J. Hyg., Camb. (1978), **81**, 433
With 4 *plates*
Printed in Great Britain

The evaluation of fabrics in relation to their use as protective garments in nursing and surgery. I. Physical measurements and bench tests

By O. M. LIDWELL and C. A. MACKINTOSH
Central Public Health Laboratory, Colindale Avenue, London NW9 5HT

(*Received* 13 *March* 1978)

SUMMARY

Eleven fabrics selected to provide a representative range of yarns and weaves have been examined microscopically and subjected to a series of tests. The observations were directed towards assessing the potential ability of each fabric to resist penetration by particles, such as skin scales, which might carry micro-organisms. The number, size and shape of pores penetrating through the material were estimated and the penetration of test dusts assessed in several ways. While, generally, the relative merits of the fabrics are similar whatever test or measurement is considered there are a number of significant exceptions which reflect peculiarities of the test system or of a fabric. Comparison with the results of dispersal experiments with volunteers wearing garments made of the fabrics is made in a following paper.

INTRODUCTION

It has been known for many years that the gown commonly used in the operating room, made of relatively loosely-woven cotton fabrics, does little to prevent the dispersal of bacteria by those wearing it. Duguid and Wallace showed, as long ago as 1948 (Duguid & Wallace, 1948) that replacing these gowns with a modified boiler suit, including integral socks for the feet, made of tightly woven heavy twill could reduce dispersal to 10% or less. Observations in hospital wards and in isolation units carried out more recently have demonstrated that the apparent airborne spread of identifiable strains of *Staphylococcus aureus* from carriers of these organisms into other rooms is much greater than can be accounted for by the observed transport of tracer particles by air movements in the building (Lidwell *et al.* 1975). This can be most easily explained if contamination on a nurse's clothing derived from one patient can be carried into the environment of another patient, perhaps some distance away, and there redispersed. Normal cotton gowns do not prevent the contamination of underlying clothing, nor does the wearing of a fresh sterile gown prevent the re-dispersal of this contamination (Hambraeus, 1973).

There are, therefore, hospital requirements for protective materials and garments suitable for a variety of situations, including in addition to the operating room, nursing of infective and susceptible patients in both special units and the general wards.

Since experiments with human subjects, and, still more, studies in working situations are extremely time consuming and have an inherently high variability, a measurement or bench test which was a reasonably accurate predictor of in-use performance would be a very valuable screening tool. We have, therefore, examined the behaviour of a representative set of fabrics in a series of bench tests and compared the results with those obtained from the same materials made up into garments and worn by volunteers (Lidwell, Mackintosh & Towers, 1978).

Two of the tests are derived from British Standard Tests designed to measure the porosity of water repellent fabrics. Two more have been designed by ourselves to measure the actual penetration of test particles (fluorescent powders, glass microspheres and talcum powder) through the fabrics, either in the airborne state, or when rubbed into the fabric. The fabrics were also examined microscopically. The fabrics tested here were chosen after preliminary examination of a much larger number in order to provide a representative selection of weaves and yarn, including those in hospital use.

MATERIALS AND METHODS

Physical descriptions of fabrics

From about 50 fabrics collected, 11 were chosen for study (Table 1) and two other materials, fine copper-wire mesh and polyvinyl chloride sheets were used in some of the tests for reference. The wire mesh provided a material with a clearly defined number of holes of nearly uniform size and regular shape. The polyvinyl sheet was without perforations and completely impermeable to air.

The structure of the fabrics was examined with a binocular microscope (× 20 magnification) and both incident and transmitted illumination were used. The following characteristics were recorded:

(*a*) The type of weave (if woven), e.g. plain, twill etc. (see Fig. 1).
(*b*) The number of yarns per cm.
(*c*) The thickness of each yarn.
(*d*) The apparent gap between yarns.
(*e*) The number of fibrils in each yarn, by dissection, using a fine needle.

(*f*) The weight of each fabric (g/m^2) was determined by weighing as large a piece as could conveniently be accommodated in the scale pan of a microbalance.

(*g*) The thickness of each fabric, measured using a micrometer with 6 mm diameter jaws. In addition to a direct measurement readings were taken with the fabric held flat between two glass microscope slides, to spread the pressure and minimize compression. The resulting descriptions of the fabric, excluding (*c*), (*d*) and (*e*) above, along with the manufacturer's stated chemical composition are given in Table 1. Low power photographs of the surfaces of the fabrics are given in Plates 1 and 2.

Pore size, shape and number

The microscope was used in conjunction with an eyepiece graticule of the square and circle type, calibrated against a stage graticule each time before use. There

Table 1. *Characteristics of fabrics tested*

Common name	Code	Composition	Weave	Threads/cm (warp and weft)	Weight (g/m²)	Thickness (µm) (non-compressed/compressed)
400-mesh sieve	S	Copper wire	Plain	162 × 162	—	26
White nylon	NB	100 % nylon	Plain	44 × 34	65	100/105
Nylon taffeta	NT	100 % nylon	Plain	34 × 52	66	125/120
Utopia plus	U	65 % Dacron 35 % cotton	Plain	23 × 39	200	320/290
Balloon cotton	B	100 % cotton	Plain	26 × 32	163	390/305
Johnson & Johnson '450'	J2	60 % terylene 40 % cellulose	Non-woven	—	65	285/195
Featherproof cotton	F	100 % cotton	Herringbone	22 × 30 + 22 × 40	230	500/350
Johnson & Johnson Dexter	J1	88 % cellulose 12 % nylon	Non-woven	—	80	255/160
'Ceramic' terylene 8085	C	100 % terylene	Plain	30 × 60	110	140/130
Pima cotton	P	100 % cotton	Oxford	28 × 72	195	295/260
Ventile 'L34'	V	100 % cotton	Oxford	34 × 92	155	230/210
Tyvek	T	100 % polyolefin	Spunbonded	—	43	140/100 or 70
PVC sheet	PVC	Polyvinylchloride	Sheet	—	—	—

Notes:

B was obtained from Uppsala University hospital and is the fabric used by Hambraeus (1973).

J1 and J2 were obtained as complete disposable garments.

C is the fabric described by Bloor & Dinsdale (1962), devised for protective garments in the pottery industry.

P is a USA cotton fabric of similar type to the British Ventile waterproofed by the Quarpel process (Moilliet, 1963).

T was Dupont Tyvek type 1443.

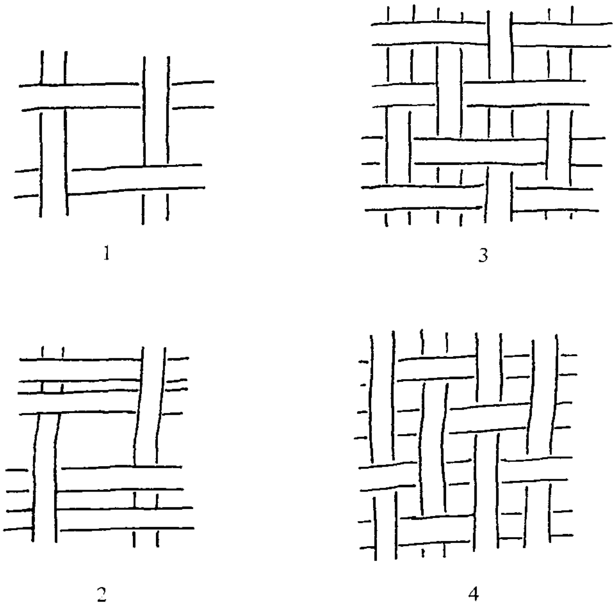


Fig. 1. Schematic illustration of types of wave. 1, Plain; 2, Oxford; 3 and 4, Twill right- and left-handed.

were problems of flare and inadequate depth of field at high magnifications. It was also difficult to be sure whether bright areas represented genuine holes passing right through the fabric or only thin portions in a relatively transparent material with possible fibrils across apparent pores. Assessment was much improved by using polarizing filters, one in the light beam before and one after passing through the fabric. When the polarizers were 'crossed' any light that passed uninterrupted through the fabric, i.e. through a pore, was plane-polarized and was cut off by the second filter. Light passing through transparent material, striking a fibre crossing a pore or at the edge of a pore usually underwent a change in polarization and was no longer completely cut off by the second filter. The polarizers which we have used (Polaroid type HN22 for microscopy) showed dark blue when 'crossed'. Genuine pores therefore appeared dark blue with fibrils and edges of the pore standing out brightly against them. This method is not always effective with darkly dyed fabrics or those whose fibrils show colours under polarized light.

Although photographic comparisons can be made of the same field of view of the same piece of fabric with the polarizers 'crossed' and 'uncrossed' (see Plate 3) the method works best by crossing and uncrossing the polarizers while observing the material.

Depth of field was adequate at a medium magnification (× 100) which gave a reasonable field of view (1 mm diameter) and yet was sufficient to detect a pore as small as 3 μm in diameter.

Pore density (pores per cm^2)

This was obtained from the percentage of yarn intersections showing pores when several fields were examined. From a knowledge of the total number of intersections per cm^2 (from warp and weft counts) the number of pores per cm^2 was estimated. For more tightly woven fabrics a large area had to be covered at a lower magnification and individual pores confirmed at a higher power using the polarizers. The average number of pores per field was then multiplied by an appropriate factor to give a count per cm^2. This latter method was also used for the non-woven fabrics.

Pore shape and size

The dimensions of the largest pores were measured. These pores are those supposedly measured by the bubble pore test. Because the irregularity of shapes did not lend themselves to concise written descriptions the pores were treated as approximately regular geometric figures and their dimensions (length × breadth, or base × height etc.) given accordingly. To provide a single characteristic measurement for comparisons the largest diameter of the largest pore was calculated. Only pores unoccluded by fibrils were measured within a defined area (that revealed with the fabric held flat in a 2 in. square slide mount, about 8·4 cm^2). Photographs of the pores through three of the fabrics are shown in Plate 4.

Bubble pressure test

This test was adapted from the British Standard Test No. 3321 (1969). It provides an estimate of the size of interstices in all types of fabrics which are permeable to air.

The pressure required to force air bubbles through a fabric wetted by and covered with a film of liquid is related to the size of the pore and the surface tension of the liquid by the equation:

$$P = 2T \times 10^4/(r\rho g),$$

where P is the pressure in cm head of water, T is the surface tension (dynes/cm) of the liquid used, ρ is the density of water at the temperature of the test, expressed in g/cm^3, r is the *equivalent* pore radius (in μm), i.e. the radius of a capillary of circular cross-section which would require the same pressure to force liquid from it. The apparatus used for this test is shown in Fig. 2.

A piece of the fabric, or portion of the garment, was soaked in white spirit for at least 3 min before being tested and then clamped between the O-ring and the upper metal ring of the test bed so that a circle of fabric, 21·5 cm^2 in area, was exposed to increasing air pressure from below. A large bottle (10 l) served to smooth out and slow down the increase in pressure and acted as a reservoir so that the pressure increased uniformly, even when bubbles started forming.

The experiment was started by switching on the pump, and immediately pouring about 5 cm^3 of white spirit onto the surface of the fabric. The pressures at which the first bubbles formed were noted and the corresponding equivalent pore

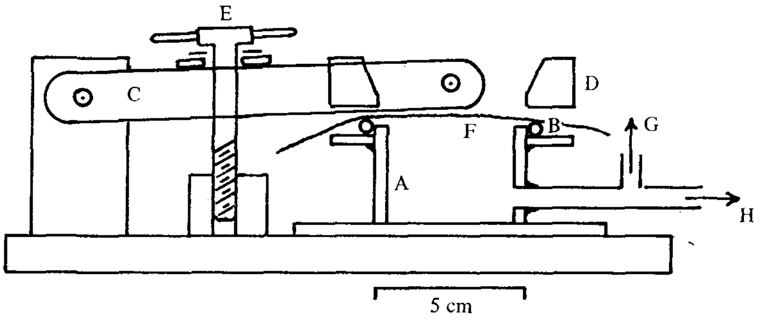


Fig. 2. Fabric holder for bubble pressure and air flow tests. A, Air chamber; B, O-ring seal; C, pivot bar (2); D, upper clamp ring; E, clamp screw; F, fabric under test; G, connexion to manometer; H, connexion to air supply.

Table 2. *Microscopic examination, bubble and airflow tests*

Code	Pore density (cm^{-2})	Largest unoccluded pore in 8·4 cm^2 (μm)	Largest dimension (μm)	Bubble pore equiv. diam. (μm)	Airflow ($cm^3/min/cm^2/cm\ H_2O$)
S	26300	35 × 35	49	60	18200
NB	1450	50 R 50	71	54	250
NT	1300	20 R 100	102	57	275
U	480	120 R 140	184	130	825
B	620	30 T 115	115	98	614
J2	1400	45 R 60	75	290	3960
F	20	15 R 50	52	70	210
J1	300	20 T 33	33	55	320
C	(180?)	15 T 15	15	22	20
P	7	30 T 45	45	45	75
V	7	3 ◇ 20	20	23	30
T	?	30 ○	30	42	5
PVC	0	—	—	—	0

R, Approx. rectangular; T, approx. triangular; ◇, diamond/slit shaped; ○, approx. circular.

sizes calculated from the formula. The British Standard requires only that the pressure at which the third bubble forms be measured. However, the pressures at which other bubbles formed, in some cases up to the fiftieth, were obtained and this was useful in giving some idea of the size distribution of the pores. Note that these bubbles formed at the lower end of the pressure rise and thus represent the largest pores found in the area tested. The figures quoted in Table 2 are given as equivalent *diameters* as this is commonly accepted as the 'pore size' when dealing with fabrics. The values quoted by manufacturers and in the literature often, however, give the equivalent *radius*, as defined in the British Standard, although this is not always made clear since the undefined term size is used (sometimes even the word diameter is applied to what is, in fact, the BS radius). Our tests departed from the British Standard Test in that the fabrics were not preconditioned to 65 ± 2% relative humidity and 20 ± 2 °C but were tested at the prevailing laboratory humidity 40 ± 10% r.h. and temperature 20 ± 4 °C and, in most cases, only duplicate and not ten replicate samples were tested. The rate of increase in

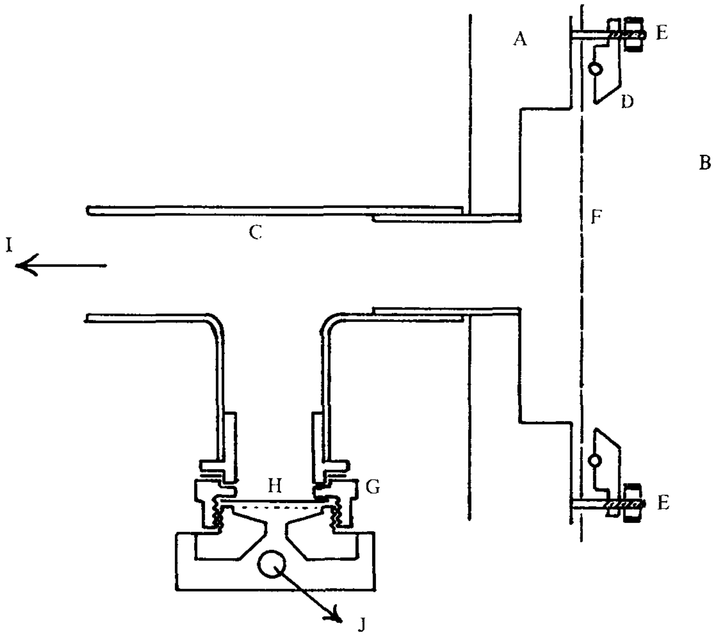


Fig. 3. Fabric holder and particle sampler for penetration tests using air borne particles. A, Panel in wall of chamber; B, interior of chamber; C, 2·5 cm tube connexion and T-piece; D, fabric holder with O-ring seal; E, clamping screws (4); F, fabric under test; G, membrane filter holder; H, membrane filter; I, connexion to suction; J, connexion to flowmeter and sampling suction.

pressure was also altered to suit the fabric by use of a needle valve controlling the flow of air to the large bottle. The results are given in Table 2.

Air permeability

This test was derived from the British Standard Test No. 3424 (1961). The same test bed was used as for the bubble pressure test with the pump reversed to suck air in *through* the fabric – the flow being measured by a calibrated rotameter. The pressure drop across the faces of the fabric was measured at the same time. Air flows were adjusted by a needle valve on the air suction tube.

A series of measurements of air flows at different pressures was made and expressed graphically. This differs from the method used in the Standard which requires only that the air flow through a defined area be made for a single pressure drop, 1 cm water gauge. The range of pressures or air flows was chosen to suit each fabric, up to a maximum of 12·5 l air/min for the more porous fabrics or 25 cm water gauge for the fabrics of low permeability. Thus fabrics could be compared even when they would have produced too high or too low an air flow to be measured at 1 cm head of water. The air flow was proportional to the pressure in all cases and was expressed as cm^3 air flow/min/cm^2 fabric exposed/cm water gauge pressure drop across the two surfaces of the fabric.

The fabrics were not preconditioned to a defined relative humidity and temperature as required by the Standard but were tested under prevailing laboratory

Table 3

	D. Airborne penetration			E. Rub through*	
	Royco	Millipore samples			
Code	% penetration by 'dust' < 0·5 µm, relative to no fabric	% penetration by fluorescent powders, relative to no fabric	% penetration by talc., relative to no fabric	Microspheres† (total numbers penetrating)	Talc‡
S	(100)	(100)	(100)	$3·0 \times 10^5$	$0·6 \times 10^5$
NB	99	49	93	910	1000
NT	Not done	Not done	99	450	1400
U	80	36	37	2700	4700
B	62	37	34	1600	3150
J2	70	17	25	1900	300
F	10	5	7	4.5	33
J1	14	5	6	4·5	0·2
C	13	13	4	0·2	0·07
P	9	2	2	0·4	0·7
V	7	4	2	0·2	0·3
T	3	1	3	0·5	0·5
PVC	Not done	Not done	Not done	< 0·1	ND

* The figures in the table are estimates of the numbers penetrating the fabric during the first minute of rubbing for a 10^6 particle load.

† The load of microspheres used was about 350 mg which at $3·1 \times 10^4$ spheres/mg was equivalent to about $1·1 \times 10^7$ particles.

‡ The load of talc. used was about 150 mg which at 2×10^5 particles/mg was equivalent to about 3×10^7 particles.

conditions and, usually, only duplicate estimates were made and not the five replicates required by the Standard. The Results are given in Table 2.

Airborne particle penetration tests

If air is drawn through a fabric this acts as a filter retaining a proportion of the airborne material. If the concentration of particles in the air which has passed through a fabric is compared with the concentration of particles in the air upstream of the fabric, this ratio gives a measure of the permeability of the fabric to airborne particles.

A panel was constructed to fit in place of an inlet filter on a door to an enclosed chamber (Fig. 3). The chamber was that used for dispersal tests, Series A (Lidwell *et al.* 1978). Six 2·5 cm diameter copper pipes were let into this panel so that they communicated with the air inside the chamber. Pieces of fabric could be clamped across the inner face of the panel so that any air drawn from the chamber through the copper tubing had passed through an 8·5 cm diameter portion of the fabric. Air was drawn separately from each of the six ports through limiting orifices into a common reservoir by means of a primary pump. For open weave fabrics flow of air was the limiting factor (up to 50 l/min/fabric) and for tightly woven fabrics the reservoir pressure was the limit (maximum: 28 cm water gauge).

A second pump was used to sample the air passing through each fabric, by drawing a portion of it at a measured rate (up to 10 l/min) through membrane filters (Millipore No. SSWP 02500). The particles deposited on the filters were counted under a microscope after removal of these from their holders.

Particle measurements were also made using a particle counter (Royco Instruments Model 215) attached to two smaller outlets at the T-junction. Two outlets were necessary to equalize the pressure on both sides of the counter pump. The counter could only be used to sample from one fabric at a time.

Penetration of fabrics by 'dust' in laboratory air

Laboratory air was used as a source of particles and the Royco counter was used to detect and count the concentration of particles penetrating the fabrics and these values were compared with the counts obtained from a control port with no fabric in place. There were too few particles greater than 5 μm in the laboratory air to provide satisfactory estimates (an average number corresponded to no more than 3 counts/min). Counts were made of all particles greater than 0·5 μm. The majority of these were under 1 μm. The counts for the different fabrics are given as a percentage of the counts obtained at the port without a fabric. Since not all the fabrics could be tested at once, Balloon cotton was used as a reference in all the experiments. The Results are given in Table 3.

Penetration by artificially generated 'dusts' of talc or fluorescent particles

By means of a piece of apparatus designed to BS 2831 (1957) to disperse test dusts into the air for filter testing, a mixture of fluorescent powders (cadmium borate and magnesium tungstate) or talc powder (Johnson & Johnson 00000, coated with blue ink to make it more easily detectable) was dispersed into the air of the closed chamber. (See Plate 4).

The particles comprising the fluorescent powder mixture had a median value for their minimum projected diameter of about 10 μm. The median for the talc particles was about 20 μm. The size distributions were approximately log-normal and the geometric standard deviations were 1·70 and 1·91 respectively. The minimum projected diameter of a particle is defined in this and succeeding papers as the shortest perpendicular distance between two parallel straight lines between which the outline of the particle can be fitted. It corresponds to the breath, *B*, defined by Heywood (1963). The geometric standard deviation is the ratio of the 84th percentile to the median or mean, or the ratio of the median or mean to the 16th percentile.

A fan, facing upwards from the floor, was used to mix the particles. Fifteen seconds after the introduction of the tracer(s) into the chamber, to allow adequate time for mixing, both pumps were switched on and sampling through the filters was continued until it was considered that virtually all the tracer had disappeared from the air. At the completion of each run the filter papers were removed and the particles collected and counted using a binocular microscope with either visible light or ultra violet illumination. The numbers of particles in at least five fields, more if penetration was low, were counted. The average number of particles

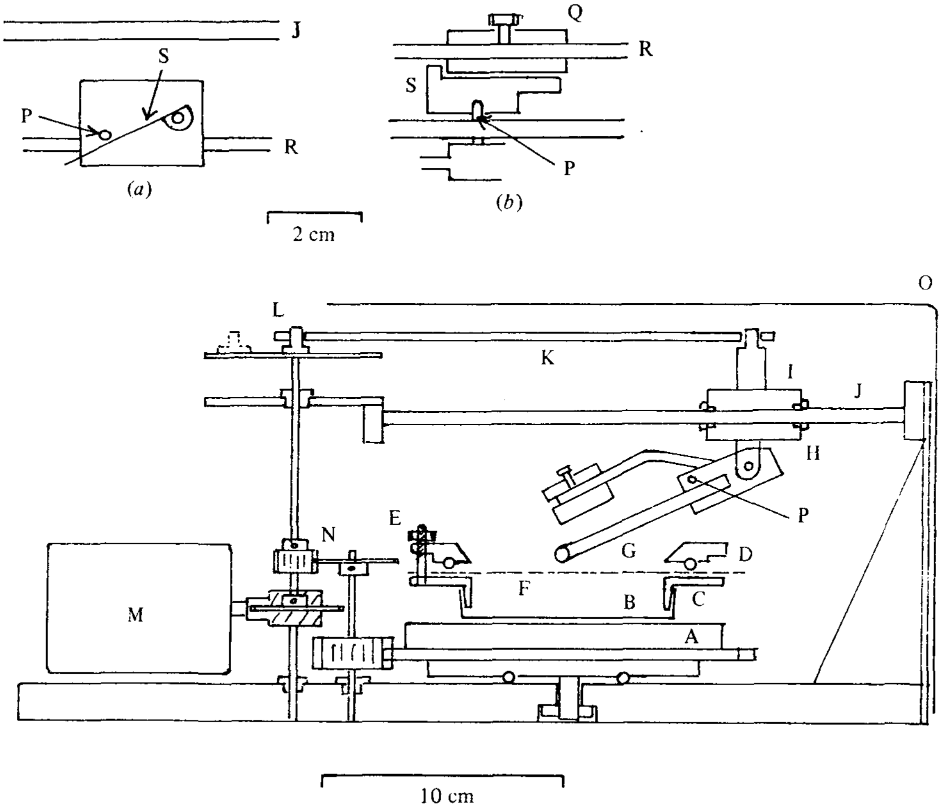


Fig. 4. Apparatus for rub-through tests. A, Rotating table; B, plastic Petri dish; C, lower fabric holder; D, upper fabric holder with O-ring seal; E, clamping screws (4); F, fabric under test; G, glass rubber; H, Teflon block (Polytetrafluorethylene); I, sliding block; J, runners (2); K, drive bar; L, eccentric drive pin; M, motor; N, drive gears; O, wind shield; P, lifting pin. (*a*) and (*b*) Detail of lifting mechanism seen from side and from above. Q, Adjustable block; R, support rod; S, pawl pivoted to fall under gravity.

per field for each fabric was then expressed as a percentage of the count with no fabric in position. It was found that about 30 mg of talc or fluorescent powder was sufficient to give a sufficiently high count on the filter when sampling at no more than 1 l/min from the port without fabric. The experiments were repeated several times with different fabrics but always retaining the balloon cotton in one or other of the ports for comparison. Where it was suspected that a fabric with an open weave might give a high count when sampling the filtered air, the rate of sampling was reduced to 1 or 2 l/min, otherwise samples were taken at the rate of 8 l/min. Results are given in Table 3.

Penetration by rubbed particles

Another way in which skin flakes might penetrate fabrics is by being rubbed directly into and through the pores. A machine was therefore devised which produced a regular, reproducible rubbing motion over the surface of a fabric (Fig. 4).

The fabric is clamped into a holder comprising two flat metal rings, the upper one of which seals down onto the fabric by means of a rubber O-ring sealing off and holding taut a circle of fabric 8½ cm in diameter. The lower metal ring has a rim which fits tightly into the lower half of a standard 10 cm Petri dish. The assembled unit is fitted between locating pins on a revolving table placed beneath the reciprocating rubbing arm. A single motor drives both the turntable and rubbing arm via gears so that, each minute, the table revolves four times completely and the rubbing arm completes fifty-two forward and backward movements. A glass spreader is fitted into the end of the rubbing arm which carries an adjustable weight. This was set so that the pressure of the spreader on the fabric was 44 g.

A known weight of particles was added to the upper surface of the fabric and the rubbing was allowed to continue for a fixed time, usually 1 min. The particles that penetrate can either be collected onto pre-weighed aluminium foil disks and weighed, or onto sticky slides using petroleum jelly or transparent adhesive tape to trap the particles and hold them in position for viewing under a microscope. The former method was used when the rate of penetration was high and the latter when few particles passed through the fabric or when the sizes of particles penetrating were compared with the original size distribution. Glass microspheres ('Swarospheres' – James & Wiggins Ltd, Old Power House Works, Gadshill, Gillingham, Kent, nominal diameter range 1–50 μm) were used, being particles which are easy to recognize under the microscope and which need only one dimension, the diameter, to define their size (Plate 4). Their median diameter was about 24 μm, the size distribution was approximately logarithmic with a ratio of the standard deviation to the mean of 1·58. Talc powder was also used since this material approaches skin flakes in shape and size and is readily available as a test material. The median projected diameter of these particles was about 20 μm, the size distribution was approximately log-normal with a geometric standard deviation of 1·91.

It was found that the machine, as described, quickly tended to rub most of the particles to the edge of the exposed area. A pawl was therefore incorporated which lifted the rubbing arm at the end of each stroke and dropped it onto the centre of the fabric during the return stroke. This ensured that the particles remained in the rubbing area. With this action, however, any draughts across the machine tended to carry away particles raised into the air by the thumping action of the rubbing arm. This was especially serious when using talc. The revolving table was therefore shielded from the motor and the whole of the rubbing portion of the machine enclosed in a draughtproof cover.

Counting under the microscope was facilitated by the use of perforated zinc strips laid over the collecting surface. Since each circular perforation was almost exactly the size of the field at medium magnification (× 100) this helped to separate and define fields for counting and aided in finding particular fields for repeat examination. A sufficient number of fields was counted to allow valid comparison to be made between fabrics. Results are shown in Table 3.

RESULTS

The results of pore size and air permeability determinations are given in Table 2 and those of particle penetration tests in Table 3. Comparisons between the different tests are discussed in terms of (*a*) reproducibility – when testing the same or different pieces of fabric, (*b*) simplicity – of equipment, setting up and operation, (*c*) rapidity – both of the test itself and the number of fabrics that can be dealt with in a given time, (*d*) compactness – i.e. how truly are they *bench* tests? (*e*) ability to test whole garments or uncut fabrics, (*f*) additional useful information obtained. The relation between the test measurements and results and the results obtained from dispersion tests using the fabrics as made up garments worn by volunteers is discussed in the next paper (Lidwell *et al.* 1978).

Reproducibility was assessed from duplicate or triplicate tests on the same piece of fabric and this variation was much less than the large differences between the several fabrics. Patterns of variability were sometimes detected across the width of rolls when using the airflow test. Some of the variability between different pieces of the same fabric was therefore probably due to variability in the fabrics and not just lack of experimental reproducibility.

The test methods were compared on the criteria outlined above and also on the order in which they placed the various fabrics and the range of values which were obtained. When the results of all the tests are compared it becomes apparent that certain fabrics behave 'anomalously' in certain of the tests. These 'anomalous' results will be dealt with after analysis of the individual experiments.

Microscopy was the simplest method in that it required no specialized apparatus that was not readily available. Samples could be processed quickly, depending upon how much detailed information was required, the apparatus took up little space and garments and large uncut pieces of fabric could be examined. Much extra information was obtained, which was useful in identifying or characterizing each fabric. A real problem is deciding the amount of information that it is useful to record. The pores vary so much in shape and size that it is very difficult to pick a 'typical' or an 'average' pore shape or size. The largest pores within a limited area were chosen for measurement as these are the easiest to detect and define and they might be expected to have some relation to the bubble pore test results which should measure these same holes. In this paper we normally define a pore as a passage through the fabric not crossed by fibrils. It may comprise the whole of the area at the intersection of the yarns, e.g. where a fabric of man-made fibre is being studied, but in fabrics such as cottons and woollens, this area is usually broken up by fibrils – in which case, since such fibrils would act as a barrier to particles, each smaller unoccluded area was termed a pore.

The pore density, however, has been defined as the number of yarn intersections per cm^2 that contained a pore, so as to give an indication of the distribution of porous areas throughout the fabric, ignoring the extent to which fibrils might subdivide the aperture at each yarn intersection. Interpretation of the results of microscopic examination is not altogether straightforward. One might expect Ventile, for instance, with few and small pores, to prove a more effective barrier than Balloon cotton, but how much more effective cannot be predicted from these observations alone. Quantitative comparisons between the protective value of fabrics with large numbers of small pores and those with a small number of large pores are not possible unless the fabrics are tested by some other means and a basis for such comparisons discovered. A further difficulty is that indirect pores, not lying in the plane of the light rays arriving at the lower face of the fabric, remain undetected unless the fabric is held at an angle to the optical axis of the microscope.

Photography is a valuable aid in keeping a record of pore structure but does not solve the problems of description or interpretation of the variety of pore types.

We found that medium power (× 100) gave a field of adequate size and depth and the smallest pore that could then be measured was about 3 μm across. Only pores larger than this were counted.

Bubble test

This test was quick to set up and carry out and many fabrics could be quickly tested. The reproducibility was good for most fabrics, better for the tightly woven fabrics than for those with larger holes. Since the calculation of pore size depends on the reciprocal of the pressure an error of $\pm 0{\cdot}2$ cm in reading the water gauge pressure results in a 16 μm uncertainty for a fabric giving a reading of about 5 cm water gauge but only a 0·04 μm error for a fabric giving a reading of about 50 cm water gauge. The test requires more space and equipment than microscopy but is still a simple bench test. With an added flow gauge it is also possible to carry out the airflow tests. The tests can be carried out on uncut garments and lengths of fabrics but the white spirit may have an effect on the structure or colour of certain fabrics. Because of the leakage and evaporation of the white spirit it is advisable to perform this test in a well ventilated room.

An uncertainty with this test is assessing what is actually being measured by the *equivalent* pore diameter and what relation the *third* largest pore bears to overall penetrability. The test appears to be insensitive to the shape of the pores. For instance, white nylon (NB) has roughly square pores, the largest of which approaches 50×50 μm (Plate 4) and nylon taffeta (NT) has slit-like pores (Plate 3), the largest of which is about 20×100 μm but both give very nearly identical bubble pore equivalent diameters of 54 and 57 μm respectively.

By measuring the pressure at which successive bubble points appear an indication is obtained of the distribution of sizes among the largest pores. As figure 5 shows this differs considerably with different fabrics. While both nylon taffeta and the Ventile cotton fabrics show little change in the diameters of the successive pores this was not so for the Pima cotton fabric where the pressure at the seventh bubble point indicated a pore diameter no more than 80% of the third. With the equipment used, the practical limits were 10–500 μm equivalent diameter but the actual range of results obtained was from 22 to 290 μm.

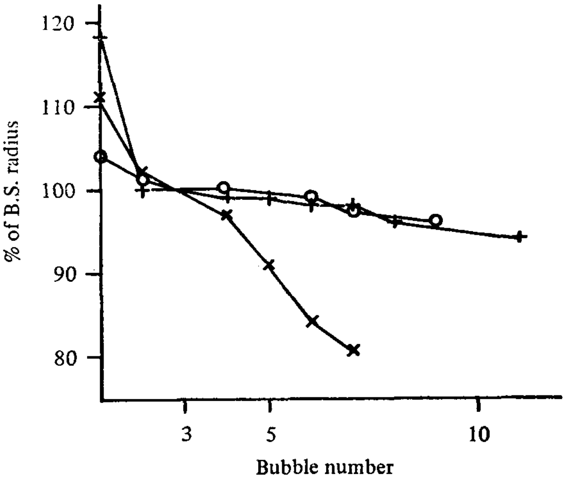


Fig. 5. Apparent diameters at successive bubble points. O, Nylon taffeta, NT; X, Pima cotton, P; +, Ventile L34, V.

Air permeability test

This test used the same apparatus as the bubble pore test and its advantages are much the same as those of that test. It does not affect the fabric. The results have no obvious direct relation to the ability of the fabric to prevent particle penetration, since the airflow depends on both the number and the size of the holes. They do, however, have a bearing on the comfort of wearing garments made from the fabric. The airflow was found to be strictly proportional to the difference in pressure between the two surfaces of the fabric for all fabric tested (i.e. flow was totally viscous).

The theoretical limits of this test depend upon the sensitivity and the range of the manometer(s) and flowmeter(s) used. In our case a single manometer was used, which could be used in a vertical position to allow a maximum reading of 25 cm water gauge, or in an inclined position to give a minimum detectable deflexion of 0·005 cm water gauge, and flowmeters covering a range from 0·1 l of air/min to 12 l of air/min were used. The limiting range of the equipment was from $1{\cdot}1 \times 10^5$ to $1{\cdot}8 \times 10^{-4}$ ml/cm^2/cm water gauge, but constrictions in the tube work etc. reduced this somewhat. The range measured was $1{\cdot}8 \times 10^4$ for a No. 400 gauge copper mesh to 0·103 for a silicone coated nylon. However, some plastic-coated nylons and the PVC produced no measureable flow at all at 25 cm water gauge and were below the bottom limit of detection. The range for the test fabrics was $3{\cdot}96 \times 10^3$ cm^3/min/cm^2/cm water gauge to 5 cm^3/min/cm^2/cm water gauge.

Airborne particle tests

These tests have the advantage over all the other tests mentioned so far in that they actually measure the penetration of particles – which can be similar in shape and size to skin flakes (see Plate 4) – through fabrics but they require more elaborate special equipment and are more time-consuming, even though a number of different fabrics may be tested at any one time.

The Royco particle counter made counting less time-consuming but could only be carried out on one fabric at a time and was not so suitable for experiments with artificially generated clouds of dust which were decaying fairly rapidly. Also it is not clear that the size ranges given by the counter are valid for flake-like talc particles.

The reproducibility was only fair and a number of samples had to be taken to allow an average penetration to be calculated. It is possible, though inconvenient, to test whole garments or uncut rolls.

The possible range for the Royco dust measurements depended upon a reduction of the count/min (cpm) from its maximum value (at the 0·5 μm setting, with no fabric present about 1000 cpm) to its minimum value which is given by 'background' levels of counting due to electronic 'noise' within the instrument. This was measured by connecting the filtered air output directly to the input on the machine. The rate was about 4 cpm. Thus, the ratio of highest dust counts to background was about 250 to 1 and this could not be improved by extending the period of sampling. The highest ratio actually observed was about 33 to 1.

When using the Millipore filters, only fabrics passing more than 1 l air/min over an area of 50 cm^2 when subjected to a pressure difference of 28 cm water gauge could be tested, otherwise there was insufficient flow for the samplers, which could not be reliably adjusted to sample less than 1 l/min. However, since this represents a minimum air permeability of 0·71 $cm^3/min/cm^2/cm$ water gauge it is clear that all the fabrics subjected to the other tests (except PVC) could be assessed in this test.

The range of sensitivity was limited by the ratio of the highest to lowest sampler flow rates that could be employed, 10 to 1, by the maximum number of particles that the observer could distinguish in any one field, about 200, and by the minimum number of particles over the whole filter area needed to give a reliable estimate, about 10. Since between 200 and 300 independent fields could be examined over the whole filter area the maximum possible range was about 5×10^4 to 1 but the actual range observed for talc and fluorescent particles was only about 50 to 1.

Particle rub-through tests

These tests also measured actual penetration of particles through the fabrics. Although the rubbing device was a special piece of equipment it was simple and inexpensive to construct and was compact and convenient. The other equipment required was an accurate balance and a microscope. Fabrics could be tested quickly and results for Balloon cotton were reproducible under the same laboratory conditions. Variability due to temperature and humidity was noted, either due to an effect on the cotton yarns or possibly on the tracer particles themselves.

The disadvantages are:

(*a*) the long times required for making an accurate count when penetration is low;

(*b*) penetration across the width of the fabric sample is not constant because the rubbing arm rubs across the centre portion more frequently than any other area – up to 13 times more than at the periphery. The ratio of counts at the edges and at

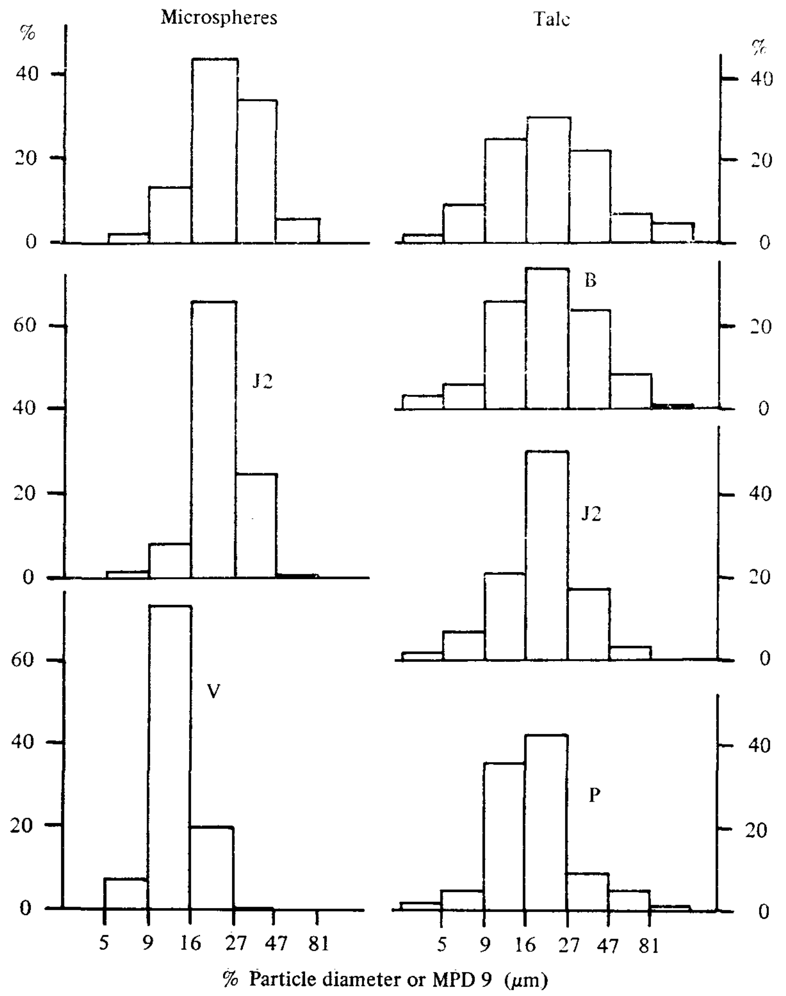


Fig. 6. Particle size distributions before and after being rubbed through fabrics. The upper two histograms show the size distributions of the particles used, the lower the size distributions of the particles which passed through the fabrics indicated. B, Balloon cotton; J2, Johnson & Johnson 450; P, Pima cotton; V, Ventile L34. The sizes given for the talc particles are minimum projected diameters. The minimum projected diameter is the shortest perpendicular distance between two parallel straight lines between which the outline of the particle can be fitted. Plate like particles, such as talc or skin scales will almost always be deposited flat and viewed normally to their largest aspect. In this case the minimum projected diameter approximates to the longest diagonal of the smallest pore through which the particle can pass.

the centre is not constant for different fabrics, and this leads to some uncertainty in comparisons between fabrics of similar penetrability. Penetration may also be very irregular over the sample when this is mostly due to a limited number of larger pores. These factors are not important when the penetrating particles are weighed because total penetration is then measured, i.e. the more porous fabrics are more easily distinguished.

(*c*) Only small squares of fabric can be tested, so garments and rolls of material must be cut.

The range of results encountered was 3×10^4 to 1 for spheres and 7×10^4 to 1 for talc, for the fabrics in this series. Other fabrics would extend this range.

With allowance for background contamination a penetration of as few as ten particles can give a valid estimate in comparison with the test load of about 10^7 particles. Since both rubbing times and the test loads could be increased substantially it is clear that the measurable range of penetration exceeds this by several powers of ten.

An advantages of the rub-through tests is that they can demonstrate differences between the size distribution of the particles applied to the fabric and those which have penetrated. This is illustrated by the results shown in Figure 6. Both the J2 non-woven fabric and Balloon cloth allow the test particles to pass through relatively freely (see Table 3) and there is little change in the size distribution of the particles which have penetrated these fabrics. The more closely woven cottons, Ventile and Pima pass the test particles less readily and those that do penetrate are mostly the smaller fraction. This is especially striking for the penetration of the microspheres through Ventile fabric.

Anomalies

Once the tests had been made on a sufficient number of fabrics it appeared that some fabrics were not behaving in some of the tests as they might be expected to from their behaviour in the other tests. These anomalous results have pointed to weaknesses in certain of the methods and also have enabled us to form an opinion on what the tests actually measure.

Microscopy using crossed polarizers. This gave apparently false results with four fabrics for different reasons. Ceramic terylene, when viewed face on, appeared to have no pores whatsoever owing to the tightness of the weave but the airflow and bubble pore tests indicated definite porosity and when the fabric was examined held at an angle of about 40° to the optical axis of the microscope some small pores almost parallel to the fabric surface could be plainly seen under the edges of the smooth terylene yarns where these crossed one another.

Some plastic coated fabrics were apparently penetrated by many pores which darkened as the polarizers were crossed. The bubble and airflow tests, however, indicated that the fabrics were almost completely impermeable. Not only do some plastic films not depolarize light, they may also produce coloured patterns of their own. This made it impossible to determine whether there were real pores in, e.g. Tyvek, or merely thin pinpoint areas which darkened in the same way as true holes. The nylon taffeta yarns produced a variety of colours which confused true slit like pores with fibrils which were approximately the same width and colour. The source of light used can determine the degree of differentiation possible, sunlight appears to be superior to tungsten lighting in this respect.

Bubble pore. Mention has already been made of the insensitivity of this test to the pore shape. A second drawback is that it appears to be insensitive to the presence of fibrils crossing the pore. This appeared from the exceptionally high value obtained for Johnson & Johnson '450' (J2) when no such giant pores could be found microscopically though many pores were grouped together. It would appear that the bubble test 'sees' the whole of a porous area (see Plate 4) as one single pore.

Another fabric, Pima cotton (P) gave an anomalously high pore size. This fabric is waterproofed with a 'Quarpel' finish (1963) and it was observable that the surface of the fabric when immersed in white spirit became silvery, indicating incomplete wetting of the fabric by the spirit. It was necessary to suck the liquid into the body of the fabric before performing the test, when more reasonable values were obtained. This method was tried on other fabrics, particularly any giving anomalous results, but no change in the bubble pore size was found. This may, therefore, be a peculiarity of this particular waterproofing finish. However, it is conceivable that other fabrics, particularly those formed from man-made fibres, may have a different angle of contact with the white spirit and give results differing from that expected from the equation given.

Tests with airborne particles. These produced few surprises, although some of the 'better', closer woven, fabrics allowed more penetration than might have been expected. This applied particularly to the penetration of dust particles and fluorescent powders through ceramic terylene. We have no explanation for this, but as has been noted above this fabric had many pores running at an acute angle to the fabric surface.

Rub-through tests. The median diameters for microspheres and talc particles were similar. However, the size dispersion of the talc was somewhat greater so that this material contained a larger proportion of very small particles. The measured penetration rates for talc, after making allowance for the larger number of talc particles in the loads used, appeared generally similar to those for the microspheres, although the microspheres ran through the copper mesh sieve five times more rapidly than the talc particles. There were, however, some interesting variations in the ratio of the values derived from the two kinds of particle. With the square holes of the nylon fabric, NB, the ratio was about 1 but with the slit-like apertures in the nylon taffeta this rose to over 3. With the two non-woven fabrics, J1 and J2, penetration by talc was much slower than with the microspheres, the rates for talc particles being only 1/20 and 1/6 of those for the microspheres. All these differences can be plausibly explained in terms of the difference in shape between the two types of particle. The smooth spheres fall more readily through the apertures of the sieve and can more easily penetrate the tortuous passages between the fibres of the non-woven fabrics. On the other hand plate-like particles can pass through a slit-like aperture, as in the nylon taffeta, which is too narrow for a sphere of diameter similar to the minimum projected diameter (see Fig. 6) of a plate. This may also apply, to a lesser extent, to the results for Utopia and Balloon cotton and might be the explanation for the much more rapid penetration of talc than spheres through the Featherproof cotton. The rates of penetration through the closely woven fabrics Pima cotton, Ventile and Ceramic terylene were too low to afford very reliable comparison between the results with the two kinds of particle.

DISCUSSION

A number of measurements and bench tests are available that appear to measure various aspects of the porosity of fabrics. The simpler do not directly relate to the penetrability by particles. Tests that are designed to do this (airborne particles and rub-through) are more complicated to perform. The real criterion of utility, however, is the extent to which they can be used to predict the performance of the fabrics when worn as clothing. This is discussed in the following paper (Lidwell *et al.* 1978). Apart from how well the results given in this paper correlate with the in-use tests the actual range of results observed might also be important in determining which bench test simulates the actual method of dispersal through the fabric, e.g. do the in-use tests show the limited range of difference, $<100:1$, that is given by talc-in-air tests or are the differences between fabrics closer to the much wider range, observed in rub-through tests.

Our thanks are due to Mr N. L. Belkin of the Superior Surgical Manufacturing Co., Huntington, New York, U.S.A. for the sample of anti-static treated nylon and for the Quarpel proofed Pima cotton fabric.

REFERENCES

Bloor, W. A. & Dinsdale, A. (1962). Protective clothing as a factor in the dust hazard of potters. *British Journal of Industrial Medicine* **19**, 229.

British Standards Institute (1957). British Standard No. 2831. Methods of test for air filters used in air-conditioning and general ventilation, Fig. 12.

British Standards Institute (1961). British Standard No. 3424. Methods of test for coated fabrics.

British Standards Institute (1969). British Standard No. 3321. Methods of test for the measurement of equivalent pore size of fabrics (bubble pressure test).

Duguid, J. P. & Wallace, A. T. (1948). Air infection with dust liberated from clothing. *Lancet* ii, 845.

Hambraeus, A. (1973). Attempts to control clothes-borne infection in a burns unit. I. Experimental investigation of some clothes for barrier nursing. *Journal of Hygiene* **71**, 171.

Heywood, H. (1963). The evaluation of powders. *Journal of Pharmacy and Pharmacology*, suppl. **15**, 56T.

Lidwell, O. M. & Brock, B., Shooter, R. A., Cooke, E. M. & Thomas, G. E. (1975). Airborne infection in a fully air-conditioned hospital. IV. Airborne dispersal of *Staphylococcus aureus* and its nasal acquisition by patients. *Journal of Hygiene* **75**, 445.

Lidwell, O. M., Mackintosh, C. A. & Towers, A. G. (1978). The evaluation of fabrics in relation to their use as protective garments in nursing and surgery. II. Dispersal of skin organisms in a test chamber. *Journal of Hygiene* **81**, 453.

Moilliet, J. L. (1963). *Waterproofing and Water Repellency.* London: Elsevier Publishing Co.

EXPLANATION OF PLATES

PLATE 1

Surface appearance of fabrics (woven cotton or cotton/terylene).

Fig. 1. Balloon cotton (B).

Fig. 2. Utopia plus (U).

Fig. 3, 4. Featherproof, face and reverse (F).

Fig. 5. Ventile cotton (V).

Fig. 6. Pima cotton (P).

PLATE 2

Surface appearance of fabrics (synthetic including non-woven).

Fig. 1. Antistatic nylon (NB).

Fig. 2. Nylon taffeta (NT).

Fig. 3. Ceramic terylene (C).

Fig. 4. Johnson & Johnson, Dexter (J1).

Fig. 5. Tyvek (T).

Fig. 6. Johnson & Johnson, 450 (J2).

The vertical bars correspond to 1 mm.

PLATE 3

Appearance of true and false pores using polarized light. Two photographs of the same area of the nylon taffeta fabric (NT) showing 16 weave intersections. (*a*) By direct transmitted light; (*b*) with crossed polarizers.

At 15/16 of the wave intersections bright areas, of various sizes, in (*a*) have darkened in (*b*) demonstrating true pores which go right through the fabric. These are indicated by arrows on (*b*). The length of the horizontal bar between the two photographs corresponds to 100 μm.

PLATE 4

Details of fabric structure and test particles.

Fig. 1. Balloon cotton (B) showing fibrils crossing a ‘pore’.

Fig. 2. White nylon (NB) showing regular square pores obscured by flare.

Fig. 3. Johnson & Johnson 450 (J2) showing complex.

Fig. 4. Microspheres.

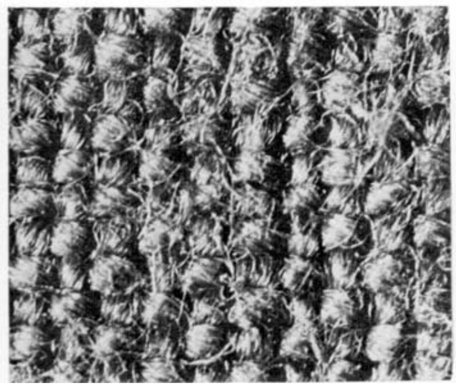
Fig. 5. Talc powder.

Fig. 6. Fluorescent powder.

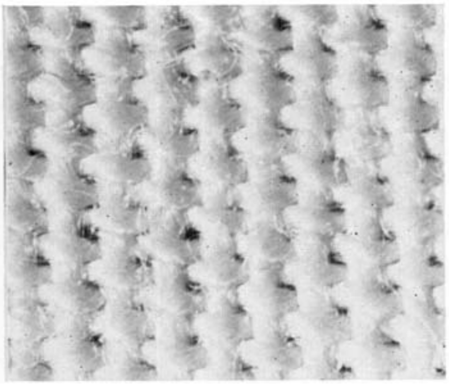
The length of the vertical bars corresponds to 100 μm.

Journal of Hygiene, Vol. 81, *No.* 3

Plate 1



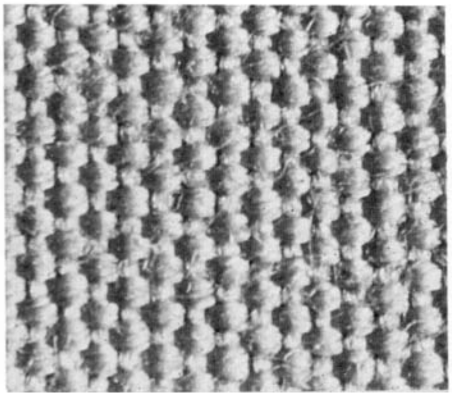
1



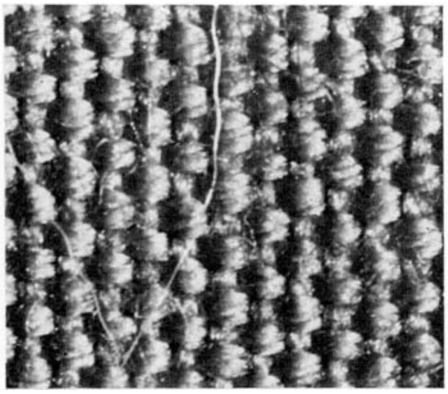
2

3

4



5



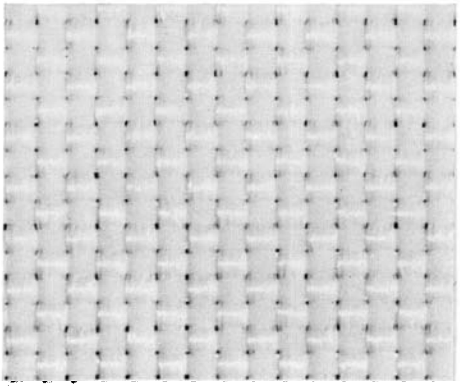
6

O. M. LIDWELL AND C. A. MACKINTOSH

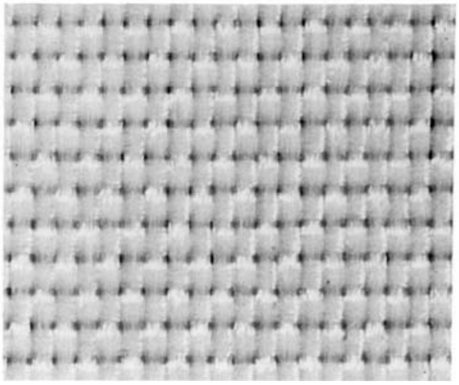
(*Facing p.* 452)

Journal of Hygiene, Vol. 81, *No.* 3

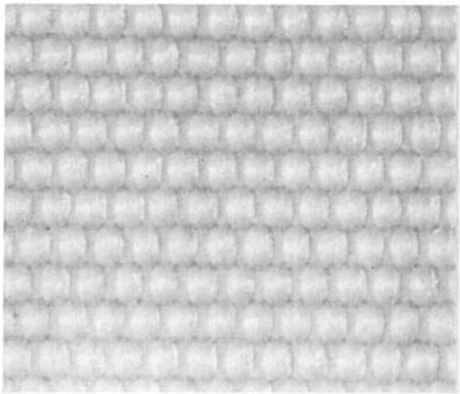
Plate 2



1



2



3

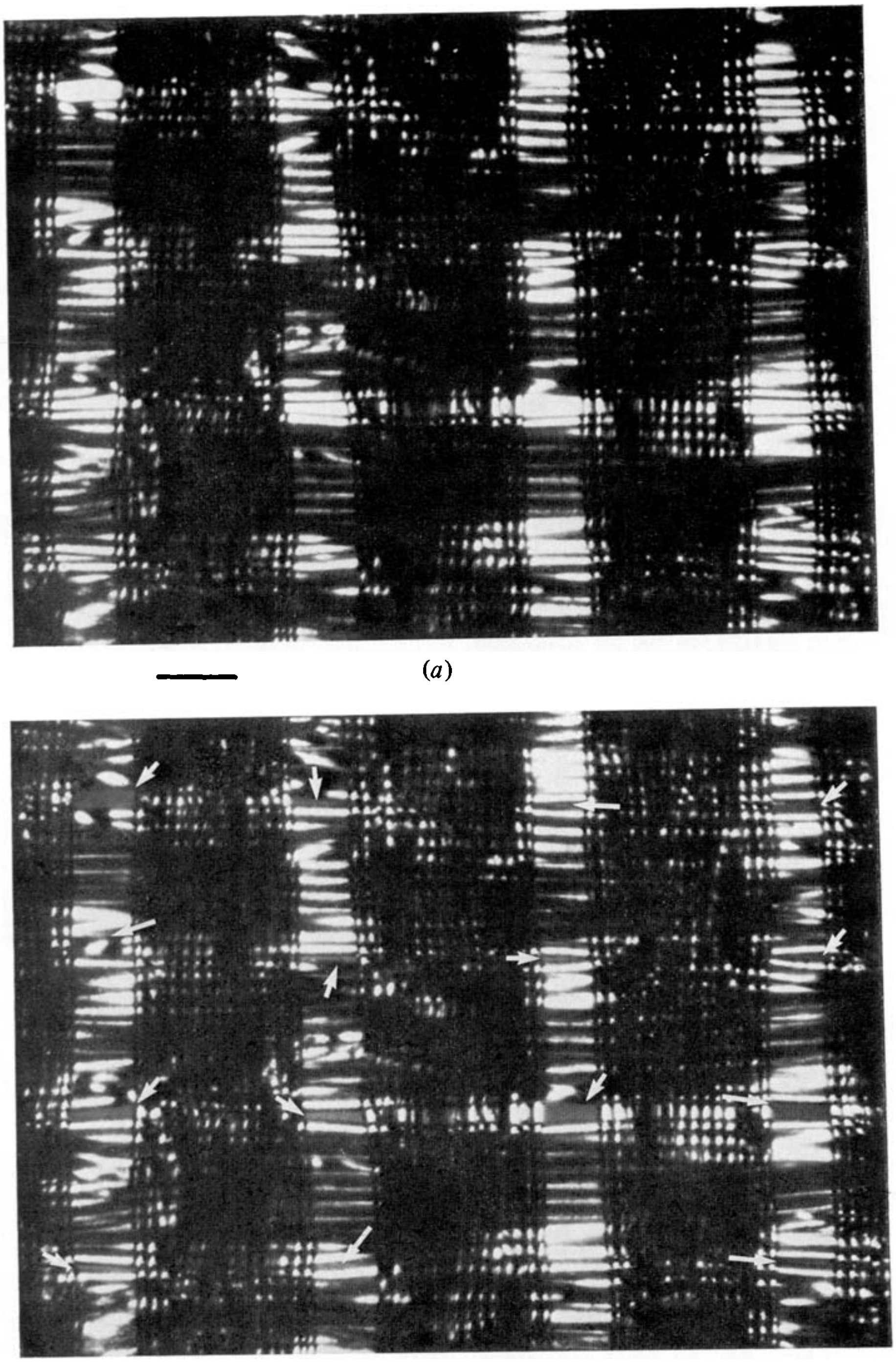
4

5

6

O. M. LIDWELL AND C. A. MACKINTOSH

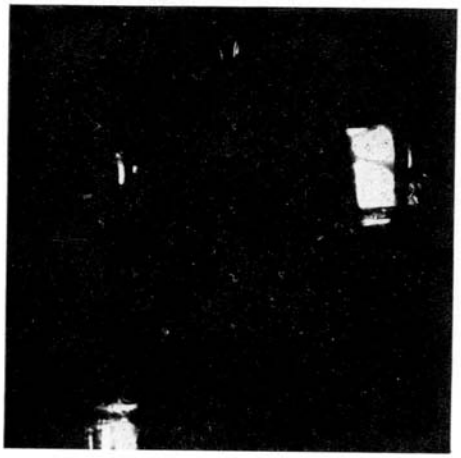
Plate 3



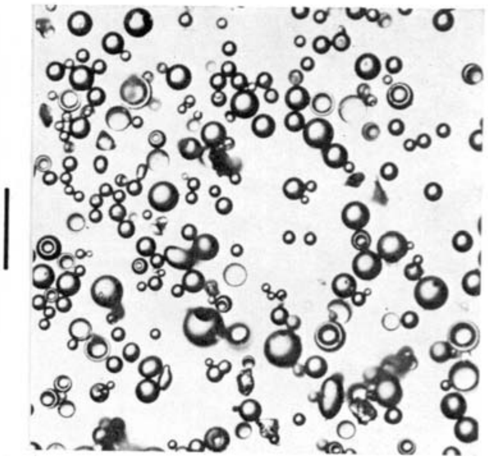
O. M. LIDWELL AND C. A. MACKINTOSH

Journal of Hygiene, Vol. 81, *No.* 3

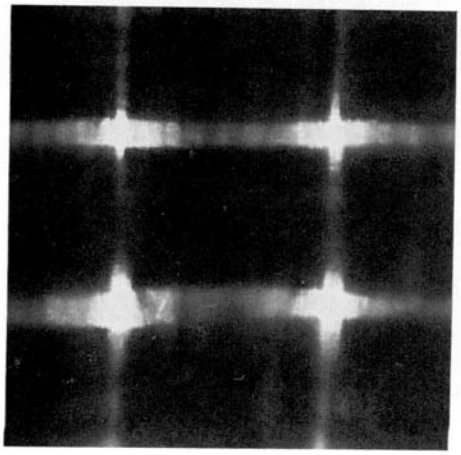
Plate 4



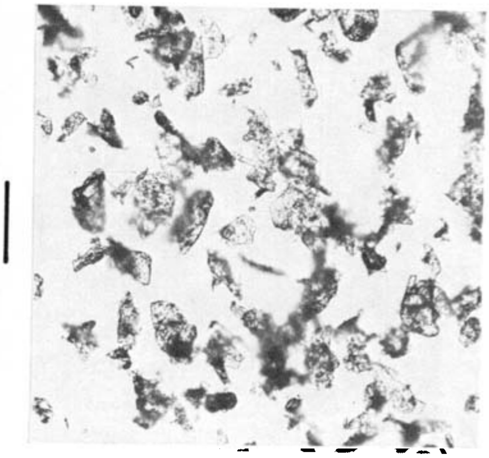
1



4

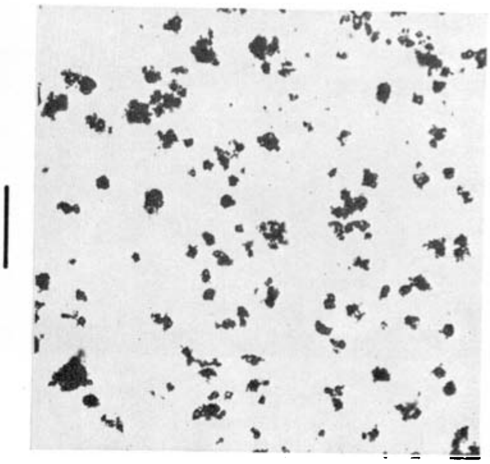


2



5

3



6

O. M. LIDWELL AND C. A. MACKINTOSH