THE COLLEGE OF AERONAUTICS, CRANFIELD

Department of Propulsion

AN EXPERIMENTAL STUDY OF AN AIRBLAST ATOMISER

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1.0 SUMMARY

Visual observations and an optical method of measuring the mean droplet size in sprays have been used to assess the performance of a prototype airblast atomiser, particularly at the low fuel and air flow conditions corresponding to engine cranking.

The results obtained from this and a shroud version of the same basic atomiser have enabled design modifications to be made which have resulted in a marked improvement in performance, both in terms of the spraying characteristics of the atomiser at low fuel and air flows, and in terms of the measured droplet size produced. The latter for the final design was very close to that predicted by Wiggs for airblast atomisers operating at the test conditions employed.

An apparatus has also been designed to enable tests on the atomisation quality of airblast atomisers to be carried out at pressures up to 250 p.s.i., using the same optical technique to make mean droplet size measurements.

List of Symbols used in the Body of the Thesis.

C_D	-	discharge coefficient
ΔP	-	Air pressure drop
ΔP_{atom}	-	ΔP at which atomisation commences
S.m.d.	-	Sauter Mean Diameter
V_{calc}	-	Air velocity from ΔP by compressible flow curves.

INTRODUCTION

Analysis of the combustion systems of modern aircraft gas turbine engines, when considered with the experimental work done by Nukiyama and Tanasawa (Ref.1) and others (Refs. 2.3.4) on the atomisation performance of the airblast type of liquid atomiser, in which a high velocity airstream is used to shatter the fuel into droplets, has indicated that the air velocities which could be generated by the pressure differences across combustion chamber flame tube walls would be sufficient to give more than adequate fuel atomisation quality at all engine operating conditions.

Fuel injection systems using airblast atomisers have important advantages when compared with the established pressure atomiser and vaporiser systems and they are becoming increasingly attractive with the trend towards higher and higher combustion chamber pressures and temperatures:-

1. They offer much greater freedom in the design of the spray to match the combustion chamber since the spray is airborne and its shape and direction could be changed by relatively simple modifications to the atomisers. It should thus be easier to counteract such undesirable effects associated with high pressures and temperatures as the excessive emission of exhaust smoke and poor combustion chamber exit temperature traverse quality

2. Spray distribution, being controlled by the combustion chamber airflow, would be relatively unaffected by changes in the engine's operating conditions.

3. Atomisation quality would be relatively uniform over the operating range since atomising air velocity and, therefore, fuel droplet size, would change very much less than the pressure applied to a pressure jet atomiser. In particular, atomisation quality would be better instead of worse as fuel air ratio was reduced, and this would help to widen the weak extinction limits.

4. Since the atomising process would no longer depend on fuel pressure, the system pressures need be no higher than would be required for fuel metering and the production of air evenly distributed fuel film at the atomising lip. Larger system flow numbers could be used and the fuel filtration problem eased.

5. Airblast burners would be simpler and much cheaper to make than pressure atomisers, and more robust than vaporisers. They would not suffer problems of pressure atomisers such as swirl chamber erosion and special heat-resistant material requirements.

6. Finally, they should be free of the carbonising problem associated with pressure atomisers and should, therefore, be less prone to deterioration in performance during service life.

There are, however, two important disadvantages associated with the airblast system:-

1) A high degree of fuel/air mixing is achieved, so that the proportion of combustion chamber primary air which can be used for atomisation must be limited to ensure local fuel air ratios rich enough to give adequate weak extinction limits.

2) Atomiser air velocities achieved during engine cranking are relatively low and while analysis indicates that they should be adequate, early evidence suggests that some means of improving engine starting performance such as auxiliary simplex atomisers may be necessary unless improvements can be made to the performance of present airblast burners at these conditions.

This thesis describes a programme of research and development work carried out at atmospheric conditions on a prototype airblast atomiser in an attempt to improve its atomisation performance, particularly at conditions corresponding to engine cranking, and to establish some design principles for future use.

An important aspect of the work has been the development and use of an optical technique due to Dobbins, Crocco and Glassman, by which

the scattering effect on a beam of light of the droplets in a spray is used to measure mean droplet size.

A rig has been designed and built (Appendix 5) for use with this optical system to enable the atomisation quality produced by airblast atomisers to be studied at simulated combustion chamber pressures up to 250 p.s.i.g. Analysis suggests that as pressure increases mean droplet size should decrease due to the higher density and hence larger disrupting force of the atomizing air.

It is important to attempt to confirm these predictions, and to examine the influence of pressure changes on the distribution of the spray as background work for future high pressure combustion tests.

REVIEW

The potential advantages of the airblast method of fuel atomisation in aircraft gas turbine engines have been appreciated for many years and a number of systems have been tried.

In 1947, for example, a Nene engine was fitted with a Duplex burner in which fuel was supplied to the main jet only and atomisation was assisted by supplying compressed air to the pilot jet (Fig.1). Promising results were obtained, especially at idling conditions at altitude, and development of this system in parallel with that of the pressure jet atomisers was proposed (Ref. 5). Later tests at the Shell Thornton Research Centre on the spray quality of this Nene burner confirmed the marked advantage to be gained by using high pressure air to assist in the atomisation process (Ref. 6).

Analysis suggested, however, that at practically all engine operating conditions the comparatively small pressure differences across combustion chamber flame tube walls should be sufficient to produce air velocities adequate for fuel atomisation (Ref. 7 and Appendix 1), and several "natural" airblast (airspray) burners working on this principle have been tested with encouraging results.

For example, in 1954 a Rolls-Royce Avon was fitted with a full set of airspray burners (Fig.2) which proved entirely adequate for all engine operating conditions except initial light-up where the engine

had to be cranked to comparatively high speeds to produce the required quality of atomisation. The altitude relighting performance of the burner proved particularly good, and demonstrated that at extreme engine conditions there were useful gains to be made by adopting the airspray system.

At about the same time an airspray burner was proposed for the Dart engine (Fig.3) in an attempt to cure weak stability difficulties, and although this burner was never installed in an engine, extensive rig performance results were obtained. Tests at the Thornton Research Centre showed it to be capable of producing a spray quality noticeably better than that of an equivalent simplex burner (Ref.3), and combustion tests indicated that combustion efficiency, weak extinction and ignition performance were all adequate and comparable with the performance given by duple and simplex burners over most of the operating range. Only at weak conditions was combustion efficiency inferior to that of the duple burner (Ref.8). More recent tests with this atomiser show that it is capable of giving combustion stability loops appreciably wider than those given by a simplex atomiser operating in the same chamber (Ref. 9). (Fig.4.)

When a fuel injection system was required for the small highly loaded combustion chamber of the Rolls-Royce RB 93, comprehensive tests at N.G.T.E. on Avon type air sprays, Figure 2, and the two alternative systems considered showed air sprays to be best suited to the application (Ref. 10), and subsequent engine experience showed them to give a performance superior to that given by simplex burners over the whole operating range, including crank lighting. Cranking speeds were still unacceptably high, however, and a compromise duple/ airspray design was eventually adopted to reduce them and ensure consistent lights (Fig. 5).

Despite their poor cranking performance, sufficient encouraging experience has now been gained with airspray burners for their use to be specified at the outset of an engine design, especially as the deficiencies of the established pressure jet and vaporiser systems in terms of excessive smoke emission, poor temperature traverse quality and mechanical frailty are becoming more apparent at the very high pressures and temperatures at which modern engines operate. As a result considerable research and development effort is currently being expended in establishing design principles and overcoming their known deficiencies.

Several research airspray atomisers have been designed and tested at the College of Aeronautics to enable combustion and droplet formation studies to be made.

In 1962, for example, Bennet experimented with a disc atomiser of the form shown in Fig. 6 in an attempt to establish the influence of the atomising lip design on droplet size (Ref. 11). Liquid was swirled on to the face of the disc and flowed over its edge as a thin film which was shattered into droplets by high velocity air passing through the annular space between the disc and the duct wall. He found great difficulty in producing an evenly distributed liquid film, and shadowgraphs show correspondingly poor spray distribution. Duct wetting would also be a problem and for these reasons the design is not a practicable basis for the gas turbine application at present.

In 1965 Miller tested several airsprays (Fig. 7) with a view to assessing their atomisation performance and effectiveness in controlling combustion chamber smoke emission (Ref. 4). The chamber pressures available were too low for the production of smoke, but atomisation quality was close to that predicted by the Nukiyama/Tanasawa formulae. Duct and air-swirler wetting was again a problem, however.

Both Bennett and Miller used the magnesium oxide slide droplet sampling technique to evaluate atomisation quality. While this gives complete information about the spray it is laborious to apply and the results obtained are open to question owing to the distance downstream of the source of the spray at which the samples must be taken. Nor can the method be used at the high pressures at which airsprays will be tested in the combustion chamber simulation rig described in Appendix 5.

To enable droplet size data to be obtained more conveniently, particularly at these high pressure conditions, Hodgkinson, in 1966, designed an optical apparatus by which the scattering effect on a beam of light of the droplets in a spray is used to measure the Sauter Mean Diameter of the droplets. (Ref. 12). Although the information obtained by this method is limited to S.M.D. the technique enables measurements to be made at any section of the spray without the mechanical interference involved in sampling.

Hodgkinson's apparatus has been used by the present author to assess the atomisation performance at atmospheric conditions of the atomisers described in this thesis. It will be used at a later date with the high pressure rig to measure droplet sizes at air pressures up to 250 p.s.i.

5.0 EXPERIMENTAL APPARATUS AND ATOMISERS

The object of the experiments was to assess the characteristics of a series of airblast atomisers at the low fuel and air flow conditions corresponding to engine cranking, and to determine their atomisation performance in terms of the mean droplet size produced over a range of operating conditions.

The test equipment and atomisers used are shown diagrammatically in Figures 8 to 15, and illustrated in Plates 1 to 6. They are described under three headings:

1. The atomiser housing and its air and water (or kerosine) supply systems.
2. The optical apparatus for measuring droplet size
3. The atomisers

In addition a test rig designed to enable droplet size measurements to be made at air pressures up to 250 p.s.i. is described in Appendix 5.

5.1 The Atomiser Housing and Supply Systems (Fig.9)

The atomiser under test was mounted in an airtight perspex chamber (plates 3 and 4) to which air at pressures up to 60 ins H_2O gauge was supplied via a Fischer-Porter float type flowmeter and its associated pressure and temperature gauges, the chamber exhausting to atmosphere through

the atomiser. The gauge static pressure within the chamber was measured by means of a water manometer.

Water at a measured pressure was supplied to the atomiser from the mains via a Rootes type compressor and gauged Fischer-Porter flowmeters. Alternatively, kerosine delivered via a Lucas swash plate pump could be supplied via the same flow and pressure measuring system.

The spray from the atomiser was disposed of by means of a fan and duct system blowing air past the perspex airpot and through an exhaust duct in the test house wall.

5.2 The Optical Apparatus (Fig. 10)

The design and development of the optical bench for the measurement of mean droplet size is fully described in Ref. 12. Some detail changes were made to improve the system and enable large numbers of measurements to be obtained more conveniently.

A high intensity mercury vapour lamp was used as the light source, the Philips ME/H lamp used by Hodgkinson (Ref. 12) being replaced by a P.E.K. Type 110 which gave a higher output and did not need a cooling air supply.

The narrow beam produced from the lamp by means of a diaphragm was focussed through a green interference filter on to a 650 micron diameter collimating aperture and thence passed via a collimating lens and a 45° mirro

through the spray in the working section, to the receiver lens which focussed it on to the plane of the 65 micron photomultiplier aperture. The interference filter replaced the Wratten 74 filter used by Hodgkinson and was made necessary by the use of the P.E.K. lamp which gave a relatively high output at all wave-lengths as well as those characteristic of the mercury vapour. The filter transmitted 45% of the incident light in the waveband 5440 ± 120 Augstrom units.

The photomultiplier could be traversed across the light beam so that the light scattering effect of the droplets in the spray through which the beam had passed could be determined. To increase the convenience of obtaining the light scattering measurements the outputs from the photomultiplier cell and a position transducer were fed to the Y and X axes respectively of a Bryans type 22000 automatic plotter.

5.3 The Atomisers (Figs. 11 to 15, Plates 4 to 6)

The prototype atomiser was designed to the following broad specification and the modifications tested, and those carried out as a result of the tests were required to be within this specification.

The atomiser was to be used in an annular combustion chamber and sited in the conventional pressure jet atomiser location (Fig. 11).

An evenly distributed conical spray of 100° included angle was to be produced.

A maximum of $2\frac{1}{2}\%$ of the compressor delivery air was to pass through the atomisers to perform the work of fuel atomisation. (k in equation 1 of Appendix 1 $\geq$ .025).

The fuel system metering orifice was to be located within the atomiser.

The overall length/diameter dimensions of the prototype were not to be exceeded.

Two additional limitations were imposed to reduce the amount of machine shop work required and further confine the number of design variables:

The same basic design of fuel feed arm was to be used throughout.

The fuel was to be introduced into the airstream through a swirler since this had been found in the past to be the simplest and most effective way of producing an even fuel distribution.

Three designs of airspray atomiser within the above specification were tested and are described as follows:

Atomiser 1 (The prototype) Fig. 12, Plate 4

The fuel feed arm, common to all three atomisers, is illustrated in Plates 4, 5 and 6. Fuel from the feed arm enters the fuel gallery of a swirler, also a common feature, through the three small holes at the top of the feed arm head.

Atomising air is introduced into the central bore of the feed arm head through twin kidney shaped ports situated on either side of the head support. (One of the ports can be seen in Plate 6). The swirler forms a profiled convergent air duct, concentric with the bore, and terminates in a sharp edged circular weir through which the atomising air issues at a velocity determined by the pressure difference applied across the atomiser head.

Fuel from the swirler gallery is introduced on to the inner surface of the convergent duct through six tangential slots (shown in Fig. 15 (b)), and rotates within the duct to form a thin evenly distributed film which passes over the circular weir and is atomised by the high speed air. The duct convergence is designed both to enable a sharp atomising lip to be used, and to concentrate the swirl so that variations in fuel film thickness are minimised.

A nut secures the swirler to the feed arm head.

The air/fuel spray is deflected into the required cone angle by means of an appropriately shaped pintle.

Atomiser 2 Fig. 13, Plate 5

The main difference between this and Atomiser 1 is that the swirler securing nut has been modified to enable air to be introduced on to both sides of the atomising lip. The holes through which the shroud air enters the nut can be seen in Plate 5.

The front face of the swirler has also been chamfered to help discourage fuel from attaching to this surface.

The modified nut and the pintle form a roughly constant area duct so that fuel droplets are subjected to high speed air over a greater distance.

Atomiser 3 Fig. 14, Plate 6

The convergent swirler has been replaced by a divergent one (in two pieces for convenience) and this, with a profiled pintle, forms a smooth converging duct through which the air accelerates towards the atomising lip.

Shroud air is introduced on to the outer surface of the atomising lip through a modified swirler retaining nut; the shroud slots can be seen in Plate 6.

All the main air and shroud air flow areas behind those at the plane of the atomising lip are made as large as possible compared to this exit area to minimise losses. In the case of the main air flow this has been done by increasing the diameter of the central bore of the feed arm head and introducing an additional air port on the underside of the head, (to be seen in the inset of Plate 6).

6.0 TEST PROCEDURE AND RESULTS

6.1 PROCEDURE

6.1.1 Starting Performance

The atomiser operating conditions of most interest in the experiments were those equivalent to engine cranking and light-up, i.e. relatively low fuel flows and air velocities. It was felt that if atomisation performance under these "worst" conditions could be improved then it would be correspondingly better at other, more favourable, conditions.

The initial tests on each atomiser were, therefore, designed to give a measure of this cranking performance.

It was assumed that the air pressure drop required across the atomiser for atomisation to commence was directly related to that required to give an atomisation quality adequate for light up, and that if this required pressure drop could be reduced by improvements in design, then engine light up performance would be correspondingly improved.

The atomiser under test was mounted in the perspex airpot and water (or kerosine) passed through it. At each of a range of water flows the air pressure in the airpot was increased from zero to the point where the water issuing from the atomiser was just beginning to be atomised by the air passing over the atomising lip. This point was approached from higher and lower pressures several times to ensure a consistent judgement,

and the pressure and airflow noted. Each standard of atomiser was tested in this way at liquid flows up to 30 lb/hr. At the same time visual assessments were made of the general characteristics of the atomiser in terms of such things as the effect of liquid swirl, any tendency for fuel to flow back, etc.

The sequence of testing and the results obtained are described in Section 6.2 and discussed in Section 7.

6.1.2 Droplet size measurement

The optical bench was used purely to compare the mean droplet size produced by each of the three basic atomisers, none of the interim standards being promising enough in the starting trials to justify its atomisation quality being measured.

Water only was sprayed because of the difficulty in maintaining constant kerosine delivery pressures over the length of time required to make each droplet size measurement.

Because of the limited time available no attempt was made to explore the sprays, the light beam being fixed to pass through and perpendicular to the spray axis at about 1 inch from the atomising lip.

The technique employed in making the measurements is described in detail since its development involved a long process of trial and error which is worth circumventing in the future:

1. With the lamp and condenser lens positioned longitudinally to focus at the collimating aperture, the lamp, filter, lenses, mirror, and collimating aperture were adjusted so that the axis of the light beam was as nearly as possible coincident with the geometrical axis of the optical bench, while the airpot was positioned so that the 1/4 inch diameter beam crossing the bench working section passed through and perpendicular to the atomiser axis at about 1 inch from the atomising lip.

2. With the photomultiplier aperture adjusted longitudinally to be in the plane of focus of the receiver lens the multiplier was traversed horizontally and adjusted vertically, at a low sensitivity, to locate the centre line of the beam using the automatic plotter, also at low sensitivity. The dial test indicator (d.t.i.) was set to zero.

3. With the spray on, the photomultiplier was traversed to about .015 inches off centre (roughly half the width of the collimating aperture) and its sensitivity increased to give about half full scale Y deflection on the autoplotter with the latter at minimum sensitivity, (1 mV / inch in this case). If the multiplier was now traversed a few thousandths either side of the .015 inch setting the edge of the collimating aperture image (which must be ignored in obtaining the final traverse plot) could be detected by a rapid change in the Y deflection of the plotter.

4. The multiplier was then further traversed to the point where the Y deflection was somewhat less than one tenth of the deflection at the .015 inch position (between .3 and .7 inches off centre depending on droplet size).

5. With the plotter sensitivity adjusted to give maximum sensitivity, the multiplier was traversed towards the beam centre line in steps of .020 inches and a plot of measured light intensity versus traverse distance obtained using the plotter pen on/off switch. Fig. (16) is an example of the result obtained.

6. The plot obtained in (5) was transferred to log-linear graph paper and extrapolated across the width of the collimating aperture image to give the peak (centre line) illumination intensity (Fig. 17).

7. The distance from the beam centre line at which the illumination intensity had dropped to one tenth of its centre line value was obtained from this plot and referred to the curve (Fig. 43) derived from the theoretical illumination profile developed by Roberts and Webb (Fig. 42) and explained in Appendix 3, to obtain the Sauter Mean Diameter of the spray through which the beam had passed.

The mean droplet size produced by each of the three atomisers was measured in this way at water flows between 20 and 90 lb/hr and airpot pressures up to 60 inches of water. The results obtained are described in Section 6.2. and discussed in Section 7.

6.2 RESULTS

6.2.1 Starting Performance

The results of the starting performance tests defined in Section 6.1.1 are shown in Figs. 18 to 32 and are described for each atomiser as follows:

Atomiser 1 Figs. 18 to 24

Fig. 18 shows the airflow characteristic and discharge coefficient based on exit area of the atomiser in its basic form, both at zero fuel flow and at a fuel flow of 90.7 lb/hr. The comparatively poor C_D is the result of the complicated flow path the air has to follow, and the fact that C_D increases with fuel flow, showing that the fuel has a beneficial smoothing effect on the air passages, confirm this view.

The starting performance of the basic atomiser using both kerosine and water is shown in Fig. 19. At liquid flows below about 11 lb/hr, where swirl velocities are very low, the pressure drop required for atomisation to commence, ΔP_{atom}, is apparently independent of liquid flow, while above this level, where the swirl velocities are becoming appreciable, ΔP_{atom} increases rapidly with flow. ΔP_{atom} for the atomiser using water is higher than that for kerosine due to the higher surface tension of water, while the water flow at which swirl becomes important is also marginally higher, which suggests that there is an effective increase in swirl slot flow number when using water due

to its lower viscosity. The scatter in the measured air flows corresponding to these starting tests reflects the difficulty in measuring very low flows.

In Fig. 20 the effect of the fuel swirl is demonstrated. By reducing the flow number of the fuel swirl slots, swirl velocity for a given fuel flow has been increased and this has resulted in an increased ΔP_{atom}.

Figs. 21 to 24 show the effects of incorporating the modifications illustrated in Fig. 15, and of the removal of the pintle. None of these changes has had a beneficial effect on starting performance and all showed the same dependence on swirl characteristic of the basic atomiser.

Atomiser 2 Figs. 25 to 29

The airflow characteristics and discharge coefficient of the basic atomiser are shown in Fig. 25. A higher C_D than that for Atomiser 1 is evident due probably to the fact that, with this atomiser, the minimum flow area is at the exit plane and is appreciably smaller than the discharge area of Atomiser 1. The fact that, in this case, C_D is reduced as fuel flow increases indicates that the smoothing effect of the fuel is more than cancelled out by its blockage effect.

Basic atomiser starting performance for operation with both kerosine and water is shown in Fig. 26, and the effect of blanking off the shroud

air in Fig. 27. While the modification has had the effect of reducing the influence of the liquid swirl on ΔP_{atom} and is thus beneficial, the contribution of the shroud airflow is very limited. The improvement is therefore more probably the result of the liquid swirling into the shroud annulus, where its swirl energy is "killed" by the baffling effect of the shroud air-holes, and then running out of the annulus to be atomised by the main air stream.

In Fig. 28 the effect of the profiled pintle is shown to be detrimental due to the large reduction in airflow which resulted. The effects of fuel blockage at flows above about 10 lb/hr is very marked. The removal of the pintle altogether, on the other hand, (Fig. 29) has a beneficial effect due to the resulting increase in air flow.

The conclusions drawn from the tests on Atomisers 1 and 2, and their importance in the design of airspray atomisers generally, and of Atomiser 3 in particular, are discussed in Section 7. Results from the starting performance tests on Atomiser 3 are described as follows:-

Atomiser 3 Figs. 30 and 31

The airflow characteristics shown in Fig. 30 indicate that airflow is some 35% greater than that for Atomisers 1 and 2, while C_D is about the same, and reduces with fuel flow as would be expected.

In Fig. 31 the effect on starting performance of the modifications resulting from the tests on Atomisers 1 and 2 are clearly demonstrated. Above about 10 lb/hr fuel flow the fuel swirl has an increasingly beneficial effect, until at about 33 lb/hr the swirl is strong enough to produce a trumpet shaped film of fuel which breaks down into droplets along its perimeter without any air assistance.

The contributions of the main and shroud air flows to starting performance at fuel flows below 33 lb/hr are also indicated in Fig. 31 and show the shroud air to be the more important, as would be expected since the fuel tends to swirl off the atomising lip into its path.

The starting performance results from Atomisers 1, 2 and 3 in their basic forms are summarised in Fig. 32, and some idea of the spraying characteristics of the three atomisers at water and airflows somewhat higher than those for the starting tests can be gained from Plates 7, 8 and 9. The improvements obtained by adopting the design principles used in Atomiser 3 are clear. All the water is being atomised, even at zero air flow (though under these conditions the droplet size is very large), and a well defined cone angle has been formed at air pressure drops below 3 inches of water.

6.2.2 Droplet Size Measurements . Fig. 33 to 36

The starting performance tests were completed on all the atomisers before any droplet size measurements were made. Thus, by providing the

droplet size characteristics of each atomiser the latter programme of measurements was intended to prove the correlation between improvements in starting performance, as defined in Section 6.1.1, and reductions in overall mean droplet size.

The mean droplet size measurements obtained for each atomiser are described as follows. They are compared with those predicted by Wigg's formula (Appendix 2).

Atomiser 1 Fig.33

The measured mean droplet sizes for atomiser water flows of 55.3 lb/hr and 85.8 lb/hr, and a range of applied air pressure drops are shown in Fig. 33. The maximum droplet size which could be measured with any confidence by the optical technique used was about 180 microns, and the droplet size produced by the atomiser does not fall to this level until the air pressure drop, Δ P, has reached the high level of 28 inches H_2O . The Wigg formula predicts that a properly designed atomiser of the characteristic dimensions, water flows, and air flows of this atomiser should produce droplets of this mean size at ΔP_s as low as 4 inches H_2O . At ΔP = 28 inches H_2O the measured mean diameter (Sauter Mean Diameter, s.m.d.) is $3\frac{1}{2}$ times that predicted by Wigg, while at 50 inches H_2O measured s.m.d. is $2\frac{1}{2}$ times that predicted.

The measured effect of reducing the water flow at a given Δ P (i.e. reducing the water/air ratio) shows the same trend as that predicted but is increased.

The reasons for the poor performance of this atomiser are probably the suppressive influence on droplet formation of the water swirl, and the fact that not all the Δ P applied across the atomiser is available across the atomising lip so that the air velocity at this point is lower than that which could be achieved.

Atomiser 2 Fig. 34

The measured s.m.d.s at the two water flow conditions tested show much closer agreement with (but are still appreciably higher than) those predicted by Wigg, which is probably mostly due to the swirl "killing" effect of the shroud-air annulus already noted in Section 6.2.1. The trend in s.m.d. with changes in water/air ratio is also as predicted.

There is appreciably more scatter in the measurements than was the case with Atomiser 1, and this probably reflects the fact that a lower proportion of the water supplied to the atomiser was being atomised, so that the spray density through which the measuring light beam passed was lower.

Atomiser 3 Fig. 35

The results show very good agreement with the Wigg formula at Δ Ps above about 15 inches H_2O , especially at the higher water flows. At Δ Ps below 15 inches H_2O , however, measured s.m.d.s are appreciably higher than Wigg's, particularly at the lower water flows, but at these conditions considerable scatter, due to low spray densities, may be present

which is not apparent from Fig. 35, and the divergence from prediction is possibly not as great as it appears. The accuracy of the optical measuring technique is also questionable at s.m.d.s above about 80 microns, due to a departure from the theoretically predicted light scattering profile. This is discussed in Section 7.

The effects of changes in water/air ratio are as predicted though less marked.

The performance of this atomiser shows that the design principles adopted as a result of the starting tests on Atomisers 1 and 2 have enabled atomisation quality to be improved to a level very close to the optimum predicted by Wigg.

7.0 DISCUSSION

7.1 The Atomiser Design Specification

The objective in the design of the prototype atomiser has been to attempt to produce the simplest possible airspray atomiser suitable for application to the annular combustion chambers used in many modern gas turbine engines, consistent with providing good atomisation quality and fuel distribution, and having a minimum effect on the overall combustion chamber airflow characteristics.

The initial design described in Section 5.3 follows closely those of previous successful airsprays in that the well-tried convergent fuel swirler and atomisation weir concept has been used, but for the sake of simplicity an attempt has been made to do without shroud air (which is known to improve performance) on the outer face of the atomising lip).

Consider the factors which have led to the specification laid down in Section 5.3 to which the atomiser has been designed.

The allowable turbine entry temperatures in a modern gas turbine engine are still well below those which would be reached if sufficient fuel were injected into the combustion chamber to consume all the air delivered from the compressor.

To avoid exceeding these temperatures the overall combustion chamber fuel air ratio must therefore be kept weaker than stoichiometric,

so weak in fact that if the fuel and air were thoroughly mixed before entry into the chamber, as might be the case with an airspray atomiser situated at the outlet of the compressor, say, the mixture would not burn. (See Fig. 4).

In order to sustain combustion at these weak overall mixture strengths, therefore, a local mixture strength close to stoichiometric must be produced by mixing the fuel with only a proportion of the compressor delivery air, say 25% . The remainder of the air must then be used to dilute the combustion products of this reaction, so that flame tube wall and turbine blade temperatures are kept within the acceptable limits.

At engine idling conditions the overall combustion chamber mixture strengths are correspondingly much weaker than those dictated by the maximum temperature conditions quoted above, so the proportion of the compressor flow which is required to produce the combustible mixture is correspondingly less, say 10%. An airspray atomiser, which uses compressor delivery air to do the work of fuel atomisation in preparation for combustion, and which thus produces a well mixed fuel/air stream, must therefore be designed for this idling condition. The maximum proportion of the compressor delivery air which must be used for atomisation is thus dictated by this condition at somewhat less than 10%.

The minimum proportion is dictated by the requirement that, for adequate combustion performance the spray velocity required in the combustion chamber is at least 50 ft/sec. Engine cranking is the worst condition from the point of view of this minimum spray velocity since the air energy available is low, while the overall mixture strength is typically at its richest to enable fast engine starts to be obtained. To achieve 50 ft/sec at this condition at least 1% of the compressor delivery air must be used.

The prototype atomiser described in 5.3 is designed to use the relatively low proportion of $2\frac{1}{2}\%$ of the compressor delivery air. It is also designed to fit into a combustion chamber in the same position as would be occupied by the more conventional pressure jet atomiser, and to have the minimum effect on the overall chamber airflow. This is achieved by passing about a quarter of the air which would normally pass through the air swirler surrounding a pressure atomiser (about 10% of the total chamber flow) through the airspray, and using a correspondingly smaller swirler so that the total effect on air flow and distribution in this region is minimised. The characteristics of current combustion chamber designs are fairly well known and understood and it is desirable that the application of the relatively new airspray technique of fuel preparation should not proceed at the same time as the more radical revisions in overall design that may ultimately be necessary to gain the maximum benefit from the adoption of the airspray.

There are other advantages in using this location for the airspray. The pressure drop available across the chamber flame tube wall to "drive" the atomiser is a maximum at the head of the flame tube, and the spray produced can be easily designed to have similar characteristics in terms of cone angle to those produced by pressure jet atomisers. Thus the advantage of the airspray in maintaining constant spray characteristics with changes in engine operating conditions is retained, while the overall effect on chamber characteristics is again minimised.

The detail design of the prototype atomiser is conservative in that it follows those of previous successful airsprays. A convergent fuel swirler duct terminating in a weir over which the evenly distributed fuel film flows and is atomised has been used successfully in practically all previous designs and is simple and effective compared to other methods which have been tried such as the rotating cup, or the disc used by Bennett. By designing the swirl slots to be the metering orifice of the fuel system the maximum advantage can be taken of the pressure energy in the fuel in achieving good distribution.

7.2 Atomiser Performance

7.2.1 Atomiser 1

The powerful detrimental effect of the fuel swirl on starting performance and atomisation quality is immediately apparent from all the tests carried out, and from the observations that were made.

At liquid flows above about 10 lb/hr the pressure drop required across the atomiser for atomisation to commence, ΔP_{atom}, is very dependent on flow, which must be due to the increasingly suppressive effect of the fuel swirl as flow, and therefore swirl velocity, increase. This conclusion is confirmed by Fig. 20, which shows the effect of increasing the swirl velocity at a given fuel flow to be an increase in ΔP_{atom}, and by observation of a marked tendency for the fuel to remain in contact with the outer surfaces of the atomiser and the perspex airpot even at quite high airflows. At high fuel flows the fuel could be seen to be swirling at radii up to 3 inches from the atomiser, and later observations in connection with the development of Atomiser 3 showed that swirling fuel was capable of adhering strongly to the outer cylindrical surface of a divergent nozzle protruding from the atomiser nut, which indicates the severity of the problem.

The effect of the swirl on atomisation quality is evident from the droplet size measurements presented in Fig. 33 which show that the pressure drop required across the atomiser to produce droplets of a given

size is very much higher than the Wigg formula would suggest is necessary. For example the ΔP to produce an s.m.d. of 160 microns is about 30 inches H_2O compared to $4\frac{1}{2}$ inches H_2O suggested by Wigg (i.e. a V_{calc} of 350 ft/sec instead of 130 ft/sec). Part of this poor performance can be attributed to the fact that not all the applied pressure drop is available at the atomising lip, but that most of the performance loss is due to the swirl is evident from a comparison with the droplet sizes produced by Atomiser 2 in which the swirl has been effectively "killed" by contact with the shroud air ports, as observed in Section 6.2.1.

Even at the high airflows corresponding to a measurable atomisation quality a significant proportion of the fuel remains attached to the atomiser and airpot surfaces and this characteristic of the design would be a serious shortcoming in the practical application where combustion chamber carboning and other problems would result. And the surface wetting problem would be further aggravated by a tendency for the larger droplets generated at the atomising lip to be carried by their own inertia on to the central pintle, and thence to form a stream of very large drops.

The random nature of the fuel spray at airflows corresponding to engine cranking, caused by the fuel swirl, is evident from Plate 7.

The problem of swirl is a fundamental one with Atomiser 1 and, as might be expected, no improvements in starting performance result from the modifications tested. The attempt to do without shroud air, or some other means of counteracting the effects of swirl, has thus proved to be unsuccessful

7.2.2 Atomiser 2

While the provision of the shroud has reduced the effect of fuel swirl on starting performance and atomisation quality due to the swirl baffling effect of the shroud ports, the shroud air itself has not succeeded in detaching the fuel from the outer surface of the atomising lip, and the shroud nut has greatly increased the blockage effect of the fuel on airflow. Plate 8 shows that the resulting low airflow "spray" characteristics are very poor.

All the fuel leaving the swirler initially passes into the shroud and blanks off the majority of the shroud air ports, a significant proportion passing through the ports and into the airpot. The fuel leaving the atomiser does so as a low energy dribble which is relatively easily atomised and produces the much improved atomisation quality compared with Atomiser 1 shown in Fig. 34.

So fuel swirl is still the main factor contributing to poor overall performance.

The main conclusion drawn from the tests on Atomisers 1 and 2 was that if fuel swirl was to be retained as the means by which an even fuel film at the atomisation lip was obtained, then it must be used in such a way that the fuel could detach itself from the atomising lip using the centrifugal force available from its swirl energy and without assistance from the atomising air. The latter would only be used to atomise the resulting drops and ligaments suspended in the air annuli.

This fuel detachment could only be achieved if the convergence of the swirler used in Atomiser s 1 and 2 was replaced by a flare so that no surface was available to which the fuel could attach itself. As already stated it was found during early tests that swirling fuel could adhere quite strongly to the outer surface of a cylinder, so it was desirable that the outer surface of the swirler should also be flared.

The replacement of the swirler convergence by flare would reduce the effective swirl at the atomising lip, of course, and therefore reduce the uniformity of film thickness at this point, but only a marginal increase in fuel system pressures would be required to restore the film quality, and it was felt that the advantages to be gained

in improved overall performance would more than compensate for this.

The use of a flared swirler would also enable other design improvements to be made. Both inner and outer flare could be designed to match the required spray cone angle, and the pintle and shroud nut could be designed to fit these respective flares to give smooth convergent ducts at the required cone angle through which the atomising air would be accelerated to a peak velocity at the atomising lip before picking up the fuel. (Shroud air would be necessary because of the tendency of the fuel to swirl away from the main air annulus, and for this reason would probably do most of the work of atomisation). The atomising lip could also be at the air exit plane so that the fuel, once atomised, did not wet any internal atomiser surfaces and cause dribbling.

Finally, the other important modification that was felt to be desirable as a result of the tests on the first two atomisers was that the atomiser air flow areas behind the atomising lip should be made as large as possible compared to those at the lip so that as much as possible of the pressure drop applied across the atomiser would be available across the plane of the lip.

Atomiser 3

It was possible to incorporate all the modifications recommended above within the overall atomiser specifications laid down in Section 5.3, and the results obtained both in terms of starting performance, Fig. 32, and mean droplet size, Fig. 36, compare very

favourably with those from Atomisers 1 and 2. The improvements are most apparent from Plate 9, where the effectiveness of the flare in procuring detachment of the fuel from the lip, even at zero air flow conditions, is demonstrated; all the fuel is being atomised, and the cone angle, well established at condition (6), changes very little as air flow increases.

The measured atomisation quality is very close to the optimum predicted by the Wigg formula, at least at the s.m.d.s below about 80 microns at which the measurements are reasonably accurate.

7.3 Accuracy of measurements

7.3.1 Starting Tests

The detail results from the starting tests defined in Section 6.1.1 depended very much on a personal assessment of "the commencement of atomisation". Provided reasonably consistent judgements were made, however, the differences in the basic performance characteristics of the atomisers tested were clear, as can be seen from Fig. 32.

The more marginal differences caused by the minor modifications made to an individual atomiser were sometimes more difficult to detect, but this very fact tended to indicate that no appreciable differences in atomisation quality would be detected either, and as can be seen from the droplet size measurements on Atomiser 1, Fig.33, large improvements were looked for. The tests have shown that, within limits,

there is a good correlation between starting performance and atomisation quality, so the assumptions made to this effect in Section 6.1.1 have been proved valid.

7.3.2 Droplet Size Measurements

Dobbins, Crocco and Glassman (Ref. 14) demonstrated that their optical technique for measuring mean droplet size, on which Hodgkinson based the design of his bench (Ref. 12) was capable of a high degree of accuracy.

An important limitation occurred with Hodgkinson's apparatus, however, in that the light scattering profiles produced were different to those predicted (see Fig. 17), which meant that the measured droplet size depended on the relative light intensity at which measurements were made. (See Appendix 3).

The 1/10 relative intensity chosen corresponded to the minimum error in mean droplet size arising from differences in the Upper Limit Distribution Function, and was used throughout so that the inaccuracies in scattering profiles, which proved difficult to remedy, were consistent.

The attempt described in Appendix 4 to calibrate the instrument , however, showed that at s.m.d.s up to 80 microns the measured droplet sizes were at least as accurate as would have been produced by the

magnesium oxide slide technique. Above this size, measured s.m.d.s are probably higher than true, to judge from the trend in the shapes of the scattering profiles, but no firm conclusion can be drawn to this effect.

While the only information available from the instrument is a mean droplet size, it is very convenient to use and is worth developing further to enable reliable and consistent measurements to be made.

8.0 CONCLUSIONS

1. Atomiser Design

The combination of fuel swirl with a divergent air duct and air flow over both sides of the atomising lip has produced an airspray atomiser with good fuel distribution characteristics at low fuel and airflows, and atomisation quality close to the optimum predicted by Wigg.

2. Correlation of Starting Performance with Atomisation quality.

Within the limits of the tests made there is evidence that a good correlation exists between the pressure drop required across an airspray atomiser for atomisation to commence and that required to produce a given atomisation quality.

3. Droplet size measuring technique

The optical technique used is capable of making good comparative measurements but needs to be developed further if the theoretically predicted performance is to be achieved.

Ref. 7.

APPENDIX 1

SIMPLE THEORY OF OPERATION OF AIRSPRAY ATOMISERS

Combustion chamber performance is controlled principally by the degree of atomisation of the fuel, and the spray velocity. In the "natural" airblast (airspray) burner both these depend on the air velocity at the atomising lip and in turn on the pressure ratio across the flame tube.

Assuming final spray velocity V_s to be the result of the fuel and atomising air streams sharing their momenta, then:

$$V_f \cdot M_f + V_a \cdot k M_a = V_s (M_f + k M_a)$$

where V_f and V_a are fuel and air velocities respectively,

M_f and M_a are total chamber fuel and air flow rates respectively,

and k is the proportion of the total chamber air flow which passes through the atomisers.

Since with an airspray burner fuel injection velocities are low compared to atomising air velocity, V_f can be assumed zero with negligible error:

Then $V_a \cdot k M_a = V_s (M_f + k M_a)$

$$\text{i.e. } V_s = V_a \cdot \frac{k M_a}{M_f + k M_a}$$

$$= V_a \cdot \frac{1}{1 + \frac{1}{k} \cdot \frac{M_f}{M_a}} = V_a \cdot \frac{1}{1 + \frac{1}{k.afr}} \qquad \text{(1)}$$

Thus V_s is dependent on available air velocity, chamber air fuel ratio, and the proportion of chamber air used for atomisation only. Hence, at a given non-dimensional engine speed, V_s will be independent of altitude and forward speed.

The available air velocity V_a is dependent on the pressure ratio across the flame tube which is a function of $\frac{M_a \sqrt{T_a}}{P_a}$

where T_a is atomising air temperature,

and P_a is atomising air total pressure.

V_a for a typical combustion chamber varies from about 500 ft/sec at maximum engine r.p.m. down to 200 ft/sec at idling and 150 ft/sec at crank-lighting conditions.

Experience indicates that for adequate combustion performance the spray velocity V_s must be at least 50 ft/sec. Assuming, for example, a typical cranking overall air/fuel ratio of, say, 50:1 then from equation 1:

$$50 = 150 \cdot \frac{1}{1 + \frac{1}{k.50}}$$

whence $k = .01$, i.e. at least 1% of the chamber air must be passed through the atomiser to ensure a spray velocity of at least 50 ft/sec. for crank lighting.

Now kx overall a.f.r. = a.f.r. issuing from the atomiser

local air fuel ratio

In this case $k \times (a.f.r.)_{o/a} = \cdot 5$. , which, if the air and fuel were completely premixed would be too rich to burn. By increasing k both the spray velocity and the local a.f.r. can be increased but since mixing in practice will not be complete and some further dilution by primary air will take place, a compromise must be decided on from similar analyses at other conditions and engine operating experience.

APPENDIX 2

THE PREDICTION OF THE DROPLET SIZE PRODUCED BY AN AIRSPRAY ATOMISER

The first and most comprehensive collection of experimental data from Airblast Atomisers was obtained by Nukiyama and Tanasawa (Ref. 1)(Fig. 37) (Fig. 37), who were able to correlate their results to produce an empirical equation predicting mean droplet size for any given set of conditions:

$$d_o = \frac{585\sqrt{\sigma}}{\Delta v \sqrt{\rho_l}} + 597\left(\frac{\mu}{\sqrt{\sigma \rho_l}}\right)^{0.45} \left(\frac{1000\, V_l}{V_a}\right)^{1.5} \qquad (1)$$

where d_o = The Sauter Mean Diameter of the droplets in microns

Δv = the relative velocity between the air and liquid, m/sec

ρ_l = the density of the liquid gm/cm^3

$\frac{V_l}{V_a}$ = the ratio of the volume flow rates of liquid to air.

σ = liquid surface tension dynes/cm

and μ = liquid coefficient of viscosity (poises)

While not dimensionally consistent, equation 1 has been shown to be generally valid for airblast atomisers operating with liquid densities

between 0.7 and 1.2 g/c.c., surface tensions between 19 and 73 dynes/cu, viscosity between 0.003 and 0.5 poises, and at subsonic air velocities. No account is taken of the properties of the air, however, so its application is limited to conditions close to atmospheric.

Wigg (Ref. 2) pointed out that equation 1 did not take into account the results of other workers in this field, and developed a dimensionally consistent equation, correlating these results, and taking into account all the variables, which described the droplet size produced by an airblast atomiser in which no droplet coalescence is occurring, equation 2, and a correction to this equation for use when coalescence is taking place, equation 3.

$$d_m = \frac{190\ \nu^{0.5}\ W^{0.1}\left(1+\frac{W}{A}\right)^{0.5}\ h^{0.1}\ \sigma^{0.2}}{\rho_a^{0.3}\ .\ V} \qquad \text{(2)}$$

and $$d_m = N\ \left(1 + 2.6\left(\frac{W}{A}\right)^{0.6}\ W^{0.1}\right) \qquad \text{(3)}$$

where d_m = mass median diameter - microns

ν = kinematic viscosity - centistokes

W, A, = liquid and air mass flow rates gm/sec.

h = height of air annulus cm

σ = surface tension dynes/cm

ρ_a = air density gm/cm^3

V = air to liquid relative velocity in/sec

N = R.H.S. of equation 2.

The droplet size predicted by equation 2 has been used by the present author as the standard to which the atomisation quality produced by the atomiser tested has been compared, since the droplet size measuring light beam was passed through the spray very close to its source.

The following air and water properties have been assumed:

$$\nu = 1.01 \text{ centistokes}$$

$$\sigma = 73 \text{ dynes/cm}$$

$$\rho_a = .0012 \text{ gm/cm}^3$$

Substituting these values, converting to Sauter Mean Diameter, since the light measurements are in these terms, and converting to lb/hr, ins, and ft/sec units for flow rates, dimensions and velocities respectively:

$$d_o = 8060 \frac{W^{0.1} \left(1 + \frac{W}{A}\right)^{0.5} \cdot h^{0.1}}{V_{calc}} \qquad (4)$$

where V_{calc} is the atomising lip airspeed calculated from the pressure drop applied across the atomiser by means of compressible flow curves.

APPENDIX 3

DROPLET SIZE MEASUREMENT

Liquid sprays in general contain a wide range of droplet sizes which can be accurately represented by size-frequency histograms of the form shown in Fig. 38

Several algebraic functions of conventional exponential type are used which, with suitable choice of parameters, can be made to fit the characteristic histograms of various types of spray. Of particular use are:

1) the empirical equation due to Nukujama and Tanasawa derived from their experiments with air atomisation:

$$\frac{dR}{dx} = a\, x^{5}\, e^{-bx}$$

where x = droplet dia.

R = the cumulative volume of droplets of size greater than x expressed as a ratio of the total droplet sample volume

and a, b, and q are constants

and:

2) the Rosin-Rammler relationship which was originally derived for particle size distribution in powders:

$$R = e^{-\left(\frac{x}{\bar{x}}\right)^n}$$

where R and x are as above and and $\bar{x}$ and u are constants.

Mugele and Evans, however, in their detailed discussion of the application of these exponential expressions pointed out that while they can, for example, adequately be made to represent size distributions, they may predict completely erroneous volume distributions or mean droplet size because of the inherent assumption of an infinite range of droplet sizes (Ref. 13). Mugele and Evans demonstrated that these shortcomings were overcome if the Upper Limit Distribution Function, which recognises that no droplets exist in a sample which are larger than a specified D_∞ , was used.

In the Upper Limit Distribution Function (U.L.D.F.) two characteristic parameters derived from the shape of the droplet size-frequency distribution curve are taken to describe the spray;

$$\frac{\bar{D}}{D_\infty} \text{ (the skewness), and } Q = \frac{D_{+\frac{1}{2}} - D_{-\frac{1}{2}}}{\bar{D}}$$

where $\bar{D}$ is the most probable droplet diameter

D_∞ is the maximum droplet diameter

and $\left(D_{+\frac{1}{2}} - D_{-\frac{1}{2}}\right)$ is the width of the distribution curve at

half the peak frequency (Fig. 39).

Because of the superiority of the U.L.D.F. in describing actual distributions Dobbins, Crocco and Glassman proposed its use in the development of their optical technique for the measurement of droplet sizes in sprays. (Ref. 14).

They hoped to demonstrate that the scattering effect on a beam of light of the droplets in a spray was dependent on the size of the droplets, and found that, for a wide range of the positively skewed distribution curves typical of liquid sprays (as characterised by $\frac{\bar{D}}{D_\infty}$ and Q ranging from 0.13 to 0.28 and 0.5 to 2.10 respectively) the calculated scattered light profiles were coincident within small limits when plotted in terms of the relative illumination intensity at angle θ , I_θ , and reduced diameter, $\frac{\pi D_{32} \theta}{\lambda}$ (Fig. 40)

where D_{32} = Sauter mean diameter

θ = angle at which I_θ is measured

λ = wavelength of light used

Dobbins et al tested their theories using the apparatus shown in Fig.(41).

and they concluded that the light scattering technique gave the most accurate measurements of particle size when compared with microphotographic and droplet collecting methods.

The theories of Dobbins et al were further extended by Roberts and Webb who showed that the range of droplet distributions considered could be greatly increased in terms of $\frac{\bar{D}}{D_{\infty}}$ and Q without affecting the Dobbins conclusions (Ref. 15) and they produced a revised Mean theoretical illumination profile, Fig. 42 , covering a range of $\frac{\bar{D}}{D_{\infty}}$ from .13 to 0.8, and Q from .50 to 2.10.

This revised curve has been used by the present author in the atomisation performance assessments described in this thesis.

APPENDIX 4

THE CALIBRATION OF THE OPTICAL BENCH

Because of the departure of the measured light scattering patterns, Fig. 17, obtained with the optical bench from those predicted by the Theoretical Illumination Profile, Fig. 42, an attempt was made to calibrate the bench against a source of known droplet size - the ultrasonic atomiser, Plate 10. The atomisation quality of this atomiser, spraying water, had previously been measured by the magnesium oxide slide technique.

The droplet density produced by the ultrasonic atomiser is low, and to enable a sufficient density to be obtained for the purposes of making light scattering measurements the spray was blown away from the atomiser head to form a plume through which the light beam could be passed, Plate 10.

The results of the optical bench measurements of mean droplet size are shown in Fig. 44 compared with the previously measured performance. The measurements have been made at the 1/10 peak light intensity point recommended in Appendix 3, and used throughout the experimental work on the airspray atomisers.

It appears from Fig. 44 that the optical bench is giving too low a value of mean droplet size at water flow rates above 40 c.c./min., and too high a value at flows below this value. While the bench may give

inaccurate final measurements it is certainly capable of detecting the rapid changes in s.m.d. with flow suggested by the slide measurements, however, and the author feels that it is the latter which are more likely to be wrong. This view is confirmed by slide measurements of the ultrasonic spray which were taken at the end of the exhaust duct during some of the light scattering measurements, and which agreed quite well with the optical results, (See Fig. 44), up to s.m.ds of about 80 microns corresponding to the maximum flow rate which could be applied to the atomiser.

The previous slides were taken at a plane below the atomiser and with the latter operating in still air, and it is possible that the measurements would be biased towards the larger droplets since these would settle out more quickly.

Unfortunately no magnesium oxide slides were taken of the sprays from the airspray atomisers which would help to confirm the optical measurements, but it is concluded from the tests described above that the optical bench is capable of giving results at least as accurate as would be obtained using the slide technique up to droplet sizes of 80 microns s.m.d.

APPENDIX 5

A RIG TO MEASURE THE EFFECT OF PRESSURE ON DROPLET SIZE OF AIRSPRAY ATOMISERS

Apparstus has been designed to enable the atomisation quality produced by airspray atomisers to be studied at simulated combustion chamber pressures up to 250 p.s.i.g. Fig. 45.

The atomiser is mounted in a housing at the centre of a perforated diaphragm through which a high pressure airstream passes, the perforations being designed to give a pressure difference across the diaphragm representing that across a combustion chamber flame tube wall. The airflow passing through the atomiser itself is measured by means of a venturi situated in a duct, coaxial with the main air duct and connected to the back of the atomiser housing.

An observation chamber is connected to the downstream side of the diaphragm to enable the droplet size produced by the airspray to be measured by means of the optical bench designed by Hodgkinson and used by the present author to make the measurements at atmospheric conditions described in this thesis.

By varying the operating pressure of the rig the performance of an airspray atomiser at varying engine operating conditions can be simulated.

REFERENCES

1. Nukiyama, S., and Tanasawa, Y., "Experiments on the Atomisation of Liquids in an Airstream" Trans.Soc.Mech.Engs. (Japan). Vols. 4, 5, 6, 1938-40.

2. Wigg, L.D., "Drop Size Prediction for Twin-Fluid Atomisers" N.G.T.E. Memo No. M.343, Sept.1960.

National Gas Turbine Establishment

3. Wood, R., "The Rolls-Royce Airspray Atomiser Spray Characteristics" Shell Thornton Research Centre Report K.123, July 1954.

4. Miller, D., "Control of Gas Turbine Exhaust Smoke Using Air-blast Fuel Atomisation" College of Aeronautics Thesis, May 1965

5. "Air-blast Burners Used on the Nene and their Effect on Performance" Unpublished Rolls-Royce Report 1947.

6. Wood, R., "Spray Characteristics of Nene Atomisers' Shell Thornton Research Centre Report No. K.112, Sept. 1953.

7. "Natural Airspray Burners" Unpublished Rolls-Royce Report, Mar.1952.

8. Unpublished Rolls-Royce Data.

9. Baker, K.M., and Poulton, W.R., "The Performance of an Airspray Atomiser in the Primary Zone of a Gas Turbine Combustion Chamber". N.G.T.E. C.P.C. Note No.23.

10. Deacon, W., and Bamford, J.A. "Altitude Tests on Three Highly Loaded Annular Combustion Chambers Designed to Rolls-Royce R.B.93 Requirements". N.G.T.E. Report R.211, Aug.1957.

11. Bennett, P.G. "Airblast Atomisation" College of Aeronautics Thesis, June 1962.

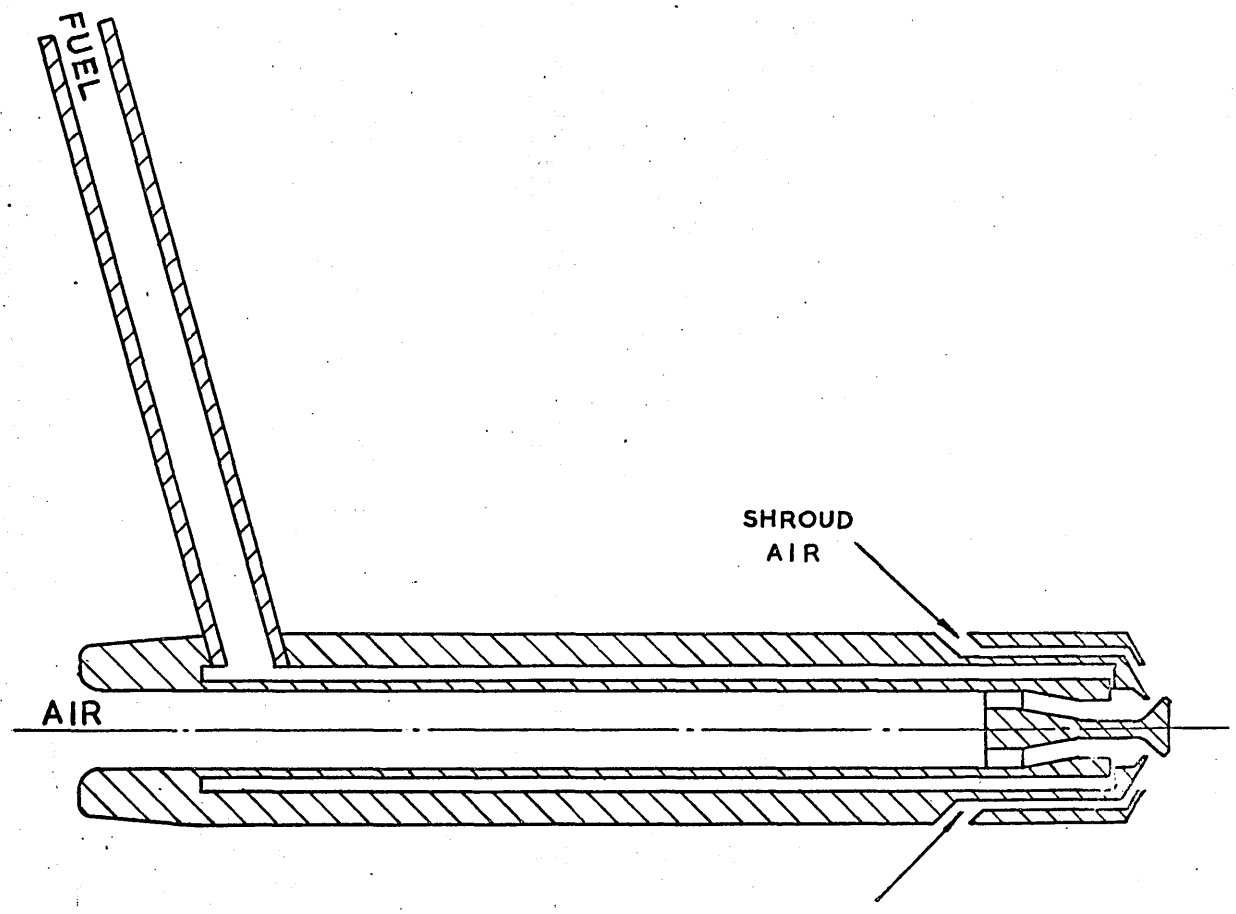
12. Hodgkinson, J.V., "An Optical Instrument for the Measurement of Mean Droplet Size of Sprays" College of Aeronautics Thesis, May 1966.

13. Mugele, R.A. and Evans H.D. "Droplet Size Distribution in Sprays" Journal of Industrial Engineering and Chemistry. June 1951.

14. Dobbins, R.A., Crocco, L., and Glassman, J. "Measurement of Mean Particle Sizes of Sprays from Diffractively Scattered Light". A.I.A.A. Journal Vol.1, No.8, Aug.1963.

15. Roberts, J.H. and Webb, M.J. "Measurement of Droplet Size for Wide Range Particle Distributions". A.I.A.A. Journal Vol. 2, No.3, March 1964.

FIG 3



ROLLS-ROYCE DART AIRSRAY ATOMISER

STABILITY LOOPS

COMPARISON OF CHAMBER WITH SIMPLEX AND AIRSPRAY ATOMISERS

FIG 4

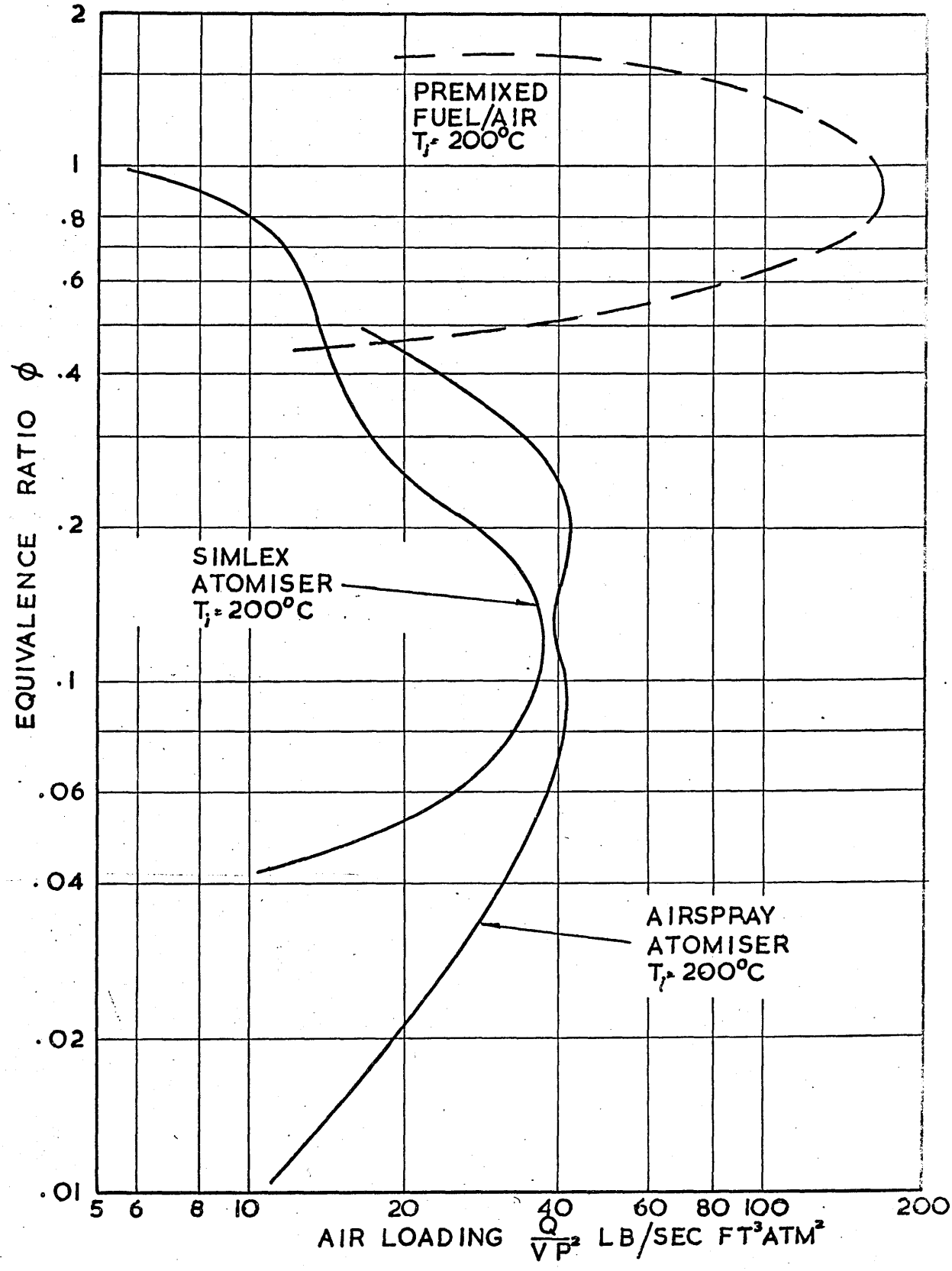
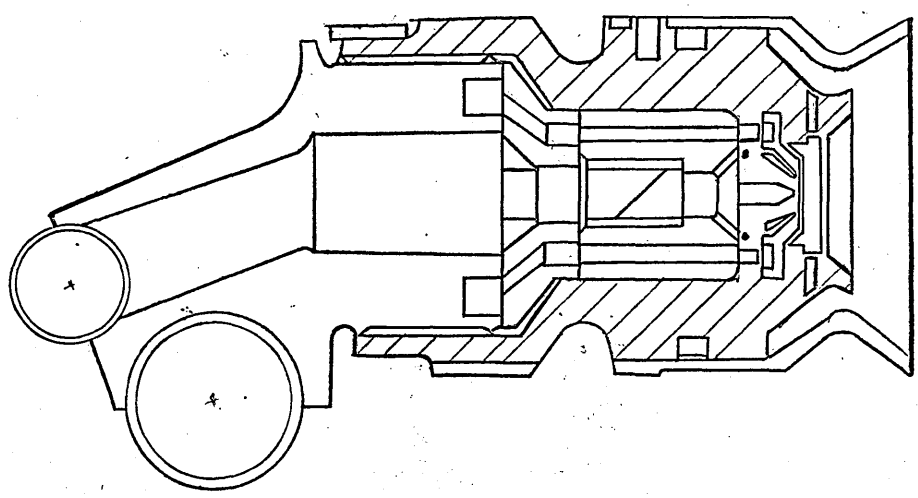
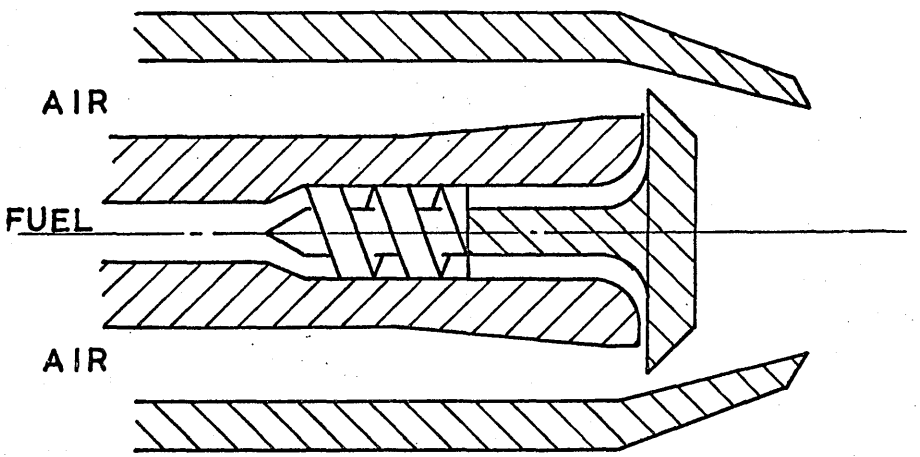


FIG 5



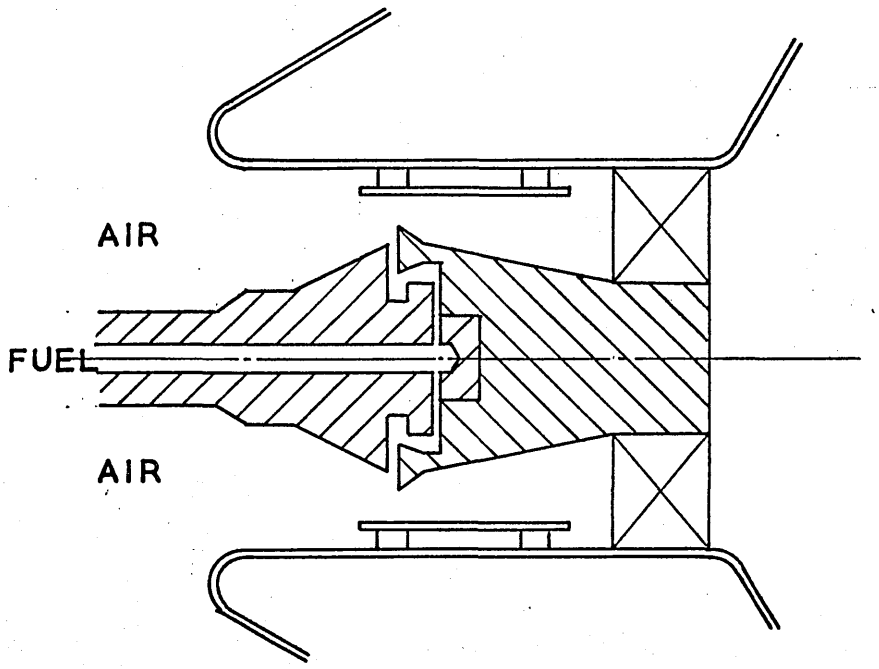
ROLLS ROYCE-RB108-AIRSPRAY ATOMISER.

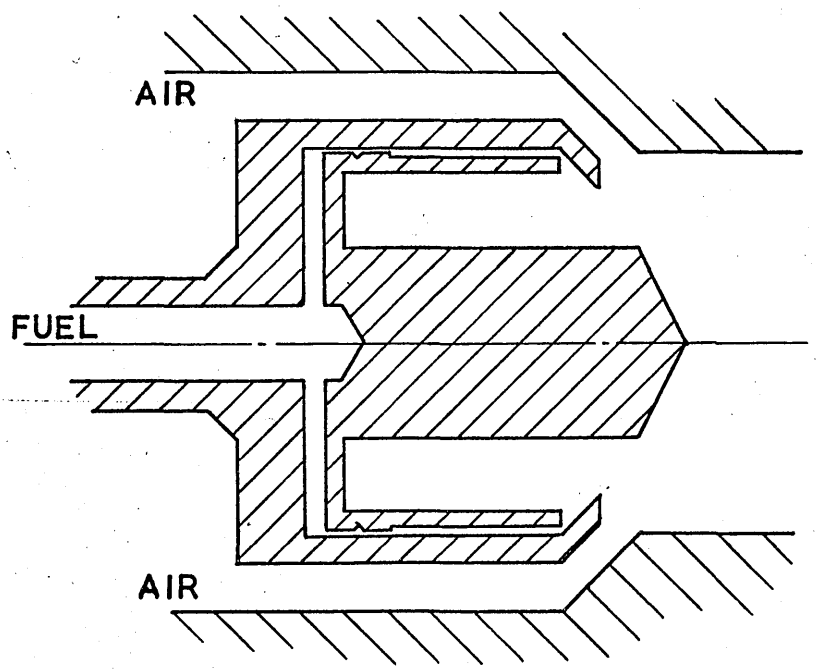
FIG 6



BENNET'S DISC ATOMISER

FIG 7





TWO OF MILLER'S ATOMISERS

FIG 8

G.A. OF TEST APPARATUS

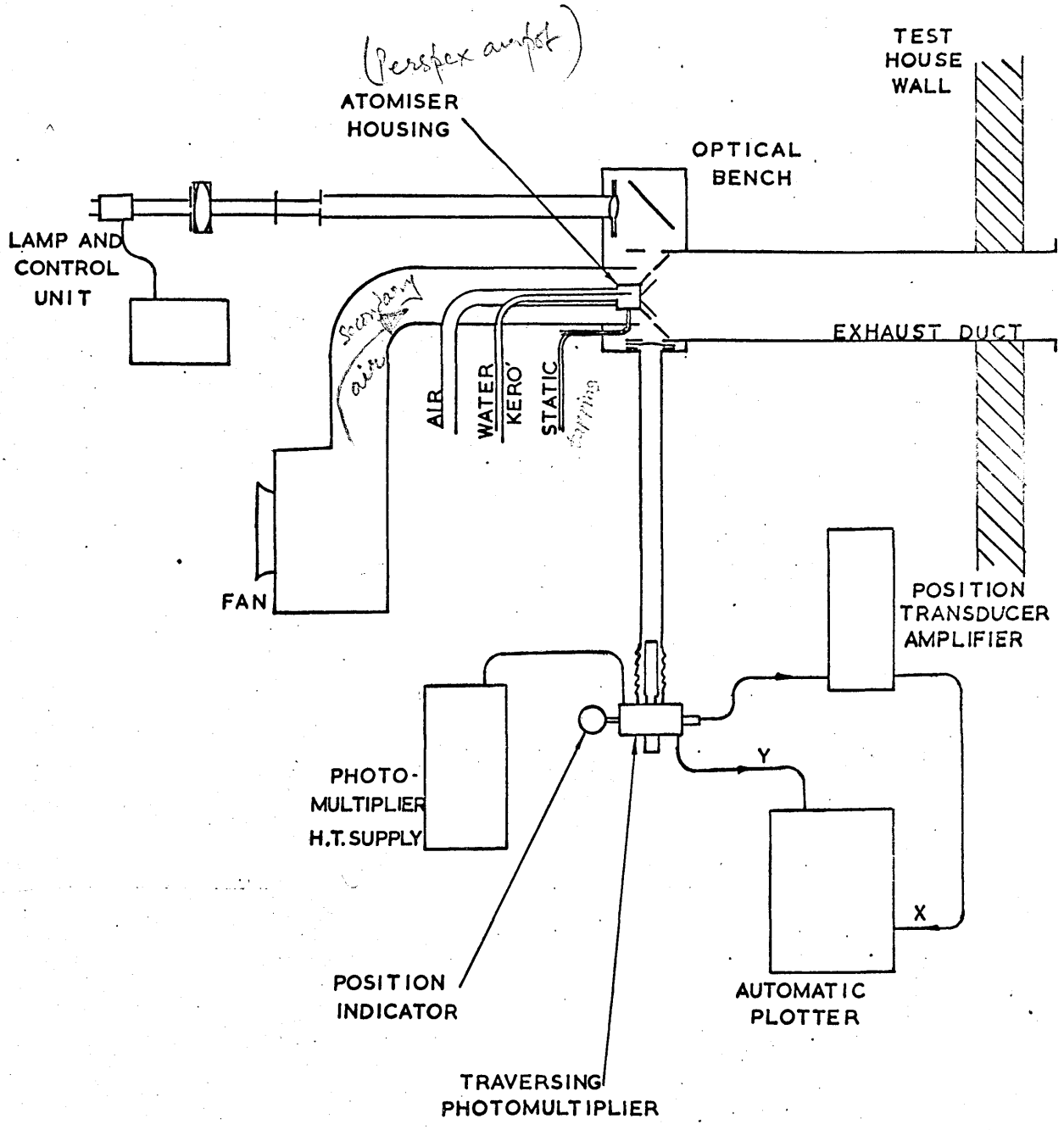


FIG 9

ATOMISER HOUSING AND SERVICES

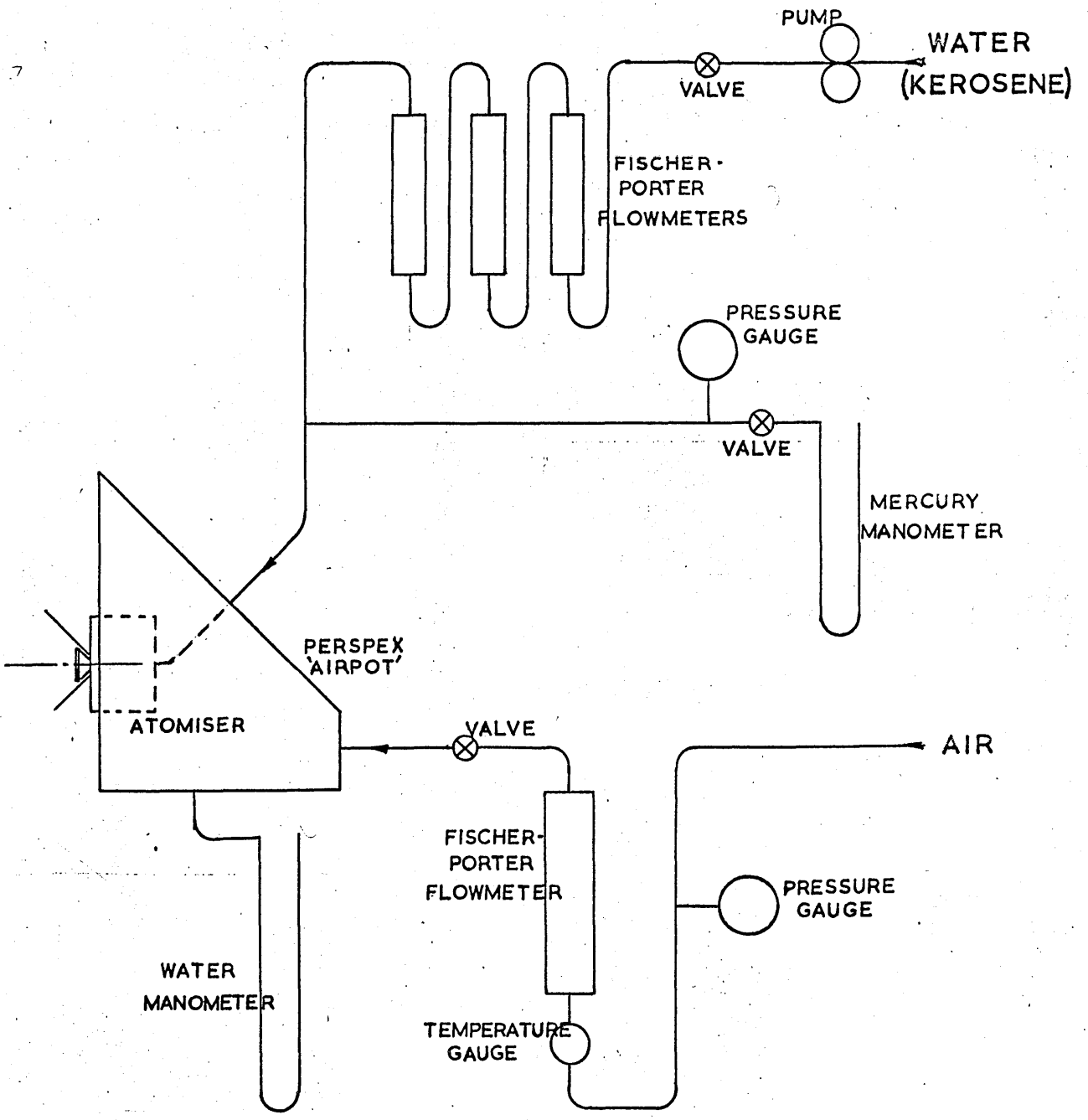
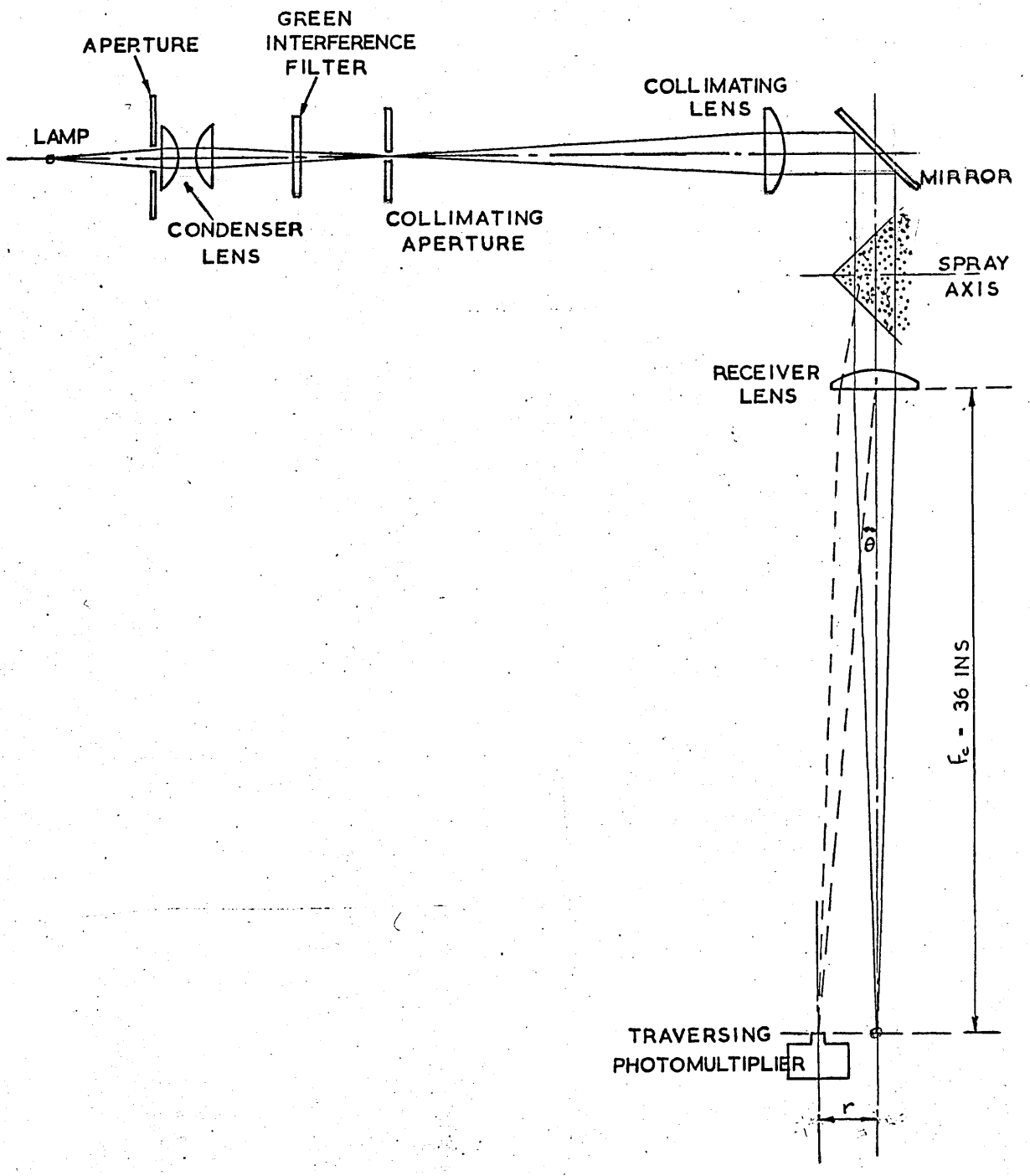
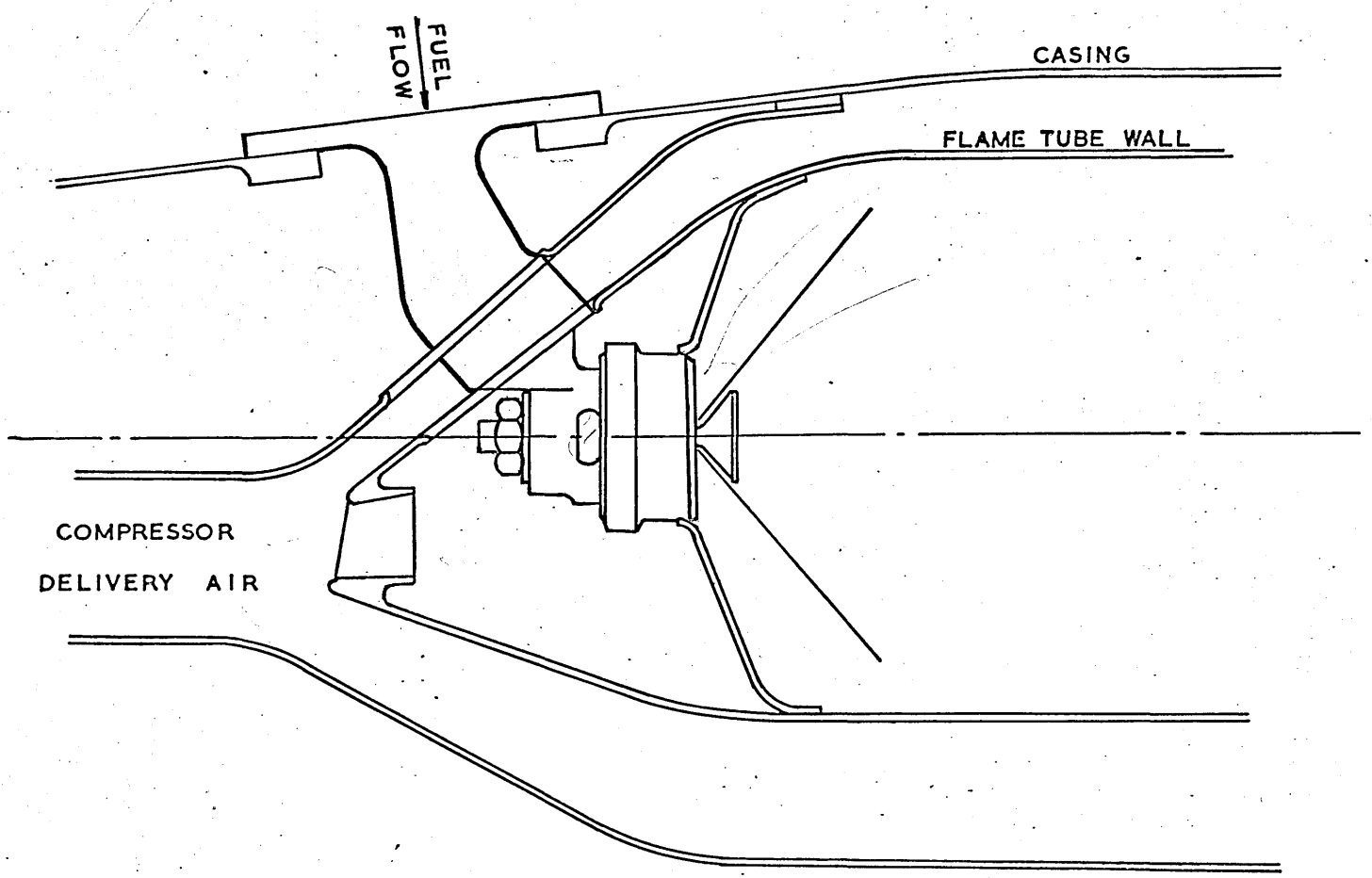


FIG 10

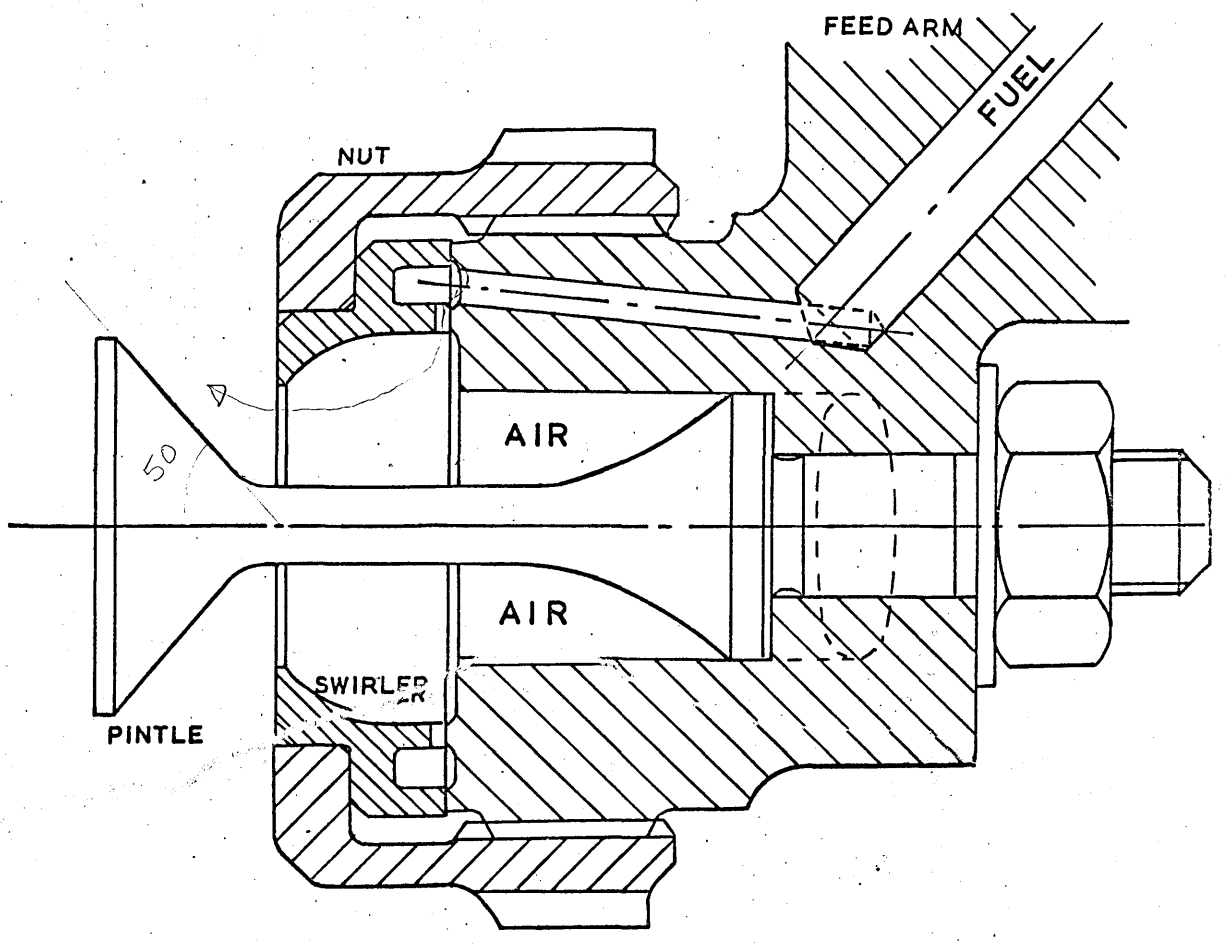
OPTICAL MEASURING APPARATUS





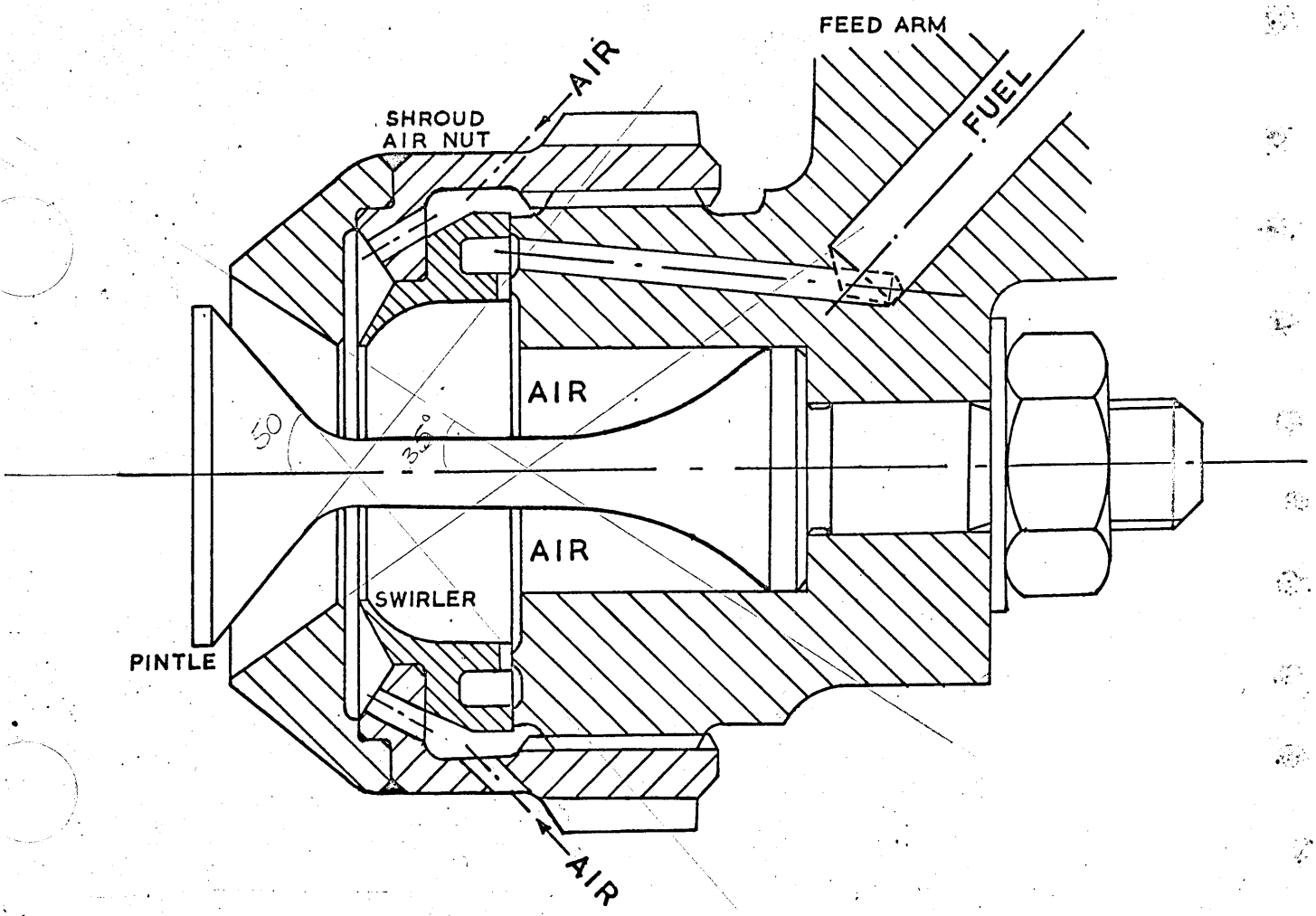
LOCATION OF AIRSPRAY IN COMBUSTION CHAMBER

FIG 12



ATOMISER 1

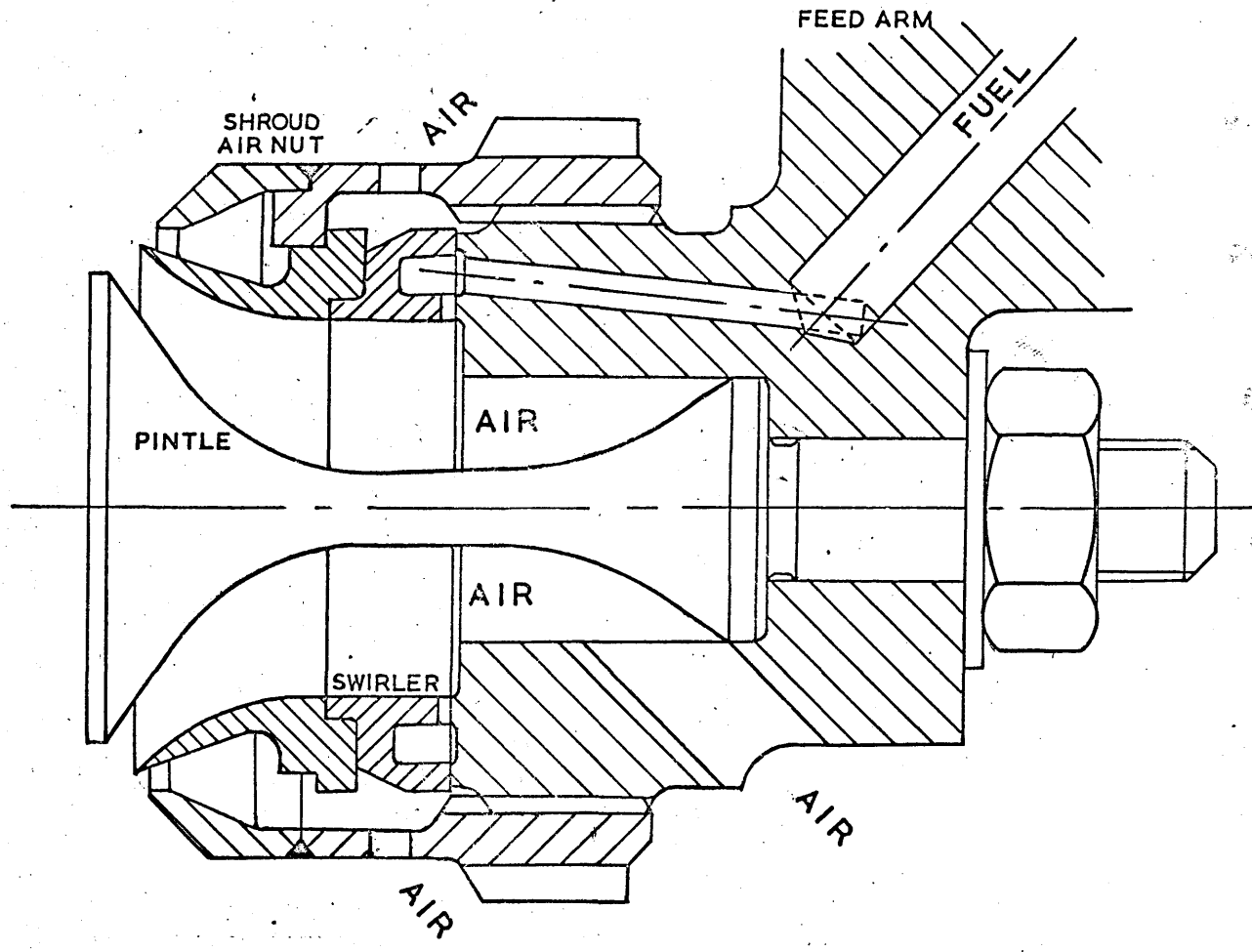
FIG 13



ATOMISER 2

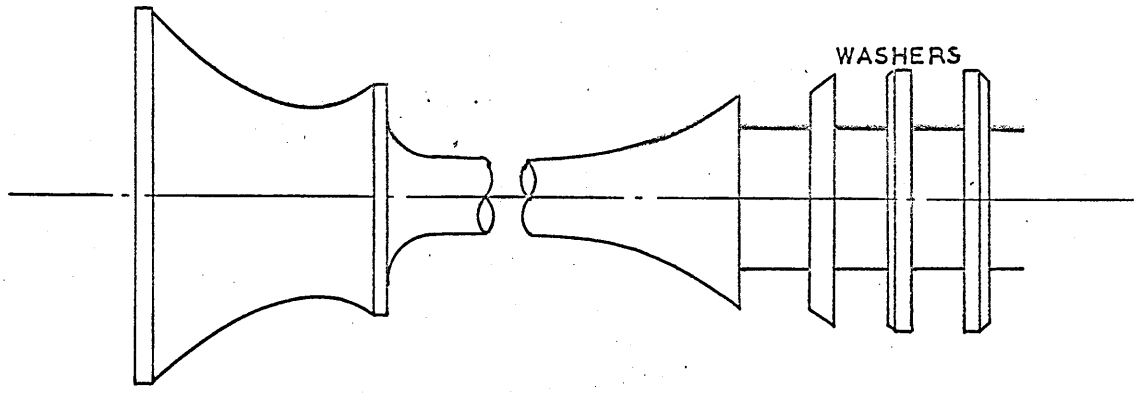
FIG 14

slots .015x.015



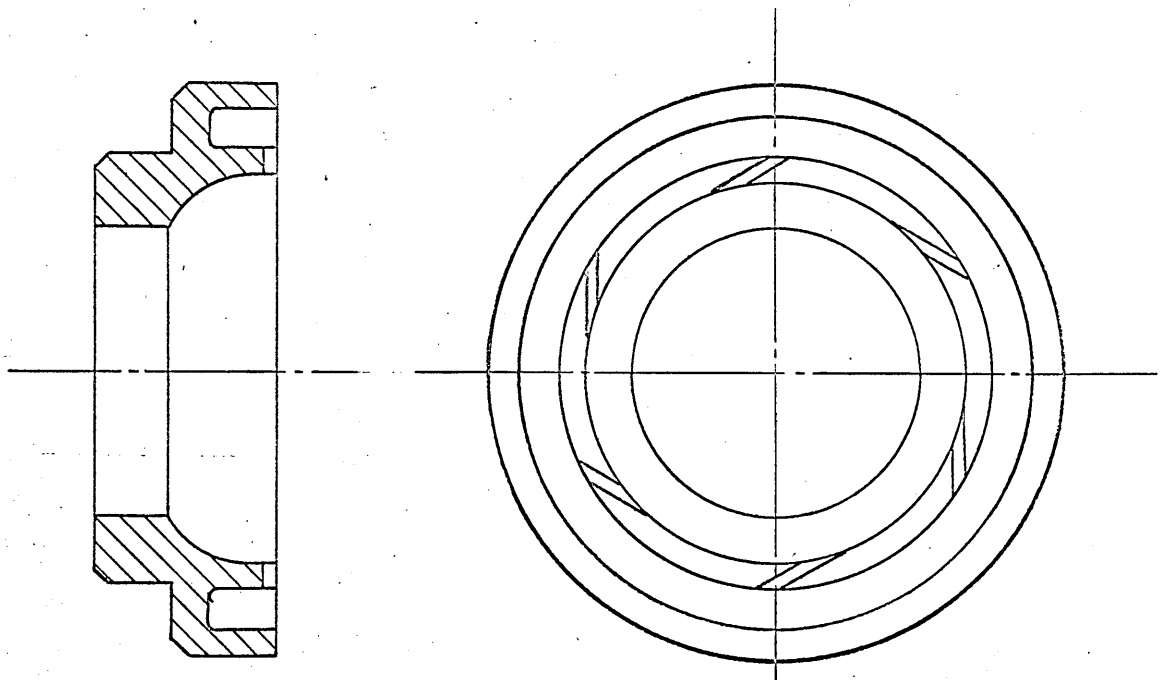
ATOMISER 3

MODIFICATIONS



LARGE PINTLE

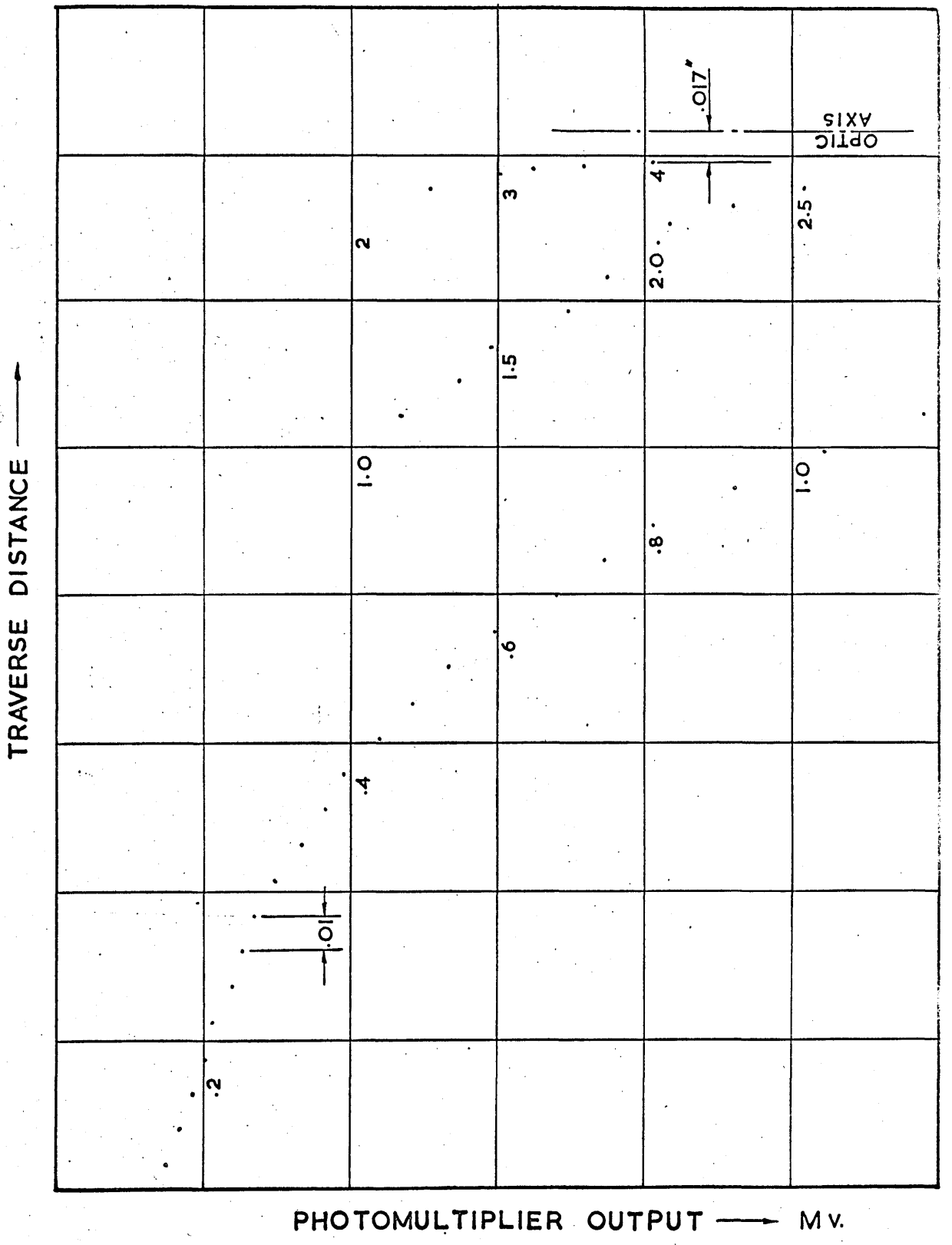
VARIABLE PINTLE POSITION



LONG ORIFICE SWIRLER

TYPICAL AUTOPLOTTER TRACE

FIG 16



EXAMPLE OF MEASURED ILLUMINATION PROFILE

FIG 17

COMPARED TO THEORETICAL
DROPLET SIZE = 70·5 MICRONS

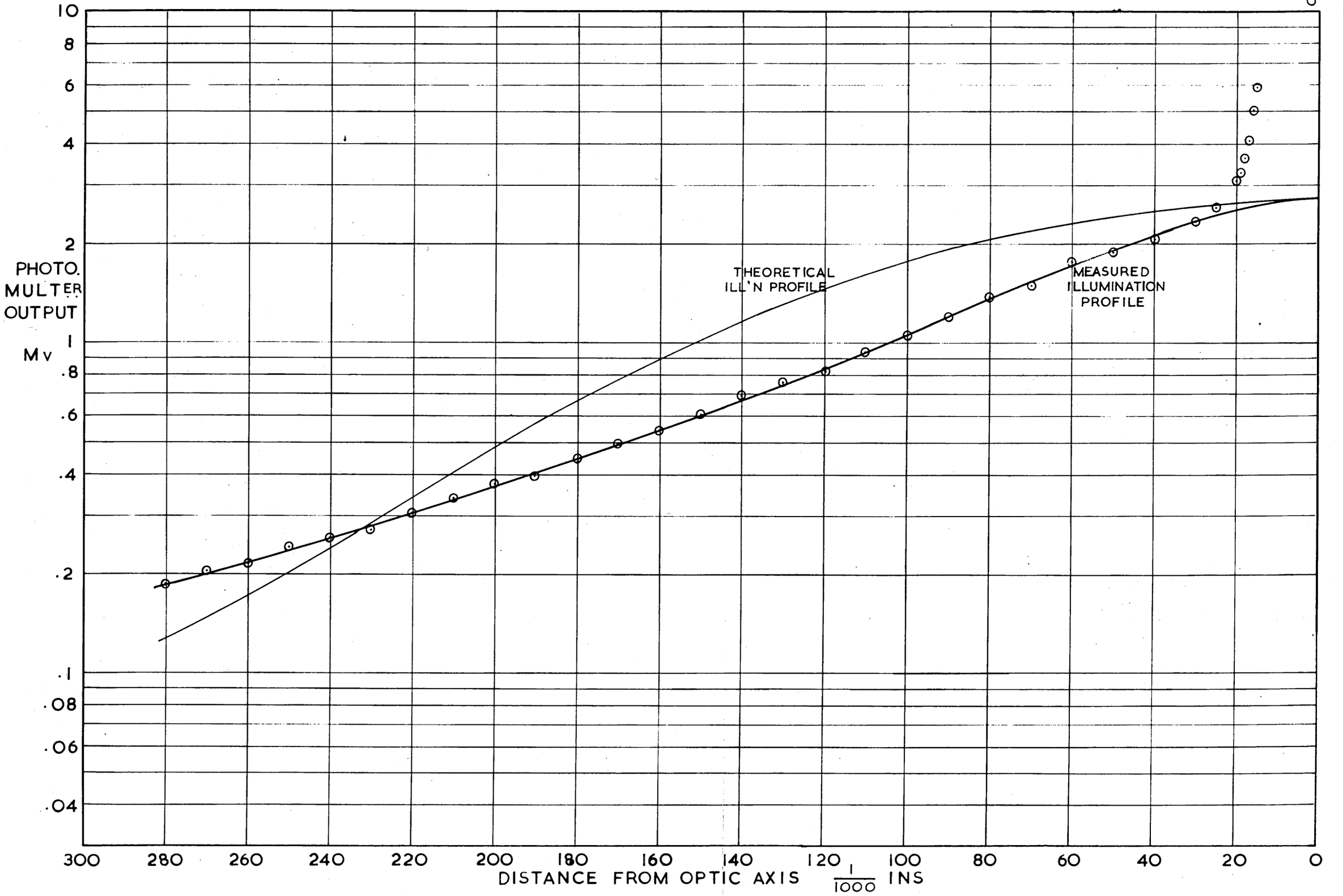
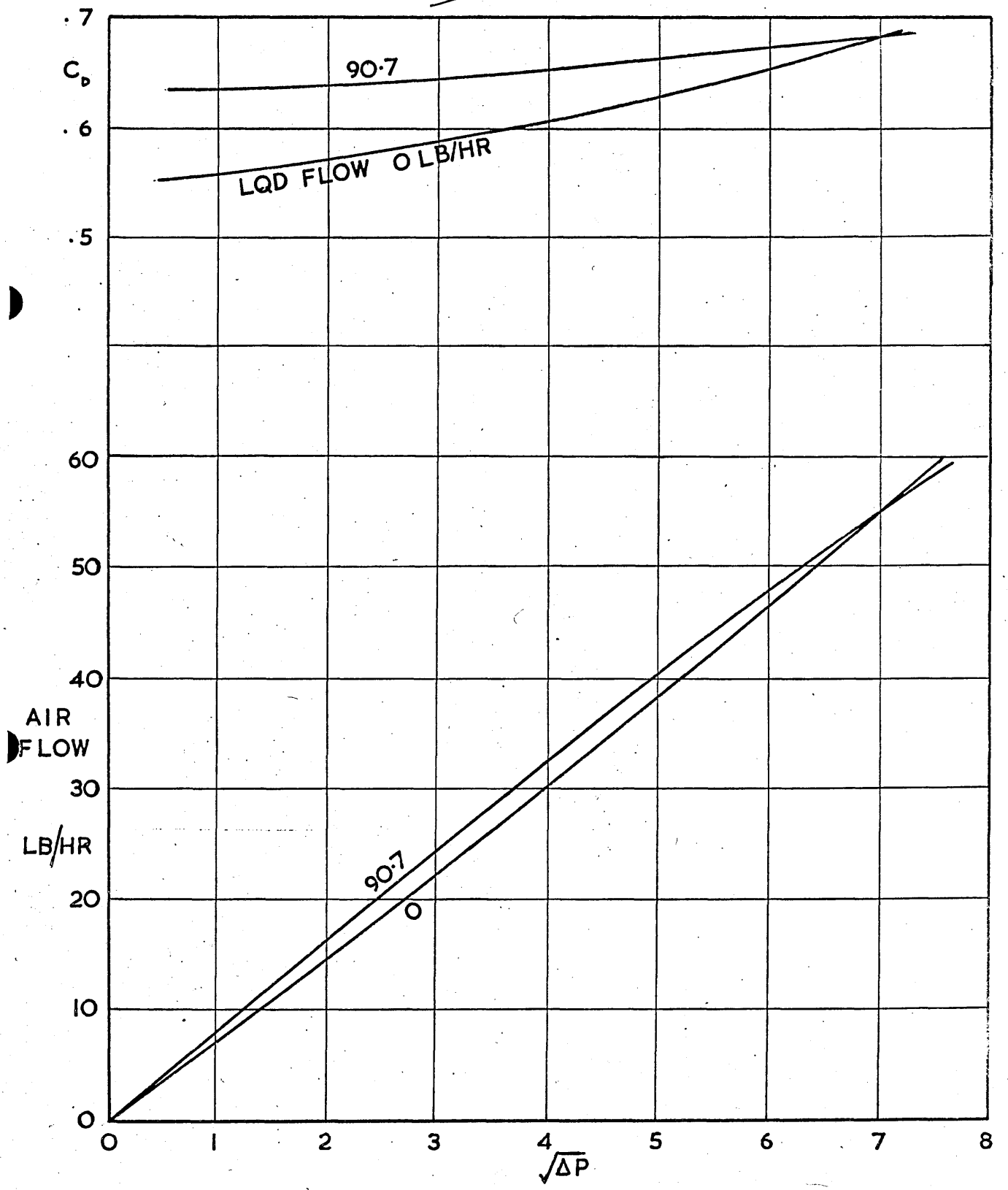


FIG 18

ATOMISER 1

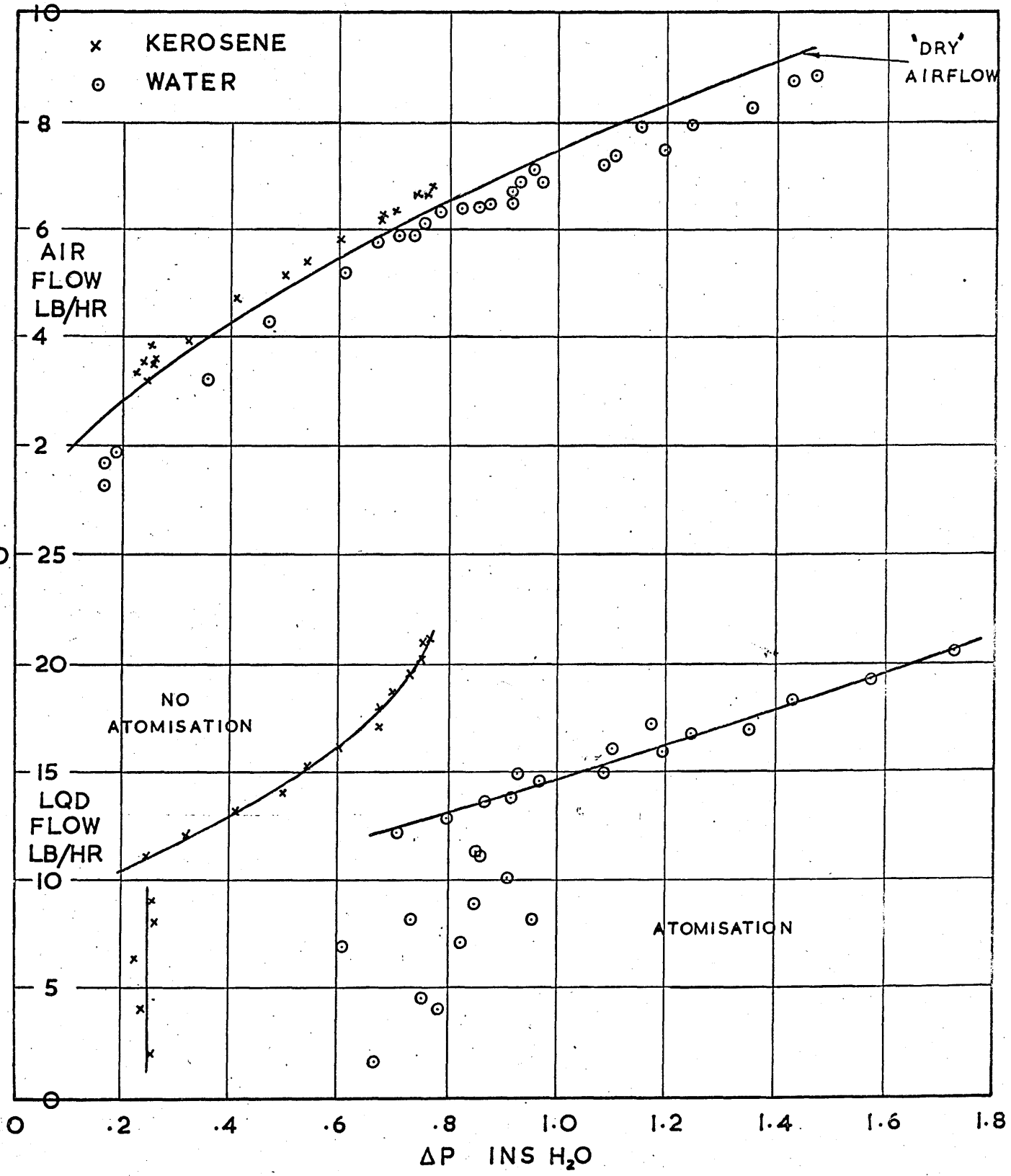
AIRFLOW CHARACTARISTICS



ATOMISER 1

FIG 19

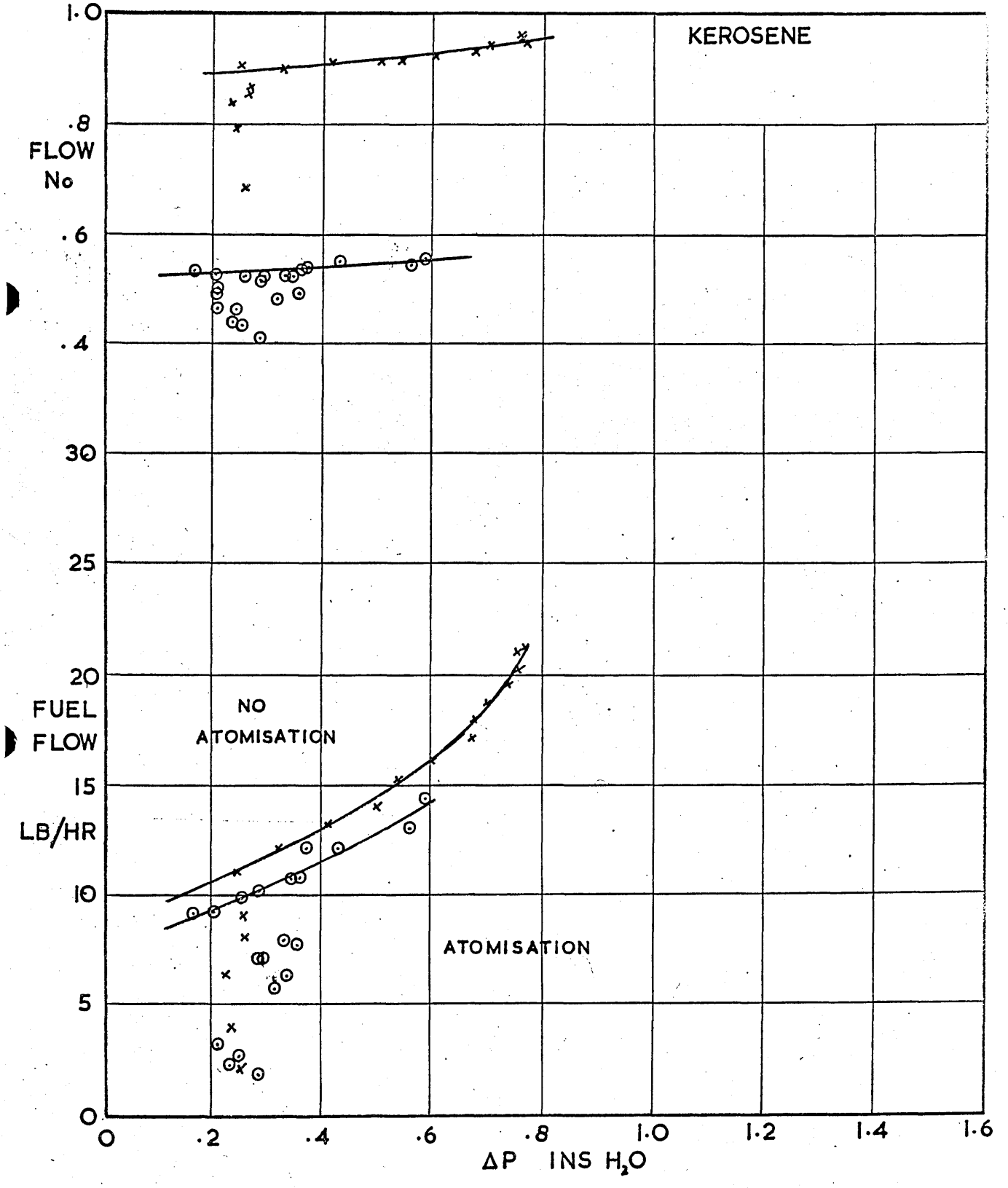
STARTING PERFORMANCE
BASIC ATOMISER



ATOMISER 1

FIG 20

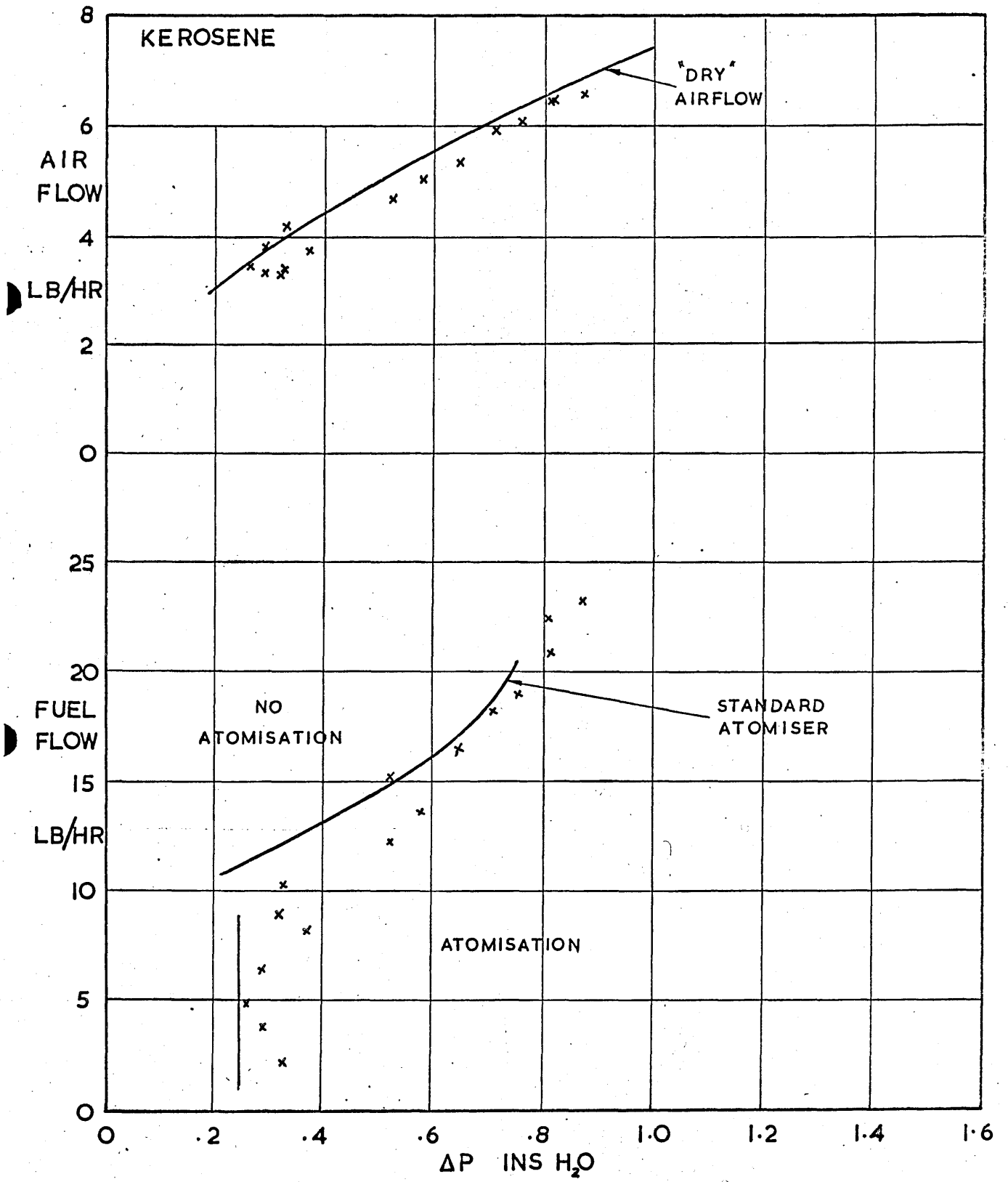
STARTING PERFORMANCE
EFFECT OF SWIRLER FLOW No



ATOMISER 1

FIG 21

STARTING PERFORMANCE
EFFECT OF LONG ORIFICE SWIRLER



ATOMISER 1

FIG 22

STARTING PERFORMANCE EFFECT OF LARGE PINTLE

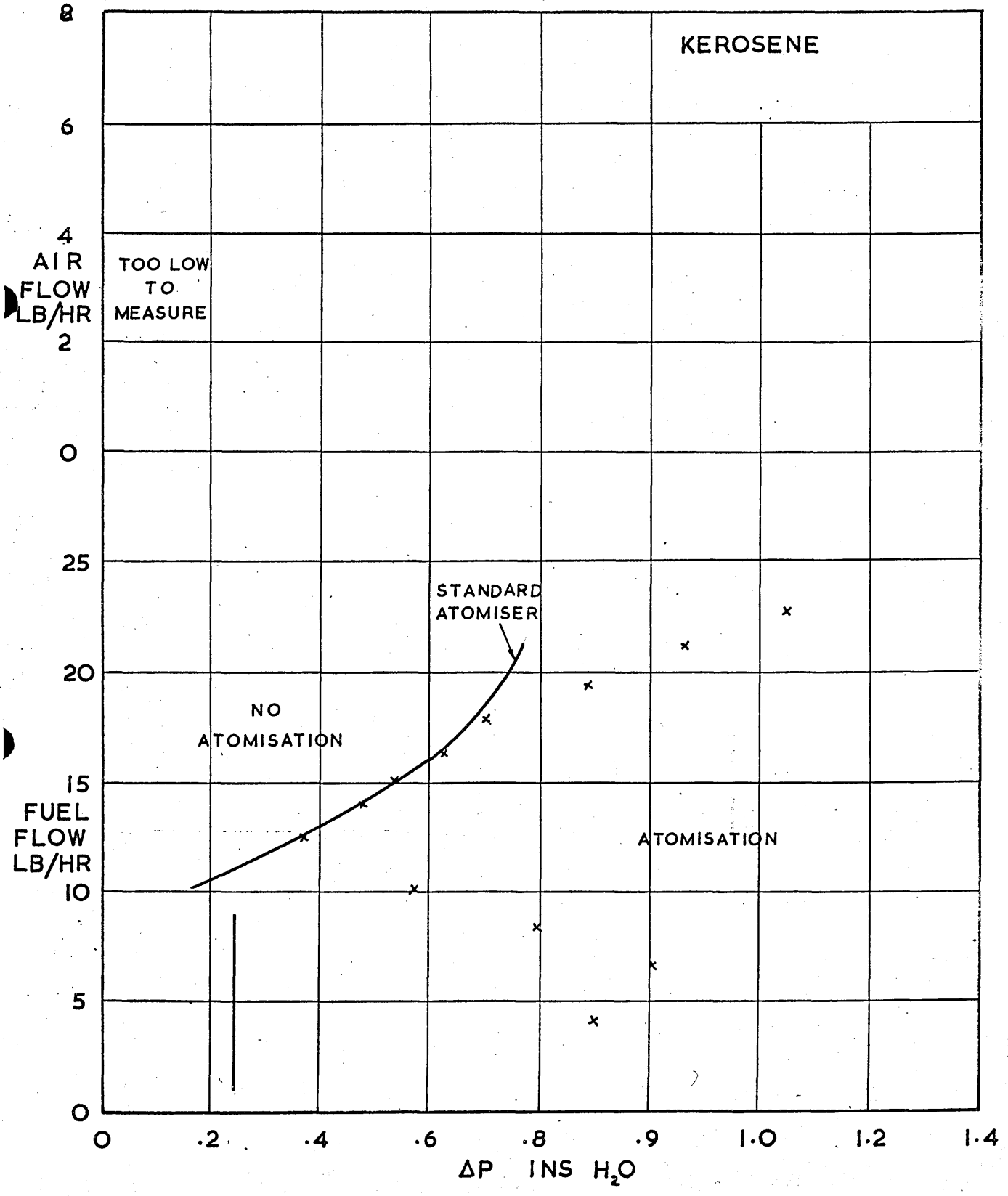
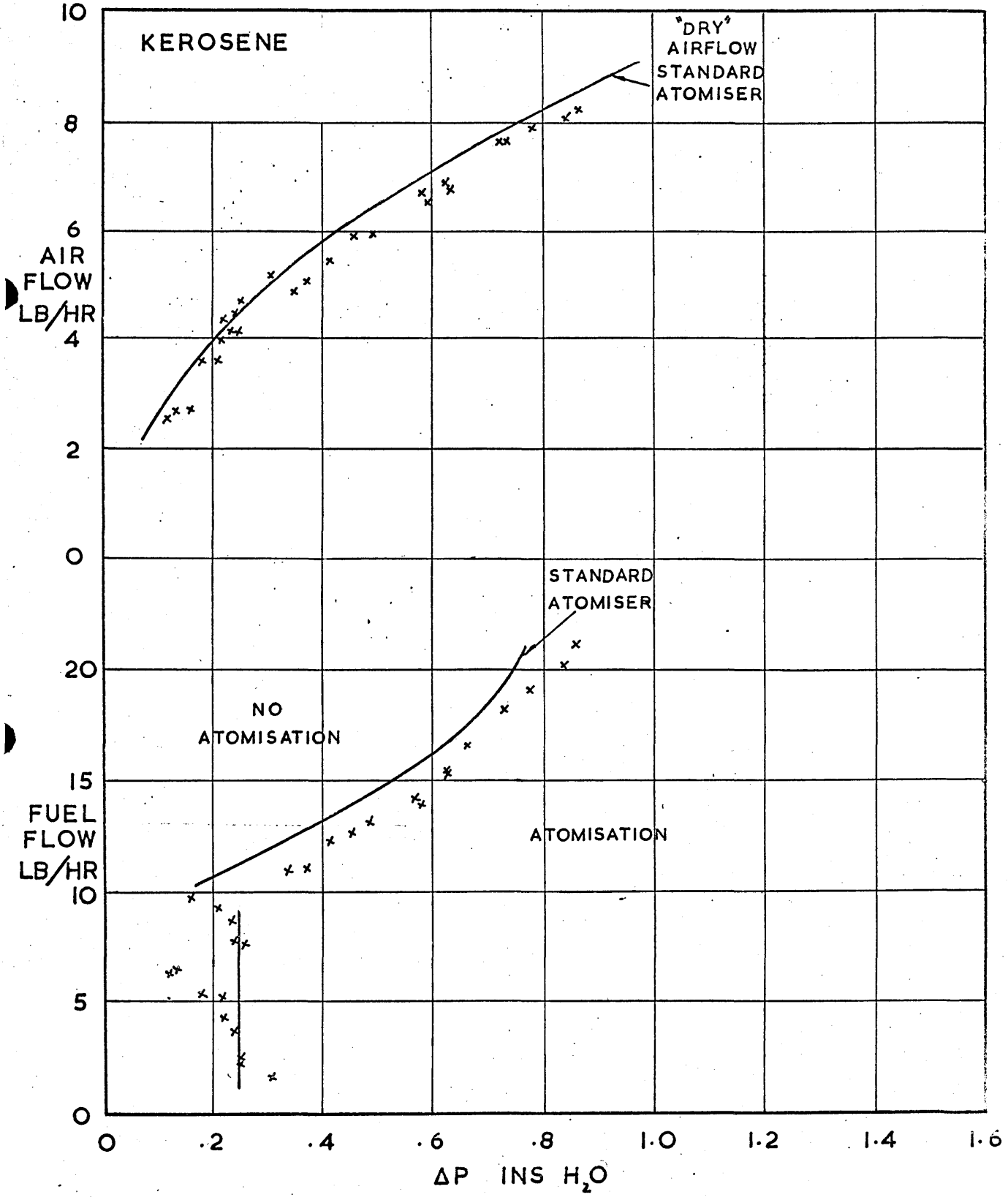


FIG 23

ATOMISER 1

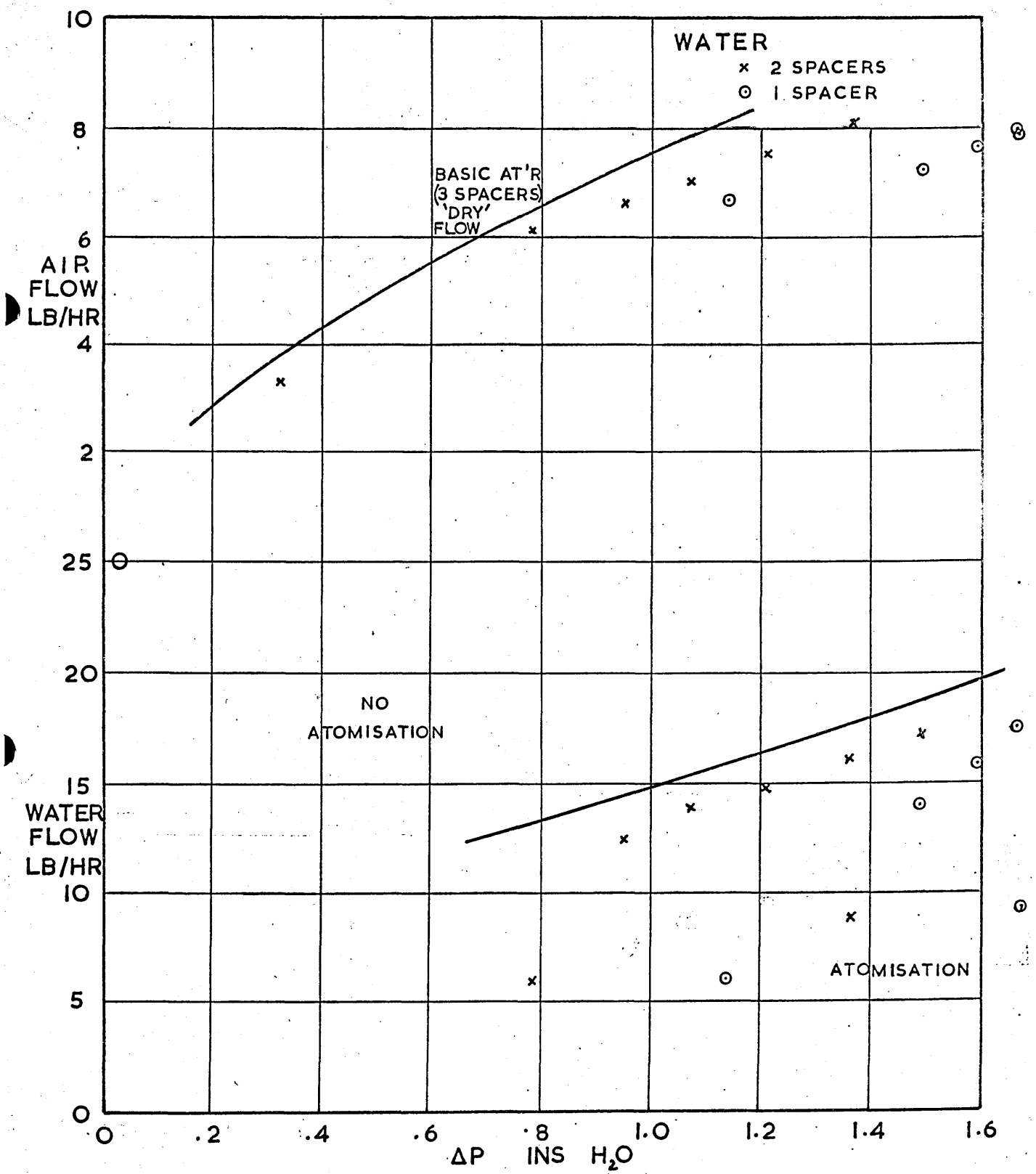
STARTING PERFORMANCE
EFFECT OF REMOVAL OF PINTLE



ATOMISER 1

FIG 24

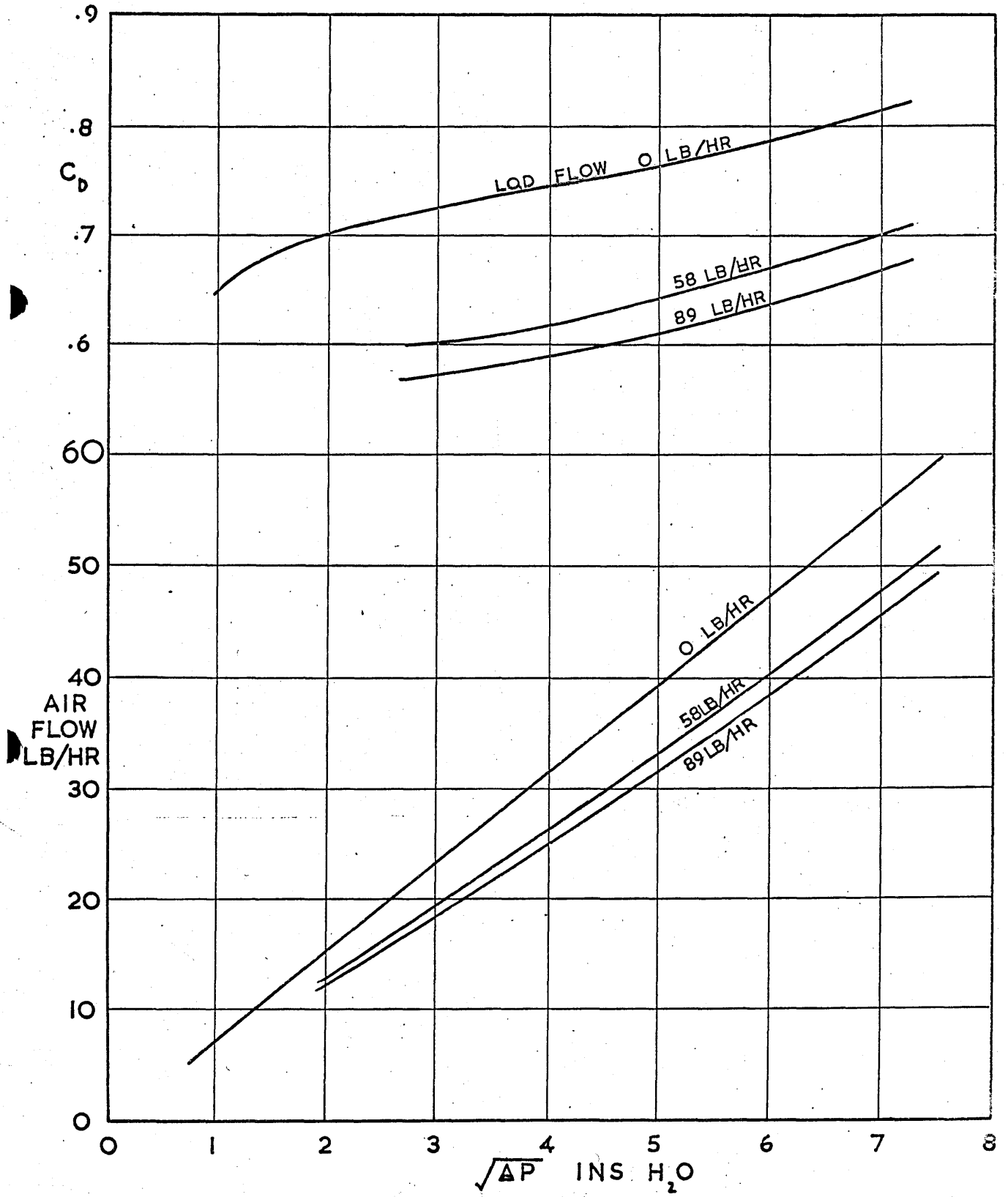
STARTING PERFORMANCE
EFFECT OF PINTLE POSITION



ATOMISER 2

FIG 25

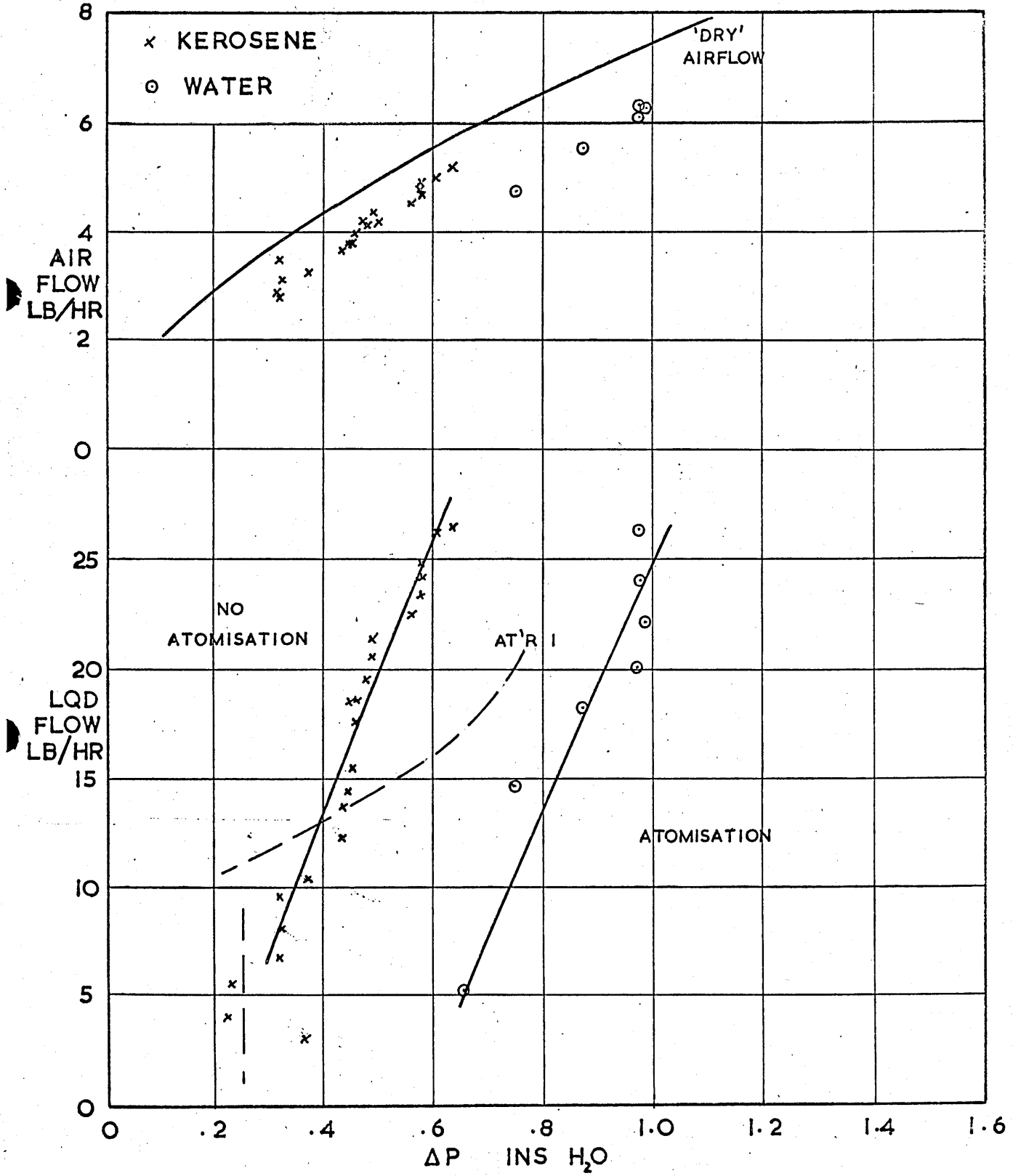
BASIC ATOMISER
AIRFLOW CHARACTERISTICS



ATOMISER 2

FIG 26

STARTING PERFORMANCE
BASIC ATOMISER



ATOMISER 2

FIG 27

STARTING PERFORMANCE
EFFECT OF SHROUD AIR BLANKING

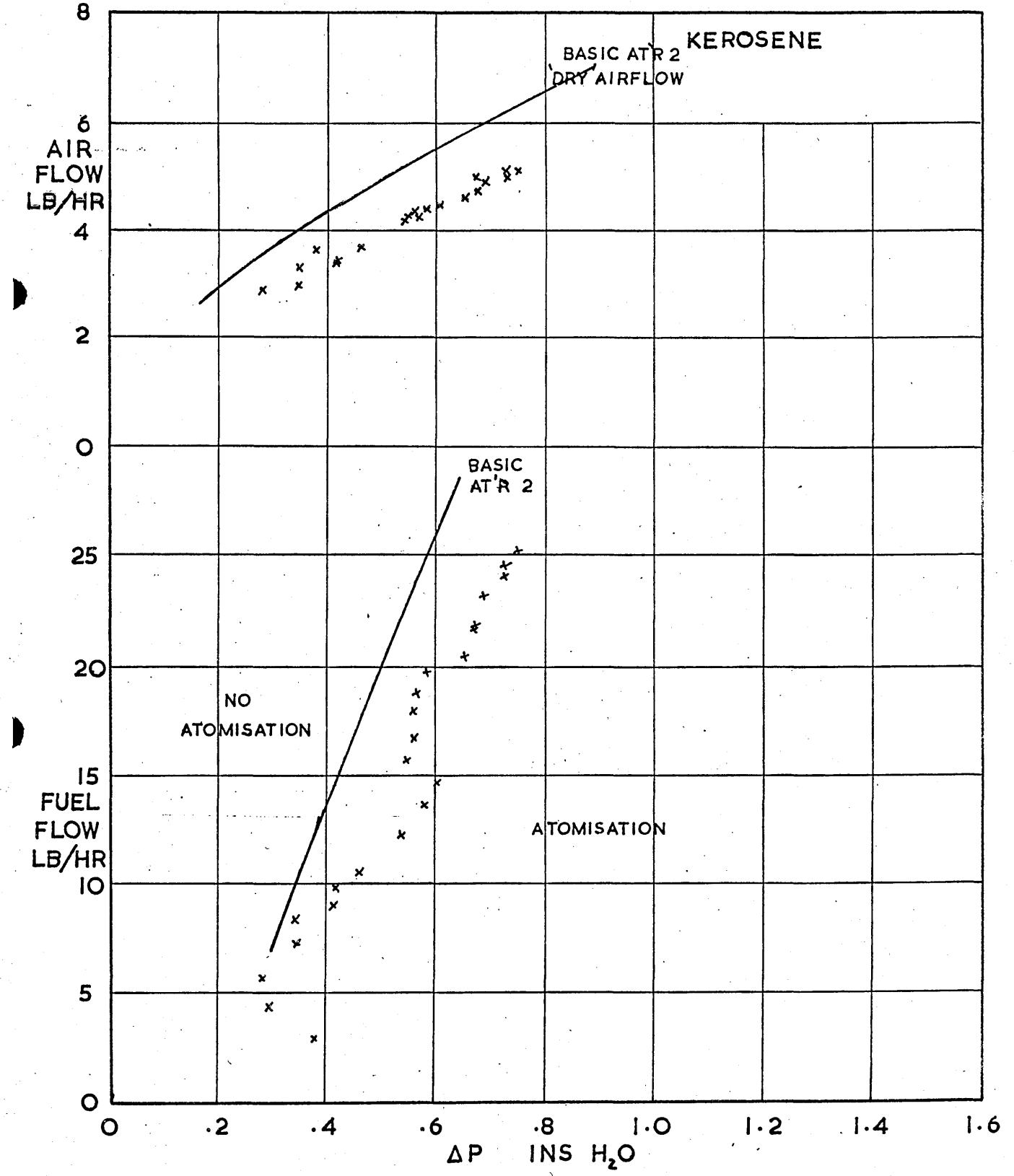


FIG 28

ATOMISER 2

STARTING PERFORMANCE
EFFECT OF LARGE PINTLE

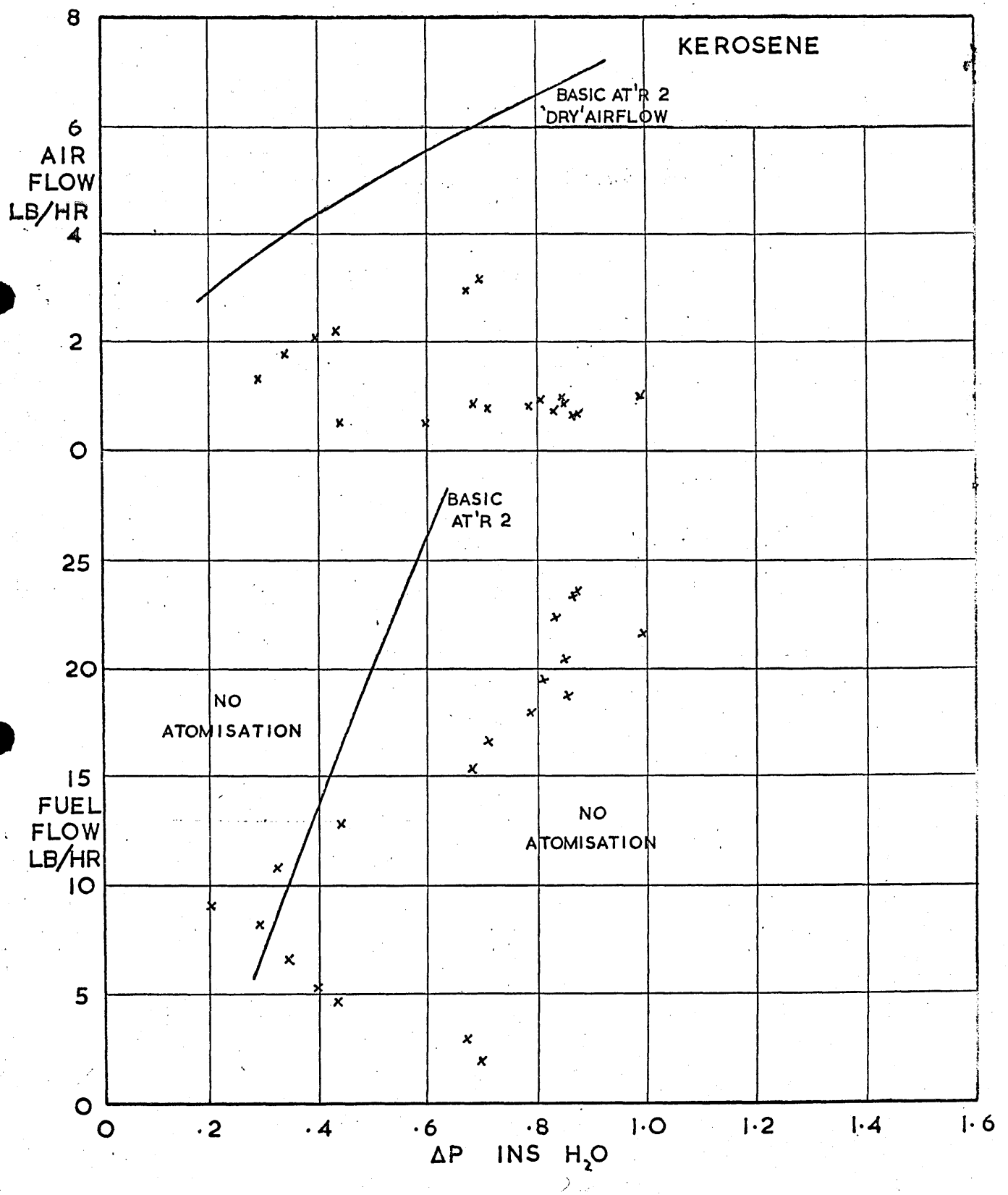


FIG 29

ATOMISER 2

STARTING PERFORMANCE
EFFECT OF REMOVAL OF PINTLE

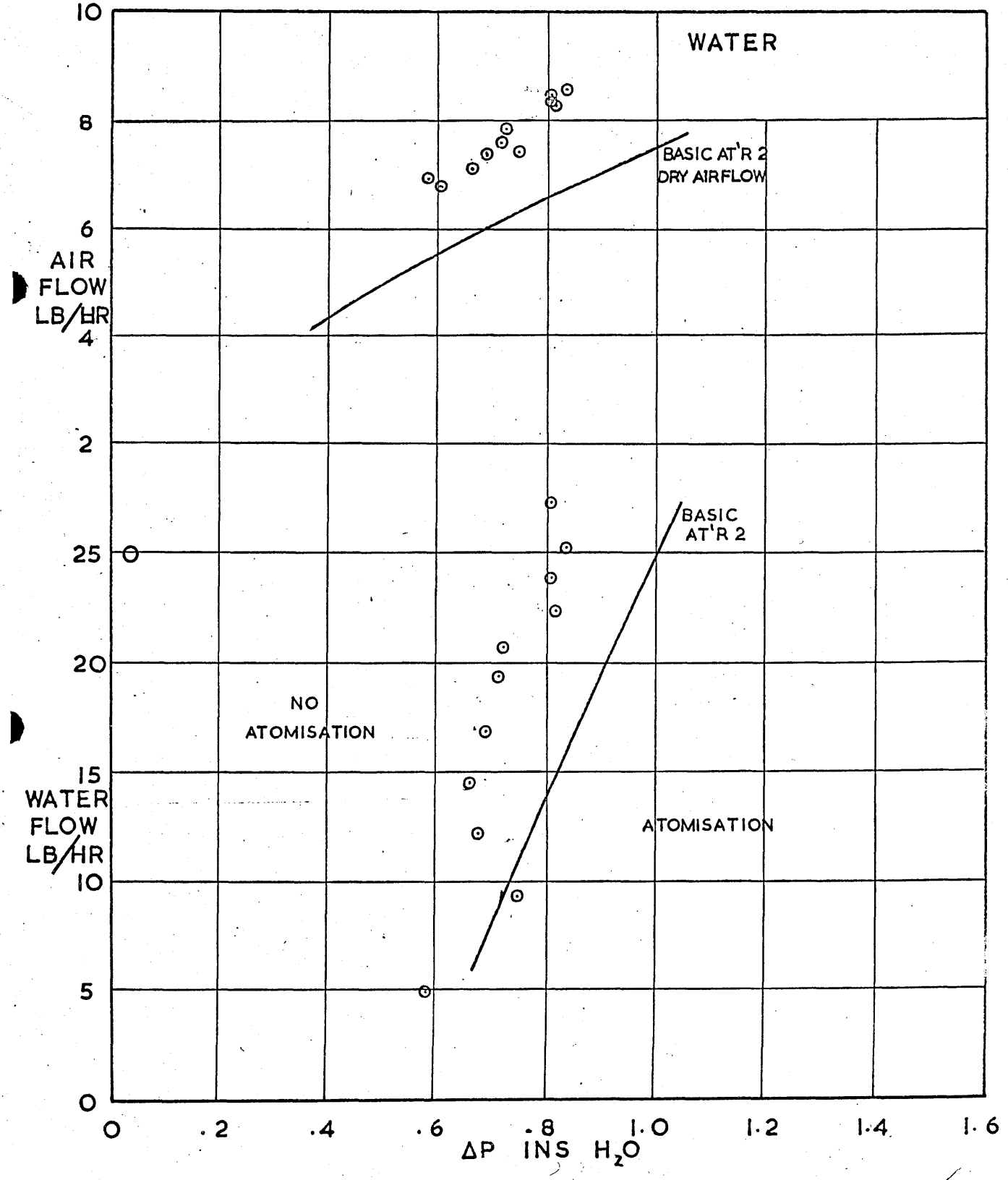
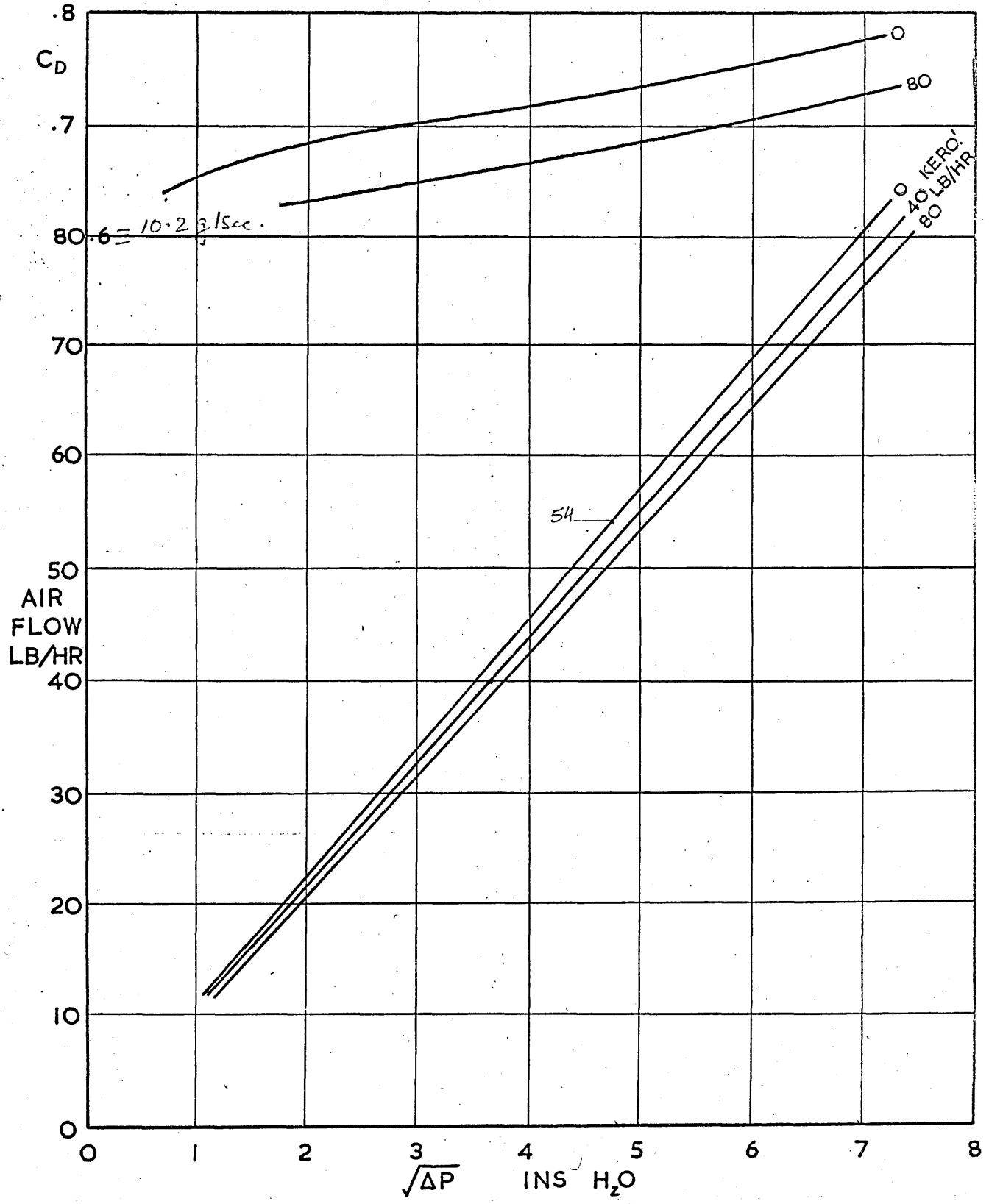


FIG 30

ATOMISER 3

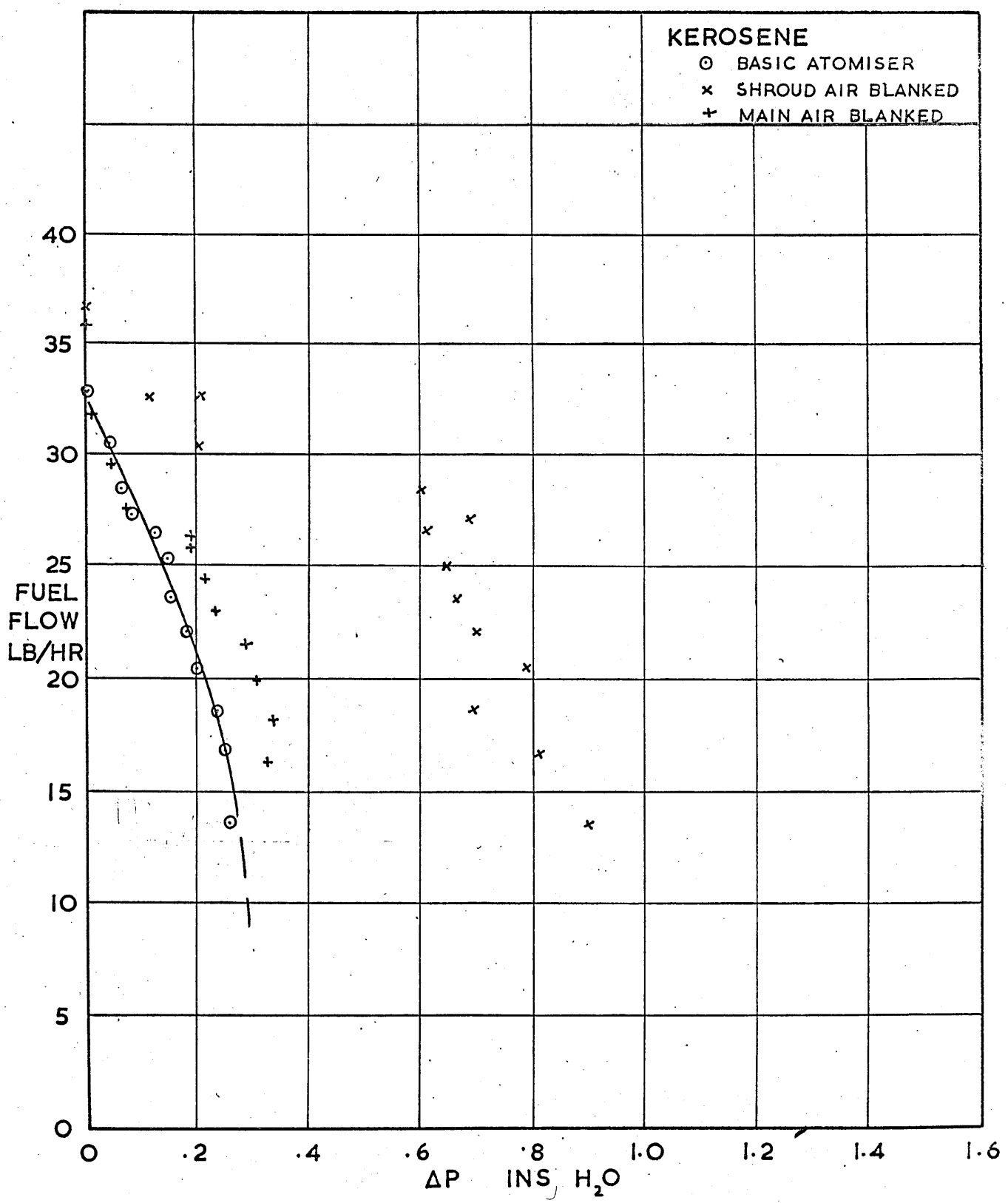
AIRFLOW CHARACTERISTICS



ATOMISER 3

FIG 31

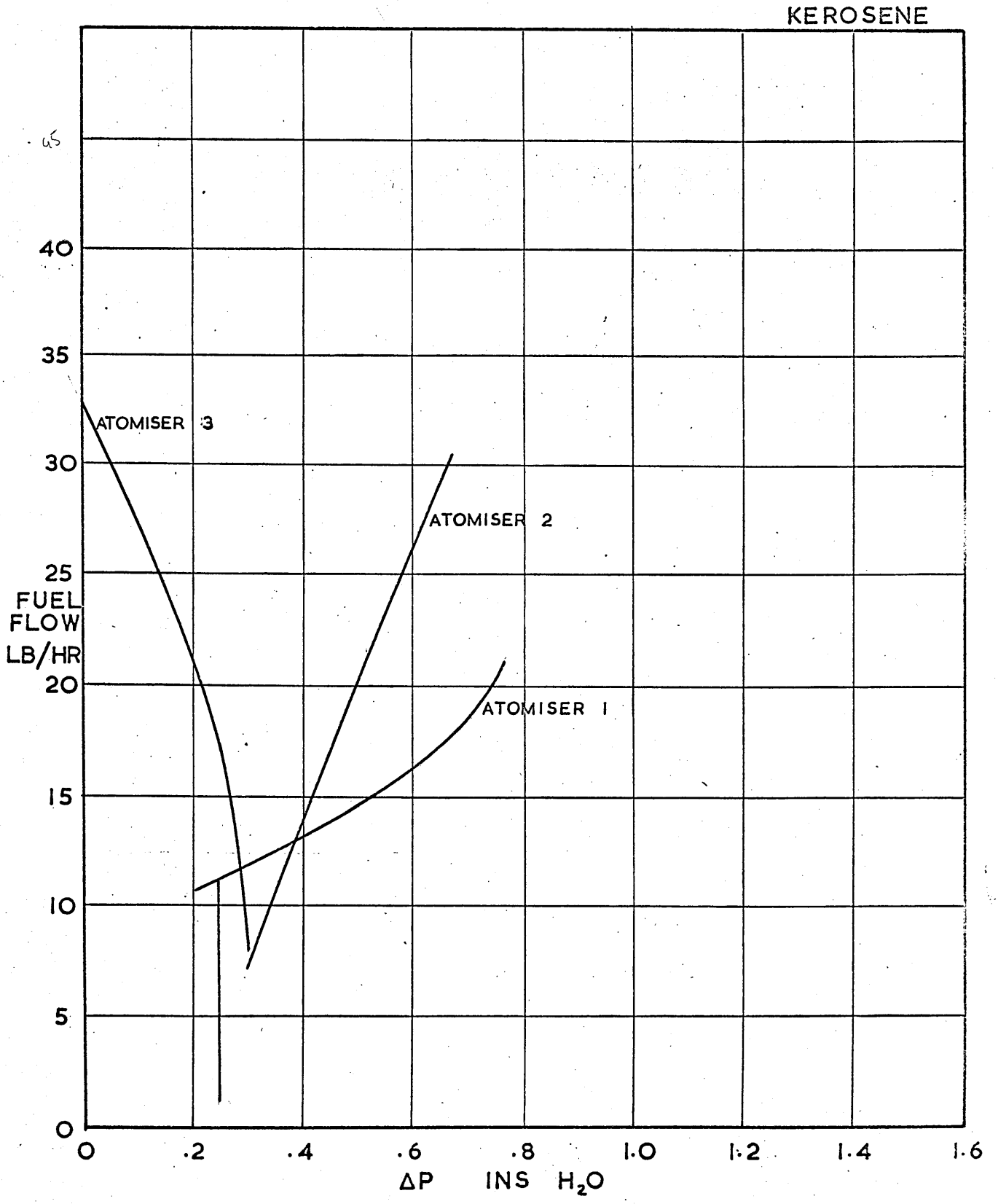
STARTING PERFORMANCE



ATOMISERS 1, 2 AND 3

FIG 32

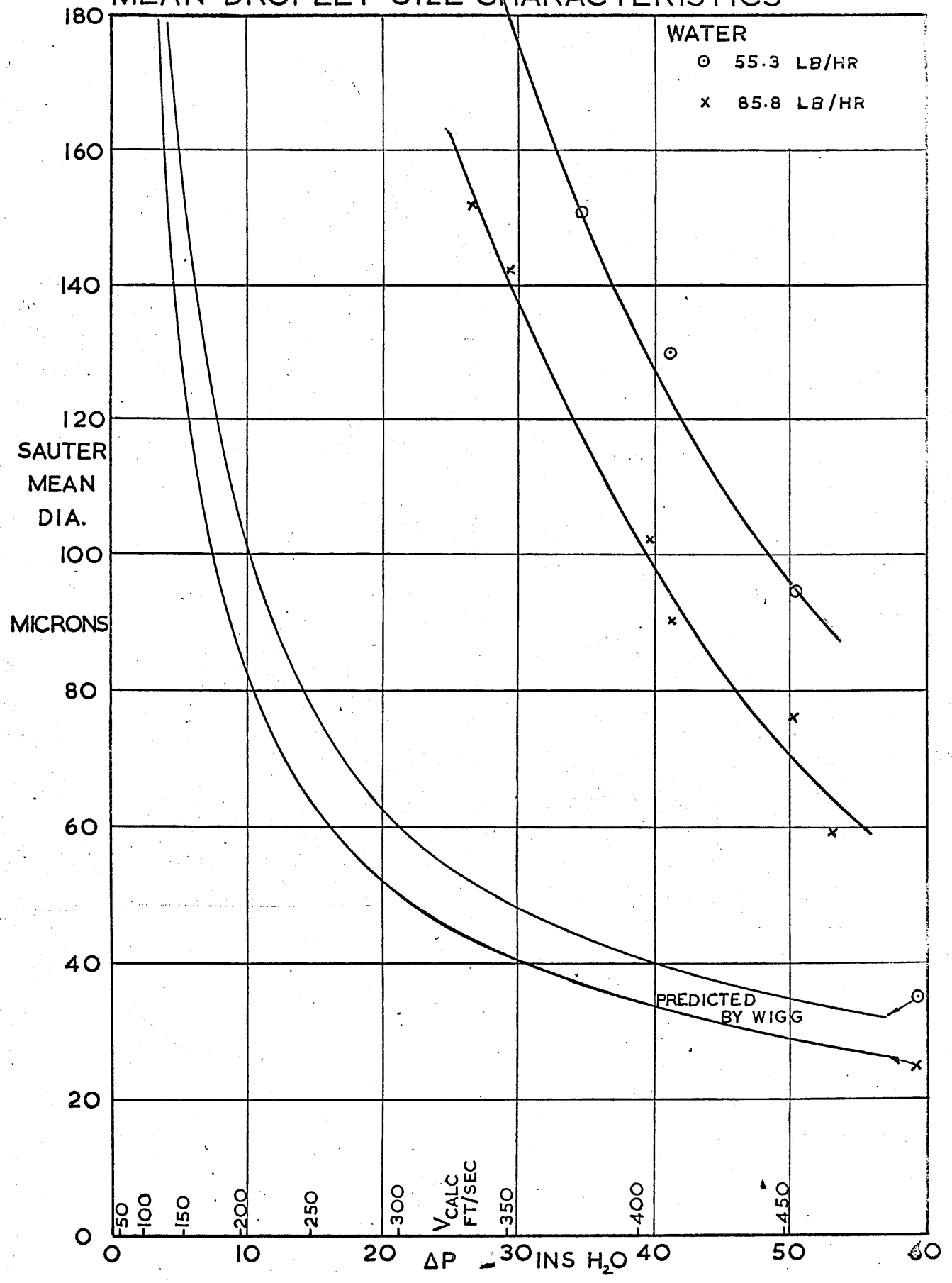
COMPARISON OF STARTING PERFORMANCE



ATOMISER 1

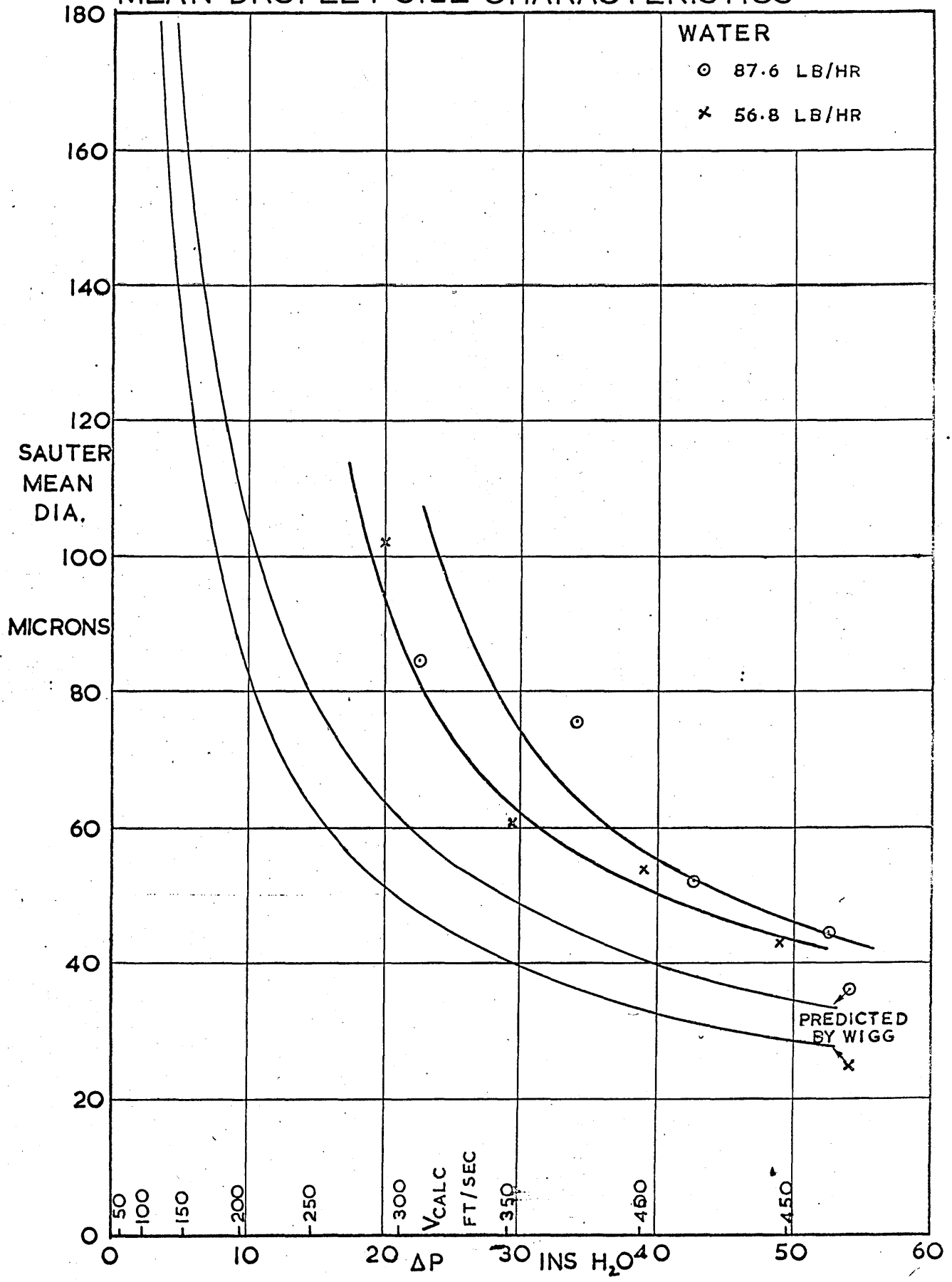
MEAN DROPLET SIZE CHARACTERISTICS

FIG 33



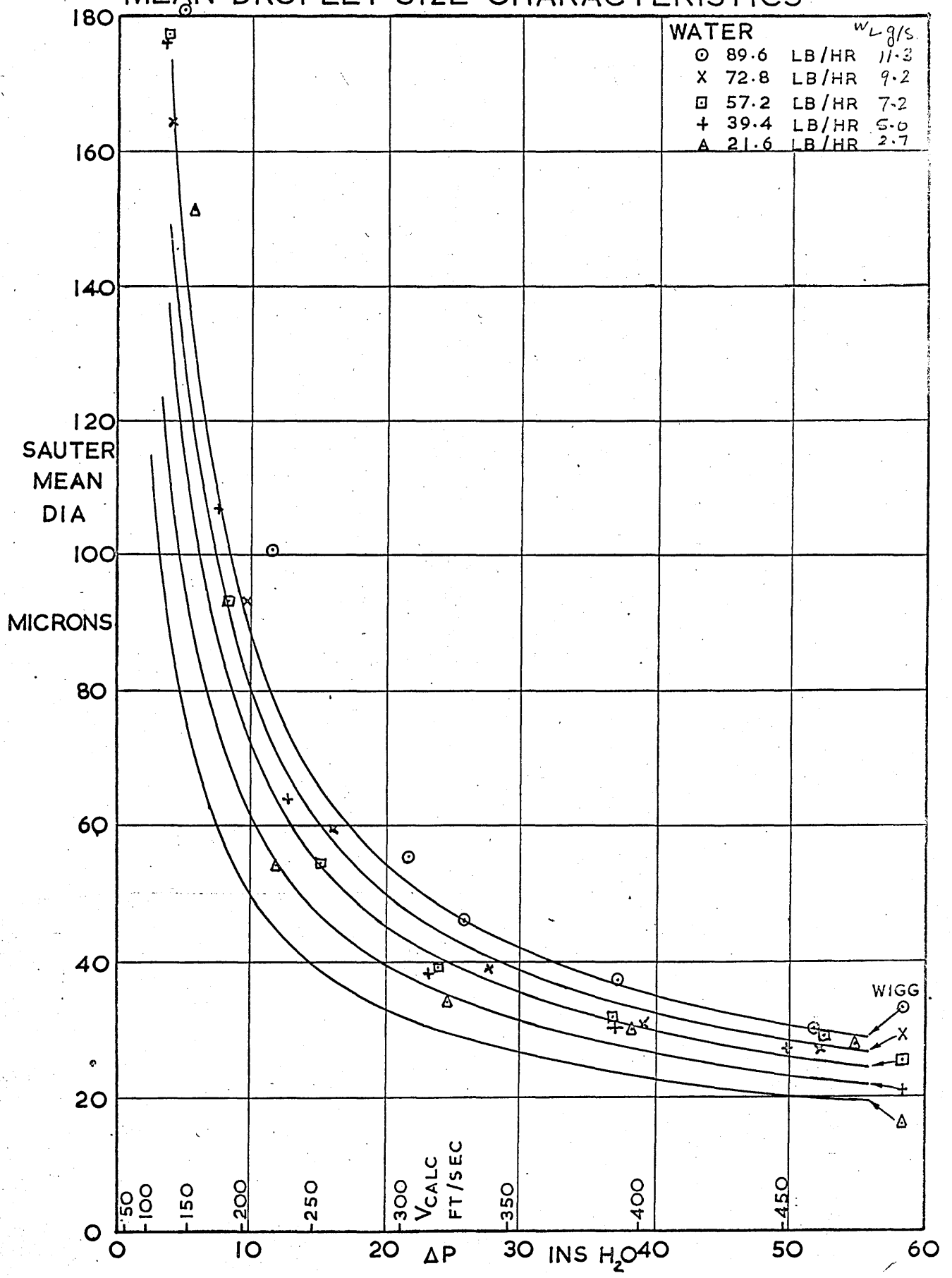
ATOMISER 2
MEAN DROPLET SIZE CHARACTERISTICS

FIG 34



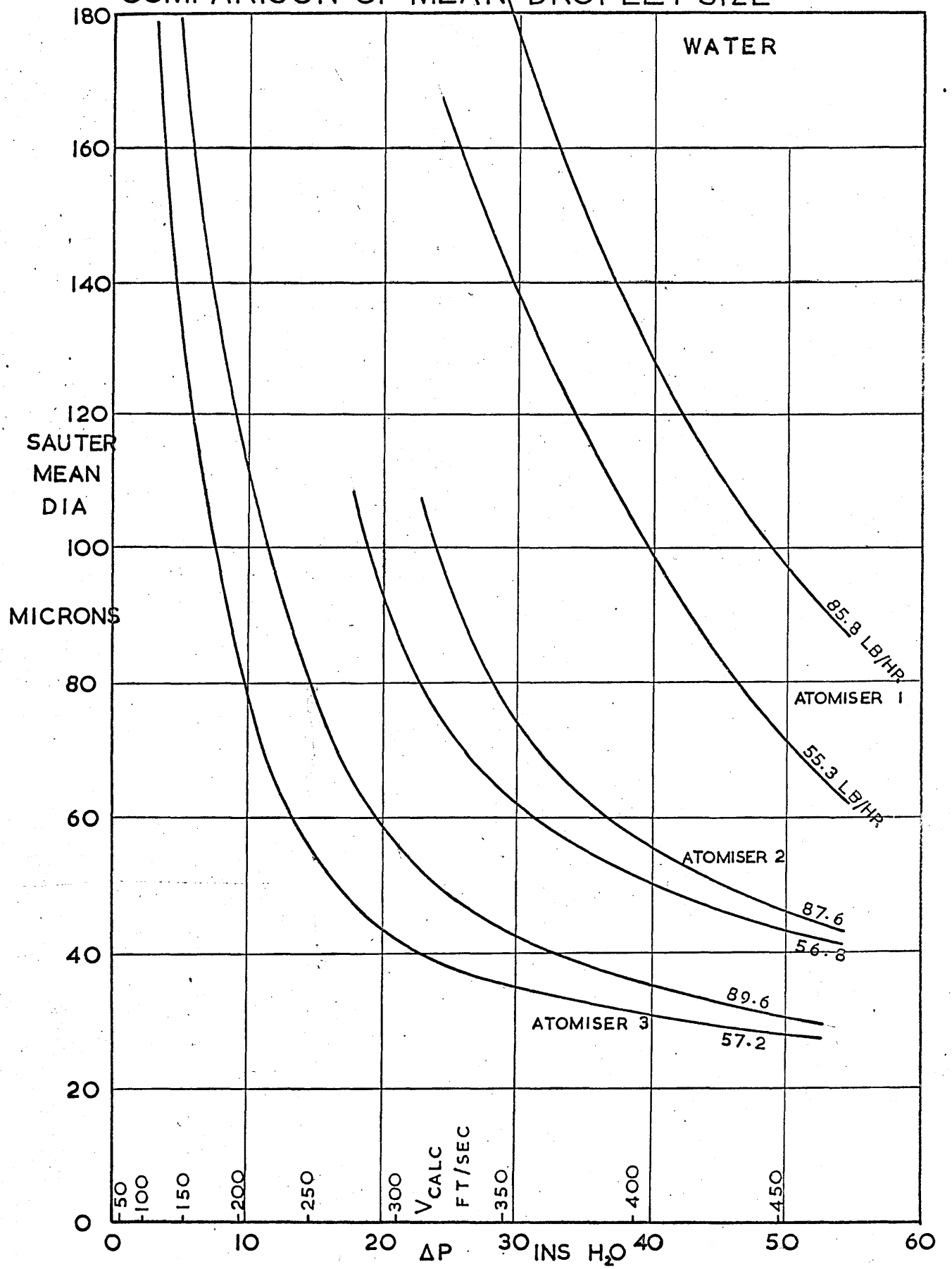
ATOMISER 3
MEAN DROPLET SIZE CHARACTERISTICS

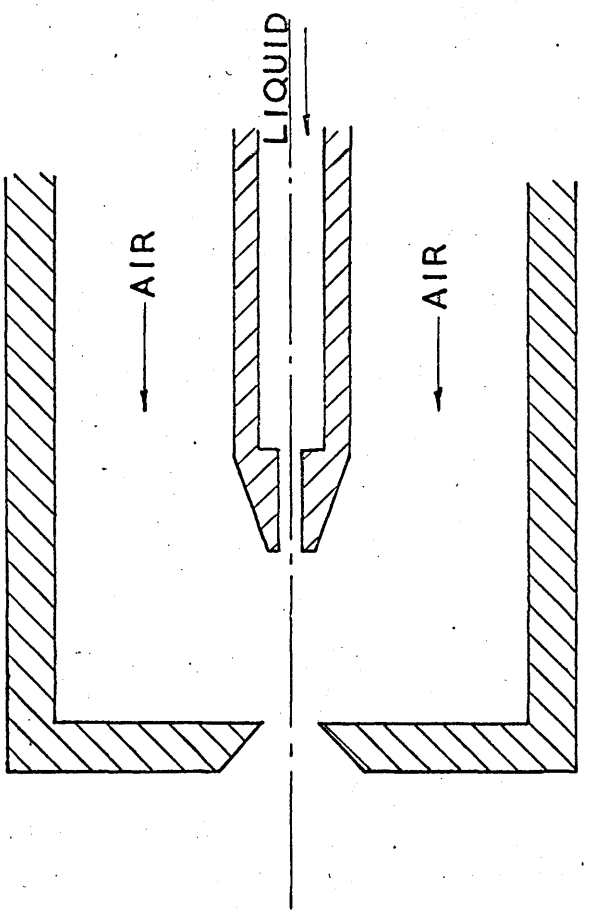
FIG 35



ATOMISERS 1, 2 AND 3
COMPARISON OF MEAN DROPLET SIZE

FIG 36





THE NUKIYAMA-TANASAWA ATOMISER

FIG 38

DROPLET SIZE-FREQUENCY HISTOGRAM

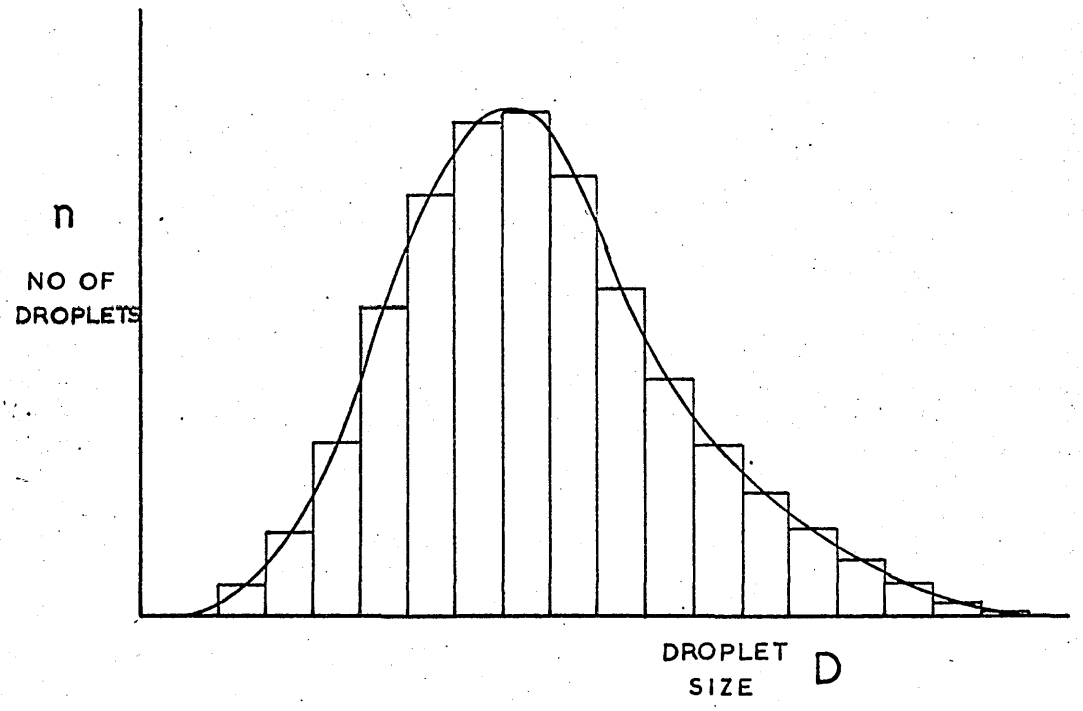
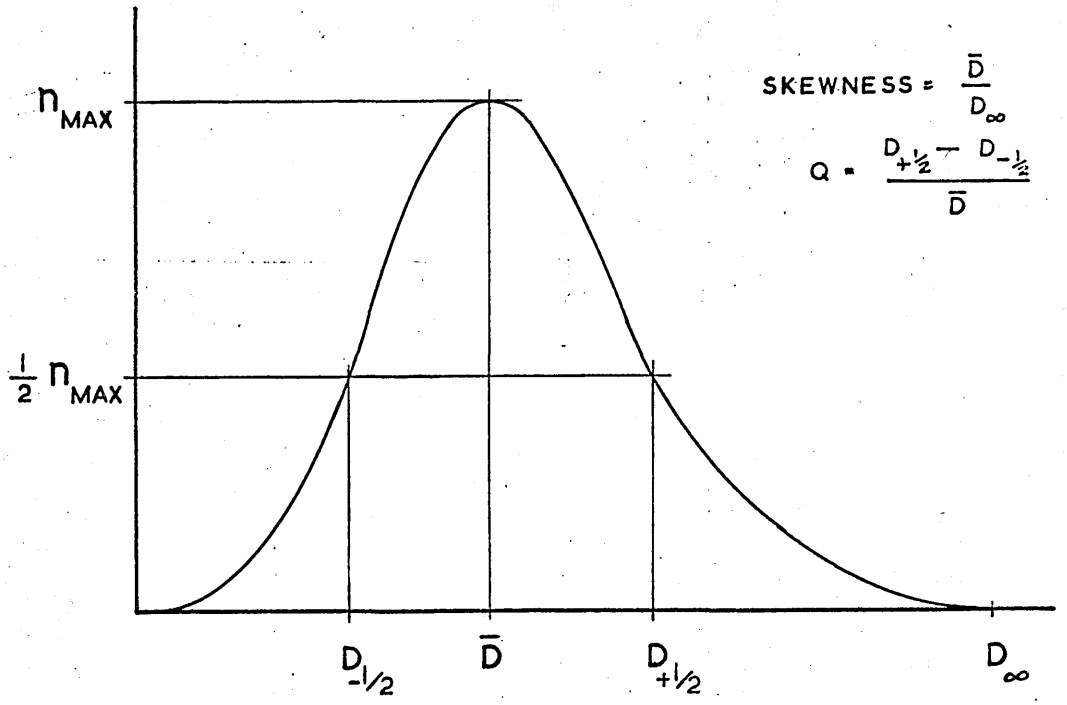


FIG 39

DEFINITION OF THE U.L.D.F.



MEAN THEORETICAL ILLUMINATION PROFILE

FIG 40

DOBBINS, CROCCO AND GLASSMAN

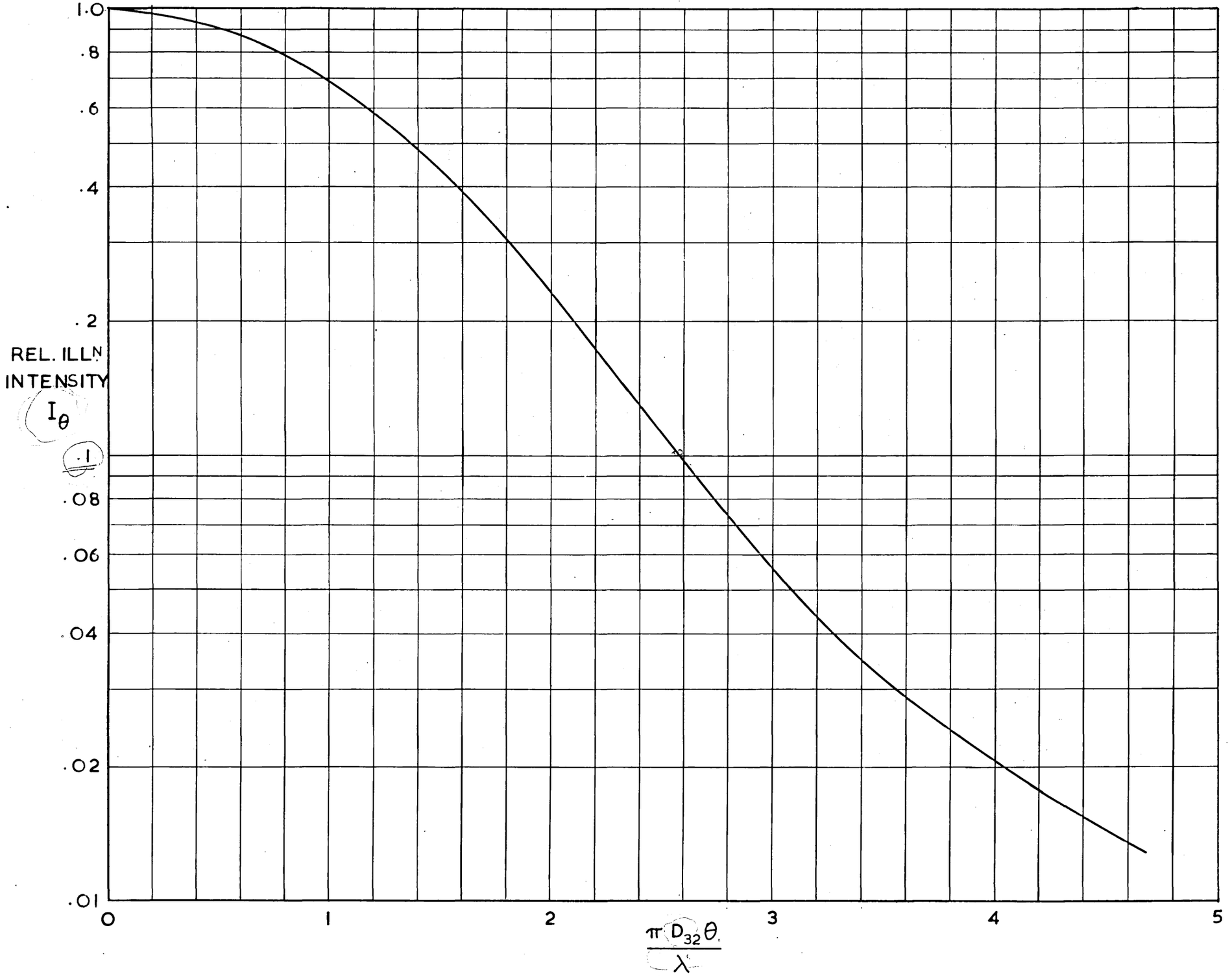
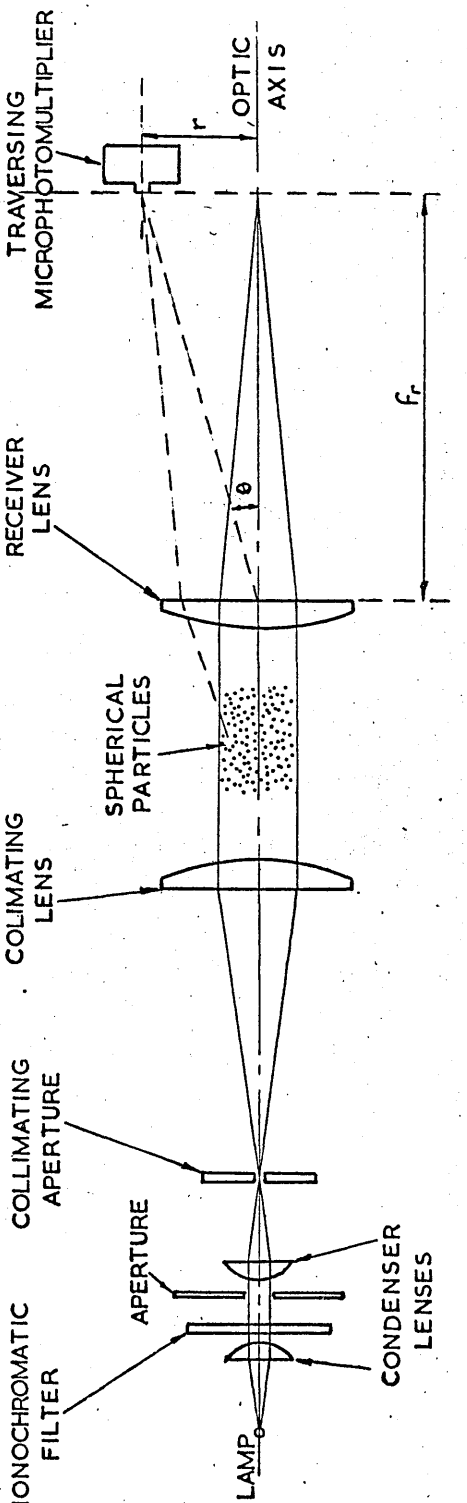


FIG 41

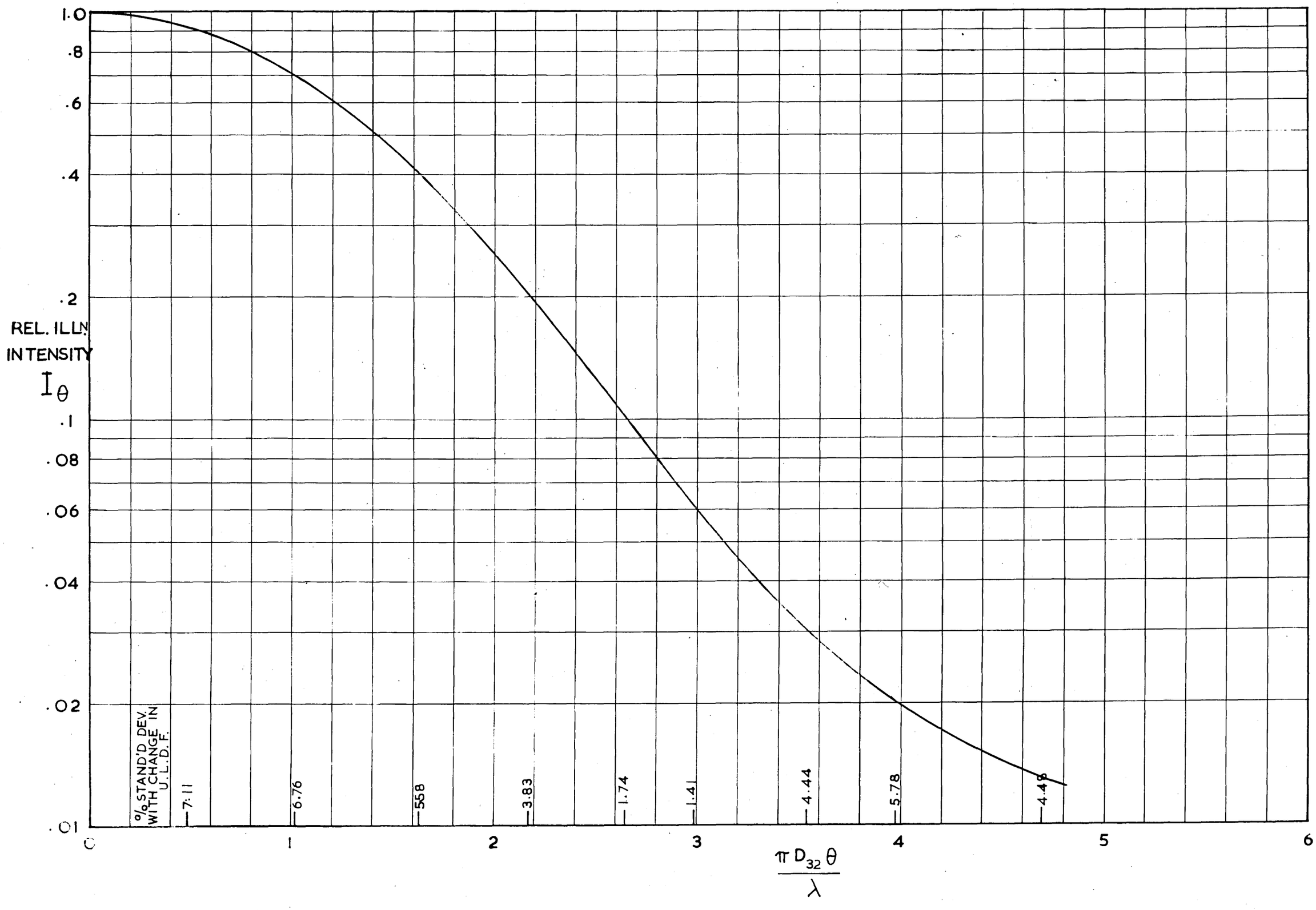


DOBBINS OPTICAL APPARATUS

MEAN THEORETICAL ILLUMINATION PROFILE

FIG 42

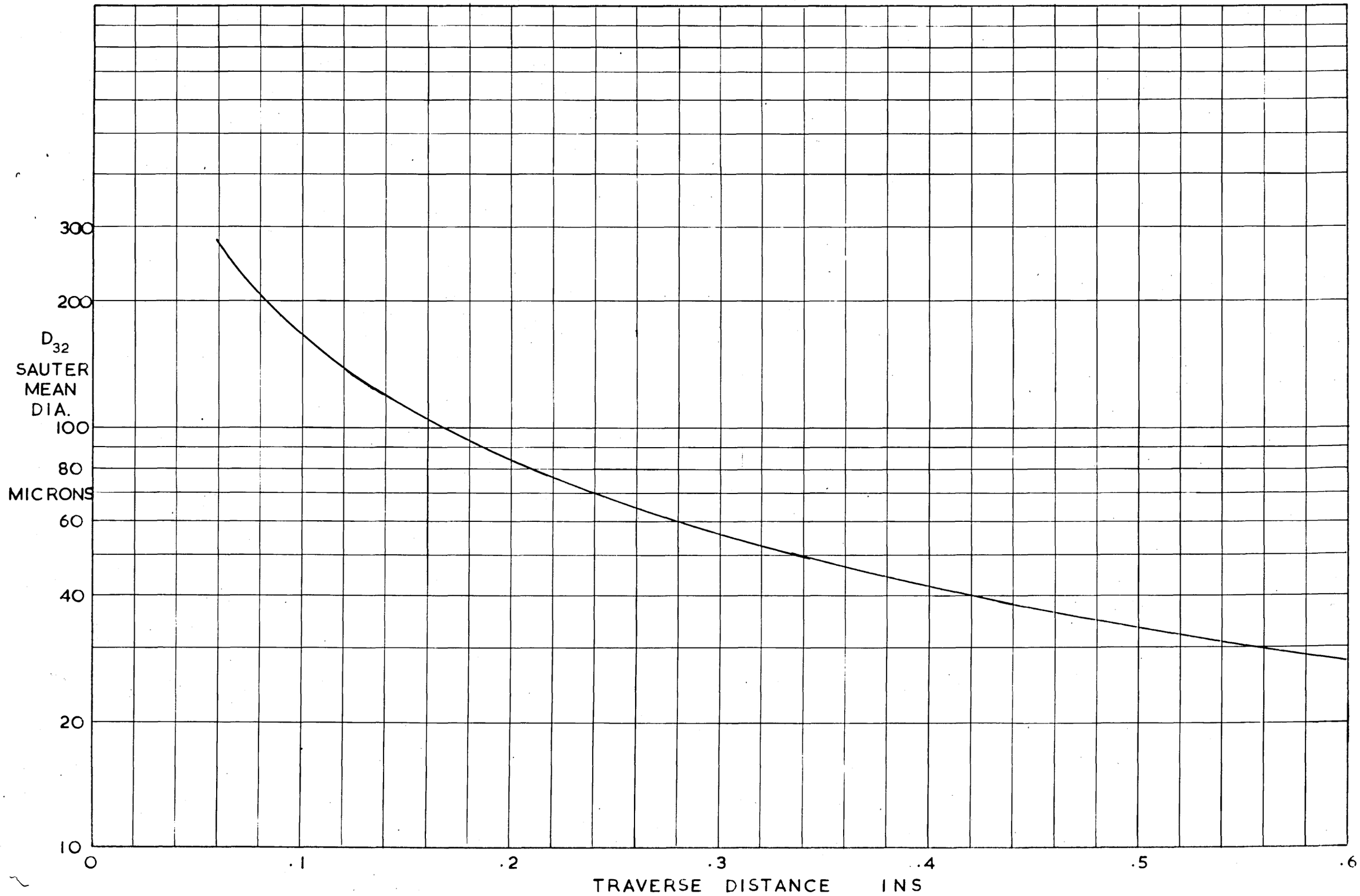
ROBERTS AND WEBB



DROPLET SIZE v. TRAVERSE DISTANCE (FROM ROBERTS AND WEBB)

FIG 43

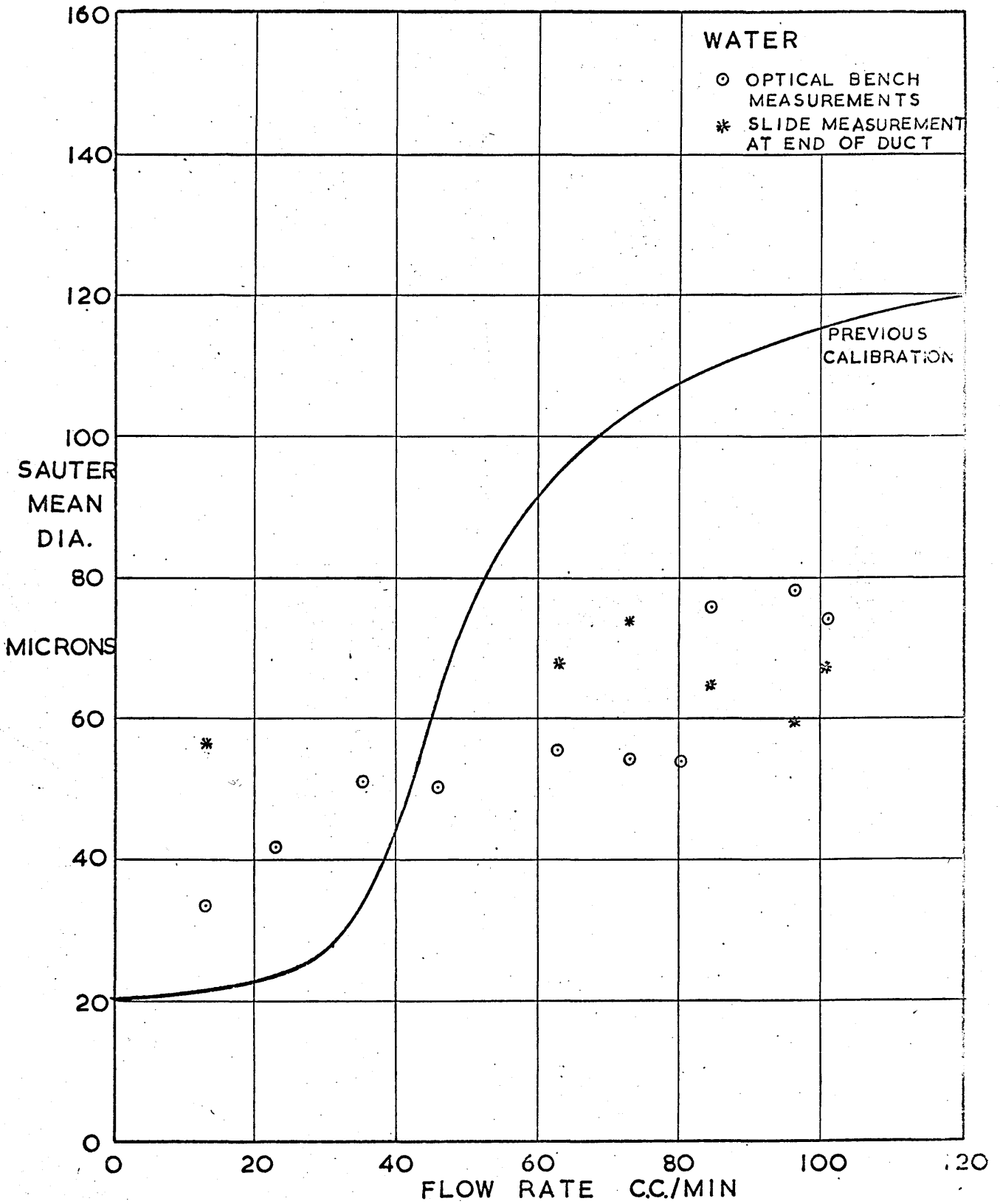
$I_\theta = .1$



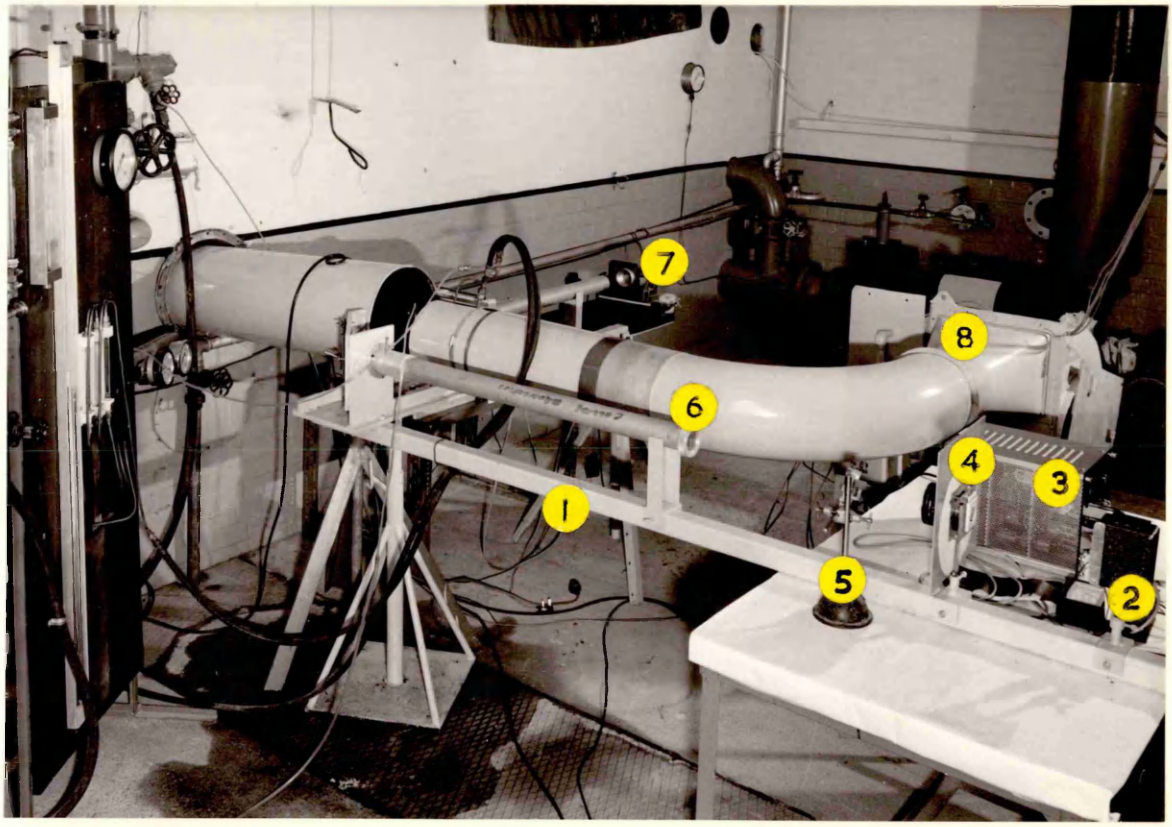
ULTRASONIC ATOMISER

FIG 44

DROPLET SIZE CHARACTERISTICS



EXPERIMENTAL APPARATUS
GENERAL VIEW



1 OPTICAL BENCH

2 MERCURY-VAPOUR LAMP

3 LAMP CONTROL UNIT

4 CONDENSER LENS

5 FILTER STAND

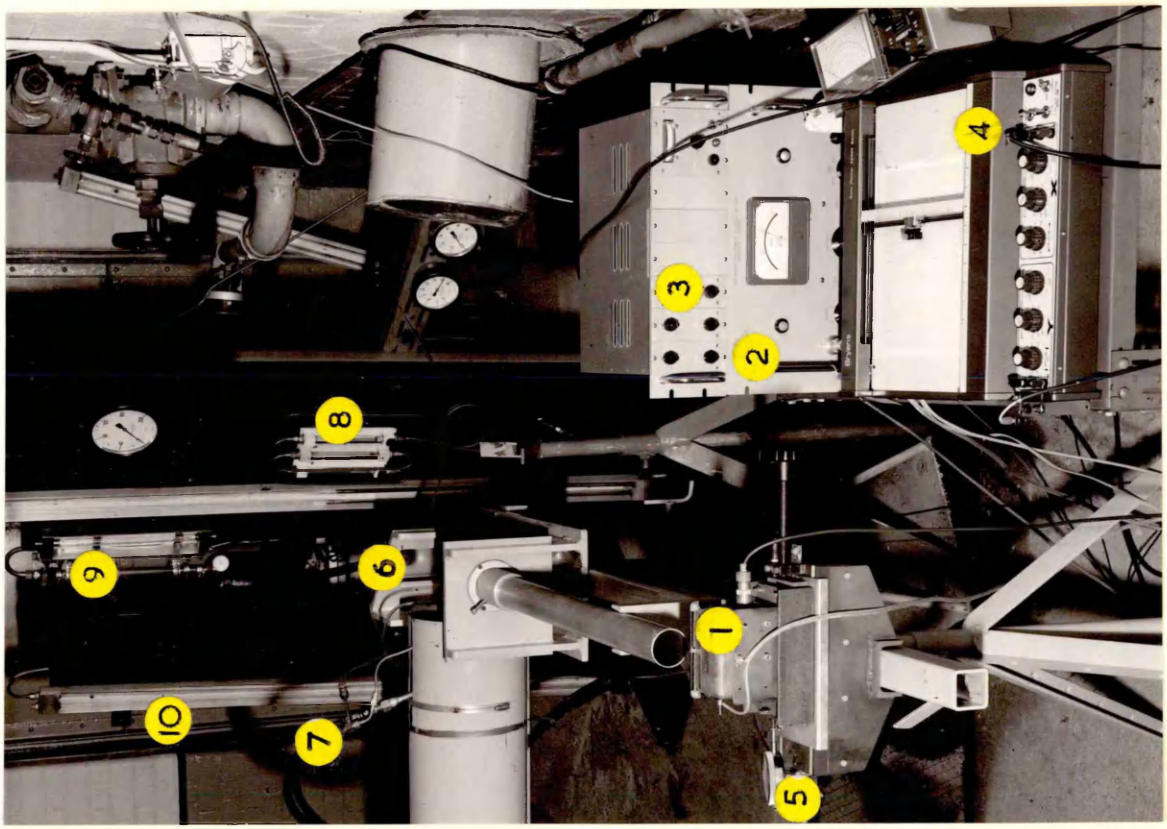
6 COLLIMATING APERTURE

7 PHOTOMULTIPLIER

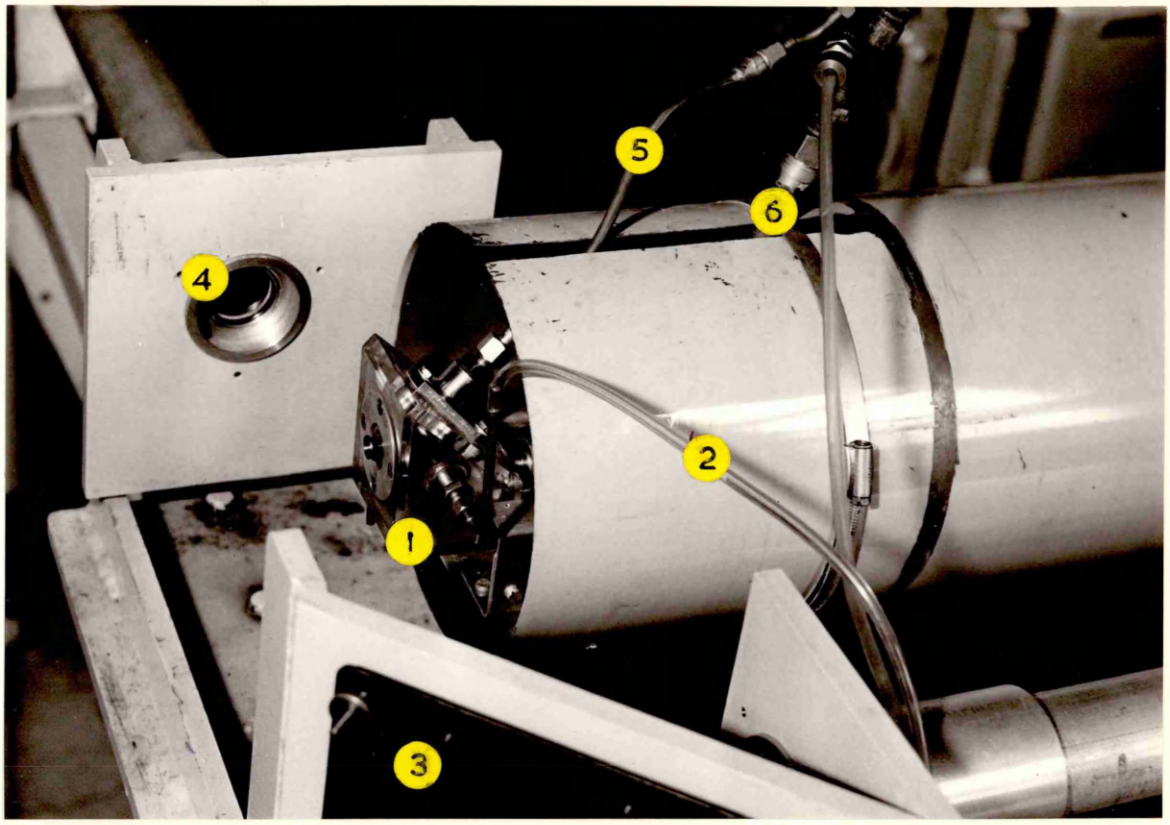
8 FAN

EXPERIMENTAL APPARATUS
PHOTOMULTIPLIER AND AUTOPLOTTER

1 PHOTOMULTIPLIER
2 H.T. SUPPLY
3 TRANSDUCER AMPLIFIER
4 AUTOPLOTTER
6 MIRROR
7 FUEL AND AIR SUPPLIES
8 LIQUID FLOWMETERS
9 AIR FLOWMETER
10 WATER MANOMETER
5 D.T.I.



EXPERIMENTAL APPARATUS
ATOMISER MOUNTING



1 PERSPEX AIRPOT AND ATOMISER

2 STATIC TAPPING

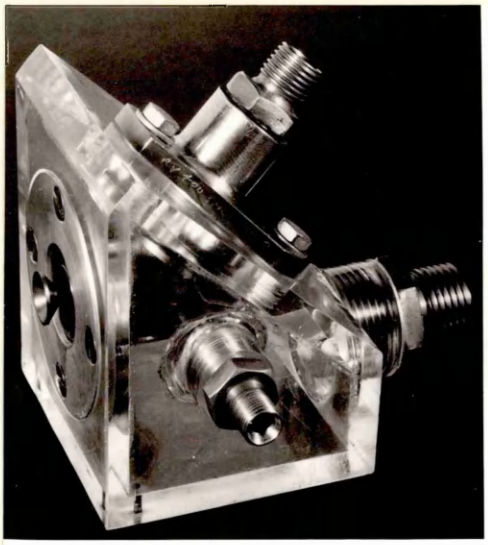
3 MIRROR

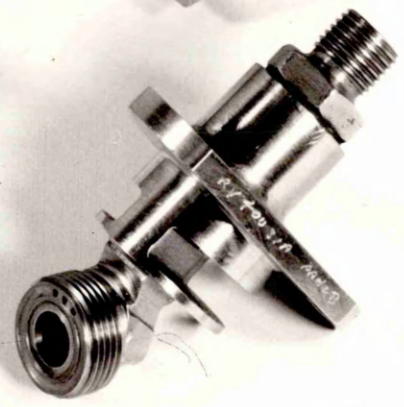
4 RECEIVER LENS

5 LIQUID SUPPLY

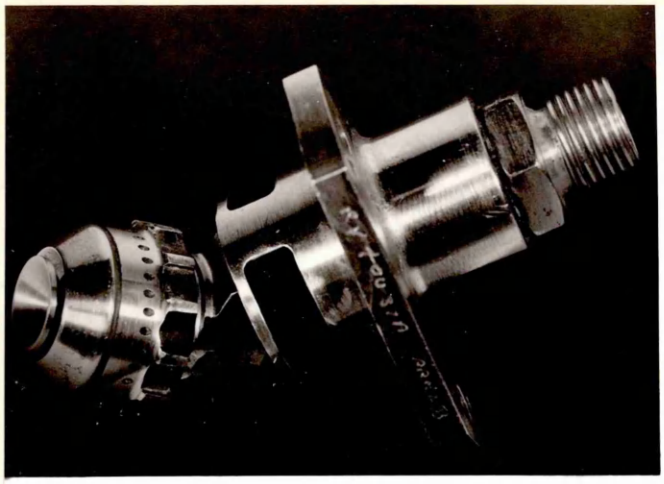
6 AIR SUPPLY

ATOMISER I





ATOMISER 2

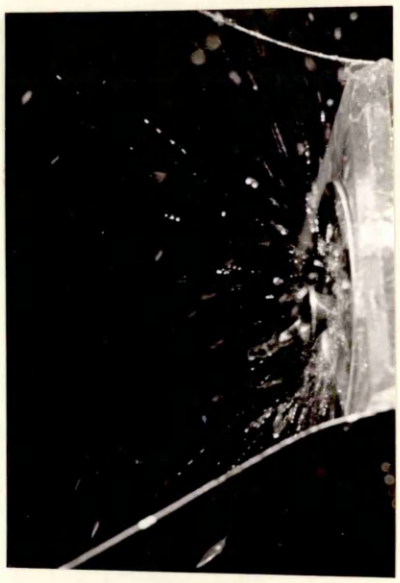


ATOMISER 3

SPRAY CHARACTERISTICS

$\Delta P = 0$

$\Delta P = 1$ INS H_2O



$\Delta P = 2$ INS H_2O

FUEL FLOW = 90 LB / HR

$\Delta P = 3$ INS H_2O

SPRAY CHARACTERISTICS

ΔP = 0

ΔP = 1 INS H_2O

ΔP = 2 INS$_2$HO

FUEL FLOW = 90 LB/HR

ΔP = 3 INS H_2O

ATOMISER 3

PLATE 9

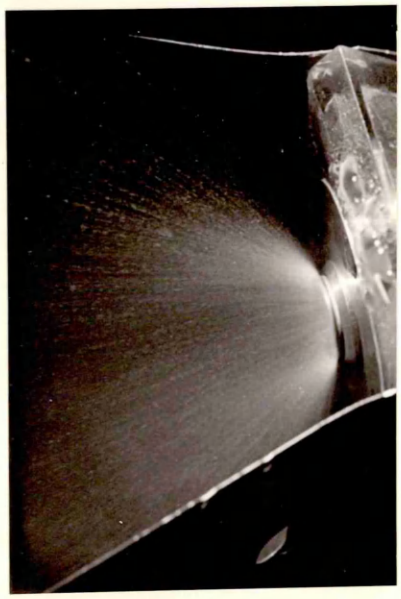
SPRAY CHARACTERISTICS

ΔP = 0

FUEL FLOW = 90 LB/HR

ΔP = 1 INS H_2O

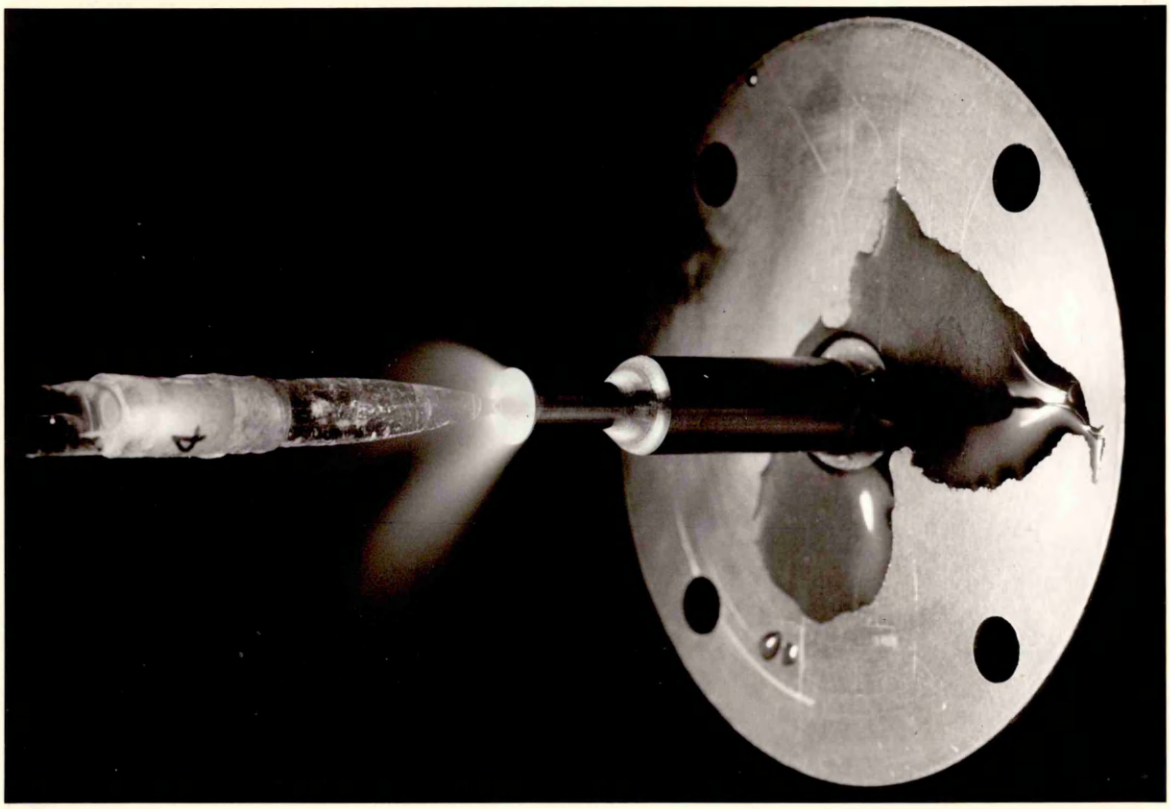
ΔP = 2 INS H_2O

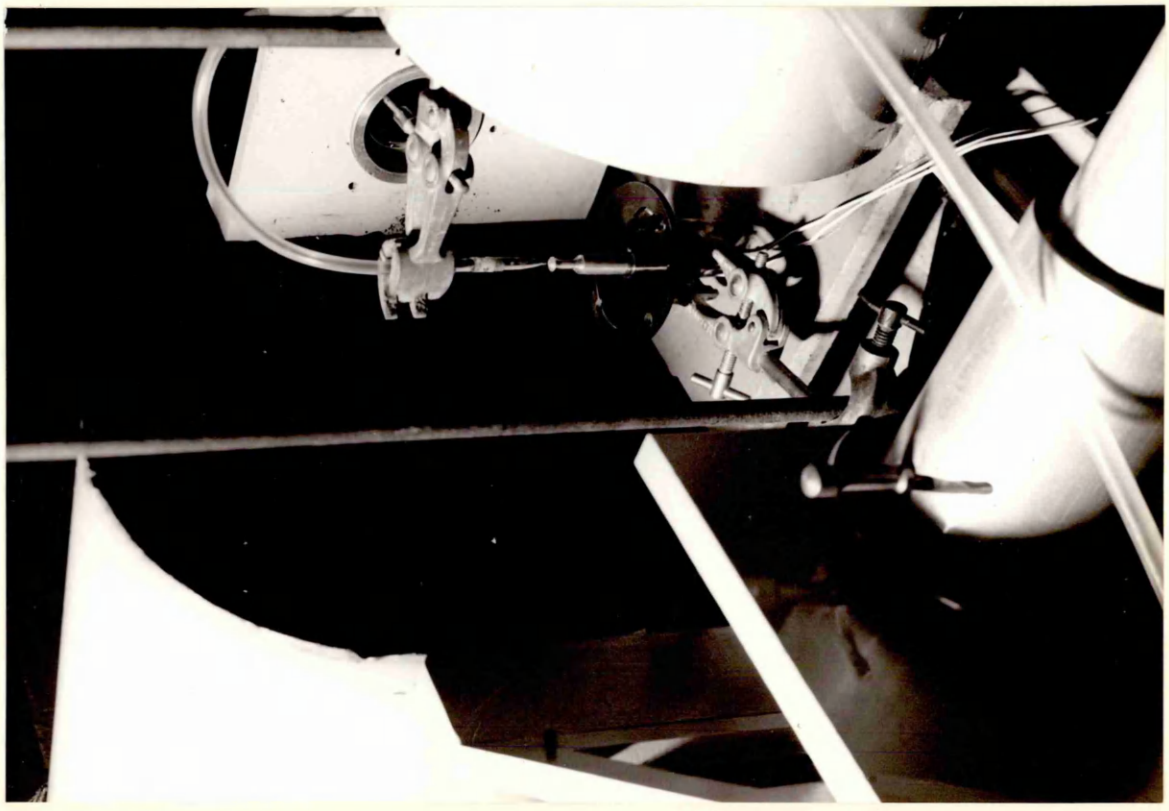


ΔP = 3 INS H_2O

ULTRASONIC ATOMISER

PLATE 10





Drawing PC7303 "Scheme for airblast atomiser H. P. test rig" retained in Propulsion Department.