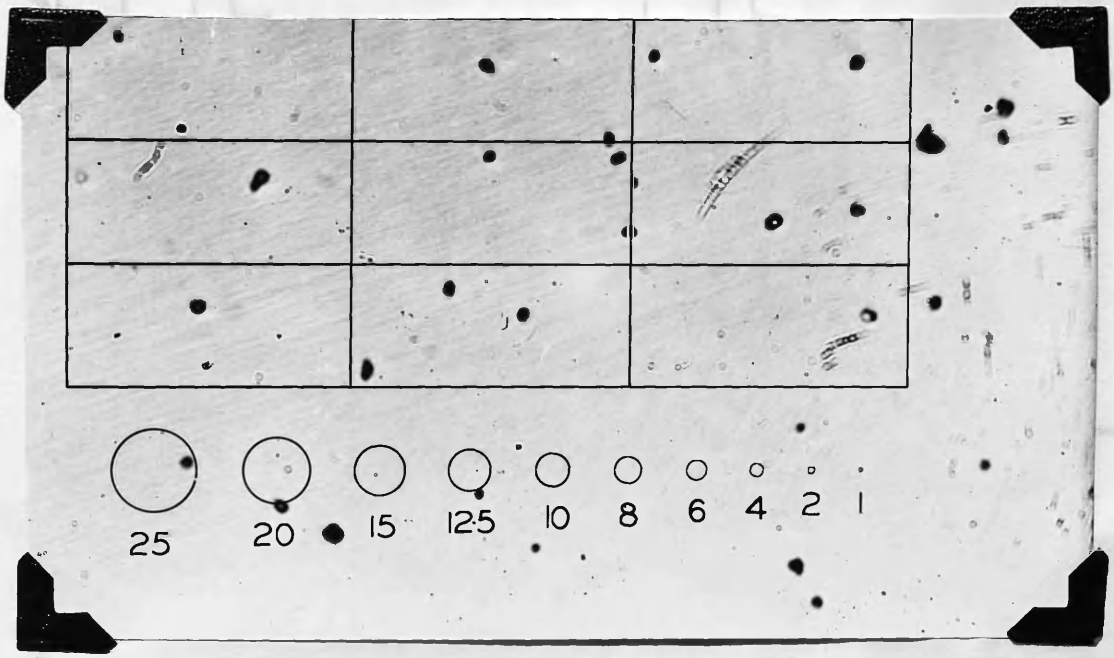
Coal dust cloud after spraying - 2 mins.



X 2400

PLATE 14.

Coal dust cloud after spraying 6 mins.



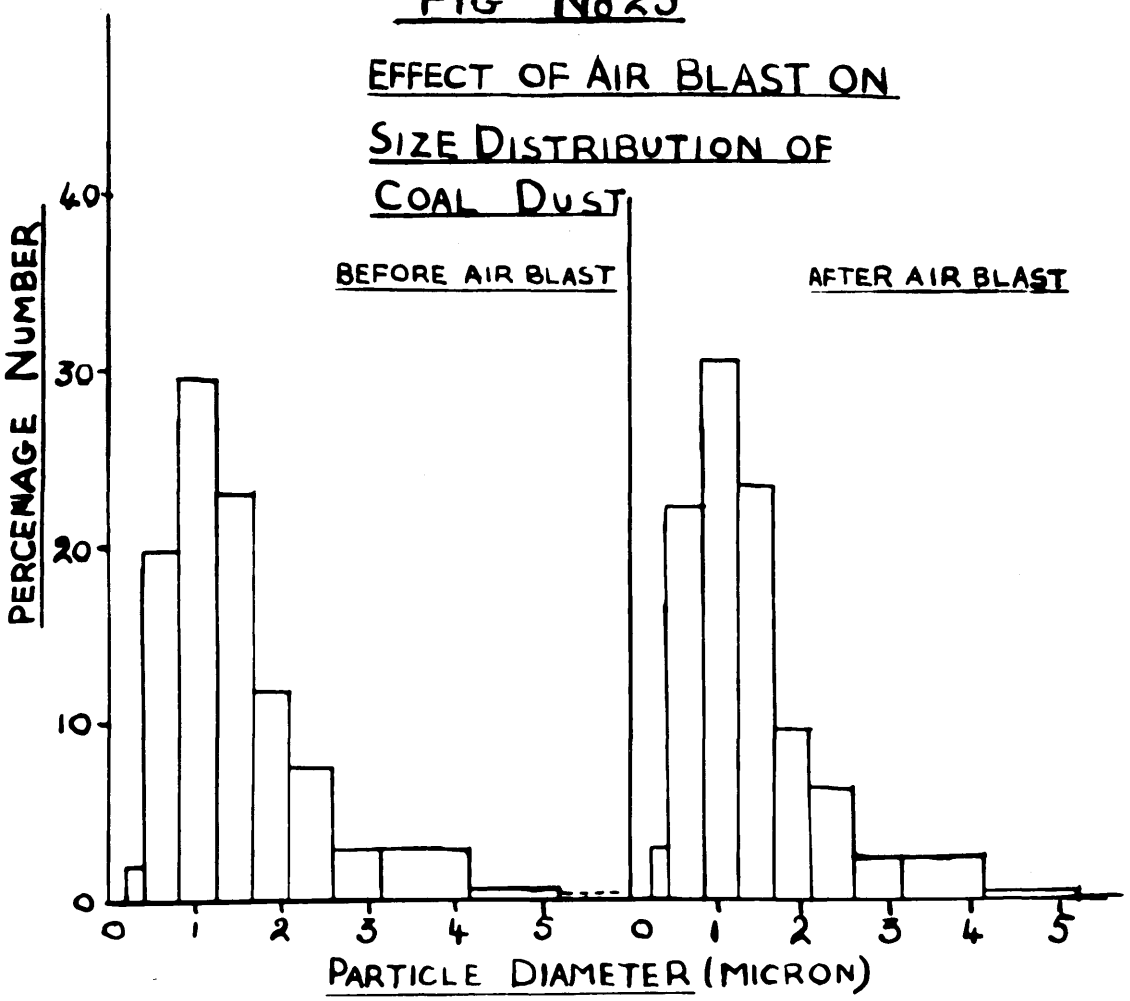
X 2400

PLATE 15.

Coal dust cloud after spraying 10 mins.

FIG No25

EFFECT OF AIR BLAST ON SIZE DISTRIBUTION OF COAL DUST



/cloud is shown in the histogram on Fig. 26. From this, it is seen that as the average droplet size of the spray is decreased, the average particle diameter of the residual dust also decreases, i.e. as the droplet size of the spray is decreased, its ability to remove the smaller suspended particles is also decreased. Table 29 constructed from the particle size analysis of the dust clouds before and after spraying and from the decrease in particle concentration shows this more clearly. From these results Table 30 was drawn up and can be seen to indicate that as the spray size is decreased, the percentage of < 0.83 micron dust removed is decreased, whereas the removal of the > 0.83 micron dust is increased.

Claims are made by some workers that particles under a size of 2 microns are not affected by water droplets from the spray (62). This was not found to be the case here.

(c) The Effect of the Duration of Spraying.

The Tables 31 and 32 and the histograms in Fig. 27 were constructed from the results obtained by increasing the time of spraying into a coal dust cloud in suspension in the chamber.

The histograms in Fig. 27 show that as the time of spraying is increased, the percentage number of smaller particles is increased with the disappearance of the larger particles ($>$ 4 micron). However,/

FIG No 26

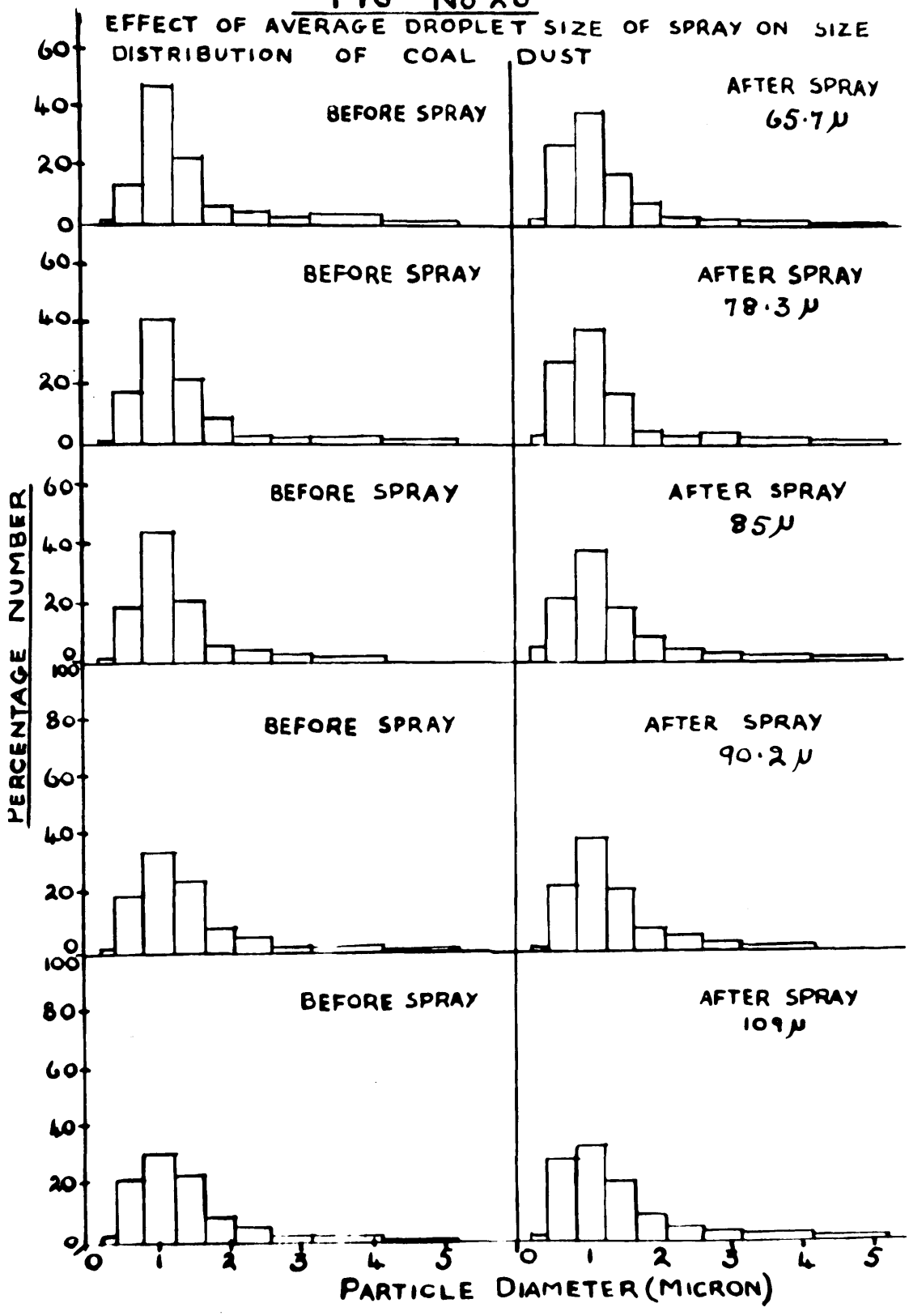

EFFECT OF AVERAGE DROPLET SIZE OF SPRAY ON SIZE DISTRIBUTION OF COAL DUST
BEFORE SPRAY
AFTER SPRAY
65·7 μ
BEFORE SPRAY
AFTER SPRAY
78·3 μ
BEFORE SPRAY
AFTER SPRAY
85 μ
BEFORE SPRAY
AFTER SPRAY
90·2 μ
BEFORE SPRAY
AFTER SPRAY
109 μ
PERCENTAGE NUMBER
PARTICLE DIAMETER (MICRON)

FIG No27

EFFECT OF DURATION OF SPRAYING ON SIZE DISTRIBUTION OF COAL DUST.

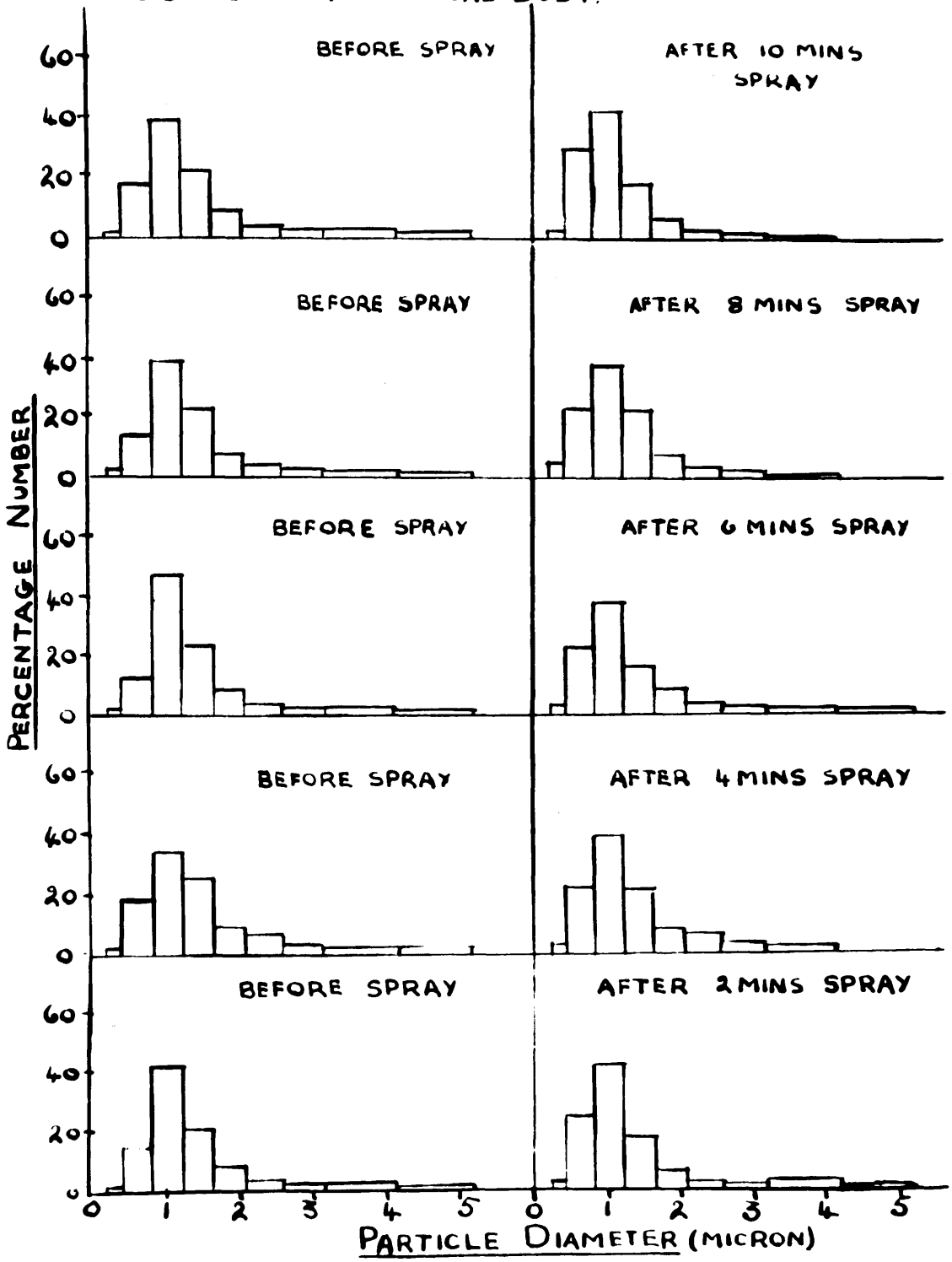


TABLE 29.

A.D.S. of Spray (Microns)	109		90.2		85		78.3		65.7	
Particle Size (Microns)	Before Spray	After Spray	Before Spray	After Spray	Before Spray	After Spray	Before Spray	After Spray	Before Spray	After Spray
< 0.83	4,110	2,120	3,340	2,340	2,570	1,640	2,780	1,980	2,340	1,370
0.83-1.25	5,040	2,380	5,640	3,700	5,790	2,390	6,590	2,480	7,730	1,900
> 1.25	7,150	2,770	7,270	3,540	4,580	2,230	6,400	2,180	6,390	1,600
TOTAL	16,300	7,270	16,250	9,580	12,940	6,260	15,770	6,640	16,460	4,870

TABLE 30.

Percentage of total dust removed.

Spray Size (Microns)	109	90.2	85	78.3	65.7
Particle Size (Microns)					
< 0.83	22%	15%	13.9%	8.8%	8.4%
0.83-1.25	29.4%	29.1%	50.9%	45.1%	50.4%
> 1.25	48.6%	55.9%	35.2%	46.1%	41.2%

TABLE 31.

Time of Spraying	2 Mins.		4 Mins.		6 Mins.		8 Mins.		10 Mins.	
Particle Size. (Microns)	Before Spray	After Spray	Before Spray	After Spray	Before Spray	After Spray	Before Spray	After Spray	Before Spray	After Spray
< 0.83	2,860	2,520	3,340	2,340	4,150	1,990	2,000	610	2,620	910
0.83-1.25	7,270	3,860	5,640	3,700	13,320	3,100	5,480	950	5,680	1,220
> 1.25	7,070	2,940	7,270	3,540	10,930	3,120	4,990	710	6,100	770
TOTAL	17,200	9,320	15,770	6,640	28,400	8,210	12,470	2,270	14,400	2,900

TABLE 32.

Percentage of dust removed.

Time of Spraying (mins.)	2	4	6	8	10
Particle Size. (Microns)					
< 0.83	4.3%	15.0%	10.7%	13.6%	14.9%
0.83-1.25	43.3%	21.9%	50.5%	44.4%	38.8%
> 1.25	52.4%	55.9%	38.8%	42.0%	46.3%

/However, from Table 32 it can be seen that in general there is

(i) A small increase in the percentage number of particles less than 0.83 micron.

(ii) A small decrease in the percentage number of particles greater than 0.83-1.25 micron.

particles. After three hours the dust [illegible] sedimented more slowly, but with a certain amount of aggregation still taking place. Full sedimentation will about the tenth hour when the finest sediments very slowly and only the smallest particles remain.

Photo-electric cells were used in the determination of the concentration of the dust but for the particle size analysis samples were taken using the Thermal Precipitator.

A compressed-air water spray [illegible] with variable air and water outlet sizes. The sprays were calibrated and adjusted to give reproducible droplet size distributions. The average droplet size was shown to depend on the method of [illegible] independent of [illegible] air orifice, but [illegible] increased. [illegible] the/

Discussion of Results and Conclusions.

In this work an apparatus is described in which a dust cloud can be generated and remain in suspension under reproducible conditions.

From the results of sedimentation studies on various dusts it was found that particle concentration in the apparatus decreased rapidly over the first two or three hours. This was found to be due to aggregation of the particles into groups whose sizes were comparable to that of large particles. After three hours the dust cloud sedimented more slowly, but with a certain amount of aggregation still taking place. This continued till about the tenth hour when the cloud sedimented very slowly and only the smallest particles remained.

Photo-electric cells were used in the determination of the concentration of the dust cloud, but for the particle size analysis samples were taken using the Thermal Precipitator.

A compressed-air water spray was developed with variable air and water outlet sizes. The sprays were calibrated and adjusted to give reproducible droplet size distributions. The average droplet size was shown to depend on the method of calculation. Degree of atomisation was shown to be independent of changes in dimension of the water and air outlets, but increased as the air velocity increased. The relationship between the ratio of

the/

/the air flow rate to the water flow rate and the average droplet size, was found to be an exponential one and agreed with results obtained by other workers (27). An increase in the relative velocity of air and water was also found to decrease the average droplet size. The average droplet size of the spray increased slightly as the sampling distance from the nozzle was increased. This may have been due to mutual collision of droplets with the formation of larger droplets.

The cone angle of the spray was found to be affected by changes in the dimensions of the air and water outlets.

The distribution of the droplets in the spray was found to follow the relationship

$$dn/dx = ax^2 \exp(-bx^{2/3})$$

where dn/dx is simply the number of droplets of diameter x, and a and b are test constant.

The average droplet diameters calculated from the formula

$$Do = \frac{585\sqrt{\sigma}}{V\sqrt{\rho}} + 597\left(\frac{\mu}{\sqrt{\sigma\rho}}\right)^{0.45}\left(1000\,\frac{Qw}{Qa}\right)^{1.5}$$

compared favourably with the experimental results wh which were obtained using (A.D.S.) $\frac{\Sigma x^3 dn}{\Sigma x^2 dn}$ (better known as the Sauter Mean Diameter (S.M.D)).

It was appreciated that studies of the action/

/action of the compressed-air spray on suspended dust in a comparatively small dust chamber would be complicated by the diluting effect of the compressed-air entering the apparatus with the water droplets. The two extreme cases were studied for the effect of air blasts on the sedimentation of ground coal and ground fly ash dust clouds. The dust removed was found to be in general, greater than that predicted. It was thought that this might be due to high initial dust concentration leading to aggregation. The effect of the spray on the concentration of ground coal and ground fly ash dust clouds was studied. The proportion of airborne dust removed increased when the degree of atomisation, the droplet velocity and the duration of spraying or the amount of water sprayed were increased.

It was found that a large percentage of the dust was removed by the air used for atomisation. In a coal mine this dust would not necessarily be "laid", but the air from the spray would cause an increase in the ventilation. The compressed-air spray would thus have a secondary beneficial effect by causing a dilution of the remaining dusty atmosphere at the working face.

The size distribution of the particles in the dust cloud was not significantly affected by the air blasts, the change in the distribution being due to the spray droplets. The efficiency of removal of/

/of the larger dust particles ($>0.83\mu$) increased as the droplet diameter was decreased. On the other hand, the efficiency of removal of the $<0.83\ \mu$ particles was decreased. An increase in the duration of spraying increased the removal of the $>0.83\mu$ particles, but decreased the removal of the $<0.83\mu$ particles.

APPENDIX.

An Instrument for Sampling Airborne Mine Dusts.

Introduction.

Although much work has been done on the theoretical aspects of pneumoconiosis using silica and other dusts, very little has been reported on the physico-chemical properties of airborne dusts generated under working conditions. This is largely due to the fact that apparatus is not available to collect large amounts of mine dust from suspension. It was therefore decided to design such a sampling apparatus which would collect about 5 gm. of airborne dust. This weight was the minimum required to carry out the various analyses.

A survey of the existing literature on sampling showed that most sampling instruments had been designed to obtain small samples employed to assess dust concentrations. Most of the instruments providing a reasonable weight of sample employed the "gravimetric" method of sampling. By this method the dust laden air is drawn through a filtering medium on which the dust is deposited.

Apparatus.

The first sampler made was similar to the one described by the Monmouthshire and South Wales Coal Owners Association (63).

This/

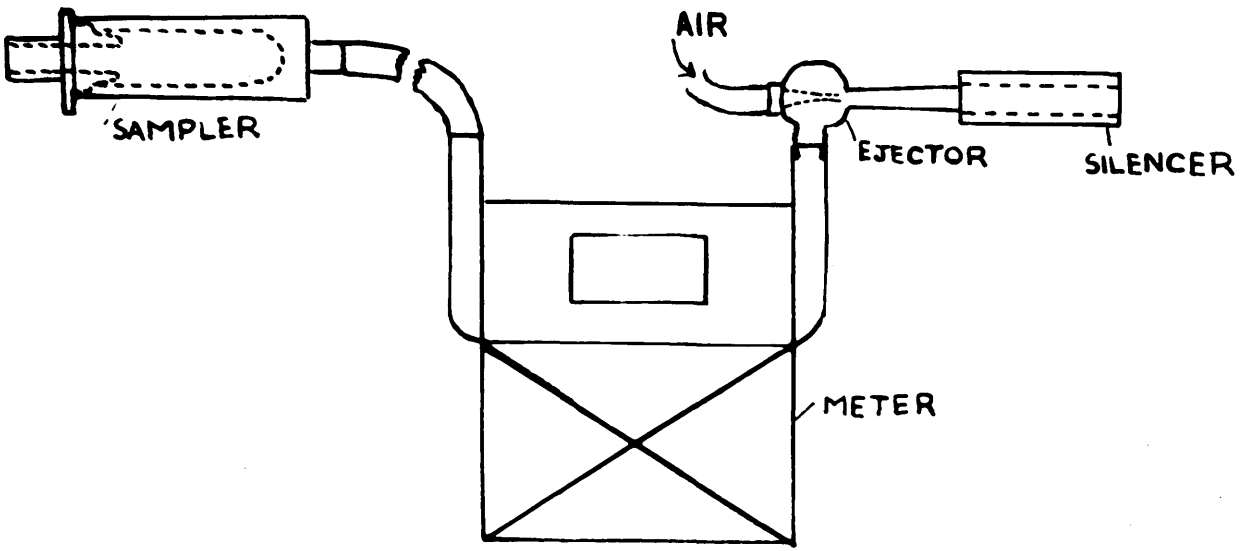
/This instrument which is seen in Fig. 28 consisted of a brass plug to which was attached a soxhlet thimble which screwed inside a brass sheath. It was connected to the inlet limb of a gas meter by rubber tubing while an ejector was screwed to the exit limb. The ejector was fitted with a felt lined silencer. Compressed air supplied to the ejector caused a suction through the system, the dust laden air passing through the soxhlet thimble where the dust was deposited. The amount of air sampled was recorded on the meter.

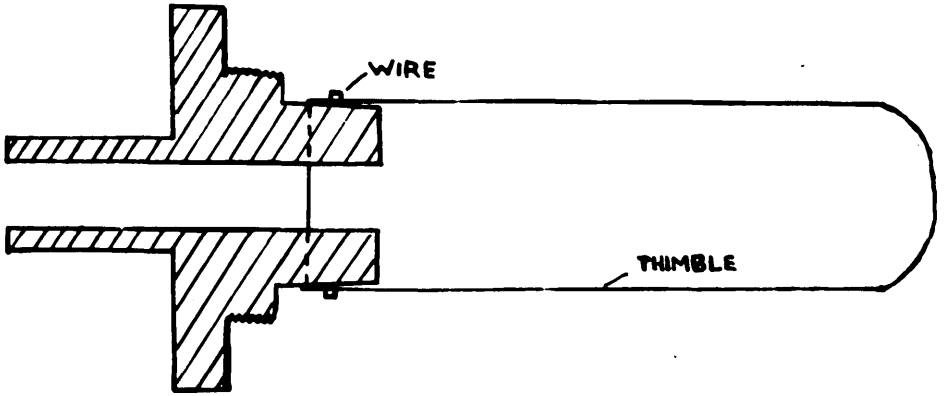
A trial carried out underground using this instrument gave very unsatisfactory results. Sampling over a period of six hours in a dusty atmosphere containing 290 p.p.c.c. yielded only 50 mg. of dust.

Further trials were carried out with this sampler using the dust chamber previously described in Section 1. For this work the dust chamber was modified. The photo-electric cell systems were removed and the openings blanked off. The fan was removed and the hole for the fan shaft enlarged to enable the dust injector to fit into the chamber. A hole was cut at the side of the chamber as an entrance for the sampler. Since a fairly constant dust cloud was required, the dust cloud generator described previously could not be used. The generator used is shown in Fig. 29. This consisted of a glass dust container floating in water contained in a straight walled gas jar and which was kept vertical by brass spacers/

DUST SAMPLER I

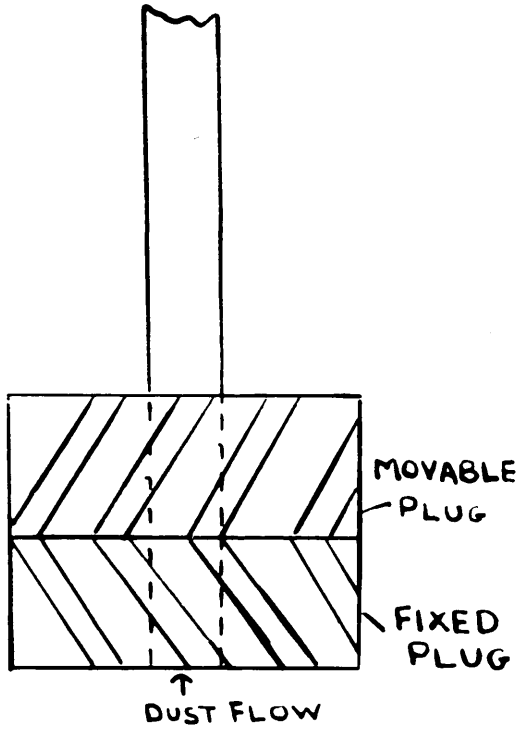
FIG No 28



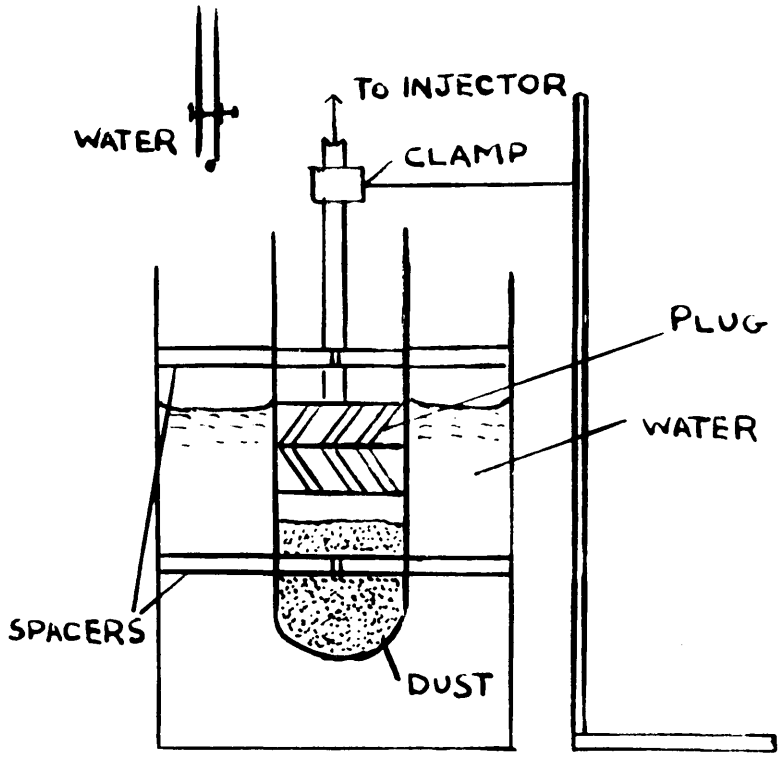


DUST CLOUD APPARATUS

FIG No 29



PLUG



/spacers at the top and bottom. A brass plug fitted inside the dust container and was clamped in such a position that the container floated freely. The plug consisted of a copper tube with a thick brass disc brazed to it and a similar loose fitting disc slipped on top. These two discs carried a set of helical grooves, the grooves of the upper one running in the opposite direction to those of the lower. This imparted a swirling motion to the dust before it was sucked up the tube. Rubber tubing connected the top of the copper tube to an injector which passed through a hole in the top of the chamber. Compressed-air applied to the injector caused a suction which lifted the dust and sprayed it inside the chamber. (The upthrust of the water on the floating dust container kept the dust in close proximity to the underside of the lower brass disc.)

Experimental.

The dust container was filled with the dust which had been ground in a mechanical mortar and dried. The plug was then clamped in position about three quarters of an inch above the surface of the dust.

The dust sampler was set in position with the mouth projecting $7\frac{1}{2}$ inches inside the chamber. A clean dry soxhlet thimble was wired on and the thimble holder screwed into position. The compressed/

/compressed-air to the chamber, injector and sampler was turned on and adjusted. Water was added to the outer vessel of the dust generator at such a rate that the level of the dust remained at a constant distance below the plug.

Samples of the dust cloud were taken at regular intervals using the thermal precipitator and the slides evaluated as before.

The Effect of the Size of Mouthpiece of the Sampler.

Different mouthpieces were constructed which could be attached to the sampler.

The apparatus was fitted up and the procedure carried out as described above. Dust samples were taken every hour and evaluated. After eight hours the sampling was stopped and the soxhlet thimble removed. After drying the thimble the dust was removed and weighed.

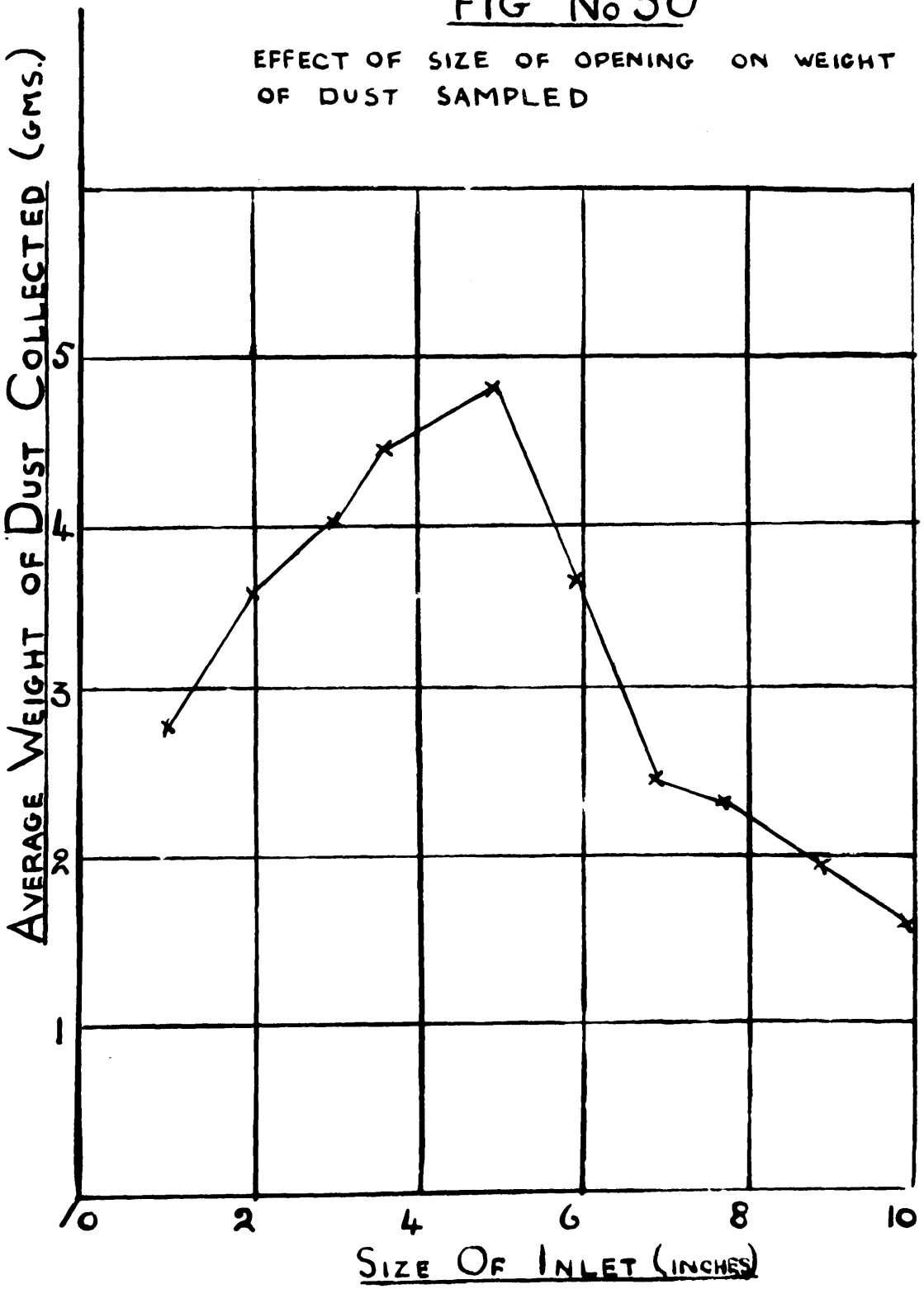
This procedure was repeated using the different sizes of mouthpiece each projecting $7\frac{1}{2}$ inches inside the chamber. The results obtained are shown in Fig. 30.

Results.

From Fig. 30 it is seen that the weight of dust sampled rose through a maximum and then decreased as the size of mouthpiece was increased. The compressed-air used in this series of experiments was supplied at 30 lbs./in.^{2} whereas that obtained in a coal/

FIG No 30

EFFECT OF SIZE OF OPENING ON WEIGHT OF DUST SAMPLED



/coal mine is about 60 lbs./in.^{2}. From the above results it was calculated that for air supplied at 60 lbs./in.^{2} the mouthpiece giving the maximum weight of dust sample would have a diameter of 10 inches.

Modifications to Sampler.

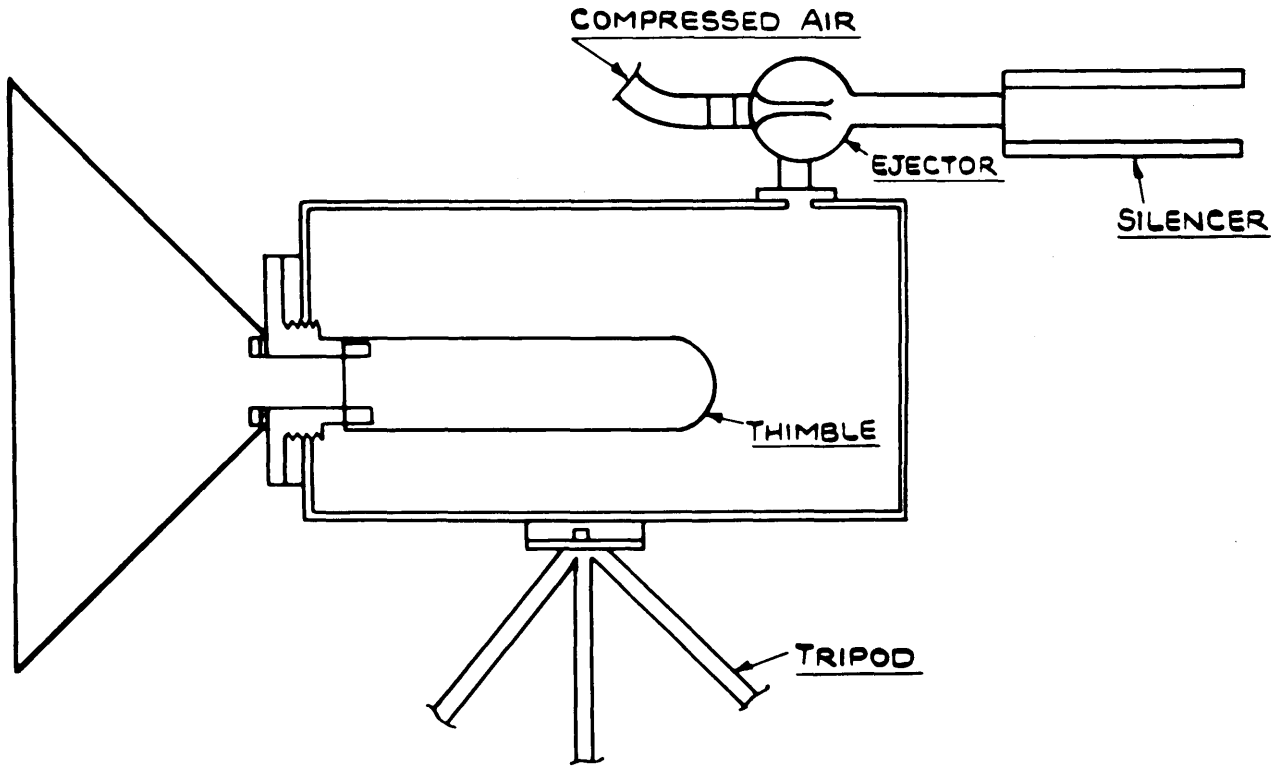
A second sampler was designed and constructed with a mouthpiece 10 inches in diameter. This apparatus (Fig. 31) consisted of an airtight box made of thin brass sheeting. This had a screwed hole at the top for holding the ejector. At the bottom a brass attachment for screwing the sampler to an adjustable tripod for use in the coal mines was brazed in place. A soxhlet thimble was used which slipped over a plug with a slight taper and was wired securely. The plug, with thimble, was then screwed into the brass box. A Kodaflector (64) was finally attached to the apparatus by means of a screwed nut. This gave a sampler mouthpiece of 10 inches in diameter.

Results.

Trials in the dust chamber and underground, with this apparatus proved to be successful. As a result of these trials, the Scottish division of the National Coal Board have had seven samplers made after slight modifications to the design. These have been used in different coal mines and satisfactory samples obtained. Some of the results obtained are/

H-J DUST SAMPLER.

FIG No. 31.



/are given in Tables 33 and 34.

TABLE 33.

Samples of coal dust obtained on sampling continuously throughout the three shifts.

Weight of dust obtained (gms.)	Time of Sampling (days)
2.0	5
13.2	6
3.6	7
16.0	5
5.5	5
2.0	5

TABLE 34.

Samples of coal dust obtained by sampling only throughout one shift.

Shift.	Average dust concentration. p.p.c.c.		Weight of sample obtained (gm)
	0.5-5(μ)	1-5(μ)	
Cutting shift.	981 333	286 164	2.2 1.2
Stripping shift.	585 824	244 381	5.5 2.5
Brushing shift.	1225 512	568 272	11.7 2.5

/Shortly after our "H-J" sampler (H-J stands for the names Hunter and Jaap, Mr. Hunter being a colleague who worked in the department,) had been manufactured, details of a sampler designed by Wright (65) and called the "Hexhlet" came to hand. This apparatus manufactured by Casella was compared with our own model.

A comparison of the H-J apparatus with the Hexhlet.

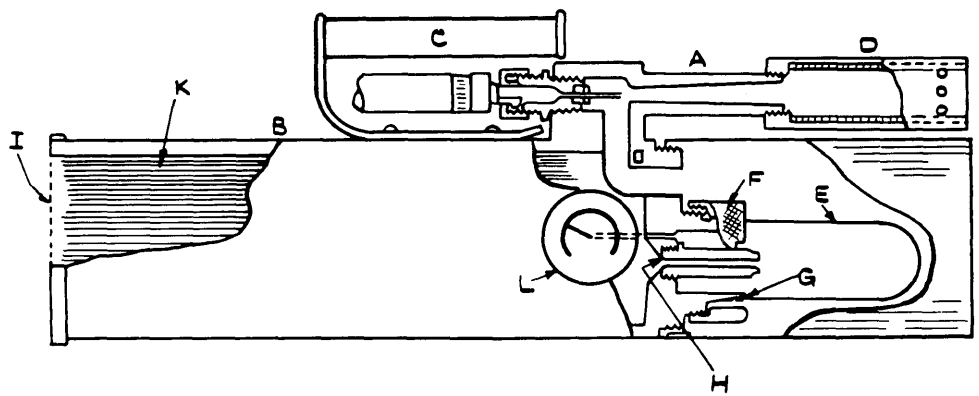
A drawing of the Hexhlet is given in Fig. 32. It is made up of four components; the horizontal elutriator (B), a critical orifice to control the air flow (H), a soxhlet thimble for collecting the dust (E) and a compressed-air ejector for providing the suction (A). The elutriator consists of a rectangular box made of aluminium alloy in which are stacked two banks of 58 aluminium plates (K). The compressed-air ejector is also fitted with a felt lined silencer (P). The instrument is fitted with a vacuum gauge (L) which is connected to the inside of the soxhlet thimble and this enables the flow through the instrument to be checked at any time while in operation.

Experimental.

The "Hexhlet" apparatus with a clean thimble attached was set in position with the mouth of its elutriator projecting 7½ inches inside the chamber, the dust cloud was blown in and sampling started./

FIG. No. 32.

HEXHLET SAMPLER



A - AIR EJECTOR.
B - RECTANGULAR ELUTRIATOR BOX. (ALUMINIUM ALLOY)
C - HANDLE.
D - FELT LINED SILENCER.
E - SOXHLET THIMBLE.
F - KNURLED SCREW RING.
G - CONICAL NOZZLE.
H - CRITICAL ORIFICE.
I - STEEL WIRE
K - ALUMINIUM PLATES.
L - VACUUM GAUGE.

/started. Sampling was continued for 8 hours, during which period thermal precipitator samples were taken at hourly intervals. After 8 hours, sampling was stopped, the thimble removed, dried and the recoverable dust weighed. This was repeated for the H-J apparatus with ground dried silica dust and then ground, dried coal dust. In the case of the Hexhlet, the elutriator was dismantled and the dust removed, dried and weighed.

Samples of the dusts obtained were re-dispersed in a cylindrical glass tube (Fig. 33) and sampled with the thermal precipitator. The cover glasses were mounted on slides and then examined.

Results.

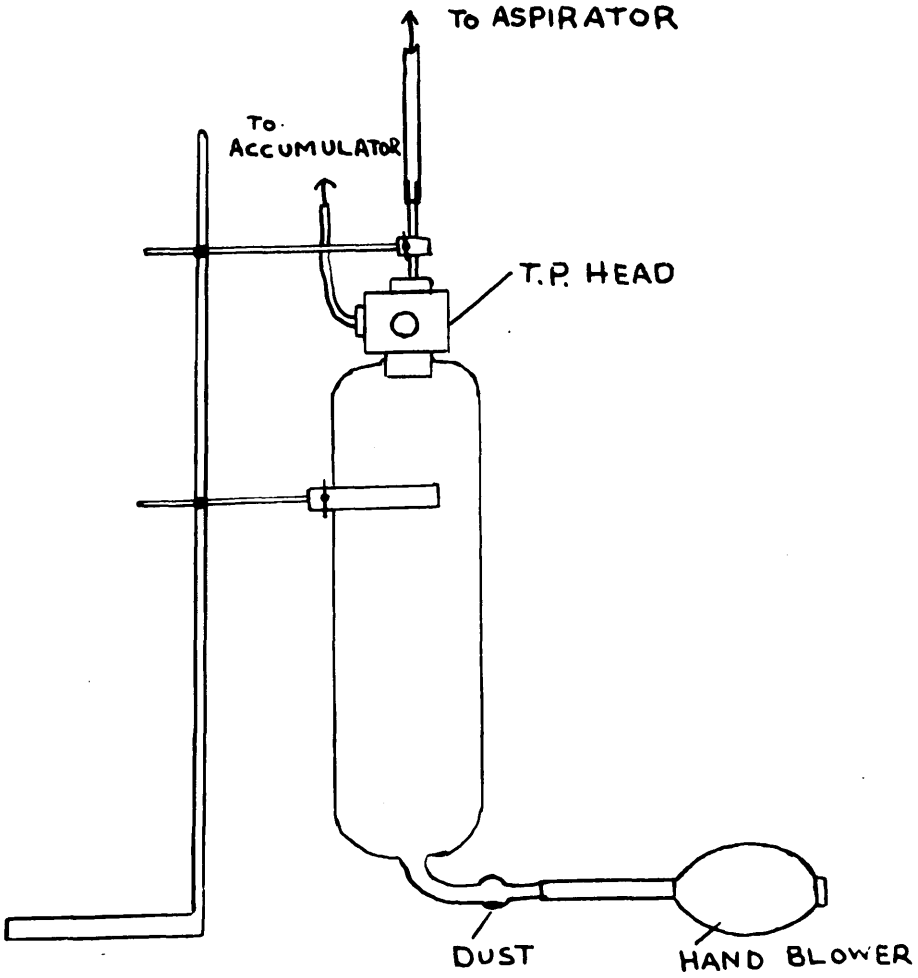
The weights of dusts obtained for 8 hour runs in a dust cloud of approximately 2,000 p.p.c.c. are shown below in Table 35.

TABLE 35.

		Silica dust (gm)	Coal dust (gm)
Hexhlet.	Thimble.	0.2652	1.3175
	Elutriator.	2.2313	1.3965
	Total.	2.4965	2.7140
H-J Apparatus.	Thimble.	2.4689	3.3756

FIG No33

DUST DISPERSION APPARATUS



/From the table it can be seen that the weight of dust obtained from the thimble of the H-J apparatus is much larger than that obtained from the thimble of the Hexhlet. Taking into consideration the weight of dust in the elutriator, however, the total weight of dust sampled shows very little difference.

The particle size distributions are given in the histograms in Figs. 34, 35, 36 and 37. The results shown for the dust clouds are the average of both runs. The particle size analysis of the Hexhlet sample is taken from the thimble only. An examination of the histograms (Fig. 34) shows that with silica dust the percentage number of fine particles ($< 2.0\mu$) collected in the samplers is not as large as the percentage number in the dust cloud. The figures are:-

Cloud.	Percentage $< 2.0\ \mu$	=	90.3
H-J.	Percentage $< 2.0\ \mu$	=	61.4
Hexhlet.	Percentage $< 2.0\ \mu$	=	78.6

The dust collected in the thimble of the Hexhlet contains a greater proportion of fine particles than the dust from the H-J apparatus. Fig. 35 shows that the percentage number of fine particles in the elutriator is slightly greater than the percentage in the thimble (percentage $< 2.0\ \mu$ in thimble = 78.6, percentage $< 2.0\ \mu$ in the elutriator = 84.7).

With/

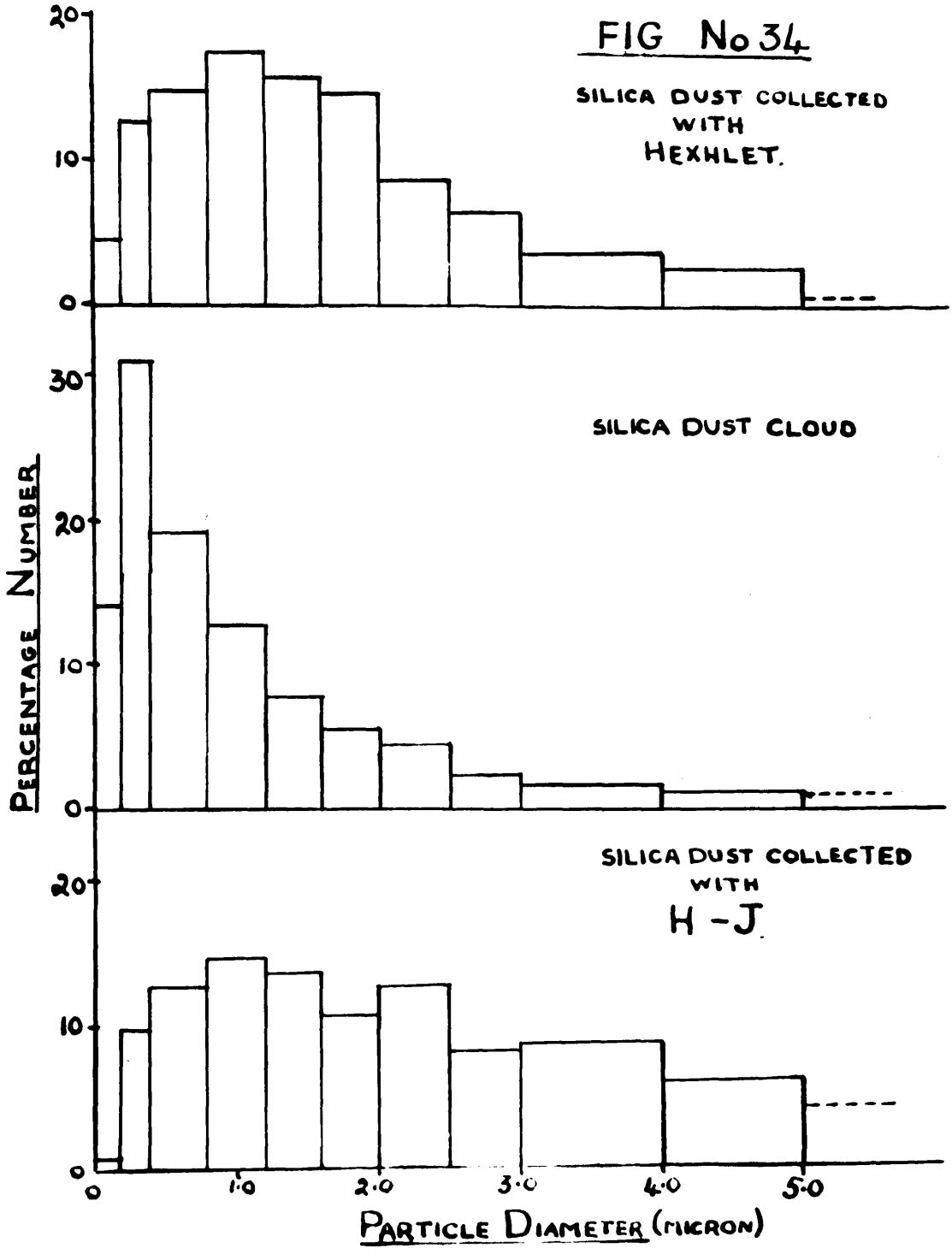


FIG No 34
SILICA DUST COLLECTED WITH HEXHLET.
SILICA DUST CLOUD
SILICA DUST COLLECTED WITH H-J.
PERCENTAGE NUMBER
PARTICLE DIAMETER (MICRON)
0
10
20
30
1·0
2·0
3·0
4·0
5·0

FIG No 35

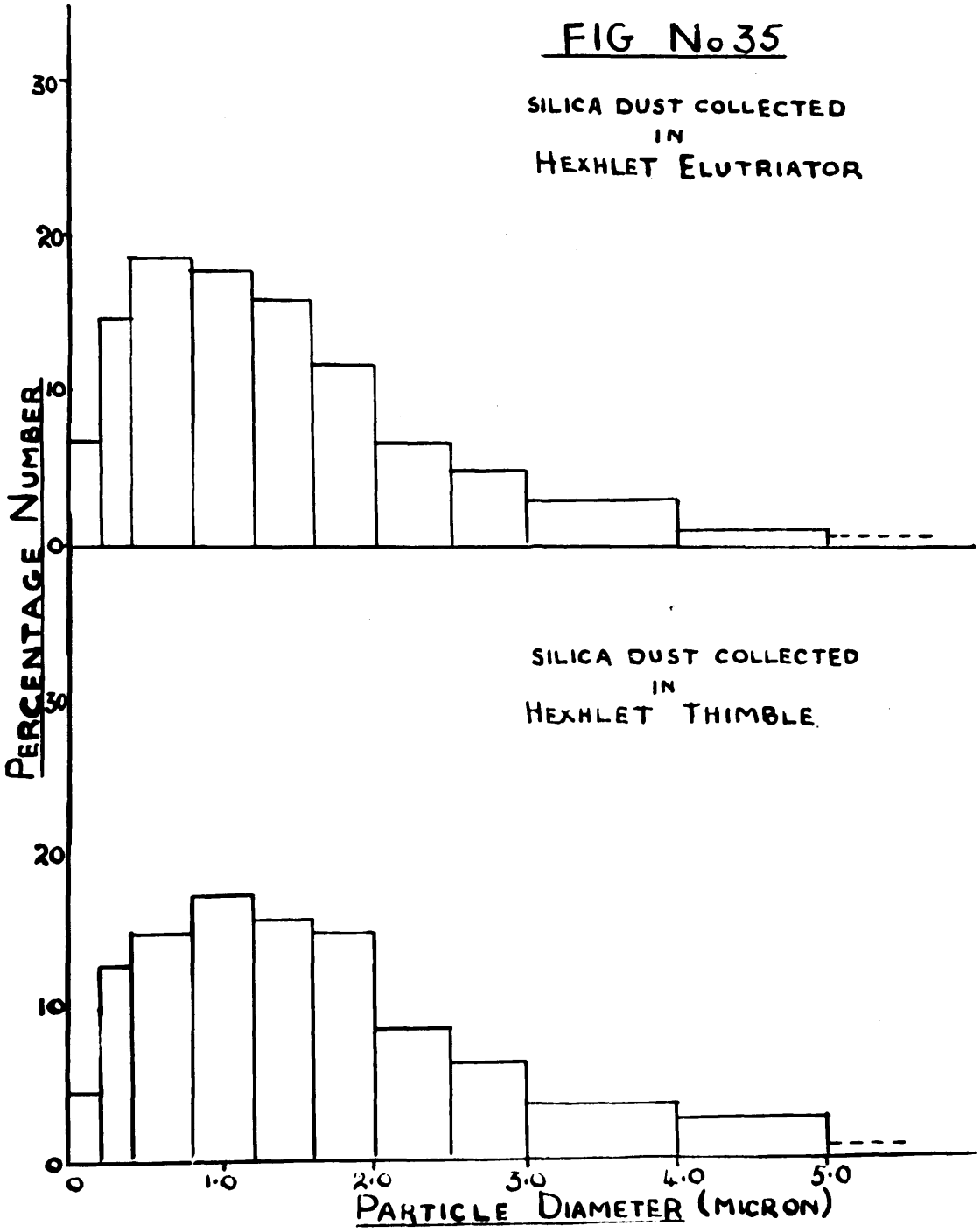

SILICA DUST COLLECTED
IN
HEXHLET ELUTRIATOR
SILICA DUST COLLECTED
IN
HEXHLET THIMBLE
PERCENTAGE NUMBER
30
20
10
0
30
20
10
0
0
1·0
2·0
3·0
4·0
5·0
PARTICLE DIAMETER (MICRON)

FIG No 36

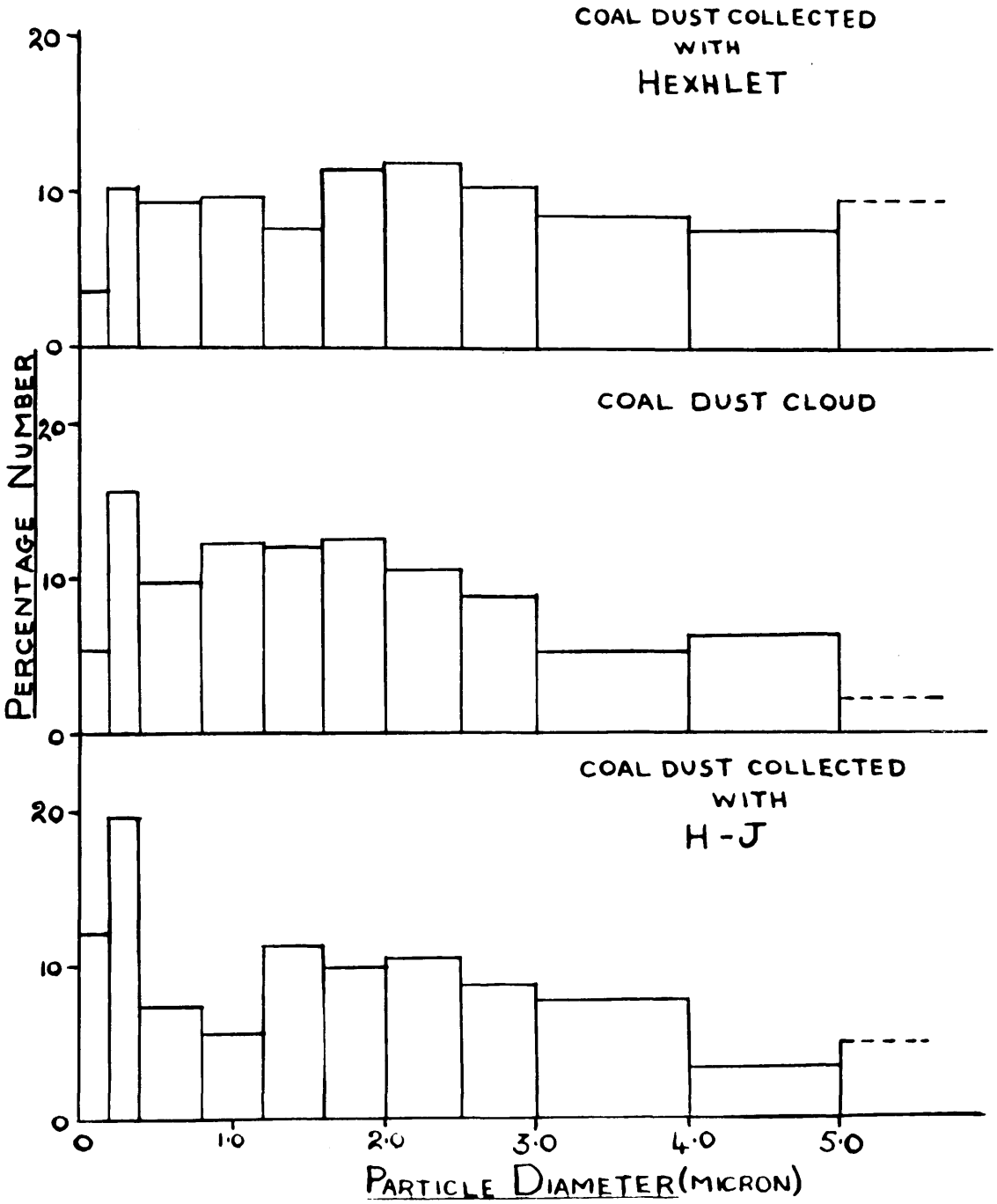
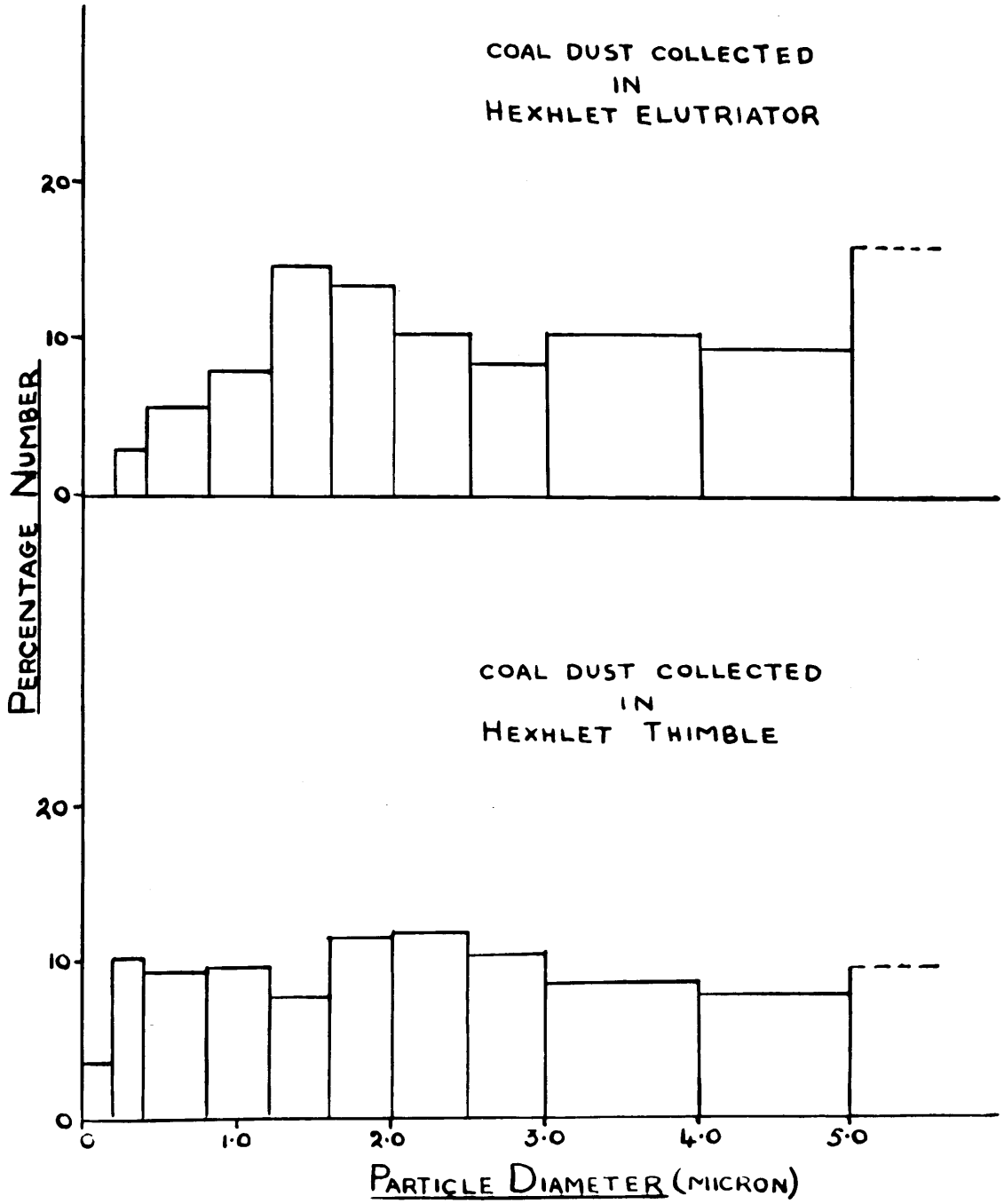

COAL DUST COLLECTED
WITH
HEXHLET
COAL DUST CLOUD
COAL DUST COLLECTED
WITH
H-J
PERCENTAGE NUMBER
20
10
0
1·0
2·0
3·0
4·0
5·0
PARTICLE DIAMETER (MICRON)

FIG No37


COAL DUST COLLECTED
IN
HEXHLET ELUTRIATOR
20
10
0
PERCENTAGE NUMBER
COAL DUST COLLECTED
IN
HEXHLET THIMBLE
20
10
0
0
1·0
2·0
3·0
4·0
5·0
PARTICLE DIAMETER (MICRON)

/With coal dust, however, both samplers give fairly good representative samples of the dust cloud. In this case the figures are:-

Cloud.	Percentage $< 2.0\ \mu$	=	67.2
H-J.	Percentage $< 2.0\ \mu$	=	65.8
Hexhlet.	Percentage $< 2.0\ \mu$	=	51.7

Here the percentage number of the larger sized particles ($> 2.0\ \mu$) is not as high in the H-J apparatus as in the Hexhlet. Fig. 37 shows that the elutriation effect is greater with coal dust than with silica dust. This is apparent from the large number of particles $> 3.0\ \mu$ and the smaller number of particles $< 1.0\ \mu$ in the dust from the elutriator.

Discussion of Results and Conclusions.

A sampler (the H-J sampler) was designed and constructed for the purpose of obtaining a fairly large representative sample of airborne mine dusts. Results of sampling runs carried out under working conditions were satisfactory.

From a comparison carried out with the H-J and Hexhlet samplers, it was found that both gave reasonably accurate samples of coal dust but not of silica dust.

The elutriator of the Hexhlet worked more efficiently with coal dust than with silica dust. This was perhaps due to the lower density of the coal dust.

It was found that the larger sample obtained with the H-J apparatus outweighed the use of the elutriator on the Hexhlet which retained a large number of the fine particles as well as of the larger ones.

Suggestions for further work.

Sedimentation studies should be carried out using a good make of photo-electron multiplier. This would replace the photo electric cells for measuring dust concentration. With these more sensitive instruments, which are now readily available, the "light scattering" method should be further developed. By this method the light reflected from the particles is used as a measure of the concentration.

The compressed-air spray should be studied with a greater number of needle and nozzle sizes and also greater air and water velocities. The effect of surface tension on atomisation should be investigated using dispersing agents and inorganic salt solutions.

The suppression of the dusts with the compressed-air spray should be investigated in an experimental tunnel with a moving dust cloud.

Dust suppression studies should be carried out in actual mining conditions with the compressed-air spray using water and solutions of different surface tensions.

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