7
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.

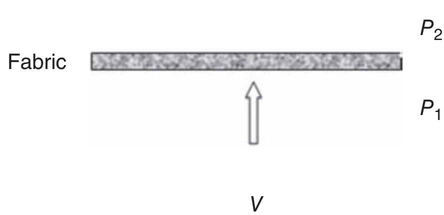
7.4.1 Air permeability

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:

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

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

$$\Delta P = KV \tag{7.3}$$

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

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

Here,

$$R = K \tag{7.5}$$

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

$$\Delta P = KV^2 \tag{7.6}$$

Rewritten,

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

and

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

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:

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

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:

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

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:

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

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.

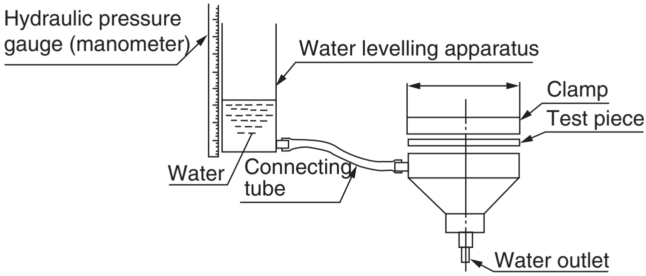
Water resistance

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.

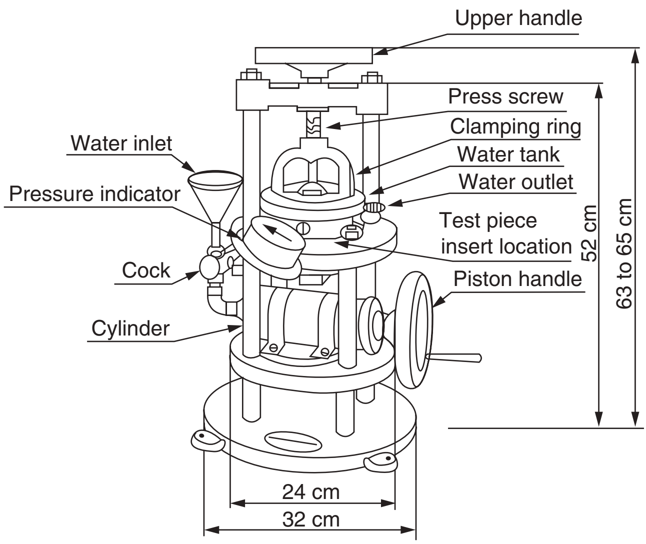
Test for water penetration (hydrostatic pressure method)
This test applies mainly to textile fabrics with no air permeability.

- 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



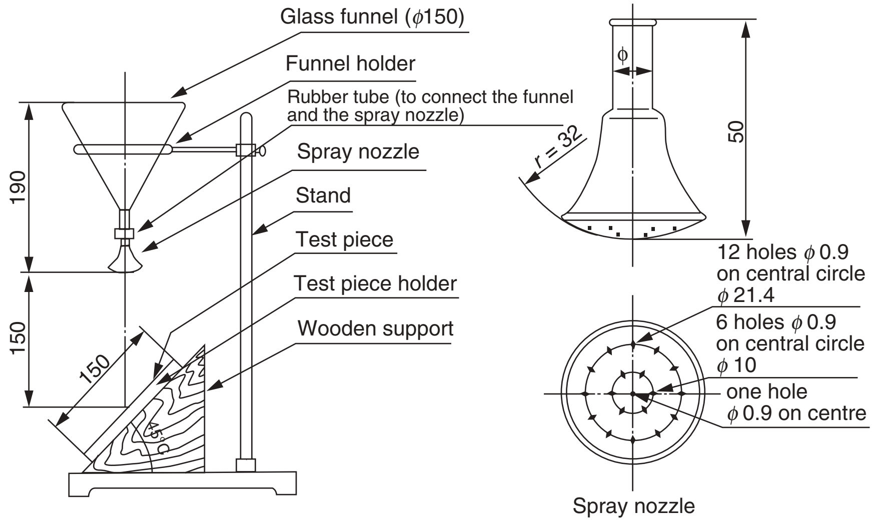
7.3 Water penetration test apparatus (for low hydraulic pressure).



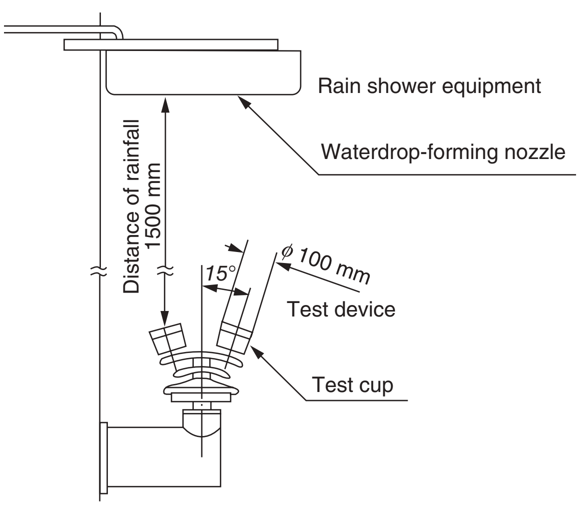
7.4 Water penetration test apparatus (for high hydraulic pressure).

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:

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

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

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:

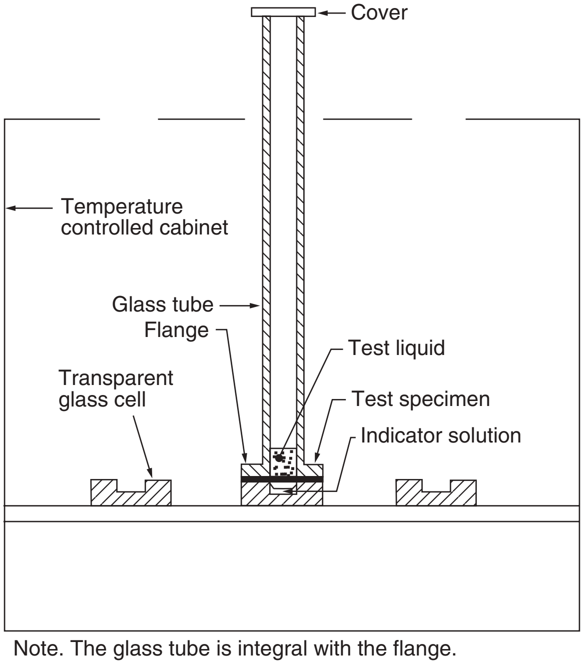
- Determination of resistance of fabric to permeation by liquids and gases
- Measurement of repellency, retention, and penetration of liquids through fabric.

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.

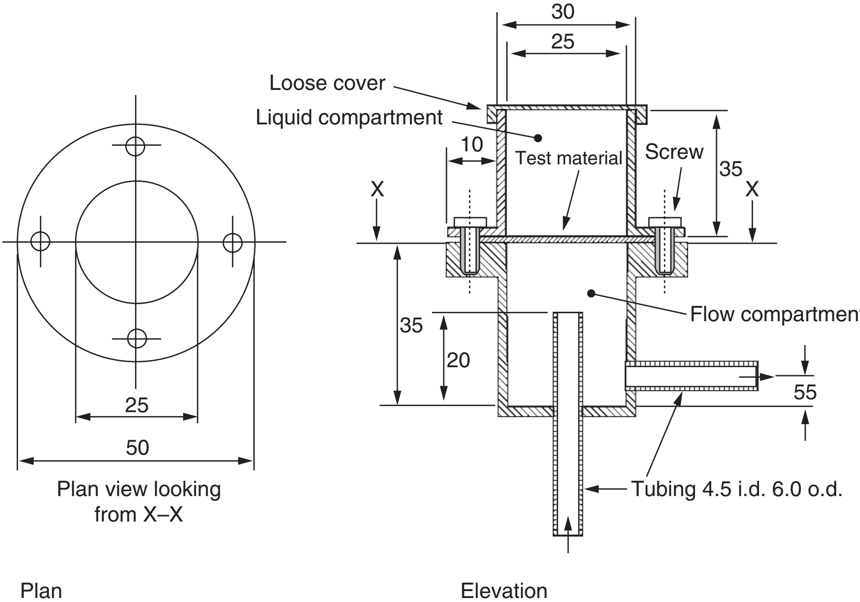
The test apparatus, as shown in Fig. 7.7, consists mainly of the following three parts:



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.



Note. Large arrows in the elevation denote direction of flow of gaseous or liquid collecting medium.

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:

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

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

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

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:

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

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:

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

$$\mathrm{PLR} = (m_{\mathrm{pc}}/m_{\mathrm{t}}) \times 100 \qquad 7.20$$

$$\mathrm{PP} = (m_{\mathrm{cl}}/m_{\mathrm{t}}) \times 100 \qquad 7.21$$

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:

$$\mathrm{EE} = [(m_{\mathrm{ap}} + m_{\mathrm{pc}} + m_{\mathrm{cl}})/m_{\mathrm{t}}] \times 100 \qquad 7.22$$

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):

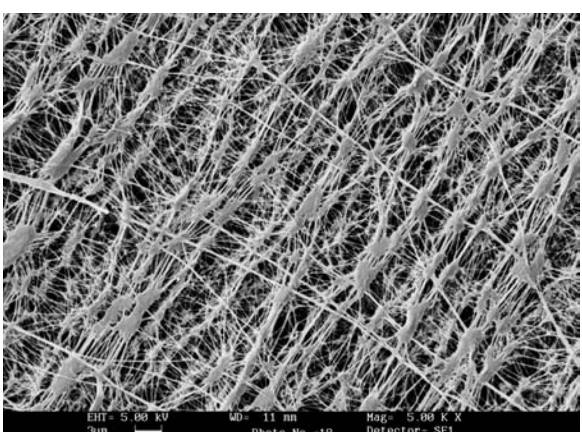
- Microporous membranes and coatings
- Hydrophilic membranes and coatings
- Combined microporous and hydrophilic layers.

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.

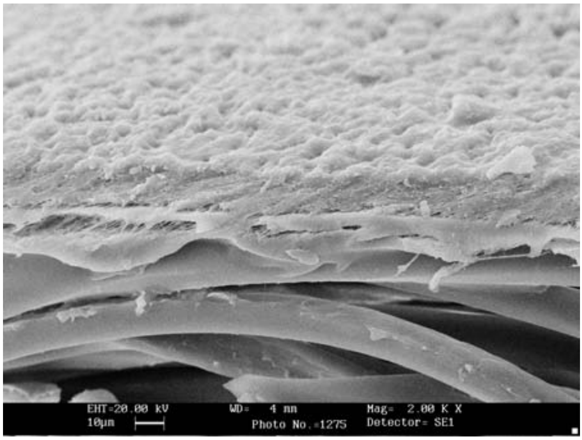
Porous membranes

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.



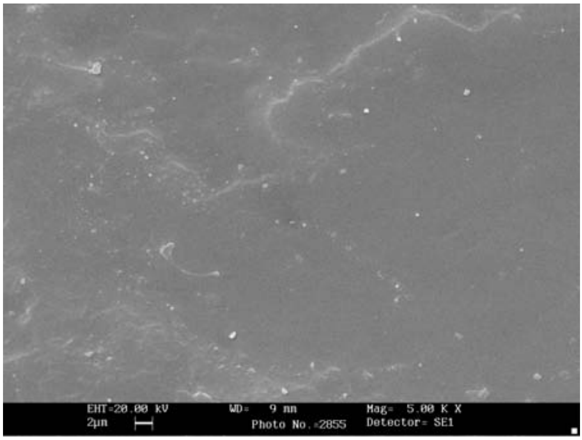
7.10 Cross-section of Gore-Tex membrane.

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).

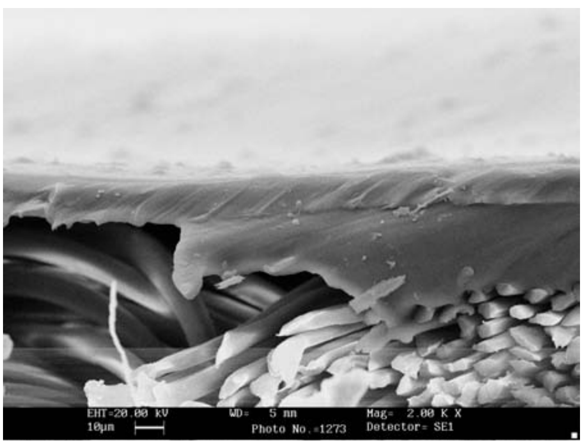
Dense membranes
Generally speaking, dense polymer membranes have no pores but there exists the thermally agitated motion of chain segments to generate penetrant-scale transient gaps in the matrix, that is, free volume of the membrane, allowing penetrants to diffuse from one side of the membrane to the 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-



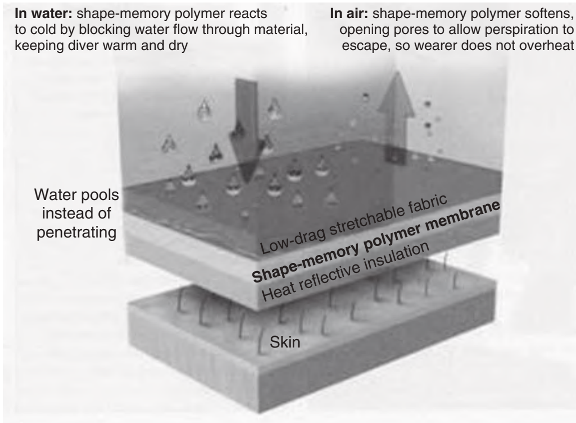
7.11 Surface of Sympatex membrane.



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 lightweight 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.

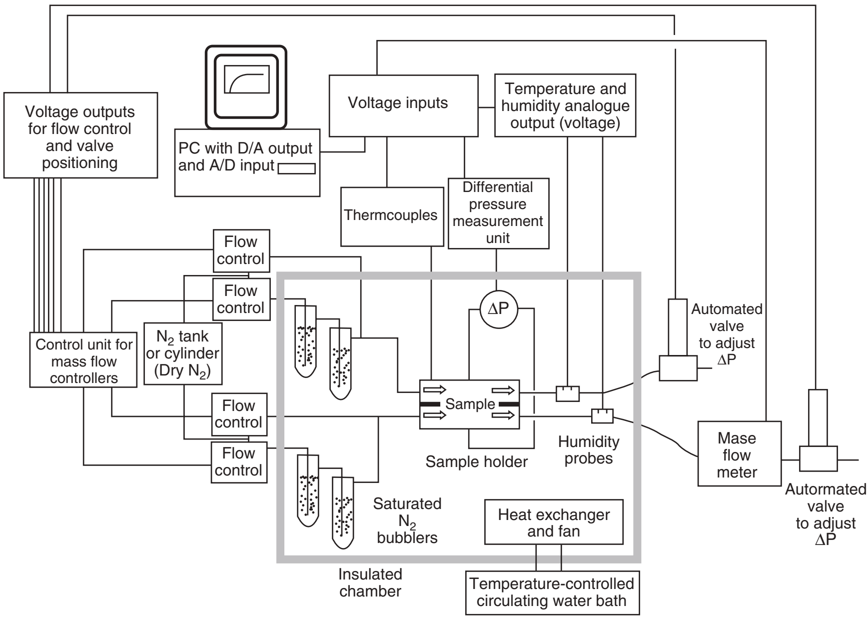
Temperature-dependent permeability

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.

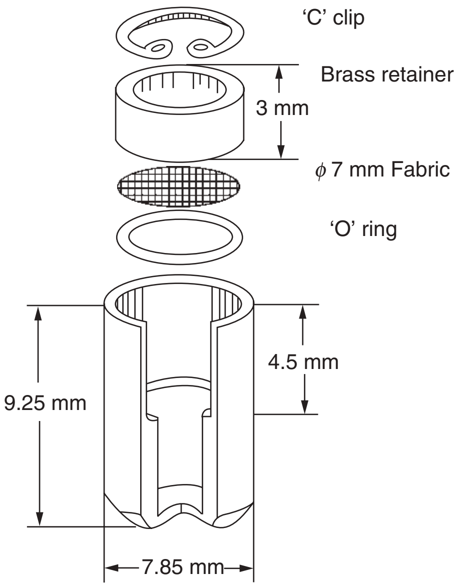
Gretton *et al.* (1996) classified the fabric samples into four categories, including air permeable fabrics, microporous membrane laminated fabrics, hydrophilic membrane laminated/coated fabrics and hybrid coated/laminated fabrics, in investigating the correlation between the test results of the sweating 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



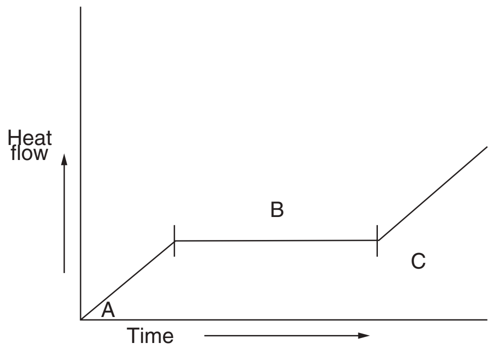
7.15 Container assembly used in modulated DSC.

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



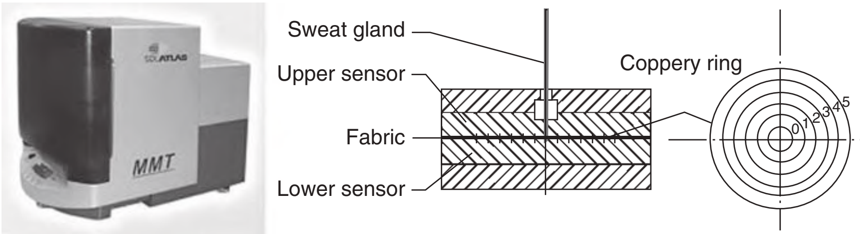
7.16 Heat flow behaviour exhibited by DSC curves.

(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.

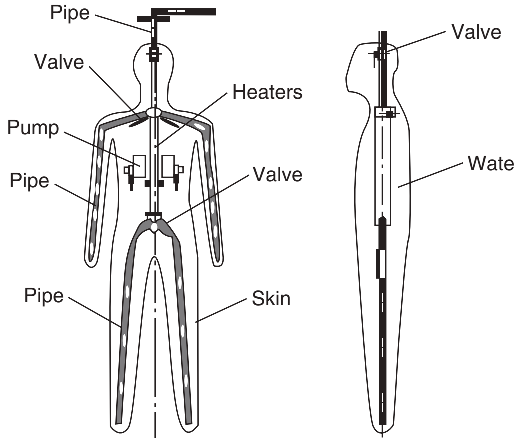
A schematic of the moisture management tester (MMT) is shown in Fig. 7.17 (Hu *et al.* 2005). Liquid moisture management properties of fabrics are tested by placing a sample of the fabric between upper and lower concentric moisture sensors. A predefined amount of test solution (synthetic sweat) is introduced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

ASTM D737-04 Standard test method for air permeability of textile fabrics.

BS EN ISO 9237:1995 Textiles – Determination of the permeability of fabrics to air.

ASTM E96-00 Standard test method for water vapour transmission of materials.

AATCC TM 70-2000 Water repellency: Tumble jar dynamic absorption test.

JIS L1092-1998 Testing methods for water resistance of textiles.

BS 4724-1:1986 Resistance of clothing materials to permeation by liquids – Part 1: Method for the assessment of breakthrough time.

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 ISO 22608:2004 Protective clothing – Protection against liquid chemicals – Measurement of repellency, retention, and penetration of liquid pesticide formulations through protective clothing materials.

8
Testing for fabric comfort

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Abstract: Comfort, a key quality of clothing and other fabric applications, has been shown to impact user performance. For the purposes of this review, comfort is categorized as thermal and sensory. Thermal comfort is primarily an issue of environmental conditions, metabolic rate, fabric characteristics, and clothing construction. Sensory comfort is primarily an issue of pressure, tactile, and psychological perceptions. Methods for evaluating fabric comfort are described. It is important to note that fabric characteristics and comfort can change over time while in use. Although objective fabric comfort testing and characterization are valuable, the most accurate means for assessing comfort are human-use tests under ecologically valid conditions.

Key words: comfort evaluation, fabric comfort characteristics, thermal comfort, sensory comfort, clothing comfort wear tests.

8.1 Introduction: defining comfort

Comfort may be among the most complex characteristics of clothing. Fourt and Hollies (1970) describe comfort in terms of (1) thermal, (2) non-thermal, and (3) wear conditions. Slater's description of comfort (Slater, 1985) takes a slightly different approach, emphasizing three components: (1) physiological, (2) psychological, and (3) physical, and considering also their impact on, and interaction with, the 'harmony' between humans and the environment. According to Slater's description, the physiological and physical aspects are interrelated and refer to homeostasis (physiological aspect) in the face of a varying environment (physical aspect). The psychological aspect of comfort refers to satisfactory mental function within a given environment. However, Li (2001) has recently suggested that comfort is the subjective integration of visual, thermal, and tactile sensations, psychological status, body–clothing interactions, and the external (macro-) environment.

Although comfort can be defined in various ways, for the purposes of this review, clothing comfort is operationally defined as general human approval of all aspects of a clothing system while being worn (as opposed to a fabric sample). Assessing discomfort may be a more practical way of evaluating clothing systems, in that comfort exists when perception of discomfort is minimal or non-existent. It follows, then, that there are relative degrees of comfort which are practically evaluated by relative degrees of the absence of discomfort. We will consider comfort as being comprised of two major components, thermal comfort and sensory comfort.

Comfort is affected by the interaction of the human body with the clothing, as well as the environment which stimulates thermal, mechanical, and even visual sensations (Li and Wong, 2006). Such sensations are a product of the simultaneous integration of multiple clothing system characteristics and the related physiological and psychological responses. Among the many sensations are thermal comfort/discomfort, or how warm/cool the clothing system feels. Thermal comfort is determined in part by neural thermosensory monitoring of the micro-environment, that area between the wearer's skin and the outermost layer of clothing (Bishop *et al.*, 2000, 2003a; Muir *et al.*, 2001).

In turn, the micro-environment is a product of both the metabolic heat and moisture generation of the subject and the macro-environment. All readers will recognize that clothing thermal comfort changes if the metabolic heat production or the environment immediately next to the skin changes. In active humans, this can be affected by moving in and out of environmentally controlled and uncontrolled areas, or by changing the intensity of physical activity, both of which often change rapidly. To further complicate matters, the micro- and macro-environmental humidity and air motion also influence thermal comfort.

Beyond thermal comfort, there is also tactile and pressure comfort, as well as psychological comfort. All of these combine to determine sensory comfort, which can also interact with thermal comfort (i.e., clothing that is tactilely comfortable in a cool environment may be uncomfortable in a warm environment). Greater complexity arises when clothing becomes damp or wet, which further impacts comfort in most cases. Moreover, duration of wear is a factor, in that clothing may be evaluated differently after some period of wear. For example, our ability to feel pressure is known to fade in only a few minutes in order to avoid overloading the sensory system.

On top of these complex issues are cultural and individual aesthetics and the human ability to relate to prior experiences. Humans are known to evaluate current comfort in relation to significant prior experiences. Prior experiences can thus impact present perceptions. To borrow from another sensory experience, most of us have had unfortunate results with particular foods. We may have become ill soon after we ate a particular food, and although the food was not the proximate cause of our illness, the association of that particular food with that negative experience impacts our attitude towards that food. The same thing can happen with clothing system comfort; but the experiences are typically more subtle. That is, clothing can be associ-

Table 8.1 Some key comfort variables

Thermal	Sensory
Clothing insulation	Pressure
Air permeability	Perceived and actual weight
Vapor permeability	Absorbency
Metabolic rate	Roughness/abrasiveness
Macro-environment	Rigidity
– Humidity	Human mood
– Radiant heat gain/loss	Other non-clothing comfort factors
– Convective heat gain/loss	Aesthetics/social expectations
– Conductive heat gain/loss	Stretch
– External convection	Cling
Micro-environment	Prior experiences
– Clothing fit	
– Internal convection	
– Sweat rates	
Internal blood circulation (convection)	
Environmental stability	

ated with a bad experience that had nothing to do with clothing, but does impact the wearer's 'comfort' in a clothing style or fabric. Additionally, preconceived notions manifested by input from others' experience could bias (positively or negatively) our expectations of a clothing system before we ever don a garment.

The purpose of this review is to consider the role of comfort in clothing and describe some basic principles for evaluating comfort. We will also consider applications of comfort principles in clothing and the anticipated future of clothing comfort evaluation. Because of the complex nature of comfort, first we will deal with each of the major classes of comfort separately and then we will combine them. Some key thermal and sensory factors that impact comfort are summarized in Table 8.1.

8.1.1 The importance of comfort

Comfort is rated by users as one of the most important attributes of clothing (Wong and Li, 2002; Li and Wong, 2006). Almost everything consumers do in terms of selecting, sizing, and modifying clothing could be considered efforts to maximize comfort (Li and Wong, 2006). Most of us suspect that comfort is important not only in the marketplace but also in the utility of the garment. A recent study (Bell *et al.*, 2005) demonstrated that performance on a cognitive exam was associated with the comfort rating of the clothing. Although not well-controlled, Bell *et al.*'s findings suggested that comfort plays an important role in other aspects of human performance. For example, the comfort of firefighter protective clothing may impact firefighter performance. Clearly thermal comfort impacts physical performance, sometimes profoundly, as will be discussed further in the next section.

8.2 Evaluating thermal comfort

Evaluating thermal comfort is complex, but there are more concrete methods for evaluating thermal comfort compared to sensory comfort. Thermal comfort is more concrete because the constructs which determine thermal comfort have been mostly elucidated. The macro-environment can be readily measured to within about 0.1°C and within a few millimeters of vapor pressure (typically about 2% relative humidity up to near saturation where the error increases to about 5%). Once conduction, convection, radiation, and evaporation are fully described, then the macro-environment is reproducible. Likewise, the metabolic rate, and therefore metabolic heat production, can be accurately measured to within about 5%. Because the micro-environment and the metabolic status can be fully described, the impact of the macro-environment on an inert micro-environment can be modeled. The accuracy of the model depends on how completely all variables are identified and quantified. As might be anticipated, this is no easy task.

For example, permeability of fabrics and clothing is just one aspect of thermal comfort. Yet, a whole sub-specialty of fabric characterization has developed which can describe the permeability to air and water vapor (as well as chemical permeability) of single and composite fabrics. These evaluations are typically conducted on dry and wet heat sources, including static and moveable manikins. These mechanical characteristics of clothing's water and air permeability are discussed in another chapter. For the purposes of comfort evaluation, it is critical to note that vapor permeability is a key fabric characteristic of clothing comfort in most situations.

Fabric characteristics are a major contributor to clothing comfort, but not the sole contributor. For example, we recently analyzed another laboratory's data on firefighter clothing (unpublished). We noted that a large variability in total heat transfer (the combination of water vapor and dry heat transfer) of the thermal barrier (the thermal barrier, which is the key element on turnout clothing, is composed of a multi-layer fabric) made a very small difference in physiological heat strain. Large variations in total heat transfer on average accounted for less than 0.1°C of rectal temperature and a few beats of heart rate. Perhaps this was due to the complex nature of clothing systems, wherein seams, fabric overlap, clothing venting, addition of different fabrics at wear points and other characteristics make a large contribution to the clothing thermal function, and thereby to clothing comfort. So, clothing testing can yield different results from fabric testing. On the other hand, not all fabric is worn as clothing. Bedding and towels, for example, would be ideal candidates for precise comfort characterization.

We would argue that fabric testing is foundational to, but not sufficient for, tests of intact clothing systems. Likewise, modeling and testing on artificial systems are foundational to, but insufficient for, determining human comfort responses to clothing. This is primarily due to the lack of a precise integrating center (i.e. brain) when testing on artificial systems. Where testing on artificial systems may involve more than one factor, it is likely that no experimental set-up incorporating artificial systems would have the capacity of the human brain to consider virtually all factors influencing comfort and do this simultaneously and maintain its effectiveness as the environment undergoes acute changes (which, as noted, it often does). Also, without a human brain to formulate a broad range of subjective responses, a great deal of ecological validity is lost.

8.2.1 Thermal comfort test methods

Thermal comfort can be predicted within reasonable accuracy using computer modeling. Prek (2004) provides a recent example of this using a thermodynamic approach to modeling, while Newsham (1997) offers an approach to modeling incorporating human behavior with respect to comfort. Laboratory simulations of humans using guarded hot plates, manikins of various types and other objective tests are useful in establishing basic fabric and clothing system characteristics. However, the comfort range ultimately must be established by human users.

NASA uses a definition of thermal comfort such as to maintain a ±69 kJ (19 Wh or 65 BTU) band of heat storage (Cline *et al.*, 2004). Humans typically require a micro-environment temperature of about 28–30°C to maintain thermal balance at rest (Astrand and Rodahl, 1986). For our purposes, the key issue is the narrow band of comfort. Fanger's text on thermal comfort (Fanger, 1970) is one of the foundations of the field. For a thorough discussion of thermal comfort see Charles (2003).

There is some question as to the human sensory inputs that determine thermal comfort. Frank *et al.* (1999) reported that the tympanic temperature and the mean skin temperature of their experimental subjects had about an equal impact on thermal comfort. However, from our view, the statistical error (discussed later) should be corrected to show closer to a three times greater contribution for tympanic compared to mean skin temperature. This useful experiment did not include the factor of time. Clearly, the skin is able to detect temperature changes much more rapidly than the core of the body because it is closer to the environment and has a smaller mass. From the Frank *et al.* (1999) experiment, it would appear that the core temperature determines long-term comfort, overruling the immediate comfort response of the skin. However, acute comfort responses might be more strongly related to the skin (before the core has had adequate time to change in response to a heat load).

There are several factors to consider in human evaluations of thermal comfort:

- Metabolic rate
- Macro-environmental conditions
- Macro-environmental air movement
- Air movement caused by human movement
- Clothing fabrics and construction.

The first consideration is to recognize that, for a given clothing system, as metabolic rate changes, thermal comfort will change. Thus clothing which is comfortable in cool temperatures at a low metabolic rate (i.e., rest) may be too warm for moderate or high metabolic rates. So, thermal comfort must first be described in relation to a specified metabolic rate. For example, in cold temperatures, clothing that is uncomfortable for a low metabolic rate will likely prove comfortable when the metabolic rate increases sufficiently. Metabolic rate is most accurately measured via direct calorimetry or from spirometry. It can also be estimated from tables (Ramsey and Bishop, 2003) or from a user's heart rate (Astrand and Rodahl, 1986).

The second consideration in thermal comfort is the macro-environment. This includes temperature, relative humidity and air movement. Temperature can be expressed more specifically in terms of radiant and dry energy gain. These characteristics along with relative humidity and air movement can be measured in a number of ways, perhaps the most popular being the wet-bulb-globe-temperature (WBGT) (Ramsey and Bishop, 2003).

Air movement has further application when considering the contribution of the human body. In motionless air, the body releases heat and humidity to the micro- and macro-environments. This impacts the macro-environment and causes local convection depending on the macro conditions. When there is macro air motion, the impact of human production of heat and humidity is less in proportion to the air speed. When clothing is permeable to air movement and there are openings in the garment (which permit exchange with the macro-environment), the air motion also impacts the micro-environment. When natural air movement is simulated by fans, the distance from the fan and the cross-sectional area of the air flow is very important because air flow rate (wind speed) varies accordingly.

Another factor in thermal comfort is the movement of humans wearing the clothing system, because human movement generates heat and causes air flow between the skin and the fabric. With encapsulating clothing, the micro-environment is the only environment the body senses, except at a few places. The macro-environment can be very cold and dry, and yet with good clothing and sufficient metabolic activity, the micro-environment near the skin can be very comfortable or even uncomfortably hot and humid. Furthermore, loose clothing with much ventilation will induce air both through the fabric and through openings. Very snug permeable clothing will reduce, but not eliminate, air movement through both sources. This air movement is not due to the macro air motion but to the movements of the human wearing the clothing. It could be described as 'relative' wind. So clothing thermal comfort as well as sensory comfort will only be absolutely accurate for a given set of movements. For example, a human walking or riding a bicycle even in still macro air will experience air motion that can impact the micro-environment.

In our research we have tried to simulate the motions involved in different tasks appropriate to the clothing. Havenith *et al.* (2002) emphasize that the contributions of body and air motions to the micro-environmental humidity and thermal comfort are so large that they must be incorporated into comfort predictions.

The last aspect of thermal comfort is the fabric characteristics and construction of the clothing. This includes the fabric itself, other construction materials, seams, overlaps (e.g. pockets, collars, and cuffs), the location and type of openings, clothing fit at various points on the body, and the closures. Clothing, unlike fabric, is highly variable in all of these characteristics. Each of these can impact thermal comfort.

Once the parameters of metabolic rate, environment, movement, and fabric and construction/fit are specified, then two types of thermal comfort measurements can be made. First, we can objectively measure the nature of the micro-environment in terms of temperature and relative humidity. Because human thermal comfort limits are relatively narrow in terms of local (micro-) environment, comfort can be predicted. However, human variability, as mentioned earlier, should never be ignored (Bishop, 1997). Second, because of this, to accurately describe comfort we also need assessment by a human test panel actually wearing the clothing system.

Thermal measurements have been detailed in a series of useful standards. Some of these include ISO 8320, ASTM E 1530, ASTM D 1518, and ASTM C 518. All of these describe aspects of using guarded hot plates and other methods to measure thermal conduction in fabric samples. ASTM F 1154 provides standard methods for qualitatively evaluating comfort in chemical protective clothing (in humans). Standards for thermal comfort measured with manikins can be found in ASTM F 1291, ASTM F 1720, ISO 7920, and ASHRAE HI-02-17-4. ASTM D 5725-99 and 4772-07 give the procedures for measuring fabric absorbency of sheeted material and terry fabrics, respectively. ASTM D 737-96 gives techniques to evaluate air permeability through fabrics, and ASTM F 2298-03 gives techniques to evaluate water vapor diffusion and air flow resistance of fabrics. ASTM D 1388 and ASTM

D 4032 give techniques to measure fabric stiffness, and ASTM D 6571 measures compression resistance and recovery of high-loft non-woven materials. It is important to note that ASTM D 1776 covers the conditioning and testing of textiles, which is important in most fabric comfort tests.

8.2.2 Thermal and sensory rating scales

The human thermal comfort rating can be assessed by asking subjects to rate their perceptions of comfort on visual analog scales. In devising thermal and sensory rating scales, there are a number of considerations. One approach is the 'Likert' scale in which a single descriptor is given and respondents are asked to choose one of five options between 'strongly agree' and 'strongly disagree'. This is useful for characteristics without clear polar opposites. The major disadvantage of this type of rating is that the scores are ordinal data and technically should not be mathematically manipulated, but rather should be analyzed using appropriate statistics for ordinal numbers. For these reasons, we do not use Likert-type scales in our laboratory.

The Likert approach can be modified to allow the respondents to choose more than five options, which would provide greater precision; however, if discrete choices are utilized, the data are still ordinal. Winakor *et al.* (1980) have used a 99-point certainty scale. We have taken a similar approach in measuring thermal comfort in a locally developed visual scale based on a 100-mm line (see Fig. 8.1). This approach offers several advantages. First, it is easy to create and modify, it is easy to score, and it is very easy to explain to test participants. Second, it is a continuous measurement allowing test subjects to choose whatever degree of opinion suits them. Third, it is interval data, which can be correctly analyzed using higher-order statistics. Lastly, the increased precision of this scale reveals differences too small to be detected using a Likert approach. Whatever number of choices is provided to the respondents, having an equal number of 'favorable' and 'unfavorable' choices is less biased.

Figure 8.1 shows an example of a scale we have used in several clothing comfort studies. After explaining the process, we administer this scale to our research test panel. Each panel member marks the scale as desired. We then apply a ruler, measuring from left to right to obtain the score to the nearest millimeter. A clear ruler works well. We record the score and often administer the comfort scale several times under similar and variable conditions. In devising scales we recommend always making the more desirable characteristic on the right, so that a higher numerical score represents more of the positive quality. When we have mixed the directions, it hasn't been any harder for the study participants, though it is much harder for us as investigators, and it would be likely to generate more errors by respondents

Questionnaire for all work bouts

Time POINT: ____ initial ____ 25 min ____ 45 min (at end of work bout)

Please rate the work experience on the following characteristics:

Mark the line anywhere with the left end representing the least amount of that quality and the right end representing the most amount of that quality.

Overall comfort, stickiness, wetness, coolness, hotness

Overall comfort
Very uncomfortable ______________________________ Very comfortable
←——— 100 mm ———→

Sticking to skin
Not sticky ______________________________ Very sticky

Wetness
Not wet ______________________________ Very wet

Coolness
Not cool ______________________________ Very cool

Hotness
Not hot ______________________________ Very hot

8.1 Comfort scale utilizing a 100-mm line.

and by investigators. We have found it very confusing to use comfort measures with mixed directions. These scales can also be used for sensory comfort measurements, as will be discussed shortly.

8.2.3 Thermal comfort and performance

Much of the research in our laboratory has examined the thermal effects of clothing on performance, particularly in hot environments. In fact, most of our efforts have been devoted to reducing the thermal discomfort associated with protective clothing. As noted earlier, even in a thermally comfortable environment, performance can be affected by comfort. The study of Bell *et al.* (2005), cited earlier, illustrates this observation. In a very hot environment, comfort is compromised by clothing which reduces heat loss, and promotes sweat accumulation and body heat storage. Heat storage can precipitate heat stroke and death. Short of that, it has been demonstrated that heat storage can also reduce attention and concentration, and other cognitive performance variables (Ramsey and Kwon, 1992), as well as lead to early fatigue. This, in turn, likely reduces safety. For example, a police officer who is over-heated, dehydrated and uncomfortable may be less safe for himself and others. It has also been demonstrated that heat storage can substantially reduce fine motor performance (Robinson *et al.*, 1988, Ray and Bishop, 1991) and physical work capacity (Bishop *et al.*, 1991, 1993, 1995; Smith *et al.*, 1994; Solomon *et al.*, 1994).

Thermal homeostasis requires that the heat loss through the clothed and unclothed parts of the body (ΔH) equals the heat produced metabolically (MH). A person may also gain heat from an environment hotter than the body, requiring that heat losses be very high. Because the human in motion is typically less than 20% efficient, over 80% of the metabolic energy goes into heat production. The total heat loss or gain is the sum of the dry heat loss/gain (through conduction, convection and radiation) through fabric and clothing openings, plus the heat loss though evaporation from the skin and subsequent transmission of water vapor through fabric and out of openings. Therefore the heat loss or gain through clothing can be represented by the following equation:

$$\Delta H = MH + \text{dry heat gain} - (\text{dry heat loss} + \text{evaporative heat loss}) \qquad 8.1$$

Likewise in cold macro-environments, to maintain a comfortable micro-environment, the heat loss must be reduced to match the heat production. Barker (2002) has attempted to model the comfort limits by employing Woodcock's energy loss formulas (Woodcock, 1962a, 1962b). Although a generalized model would be very useful, it is important to bear in mind that exact values for metabolic rate, body surface area, sweat production, sweat distribution, and sweat evaporation can vary greatly among humans even for standardized conditions (Bishop *et al.*, 1991) and usually vary across time.

8.3 Moisture and comfort

Moisture has a big impact on thermal comfort, but also on sensory comfort. This sensory comfort may change with different activity rates and environmental conditions, along with different garment designs. Most obviously, moisture from sweat or from external sources (e.g. rain) will impact both the micro- and macro-environments, which in turn impacts the comfort perception of both hot and cold conditions. Less obviously, the permeability of the fabric to gas movement is impacted a great deal in some fabrics such as wool and cotton, but very little in polyester, and intermediately in rayon (Wehner *et al.*, 1987). This occurs in part because moisture causes individual fibers to swell. Also, as in the case of rain, liquids can actually fill the voids between fibers and thus impact permeability directly.

In many situations, the impact of liquids on the fabric, and therefore comfort, depends upon the volume of free liquid, absorbed liquid in the fibers, and water vapor. Some fabrics can handle small amounts of liquid or water vapor well, but above a certain level the fabric is overwhelmed. For example, it is a common observation that some multi-layer fabrics (e.g. Gore-Tex®) do well at transferring water vapor outwards under mild conditions, but become 'overwhelmed' under conditions with very high micro-environmental vapor pressures.

Liquid volume and liquid location both impact comfort. Liquid conducts heat much more readily than air, so if the volume of liquid is sufficient, and the fabric characteristics are such as to form a continuous medium of thermal conduction from the skin to a cooler substance (macro-air for example), then the liquid will facilitate heat loss. The volume of liquid required to saturate a fabric will depend upon fabric moisture characteristics, fabric thickness, and rate of loss due to evaporation. This is true even for 'wicking' fabrics such as polyester. Liquids may also reduce insulation if material loft is reduced due to wetting (e.g. wet goose-down insulation is greatly reduced if it becomes wet). The impact of the fabric on comfort can be different when the volume of liquid is less. For example, wicking fabrics such as polypropylene are able to move moisture off the skin and towards the micro-environment. Moisture wicking away from the skin is most useful in cold environments where sweat evaporating from the skin can cause high rates of undesirable heat loss. If reducing the loss of body heat is important to comfort, as it is in cold macro-environments, then evaporating sweat some distance from the skin aids thermal and sensory comfort. If the fabric becomes totally wet, however, conduction occurs and the advantage may be lost.

The moisture transmission capabilities of fabrics can be different from that of clothing systems. A semi-permeable multi-membrane fabric might have a low vapor transmission rate, but if the garment is a poncho, or other design which ventilates well due to clothing pumping, the comfort and protection afforded by the garment may be quite acceptable (Barker, 2002). Although articulated moving manikins may serve as good means to characterize garments, the ultimate test of comfort is to obtain measures of comfort from human subjects performing realistic activities in realistic environments including wet and dry conditions, as appropriate. Barker (2002) gives an example of a practical test of surgical gowns that used alternating rest and varying physical activities. We have done the same in our tests of protective clothing (Bishop *et al.*, 1991, 1993, 1995, 2003b; Smith *et al.*, 1994; Solomon *et al.*, 1994).

In very warm environments, when sweat rates are much higher than evaporation rates, the fabric may become saturated, negating the value of the wicking but facilitating conductive heat loss. In this case, fabric wetting occurs to an extent that varies from body region to body region. At any rate, fabrics which are effective in wicking moisture away from the skin are generally perceived as more comfortable (Wickwire *et al.*, 2007). However, these fabrics have not been found to improve heat loss (Ha *et al.*, 1995; Gavin *et al.*, 2001; Wickwire *et al.*, 2007), though others have shown some fabrics to have potential heat transfer advantages (Yasuda *et al.*, 1994; Kwon *et al.*, 1998). Even though a wicking fabric may not offer any advantage regarding heat transfer, the comfort may nonetheless be enhanced under certain circumstances.

Thoroughly wetting fabrics may also change their mechanical characteristics and generally reduce sensory comfort. For example, as moisture content increases, the friction with the skin increases and reduces comfort (Li and Wong, 2006, p. 131). As water vapor moves though fabrics, fabric fibers absorb and desorb moisture, which may impact the fiber characteristics. The degree of impact depends on several factors, the most important of which is the physical properties of the fiber composition (Li and Wong, 2006, pp. 78–79).

Given the issues that arise when fabric absorbs liquid, several studies have evaluated the effect of clothing made with hydrophobic fabrics. Kwon *et al.* (1998) found no difference between three different clothing ensembles for rectal, skin, or mean body temperature in warm environments (30°C at 50% relative humidity), while there was no air motion. However, with air motion (1.5 m/s), rectal temperature was significantly lower while wearing a high moisture-regain fabric (wool–cotton blend) than for polyester. In that study, fabrics with high moisture regain could reduce heat stress relative to the low moisture-regain material but only when air motion impacted the micro- and macro-environments. This underscores the importance of the micro- and macro-environmental conditions on fabric testing.

However, Yasuda *et al.* (1994) found that the surface temperature of the fabric rose more quickly with wool than with polyester, perhaps due to better sweat evaporation from the surface of the polyester. Similarly, Ha *et al.* (1995) showed that clothing surface temperatures were higher in cotton than in polyester. But, four out of five subjects felt wetter in polyester during the latter half of the experiment. The authors speculated that the fabric wetness insulation due to the absorption of moisture in cotton fabrics reduced the thermal insulation and accelerated the dry heat loss. This slowed the rate of increases in both core temperature and pulse rate. Gavin *et al.* (2001) found no advantages for rectal, skin, or mean body temperature while wearing synthetic clothing purported to enhance sweat evaporation. However, in this study only three out of eight skin temperature measurements were made under the clothing.

Hu *et al.* (2006) report some comparative data on moisture handling among eight different knitted fabrics. A plain knitted fabric of 92% nylon and 8% Spandex had the highest liquid moisture-management capacity, one-way transfer capacity, a large spreading rate, and a medium wetted radius. This suggests that this fabric can readily transfer sweat from the skin to the surface and will also dry relatively quickly. In contrast, two knitted fabrics of 92% cotton and 5% Spandex had the worst moisture handling ability, low wetted radii and spread rates coupled with negative one-way transport capacities, suggesting that these fabrics would likely be uncomfortable in high-sweat conditions. Another rib-knitted fabric of 94% cotton and 6% Spandex had limited ability to move sweat or other liquids away from the skin and to the surface for evaporation and were slow in drying. This same study demonstrated that a plain-knitted fabric of 88% polyester and 12% Spandex had intermediate ability to transfer liquid away from the skin and good drying capacity. Another polyester fabric (88% polyester and 2% Spandex) could move liquid away from the skin well, but was not as quick to dry.

The drying of wet fabrics during wear also plays a role in comfort. Fabric wicking impacts the rate of drying and the comfort during drying. As water evaporates, it impacts the relative immediate macro-humidity. Likewise, the water absorbed by the fabric is evaporated last (Li and Wong, 2006, p. 79), so the moisture continues to impact comfort until the fabric is totally dry. For all comfort characteristics, including moisture, the degree of fabric–skin contact plays a major role. Fabric that does not contact the skin will have only an indirect impact on comfort through its influence on the micro-environment.

One other issue with moisture is condensation in the clothing. When a temperature gradient exists in single or multiple layers of clothing, it is possible for moisture to evaporate from the skin or an inner layer due to the temperature of the micro-environment. The moisture will then condense in a cooler outer layer once the dew point temperature is reached. This condensed moisture will act in accordance with the principles outlined earlier.

Using double jersey fabrics of similar yarn count and weight and somewhat similar thickness, Li and Luo (2000) reported that wool had greater water vapor sorption and led in initial rate of sorption, followed by cotton, porous acrylic, and polypropylene. Wool also showed the highest initial temperature increase due to the sorption of water vapor, followed by cotton and porous acrylic. Polypropylene again had the lowest temperature increase. Wool and cotton are considered to be highly hygroscopic and the artificial fibers are classed as weakly hygroscopic.

Our laboratory has considerable experience in measuring the thermal comfort conditions of humidity and temperature of the micro-environment. Formerly, we used a small capacitive humidity meter and thermocouple attached underneath the clothing for the duration of the observation to measure the micro-environment with the output shown on a remote monitor connected by a small cable. That system is no longer available, so we have switched to a portable humidity device so that we can temporarily locate the pickup for the meter under the clothing, and then take a humidity reading. We now use a thermocouple placed under the clothing for the duration of the observation to assess micro-temperature.

Skin temperature is readily measured through the use of thermocouples (bimetallic devices which develop an electrical voltage in relation to temperature) or thermistors (devices whose electrical resistance responds to temperature) applied to the skin under the clothing. The thermometers must be attached in a manner that does not impact the thermal characteristics of the clothing or skin. This is best done by fabricating small elastic holders that cover minimal skin and minimally overlay the actual measurement sensor, with a light large mesh or other material that does not insulate. For areas of skin where this is difficult (e.g. the chest or back) we recommend a single layer of sticky heat-conductive tape. We typically use a piece of surgical dressing obtained from medical supply stores.

To conclude, the influence of moisture on comfort is complex. Liquids and vapors can influence both fabric characteristics and comfort. The volume of liquids and vapors, locations, distributions, fabric composition and construction, along with the macro-environment and physical activity, all determine the impact of moisture on comfort of clothing and fabrics. There remains much work for investigators in this area.

8.4 Ease of movement

The ease of movement of the clothed human is not always considered a major factor in clothing comfort. Certainly, when clothing binds or constricts the user, discomfort is perceived. This is why most users find loose clothing to be more comfortable than tight clothing. However, the psychological discomfort arising from style/fashion requirements can override the desire for comfort. It is often overlooked that clothing also contributes to total energy costs for activity. This indirectly influences comfort because it adds to metabolic rate and increases heat storage under some clothing and environmental conditions (Bishop and Krock, 1991). The manufacturers of firefighter protective garments understand this and work to develop styles which require less energy for normal firefighter movements.

8.5 Evaluating sensory comfort

Simply put, the feel of fabric is usually described as 'handle' or 'hand' and can be evaluated in several ways. The most commonly used objective evaluation is by the Kawabata Evaluation System (KES) (Kawabata, 1980; Barker, 2002). The intention of evaluating hand is to predict the mean human sensory comfort perception. The Kawabata Evaluation System attempts to measure a combination of softness, stiffness, and smoothness. The KES is also specific to the end-use of the clothing (Barker, 2002). This means that the KES rating applies to the clothing system and not to the fabric particularly. Barker (2002) illustrates that the KES changes for woven versus knit fabric and provides equations for calculating the hand for men's suits, single and double knit fabrics, and sheeting.

This latter observation raises the earlier issue regarding thermal comfort. The comfort of a fabric may be quite different from the comfort of a garment made from that fabric. A fabric's hand would be a major variable in clothing comfort, but fabric hand can never fully predict the comfort of a clothing system with multiple pieces, differences in fit, differences in type and location of seams, total weight of the clothing, movement in the clothing and aesthetic comfort. For example, Schutz *et al.* (2005) found fit to be the most important 'customer satisfaction' factor in military daily-wear uniforms. They also found that tactile rating and appearance were as important as functional factors (e.g. 'protection') (Schutz *et al.*, 2005).

Fabric weight is a common sensory characteristic of interest. The actual physical weight of the garment also has a major impact on comfort, particularly for prolonged wear. Firefighters are conscious of the overall garment weight and prefer lighter garments for ease of movement and because they must carry the weight of the garments in addition to the other equipment they carry. The total weight of the worn garment can also affect pressure comfort.

Measuring sensory comfort is even more difficult than measuring thermal comfort. Whereas thermal comfort has a fairly narrow set of concrete conditions that are comfortable, sensory comfort depends on the interactions of numerous abstract characteristics. The same hierarchy of comfort testing mentioned for thermal comfort measurement also applies to sensory comfort. Bench tests of fabric characteristics including hand, stickiness, and other qualities shown in Table 8.2, are the most basic sensory comfort measurement techniques. Barker (2002) supports the notion that subjective evaluation by human wearers represents the only way to accurately measure the combined effects of all relevant variables of clothing systems on comfort.

One dimension of sensory comfort that is overlooked on occasion is psychological or aesthetic comfort. Though subject to both cultural and time-period influences, some people find some clothing to 'feel comfortable', not from a tactile or physical pressure sense but from a societal pressure sense. For example, baggy short trousers worn very low on the hips

Table 8.2 Sensory attributes identified by numerous authors and approximately grouped by type

Stiffness/crispness/pliability/flexibility/limpness
Softness/harshness/hardness
Thickness/bulkiness/sheerness/thinness
Weight/heaviness/lightness
Warmth/coolness/coldness (thermal characteristics)
Anti-drape/spread/fullness
Tensile deformation/bending/surface friction/sheer
Compressibility
Snugness/looseness
Clinginess/flowing
Dampness/dryness/wetness/clamminess
Quietness/noisiness
Prickliness/scratchiness/roughness/coarseness/itchiness/tickliness/stickiness/smoothness/fineness/silkiness
Looseness/tightness

would be extremely uncomfortable for me and for many people around the world; however, young men in the USA seem very comfortable in such attire.

Our understanding of sensory comfort has evolved over time. Sensory data can be described in several ways, starting most basically with Weber's Law. More recently investigators have found that Stevens' Power Law (Stevens, 1946) better describes some sensory comfort variables. Weber's Law states:

$$\Delta \mathrm{Sp}/\mathrm{Sp} = K \tag{8.2}$$

where K is a constant describing the ability of a human to detect a sensation, and Sp is the magnitude of the sensation. ΔSp is the smallest detectable difference. Thus, we see that the precision of human detection of a given sensation is highly dependent upon the magnitude of the sensation. For example, the magnitude of thermal sensations is relatively large, since humans can detect a range of temperatures from very cold to very hot. In contrast, in rating clothing such as how clingy or how flowing, the ability to differentiate these is limited.

This relationship between precision of detection and magnitude is expressed in more stark terms in Fechner's Law, which is:

$$\mathrm{Rs} = k \log \mathrm{Sp} \tag{8.3}$$

where Rs represents the perceived sensation, k is the lowest detectable stimulus (stimulus threshold), and Sp is magnitude of the sensation. Therefore, the sensation must increase logarithmically for the perception to increase arithmetically.

Finally, Stevens proposed that the relationship between stimulus sensation and human detection is not always logarithmic but may be a power function. Thus the 'Stevens' Power Law' is expressed as:

$$\mathrm{Rs} = c\,\mathrm{Sp}^{x} \qquad 8.4$$

where Rs represents the perceived sensation, c is a constant scaling factor, and Sp is the magnitude of the sensation which is raised to some power x, which is dependent on the nature of the sensation being measured.

These laws are shown here in the order in which they were developed. As experience with comfort measurement has grown, the relationship has been found to be more complex and has been described accordingly by the various researchers. For example, Li (2005) conducted a series of trials with a test panel comparing objective measurements with subjective ratings to elucidate the mechanisms involved in temperature and moisture sensations in clothing systems during environmental changes. The mean subjective perceptions of warmth seemed to follow Fechner's law and Stevens' power law, whereas dampness seemed to follow Fechner's law most closely. Comfort was positively related to the skin temperature and negatively related to the relative humidity of the microclimate.

8.5.1 Objective tests of sensory comfort

Just as there have been objective laboratory tests developed to establish the thermal characteristics of fabrics, there have also been objective bench tests developed to describe the sensory characteristics of clothing. Barker (2002) summarizes concisely the objective measurement of fabrics. Barker notes that Kawabata's system (Kawabata, 1980) is the most detailed. Kawabata (1980) reports that The Hand Evaluation and Standardization (HES) Committee determined seven characterizations of fabric for men's suits. These were smoothness, crispness, stiffness, anti-drape (spread), fullness and softness, appearance of the surface, and 'others'. The HES Committee determined that different fabric applications required different descriptors, which complicates sensory measurement. For example, for men's summer and winter suits these descriptors were given different percentage weightings which summed to 100%. For detail and descriptions see Kawabata (1980). Likewise in the same publication, the key mechanical properties are delineated and described including measurement methods. The HES Committee identified six mechanical-property groups: tensile deformation, bending, surface friction and roughness, shear, compressibility, and weight/thickness. Kawabata describes his own development of objective test equipment for measuring fabric characteristics (Kawabata, 1980). For example, the Kawabata Thermolab measurement of warm/cool feeling of fabrics is well known.

Methods of objectively assessing specific sensory comfort fiber characteristics are as follows.

- *Prickliness* can be measured with a KES-FB compression tester modified to measure initial bend in protruding fibers, plus some method to quantify the number of protruding fibers per area of fabric, plus quantification of skin–fabric contact. Obviously many factors impact the fabric prickliness.
- *Stiffness* can be measured with a Shirley cantilever, a Shirley cyclic bending tester, or a Cusick Drapemeter. For details see Kenkare and May-Plumlee (2005).
- *Softness* has been measured with a compression load cell in an Instron tensile tester. Softness has also been measured as friction on an Instron load cell (Li and Wong, 2006, p. 134). One of the more innovative approaches to measuring softness was performed by taking stereo photographs and using computer software to generate topographical maps of the fabric samples (Li and Wong, 2006, p. 134). Friction, as a key characteristic of softness, can be measured with a Kawabata surface tester. Softness is associated with objective physical properties such as roughness, friction, prickle, shear and bending stiffness, thickness and areal density.
- *Garment pressure* can be most readily assessed in clothing by direct measurement of pressure by way of pressure transducers of various types. For example, Chan and Fan (2002) reported the use of a digital pressure meter to objectively assess clothing pressure. One crucial issue that must be taken into account is that the thickness of the device can contribute to the pressure measured. Small fiber optic pressure measurement devices offer an option for clothing pressure measurements. Key areas seem to be the knees, elbows, seat, and back. One way to measure garment pressure is to draw a series of spaced perpendicular lines on the skin. The percentage of displacement of the line associated with various movements (e.g. standing to sitting) can be recorded as a measure of skin strain as reflective of garment pressure on the skin. Additionally, clothing fit would impact pressure sensory measurement.

Just as there have been attempts to model thermal comfort, there have been numerous attempts to model sensory comfort often using the above fabric characteristics. Wong *et al.* (2004) used different combinations of inferential statistics, fuzzy logic, and neural networks to predict the sensory responses derived from data from 28 young females on a test panel. Using a relatively small test panel ($n = 10$), the derived models yielded correlations of $r = 0.61$ to 0.82.

8.5.2 Subjective measures of sensory comfort

Hollies (1997) gives a general outline for developing subjective sensory comfort measurements of clothing by means of the following steps.

1. Delineation of clothing attributes
2. Descriptors of these attributes
3. Development of a sufficiently precise scale to assess perceptions of key attributes
4. An appropriate human sample to assess the clothing
5. Accurate data analysis techniques.

An alternative procedure is to allow a test panel to develop a list of descriptors in their own terms. Then these descriptors can either be qualitatively grouped, or alternatively the panelists can come together as a group and provide their own consensus as to the best descriptors, and these descriptors for a given fabric can be arranged as polar-pairs and scored using a scale chosen by the investigator. Alternatively, as shown in Fig. 8.1, research subjects can rate a given clothing system individually using sensory polar-pairs and a 100-mm line. Each subject rates a clothing system under a given set of environmental conditions and work rate, and these scores are treated as interval data.

These descriptor approaches are most useful when a few fabrics are being considered for a particular application. For example, if several different fabrics are being considered to comprise the inner liner of a jacket, the test panel would use the candidate fabrics in the situations and with the movements in which it would be employed. They would then rank the fabrics on criteria such as hotness/coolness, or abrasiveness/smoothness, etc. The same scale would be used for each rating, with the highest summed rating being the most favorable. If differing scales are used, then the data would have to be normalized before being combined for comparative purposes.

For both thermal and sensory measurements, there are numerous subjective comfort rating scales. Winakor *et al*. (1980) gave a classic example of subjective assessment of fabrics. They used a 99-point certainty scale with a large panel of 59 judges. Large F values were found for discrimination between fabrics evidencing different levels of stiffness, roughness, and thickness, suggesting good sensitivity in the rating scale.

It is important to recognize and examine the wide range of applications for a given fabric. The environmental interaction may be substantial. The duration of the trial is also important, in that a fabric that is initially comfortable may become increasingly uncomfortable over a few hours. Likewise, a clothing system may have initial pressure discomfort that decreases to acceptable pressure over time. Laundering also impacts comfort. For example, it is well known that some cotton denims change their characteristics after repeated launderings.

So, practically speaking, comfort measurements only apply to a set of conditions which should always be clearly and completely specified. Issues such as test duration, pre-laundering, and panelists' experience are among the many issues which must be specified.

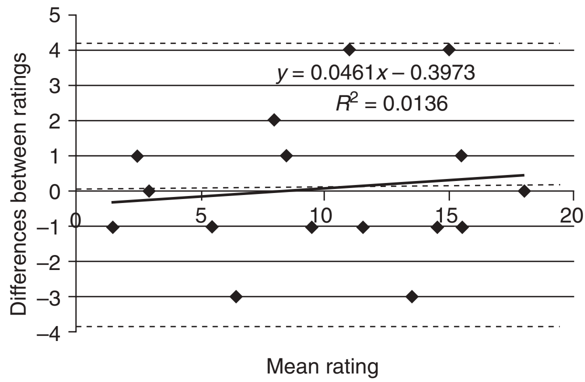
8.6 Statistical considerations in comfort measurement

The ultimate goal of textile comfort research would be to fully account for the many variables along with their interactions which describe clothing comfort across all reasonable activity levels and environments. Much of the prior modeling has advanced us towards this goal. However, as befits good science, we must continue to be appropriately critical of modeling.

Establishing the relationship between fabric characteristics and human reports of comfort seems a logical approach to modeling. Our recent experience is that error analysis would sometimes be more useful than correlation analyses in evaluating objective surrogates for human comfort factors (Wickwire *et al.*, 2007). However, it is common in human modeling to see a good R-square for the derivation model, only to see that explained variation to decline precipitously in the calibration model. In addition, we typically derive our initial model on a very diverse sample of fabrics and conditions, which are not normally distributed. As pointed out by Altman and Bland (1983), such a situation leads us to overestimate the true relationship. For example, Figure 5 in Barker (2002) compares the ranking data for the Kawabata Thermolab measurement of warm/cool feeling of fabrics with human subjective assessment of the same quality.

We reanalyzed the Kawabata Thermolab data in terms of error (see Fig. 8.2). The Pearson correlation coefficient ($r = 0.93$, $R^2 = 0.85$) is very similar to the Spearman correlation coefficient for ranked data ($r = 0.92$). This correlation looks very good and there is little bias in the Thermolab data, but the error is pretty large. If you look at the 95% boundaries of agreement, you can see that the confidence interval is about 8 units out of a total ranking of 16 (all scores are between 2 and 18) units or about 50% of the usable scale. This is to say, a Thermolab ranking of 10 would yield a human ranking between 6 and 14 about 95% of the time. There are some contexts where such a large variation would be acceptable and some where it would not be.

Wolins and Dickinson (1973) suggest that weighting sensory scores based on deviations from the mean improves the validity of the scores. Extreme scores get higher weights because those raters appeared more certain about



8.2 Errors between cool touch and subjective ratings (adapted from Barker, 2002).

their choices (Wolins and Dickinson, 1973). This approach seems a matter of opinion. It could be argued that this procedure merely gives more weight to more expressive or passionate panel members rather than to the actual perception. We would argue that all scores be rated equally, because an appropriately drawn sample should be representative of the actual user population.

In their well-designed study, Frank *et al.* (1999) made a statistical error that all of us should consider. Considering Fig. 2 of that paper, we see two temperature measures, tympanic temperature and mean skin temperature. The problem is that these two data sets have very different distributions. That is, rectal temperature is constrained between about 35 and 37.5°C, whereas mean skin temperature varies between 28 and 37°C, as is apparent in their figure. When data from two different distributions are used in a multiple regression, the beta weights are not comparable. If beta weights are to be compared among variables with different distributions, all the data must first be normalized.

Although it is not possible to do this accurately without the raw data from that study, if we approximate the distribution, we would expect that each 3°C of mean skin temperature corresponds to approximately 1°C of tympanic temperature. Therefore, when the ratios appear to be 1:1, as reported, a better estimate would be about 3:1, with tympanic temperature making three times the contribution that mean skin temperature makes. When computing derivations such as total heat storage and others, it is important to consider the distributions of the data and use appropriate transformations when necessary. Likewise, when we choose to mathematically manipulate different sensory or thermal comfort variables, we must consider the data distributions.

8.7 Comfort measurement summary

In this review we have sought to address 'objective' measures of comfort. Whereas we always seek that all of our measurements be as objective as possible, it may be mis-communication to speak of objective measures of comfort and more correct to say that we are objectively measuring fabric or clothing characteristics, rather than comfort. That is, we are quite capable of objectively characterizing important comfort factors of fabrics, but a bit less capable of objectively characterizing comfort factors for clothing systems. Subjective mean comfort ratings can sometimes be predicted with acceptable accuracy using these objective fabric characteristics. Assuming that we can often accurately and objectively characterize or predict human responses to clothing systems seems ill advised in view of the observed variable nature of humans with respect to comfort (Bishop *et al.*, 1991).

Objective measurement of fabric/clothing characteristics forms a necessary but insufficient foundation for measuring human comfort. As has been pointed out, humans are the ultimate determination of comfort and human variability is large. As we have also discussed, it is important to describe comfort in terms of all relevant factors including varying fits, activities, environments, durations, and aesthetic comfort, among others.

Reaching some consensus on comfort scales would be beneficial to all investigators because it would allow us to more readily compare findings among studies. Scientific history suggests that this is unlikely, at least in the near future. Fortunately, there is a wealth of published research that has done much to advance our knowledge of clothing comfort. Also fortunately for those of us employed in this field, there is still much work to be done.

8.8 Applications of comfort assessments

Most practical applications of comfort measurement involve intact clothing systems. Our laboratory has collected comfort data on non-woven encapsulating coveralls, military chemical protective clothing, and fire protective clothing. Obviously, comfort data can be gathered for both clothing and non-clothing situations. When clothing is used, it is important to evaluate the entire ensemble because there will be interactions among clothing parts. In each comfort assessment, it is important to include all clothing parts that are likely to be used together, using activities that are likely to be performed, for durations long enough to allow for some plateau in comfort, and in environments users are likely to encounter. For example, we are about to begin an evaluation of firefighter protective clothing. In this particular study, we are trying to assess the role of each component in the overall thermal comfort, energy costs, and heat storage.

8.9 Future trends

The future of comfort measurement is exciting. The move towards active fabrics that respond to activity and environment will have a great impact on comfort. Perhaps one day we will see fabrics and clothing systems that sense the environment and respond appropriately to maximize comfort. Clothing systems will automatically adjust gas transmission capacity both through the fabric and at openings. Clothing systems will also actively supply and remove heat as the activity and environments demand. As these clothing systems progress, a range of adjustments will be possible to allow each user to individualize their preferences to personalize their clothing comfort. Fashion and style, although less technical in nature, will also change periodically.

To facilitate these advancements in clothing, textile scientists must continue to explore the art and science of clothing comfort. As I have tried to portray in this chapter, this is a great challenge. To progress in clothing comfort, continued efforts must be made to quantify and qualify human comfort. Because of the complexity of both clothing systems and humans, I strongly doubt that comfort will ever be fully predictable from purely objective characteristics of fabric or clothing. Perhaps the development of rather sophisticated models will permit specification of some parameters and identification of the range of adjustment needed to accommodate 95% of the user population. The attempt by Wong *et al.* (2004) to use a combination of approaches to modeling comfort probably offers the best hope. Fashion and style may never be predictable.

Clearly those scientists who work in textiles and clothing systems will have to constantly reassess their approaches and adapt to advancing knowledge. It is a great challenge, but that is one of the things that keeps textile research appealing.

8.10 Sources of further information and advice

For further information and advice on comfort, I recommend foremost the text, *Clothing Biosensory Engineering*, edited by Y. Li and A.S.W. Wong, Woodhead Publishing, Cambridge, 2006. For further information on thermal comfort, the foundation work would be Fanger (1970), *Thermal Comfort*, Danish Technical Press, Copenhagen. For a summary that would be easy to obtain, see Charles (2003), Fanger's Thermal Comfort and Draught Models, *IRC Research Report RR-162*, Institute for Research in Construction, NRC Canada (available at http://www.nascoinc.com/standards/breathable/PO%20Fanger%20Thermal%20Comfort.pdf).

Havenith, Holmer and Parsons (2002) give good insight into the roles of body and air motions on micro-environmental humidity and thermal comfort. For those unfamiliar with characterizing the thermodynamics of humans in clothing, they give some of the key equations.

If you are interested in Kawabata's objective hand evaluation, the obvious source is *The Standardization and Analysis of Hand Evaluation*, 2nd edition, The Textile Machinery Society of Japan, Osaka, 1980. A concise summary of comfort is available in Roger Barker's (2002) 'From fabric hand to thermal comfort: the evolving role of objective measurements in explaining human comfort response to textiles', *International Journal of Clothing Science and Technology*, 14: 181–200.

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