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Fabric permeability testing

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Abstract: Fabric permeability is a property not well defined in the textbooks and not well understood by anyone outside the scientific fraternity. This chapter begins by introducing the terms and definitions of fabric permeability testing as well as testing principles. It then introduces the different techniques adopted in the measurement of this property which are divided into three types of permeation based on the different penetrants. It summarizes various applications of the test methods for different purposes as well. Finally, this chapter presents a review on innovative test methods for fabric permeability.

Key words: fabric permeability, water vapour permeability, air permeability, chemical permeability, test method.

7.1 Introduction: terms and definitions

Fabric permeability is a property of fabric which is used to assess the ability of fabric to allow a penetrant, such as a gas, liquid or solid material, to pass through such a barrier and then desorb into a specified medium. Since the 1960s and particularly during the past two decades, fabric permeability has been the subject of a great number of investigations that revealed very interesting properties and offered new insights into mass transfer through fabric materials. Such research leads to fabrics that can display very different properties and have various classical and non-classical applications, such as protective clothing, sportswear, laminated and coated fabrics, textiles for filtration, medical textiles, textiles for transportation, and other technical textiles (Raheel 1996; Byrne 2000).

Permeability is a property of a material, but the permeability of a body that performs like a material may be used. Permeability is the arithmetic product of permeance and thickness, which is often defined as the time rate of penetrant transmission through unit area of flat material of unit thickness induced by unit penetrant pressure difference between two specific surfaces. Fabric permeability is certainly the first species to have been considered for sorption, diffusion and permeation studies. Most investigations were undertaken to understand the basic relationships between the fabric structure and sorption or permeability, in order to control the permeable character by a proper structure design.

7.2 Aspects of wear comfort

Wear comfort is one of the most important topics in the field of textiles and clothing. Human beings cannot function efficiently if they are not comfortable, and if a person is operating machinery or driving a car, comfort becomes a factor determining safety. However, comfort has many different aspects, as summarized by one writer: 'Comfort is a complex matter, with physical, physiological, and psychological factors interrelated in an unpredictable combination which constantly undergoes variation.' (Saville 1999).

Clothing has a large part to play in the maintenance of wear comfort as it modifies the heat loss from the skin surface and at the same time has the secondary effect of altering the moisture loss from the skin. Perspiration is an important mechanism which the body uses to lose heat when its temperature starts to rise. Heat is taken from the body in order to supply the latent heat needed to evaporate the moisture from the skin.

There are two forms of perspiration:

- Insensible: in this form the perspiration is transported as a vapour and it passes through the air gaps between yarns in a fabric.
- Liquid: this form occurs at higher sweating rates and it wets the clothing which is in contact with the skin.

When perspiration takes place to cool the body, the water exuded through the skin appears initially as liquid which evaporates at once (in comfortable situation) and forms moisture vapour. This vapour is removed from the vicinity of the body, either by convection or through the clothing worn on the person, carrying heat away with it (Slater 1971).

When the moisture vapour reaches the inner surface of the fabric, several events can take place. The vapour may pass through the fabric system to its outermost surface, there to be carried away by the air. At the other extreme, it may be prevented from escaping through the fabric system if a component of the latter is impermeable, and will condense at some position in the system. The transfer of additional moisture vapour through the system will then be impeded by the liquid water layer so formed, and the plane of condensation will gradually move inwards form the impermeable barrier until eventually condensation takes place at the inner layer of the system, at the surface of the body, as soon as moisture is exuded through the skin, marking the onset of sensible perspiration.

There are two forms in which this discomfort is manifested. In hot weather, perspiration is the only problem, and the sensation of wetness, though a nuisance, does not lead to danger unless the temperature is so great that heat stroke or dehydration is possible. In cold weather, though, a more urgent risk arises. If, for instance, heavy work has been in progress and then is discontinued, the production of heat (and moisture) will continue for some time after work has ceased. If this moisture is not evaporated (by the heat generated in working, for instance), condensation will occur and the wetness will be evident, as before. Another hazard now comes into operation. The liquid moisture which forms inside the fabric acts as a much better conductor of heat than the air which it has displaced, so that the heat loss from the body increases by a very large factor. The resulting initial cooling effect of this liquid water by conduction is then increased by the enhanced loss of heat from the body surface in an effort to supply latent heat of vaporization to transform the liquid water into vapour. Because of this demand, heat losses from the body become immense and a grave risk of frostbite or hypothermia develops, possibly leading to irreparable damage or even death.

7.3 Principle of different test methods for fabric permeability properties

Various test methods are available for assessment of the fabric permeability. The most conventional method is to calculate the permeability by Equation 7.1:

$$P = D \cdot S \tag{7.1}$$

where P is permeability coefficient, D is diffusion coefficient and S is solubility coefficient. This equation has been widely used in the literature. However, the problem of penetrant diffusion in and permeation through inhomogeneous fabrics is more complex. This equation is only available in ideal permeation conditions such as at the limit of low permeability and diffusion concentration (Molyneux 2001). At the same time, a number of standard methods have been developed by several national and international organizations such as the American Society for Testing and Materials (ASTM), the American Association of Textile Chemists and Colorists (AATCC), the British Standard (BS), the Japanese Industry Standard (JIS), the International Standards Organization (ISO), and others to assess the permeability of fabric to air, water, chemical, etc. These test methods are able to meet the requirements for quality control as well as research work to a certain extent.

7.4 Types of fabric permeability tests

In general, fabric permeability tests include air permeability, water permeability and chemical (gaseous, liquid or solid chemical) permeability, which is related to the penetration of a gas, liquid or solid material to pass through such fabric barrier and then desorb into a specified medium. Each type of fabric permeability has different testing methods.

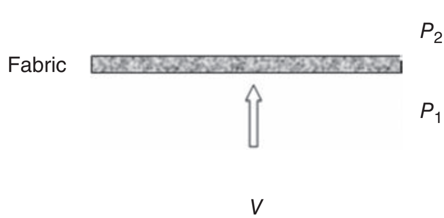
7.4.1 Air permeability

Air permeability is defined as velocity of an air flow passing perpendicularly through a test specimen under specified conditions of test area, pressure drop and time (BS 3424-16-1995). The principle of the test is that the rate of flow of air passing perpendicularly through a given area of fabric is measured at a given pressure difference across the fabric test area over a given time period. In the field of textiles and clothing, air permeability is often used in evaluating and comparing the 'breathability' of various fabrics (coated and uncoated) for such end uses as raincoats, tents, and uniform shirtings. It helps evaluate the performance of parachutes, sail cloth, industrial filter fabrics, and the covering fabrics of pillows and duvet covers.

Usually, an air permeability test apparatus consists of:

- A clamping device for securing the test specimen in a flat tensionless state.
- A device to prevent air leaking from the edges of the test area, usually called a guard ring.
- A pressure gauge or manometer to measure the pressure drop from one side of the specimen to the other.
- An air pump to draw a steady flow of air through the clamped specimen.
- A means of adjusting the rate of airflow to achieve and hold the specified pressure drop from one side of the specimens to the other.
- A flow meter to measure the actual rate of air flow through the specimen.

The Kawabata KES-F8-API Air Permeability Tester (Fig. 7.1) is one of the apparatus which is able to measure air permeability of fabric. In this apparatus, air is pumped by a piston at a constant volume of 8π cm^3/s. The velocity of the air is dependent on the plate chosen on the tester; each plate has a different aperture size, and air velocities of 0.4, 4 or 40 cm/s are



7.1 Schematic representation of Kawabata KES-F8-API air permeability tester.

possible. The pressure drop caused by the resistance of the specimen is measured by a differential pressure gauge. The output is the air resistance R, measured in kilopascals times seconds per metre (kPa · s/m), found from Equation 7.2:

$$R = \frac{P_1 - P_2}{V} = \frac{\Delta P}{V} \qquad 7.2$$

There are some defining equations of fluid flow that should be explained. If a specimen has small holes, the pressure drop is due to frictional loss and is defined as

$$\Delta P = KV \qquad 7.3$$

where ΔP is the pressure difference, V is the air velocity, and K is the constant for the specimen. This can also be expressed as

$$K = \frac{\Delta P}{V} \qquad 7.4$$

Here,

$$R = K \qquad 7.5$$

where R is resistance and is linear with respect to velocity for the specimen. A material with this response can be considered as a 'linear resistor'.

If the specimen exhibits large holes, then Bernoulli's law holds true, where

$$\Delta P = KV^2 \qquad 7.6$$

Rewritten,

$$KV = \frac{\Delta P}{V} \qquad 7.7$$

and

$$R = KV = \frac{\Delta P}{V} \qquad 7.8$$

Then, R is not constant because it is now a function of changing velocity. Such a material is considered as a 'non-linear resistor' (Dunn 2001).

Other test methods, such as ASTM D737-04 and BS EN ISO 9237:1995, are used extensively in the trade for acceptance testing. These two test methods apply to most fabrics including woven fabrics, non-woven fabrics, air bag fabrics, blankets, napped fabrics, knitted fabrics, layered fabrics, and pile fabrics. The fabrics may be untreated, heavily sized, coated, resin-treated, or otherwise treated (ASTM D737-04; BS EN ISO 9237:1995).

Construction factors and finishing techniques can have an appreciable effect upon air permeability by causing a change in the length of airflow paths through a fabric. Hot calendering can be used to flatten fabric components, thus reducing air permeability. Fabrics with different surface textures on either side can have a different air permeability depending upon the direction of air flow (ASTM D737-04).

For woven fabric, yarn twist also is important. As twist increases, the circularity and density of the yarn increase, thus reducing the yarn diameter and the cover factor and increasing the air permeability. Yarn crimp and weave influence the shape and area of the interstices between yarns and may permit yarns to extend easily. Such yarn extension would open up the fabric, increase the free area, and increase the air permeability (ASTM D737-04).

Increasing yarn twist also may allow the more circular, high-density yarns to be packed closely together in a tightly woven structure with reduced air permeability. For example, a worsted gabardine fabric may have lower air permeability than a woollen hopsacking fabric (ASTM D737-04).

7.4.2 Water permeability

Water permeability is used to assess the ability of a fabric to allow perspiration in its vapour or liquid form (which depends on the whole clothing system) to pass through it. Usually, several indexes can be applied to evaluate this ability, such as water vapour permeability, water repellency, water resistance and so on. These indexes have different applications respectively, which depend on different testing conditions and requirements.

On a normal condition, perspiration will pass through the clothing system in the vapour form. However, if the production of perspiration is greater than the amount the clothing system will allow to escape, moisture will accumulate at some point in the clothing system. If the outer layer is the most impermeable, moisture will accumulate in the inner layers. When excess moisture accumulates it causes a reduction in thermal insulation of the clothing and eventually condensation and wetting. The level of perspiration production is very dependent on the level of activity: clothing that may be comfortable at low levels of activity may be unable to pass sufficient moisture vapour during vigorous activity. However, when activity ceases, freezing can occur because the clothing is now damp and body heat production has been reduced, leading to after-exercise chill and, if the temperature is low enough, frostbite.

Therefore, it is important to be able to measure the rate at which a material can transmit moisture vapour if any assessment of the potential of that material in enhancing or reducing comfort needs to be made. A fabric of low moisture vapour permeability is unable to pass sufficient perspiration and this leads to sweat accumulation in the clothing and hence discomfort. As a result, the mechanism of permeability becomes of great theoretical interest, and direct measurement of permeability of fabric has been suggested. Some testing methods have been applied successfully in both research areas and industrial fields.

Water vapour permeability

For measurement of water vapour permeability of fabric, one of the main methods is the water cup method, which is especially suitable to evaluate fabrics with low sorption and permeability (Hsieh *et al.* 1990, 1991; Jeong *et al.* 2000a, 2000b). Such a comparatively simple method for testing the water vapour permeability of textiles will provide the manufacturer with a clearly recognized method for quality control within the plant.

ASTM E96-00 is based on this method to measure water vapour permeability of fabric. In this standard, two basic methods, the desiccant method and the water method, are provided for the measurement of permeance, and two variations include service conditions with one side wetted and service conditions with low humidity on one side and high humidity on the other.

In the desiccant method the test specimen is sealed to the open mouth of a test dish containing a desiccant, and the assembly is placed in a controlled atmosphere. Periodic weighings determine the rate of water vapour movement through the specimen into the desiccant. In the water method, the dish contains distilled water, and the weighings determine the rate of vapour movement through the specimen from the water to the controlled atmosphere. The vapour pressure difference is nominally the same in both methods except in the variation, with extremes of humidity on opposite sides. In this method, the water vapour transmission rate (WVT) is defined as the steady water vapour flow in unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface, which can be calculated by Equation 7.9:

$$\mathrm{WVT} = G/tA = (G/t)/A \tag{7.9}$$

where

G = weight change (from the straight line), g
t = time during which G occurred, h
G/t = slope of the straight line, g/h
A = test area (dish mouth area), m^2
WVT = rate of water vapour transmission, $g/h \cdot m^2$.

Water vapour permeance is defined as the time rate of water vapour transmission through unit area of flat material or construction induced by unit vapour pressure difference between two specific surfaces, under specified temperature and humidity conditions. It can be calculated using Equation 7.10 as follows:

$$\text{Permeance} = \text{WVT}/\Delta p = \text{WVT}/S(R_1 - R_2) \quad 7.10$$

where
- Δp = vapour pressure difference, mm Hg (1.333 × 102 Pa)
- S = saturation vapour pressure at test temperature, mm Hg (1.333 × 102 Pa)
- R_1 = relative humidity at the source expressed as a fraction
- R_2 = relative humidity at the vapour sink expressed as a fraction.

Water vapour permeability (WVP) is defined as the time rate of water vapour transmission through unit area of flat material of unit thickness induced by unit area vapour pressure difference between two specific surfaces, under specified temperature and humidity. The average water vapour permeability can be calculated using Equation 7.11 as follows:

$$\text{WVP} = \text{permeance} \times l \quad 7.11$$

where l = thickness of the membrane.

The purpose of these tests is to obtain, by means of simple apparatus, reliable values of water vapour transfer through permeable and semipermeable materials, expressed in suitable units. These values are for use in design, manufacture and marketing. A permeance value obtained under one set of test conditions may not indicate the value under a different set of conditions. For this reason, the test conditions should be selected that most closely approach the conditions of use (ASTM E96-00).

Water repellency

Water repellency in the field of textiles refers to the characteristic of a fibre, yarn or fabric to resist wetting. Water repellency of a fabric can be measured according to AATCC test method 70-2000 Water repellency: Tumble jar dynamic absorption test. In this test method, preweighed specimens are tumbled in water for a fixed period of time and are reweighed after the excess water has been removed from them. The percentage increase in mass is taken as a measure of the absorption or resistance to internal wetting. That is, the water absorbed for each specimen can be calculated using the following equation:

$$\text{WA} = \frac{W - C}{C} \times 100 \quad 7.12$$

where:
- WA = water absorbed, %

7.2 Dynamic absorption tester.

W = wet specimen weight, g
C = conditioned specimen weight, g.

This test method is applicable to any textile fabric, which may or may not have been given a water-resistant or water-repellent finish. It measures the resistance of fabrics to wetting by water. It is particularly suitable for measuring the water-repellence efficacy of finishes applied to fabrics, because it subjects the treated fabrics to dynamic conditions similar to those often encountered during actual use. It is not intended for use in predicting the probable rain penetration resistance of fabrics, since it measures absorption of water into, but not through, the fabric (AATCC TM 70-2000). A dynamic absorption tester is shown in Fig. 7.2.

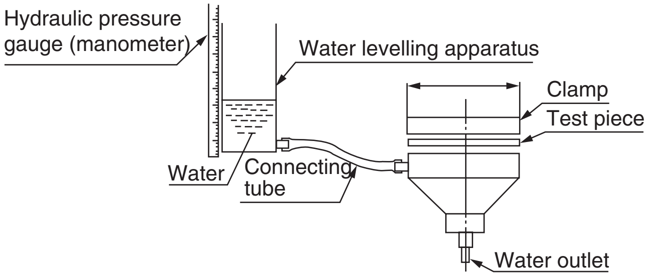
Water resistance

Water resistance of fabric is the characteristic of this material to resist wetting and penetration by water. According to JIS L1092-1998, the tests can be classified as shown below.

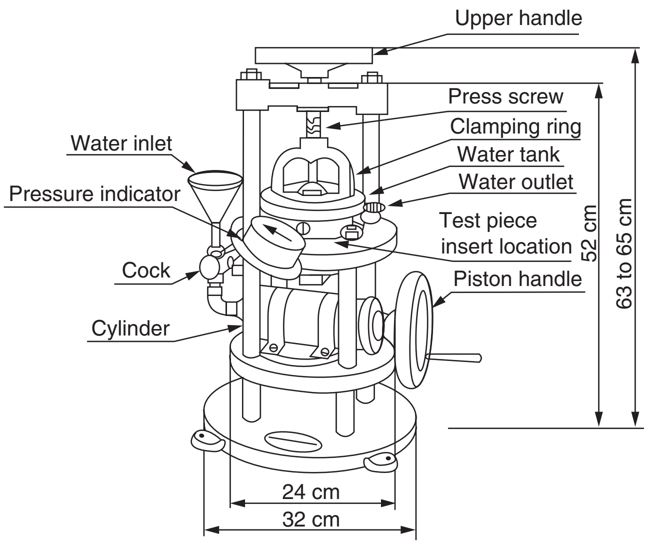
Test for water penetration (hydrostatic pressure method)
This test applies mainly to textile fabrics with no air permeability.

- Method A (low hydraulic pressure method)
- Method B (high hydraulic pressure method) (This method usually applies to test specimens that can be tested by applying a hydraulic pressure exceeding 10 kPa.)

The apparatus shown in Figs 7.3 and 7.4 are applied to carry out tests for water penetration in according with method A (low hydraulic pressure



7.3 Water penetration test apparatus (for low hydraulic pressure).

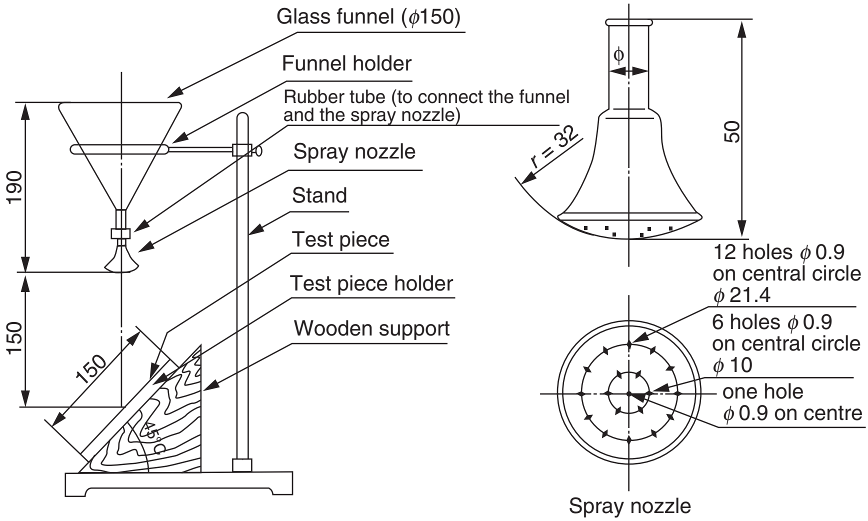


7.4 Water penetration test apparatus (for high hydraulic pressure).

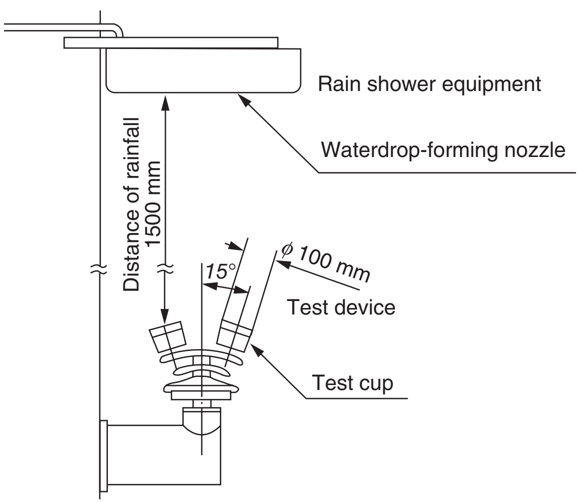
method) and method B (high hydraulic pressure method) respectively. In these methods, the water level/water pressure is measured at the time when the water comes out from three places on the reverse surface of the test pieces (JIS L1092-1998).

Test for resistance to surface wetting (spray method)

This test applies to fabrics with air permeability. The apparatus in Fig. 7.5 is used to test for resistance to surface wetting (spray method). After dropping the excess water, the wet condition of the test specimen is assessed in comparison with the reference sample.



7.5 Apparatus for the test of resistance to surface wetting.



7.6 Bundesmann rain-shower test apparatus.

Rain test (shower test), method A

The apparatus in Fig. 7.6 is applied to the rain test (shower test). After exposure to a rain shower for 10 minutes (rain falling time may be 1 minute or 5 minutes), the wet condition of the test specimen is assessed in comparison with the reference sample. The amount of water absorption (g) and rate of water absorption (%) are calculated by means of Equations 7.13 and 7.14:

$$\text{Amount of water absorption(g)} = M - M_0 \qquad 7.13$$

$$\text{Rate of water absorption(\%)} = \frac{M - M_0}{M_0} \times 100 \qquad 7.14$$

where
M_0 = mass of test pieces before the test, g
M = mass of test pieces after the test, g.

7.4.3 Chemical permeability

Chemical permeability of fabric is used to assess the ability of fabric to allow molecular diffusion of a chemical (often referring to liquid and gaseous chemicals) through the fabric and its desorption into a specified medium. In general, two kinds of test methods are used to assess chemical permeability of fabric, that is:

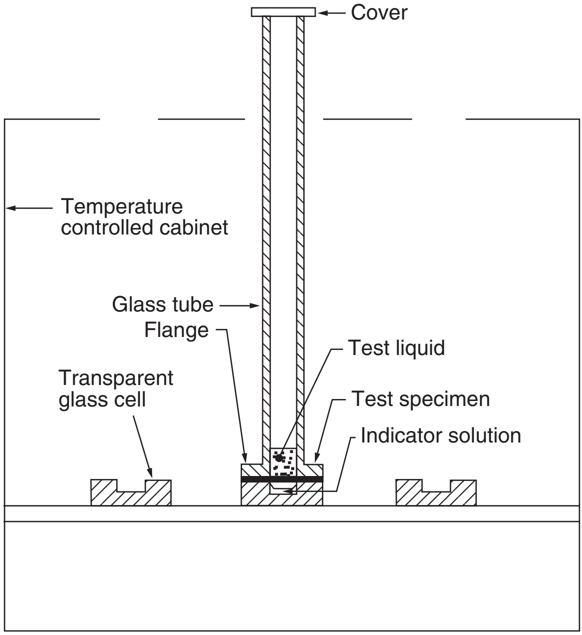
- Determination of resistance of fabric to permeation by liquids and gases
- Measurement of repellency, retention, and penetration of liquids through fabric.

Resistance of clothing materials to permeation by liquids

BS 4724 specifies a laboratory test method that enables an assessment to be made of the resistance afforded by clothing materials to permeation by liquids. According to BS 4724, the test methods can be classified as shown below (BS 4724-1:1986; BS 4724: Part 2:1988).

Method for the assessment of breakthrough time
In this method, an indicator detects the presence in the vapour phase of a test liquid that has passed by permeation through the test specimen. If the volatility of the test liquid is not sufficient for its vapour to be detected directly by an appropriate indicator, a tracer, consisting of a volatile organic base or acid, is selected and mixed with the test liquid. The appropriate indicator solution is placed in a transparent glass cell and covered with a sample of the material under test. The test liquid, either alone or mixed with a tracer, is applied to the top surface of the material. The time for the test liquid itself or the tracer carried with the test liquid to cause the indicator solution to change colour is recorded. Therefore, breakthrough time in this method refers to the time interval between the application of a test liquid to the appropriate surface of the material and the detection, by any suitable method, of the test liquid on the other side of the material.

The test apparatus, as shown in Fig. 7.7, consists mainly of the following three parts:

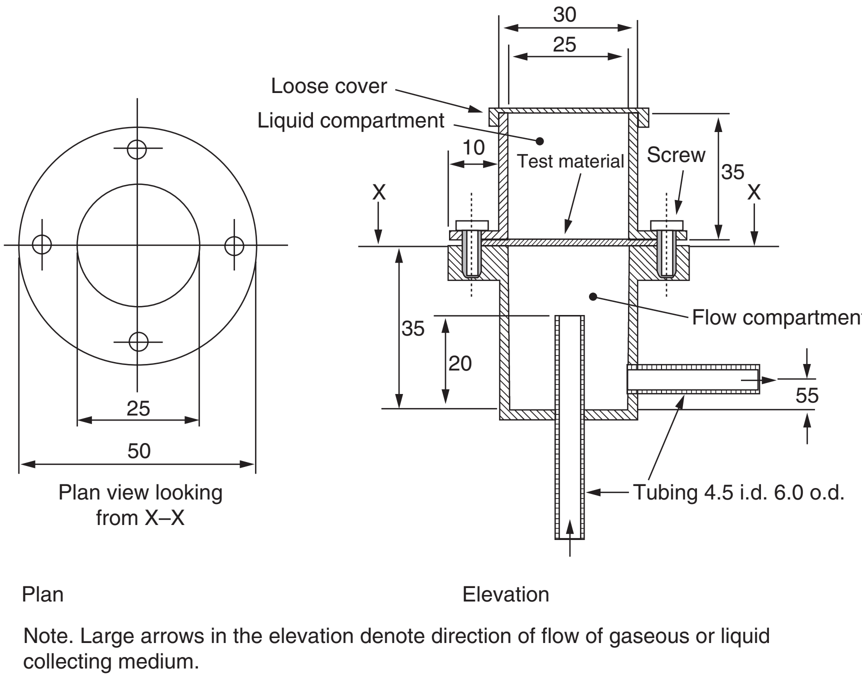


Note. The glass tube is integral with the flange.

7.7 Apparatus for assessment of breakthrough time.

- Glass tub, flanged at one end. The flange diameter is 30 mm. The tube has an internal diameter of 10 mm and a length of stem of not less than 100 mm and is provided with a loose glass cover.
- Transparent glass cell, with an overall height of 10 mm and with a central cavity 5 mm deep and 10 mm in diameter.
- Glass-fronted temperature-controlled cabinet to enable tests to be carried out at different temperatures if required.

Method for the determination of liquid permeating after breakthrough
In this method, the test specimen acts as a barrier between one compartment of a permeation cell, which contains the test liquid, and another compartment through which a stream of gas or liquid is passed for the collection of diffused molecules of the test liquid or its component chemicals for analysis. The mass of the test liquid or its component chemicals in the collecting medium is determined as a function of time after application to the test specimen, the breakthrough time and the masses permeating after breakthrough being derived graphically. Therefore, breakthrough time in this method refers to the elapsed time between the initial application of a test liquid to the appropriate surface of the material and its subsequent presence on the other side of the material.



7.8 Permeation cell.

The permeation cell, as shown in Fig. 7.8, comprises two flanged compartments with dimensions forming a hollow cylinder when bolted together through the flanges. The upper compartment (or liquid compartment) for containment of the test liquid is fitted with a loose cover to avoid build-up of pressure and prevent excessive contamination of the immediate environment when volatile chemicals are under test. The lower compartment (or flow compartment) is fitted with pipework with dimensions to allow gas or liquid to circulate freely at the appropriate rates without build-up of pressure.

Measurement of repellency, retention, and penetration of liquids through fabric

BS ISO 22608:2004 specifies a test method to measure repellency, retention and penetration of a known volume of liquid pesticide when applied to protective clothing material. No external hydrostatic or mechanical pressure is applied to the test specimen during or after the application of the liquid pesticide. The degree of contamination depends on numerous factors such as type of exposure, application technique, and pesticide formulation.

As the level of exposure can vary considerably, this method is designed to rate relative performance of personal protective equipment (PPE) materials at two levels of contamination. Low level of contamination is achieved by applying 0.1 ml liquid formulation and high level by applying 0.2 ml (BS ISO 22608:2004).

In BS ISO 22608, a test liquid is applied using a pipette to the surface of the test assembly, which consists of single or multiple layer protective clothing material (test specimen) and an absorbent paper backed by polyethylene film (collector layer). After a specified time, another absorbent paper backed by polyethylene film (top layer) is placed on the surface of the test specimen to remove the remaining liquid. The top layer, the contaminated test specimen and the collector layer are separated. The amount of test liquid in each layer is measured either by gravimetric analysis (weighing) or by other appropriate analytical techniques. Method A is a gravimetric method that measures the mass of the test liquid in each layer, whereas method B is an analytical method that requires extraction of the test liquid and measures the mass of the active ingredient. Data is obtained to calculate percent repellency, pesticide retention, and penetration (BS ISO 22608:2004).

For method A, the percentage repellency (PR), the percentage retention (PLR) and the percentage penetration (PP) of the test liquid are calculated using Equations 7.15 to 7.17 respectively:

$$\mathrm{PR} = (m_{\mathrm{ap}}/m_{\mathrm{t}}) \times 100 \qquad 7.15$$

$$\mathrm{PLR} = (m_{\mathrm{pc}}/m_{\mathrm{t}}) \times 100 \qquad 7.16$$

$$\mathrm{PP} = (m_{\mathrm{cl}}/m_{\mathrm{t}}) \times 100 \qquad 7.17$$

where

m_{ap} = mass of test liquid in 80 mm × 80 mm absorbent paper used to remove excess liquid pesticide after 10 min, mg

m_{pc} = mass of test liquid in the protective clothing material test specimen, mg

m_{cl} = mass of test liquid in the collector layer, mg

m_{t} = total amount of test liquid, mg.

The evaporation loss (EL) for each test specimen is calculated using Equation 7.18:

$$\mathrm{EL} = 100 - (\mathrm{PT} + \mathrm{PLR} + \mathrm{PP}) \qquad 7.18$$

For method B, the percentage repellency (PR), the percentage retention (PLR) and the percentage penetration (PP) of the test liquid are calculated using Equations 7.19 to 7.21 respectively:

$$\mathrm{PR} = (m_{\mathrm{ap}}/m_{\mathrm{t}}) \times 100 \qquad 7.19$$

$$PLR = (m_{pc}/m_t) \times 100 \quad 7.20$$

$$PP = (m_{cl}/m_t) \times 100 \quad 7.21$$

where

m_{ap} = the mass of active ingredient in 80 mm × 80 mm absorbent paper used to remove excess liquid pesticide after 10 min, mg

m_{pc} = the mass of active ingredient in the protective clothing material test specimen, mg

m_{cl} = the mass of active ingredient in the collector layer, mg

m_t = total amount of active ingredient applied, mg.

The percentage extraction efficiency (EE) is determined using Equation 7.22:

$$EE = [(m_{ap} + m_{pc} + m_{cl})/m_t] \times 100 \quad 7.22$$

where m_t is the total amount of active ingredient applied, mg.

7.5 Fabric permeability testing methods: applications

Testing methods for fabric permeability can have two types of applications:

- Quality assurance, i.e. routine quality control and marketing purposes
- Research and development, for innovative fabrics which can be applied to sportswear, protective clothing, smart textiles and other functional fabrics.

7.5.1 Quality assurance

Product testing is carried out for a number of reasons, the main one being to ensure complete customer satisfaction, thus making it very likely that repeat orders will follow. This is understandable, but monitoring of production during the manufacturing process is also important to ascertain if the product is suitable for the next stage in the production sequence (Fung 2002).

Quality assurance (QA) includes all factors which are relevant to quality and customer satisfaction, and has grown out of simple quality control. It goes from the earliest stages of product design, product development, purchase and monitoring of raw materials through to manufacturing, testing and inspection of the finished product. Quality assurance also involves contact with the customer, from the early stages of product design to meetings after delivery, to ensure customer satisfaction has been achieved. The QA department ensures that every member of the workforce and each member of staff is trained to regard quality as their duty and not just that of the quality department (Fung 2002).

The increasing popularity of sportswear, leisurewear, protective clothing and smart textiles and other functional clothing is reflected by the increasing trend in global sales. The variety of speciality fabrics used in these clothing sectors has expanded with the advance of new technology and consumer interest. An example is the recent success claimed by the breathable-waterproof fabric sector. The 'breathability' of a waterproof fabric has proved to be consumer desirable and can command a price premium. A variety of test methods have been developed to measure the fabric permeability and thus to communicate the fabric's potential to the would-be purchaser. The main commercial test methods in relation to fabric permeability are listed in Tables 7.1–7.3). These standards describe a comparatively simple method for testing the permeability of fabric that will provide the manufacturer with a clearly recognized method for quality control within the plant.

The test parameters generated from the above test methods are variable. Consequently, the results from different methods are not only not directly

Table 7.1 Test methods associated with air permeability (selected)

Standard code	Standard title
ASTM D6476-05	Standard Test Method for Determining Dynamic Air Permeability of Inflatable Restraint Fabrics
ASTM D737-2004	Test Method for Air Permeability of Textile Fabrics
ASTM D5886-1995 (Reapproved 2006)	Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation Through Geomembranes for Specific Applications
ASTM D2752-1988 (Reapproved 2002)	Standard Test Methods for Air Permeability of Asbestos Fibers
BS ISO 7229-1997	Rubber- or Plastics-Coated Fabrics – Measurements of Gas Permeability
BS 3424-16-1995	Testing Coated Fabrics Part 16: Method 18: Determination of Air Permeability
BS EN ISO 9237-1995	Textiles – Determination of the Permeability of Fabrics to Air
BS EN ISO 4638-1995	Polymeric Materials, Cellular Flexible – Determination of Air Flow Permeability
BS 5636-1990	Determination of Permeability of Fabrics to Air
BS 3424-18:1986	Testing coated fabrics – Part 18: Methods 21A and 21B: Methods for determination of resistance to wicking and lateral leakage to air
NF G07-111-1995	Textiles – Determination of permeability of fabrics to air
NF G37-114-1983	Fabrics coated with rubber or plastics. Gas permeability test
ISO 9237-1995	Textiles – Determination of the permeability of fabrics to air

Table 7.2 Test methods associated with water permeability, water repellency and water resistance (selected)

Standard code	Standard title
AATCC 22-2005	Water Repellency: Spray Test
AATCC 193-2004	Aqueous Liquid Repellency: Water/Alcohol Solution Resistance Test
AATCC 70-2000	Water Repellency: Tumble Jar Dynamic Absorption Test
AATCC 35-1980	Water Resistance: Rain Test
ASTM E96/E96-M 05	Standard Test Method for Water Vapour Transmission of Materials
ASTM D6701-01	Standard Test Method for Determining Water Vapour Transmission Rates Through Nonwoven and Plastic Barriers
ASTM D5886-95 (Reapproved 2006)	Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation Through Geomembranes for Specific Applications
ASTM D583-1963 (Withdrawn 1971)	Methods of Test for Water Resistance of Textile Fabrics
JIS L1092-1998	Testing methods for water resistance of textiles
JIS L1099-1993	Testing methods for water vapour permeability of textiles
BS ISO 8096:2005	Rubber- or plastics-coated fabrics for water-resistant clothing – Specification
BS EN ISO 15496-2004	Textiles – Measurement of water vapour permeability of textiles for the purpose of quality control
BS EN 13515-2002	Footwear – Test Methods for Uppers and Lining – Water Vapour Permeability and Absorption Chaussures
BS EN 13518-2002	Footwear – Test methods for uppers – Water resistance
BS 3546-2001	Coated fabrics for use in the manufacture of water penetration resistant clothing
BS EN 13073-2001	Test Methods for Whole Shoe – Water Resistance
BS ISO 7229-1997	Rubber- or Plastics-Coated Fabrics – Measurements of Gas Permeability
BS EN 29865:1993	Textiles – Determination of Water Repellency of Fabrics by the Bundesmann Rainshower Test
BS 3424-34-1992 (R1999)	Testing Coated Fabrics Part 34: Method 37: Method for Determination of Water Vapour Permeability Index
BS EN 20811-1992	Resistance of Fabric to Penetration by Water (Hydrostatic Head Test)
BS 3546-4-1991	Coated fabrics for use in the manufacture of water penetration resistant clothing – Part 4: Specification for water vapour permeable coated fabrics
BS 7209-1990	Specification for Water Vapour Permeable Apparel Fabrics. Appendix B. Determination of Water Vapour Permeability Index

Table 7.2 Continued

Standard code	Standard title
BS 3424-26:1990	Testing coated fabrics – Part 26: Methods 29A, 29B, 29C and 29D. Methods for the determination of resistance to water penetration and surface wetting
BS 5066:1974	Method of Test for the Resistance of Fabric to an Artificial Shower
NF G62-107-2002	Footwear – Test methods for uppers and lining – Water vapour permeability and absorption
NF G38-140-1999	Geotextiles and geotextile-related products. Determination of water permeability characteristics normal to the plane, without load
NF G07-058-1994	Textiles. Determination of water repellency of fabrics by the Bundesmann rain-shower test
NF G38-016-1989	Textiles: articles for industrial use; tests for geotextiles, measurement of water permeability ratio
NF G07-135-1978	Textiles. Tests of woven fabrics. Determination of impermeability of linen cloth for covers, tents and equipment. 'Pocket' method
EN 31092-1993E	Textiles. Determination of Physiological Properties. Measurement of Thermal and Water-vapour Resistance under Steady-state Conditions (Sweating Guarded-hot plate Test)
ISO 11092-1993	Textiles. Determination of Physiological Properties. Measurement of Thermal and Water-vapour Resistance under Steady-state Conditions (Sweating Guarded-hot plate Test)
ISO 9865:1991	Textiles. Determination of Water Repellency of Fabrics by the Bundesmann Rainshower Test

comparable but they may not even show a clear correlation. The differences in approach and in test conditions have an appreciable effect on the final result. To truly compare one fabric with another, it is essential to ensure that they have been assessed by the same method under the same conditions. To do otherwise could be misleading and have litiginous consequences.

7.5.2 Research and development of innovative materials and fabrics

New developments in fibre science and technology have resulted in fibres with tailored properties, thus expanding their uses beyond the domain of conventional textiles. A great deal of new technology was applied to research and develop innovative materials and fabrics for application in the field of

Table 7.3 Test methods associated with chemical permeability (liquid and gas) (selected)

Standard code	Standard title
ASTM F1461-07	Standard Practice for Chemical Protective Clothing Program
ASTM F903-03 (Reapproved 2004)	Test Method for Resistance of Materials Used in Protective Clothing to Penetration by Liquids
ASTM F1296-03	Standard Guide for Evaluating Chemical Protective Clothing
ASTM F1194-99 (Reapproved 2005)	Guide for Documenting the Results of Chemical Permeation Testing of Materials Used in Protective Clothing
ASTM F1154-99a (Reapproved 2004)	Practices for Qualitatively Evaluating the Comfort, Fit, Function, and Integrity of Chemical-Protective Suit Ensembles
ASTM F1001-99a (Reapproved 2006)	Guide for Selection of Chemicals to Evaluate Protective Clothing Materials
ASTM F1407-99a (Reapproved 2006)	Standard Test Method for Resistance of Chemical Protective Clothing Materials to Liquid Permeation – Permeation Cup Method
ASTM F1383-99a	Standard Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Intermittent Contact
ASTM F739-99a	Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids or Gases Under Conditions of Continuous Contact
ASTM D5886-95 (Reapproved 2006)	Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation through Geomembranes for Specific Applications
ASTM-F739-91	Test Method for Resistance of Protective Clothing Materials to Permeation by Liquids and Gases
BS EN 14786:2006	Protective clothing – Determination of resistance to penetration by sprayed liquid chemicals, emulsions and dispersions – Atomizer test
BS EN 14605:2005	Protective clothing against liquid chemicals – Performance requirements for clothing with liquid-tight (Type 3) or spray-tight (Type 4) connections, including items providing protection to parts of the body only (Types PB [3] and PB [4])
BS EN 13034:2005	Protective clothing against liquid chemicals – Performance requirements for chemical protective clothing offering limited protective performance against liquid chemicals (Type 6 and Type PB [6] equipment)
BS EN ISO 6530:2005	Protective clothing – Protection against liquid chemicals – Test method for resistance of materials to penetration by liquids
BS ISO 22608:2004	Protective clothing – Protection against liquid chemicals – Measurement of repellency, retention, and penetration of liquid pesticide formulations through protective clothing materials

Table 7.3 Continued

Standard code	Standard title
BS EN 14325:2004	Protective clothing against chemicals – Test methods and performance classification of chemical protective clothing materials, seams, joins and assemblages
BS EN 374-3:2003	Protective gloves against chemicals and micro-organisms – Part 3: Determination of resistance to permeation by chemicals
BS EN 374-2:2003	Protective gloves against chemicals and micro-organisms – Part 2: Determination of resistance to penetration
BS EN 943-2:2002	Protective clothing against liquid and gaseous chemicals, including liquid aerosols and solid particles – Part 2: Performance requirements for 'gas-tight' (Type 1) chemical protective suits for emergency teams (ET)
BS EN 943-1:2002	Protective clothing against liquid and gaseous chemicals, including liquid aerosols and solid particles – Part 1: Performance requirements for ventilated and non-ventilated 'gas-tight' (Type 1) and 'non-gas-tight' (Type 2) chemical protective suits
BS EN ISO 6529:2001	Protective clothing – Protection against chemicals – Determination of resistance of protective clothing materials to permeation by liquids and gases
BS 2F 142:1999	Hydrolysis resistant, thermoplastic polyether polyurethane elastomer-coated nylon fabric for aerospace purposes
BS ISO 13994:1998	Clothing for protection against liquid chemicals – Determination of the resistance of protective clothing materials to penetration by liquids under pressure
BS EN 468:1995	Protective clothing – Protection against liquid chemicals – Test method: Determination of resistance to penetration by spray (Spray test)
BS EN 467:1995	Protective clothing – Protection against liquid chemicals – Performance requirements for garments providing protection to parts of the body
BS EN 463:1995	Protective clothing – Protection against liquid chemicals – Test method: Determination of resistance to penetration by a jet of liquid (Jet test)
BS EN 465:1995	Protective clothing – Protection against liquid chemicals – Performance requirements for chemical protective clothing with spray-tight connections between different parts of the clothing (type 4 equipment)

Table 7.3 Continued

Standard code	Standard title
BS EN 466:1995	Protective clothing – Protection against liquid chemicals – Performance requirements for chemical protective clothing with liquid-tight connections between different parts of the clothing (type 3 equipment)
BS EN 466-1:1995	Protective clothing – Protection against liquid chemicals – Part 1: Performance requirements for chemical protective clothing with liquid-tight connections between different parts of the clothing (type 3 equipment)
BS F 142:1995	Specification for hydrolysis resistant, thermoplastic polyether polyurethane elastomer-coated nylon fabric for aerospace purposes
BS EN 464:1994	Protective clothing – Protection against liquid and gaseous chemicals, including liquid aerosols and solid particles – Test method: Determination of leak-tightness of gas-tight suits (Internal Pressure Test)
BS EN 374-1:1994	Protective gloves against chemicals and micro-organisms – Part 1: Terminology and performance requirements
BS EN 368:1993	Protective clothing – Protection against liquid chemicals – Test method: Resistance of materials to penetration by liquids
BS EN 369:1993	Protective clothing – Protection against liquid chemicals – Test method: Resistance of materials to permeation by liquids
BS 7182:1989	Specification for air-impermeable chemical protective clothing
BS 7184:1989	Recommendations for selection, use and maintenance of chemical protective clothing
BS 4724: Part 2:1988	Resistance of clothing materials to permeation by liquids – Part 2: Method for the determination of liquid permeating after breakthrough
BS 4724-1:1986	Resistance of clothing materials to permeation by liquids – Part 1: Method for the assessment of breakthrough time
IS0 7229:1997(E)	Rubber- or plastics-coated fabrics – Measurement of gas permeability

sportswear, protective clothing, smart waterproof and breathable fabric and so on. Therefore, fabric permeability, which is related to the ability of fabric to allow a penetrant, such as a gas, liquid or solid material, to pass through, is the most important property because it has a very close relationship with clothing comfort and safety.

Sportswear

There has been a strong growth in the development and use of highly functional materials in sportswear and outdoor leisure clothing. The performance requirements of many such products demand balance of widely different properties of drape, thermal insulation, barrier to liquids, antistatic, stretch, physiological comfort, etc. The research in this field over the past decade has led to the commercial development of a variety of new products for highly functional end-uses (Buirski 2005).

Many smart double-knitted or double-woven fabrics have been developed for sportswear in such a way that their inner face, close to human skin, has optimal moisture wicking and sensory properties whereas the outer face of the fabric has optimal moisture dissipation behaviour. An example is Nike Sphere Dry, of which Nike supplied kits for the teams of the USA, Brazil, The Netherlands, Portugal, Korea, Mexico, Croatia and Australia in the World Cup 2006. It was reported that Nike Sphere Dry wicks sweat away from the body and through the shirt to keep the skin drier. The fabric's technology helps air move quickly through the garment and over the skin to assist the body's own natural cooling system and encourage the evaporation of sweat. At the same time, raised nodes on the underside lift the jersey away from the player's body and reduce clinging (McCurry and Butler 2006).

By designing new processes for fabric preparation and finishing, and as a result of advances in technologies for the production and application of suitable polymeric membranes and surface finishes, it is now possible to combine the consumer requirements of aesthetics, design and function in sportswear for different end-use applications. Hence, water permeability is one of the most important properties, which will affect the thermal insulation, quick liquid absorption and ability to evaporate water while staying dry to the touch, and be capable of transporting perspiration from the skin to the outer surface and then quickly dispersing it. Evaluation of water permeability becomes one of the most important requirements for research and development of sportswear (Buirski 2005).

Protective clothing

Scientific advancements made in various fields have undoubtedly increased the quality and value of human life. However, it should be recognized that the technological developments have also exposed us to greater risks and danger of being affected by unknown physical, chemical and biological attacks. One such currently relevant danger is from bioterrorism and weapons of mass destruction. In addition, we continue to be exposed to hazards from fire, chemicals, radiation and biological organisms such as bacteria and viruses. Fortunately, simple and effective means of protection from most of these hazards are available. Textiles are an integral part of most protective equipment. Protective clothing is manufactured using traditional textile manufacturing technologies such as weaving, knitting and non-wovens and also by specialized techniques such as 3-D weaving and braiding using natural and man-made fibres (Zhou *et al.* 2005).

Protective clothing is now a major part of textiles that are classified as technical or industrial textiles. Protective clothing refers to garments and other fabric-related items designed to protect the wearer from harsh environmental effects that may result in injuries or death. Today, the hazards that workers are exposed to are often so specialized that no single type of clothing will be adequate for protection. Providing protection for the general population has also been taken seriously in view of the potential disaster due to terrorism or biochemical attacks. Extensive research is being done to develop protective clothing for various regular and specialized civilian and military occupations (Zhou *et al.* 2005).

General requirements applicable to all types of personal protective equipment (PPE) concern design principles, innocuousness of the PPE, comfort and efficiency, and the information supplied by the manufacturer. Of these requirements, comfort and efficiency are among the most important and are related to water permeability and chemical permeability of fabric. Various test methods have been devised to measure the resistance of chemical protective clothing materials to penetration by liquid and gas, or qualitatively to evaluate the comfort, fit, function and integrity of chemical protective suit ensembles, etc. Moreover, new test methods will be established in parallel with progress in research and development of innovative protective clothing.

Waterproof and breathable fabric

Over the past few decades, there have been many advances in apparel textiles and clothing design that take account of the extremes of human thermoregulation and the environment. The main objective is to maintain the wearer in a state of thermo-physiological comfort under the widest possible range of workloads and ambient conditions. One approach has led to the proliferation of waterproof and breathable fabrics (WBF) for foul-weather clothing and other active sports and leisurewear. These materials have been scientifically engineered to balance the conflicting properties of high water vapour permeability (in order to expel perspiration) and waterproofness (to repel atmospheric precipitation). Therefore, as one type of interactive fabrics, waterproof and breathable fabrics could prevent the penetration of liquid water from outside to inside the clothing yet permit the penetration of water vapours from inside the clothing to the outside atmosphere. They are designed for use in garments that provide protection from the weather, that is, from wind, rain and loss of body heat (Lomax 1991; Holmes 2000; Fung 2002).

In general, polyurethane membranes used in breathable fabrics can be classified into three main groups (Lomax 1990):

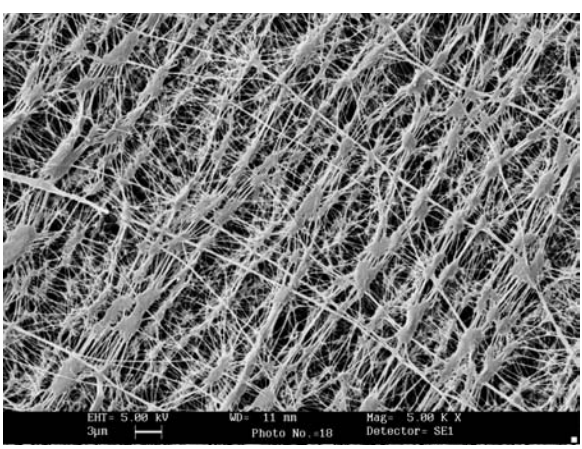
- Microporous membranes and coatings
- Hydrophilic membranes and coatings
- Combined microporous and hydrophilic layers.

Gore-Tex™ and Sympatex™, as the representatives of commercial WBFs, have received wide interest. These two types of WBFs have been used to develop various applications in the textile industry. Gore-Tex is one type of WBF laminated with porous PTFE film, while Sympatex is another type of WBF laminated with dense hydrophilic polyester film and hydrophilic polyurethane film. Due to the obvious differences in water vapour penetrating mechanism, production technology and product properties, research and development in these two types of WBFs are still being undertaken throughout the world.

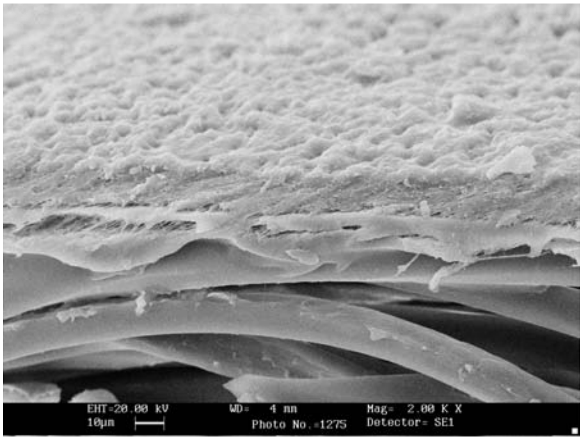
Porous membranes

For porous membranes applied to WBFs, the maximum size of micropore is between the diameter of a water vapour molecule and that of a water droplet. So the fabric laminated/coated with the porous membrane is able to separate water molecules from liquid water, and therefore can provide a good overall balance between breathability and waterproofness.

The surface and cross-section of Gore-Tex membrane were detected using SEM as shown as Figs 7.9 and 7.10. It is apparent that Gore-Tex



7.9 Surface of Gore-Tex membrane.



7.10 Cross-section of Gore-Tex membrane.

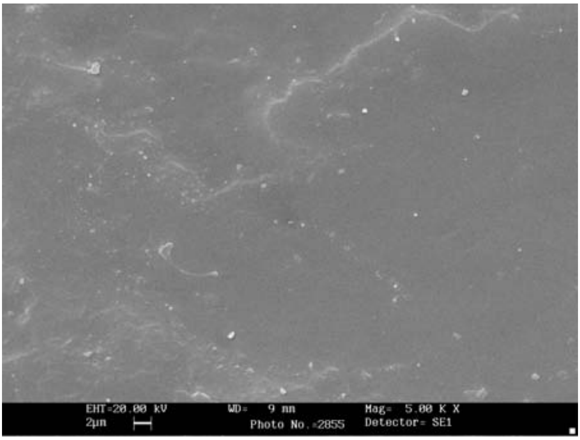
membrane is microporous and can provide the path for water vapour penetration (Ding *et al.* 2001). For the microporous membrane, if a pressure difference across the sample is present, convective gas flow through the sample carries water vapour along with the flow, which may add to or subtract from the diffusive flux, depending on the direction of the convective gas flow (Gibson 2000).

Dense membranes

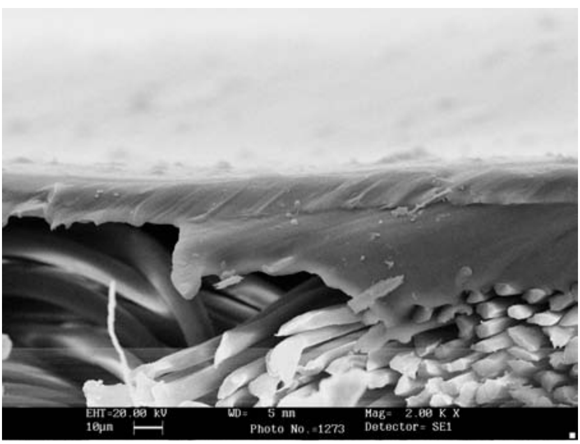
Generally speaking, dense polymer membranes have no pores but there exists the thermally agitated motion of chain segments to generate penetrant-scale transient gaps in the matrix, that is, free volume of the membrane, allowing penetrants to diffuse from one side of the membrane to the other. Accordingly, it is reasonable to regard a dense polymer as a 'porous medium', where the 'pores' are gaps among the polymer matrix (Chen *et al.* 2001).

The surface and cross-section of Sympatex membrane were detected using SEM as shown in Figs 7.11 and 7.12. It is apparent from the SEM pictures that Sympatex membrane is dense and offers no path for water vapour penetration (Ding *et al.* 2001).

Smart/intelligent/adaptive materials are composed of three basic elements: sensors, actuators, and control processors (Liang *et al.* 1997). Such materials can undergo a response adaptively triggered by small changes in their environment, such as a change in temperature and loading. A famous example among textile applications is smart waterproof and breathable fabrics (SWBFs) using temperature-sensitive polyurethane (TS-PU). TS-PU is one type of smart polymer that is able to sense and respond to external tem-



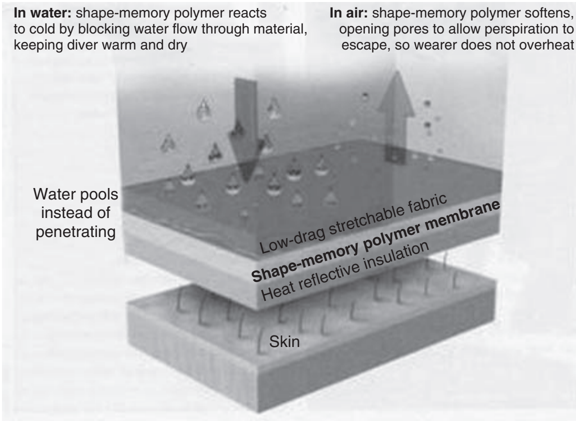
7.11 Surface of Sympatex membrane.



7.12 Cross-section of Sympatex membrane.

perature in a predetermined way. That is, this material can sense the change of external temperature, which will lead to a significant increase in water vapour permeability (WVP) of the polymeric membrane. Particularly, by means of appropriate molecule design, the abrupt change in water vapour permeability of TS-PU membrane can be controlled within desired temperature ranges such as room temperature range (Ding *et al.* 2003, 2004a, 2004b, 2005, 2006, 2008).

Such a property enables TS-PU materials to have broad application to the textile industry, medicine, environmental projects and so on, as shown in Fig. 7.13. The figure shows the structure of an amphibious diving suit that



7.13 Fabric structure of dual-purpose clothing.

was designed by the US Army's Soldier and Biological Chemical Command Laboratory in Natick, Massachusetts, and that is expected to enable wearers to be comfortable both in and out of the water. In the water, the amphibious diving suit performed like any other dry suit, keeping the wearer warm by preventing water from reaching the skin. But once out of the water, the structure of its novel three-layer membrane changed to let perspiration escape, preventing the wearer from overheating. Therefore, the amphibious suit was considered suitable for divers from the US Navy's Sea-Air-Land (SEAL) division who can get out of the water ready for action in light-weight garb (Graham-Rowe 2001).

7.6 Innovative test methods for fabric permeability

The movement of moisture, air and chemical liquids and gases is a complex series of processes. Over many years, a number of innovative ideas and novel test methods for fabric permeability have been created by constant exploration and modification.

7.6.1 Dynamic testing methods

Laboratory testing is usually a necessary first step in evaluating the comparative water vapour transport properties of candidate materials for new clothing system designs. However, comparison of material properties often becomes complex due to changes in tested properties under different test conditions. One material may be rated better than another material at one particular set of test parameters, yet the ranking may reverse under a different set of conditions. The two effects that are usually responsible for changes in ranking of materials are concentration-dependent permeability and temperature-dependent permeability (Gibson 2000).

Concentration-dependent permeability

Membranes that contain a continuous hydrophilic component, such as Gore-Tex and Sympatex, change their transport properties based on the amount of water contained in the hydrophilic polymer layer. The magnitude of the relative changes in water vapour transfer rate as a function of membrane water content are quite large for several common clothing materials and systems. The water content of these materials is a function of the water vapour content (humidity) of the environment on either side of the clothing layer. Test methods that evaluate concentration-dependent permeability need to be capable of independently varying the relative humidity of the environment on the two sides of the material.

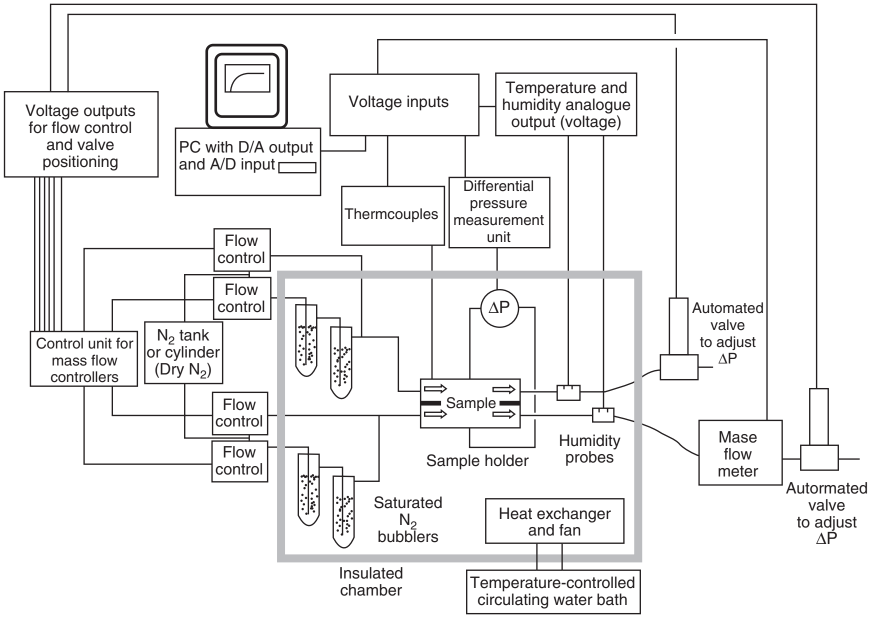
Temperature-dependent permeability

Some polymer membranes may exhibit lower intrinsic water vapour transfer properties at low temperatures. This effect is of practical importance for the ability of cold-weather clothing to dissipate water vapour during active wear, or for boots, gloves and sleeping bags to dry out under cold conditions. Knowledge of temperature-dependent permeability is also important when comparing test results between test methods or laboratories that may conduct standard testing at different temperatures. Analysis of temperature-dependent permeability must distinguish between changes in the intrinsic transport properties of the material, and the apparent decrease in water vapour transport rates due simply to the lower vapour pressure of water at lower temperatures (Gibson 2000).

It is reported that one test method, the dynamic moisture permeation cell (DMPC), can control the humidity and flow rate on the two sides of the test sample, and hence control the temperature of the test system (Fig. 7.14). This allows temperature-dependent effects to be separated from concentration-dependent effects on mass transfer phenomena. The DMPC permits the experimenter to explore the temperature dependence of the diffusion behaviour at different points on the vapour sorption isotherm of the hydrophilic polymer component of a polymer film or membrane laminate (Gibson 1993, 1999, 2000; Gibson *et al.* 1995).

7.6.2 Whole assessment methods

Moisture transfer properties of textile fabrics and garments are important to the thermal comfort of clothed persons. A number of test methods have



7.14 Schematic of DMPC test arrangement.

been developed to evaluate the moisture transfer properties of textile fabrics and garments. In these test methods, different techniques and testing conditions were used in order to try to provide complete assessment of moisture transfer properties of textile products. Although every test method was close to real use conditions at some point, no one test method has been able to simulate the complicated process. Therefore, many researchers are trying to investigate the differences and interrelationships between the results from these different test methods.

Dolhan (1987) compared two Canadian standards (CAN2-4.2-M77 and CAN/CGSB-4.2 No. 49-M91) and the ASTM E96 test methods for measuring the water vapour transmission properties and found that the results of these tests were not directly comparable because of the differences in the water vapour pressure gradients driving the moisture transmission in the different test methods.

Gibson (1993) conducted an extensive investigation on the relationship of the test results from the sweating guarded hot plate (ISO 11092) and those from the ASTM E96 Cup Method. In his work, permeable materials, hydrophobic and hydrophilic membrane laminates were tested and the results were standardized in the units of air resistance and water vapour transmission rate. It was found, except for the hydrophilic samples, that there is a clear correlation between the results from the two tests. As the test condition in the guarded sweating hot plate tests resulted in much higher equilibrium water content in the hydrophilic polymer layer, which influences the polymer's permeability, the water vapour transmission rate through the hydrophilic membrane is greater when tested using the sweating guarded hot plate.

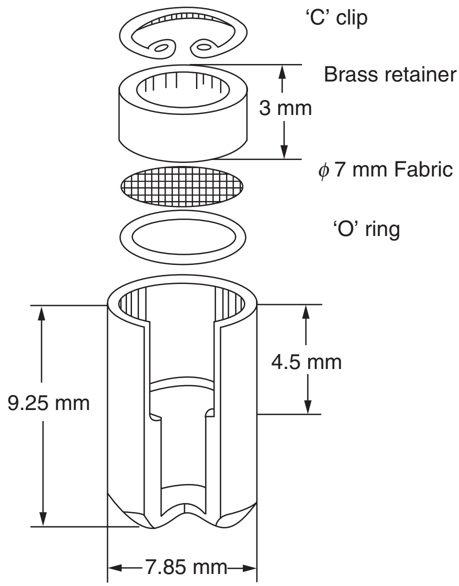
Gretton *et al.* (1996) classified the fabric samples into four categories, including air permeable fabrics, microporous membrane laminated fabrics, hydrophilic membrane laminated/coated fabrics and hybrid coated/laminated fabrics, in investigating the correlation between the test results of the sweating guarded hotplate (ISO 11092) and the evaporative dish method (BS 7209). They showed that there is a good correlation between the two test methods for all fabrics except for the hydrophilic coated and laminated fabrics that transmit water vapour without following the Fickian law of diffusion.

McCullough *et al.* (2003) measured the water vapour permeability and evaporative resistance of 26 different waterproof, windproof and breathable shell fabrics using five standard test methods. The water vapour transmission rate (WVTR) was measured using the ASTM E96 upright and inverted cup tests with water, the JIS L1099 desiccant inverted cup test and the new ASTM F2298 standard using the dynamic moisture permeation cell (DMPC). The evaporative resistance was measured using the ISO 11092 sweating hot plate test. The WVTRs were consistently highest when measured with the desiccant inverted cup, followed by the inverted cup, DMPC and upright cup. The upright cup was significantly correlated with the DMPC (0.97), and the desiccant inverted cup was correlated to the sweating hot plate (–0.91).

7.6.3 Modern characterization methods

Measurement of water vapour transport property of fabrics by differential scanning calorimeter

Measurement of the rate of water vapour evaporation can be carried out using a TA Instruments model 2920 Modulated Differential Scanning Calorimeter (DSC). Experiments are carried out using dry nitrogen as the carrier gas at a flow rate of 40 mL/min to remove the evaporated water from the cell environment. The standard sample pans are replaced with brass containers (one reference assembly and the other containing the test sample). The special container assembly (Fig. 7.15) was designed based on Day's technique (Day and Sturgeon 1986) and it essentially consists of a small water-holding brass cup and a brass retainer. The fabric sample to be tested is placed over the 'O' ring which in turn is fitted to the inside of the groove. A brass retainer of diameter slightly less than the inner diameter



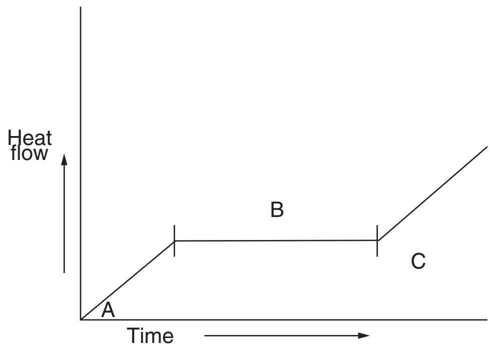
7.15 Container assembly used in modulated DSC.

of the brass cup is placed over the test specimen and properly secured in place by a 'C' clip. A similar arrangement for the empty reference cup is used for comparative purposes. The rate of evaporation of samples is measured with the help of a DSC curve choosing time versus heat flow. The quantity of water taken in the container for all the samples is constant (5 mg) and the exact quantity of water is placed in the containers with the help of a micro-burette. The experiments are conducted with temperatures programmed from room temperature to 40°C and a heating rate of 20°C/min is used. The isothermal temperature of 40°C is chosen so as to simulate the normal skin temperature of the human being (Indushekar *et al.* 2005).

The water vapour flux through the fabric occurs in four different ways (Chen *et al.*, 2001). They are:

- Diffusion of water vapour through the air spaces between the fibres
- Absorption, transmission and desorption of the water vapour by the fibres
- Adsorption and diffusion of the water vapour along the fibre surface (wicking)
- Diffusion of the water vapour between yarn spaces.

Therefore, heat flow behaviour can be exhibited by DSC curves as shown in Fig. 7.16. The first part of the curve (A) indicates the quantity of heat flow required to heat the specimen cups from room temperature up to the isothermal temperature of 40°C. The curve then follows a steady flow path



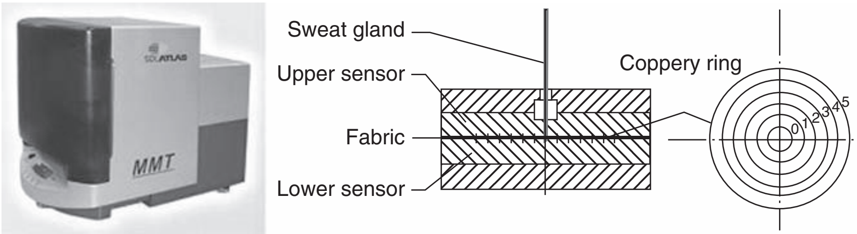
7.16 Heat flow behaviour exhibited by DSC curves.

(B) indicating that the equilibrium has been established and gives an indication of the heat flow and time required for evaporating the water. The curve then again follows an upward path (C) indicating that there is a sudden change of the heat flow as the water in the cup is completely evaporated and the measured heat flow reverts to that of the two empty cups. From the initial weight of the water (5 mg) and the curve path (A–B), i.e., the observed time required for complete evaporation, the evaporation rates for the specimen are computed. The evaporation rates are generally expressed as a function of the specimen area and hence the results are also expressed in $g/m^2/h$ (Indushekar *et al.* 2005).

The DSC employing special specimen cups offers a simple experimental procedure for measuring the water vapour transport property of fabric. The results can be applied to evaluating the relative evaporative cooling efficiencies of fabrics as well as providing indications of the potential metabolic heat problem associated with impermeable vapour barriers. However, Indushekar *et al.* compared the water vapour transmission rates measured by a modulated differential scanning calorimeter (MDSC) and those by the conventional dish technique as specified in BS7209 for a wide range of woven-based fabrics used in cold-weather protective clothing. The study showed that results from these two test methods differ widely due to the differences in the water vapour gradients that occurred in the two methods (Indushekar *et al.* 2005).

Measurement of liquid moisture management property using the moisture management tester

Moisture management properties influence the human perception of moisture and comfort. The moisture management properties of fabrics depend on their water resistance, water repellency, water absorption, wicking of the



7.17 Schematic of Moisture Management Tester (MMT).

fibres and yarns, as well as the geometric and internal structures of constituting materials such as fibres, yarns and fabrics. The moisture management tester (MMT) provides a procedure for the evaluation of the dynamic movement of liquid moisture in porous fabrics.

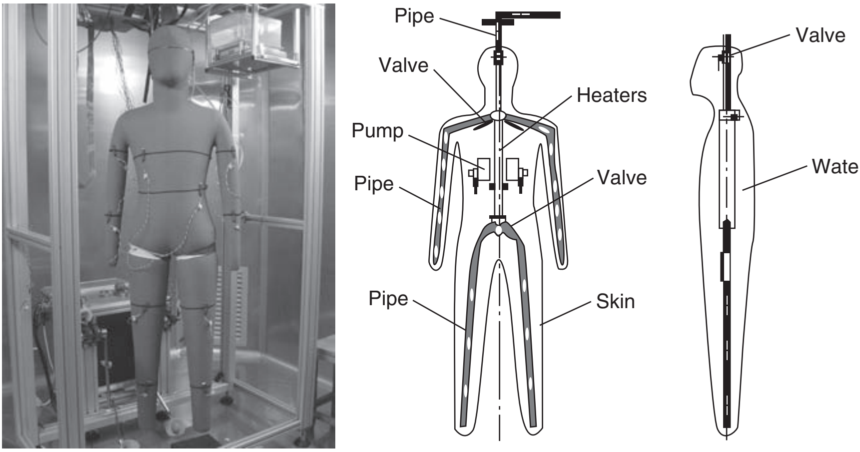
A schematic of the moisture management tester (MMT) is shown in Fig. 7.17 (Hu *et al.* 2005). Liquid moisture management properties of fabrics are tested by placing a sample of the fabric between upper and lower concentric moisture sensors. A predefined amount of test solution (synthetic sweat) is introduced onto the upper side of the fabric, and then the test solution will transfer onto the fabric in three directions:

- Spreading outward on the upper surface of the fabric
- Transferring through the fabric from the upper surface to the bottom surface
- Spreading outward on the lower surface of the fabric and then evaporating.

The liquid moisture content measured can be applied to assess the dynamic liquid moisture transport behaviours in these multiple directions inside the material.

Measurement of moisture vapour resistance using thermal manikin

There are relatively few sweating manikins available for measuring the evaporative resistance or vapour permeability of clothing. Some manikins are covered with a cotton knit suit and wetted out with distilled water to create a saturated sweating skin. However, the skin will dry out over time unless tiny tubes are attached to the skin so that water can be supplied at a rate necessary to sustain saturation. Other manikins have sweat glands on different parts of the body. Water is supplied to each sweat gland from inside the manikin, and its supply rate can be varied. A new type of sweating manikin (as shown in Fig. 7.18) uses a waterproof but moisture-permeable fabric skin, through which water vapour is transmitted from the inside of the body to the skin surface (Fan and Chen 2002; Fan and Qian 2004). Some



7.18 The perspiring fabric thermal manikin and the inner construction.

manikins keep the clothing from getting wet by using a microporous membrane between the sweating surface and the clothing, but this configuration may increase the insulation value of the nude manikin (McCullough 2005).

ASTM F2370 specifies procedures for measuring the evaporative resistance of clothing systems under isothermal conditions, i.e. where the manikin's skin temperature is the same as the air temperature so that there is no temperature gradient for dry heat loss. An alternative protocol in the standard allows the clothing ensemble to be tested under environmental conditions that simulate actual conditions of use; this is called the non-isothermal test. The same environmental conditions are used for the insulation test and the non-isothermal sweating manikin test. The air temperature is lower than the manikin's skin temperature, so dry heat loss is occurring simultaneously with evaporative heat loss, and condensation may develop in the clothing layers. The evaporative resistance determined under non-isothermal conditions is called the apparent evaporative resistance value. The apparent evaporative resistance values for ensembles can only be compared to those of other ensembles measured under the same environmental conditions (McCullough 2005).

Kar *et al.* (2007) investigated the correlations between the moisture vapour resistances/transmission rates measured using the newly developed sweating fabric manikin (Walter) (Fig. 7.18), the moisture transmission test (Model CS-141), the ASTM E96 testing method and the sweating guarded hot plate method. For the range of air-permeable knitted fabrics tested, it was found that good interrelationships exist between the results from the four types of test methods, although some discrepancies exist between different tests due to differences in testing conditions. Test results from different moisture transfer test methods can therefore be convertible with due consideration.

7.7 Conclusions

Fabric permeability is an important factor in the performance of most textile materials. It is related to wear comfort and wear safety, as well as having various applications in the industrial field. At the same time, progress in textile science and technology results in the continued appearance of novel testing instruments and technologies for fabric permeability. Therefore, innovative test methods for fabric permeability will continue to be developed.

7.8 References

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Standards

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