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TECHNIQUES FOR EXAMINING DROP SIZE SPECTRA IN WATER SPRAYS AND CLOUDS

by

F. W. SKIDMORE and R. E. PAVIA

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SUMMARY

Qualitative comparisons have been made of water drop sampling methods for sprays and clouds, employing slides coated with oil, gelatin and soot. Oil-wetted and soot coated slides have been compared quantitatively when exposed in nominally identical water sprays simulating natural clouds. When compared with gelatin and oil-wetted slides, soot slides are more convenient to prepare, expose and analyse, and records are permanent. Within the inherent limitations of all spray sampling methods, drop size distributions and mean drop sizes given by the oil and soot methods are in substantial agreement, provided that known sources of error of the oil-wetted method are allowed for. Soot slides appear to be capable of detecting ice particles in clouds; quantitative calibrations relating ice impingement impressions to crystal size are required.

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ABSTRACT

Qualitative comparisons have been made of water drop sampling methods for sprays and clouds, employing slides coated with oil, gelatin and soot. Oil-wetted and soot coated slides have been compared quantitatively when exposed in nominally identical water sprays simulating natural clouds. When compared with gelatin and oil-wetted slides, soot slides are more convenient to prepare, expose and analyse, and records are permanent. Within the inherent limitations of all spray sampling methods, drop size distributions and mean drop sizes given by the oil and soot methods are in substantial agreement, provided that known sources of error of the oil-wetted method are allowed for. Soot slides appear to be capable of detecting ice particles in clouds; quantitative calibrations relating ice impingement impressions to crystal size are required.

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1. INTRODUCTION

The work described in this note was undertaken in support of a series of trials of a modified engine anti-icing system for a Nomad 24A aircraft. In these trials, tests were conducted in an icing tunnel at ARL, in flight trials using a tanker aircraft and a boom sprayer to simulate ice-forming clouds, and in natural icing conditions in the United Kingdom.

In all these trials, measurements of the size distribution and volumetric mean drop size* of the spray or clouds reaching the engine intake were required. Separate measurements of liquid water content of the sprays were undertaken using a different method which will be the subject of a separate report.

Alternative methods of sampling spray clouds include magnesia coated targets, oil-wetted microscope slides, gelatin coated slides and soot coated slides. Of these, the magnesia coated target method has been used for examination of fuel sprays in combustion systems (Doogood, 1961) and in earlier icing investigations (Smedley and Dick, 1975). For the present tests, however, this method was discarded because of the imprecise information available relating drop diameter to the diameter of the impression formed, because of difficulties in producing reproducible coatings, and the bulk and complexity of the available sampling device. Additionally, it is noted by Bigg and Abel (1953) that magnesia coatings do not adhere well at air velocities above 120 knots.

The oil-wetted slide technique, in which incident water drops are held in suspension in a fairly thick oil film, was initially regarded as a method having high inherent accuracy as the drops might be considered to be almost perfect spheres and could thus be accurately measured. However, the smaller drops evaporate rapidly, and larger ones fall through the film in a comparatively small time, so that microscope examination and photography of the slide must be carried out within minutes of exposure, which would be difficult or impossible in flight. It was therefore proposed to use the technique, in ground based tests, as a reference datum against which to judge more convenient methods which might not yet have gained acceptance by aircraft certification authorities. Subsequent to commencing this work, however, information casting considerable doubt on the absolute accuracy of the technique has been obtained; the work of Gull and Floyd (1971), supported by Keller (1978), indicates that mean dropsizes obtained by analysis of oil-wetted slide samples are greater than the true mean by a factor varying between 1.6 and 1.8. This factor has been applied in analysing the results of the current investigation.

The gelatin coated slide method was developed by Pennsylvania State University and is described by Jiusto (1967). In this system, narrow strips of microscope slide glass are coated with a gelatin-water emulsion and allowed to dry; when exposed to a natural cloud or spray in a suitable sampling device, the impact of water drops dissolves the emulsion surface, leaving impressions which are stated to bear a constant ratio, independent of impact velocity, to the drop diameter. PSU calibrated their slides by reference to oil-wetted slides immersed in the same stream; it is understood that use of this technique has been accepted by FAA. A commercial firm, K. E. Yeoman, of Texas, currently employs this method.

The soot coated slide technique employs narrow glass slides coated with a very thin layer of soot from a kerosene flame. Impact of a drop on this coating causes removal of soot in a circular splash impression with a small central deposit of soot. CSIRO Division of Cloud Physics has standardised cloud particle measurements using this method, and Squires (1958) has conducted extensive calibrations to relate the impression diameter to the original drop size, over a range of forward velocities; further comments on the accuracy and reliability of the

* In conformity with usual practice in cloud physics and aircraft icing investigations, mass mean or 50%, volumetric mean diameters have been used to specify mean drop size. That is, the mean drop size is that size at which 50% of the mass or volume is contained in drops greater than that size.

method are made by Warner (1969). The principal objections raised by Jones and Lewis (1949) to this method, in their survey of cloud dropsize measuring techniques, concerned the lack of data concerning dropsize/impression diameter ratios and the effect of velocity; these objections have thus been answered by the later work.

At ARL, initial trials were made of all three methods and the following conclusions were reached:

- (i) The oil-wetted slide (Fig. 1) is comparatively convenient to use; drops are easily visible and can be photographed in a conventional microscope with transmitted light illumination, and the drops appear to be spheres. The short time available for examination and photography, before degradation of the specimen, renders the technique unsuitable for flight trials without the use of an automated sampler and camera set-up as used by Bigg and Abel (1953).
- (ii) Gelatin coated slides present some problems in obtaining smooth bubble-free coatings. Very close attention to lighting of the slides is required before the impressions can be clearly seen under the microscope, and measurement of the (sometimes non-circular) impressions is difficult. There appears to be a tendency for the smaller drops to be missed. A photograph of a slide taken using this method is shown in Figure 2. Only scanty data, of unknown reliability, concerning calibration of the technique over a range of air velocities was available.
- (iii) Soot coated slides (Fig. 3) have been found very easy to prepare satisfactorily, and the impressions are clearly seen and identified without special microscope lighting arrangements. Even with the naked eye it is practicable to assess whether an adequate exposure has been obtained. Like the gelatin slides, the impressions are permanent, provided normal precautions against damage to the surface are taken. Detection of small drops appears equal or better than in oil-wetted slides. The CSIRO calibration is given in Table 1 and plotted in Figure 4; it extends over a sufficiently wide range of aircraft velocities to encompass all flight velocities envisaged with the present tests.

As a result of these comparisons, it was decided to standardise on soot coated slides as the dropsize measuring technique in rig tests, tanker aircraft flight trials, and subsequent natural icing trials, using oil-wetted slides only as a calibration datum. The tests described in this note were undertaken to demonstrate a correlation between these two methods for aircraft certification purposes.

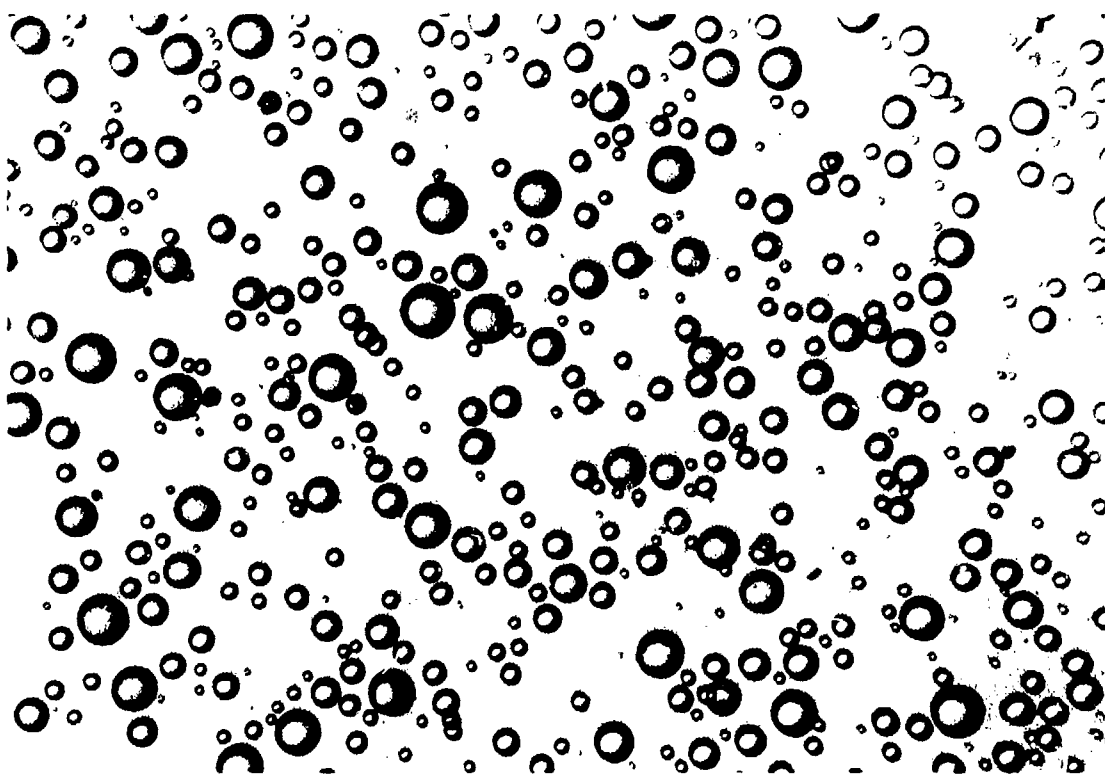


FIG 1. OIL SLIDE (x138)

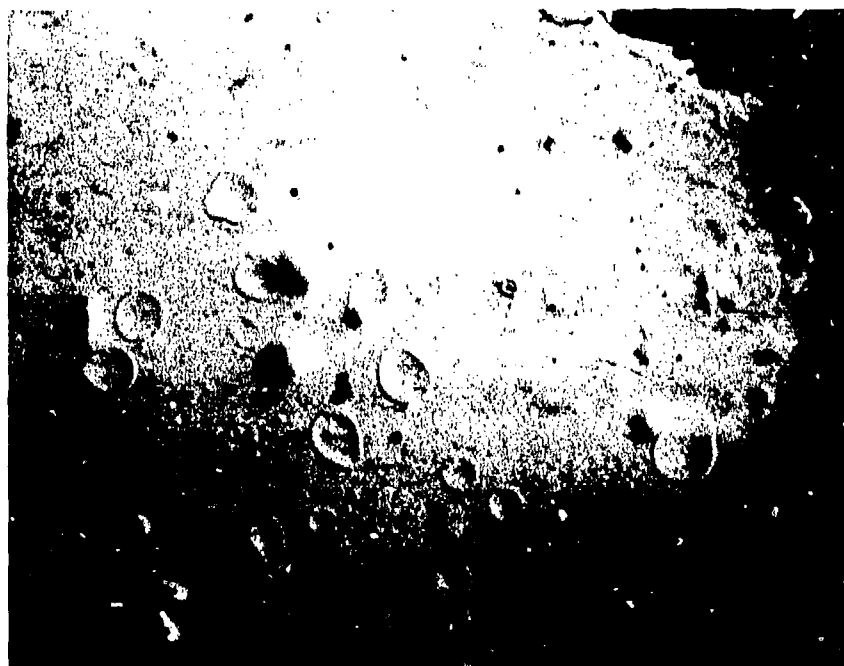


FIG 2. GELATIN SLIDE (x120)

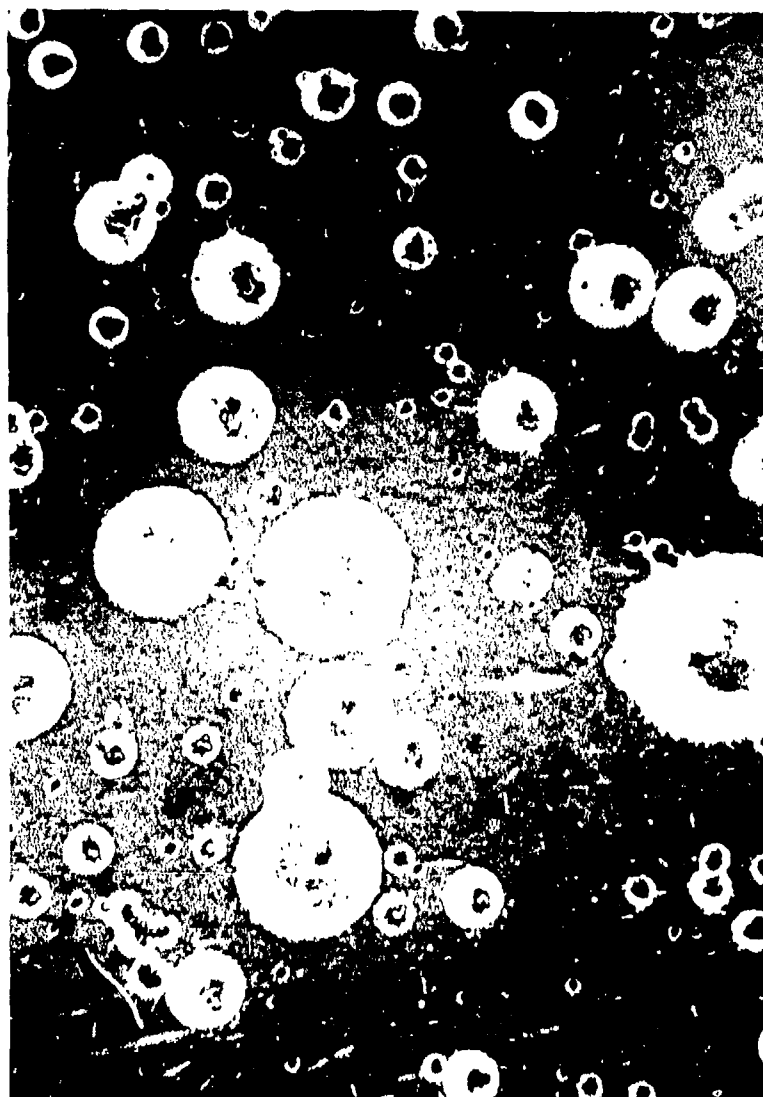


FIG 3. SOOT COATED SLIDE (x138)

Ratio: Hole diameter
Drop size

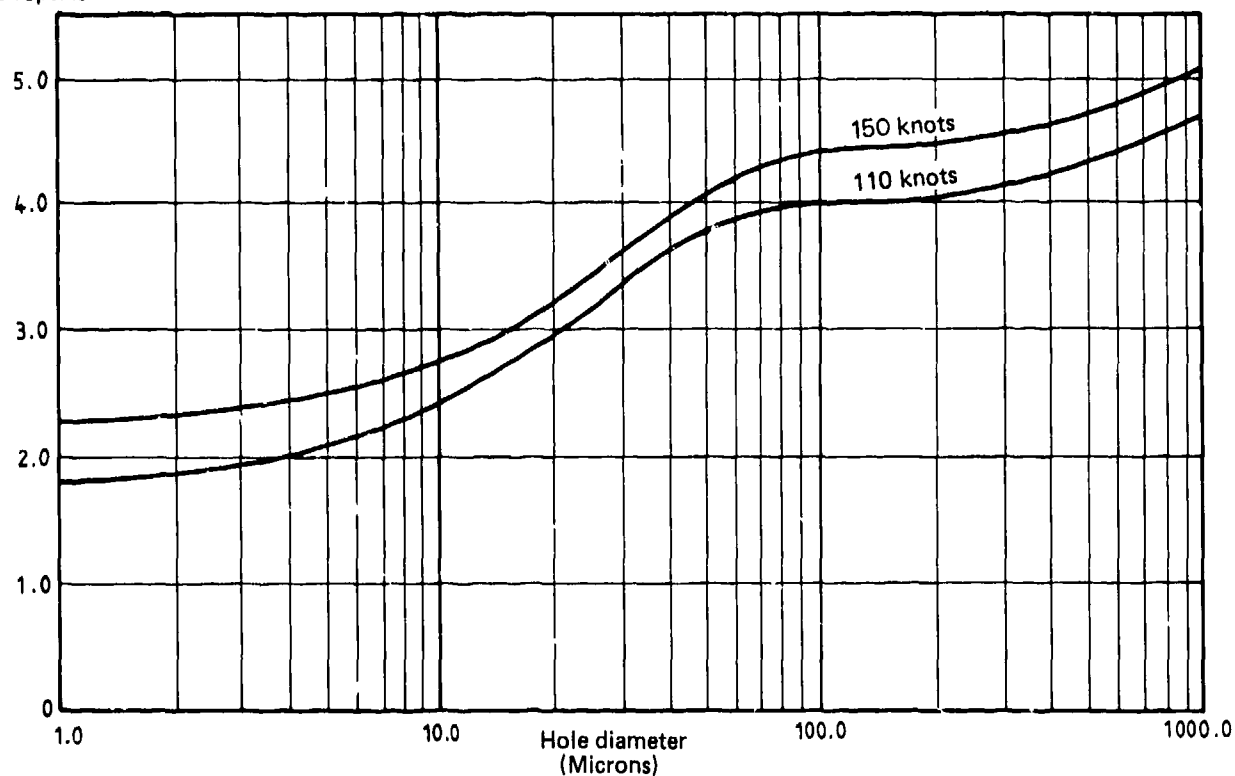


FIG 4. RELATIONSHIP BETWEEN DROP IMPRESSION ON SOOT COATED SLIDES
AND TRUE DROP DIAMETER FOR TWO IMPACT SPEEDS

FIG 4. RELATIONSHIP BETWEEN DROP IMPRESSION ON SOOT COATED SLIDES
AND TRUE DROP DIAMETER FOR TWO IMPACT SPEEDS

TABLE 1
Hole Diameter (HD), Microns, vs. Ratio of Hole Diameter to Drop
Diameter for Various True Air Speeds (TAS), Knots

TAS	110	120	130	140	150
HD	Ratios				
1.0	1.78	1.96	2.07	2.14	2.27
1.3	1.79	1.98	2.08	2.16	2.29
1.6	1.82	2.00	2.10	2.17	2.30
2.0	1.85	2.02	2.13	2.20	2.32
2.5	1.89	2.05	2.16	2.23	2.35
3.2	1.93	2.09	2.19	2.27	2.38
4.0	1.99	2.14	2.24	2.31	2.43
5.0	2.06	2.20	2.30	2.37	2.48
6.3	2.15	2.27	2.37	2.44	2.54
7.9	2.25	2.36	2.45	2.53	2.62
10.0	2.38	2.47	2.56	2.64	2.72
12.6	2.53	2.60	2.69	2.77	2.84
15.9	2.70	2.76	2.84	2.93	2.99
20.0	2.90	2.95	3.03	3.11	3.17
25.1	3.10	3.17	3.25	3.32	3.39
31.6	3.31	3.39	3.47	3.54	3.62
37.8	3.53	3.59	3.68	3.76	3.85
50.1	3.70	3.79	3.87	3.96	4.05
63.1	3.85	3.94	4.03	4.12	4.22
73.4	3.94	4.05	4.15	4.25	4.35
100.0	3.96	4.06	4.17	4.29	4.39
125.9	3.98	4.07	4.19	4.30	4.41
158.5	4.00	4.10	4.22	4.32	4.43
199.5	4.03	4.13	4.25	4.35	4.46
251.2	4.07	4.17	4.29	4.39	4.50
316.2	4.12	4.22	4.33	4.44	4.55
398.1	4.18	4.28	4.39	4.50	4.60
501.2	4.26	4.36	4.47	4.57	4.68
631.3	4.36	4.45	4.57	4.67	4.77
704.3	4.49	4.58	4.69	4.79	4.89
1000.0	4.64	4.73	4.84	4.93	5.03

2. EXPERIMENTAL METHODS

2.1 Oil Wetted Slides

The principal requirement for oil-wetted slides appears to be that the oil should be sufficiently viscous not only to form a stable film of at least 0.5 mm thickness on a glass slide, without dripping off under gravity, but also to prevent larger drops falling too quickly under gravity through the film to the surface of the slide (where they immediately spread under the influence of surface tension and are lost). Conversely, the oil should be thin enough to obviate shattering of the drops when they hit, and to allow drops to maintain their spherical shape. A silicone oil of 30 000 centistokes viscosity at 25°C was found satisfactory in these respects. Slides 25 mm in width were used in most tests except for a small number of 3 mm width which were used interchangeably with soot coated slides in the sampling gun (see 2.3).

2.2 Soot Coated Slides

Slides for most rig and all flight tests were narrow (3 mm) strips of glass microscope slide, cemented to a stainless iron or cadmium plated mild steel slide body (see Fig. 5), the design of which was kindly supplied by CSIRO Division of Cloud Physics. Coating of these slides with soot was achieved by attaching the slide bodies magnetically to the underside of a horizontal disc which was rotated at constant speed for a predetermined number of turns above a carefully regulated luminous flame from a kerosene lamp.

A nearly transparent, pale buff coating was relatively easily achieved; while the precise thickness of coating does not appear to affect the ratio of impression-to-drop diameter, too great a thickness gave fuzzy impression outlines, while excessively thin coatings were hard to discern in the microscope. In the present tests, a number of slides 25 mm in width were used to provide targets of greater capture area; these were hand-coated in the flame, as required.

2.3 Spray Cloud Sampling

In the flight tests, it is desirable to sample the spray cloud over a known time interval, in order that an approximate liquid water content can be computed from the drop count knowing the aircraft speed. For this reason a simple drop sampling gun was designed and built.

This device, which will be described in a later note, is shown in Figs 6A and 6B; it comprises a spring-loaded rotary shutter A, covering a stationary slide holder B, which accepts metal-and-glass slides of the CSIRO design. Operation of the trigger of the device releases the shutter to make an approximately 270° rotation, exposing the slide to the air stream for a known interval depending on the spring tension. In use, the operations of loading a previously coated slide, cocking the shutter, inserting the target end into the airstream, exposing, withdrawal and removing the exposed slide may be achieved in less than 10 seconds. Exposure times ranging from 0.010 sec. to 0.080 sec. were determined by high speed photography.

In the comparison tests, slides of the CSIRO design, coated either with oil or with soot, were compared in identical spray conditions using this sampling device; however, for the former coating, it was necessary to have the glass strips lightly cemented in, to enable their removal for examination by transmitted light. Difficulties in handling, and in maintaining a sufficiently thick oil film on the narrow slides, dictated use of wider (25 mm) slides in later tests, where the targets were merely waved through the spray stream. This of course precluded any computation of liquid water content from the drop size count, as the exposure times were not accurately known.

2.4 Test Rig

All tests were conducted in a uniform airstream issuing from a 250 mm diameter convergent nozzle, into which a conical water spray was injected using an airblast atomiser (see 2.5). Samples were taken 1 m downstream of the spray injection point, where initial tests showed a reasonably uniform distribution of spray over a 100 mm diameter circle. Actual airstream velocities were measured at this point, using a pitot-static tube; care was taken always to expose slides at the same location. Figure 7 shows a general view of the test rig.

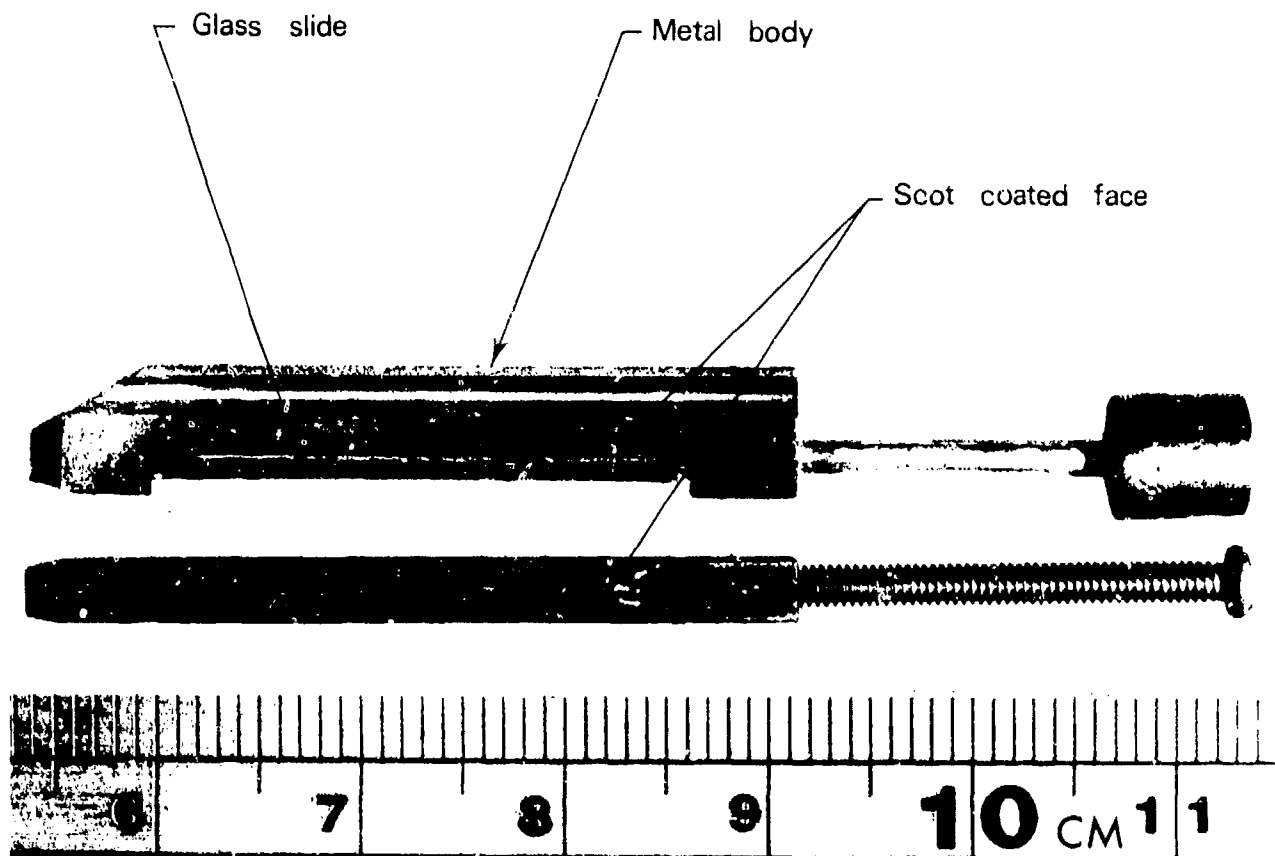


FIG 5. CSIRO TYPE SLIDE USED FOR SOOT IMPRESSIONS

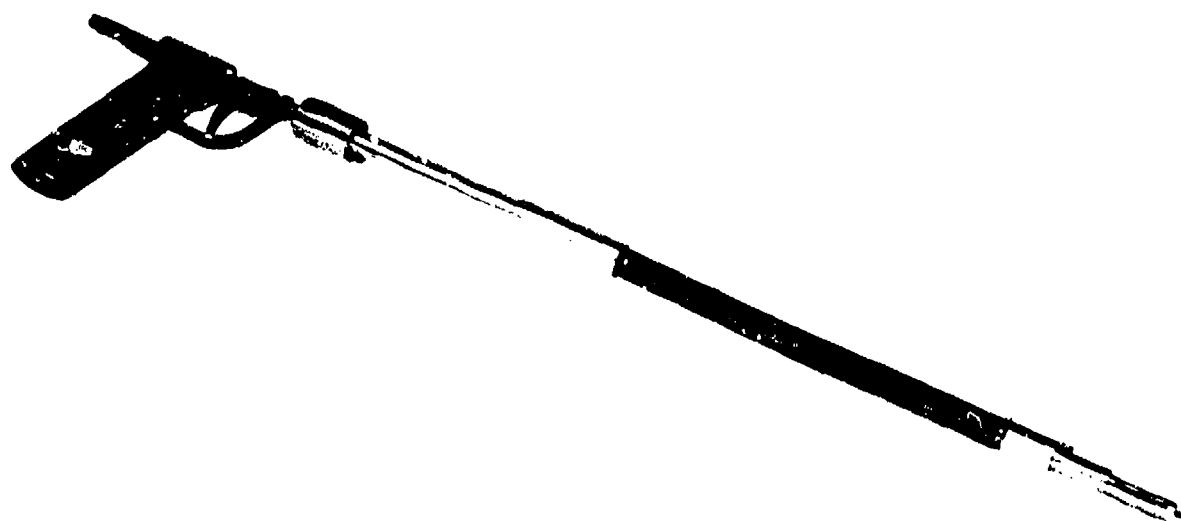


FIG 6(a). SPRAY CLOUD SAMPLING GUN

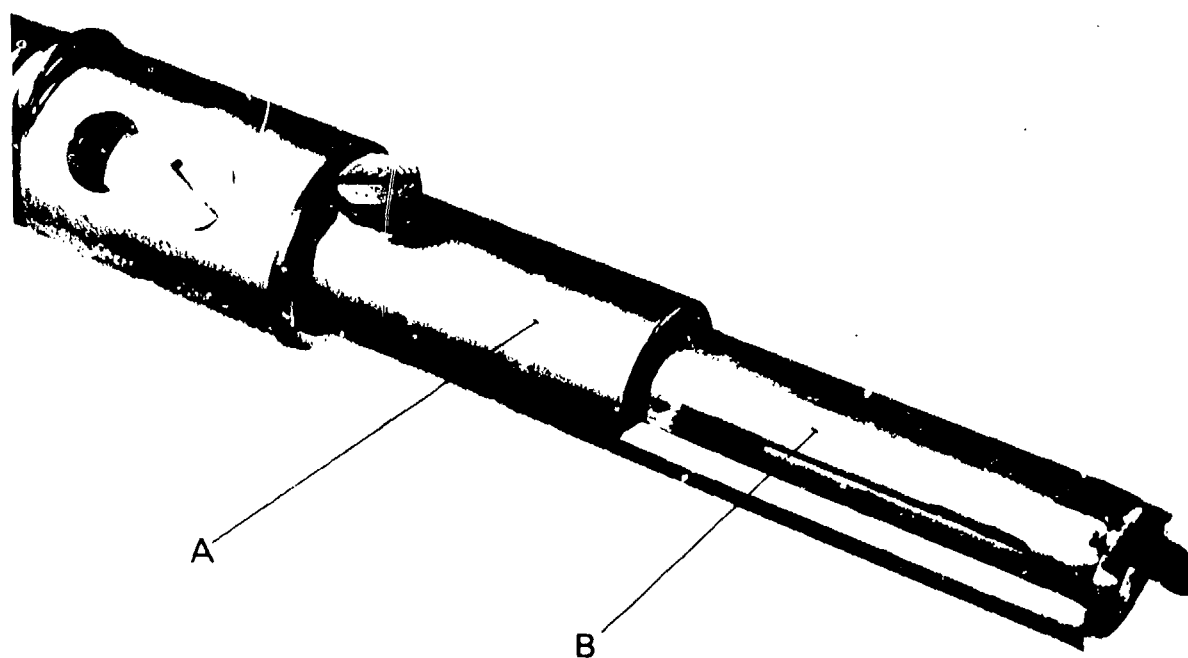


FIG 6(b). SPRAY CLOUD SAMPLING GUN SHUTTER (A) AND SLIDE HOLDER (B)

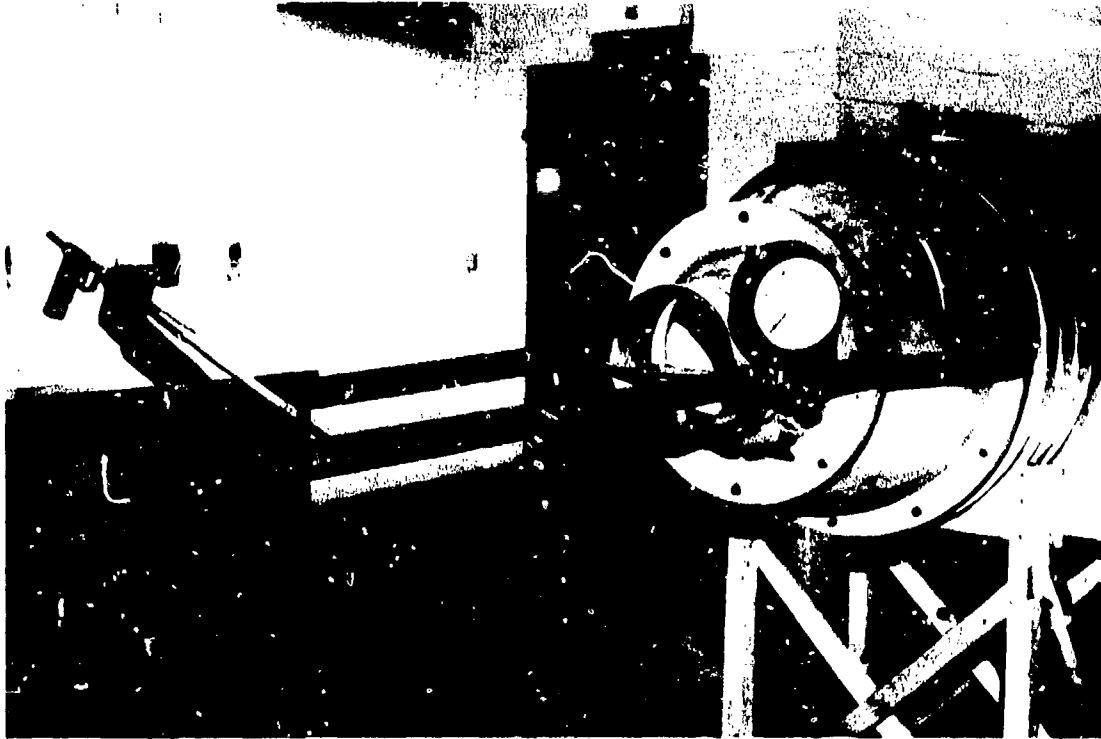


FIG 7. SPRAY SAMPLING RIG

2.5 Spray Atomiser

The water spray was produced by a small twin-fluid atomiser of the prefilming, liquid-inside type originally designed by Clare (1956): a general view of this atomiser is shown in Figure 8. This atomiser is identical with those used in the spray boom of the tanker aircraft, and has the characteristic that the spray fineness is markedly influenced by the mass ratio of atomising air to water. Thus, some control of maximum and mean drop size could be achieved by varying this ratio.

3. EXPERIMENTAL PROGRAMME

Eight comparisons were made as set out in table 2 (Page 16). In tests *A*, *B*, and *C* the cloud sampling gun was used for both oil and soot; in tests *D*, *E* and *H* the 25 mm slide was used for both soot and oil, and in tests *F* and *G* soot slides only were exposed using the sampling gun while 25 mm slides were used for the oil-wetted method.

Several slides were exposed in an icing tunnel to check spray distribution in the tunnel and to gain experience at low temperatures.

4. RECORDING AND REDUCTION OF SPRAY SAMPLES

4.1 Recording

Spray slides were examined using a Leitz binocular microscope with a Polaroid photographic attachment, using transmitted light for oil-wetted slides, and front (through the lens) illumination for soot coated specimens. Black and white photographs of randomly selected areas of the slides were taken using one of two linear magnifications which were determined, using a calibrated test slide, to be 42 or 84. The photograph sizes were 73 mm $\times$ 96 mm, corresponding to a slide area of 1.7 mm $\times$ 2.3 mm for the 42 magnification. Thus, up to 11 photographs could be taken of a standard CSIRO slide.

4.2 Counting—Soot Coated Slides

Counting of soot coated slides was carried out using a square grid of 4.3 mm spacing, printed on transparent material and superimposed on the photograph (see Fig. 9). At the two standard magnifications, this spacing corresponds to 51.5 or 103 microns respectively. The size of each drop was estimated as a decimal of the grid spacing, each drop being marked off on the grid as it was counted. Using a team of two to count and record results, an experienced operator could obtain a full count in about 10 minutes per photograph. Usually, about 500 impressions were counted which required up to 4 photographs.

A computer program, written by Government Aircraft Factories, based on a program supplied by CSIRO, was used to compute true drop sizes and the 50% volumetric mean diameter.

4.3 Counting—Oil Wetted Slides

Because, in this method, there is no "magnification" of drop impressions, use of a grid was found impracticable. Instead, selected areas of the slide were photographed and counted using a wedge shaped graticule, each drop being marked off as it was counted. The fact that true or "unmagnified" drop diameters are recorded allows a greater density of coverage of the slide surface to be achieved without significant overlap; hence, total counts of between 500 and 800 drops could be made from two photographs, the time per photograph being about 30 minutes. Computations of mean drop size are simpler and were carried out on a hand calculator.

5. RESULTS

5.1 Operator Experience

5.1.1 Soot Coated Slides

Providing moderate care was taken in properly coating slides, no difficulty was experienced in obtaining drop impressions which were easily identified and counted. However, because of

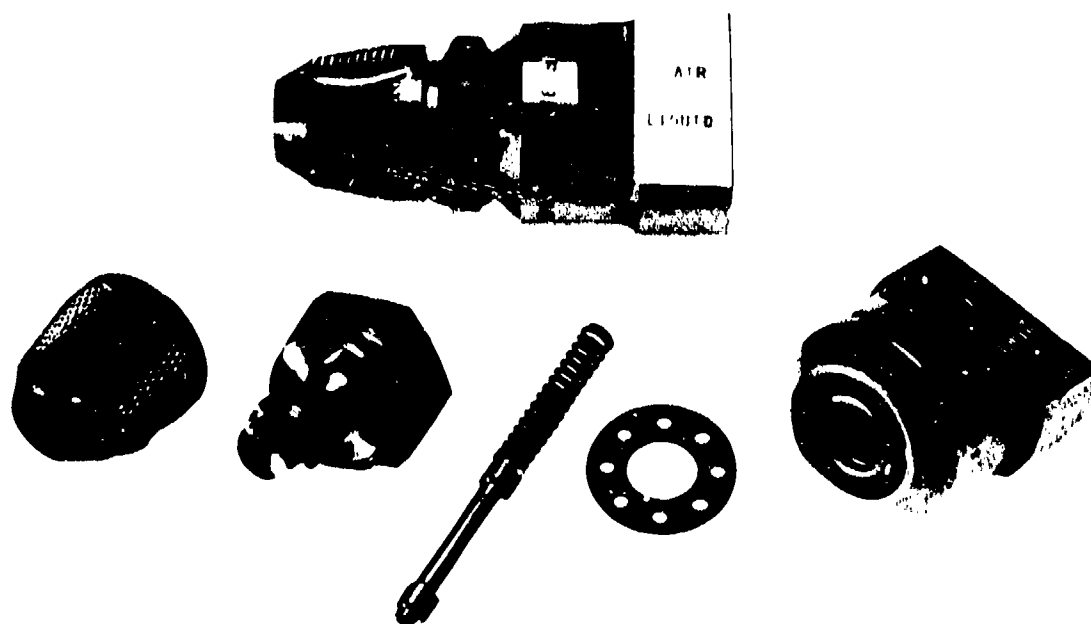
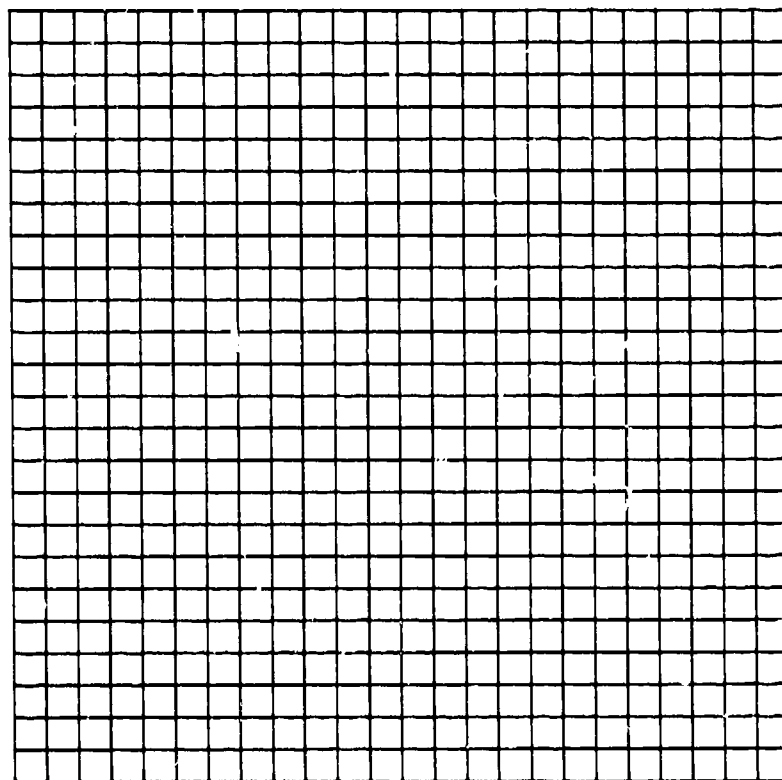


FIG 8. AIR BLAST ATOMISER



Spacing of horizontal and vertical lines 4.32mm (0.17 inches)

FIG 9. GRID USED FOR SIZING IMPRESSIONS ON SOOT SLIDES

the 2 to 4 times magnification of true drop diameters, resulting in an area magnification of 4 to 16 times, it was found necessary to reduce exposure times considerably, compared with oil-wetted slides, to avoid saturation or "washing out" of slides. An exposure time resulting in impressions covering 5% to 10% of the slide area was found to give almost no overlapping or multiple impressions. Alignment of the slide surface perpendicular to the air stream was essential to avoid elliptical or comet-like impressions.

5.1.2 Oil Wetted Slides

While, with this technique, very clear photographs were obtained on the microscope using transmitted light, it was found that noticeable evaporation of smaller drops, at quite moderate air temperatures (20°C), occurred within three minutes. This precluded photographing several sections of the same slide; precautions to cool and humidify the air surrounding the slide would be required to obviate this. Within a 5 minute period after exposure, however, no evidence was obtained of larger drops penetrating the oil film and being lost. Difficulty was experienced in coating small slides for the sampling gun and in quickly removing them for examination.

5.1.3 Detection of Ice

When exposed in an icing tunnel airstream at temperatures less than 0°C, soot coated slides exhibited impressions differing greatly from those of water drops. These impressions, shown in Figure 10, are thought to be caused by ice particles formed by condensation and freezing of atmospheric moisture, for the following reasons:

- (a) The physical nature of the ice build-up on aircraft parts tested in the tunnel under these conditions differs markedly from the build-up formed when liquid water was injected upstream.
- (b) This type of impression only occurred when no water was so injected.
- (c) Injection of water in the tunnel produced drop impressions identical in nature with those formed by sprays injected into airstreams of higher temperatures.
- (d) No such particles were evident in the oil-wetted slides exposed under the same conditions; instead, water drops were visible. Bigg and Abel (1953) show the process of ice crystals forming into water drops on oil-wetted slides.

It thus seems practically certain that soot-coated slides do in fact detect ice better than the oil-wetted technique. Further tests, supported by high speed macro-photography, would be required to conclusively prove the presence of ice and determine the quantitative relationship of impression size to original ice crystal mass.

5.2 Comparison of Drop Sizes and Distributions

Figures A1 to A8 of Appendix I present plots of the eight comparisons. Drop diameter is plotted as a histogram against percentage of total mass and percentage of total number, in 5 micron steps. A summary of the results is presented in Table 2. It should be noted that for the last four tests, mean drop sizes obtained by the (uncorrected) oil-wetted slide method are similar to those commonly recorded in natural clouds, using the same technique.

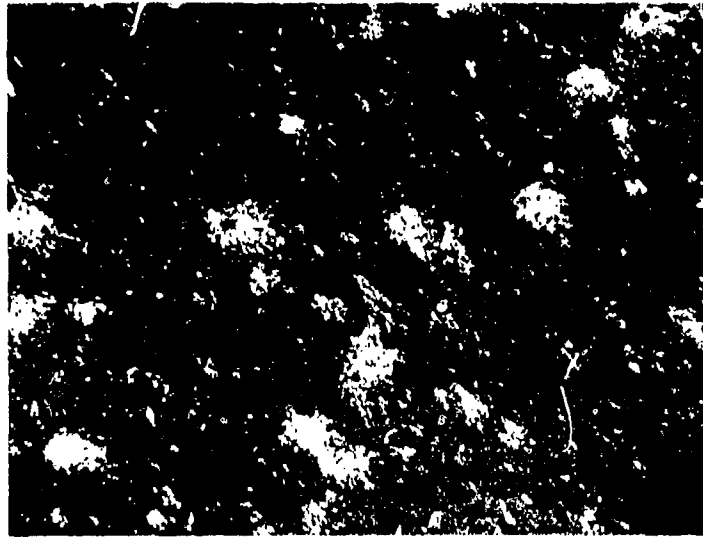


FIG 10. ICE IMPACTS ON SOOT COATED SLIDES (x84)

TABLE 2
Results of Dropsize Correlation Tests

Test Conditions			Soot Method		Oil Method		Corrected Oil Results		
Test	<i>V</i>	Air/ Water Ratio	<i>D</i> (μ)	$\bar{D}$ (μ)	<i>D</i> (μ)	$\bar{D}$ (μ)	<i>R</i>	$\bar{D}^*$ (μ)	Var (%)
A	94	0.50	40	24	55	35	1.6	22	-8.3
B	96	0.36	50	27	70	48	1.6	30	+11.1
C	118	0.50	40	20	65	27	1.6	17	-15.0
D	97	0.39	90	38	75	34	1.6	21	-44.7
E	94	6.1	35	17	40	18	1.6	11	-35.3
F	96	7.4	30	13	40	22	1.6	14	+7.7
G	94	7.7	25	13	40	22	1.6	14	+7.7
H	95	9.9	25	14	30	16	1.6	10	-22.1

V velocity (knots)

D maximum drop diameter

$\bar{D}$ volume mean drop diameter

$\bar{D}^*$ adjusted oil volume mean diameter

Var percentage variation relative to soot

R ratio used to correct oil results

6. DISCUSSION

6.1 Achievable Accuracies of Cloud and Spray Sampling Techniques

During this work, it has become obvious that sampling of clouds or sprays by counting drop populations is subject to serious limitations on achievable accuracy, these limits becoming wider as the heterogeneity of the spray increases. In particular, the random incidence of large drops, which occur so infrequently that their sampling in a given area is a matter of chance, can markedly affect the 50% volume mean calculations, even though the number distribution is less severely affected. Figure A3 is a good example; four only drops of large diameter, in a total of 429 counted, contribute 18½% of the volume. Conversely, very large numbers of drops counted in the smaller diameters, make very little difference to the mass distribution graph.

Table 3, taken from Jones and Lewis (1949), shows the influence of these and similar factors on the accuracies considered acceptable or achievable (with difficulty) in measuring cloud parameters by sampling techniques.

TABLE 3
Spray Sampling Data—Desirable and Acceptable Accuracies
From Jones and Lewis (1949)

Item	Basic research		Statistical data	
	Acceptable accuracy	Desirable accuracy	Acceptable accuracy	Desirable accuracy
Liquid-water content	±15%	±5%	±25%	±10%
Free-air temperature	±3°F	±1°F	±5°F	±2°F
Altitude	±300 ft	±100 ft	±500 ft	±200 ft
Average drop diameter	±30%	±10%	±35%	±10%
Maximum drop diameter	±30%	±10%	±40%	±10%

6.2 Soot Coated Slides

6.2.1 Drop Size Distribution

It is apparent from the Figures A1 to A8 that in every case many more drops of the smallest sizes are counted using the soot method. This is due to the "magnifying" effect of the soot technique, so that small-drop impressions on soot slides are much easier to see—in fact increasing the size of the photograph from the standard Polaroid size of 73 mm × 96 mm to 203 mm × 254 mm, as suggested by J. D. Bell (1978), produced no new drop impressions. Despite the modifying effect of the larger numbers of small drops, the number distribution curves in most cases are similar in general form to those obtained with oil-wetted slides.

6.2.2 Volumetric Mean Diameter

When examined on a basis of atomiser operating conditions, i.e. of atomising air/water flow ratio, the volumetric mean diameters obtained in the soot slides are fairly consistently related. The largest mean drop size is obtained at the lowest value of this ratio, except for condition *D*, where a few very large drops have greatly increased the mean diameter. The effect of increasing air velocity (condition *C*) appears to be a reduction of mean diameter, but this could well have been an elutriation effect, which changed the actual spray characteristics at the point of measurement.

It is known that CSIRO Division of Cloud Physics make some attempt to compensate for random large drops. All drops above a certain size are counted over a much larger slide area than is used for the smaller drops count. A weighted number for the large drops is then applied to the overall count. This technique would involve taking a large number of photographs of different parts of the soot slide but was applied to only one comparison, as, because of evaporation, an equivalent number of photographs of oil-wetted slides could not be made.

6.3 Oil Wetted Slides

6.3.1 Drop Size Distribution

While the shapes of the drop-size distribution curves are similar to those obtained from the soot slides, it is noticeable that the number percentage of small drops is much less. Two reasons can be ascribed to this. Firstly, because of the absence of the magnifying effect of drop impressions on the soot slides, small drops are more difficult to see. Secondly, the greater surface/volume ratio of the small drops gives faster preferential evaporation of these sizes before they can be photographed.

6.3.2 Volumetric Mean Diameter—Uncorrected

Inspection of Table 2, and the plot in Figure 11 shows that, with the exception of condition *B* where a number of large drops were counted, volumetric mean diameters follow closely similar trends, in respect to atomising air/water ratio, to those obtained from soot coated slides. In this case also, a higher airstream velocity has produced a lower reading. However, in almost all cases, mean diameters are significantly higher, for the same atomising air/water ratio.

6.3.3 Volumetric Mean Diameter—Corrected

With the advent of non-intrusive drop sizing and counting methods of known absolute accuracy, such as holography and laser dispersion probes, several recent publications have criticised the accuracy of the oil-wetted slide technique. Keller (1978) points out that oil slides are subject to the following sources of error:

- (i) Evaporation of small drops preferentially. This was encountered in the ARL tests and markedly influences number distribution.
- (ii) Coalescence of adjacent drops forming single larger ones.
- (iii) Overlapping of small drops by larger ones.
- (iv) Shape Errors. The drops are assumed to be spherical when photographed on the slide but may in fact be flattened, hence diameters recorded may be too high.

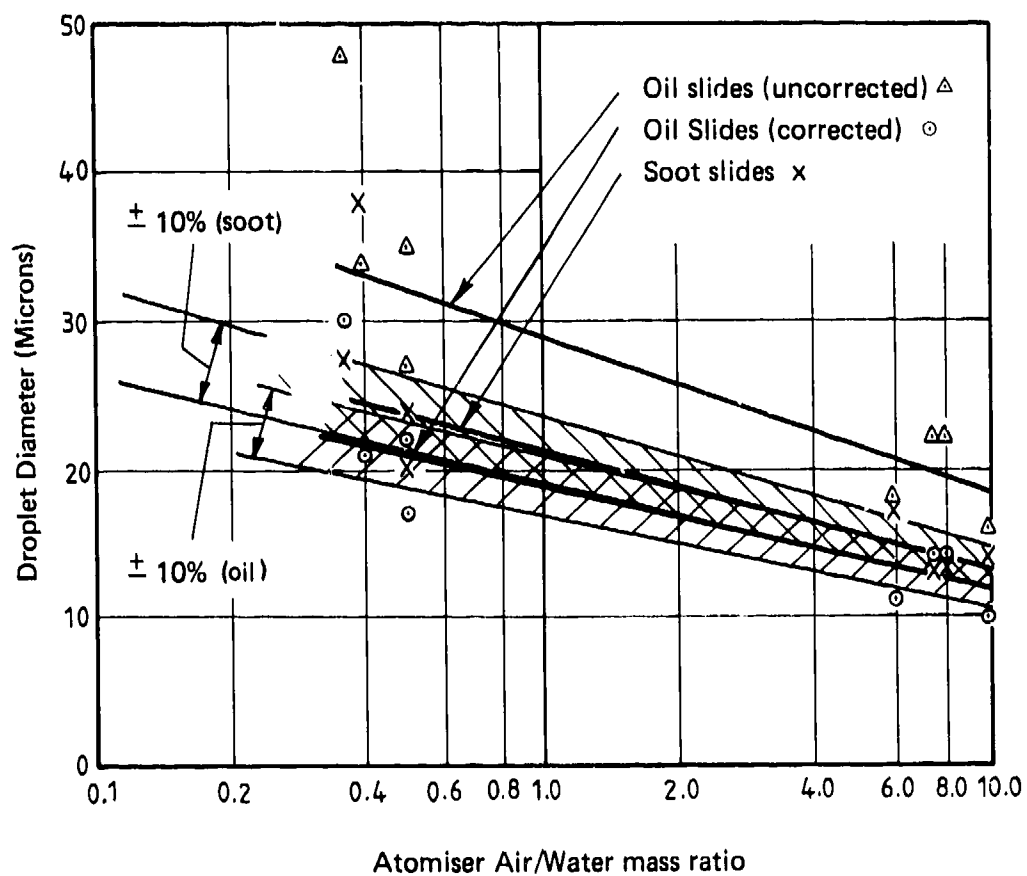


FIG. 11 MEAN SPRAY DIAMETER OF AIRBLAST ATOMISER BY OIL-WETTED AND SOOT-COATED SLIDE TECHNIQUES

Of these errors, the first has negligible effect on volume mean diameter, and the second and third may be minimised by avoiding excessive exposure times. However, the shape distortion has important effects. Gull and Floyd (1971) when using holographic techniques to compare true drop sizes with those obtained from oil slides, found a consistent ratio of about 1.6 between volumetric mean sizes determined from oil slides, and those from holograms. Keller (1978) in similar studies using laser scattering techniques obtained a ratio closer to 1.8. As the holographic method is probably capable of greater absolute accuracy, a ratio of 1.6 has been used to correct the oil slide results in Table 2 and Figure 11.

6.4 Comparison of Results from Each Technique

It is clear that considerable divergences occur when comparing mean drop sizes obtained by the soot method with uncorrected sizes obtained from oil-wetted slides, taken under nominally identical conditions; sizes from the oil method are consistently higher. However, when drop sizes corrected by the factors mentioned in 6.3.3 are compared (see Fig. 11) quite close agreement is obtained except in one or two "rogue" points which could justifiably be attributed to the effects of random sampling of very large drops. When plotted, as in Figure 11, most of the soot slide results fall within a $\pm 10\%$ band from the mean, while the oil-wetted slides are slightly more scattered; however, the $\pm 10\%$ bands for the two techniques are almost coincident, the divergence being about 12% for mean spray sizes of about 25μ , decreasing to about 9% at mean diameters of around 12μ . These divergences are close to those given in Table 3 as the best likely to be obtained from cloud sampling techniques.

It must be emphasised that even better correlation of results would be obtained if a correction factor greater than 1.6 was used for the raw results from the oil slides. However, no valid justification can be advanced for doing this; it is considered that the correlation obtained from a soundly based factor of 1.6 is sufficiently close.

FAA design icing envelopes for drop sizes at different cloud liquid water contents were most likely based on oil-wetted slide results, uncorrected for size distortion errors. Therefore, for the purpose of aircraft certification, soot slide dropsizes results must be *increased* by the same factor.

7. CONCLUSIONS

Although undertaken primarily to provide verification of the soot coated slide technique, as a basis for aircraft certification trials, these tests have highlighted some of the inherent uncertainties of all drop counting methods caused by the random occurrence of large drops, and have confirmed the conclusions of other workers as to the basic inaccuracies of the oil-wetted slide technique which has up to the present been used as a datum reference method. In fact, when correction factors established by these workers are applied to the raw data from oil slides, agreement close to accepted limits of accuracy is obtained with the results from soot slides.

From this it may be concluded that the soot slide technique is a reliable and accurate method of determining droplet distributions and mean drop sizes in sprays and clouds. In addition it has been found to have important advantages of ease of slide preparation, ease of identification and counting of drop impressions, and permanence of records.

The permanence of records facilitates examination of larger areas of the sample slide and application of more statistically accurate counts of larger drops. Hence this method could give more accurate results than the oil-wetted technique, where multiple photographs may be precluded by rapid evaporation of smaller drops.

A further very important advantage is that the presence of ice particles can be easily identified. However, at present no studies are known relating the size of impressions caused by ice to the particle size; this is suggested as a useful field for future research.

The work has indirectly confirmed the shape error factor of 1.6 for oil-wetted slides. Therefore, in applying results obtained by soot slides to aircraft certification trials for which the cloud water particle size limits were originally obtained by the oil-wetted slide technique, the same factor must be applied to mean diameters from soot slides to *increase* them to an "equivalent oil-method particle size". Results so factored may be applied with confidence for certification purposes.

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APPENDIX I
Comparison of Spray Sampling Data.

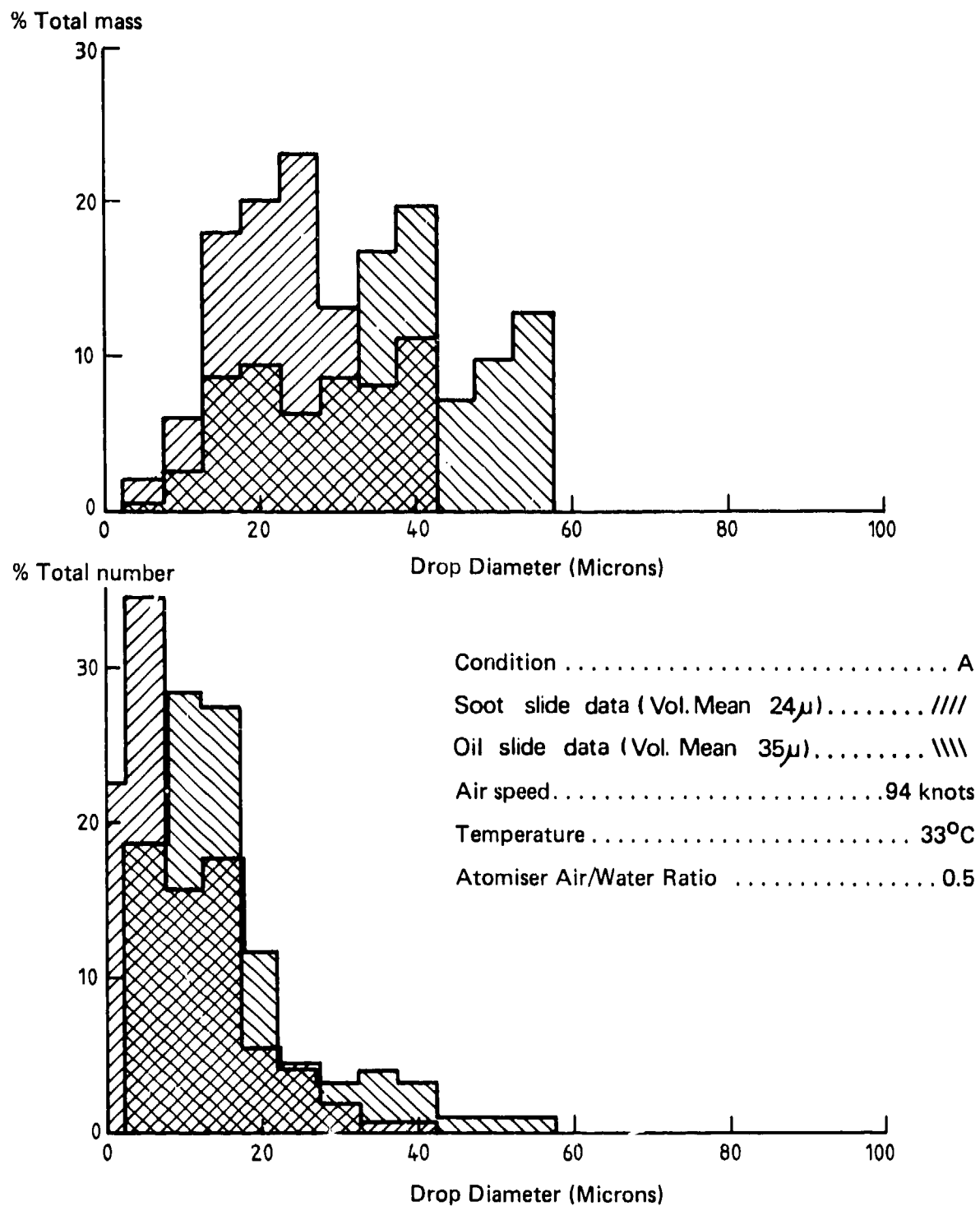


FIG.A1 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

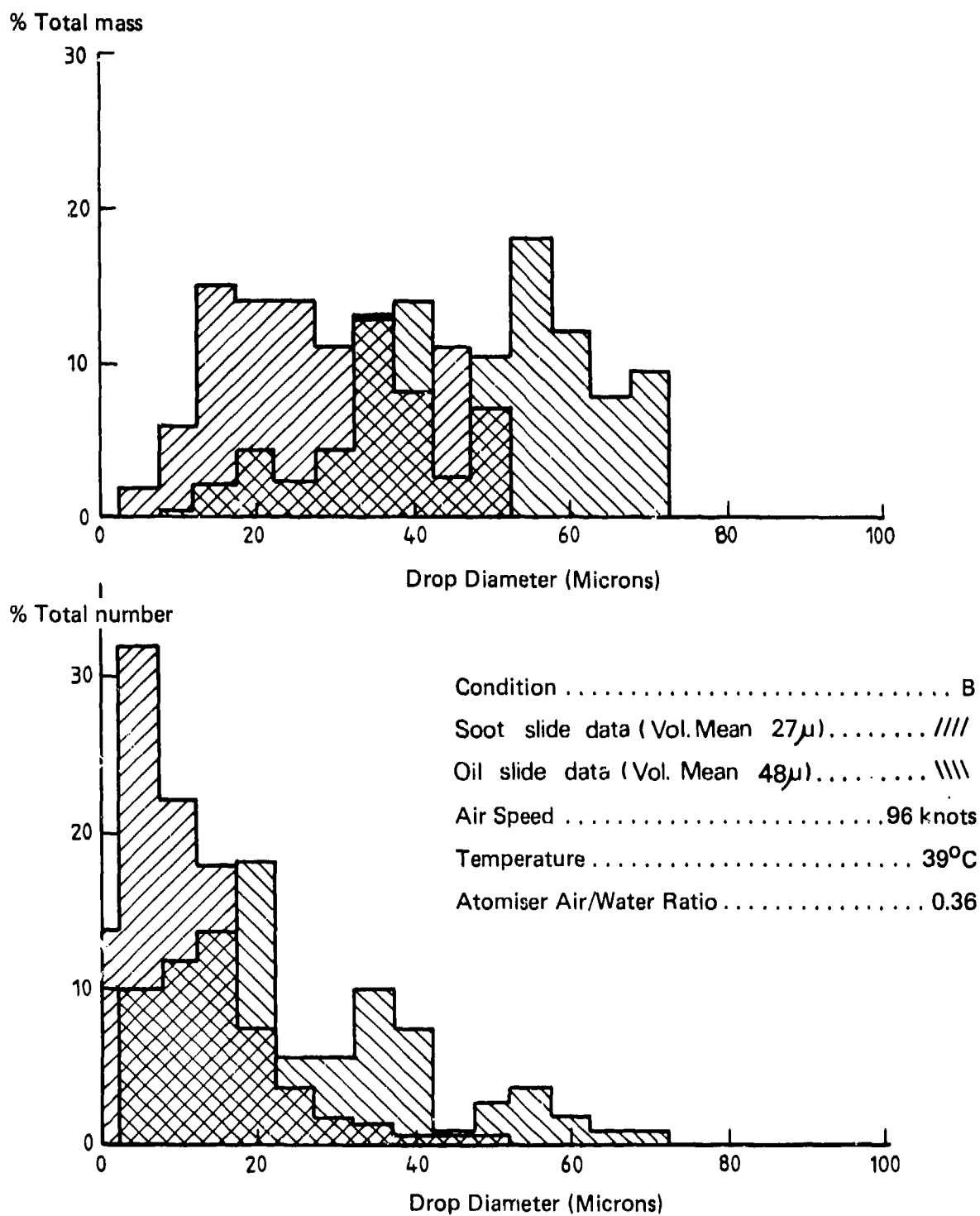
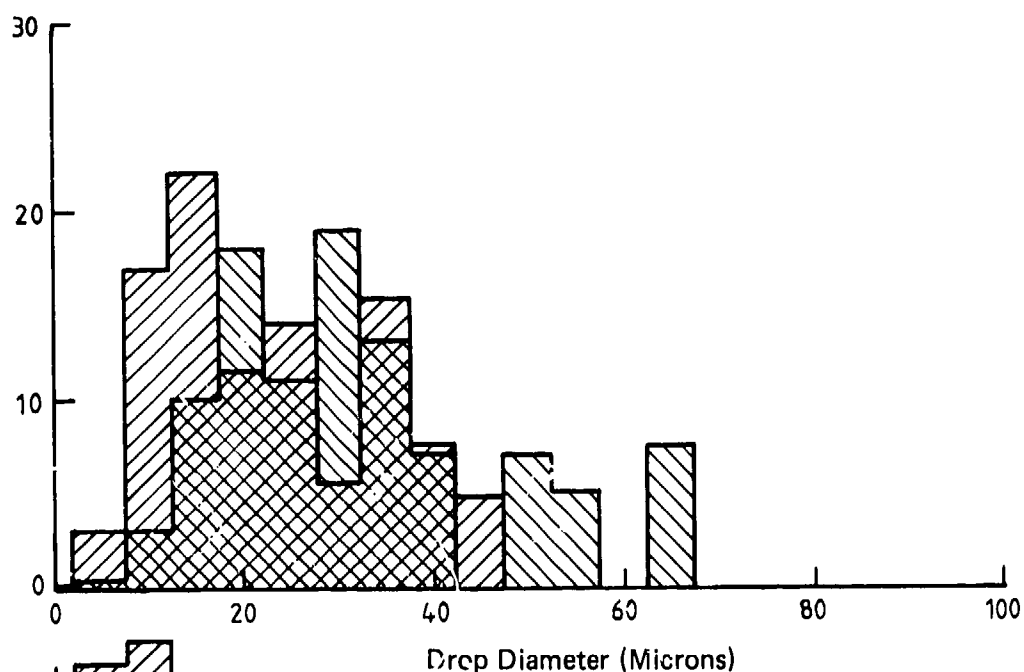


FIG. A2 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

% Total mass



% Total number

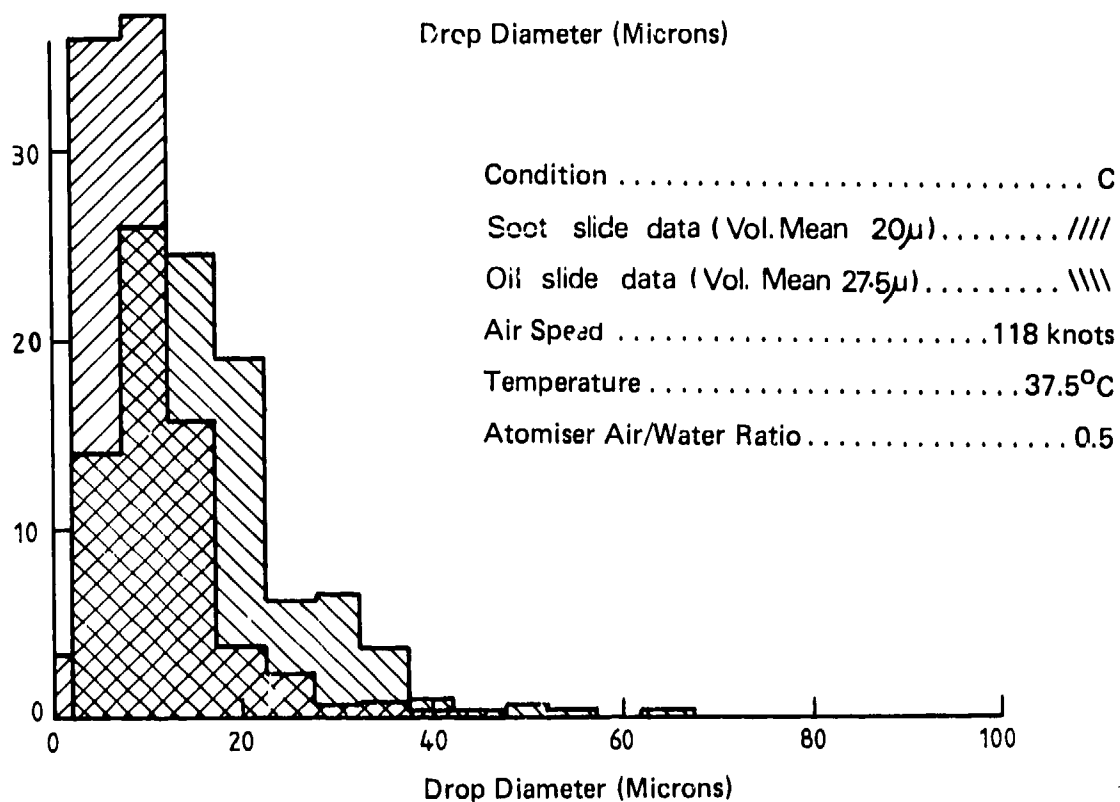


FIG.A3 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

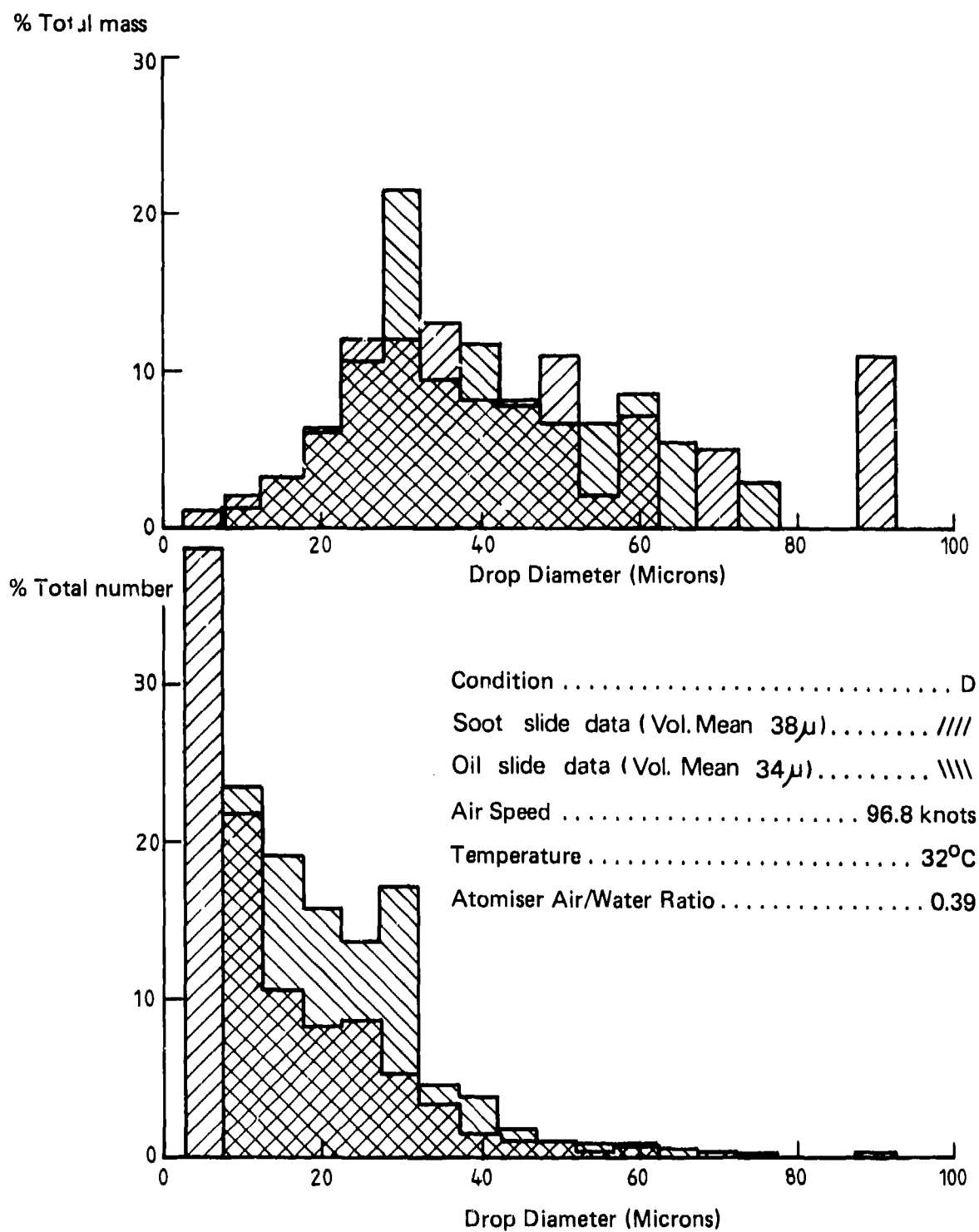


FIG. A4 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

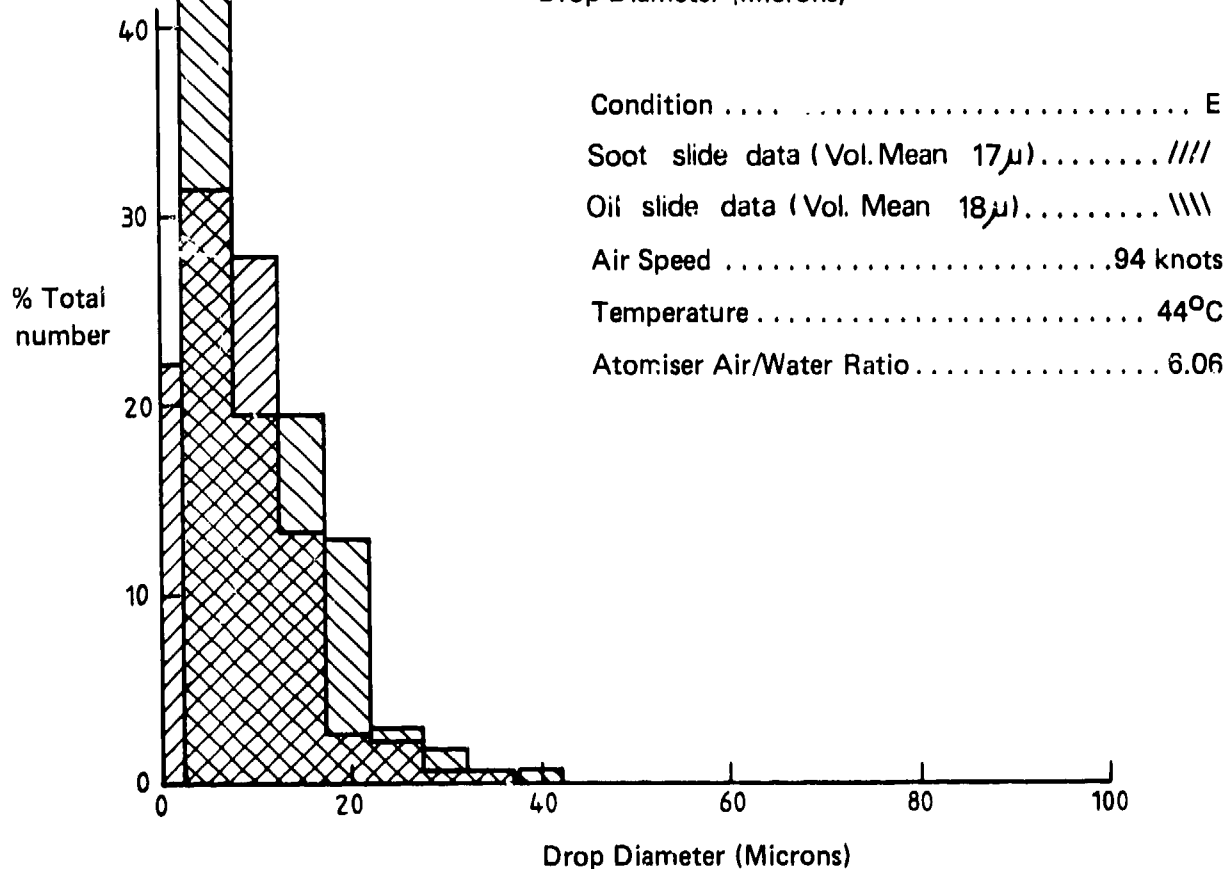
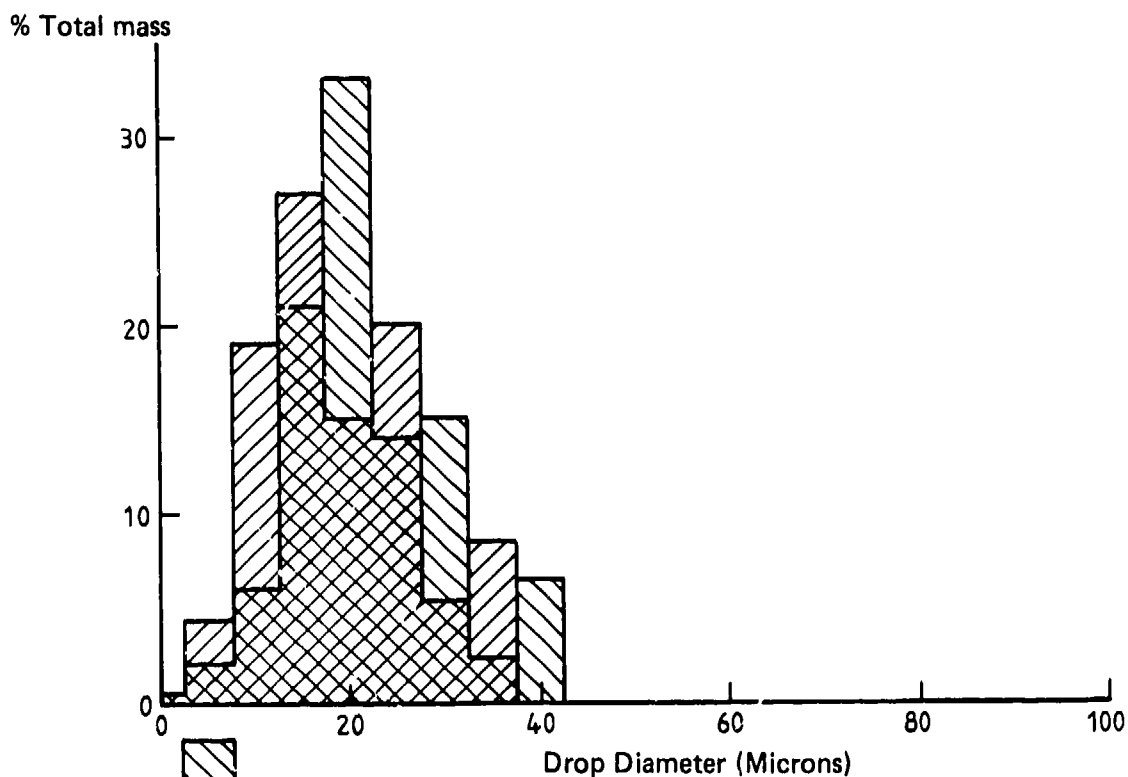


FIG.A5 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

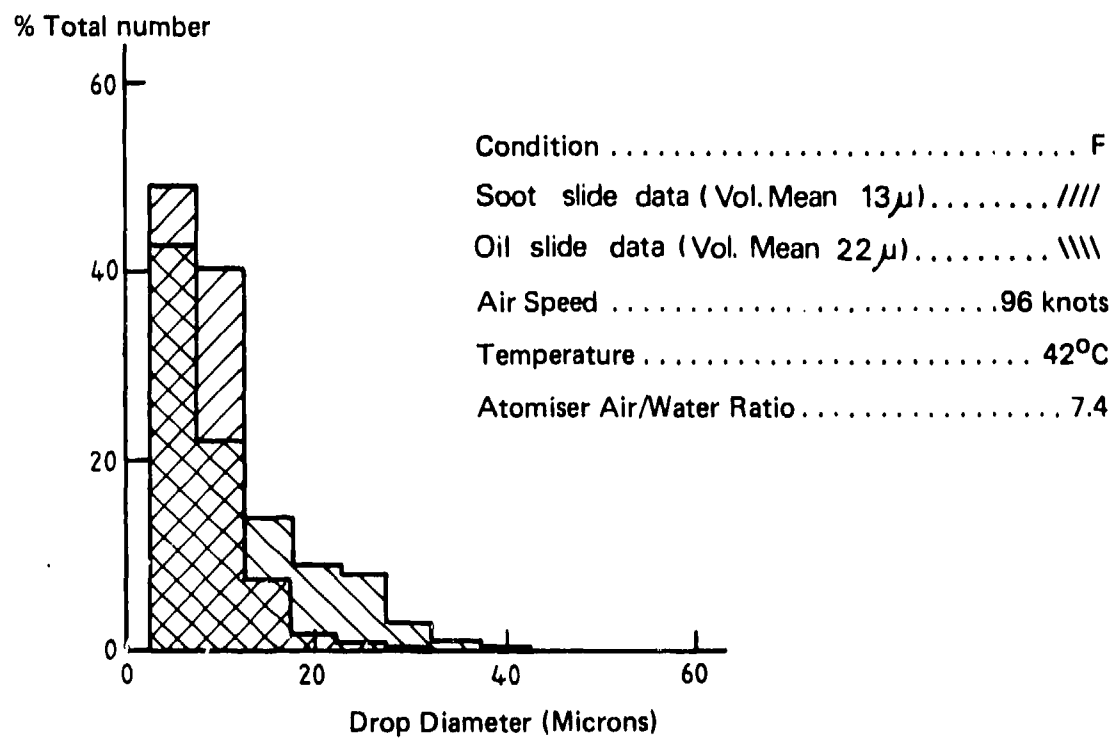
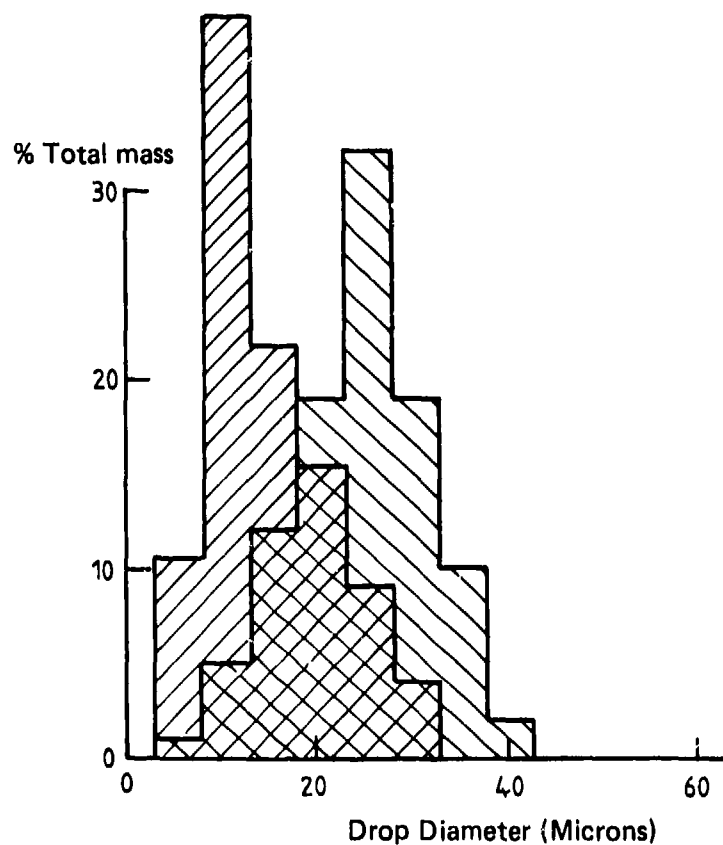


FIG.A6 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

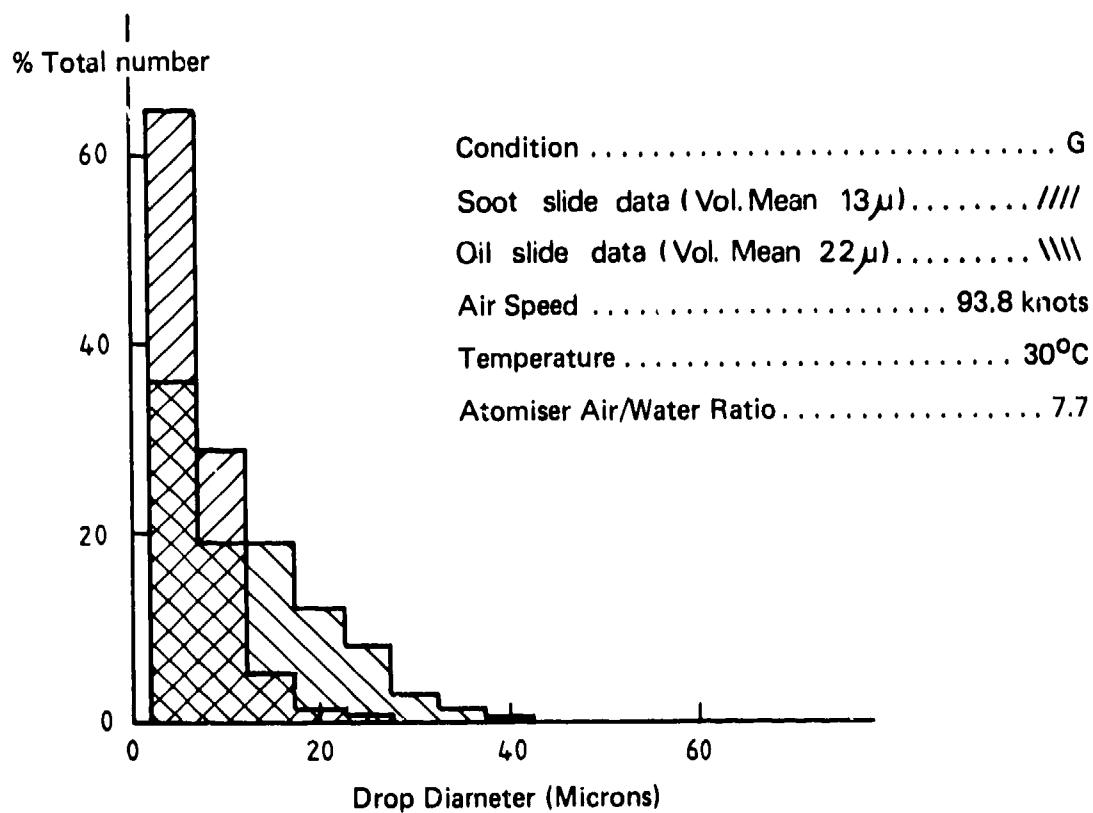
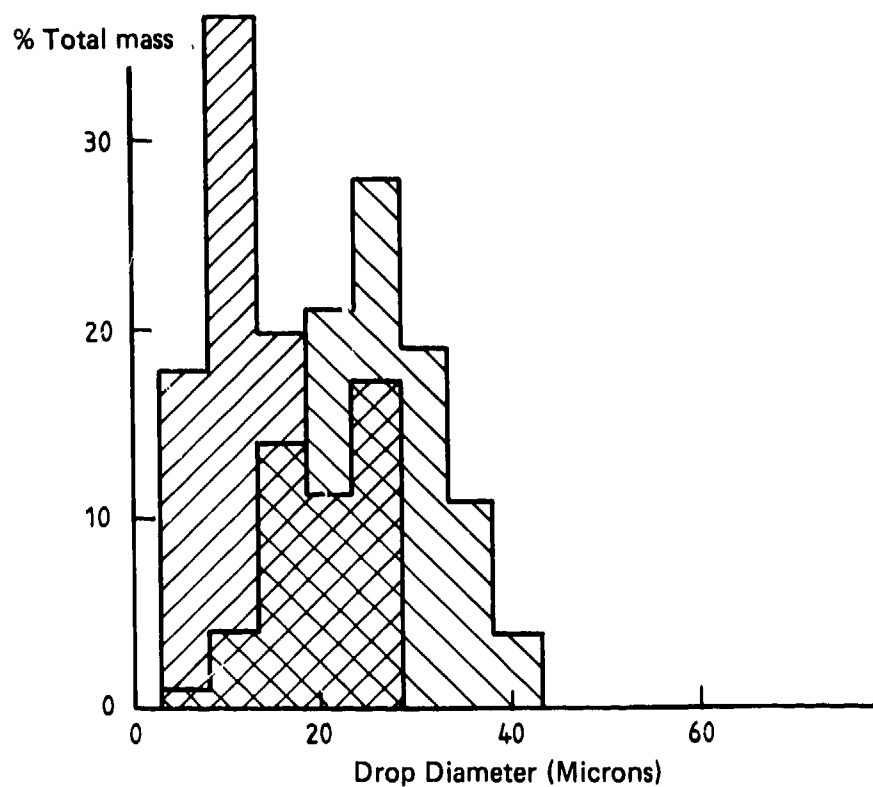


FIG. A7 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

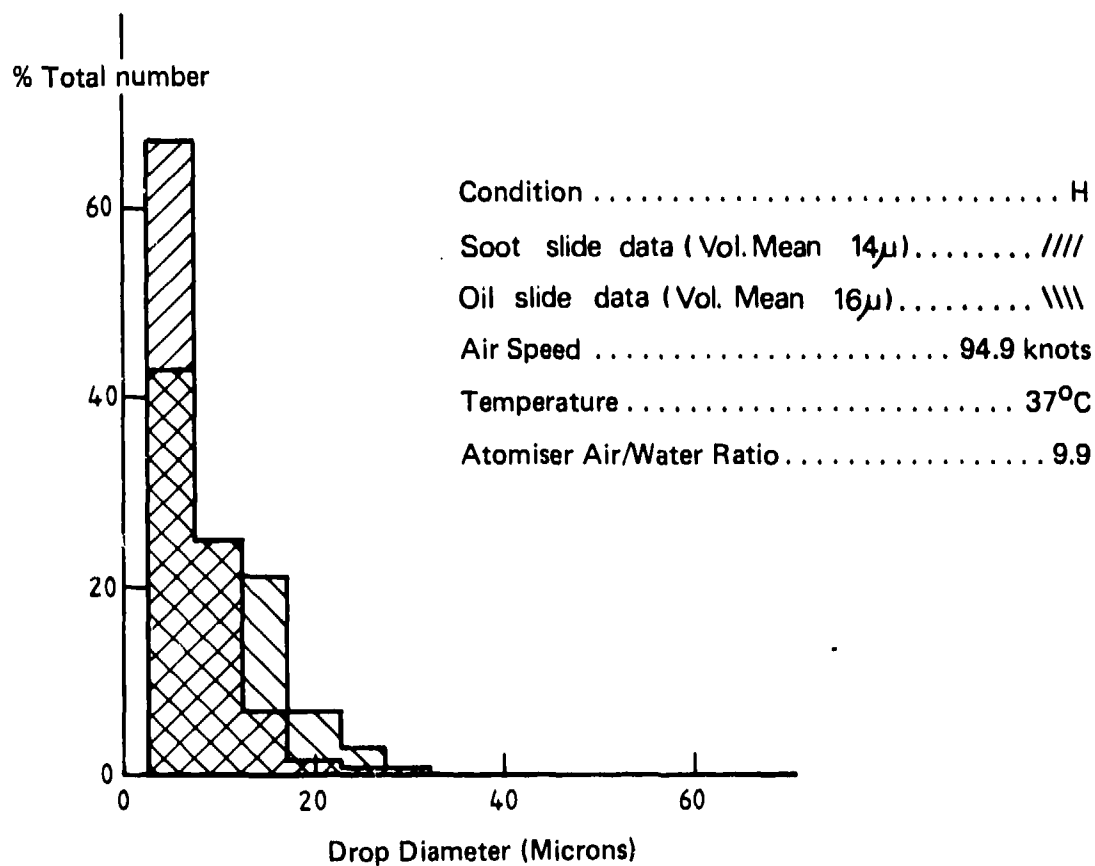
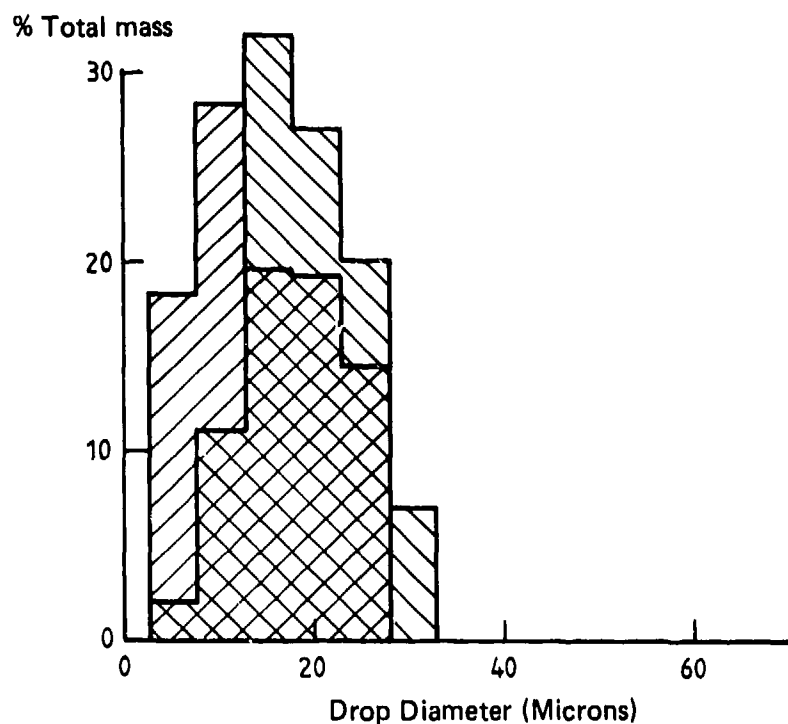


FIG.A8 COMPARISON OF SPRAY SAMPLING DATA FROM SOOT AND OIL COATED SLIDE METHODS

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