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Performance of Glass Fiber Filter Material Measured with Monodisperse and Standard Aerosols

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Abstract

Comparisons have been made of the penetration, through filters, of monodisperse aerosols of between 0.01 and 0.3 μm in diameter, and of both sodium chloride and paraffin oil mist standard aerosols. The filters were papers prepared from mixtures of glass fibre with a mean diameter of 0.76, 1.8 and 3.0 μm in various proportions, and the face velocity of aerosol through the filters was 0.1 m s^{-1} . The penetration of the standard aerosols through the filters ranged from 73%–0.02%. A good correspondence between the results of two types of standard tests was obtained, though the sodium chloride aerosol was invariably more penetrating than the oil mist. The 0.1 μm diameter monodisperse aerosol was, in general, the most penetrating of those used in the tests. Correspondence between the penetration of the 0.02 μm aerosol and both standard aerosols was moderate and correspondence of aerosol penetrations in the other size ranges was good. In particular, the 0.1 μm aerosol was more penetrating than the sodium chloride aerosol by factors between about 1 and 5, and it was more penetrating than the oil mist aerosol by factors of between about 1.2 and 40.

Introduction

Standard tests are widely used in assessing filter suitability for specific purposes. Two popular standard aerosols used in filter tests are the sodium chloride aerosol (EN 143:1991, BS 4400:1969, BS 3928:1969) and the paraffin oil mist aerosol (EN 143:1991 and DIN 24 184: 1990). Useful as such tests are, they cannot completely specify the performance of a filter material. It is important, therefore, that comparisons are carried out between the performance of filters in standard tests and their performance in industrial use. At a more fundamental level, it is important to compare the results using standard aerosols with those using monodisperse aerosols, because these give a precise grade efficiency curve for a specific filter material. A standard test

gives only one figure, and so it is useful to know how this figure relates to the behaviour of other aerosols. Since standard aerosols are largely composed of submicrometre particles, comparison with monodisperse aerosols in this size range is likely to be most fruitful. A comparison exercise has been carried out using both the sodium chloride and the paraffin oil mist standard aerosols, and submicrometre monodisperse aerosols. The tests also enable a comparison to be made between the performance of the two standard aerosols, similar to recent work on sodium chloride, di-octyl sebacate (DOS) and silica aerosols (Myogo and Sugimoto, 1997). The work was carried out as a joint exercise between the Central Institute of Labour Protection

(CIOP), Poland, and the Health and Safety Laboratory (HSL), Britain, the tests with polydisperse

aerosols being carried out at CIOP, and the tests with monodisperse aerosols at HSL.

Filter Materials Tested

In general penetrations of standard aerosols through filters must be relatively low for the filters to satisfy the standards. Perhaps the most significant European standard referring to the standard tests is EN143 (1991). In this, respirator filters are considered to meet levels P3, P2 or P1 according to whether they allow no more than 0.05%, 6% or 20% of the sodium chloride aerosol to penetrate. Other devices than respirators can be assessed with the sodium chloride aerosol. According to BS 6410 (1991) filter papers should not allow more than 2% of the BS4400 (1969) sodium chloride aerosol to penetrate. According to Interim Defence Standards 68-186 (1993) and 68-234 (1994) glass fibre filter papers are assessed with the sodium chloride particulate test, though no qualifying values for penetration are given.

The most useful comparison is likely to be obtained from tests on filters that have a wide range of efficiency against the aerosols of interest because

tests carried out over a limited range of efficiency will not usually reveal any strong correspondence. Filters vary considerably in their structure and nature and so for simplicity's sake attention has been confined to filters made from glass fibres; many filters in the high efficiency range are made of such material. Glass fibres are available in a range of diameters, and in order to produce filters of a wide range of efficiencies fibres with components of mean diameter 0.76 μm , 1.8 μm and 3.0 μm were mixed in various proportions to produce filters with a wide range of mean fibre size. The filters had been produced by a normal liquid laying paper process but a minimum of binder was used in their construction. The thickness of each material sample was measured, with the material compressed at a pressure of 6 kPa, and the area weight was measured directly. These results, along with the composition, are given in Table 1.

Sample Preparation

Discs of filter material 47 mm in diameter were cut from each of the fibre mixtures to be tested. These were placed into supports in the form of grids, as illustrated in Fig 1. The grid used has been designed to provide maximum support of the filter material with minimum occlusion of the available surface area. Since the filter materials are thin the two grids on opposite faces can be stuck together with a layer of glue the same thickness as the filter. A thin layer of glue is also placed at the edge of the filter material itself, to seal any possible leaks, and

the supports are then taped around the circumference with adhesive tape. Each sample of filter material remains within its robust support for the entirety of the tests. In this form the material is supported and protected and so can be transferred from one test apparatus to another without risk of damage. This was particularly important for the exercise described in this paper, because it involved collaboration between laboratories in different countries, and so transport of the filters over long distances was required.

Tests with Monodisperse Aerosols

Each filter in its grid support is placed into a specially designed holder which will accommodate filters of this size without leakage. This holder is contained within apparatus consisting of a 3071A electrostatic aerosol classifier and a condensation nucleus counter, both from TSI Inc, St Paul, USA. A primary polydisperse aerosol of sodium chloride is produced by pneumatic atomisation of a 0.5% solution. The particles are then charged and monodisperse fractions are selected by the principle of electrostatic classification (Knutson and Whitby, 1975). On leaving the classifier the particles are passed through a radioactive aerosol neutraliser,

which will remove the charge from most particles of this size.

By this means monodisperse aerosols in a size range 0.02-0.3 μm were produced, and these were used sequentially in the tests of performance of the filters. The monodisperse classified aerosol is passed into a small plenum chamber into which projects the filter holder containing the test filter in its support and a parallel empty line for reference. The system is based on one used for micrometre sized aerosols (Blackford *et al.*, 1985) but does not feature aerodynamic design, because particles in the submicrometre

Table 1. Composition, area weight and pressure drop of glass-fibre filters.

Filter no.	Percentage, by weight of components with mean fibre diameter			Area weight gm^{-2}	Thickness (mm)	Pressure drop at 0.1 ms^{-1} Pa (HSL) measured along with monodisperse aerosol penetration	Pressure drop at 0.1 ms^{-1} Pa (CIOP) measured along with polydisperse aerosol penetration
	$0.76 \mu\text{m}$	$1.8 \mu\text{m}$	$3.0 \mu\text{m}$				
1	100			64.8	0.71		750
2	70	30		68.3	0.61	491	512
3	50	50		71.4	0.64	408	405
4	20	80		71.1	0.51	339	324
5	5	95		73.2	0.45	264	250
6	2	98		74.5	0.43	253	240
7		100		72.4	0.41	202	193
8		70	30	75.0	0.49	193	184
9		50	50	74.3	0.51	122	123
10		20	80	75.1	0.52	81.8	75
11		5	95	68.3	0.51	53.2	47
12		2	98	73.9	0.51	42.8	37
13*			100	58.1	0.49	54.0	36
14	2		98	71.5	0.42	45.7	41
15	5		95	72.9	0.46	64.8	55
16	15		85	78.6	0.40	80.7	74
17	30		70	68.3	0.42	148	157
18	50		50	71.5	0.57	294	285
19	70		30	71.6	0.65	435	426

* This result was obtained on a separate occasion from the others.

size range do not respond to deviations in flow pattern. The response of a particle to changes in flow is quantified by its Stokes number, which is the quotient of its stopping distance in viscous drag conditions and the scale of any changes in flow pattern. In our apparatus this quotient is so small that aerodynamic design is unnecessary.

The two lines pass out of the chamber and are united by a Y-piece in which are incorporated solenoid valves that switch the flow between the two lines. The lines pass to the condensation nucleus

counter, which is interfaced with a computer. The computer records the aerosol penetration and, on the basis of counts registered, controls the relative time spent sampling the filtered and unfiltered aerosols, since numerical error can be reduced by devoting rather more experimental time to sampling the filtered aerosol. The apparatus has pressure ports upstream and downstream of the filter and this allows the pressure drop to be measured simultaneously with the penetration. We used an Air Instrument Resources micromanometer type MP3KDM for this purpose.

Tests with Standard Aerosols

During testing with standard aerosols of sodium chloride aerosol and paraffin oil mist aerosol each specimen filter in its support was placed into a

similar filter holder to that used for tests with monodisperse aerosols

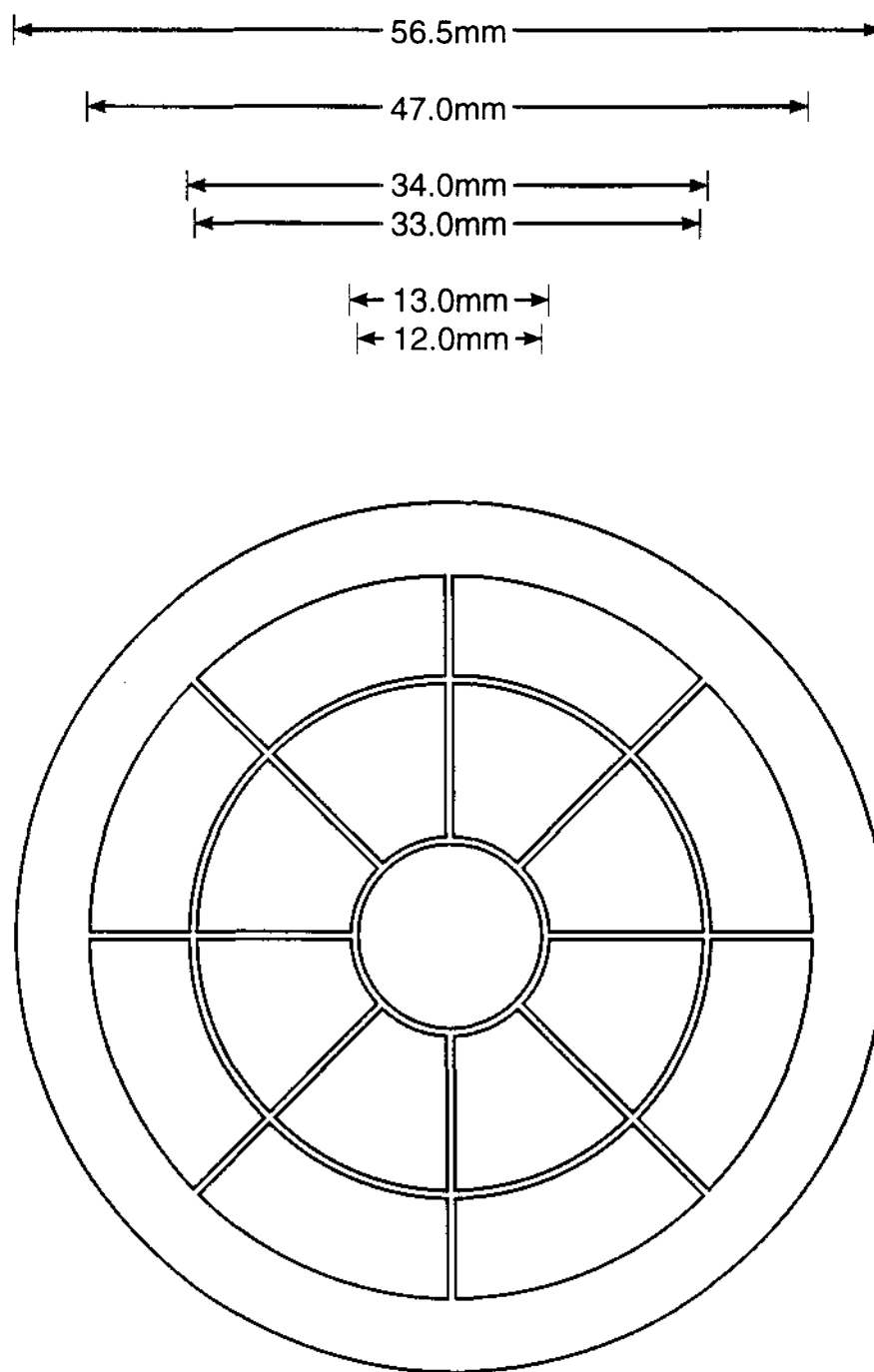


Figure 1. Grid from filter support.

When tests with sodium chloride aerosol were carried out the holder was connected to a Bench Mounted Rig Type 1100-7.100 series apparatus (Moore's, Wallisdown Ltd, UK). The design of this bench rig was based on the method described in British Standard BS4400 (1969) for testing respirator filters, canisters and filter materials. The manner is similar to the BS3928 (1969) rig, and it also complies with the standard EN 143 (1991). Particles of sodium chloride were generated from 1% aqueous solution, by means of a Collison atomiser with three spray nozzles, and mixed with dry air to ensure evaporation. According to the standard (EN 143, 1991) the particles have a nominal mass median diameter of 0.6 μm with approximately 10% of the mass consisting of particles with a diameter less than 0.23 μm and approximately 10% of the mass consisting of particles with a diameter greater than 1 μm . It must be stressed that this distribution is nominal, and should not be used in the same way as rigorous data.

The penetrating sodium chloride aerosol was quantified by flame photometry, after vaporisation in a hydrogen flame giving the characteristic sodium emission. The intensity of the light is a function of the sodium chloride concentration, and is measured with the aid of a photomultiplier.

The aerosol penetration through a filter is calculated by and displayed on the microprocessor control unit (Moore's Wallisdown Ltd, UK). The pressure drop across the filter was measured simultaneously by a differential pressure meter type DELTA (Grimm Labortechnik, Airling, Germany). The complete results were printed after each test.

The filters were tested with paraffin oil according to the standards EN 143 (1991) and DIN 24 184 (1990). The same filter holder was used as before, and the rig consisted of: an oil mist generator type AGW/BM VI (LORENZ Messererbau, Katlenburg-Lindau, Germany), a photometer type UP 92-TN (Sigrist Photometer AG, Ennetburgen, Switzerland) a differential pressure meter (Mechanics Institute of PAN, Cracow, Poland), a flow meter type ROL 162 (CHEMOPOMAIR, Giliwice, Poland) and vacuum pumps.

The paraffin oil mist generator was a AGW/BM VI generator, the design of which is based on the test method described in BS EN 143 (1991) and DIN 24 184 (1990). Its main parts are the atomizer, the separator and the two dilution stages. The

atomization vessel was heated, so that the temperature of the oil could be held at 100 degrees Celsius. The rotating airflow in the separator removes the bigger oil droplets, and expansion of the air causes cooling resulting in the condensation of oil vapour into droplets. Finally dilution produces the aerosol shown in standards EN 143 (1991) and DIN 24 184 (1990), the size distribution of which is nominally lognormal with a number median Stokes diameter of 0.4 μm and a logarithmic standard deviation of 0.26. Approximately 10% of the particles are smaller than 0.18 μm and approximately 10% larger than 0.9 μm . Again the size distribution is nominal and not rigorous.

The pressure of the compressed air supplied to the AGW/BM IV generator, its temperature, its flowrate and all other parameters were controlled by a built in control unit. The concentration of the oil mist upstream and downstream of the test filter was measured by light scattering, using a photometer type UP 92-TN, previously calibrated with one of a range of standard optical filters, chosen according to the quotient of upstream and downstream concentrations. The pressure drop was measured at the same time, with a differential pressure meter (Mechanics Institute of PAN, Cracow, Poland).

Each test was carried out on a single specimen of each specific mixture. The same samples of material were subjected to both penetration tests, and the pressure drop was measured at both laboratories during the experiments.

Any form of filter test will cause some slight loading of the filter, and significant loading will alter the penetration characteristics. The tests on monodisperse aerosols were carried out first because classification significantly reduces the mass of aerosol used in the test, and a counting method can be applied to a very small mass of aerosols if these are submicrometre. Loading of the filters during these tests is, therefore, very low indeed. The tests on standard aerosols were carried out later. Since the filters are purely mechanical in action, loading will cause a decrease in penetration and an increase in pressure drop, but since measurements are made in real time this would be noticeable from the results obtained, and no significant change in reading was observed during the duration of the test. We can therefore safely conclude that the results we have apply to tests on clean filters.

Results

All of the tests were carried out at a face velocity of 0.1 m s^{-1} . Since the tests were carried out on the same filters by two laboratories it is important to have some assurance that measurements were carried out in a corresponding way. Fortunately, this can be provided by measurements of pressure drop. When a filter is operated in static conditions the pressure drop is a unique function of the velocity of air flowing through it; in the tests described in this paper the filters obey Darcy's law, with the pressure drop across a filter directly proportional to the air velocity. If, therefore, the tests were carried out in identical conditions at the two laboratories the observed pressure drops would be the same. The

results are illustrated in Fig 2. The points lie close to a 1:1 correspondence line, though there is a very slight tendency for higher values of pressure drop to be recorded at HSL than at CIOP. This indicates that confidence can be placed upon the conditions being similar at the two laboratories.

The complete set of results for area weight, thickness, pressure drop and penetration of mono-disperse and standard aerosols is summarised in Tables 1 and 2. The wide range of efficiencies obtained by using the materials as variable as these is apparent.

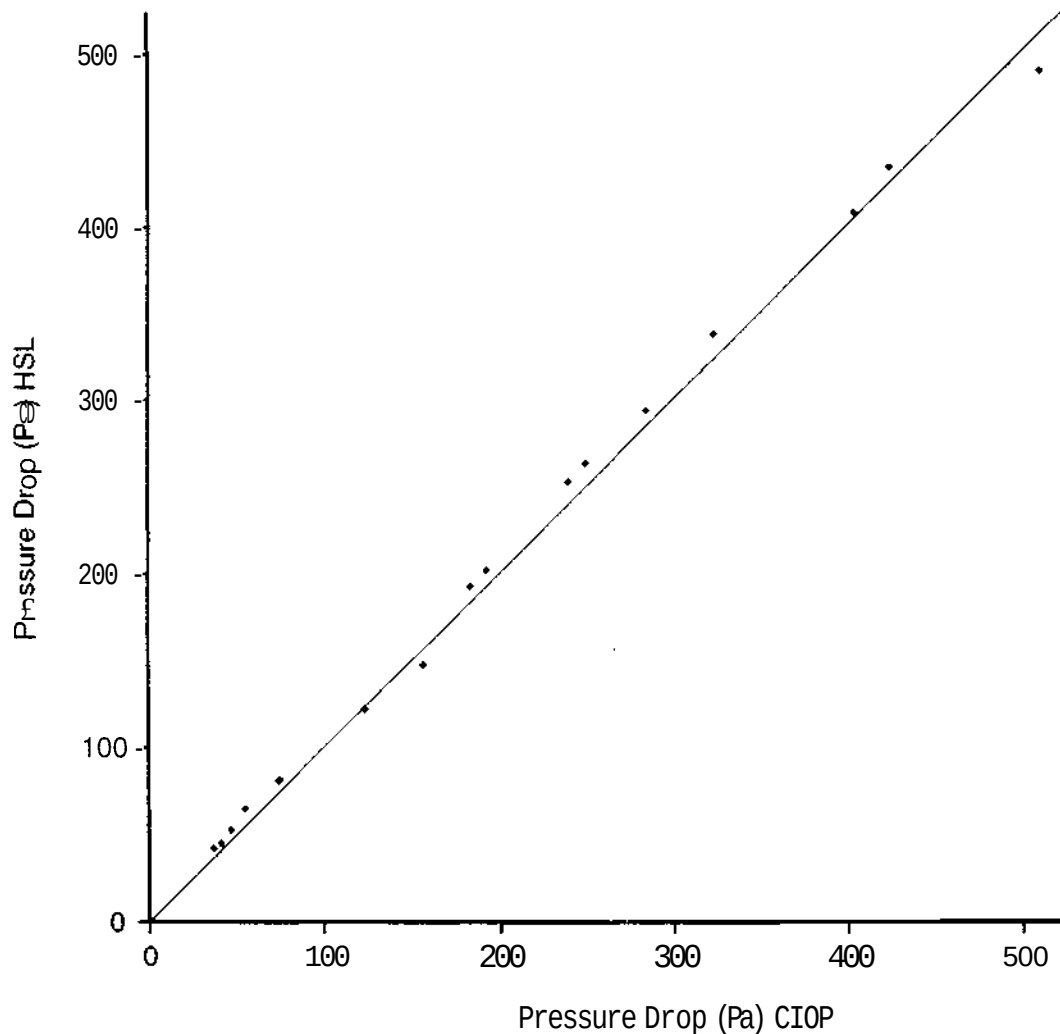


Figure 2. Comparison between pressure drop measurements made at CIOP and at HSL.

Table 2. Penetration of monodisperse aerosols of a range of diameters and of standard aerosols through glass-fibre filters.

Aerosol Penetration (%)										
Filter no	Monodisperse aerosols of various diameters								Standard aerosols	
	0.01 μm	0.02 μm	0.04 μm	0.06 μm	0.08 μm	0.1 μm	0.2 μm	0.3 (am	NaCl	Paraffin
1*									0.072	0.017
2	0.02	0.019	0.062	0.14	0.24	0.33	0.19	0.051	0.13	0.021
3	0.066	0.021	0.24	0.87	1.21	1.47	0.73	0.58	0.32	0.034
4	0.037	0.075	0.81	2.14	3.54	4.13	1.70	1.13	2.57	0.11
5	0.045	0.066	1.22	3.41	5.51	6.69	3.87	2.50	4.33	0.38
6	0.011	0.081	1.01	4.48	9.19	8.07	7.21	3.24	5.03	0.55
7	0.11	0.037	1.46	4.15	8.55	8.20	5.44	5.18	4.55	1.02
8	0.20	0.74	2.78	10.0	13.0	15.3	13.1	7.04	8.34	1.67
9	2.33	1.91	9.41	9.22	13.6	33.5	15.3	15.0	17.9	7.2
10	2.17	7.89	25.1	42.9	42.4	47.2	49.7	47.2	36.0	21.2
11	8.97	11.2	22.5	50.0	63.9	68.8	64.9	56.8	51.4	36.5
12	5.17	21.6	34.5	47.4	58.1	71.6	64.1	68.9	60.8	42.3
13*									73.0	51.1
14	5.94	15.3	36.9	50.1	59.4	62.1	68.7	61.2	55.2	51.4
15	0.63	7.19	29.5	41.4	49.5	54.9	58.1	52.6	58.0	37.2
16	0.78	5.5	11.4	33.5	39.6	44.0	44.3	27.6	33.9	24.7
17	0.04	0.33	3.54	7.79	11.3	13.0	11.1	7.33	8.83	1.85
18	0.018	0.028	0.29	1.78	2.83	3.52	1.53	1.43	9.22	0.21
19	0.0040	0.0034	0.055	0.43	0.72	0.88	0.48	0.26	0.14	0.04

* No penetration measurements were made on these filters with monodisperse aerosols, but the results of measurements with polydisperse aerosols are used in Fig 3

Comparison of Penetration of Standard Aerosols

Figure 3 shows a plot of the penetration of the two standard aerosols against each other for all of the materials tested with them. When the penetration through materials is high there is only a small difference between the behaviour of the two standard aerosols. When the penetration is low the sodium chloride aerosol is considerably more penetrating than the paraffin oil mist. The data corresponding to penetration of more than 1% for the sodium chloride aerosol, or more than 0.1% for the paraffin oil mist fall more or less on a straight line. However, the addition of the remaining four data points causes a deviation into a curve. Data like

these can be compared with measurements made using standard aerosols by Brown et al (1987), and a discrepancy of this sort could be explained by the sodium chloride aerosol having a mean penetration slightly greater than that of the paraffin oil mist and, since the aerosol is polydisperse, a standard deviation of penetrations also rather greater.

The effective mean size of an aerosol depends on the method of detection employed. Since the sodium chloride aerosol is detected by flame photometry it is reasonable to associate the behaviour of the aerosol with the mass weighted parameters of the

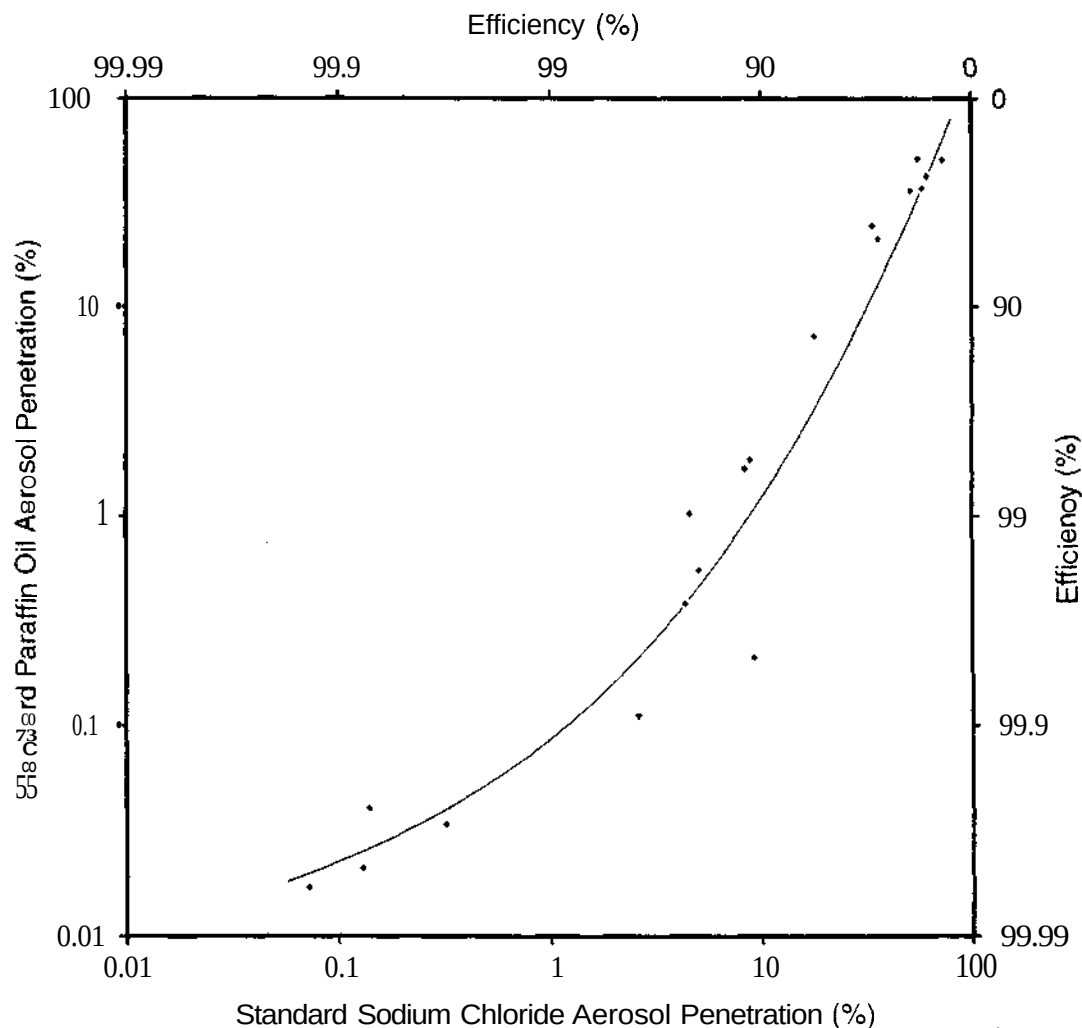


Figure 3. Comparison between sodium chloride aerosol and oil mist aerosol penetrations.

distribution. The paraffin oil mist, on the other hand, is detected by light scattering, so the required weighting of the distribution is quite different, and probably closest to surface area weighting. The data in the standard would suggest that this results in a higher mean size for the paraffin oil, which would make it less penetrating. Moreover, very small particles scatter light only very weakly and this may be the reason why the measured penetration of this aerosol is considerably less when penetration is small.

The results can be compared with those of Myogo and Sugimoto (1997), who measured the penetration of silica dust and sodium chloride aerosol through filters with a wide range of efficiencies, finding the sodium chloride aerosol consistently

more penetrating. They also compared sodium chloride aerosol penetration with DOS aerosol mist, both with a mass median diameter of 0.28 μm , but with the sodium chloride aerosol much more polydisperse. In this situation they found the mist rather more penetrating, in contrast with our results.

Our results are consistent with the current European Standard EN143 (1991), in which corresponding values of penetration of sodium chloride and oil mist through filters are set at 0.05% and 0.01% for P1, and 6% and 2% respectively for P2. They are not consistent with the proposed revision prEN143 (1997), which suggests that the values formerly ascribed to the sodium chloride should apply to both aerosols.

Comparison of Penetration of Standard Aerosols and Monodisperse Aerosols

Figure 4 shows the penetration of monodisperse aerosols through the materials plotted against penetration of the sodium chloride aerosols. Data are plotted for the monodisperse aerosols of 0.02, 0.04, 0.1 and 0.3 μm in diameter. The points are joined by straight lines, not to attribute any presumed value to intermediate regions, but simply to make it clear which points are associated with each other. The graphs are plotted in two distinct limbs, corresponding to the separate binary mixtures of 0.76 and 3.0 μm fibres mixed respectively with 1.8 μm diameter fibres. The data for the third mixture follow the same basic pattern but are more scattered. In the case of the 0.02 μm particles there is a correspondence, but scatter is large; the reason is probably the small numbers of particles counted, giving rise to large potential numerical error. For the other particles the behaviour is more ordered and in fact the two limbs of each graph fall together.

A fraction of the monodisperse aerosols may be charged, and this means that image forces between the charged particle and the neutral fibre would have some effect on filtration efficiency. Expressions exist for single fibre efficiency when capture is by diffusion and when it is by image forces (Brown, 1993). Calculation of these using the parameters of the experiment indicates that diffusion effects are about an order of magnitude larger, and so the effect of charge on the particles is not likely to be critical. The charge on the standard sodium chloride aerosol has been measured by us (unpublished work, HSL), indicating that about 90% of the mass of the aerosol is in the form of charged particles. The charge on the oil mist aerosol is not known, but since it is a condensation aerosol the charge is likely to be low.

Standard filtration theory for the capture of particles in filters by interception and diffusional deposition predicts a most-penetrating particle size, and this is widely observed in practice (Brown, 1993). In many instances this size is close to 0.1 μm though it depends on properties of the filter, in particular the fibre diameter, and on the face velocity

of the air being filtered. In Table 2 the most penetrating particle is usually the 0.1 μm particle, and when this is not the case neither the size nor the penetration of the most penetrating particle used in the tests is far removed. This means that the 0.1 μm results give a reasonable representation of the actual most penetrating particle.

The results on particles of this size are of greatest interest because estimates of the size of the most penetrating particle tend to fall in this region (Brown, 1993), and in Fig 4 a straight line approximation would be a reasonable fit to the data. The 1:1 graph is also drawn, and this illustrates that there is a reasonable correspondence between the penetration of the standard sodium chloride aerosol and that of the most penetrating particle. At low penetrations the most penetrating particle is approximately five times as penetrating and at high penetrations the factor approaches unity. Data for the remaining mixture, the 0.76/3.0 μm mixture, follow more or less the same pattern but there is more scatter, for a reason that is not known. Filter 15 shows a slightly higher penetration for the sodium chloride aerosol than for the 0.1 μm aerosol, but this is probably within experimental error. There is a significant discrepancy for filter 18, but since the sodium chloride penetration value for this filter does not follow the general trend of other measurements, the result must be questioned.

The same data for the monodisperse aerosol penetration are plotted against the penetration of paraffin oil in Fig 5. The same basic pattern is followed, but agreement between the two sets of data is not as good as before, and many of the monodisperse aerosols are more penetrating than the oil mist. The graph relating the penetration of the oil mist to that of the 0.1 μm aerosol is not so well described by a straight line function. The 0.1 μm aerosol is about 40 times as penetrating as the standard aerosol at small penetrations, but for larger penetrations the ratio drops to about 1.5.

Conclusions

The results of measurements have shown that the penetration of monodisperse aerosols in the size range of 0.02–0.3 μm correlate reasonably well with the standard sodium chloride aerosol and not quite

so well with the standard paraffin oil mist aerosol for glass fibre filters with a range of fibre sizes from 0.75 μm diameter to 3.0 μm diameter. The correspondence is encouraging but it would be dangerous to

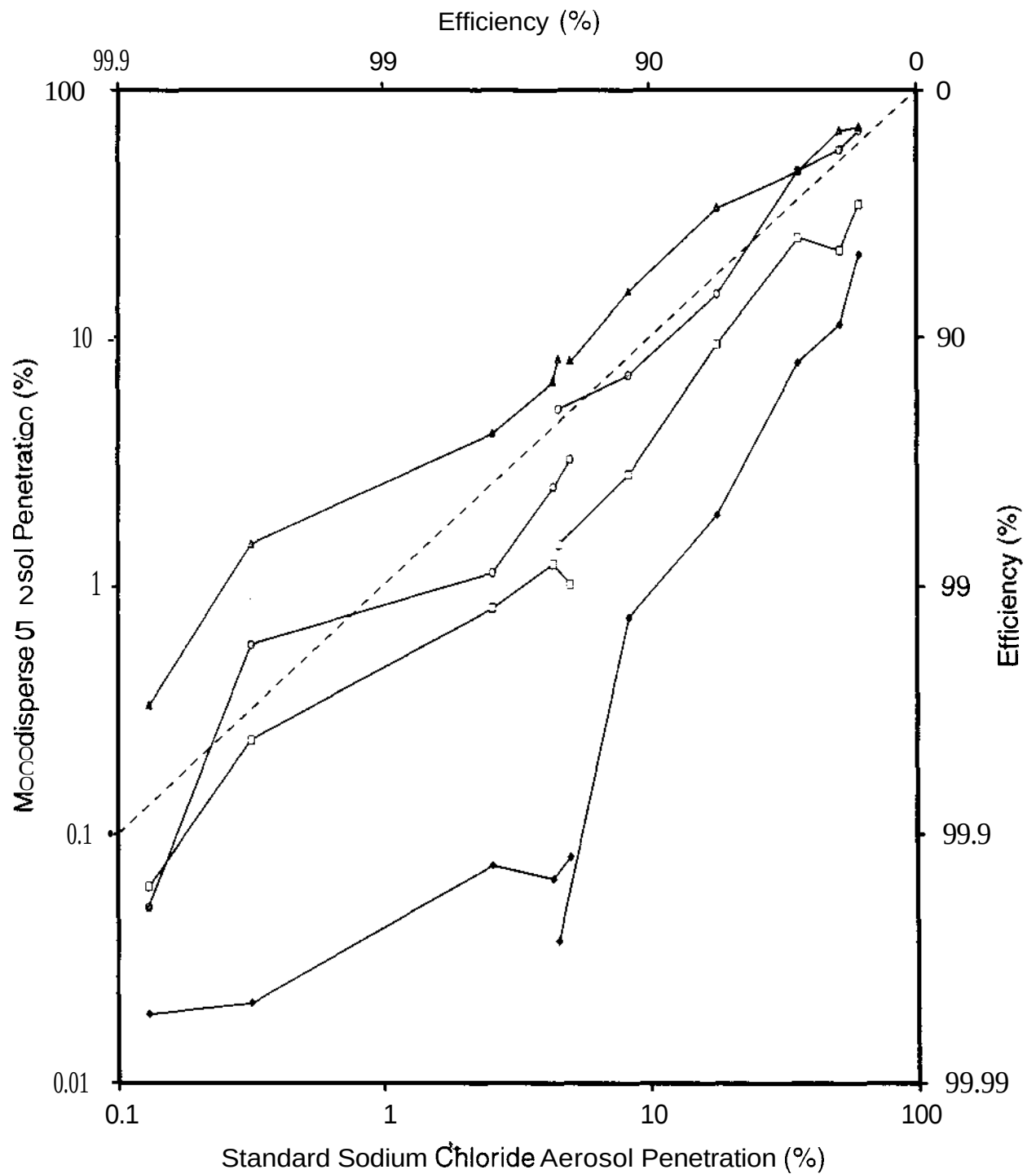


Figure 4. Comparison between monodisperse aerosol and sodium chloride aerosol penetrations.

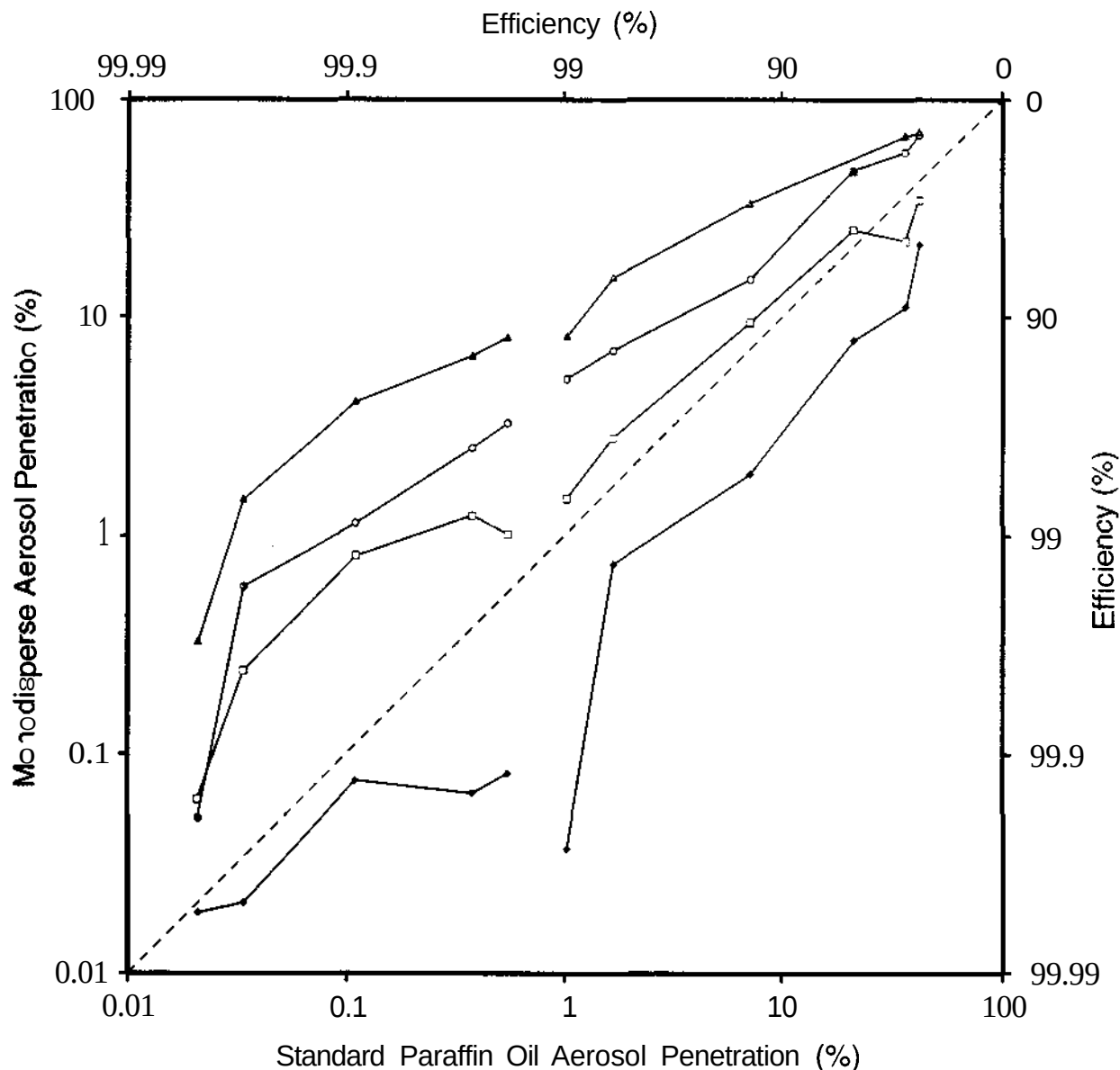


Figure 5. Comparison between monodisperse aerosol and oil mist aerosol penetrations.

extrapolate it too far, for instance to electrically charged filter materials or filter materials that differ completely in structure.

Of the two standard aerosols the sodium chloride aerosol penetrations through the filters correlate

rather better with the penetration of the most penetrating monodisperse particles used in the tests and the absolute values of penetration are closer together.

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