Performance evaluation of thermal protective clothing

5

Fire-resistant/retardant fibers are processed through various steps (eg, yarn processing, fabric and garment engineering) to manufacture thermal protective cloth- ing for firefighters. The main function of this clothing is to resist heat transfer from firefighters’ ambient environment towards their bodies to protect them from burn inju- ries. To accomplish this function, the clothing must have thermal stability and insulative characteristics when exposed to thermal environments (eg, radiant heat, flame, hot surfaces) for determined durations [37,38,304,305]. On the other hand, the clothing should properly transmit and evaporate the metabolic heat and sweat- vapor from firefighters’ bodies towards their ambient environment. This function of the clothing helps to maintain a constant core temperature of firefighters’ bodies at 37°C in a range of thermal environments and levels of activity, which can provide physiological comfort to firefighters by reducing their heat stress [306–310].

One of the main requirements to confirm the thermal stability of the clothing is determination of softening and melting temperatures of the fire-resistant/retardant fibers. This further requires the determination of combustibility or flammability of these fibers or fabrics. The determination of softening and melting temperatures, along with the flammability, helps to verify how well the integrity of the clothing can be maintained during exposure to thermal environments and, therefore, prevent fire- fighters from burn injuries [220,245]. The next critical feature for protective clothing is its thermal insulation characteristics. By testing its thermal protective performance , researchers can establish if it provides effective protection for firefighters from burn injuries [75,76]. Finally, the physiological comfort provided by thermal protective clothing should be tested by evaluating its thermal and evaporative resistance along with total heat loss (THL) through the clothing; the results of these tests will help in understanding the metabolic heat and sweat-vapor transfer characteristics of thermal protective clothing to prevent/reduce the heat stress of firefighters [306,307,311]. In this context, it is necessary to mention that THL is commonly evaluated in North America using the ASTM F 1868 standard. Contextually, it is necessary to mention that ISO is currently working on a standard (ISO CD 18640) using sweating torso developed by Psikuta, Wang, and Rossi [30]. This standard can more realistically evaluate the physiological comfort properties of protective clothing.

# Softening/melting temperature and flammability evaluation

Fiber-softening temperatures can be evaluated using the ASTM E 2347 standard. In this standard, a fiber specimen is heated in a thermo-mechanical analyzer until the specific modulus of the fiber specimen reaches 6.65 MPa. The temperature at which

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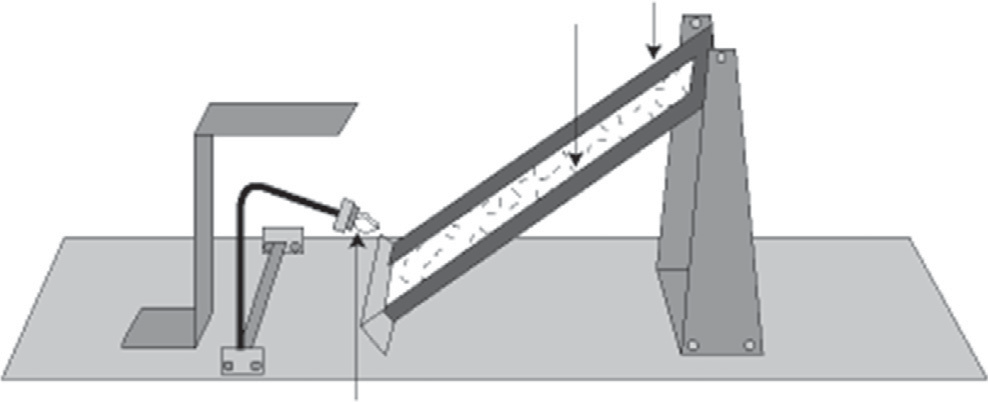
the specific modulus becomes 6.65 MPa is identified as an indentation-softening tem- perature. For some fibers, it may show their softening temperatures in a range; how- ever, this test standard (ASTM E 2347) does not consider the range aspect while calculating the softening temperature. Additionally, this standard is applicable only when the conditions of time, temperature, and method of loading are similar to those specified in the test. This indicates that the data obtained from this test standard cannot predict the behavior of fibers at a higher temperature than the actual test temperature. The ASTM D 7138 standard is also available to determine the melting temperatures of fibers. Using this standard, a fiber specimen is positioned in a melting temperature evaluating device. The temperature of the device is raised until the fiber specimen melts as determined by visual observation. The minimum temperature at which the fiber specimen starts melting is inferred as the melting temperature. The limitation of the ASTM D 7138 is quite similar to the ASTM E 2347, because this standard also does not highlight the range of melting temperatures that might be applicable for some fibers. Also, this standard depends upon the visual observation of an experimenter. Hence, the ASTM D 7138 standard is limited to quality control and research purposes only [312,313].

For flammability evaluation, various standardized test methods have been devel- oped [314,315]. Flammability is defined as how easily a fiber or fabric will burn or ignite, resulting in fire or combustion. It has been identified that various parameters need to be considered for the determination of flammability; these parameters include flame duration, the rate and extent of flame spread, ease of flame extinction, the tem- perature of burning fibers or fabrics, and the amount of heat during burning [316–321]. The selection of a particular parameter to evaluate flammability depends on the nature of the ignition source, orientation of the tested fibers or fabrics (top, bottom, edge, or face), location of the ignition source, and environmental conditions [35]. As a conse- quence, various standardize test methods are available to evaluate the flammability of fibers or fabrics [322].

The flammability of apparel textiles can be measured according to the ASTM D 1230 (as well as ISO 15025) standard method; this test was developed to evaluate the flammability of fabrics made of natural or synthetic fibers. The key with this stan- dard is that it can measure two aspects of fabric flammability: ease of ignition (how fast a fabric catches fire), and flame spread time (the time it takes for the flame to spread a certain distance). In this test, a fabric specimen (50 mm× 165 mm) is cut and brushed (if there is any raised fiber surface on the specimen). Then, this specimen is placed on a flammability tester at a 45 degree angle, and a flame is applied to the lower end of the fabric specimen for 1 s ([Fig. 5.1](#_bookmark0)). Then, the time required for the flame to proceed up to the specimen’s other end (a distance of 127 mm) is recorded. This standard applies only to flammable fabrics; thus, this standard may not be suit- able for fire-retardant/resistant fabrics. However, this standard can easily, accurately, and reliably identify/distinguish between flammable fabrics.

The flammability of apparel textiles can also be evaluated by the ASTM D 3659

standard, which is also called the semirestraint method. This method was developed to evaluate the flammability of fabrics in a vertical configuration, in which the fabrics have a limited mobility from the vertical plane of suspension. The nature of this test

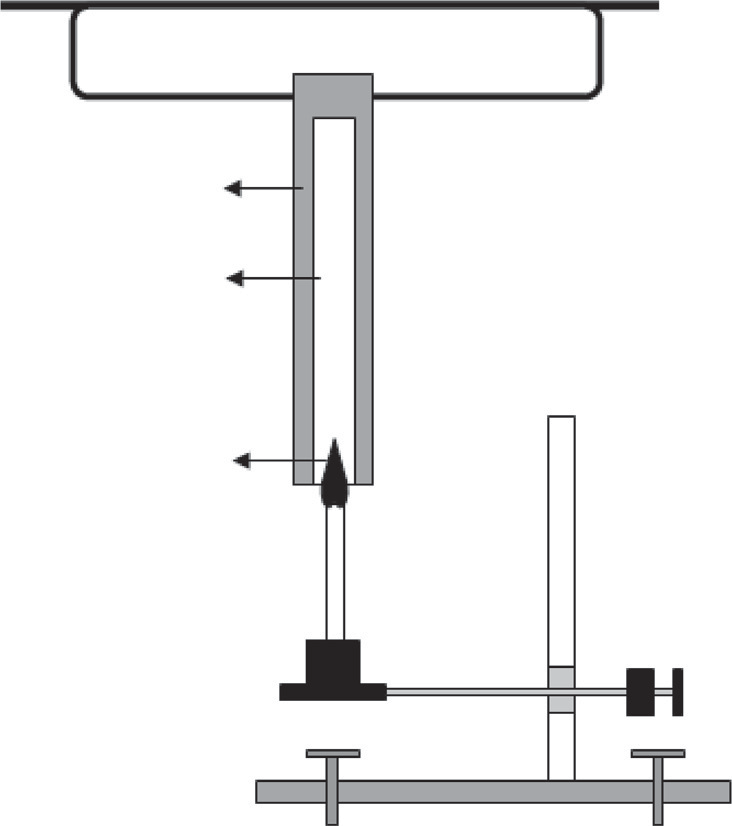
Exposed sample

Specimen holder

Test flame

Fig. 5.1 Forty-five degree flammability tester described in ASTM D 1230.

standard is to simulate the flammability performance of an A-line type garment on a manikin. During the test, a fabric specimen is exposed to a vertical flame, and after exposure, the char-length, after-flame, and after-glow times are measured [323–326] ([Fig. 5.2](#_bookmark1)). The reliability of the individual test may vary significantly. Due to this lim- itation, this test standard has been temporarily withdrawn from the ASTM standard manual.



Specimen holder

Exposed sample

Test flame

Fig. 5.2 Vertical flammability tester described in ASTM D 3659.

The fire-retardant/resistant property of a fiber or fabric can be expressed in terms of amount of oxygen required for its combustion, referred to as limiting oxygen index (LOI) as described in ASTM D 2863 [173,327–330]. This standard describes a pro- cedure for measuring the minimum concentration of oxygen (expressed as a volume percentage) that will support the flaming/combustion of a fiber or fabric in a flowing mixture of oxygen and nitrogen. In this test, a small fiber or fabric specimen is

supported vertically in a mixture of oxygen and nitrogen, which flow upward through a transparent chimney ([Fig. 5.3](#_bookmark2)). The upper end of the specimen is then ignited. The subsequent burning behavior of the specimen is observed in order to measure the time period for which burning continues, and/or the length of the specimen burnt. By test- ing a series of specimens in different oxygen concentrations, the minimum oxygen concentration is determined.

Mixture of N2/O2



Ignited upper end Exposed sample

Fig. 5.3 Limiting oxygen index (LOI) tester by ASTM D 2863.

# Thermal protective performance evaluation

Many researchers took the initiative to evaluate the thermal protective performance of fabrics and clothing in a laboratory setting [75,76]. For thermal protective perfor- mance evaluation, development of a proper type of sensor was critical to estimate heat flux flow through clothed firefighters’ bodies under a particular thermal exposure. Currently, several types of sensor are used within the scientific community for the evaluation of thermal protective performance using bench-scale tests, full-scale sta- tionary, and dynamic manikin tests [331,332].

### Development and application of different sensor types

In order to develop a sensor that can measure heat flux flow through human (firefighters’) bodies, numerous specific features need to be considered [333]. The developed sensor must be (1) a close representation of human skin, (2) small and light-weight, (3) inexpensive, (4) accurate (within 10%) and reliable to measure con- vective and radiative heat flux in an operating range of 0–105 kW/m2, (5) rapid for proper data acquisition, (6) immune from noise produced under the convective and

radiative heat exposures, (7) highly sensitive to detect heat flux in the lowest operating range, with only slight variation due to heat leakage/loss or thermal storage within the sensor, (8) designed to minimize the storage of thermal energy within the sensor under repetitive and highly intensive thermal exposures, (9) rugged/durable enough to with- stand repeated thermal exposures and cleaning, (10) minimally impacted by the thermal history (heat sink, temperature gradient) of any overlaying materials used in the sensor, and finally (11) easy and economical to fabricate and/or easily available in the market [331,333–336]. Keeping these features in mind, several sensors have been developed: the thermal protective performance (TPP) sensor (copper slug sensor), the embedded sensor (thin-skin sensor), the skin simulant sensor, the NCSU PyroCal sensor (new cop- per slug sensor), and the water-cooled sensor [333,337]. In the following section, each of these sensors is thoroughly discussed and they are compared to identify the most suitable sensors for close study of thermal protective clothing. Furthermore, application procedures of these identified sensors in the context of thermal protective clothing are discussed below and a few case studies of their application are also highlighted.

*TPP sensor (copper slug sensor)*: In this sensor, a copper disk of 1.6 mm in thick- ness and 40 mm in diameter is used ([Fig. 5.4](#_bookmark6)). The thickness is determined so that the temperature increase of the disk approximates the temperature increase of human tis- sue under a particular thermal exposure; and the large diameter of the disk is preferred to conveniently monitor its surface temperature in a wide range [331,332]. On the back surface of the disk, four 30-gauge type-J (iron-constantan) thermocouples are uni- formly secured in a parallel manner at 120 degree intervals and at the center to measure the average front surface temperature of the disk. This average temperature is further used to determine the heat flux through the sensor. The four thermocouples are used to average out any variation of the front surface temperature of the disk; the 30-gauge thermocouples are employed because they are large enough to work with, and small enough to minimize, heat loss. The uniform distribution of the thermocouples can cover the entire surface of the disk and the parallel configuration can average the volt- age of all four thermocouples. The entire disk with thermocouples is mounted in an insulating block. The front face of the disk is blackened to approximate its emissivity characteristics to that of human skin. In this sensor, the heat flux under a particular thermal exposure is calculated using Eq. [(5.1)](#_bookmark3), where, *q* =heat flux (cal/s/cm2), *M* =mass of the disk (g), Cp=specific heat of the disk (cal/g °C), *A* =area of the disk

(cm2), Δ*T* =temperature rise of the disk (°C), and Δ*t* =exposure time (s). *M* can be further represented by Eq. [(5.2)](#_bookmark4), where, *A* =area of the disk (cm2), *b* =thickness of the disk (cm), and *ρ* =density of the disk (g/cm3). Eventually, Eq. [(5.1)](#_bookmark3) can be rewrit-

ten as Eq. [(5.3)](#_bookmark5), which can be conveniently used to calculate heat flux through the sensor. According to Eq. [(5.3)](#_bookmark5), it is clear that the *ρ* and Cp are constant; consequently, *q* is directly dependent upon *b* and Δ*T*/Δ*t*. It seems that the accurate measurement of

Δ*T*/Δ*t* is essential to precisely calculate *q*, and *b* is the most important affecting param-

eter to accurately measure Δ*T*/Δ*t* or *q*. The result of the TPP sensor can also be used to predict human skin burns based on the Stoll Curve (Fig. 3.2) [129,131,154,155].

*M* · Cp · Δ*T*

*q* =

*A* · Δ*t*

(5.1)

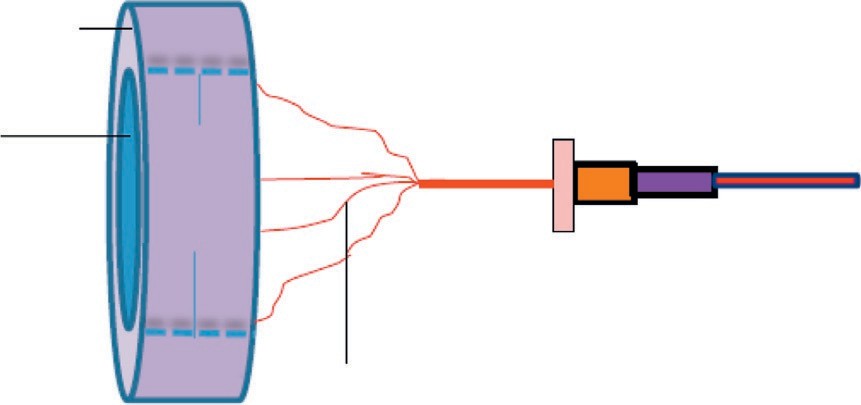
*M* = *A* · *b* · *ρ* (5.2)

*q* = *b* · *ρ* · Cp · Δ*T*

Δ*t*

(5.3)

Insulating block

(Internal diameter = 40 mm and thickness = 1.6 mm)

Copper disk

40 mm

1.6 mm

Type-J thermocouple

Fig. 5.4 TPP sensor.

Adapted from S. Mandal, G. Song, Text. Res. J. 85 (1) (2015) 101–112.

This type of sensor is highly reliable, accurate, rugged for repetitive thermal expo- sures, durable during intensive thermal exposures, and can also withstand long ther- mal exposures. As a consequence, this sensor is widely accepted within the scientific community. However, this sensor does not factor in potential heat loss under a par- ticular thermal exposure when calculating heat flux. Hence, the calculated heat flux from this sensor can be overestimated [331].

*Embedded sensor (thin-skin sensor)*: The embedded sensor was developed by the DuPont Company with the Thermo-Man flash fire manikin ([Fig. 5.5](#_bookmark7)). This type of sensor is constructed using a thermo-set polymer resin that is cast into a small solid cylindrical-shaped plug [35,332,334]. This polymer resin exhibits thermal inertia (a product of density, thermal conductivity, and specific heat) similar to that of undamaged human skin. In this skin-simulant resin-cast plug, a type-T thermocouple (copper-constantan) is embedded just below the front surface of the resin-cast plug (at a depth of 0.127 mm). This thermocouple measures the front surface temperature of the resin-cast plug under a particular fire exposure; this temperature is later used to evaluate the heat flux flow through the sensor. The resin-cast plug is designed with

Type-T thermocouple

Thermo-set polymer

26 mm

27 mm

Fig. 5.5 Embedded sensor.

Adapted from S. Mandal, G. Song, Text. Res. J. 85 (1) (2015) 101–112.

a 26 mm diameter and 27 mm thickness. The sensor can be treated as infinite slab geometry for certain durations of fire exposures.

This type of sensor is rapid and accurate for properly measuring the heat flux under an intensive thermal exposure. However, the measurement of heat flux by this sensor is highly dependent on the exact location of the thermocouple. Because determining the exact location of the thermocouple is usually uncertain, this type of sensor has an inherent tendency to produce inaccurate results [35,334]. Additionally, this sensor is not very durable, because the used polymer resin may crack under repetitive thermal exposures [331].

*Skin simulant sensor*: This sensor, developed by researchers at the University of Alberta, Canada ([Fig. 5.6](#_bookmark9)), behaves similarly in heat transfer to human skin [24,331,337]. This sensor is made up of an inorganic material called colorceron, a mixture of various compounds such as calcium, aluminum, silicate, asbestos fiber, and a binder. This inorganic material does not have the same values of density (*ρ*), thermal conductivity (*k*), or specific heat (Cp) when compared with human skin, but the thermal inertia [a product of *ρ* (kg/m3), *k* (W/m °C), and Cp (J/kg °C) or ther- mal absorptivity (a square root of thermal inertia)] of the material is similar to that of human skin. As thermal inertia is the most important property of a material in deter- mining heat flow in sensor development, colorceron is used for the skin simulant sen- sor. In this sensor, a type-T thermocouple (copper-constantan) is held on the surface of a colorceron slab by an epoxy-phenolic adhesive that can tolerate the temperature up to 370°C. A hole is drilled along the length of the colorceron slab to allow the ther- mocouple to permeate inside the sensor. The thermocouple’s attached surface is gen- erally painted black to control the emissivity of the sensor. The thermocouple measures the temperature increase in any intensified thermal environment and this increase is used to calculate the heat flux through the sensor using Duhamel’s theorem [Eq. [5.4](#_bookmark8), where, *T*i =initial uniform surface temperature (°C), *T*s(*t*) =surface temper- ature (°C) at time *t* (s), *q*''(*t*) =heat flux (W/m2) at time *t*] [36,335]. The length and diameter of this sensor are 32 mm and 19 mm, respectively. The length of the sensor is chosen for convenience because the colorceron is commercially available in 32 mm thick slabs; the diameter is selected such that sufficient lead length could be given to the thermocouple on the surface for eliminating the conductive heat transfer effect at the junction of the colorceron and thermocouple.

Type-T thermocouple

Colorceron body

19 mm

32 mm

Fig. 5.6 Skin simulant sensor.

Adapted from S. Mandal, G. Song, Text. Res. J. 85 (1) (2015) 101–112.

'' rﬃ*k*ﬃﬃ*ρ*ﬃﬃCﬃﬃﬃpﬃ**ﬃ** 1 ð*t T*s(*t*) — *T*i

*q* (*t*) =

(5.4)

*π*

2

0

*t*1/2

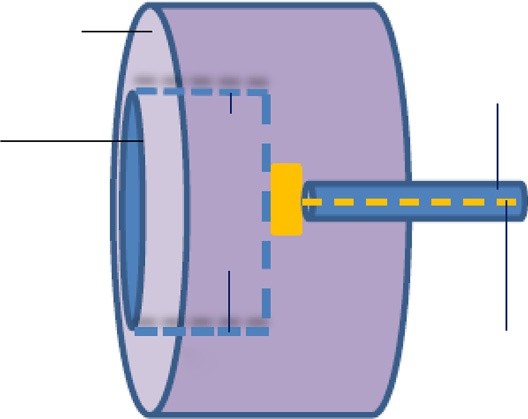
This type of sensor is rapid and accurate for properly measuring the heat flux under a short-duration intensive fire exposure. This sensor is widely used to evaluate the per- formance of protective clothing using the Harry Burns full-scale instrumented flash- fire manikin test. However, this sensor does possess a few drawbacks, one of which is

that it cannot withstand long duration (>120 s) exposure at high heat flux [331]. If the measuring surface of this sensor is not properly painted black, the thermocouple bead

(placed on the surface of the sensor) will be directly exposed to fire, and it may reflect some amount of radiative energy away from the surface of the sensor, resulting in a lower sensor response rate.

*NCSU PyroCal sensor (new copper slug sensor)*: Recently, the TPP sensor was modified and improved by Grimes [333] from NCSU. This improved sensor is called the PyroCal sensor ([Fig. 5.7](#_bookmark10)). The PyroCal sensor is thermally insulated; hence, it cau- ses less heat loss than the noninsulated TPP sensor under fire exposure. As the mass of the insulated PyroCal sensor (1.3 g) is much lower than that of the TPP sensor (17.9 g), heat storage within the PyroCal sensor under repetitive and highly intensive fire exposures is less compared to the TPP sensor. Overall, the PyroCal sensor demonstrates more reliability, repeatability, and versatility than the traditional and extensively used TPP sensor [35,331].

Insulating block

(external diameter =

26.3 mm and thickness =

26.6 mm)

Copper disk

Heat shrunk tube

12.7 mm

1.5 mm

Type-T thermocouple

Fig. 5.7 PyroCal sensor.

Adapted from S. Mandal, G. Song, Text. Res. J. 85 (1) (2015) 101–112.

Inthe PyroCal sensor(asshown in [Fig. 5.7](#_bookmark10)), a copper 110 alloy (density= 8910 kg/m3; specific heat= 0.385 kJ/kg) disk (about 12.7 mm in diameter and 1.5 mm in thickness) surrounded by a radial thin copper ring (ring acts as a thermal guard) is mounted in an insulating block (diameter 26.3 mm and thickness 26.6 mm) to minimize heat transfer toand fromthe bodyofthe disk. Thisdesignapproximatesa one-dimensionalenergyflow through the sensor. The copper disk with ring is secured within the insulating holder by three pins, located 120 degree apart, perpendicular to the central axis and 1.02 mm back from the front surface of the disk. The pins are inserted through 1.57 mm holes in the insu- lating holder and the copper disk, and seated into conical notches (0.76 mm diameter and

0.38 mm deep) at the front surface of the disk in order to reduce the amount of heat loss from the disk. A 6.35 mm air gap is kept behind and on the side of the disk; this insulates the backandsidefaces ofthedisk. Thedisktemperature is measuredbya 30-gauge type-T thermocouple(copper-constantan), affixed atthebackofthedisk; this temperatureisused to assess the heat flux through the sensor. As described by Grimes[333], a flat base hole of

1.19 mm diameter and 1.02 mm depth is drilled into the rear surface of the disk and into this hole two leads of the thermocouple are inserted and secured in place by an 18 gauge copper plug. The pressure exerted by the plug results in an intimate contact between the disk and thermocouple, which can improve the sensor’s accuracy reliability. After the proper attachment of the disk and thermocouple, a 3.18 mm length of heat-shrunk tubing is applied to the remaining length of the thermocouple to protect it. To secure the ther- mocouple, it is further fed through a strain relief tube mounted into the insulating disk-holder. The entire assembly (copper disk with ring, insulating holder, and thermo- couple) is then inserted and secured with #10-32 nuts within a protective shell made from the thermo-set polymer resin used in the embedded sensor. This shell protects the insu- lating holder and keeps the copper disk with ring in place. The front surface of the disk is usually painted with a 0.025–0.038 mm layer of low gloss, high-temperature black enamel paint to protect the surface and raise its diffuse emissivity to a value close to

1.0 under a particular fire exposure.

Based on the above sensor design, heat received at the front face of the copper disk is equal to the energy conducted axially within the sensor. However, it is impos- sible to keep the disk in a perfect insulator; thus, some amount of heat transfers to and from the disk and results in heat loss. It is assumed that the incident (*q*'' incident) heat (W/m2) on the sensor under any intensified thermal environment can lose through convection (*q*'' convection), conduction (*q*'' conduction), and/or radiation (*q*'' radiation). Simultaneously, some amount of heat does store (*q*'' storage) inside the sensor ([Fig. 5.8](#_bookmark11)).

*q* radiation *q* incident *q* convection

Lgap

*q* conduction

Type-T thermocouple

Insulating block

*q*

conduction

Copper disk

Fig. 5.8 Heat loss through PyroCal sensor.

Adapted from S. Mandal, G. Song, Text. Res. J. 85 (1) (2015) 101–112.

As per [Fig. 5.8](#_bookmark11), the thermal energy balance of a PyroCal sensor can be written as

''

*q*

incident

''

storage

— *q*

''

convection

— *q*

''

radiation

— *q*

''

conduction

— *q*

= 0 (5.5)

''

*q*

storage

*dT*

= *ρ*Cp*dL*

*dt*

(5.6)

where *ρ* =density of the copper disk (kg/m3), Cp =specific heat of the copper disk (J/kg °C), *dL* =length of the heat exposed area (m), and *dT*/*dt* =change of temperature with respect to time (°C/s). Thus,

*q*''

= *ρ*Cp*dLdT* + *q*''

+ *q*''

+ *q*''

(5.7)

incident

*dt* convection

radiation

conduction

The convective and radiative losses can be defined as a Newtonian cooling term and a function of temperature to the fourth power, respectively. The convective and radia- tive losses can be represented by Eqs. [(5.8), (5.9)](#_bookmark13), respectively, where, *h* =convective heat transfer coefficient (W/m2 K); *ε* =emissivity of the copper disk; *α* =Stefan– Boltzmann constant (W/m2 K4); *T*(*t*) =temperature of the copper disk (°C); and *T*air =temperature of the outside air (°C). Moreover, the conductive loss can be broken down into two distinctive components: radial and axial, as shown in [Fig. 5.9](#_bookmark16). Assum- ing that there is no contact resistance, the conductive loss can be calculated based on Eq. [(5.10)](#_bookmark14), where *k* =thermal conductivity (W/m °C) of the gasses in *L*gap (m). By entering the values of Eqs. [(5.8)–(5.10)](#_bookmark13) into Eq. [(5.7)](#_bookmark12), the incident heat of heat flux value is calculated; this final equation for heat flux calculation is Eq. [(5.11)](#_bookmark15).

''

*q*

convection

= *h*[*T*(*t*) — *T*air] (5.8)

''

*q*

radiation

*q*''

= *εα*h*T*(*t*)4 — *T*4 i (5.9)

= *kL*gap[*T*(*t*) — *T*air] (5.10)

air

conduction

''

*q*

incident

*dT*

= *ρ*Cp*dL* + *h*[*T*(*t*) — *T*

*dt*

air

] + *εα*h*T*(*t*)4 — *T*4 i + *kL*

gap

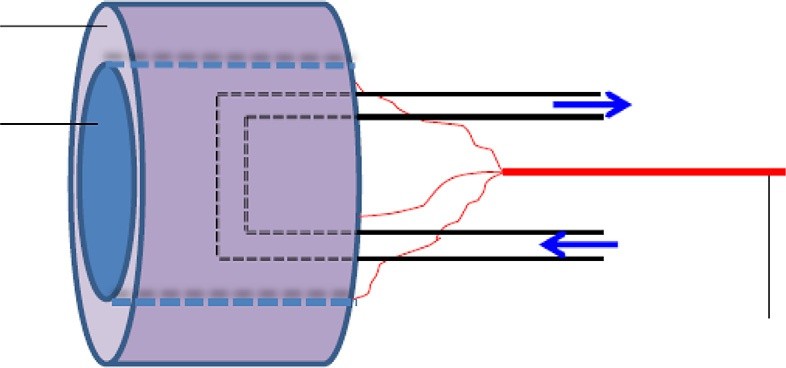
[*T*(*t*) — *T*

air]

(5.11)

air

Disk holder



Coolant outlet

Coolant inlet

Thermocouple

Copper disk

Fig. 5.9 NCSU water-cooled Prototype sensor.

Adapted from S. Mandal, G. Song, Text. Res. J. 85 (1) (2015) 101–112.

The PyroCal sensor possesses superior features such as simplicity in design, small size, ease of operation, durability under repetitive fire exposure, accuracy under highly intensive exposures, and easily available materials (eg, copper disk and ring, insulating holder, thermo-set polymer resin). Thus, this sensor is extensively used for evaluating the performance of firefighters’/industrial-workers’ clothing using the “PyroMan” full-scale instrumented flash fire manikin test. However, the application of this sensor possesses several drawbacks [27,331]. For example, this sensor does not absorb heat accurately in the same fashion as human skin in long duration exposures [27]. Actual human skin temperature rises faster than the PyroCal sensor; thus, the calculated heat flux by the sensor may inaccurately represent heat transferred into skin.

*Water-cooled sensors*: It can be identified from the above-mentioned sensors that they are all unsuitable for use in long duration fire exposures. To overcome this prob- lem, the water-cooled sensor is used. The water-cooled sensor is an example of a clas- sic sensor, which uses a novel dynamic cooling technology for its development. Three different types of water-cooled sensors are available: The Schmidt-Boelter sensor, the Gardon sensor, and the Prototype sensor [334,337–339]. The Schmidt-Boelter and Gardon sensors are standardized by ASTM and NIST and the Prototype sensor is developed by NCSU. Normally, the measuring thin constantan foil or copper disk faces of these sensors (placed and secured in a disk holder using sealants) are painted black to properly absorb all the radiant heat, especially when exposed to any intensi- fied fire exposure. The Schmidt-Boelter sensor operates by measuring the axial tem- perature differential between the front face of the disk and a water-cooled copper or aluminum heat sink with thermopile. The Gardon sensor operates by measuring the radial temperature differential between the front face of the disk and a water-cooled copper heat sink with thermopile [338]. In the Prototype sensor, the temperature dif- ferential of water flowing in (coolant inlet) and out (coolant outlet) of the area under the copper disk is measured ([Fig. 5.9](#_bookmark16)). The temperature differential is used to deter- mine the heat flux within these sensors. In this context, Eq. [(5.12)](#_bookmark17) is developed to calculate the heat flux by the Prototype sensor, where, *q*'' =total heat flux (kW/m2), *ρ*cu =density of the copper disk (kg/m3), *CP* =specific heat of the copper disk (kJ/kg K), *t*cu =thickness of the copper disk (m), *A*cu =area of the copper disk (m2), *T*cu =temperature of the copper disk (K), *t* =time step of the experiment (s),

cu

*m*\_ H2 O =the mass flow rate of the coolant (kg/s), *CP*H O =specific heat of the coolant

2

(kJ/kg K), *T*I =incoming coolant temperature (K), *T*O =exit coolant temperature (K), *h*H =heat transfer coefficient of the sensor housing (kJ/s m2 K), *A*H =wetted area of the sensor housing (m2), and *T*H =temperature of the sensor housing (K).

*q* = *ρ*cu

*CP*cu *t*cu

*A*cu

*dT*cu + *m*\_

*dt*

H2O

*CP*H O

(*T*I — *T*O

) — *h*H*A*H

(*T*H

— *T*I) (5.12)

A water-cooled sensor has a built-in cooling system that removes the energy absorbed by the disk during an exposure; this heat removal process prevents an overload in disk temperature during exposure. This allows the disk to maintain a constant temperature gradient even with continuing exposure of the heat source. This means the water- cooled sensor can function for much longer duration of exposures than the other

2

nonwater-cooled sensors (TPP, embedded, PyroCal, skin simulant) [331,337,340]. However, the water-cooled sensor is unsuitable for measurement of rapid, intensive heat transfer because of the thermal inertia of its cooling system and its relatively slow response time; the capability and accuracy of this sensor is also limited to intensity and duration of exposure. In addition, the accuracy of any water-cooled sensor is directly associated with the characteristics of its water cooling system. Thus, there is a need to precisely evaluate the heat evacuated by the sensor’s cooling system in order to accu- rately assess the heat flux. Other significant drawbacks associated with this type of sensor are that it is expensive and cumbersome to use [334]. Due to all these draw- backs, water-cooled sensors are not preferable for regular commercial use; however, this sensor is acceptable for use as a calibrator for other sensors [35,334,340].

*Types of sensors and their applicability*: The TPP, embedded, skin simulant, and PyroCal sensors operate using thermocouple technology; however, the water-cooled sensors work based on dynamic cooling technology. Embedded and skin simulant sen- sors measure temperature increases of predetermined duration by thermocouples, and these temperatures are used to determine heat flux (Eq. [5.4](#_bookmark8)). Because embedded and skin simulant sensors require an inverse heat transfer calculation to estimate the heat flux from temperature, these sensors may cause an estimation error associated with heat flux calculations. The TPP, PyroCal, and water-cooled sensors directly measure the heat flux (Eqs. [5.1, 5.11, 5.12](#_bookmark3)), thus avoiding miscalculations of heat flux as is the case with embedded and skin simulant sensors [331,336,340]. Among the sensors, embedded and skin simulant sensors represent a human skin model ([Fig. 5.10](#_bookmark19)); even- tually, the heat transmission behavior within these sensors is similar to that of human skin [23,26,341]. As embedded and skin simulant sensors work according to the skin model, the temperature readings of these sensors under fire exposures can be used to calculate the time required to generate skin burn injuries based on the Henriques burn integral equation (Eqs. 3.1, 3.2), which can be used to gauge the performance of ther- mal protective clothing [125,129]. [Table 5.1](#_bookmark18) summarizes the advantages and disad- vantages of these sensors in protective clothing studies.

Considering the above applicability of different sensors, several standards have been developed by international and national organizations, such as ASTM, NFPA (National Fire Protection Association), ISO (International Organization for Standard- ization), and CGSB (Canadian General Standard Board). These test standards (eg, ASTM F 1939:2008, ASTM F 2702:2008, ASTM F 2703:2008, ASTM F 1930:2013, NFPA 1971:2013, ISO 9151:1995, CGSB 155.20:2000) are mainly used

to evaluate the thermal protective performance of fabric or clothing under a particular fire exposure using bench-scale tests or full-scale manikin tests [137,138,342–347]. In these standards, the sensors are used in bare and clothed conditions for two main pur- poses: (1) heat flux calibration in bare conditions, and (2) heat flux measurement in clothed conditions. For these tests, the sensors measure the heat transferred through them under radiant heat and/or flame exposures. Subsequently, the analog output sig- nals from these sensors are fed into an analog amplifier multiplexer to produce a dig- ital voltage signal. Next, these digital voltage signals are fed into a software program to translate into temperature readings every second; these temperature readings are simultaneously used to determine heat flux.

## Table 5.1 Advantages and disadvantages of various thermal sensors

Performance evaluation of thermal protective clothing

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|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Thermal sensors | | | | |
| TPP | Embedded | Skin simulant | PyroCal | Water-cooled |
| Advantages | l Reliable and accurate  l Rugged for repetitive fire exposures  l Durable in intensive fire exposures | l Simulates human skin  l Rapid and accurate in intensive fire exposures | l Simulates human skin  l Rapid and accurate in highly intensive, short-duration exposures | l Simple design  l Small in size  l Ease of operation  l Relatively rugged under repetitive fire exposure  l Accurate under highly intensive exposures  l Heat absorption dissimilar to human skin in long duration fire exposures | l Suitable for calibration purposes of the other sensors: TPP, embedded, skin simulant,  PyroCal  l Functions for longer duration than other sensors in radiant heat exposures |
| Disadvantages | l Uncertain heat loss from this sensor renders it unsuitable for low- intensity and long time exposure  l Calculated heat flux from this sensor can be underestimated in long duration  exposures | l Calculated heat flux is highly dependent on exact location of thermocouple within the sensor  l Nondurable under long duration and/ or repetitive fire exposures | l Cannot withstand long exposures at high heat flux  l Directly exposed thermocouple may result in inaccurate heat flux under intensive fire exposures | l Unsuitable for measurement of rapid, intensive heat transfer  l Relatively slow response time  l Limited capability and accuracy  l Expensive and cumbersome to use |

Dermis

Epidermis

Subcutaneous

Fire exposures

Fig. 5.10 Skin model for a sensor.

*Case studies on the applications of different sensor types*: In most of the above- mentioned standards, TPP sensors are used. However, many researchers also conducted their studies using other sensors; these studies are useful to analyze the prediction variability of sensors depending upon the intensity of fire exposure and clothing used for testing [331,332,340]. In this context, Barker et al. [331] compared the heat flux readings obtained from four sensors (TPP, embedded, skin simulant, and PyroCal) in both bare/nude (calibration) and clothed conditions under different inten- sive fire exposures. In the case of bare sensors, three different types of fire exposures were applied: (1) 100% radiant heat source at 0.14 cal/cm2/s for 20 s, (2) 100% radiant heat source at 0.30 cal/cm2/s for 20 s, and (3) 50/50 convective/radiant heat source at 2 cal/cm2/s for 5 s. Only a single fire exposure (50/50 convective/radiant heat source at 2 cal/cm2/s for 10 s) was selected for the clothed sensors. For the clothed conditions, the front surfaces of the sensors were covered with specimens of three different fabrics (Nomex-III of 5.33 oz/yd2, fire-retardant cotton of 6.93 oz/yd2, and fire-retardant wool of 10.23 oz/yd2). In this comparison, the bare PyroCal sensor corresponded closely with the bare TPP sensor under all three types of fire exposures, as both were copper slug sensors. On the other hand, the heat flux reading of the bare skin simulant sensor could not be compared to the bare TPP sensor in a fire exposure of 2 cal/cm2/s, because the skin simulant sensor reflected some of the radiative energy away from the surface of the sensor. The bare embedded sensor did provide a reasonably close esti- mate of average heat flux with the bare TPP sensor for all three fire exposures; how- ever, there was considerable variation in heat flux readings between individual bare embedded sensors because the position of thermocouples can be different in these sen- sors. Additionally, both the bare PyroCal and embedded sensors provided a consistent average reading of heat flux in repeated measurements for the exposure conditions tested. Nevertheless, the PyroCal sensor data was more repeatable than the embedded

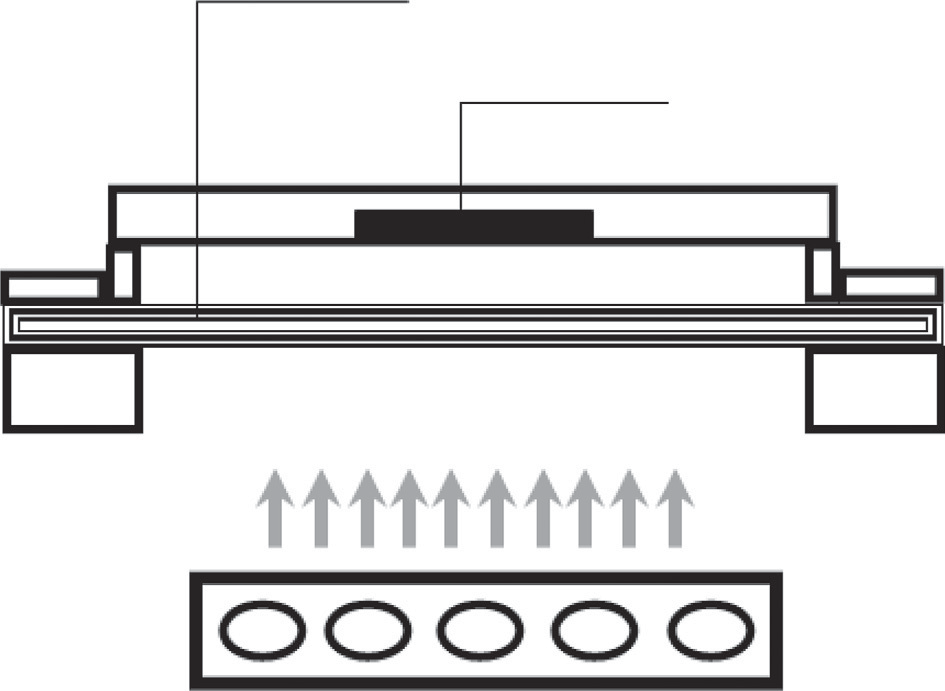
sensor data. Furthermore, this study demonstrated that the clothed PyroCal sensor responded quickly and accurately to calculate the heat flux under a particular fire exposure in comparison with the clothed embedded or skin simulant sensor. This is because the PyroCal sensor provided a larger integrating measurement surface area to promptly monitor the bulk heat transfer through the fabric specimen. This measur- ing surface can also even out the constructional variation in the specimen and give an accurate average for the heat transmitted through the interstices (made by the inter- section of warp and weft yarn) in the tested fabric specimen. On the other hand, the buried or surface mounted thermocouple in the clothed embedded or skin simulant sensor can reflect the heat away from the surface of the sensor and this reflection can slow the response to calculate heat flux. It is also notable that most of the bare or clothed sensors lose a significant amount of energy under fire exposures; hence, there is a need to accurately measure a calibration factor to correct the heat loss from the sensors. Barker, Hamouda, and Grimes [332] determined the heat flux through each of four sensors in clothed conditions under a single fire exposure for 5 s (50/50 convec- tive/radiant heat source at 1.3 cal/cm2/s). Here, the surface of the sensors were covered with a poly(p-phenylene terephthalamide)/polybenzimidazole fabric (Kombat 750 of 7.5 oz/yd2). After the 5 s exposure, the heat flux values of these sensors were continually determined for another 5 s with or without any fabric. In this case study, it was found that the clothed TPP, skin simulant, and PyroCal sensors measured sim- ilar levels of heat flux both during and after exposure when tested with a fabric after the exposure. However, these sensors measured similar levels of heat flux only during exposure when tested without a fabric after the exposure. It was also found that the skin simulant sensor measured the highest heat flux (~0.6 cal/cm2/s), whereas, the embedded sensor measured the lowest heat flux (~0.4 cal/cm2/s). In this case study, it was suggested to carefully study the repeatability and durability of the sensors under different fire exposures along with their heat flux estimation.

### Evaluation of thermal protective performance using bench-scale tests

The thermal protective performance of a firefighter’s clothing refers to its ability to insulate the transmission of thermal energy in order to reduce the burn injuries of fire- fighters, and many researchers have evaluated the performance of firefighters’ cloth- ing under various laboratory-simulated thermal exposures [22,24,25]. In order to evaluate the performance of firefighters’ clothing under various thermal exposures with varying intensities, two main types of tests are available: bench-scale tests and full-scale manikin tests [23,26,27,341]. In the bench-scale test, a specimen of fab- ric used to manufacture thermal protective clothing is tested under a thermal exposure of varying intensities, whereas, whole thermal protective clothing is tested in the full- scale manikin test. This full-scale manikin test is cumbersome, expensive, and diffi- cult to carry out in the laboratory because whole pieces of thermal protective clothing are tested. Consequently, previous studies largely focused on bench-scale tests to eval- uate the performance of fabrics [22,24,25]. The thermal protective performance for

fabrics or their combinations can be evaluated under various thermal exposures; typ- ically, these can be categorized as six different thermal exposures of varying intensi- ties: radiant heat, flame, hot surfaces, molten metal substances, hot liquids, and steam [22,24,25].

*Evaluation of thermal protective performance under radiant heat exposure*: The thermal protective performance of fabrics under radiant heat exposure can be evalu- ated according to the ASTM F 1939 (or ISO 6942) test standard ([Fig. 5.11](#_bookmark20)). In this test standard, a fabric specimen with a dimension of 250 mm× 150 mm is vertically exposed to radiant heat generated (21 and 84 kW/m2) from a bank of quartz tubes. A TPP sensor (copper slug sensor) is placed behind the exposed fabric specimen to measure the total thermal energy passed through the fabric specimen. The accumu- lated energy for a certain exposure time is also calculated according to the empirical Eq. [(5.13)](#_bookmark21), where, *t*i =time value in seconds. The time value, *t*intersects, represents where the measured energy (obtained from the TPP sensor) intersects with the calcu- lated energy (obtained from the empirical Eq. [5.13](#_bookmark21)). By using this time value (*t*intersects), the radiant heat resistance (RHR) of the fabric specimen is determined (in J/cm2) as thermal protective performance by employing Eq. [(5.14)](#_bookmark22).



Fabric

TPP sensor

Radiant-heat

Quartz tube

Fig. 5.11 Laboratory-simulated radiant heat exposure test described in ASTM F 1939.

Accumulated energy  J/cm2 = 5.0204 × *t*0.2901

i

(5.13)

RHR value J/cm2 = *t* (s)

intersects

× Radiant Exposure Heat Flux Value kW/m2 (5.14)

Although the ASTM F 1939 test standard is well-established to evaluate the RHR of fabrics with continuous heating, this standard does not account for the thermal energy

contained in the test specimen after radiant heat exposure has ceased. Thus, this stan- dard does not account for thermal stored energy in fabrics. Test standard ASTM F 2702 was established to account for thermal stored energy. This test standard is sim- ilar to ASTM F 1939; however, this test standard accounts for thermal energy con- tained in the exposed test specimen (250 mm × 150 mm) after the standardized radiant heat exposure has ceased. Here, a radiant heat performance (RHP) value of the fabric test specimen is determined iteratively as the thermal protective perfor- mance. For this, a fabric specimen is first vertically exposed to radiant heat for a deter- mined duration. During the exposure, the thermal energy transferred through the exposed specimen is measured by a TPP sensor (copper slug sensor). From this sensor, the total accumulated thermal energy for a particular exposure time (*t*i) is measured. For the same exposure time (*t*i), the required energy for second-degree skin burn injury is calculated by Eq. [(5.15)](#_bookmark23). The exposure time at which the total accumulated thermal energy meets/exceeds the required thermal energy for second-degree skin burn injury is determined. This exposure time is represented as *t*max. This *t*max value is further divided by 2 and is referred to as trial exposure time (*t*trial) (Eq. [5.16](#_bookmark24)). Subsequently, another fabric specimen is exposed to radiant heat for the *t*trial time, and the energy transmitted through the specimen is measured by the sensor, with a continually mea- sured cool phase period. From the measured total thermal energy, the *t*trial value is recalculated using the same method as before. Then, the difference between the cur- rent *t*trial and the previous *t*trial is calculated. If the difference is 0.5 s, the current *t*trial value is used to calculate the RHP according to Eq. [(5.17)](#_bookmark25). In both ASTM F 1939 and ASTM F 2702, an improper placement of the fabric specimen may result in an inac- curate measurement.

Required energy  J/cm2 = 5.0204 × *t*0.2901

i

(5.15)

*t*trial = *t*max/2 (5.16)

trial

RHP value J/cm2 = Current *t* (s)

× Radiant Exposure Heat Flux Value kW/m2 (5.17)

Furthermore, the ASTM E 1354 standard has been developed to study the fire behav- ior of various materials, including fabrics under radiant heat exposure with or without an external ignitor ([Fig. 5.12](#_bookmark26)). Here, a fabric specimen (100 mm× 100 mm) is exposed to heat flux of up to 100 kW/m2. The normal specimen testing orientation is horizontal, independent of whether the end-use application involves a horizontal or a vertical orientation. However, the testing apparatus used in this standard also has the capability for vertical orientation testing in order to conduct exploratory or diagnostic study only. The heat flux is generated from a conical heater until the fabric specimen starts burning in an ambient air condition. Here, the fire behavior of the fab- ric specimen at a specified heat flux can be measured in terms of ignitability, heat release rates (HRR), effective heat of combustion, mass loss rates (MLR), and/or vis- ible smoke development of fabric materials. The ignitability is determined as a mea- surement of time (s) from initial exposure to sustained burning (existence of flame on or over most of the specimen surface for periods of at least 4 s) of the ignited

specimen; the HRR is determined by the heat evolved from the ignited specimen per unit of time; the effective heat of combustion is determined by the amount of heat evolved from per unit mass of the ignited specimen; the MLR is determined by the loss of mass of the ignited specimen per unit of time; and the visible smoke develop- ment is measured by the reduction/attenuation of transmission of a monochromatic and highly collimated light source due to smoke generated from the ignited specimen. Although this standard is widely used to measure and describe the response of fabric materials or assemblies under controlled radiant heat exposure, this standard does not incorporate by itself all parameters required for fire hazard or fire risk assessment of fabrics under actual fire conditions.

Hood



Cone-shaped electrically heated coil

Fabric

Fig. 5.12 Laboratory-simulated radiant heat exposure test in ASTM E 1354.

A great deal of research [24,29,76] used either the above-mentioned original ASTM standards with slight modifications, or the standards developed by other organizations (eg, NFPA, ISO). Sun et al. [29] and Song et al. [24] evaluated thermal protective per- formance according to the NFPA 1971 and modified ASTM F 1939 standards, respec- tively. Recently, Mandal et al. [76] evaluated performance under radiant heat exposures using the heat source described in the ASTM E 1354 standard. As a modification, Song et al. [24] and Mandal et al. [76] did not use the performance analysis as described in the original ASTM F 1939 and ASTM E 1354 standards. In these studies, the performance was evaluated in terms of time required to cause second-degree burns to the sensors (firefighters’ bodies); a fabric with a high second-degree burn time was considered a fabric with high performance. It is also notable that the above-mentioned various test standards (ASTM F 1939, ASTM F 2702, ASTM E 1354) evaluated the performance of fabric specimens in their relaxed state. These standards did not consider the deforma- tion of specimens in the presence of extreme radiant heat during performance evalua- tion. However, this deformation may affect the transfer of thermal energy through the fabric specimen, which also affects thermal protective performance. It is necessary to design test standards which can account for the impact of a deformed fabric state on thermal protective performance.

*Assessment of thermal protective performance under radiant heat exposure*: Sun et al. [29] reported that the intensity of radiant heat exposure in a fire hazard can be >20 kW/m2 and that such high intensity radiant heat exposure can cause life- threatening burn injuries to firefighters. Furthermore, Perkins [93], and Song et al.

[24] derived through critical analyses of the research that the protection of firefighters from low-intensity (<20 kW/m2) radiant heat exposures is equally important in a fire hazard [92]. Mandal et al. [76], Perkins [93], Sun et al. [29] and Song et al. [24] ana- lyzed the inherently and/or chemically modified fire-retardant natural and synthetic fiber-based fabrics under laboratory-simulated radiant heat exposures to evaluate ther-

mal protective performance; they found that fabric attributes are important to consider for providing effective protection to firefighters in radiant heat exposures. Song et al.

[24] observed that layered fabrics store more thermal energy inside their structures than nonlayered fabrics. Therefore, clothing made with layered fabrics discharge more thermal energy during compression with wearers’ bodies than clothing made up of nonlayered fabrics. As this discharged energy may cause significant burns on fire- fighters’ bodies, the chances of burn injuries (due to stored energy) in the case of lay- ered fabric clothing are higher than with nonlayered fabric clothing. Perkins [93], Mandal et al. [76], and Sun et al. [29] inferred that thicker or heavy-weight fabrics comprise more still or dead air inside their structures than thinner or light-weight fab- rics. The authors suggest that this dead air acts as a thermal insulator and controls the thermal resistance of the fabrics. Because thicker or heavier fabrics comprise more dead air than thinner or lighter fabrics, the thicker or heavier fabrics possess higher performance and can provide a better thermal protection than thinner or lighter fabrics. Perkins [93] also found that a fabric with open constructions allows more thermal energy to pass through and lowers the performance; additionally, a fabric in touch with wearers’ bodies may also enhance the conductive transfer of thermal energy toward wearers and cause more extensive burn injuries. Kalekar and Kung [121] mentioned that opaque fabric has high transmissivity of thermal energy and causes quick burns on wearers’ bodies. Backer et al. [348] expressed concern that a fabric with high opacity can be highly ignitable under radiant heat exposure, which may aggravate a burn injury even before wearers have received sufficient thermal energy to their skin to register pain and initiate escape. Furthermore, Mandal et al. [76], and Song et al.

[24] established that fabrics with low density and high thermal resistance show higher performance than fabrics with high density and low thermal resistance; this is because low-density and high thermal resistance fabrics trap more still or dead air inside their structures than high-density and low thermal resistance fabrics [29]. Sun et al. [29] also confirmed that fabric color has a negligible impact on the performance of thermal protective clothing.

Barker et al. [92,167], Song et al. [24], and several other researchers have studied the moisture effect on thermal protective performance [349]. Barker et al. [92] found that small amounts of moisture in fabric have a negative impact on the performance of thermal protective clothing under low radiant heat exposures. This reflects that the thermal conductivity of fabric increases in the presence of moisture; as a result, the performance of fabric is reduced [167]. Barker et al. [92] also stated that fabric becomes wet in the presence of more than 15% moisture, which results in an increase in the performance of the fabric. In the same context, Song et al. [24] found that wet

fabric generally shows greater performance than dry or slightly damp fabric under low radiant heat exposures. They explained that the presence of high amounts of moisture inside a fabric’s structure increases the thermal resistance of the fabric, which lowers the transfer rate of radiant heat through the fabric toward the skin. Therefore, it takes longer time to generate burns on firefighters’ bodies. Lawson et al. [349] also inferred that moisture has varying levels of impact on thermal protective performance under high and low radiant heat flux. Moisture added to the test fabrics enhances perfor- mance under high radiant heat flux; however, added moisture lowers performance under low radiant heat flux. They also confirmed that the effect of moisture on per- formance depends upon the amount of moisture added to the test fabrics, the timing of moisture addition (before, during, or after the radiant heat exposure), and the duration of heat flux application.

*Evaluation of thermal protective performance under flame exposure*: In the ASTM D 4108 standard, a test device and a method were introduced to test thermal protective performance under the flame exposure ([Fig. 5.13](#_bookmark28)). In this test standard, a blackened TPP sensor (copper slug sensor) is placed behind a flame-exposed (84 kW/m2) fabric specimen (150 mm× 150 mm) with or without a 6.4 mm spacer. The measured ther- mal energy data from this sensor is used to determine the time to exceed the Stoll second-degree burn criterion. The thermal protective performance of the fabric spec- imen is then rated on the basis of Eq. [(5.18)](#_bookmark27), where, *F* =exposed heat flux (W/cm2); *T* =exposure time (s). Here, a fabric with a high performance rating is considered bet- ter than a fabric with a low performance rating.

TPPrating = *F* × *T* (5.18)

Fabric

TPP sensor

Flame

Meker burner

Fig. 5.13 Laboratory-simulated flame exposures tests in ASTM D 4108.

Although the ASTM D 4108 standard was primarily developed to compare the ther- mal energy insulating values of protective fabrics, this test standard confused textile scientists. In short, they misinterpreted that a measured performance rating value equaled the fabric’s ability to protect firefighters from second-degree burn injuries. However, this test standard was not designed for second-degree burn injury predic- tion, because it does not account for the thermal energy contained in the exposed fab- ric specimen after the standardized flame exposure has ceased. Due to this confusion, an ASTM F23.80 subcommittee (on flame and thermal) developed a new standard, ASTM F 2703 ([Fig. 5.14](#_bookmark29)). In this standard, a fabric specimen (150 mm× 150 mm) is exposed to two Meker burners and a bank of quartz tubes in order to simulate a combined flame and radiant heat exposure (84 kW/m2). Here, the unsteady state trans- fer of thermal energy through the test fabric specimen is measured using a TPP sensor placed behind the flame-exposed fabric specimen with or without a 6.4 mm air gap. The thermal energy contained in the test fabric specimen is assessed after the exposure has ceased. The measured thermal energy value to generate second-degree skin burn injuries is used as per the methods described in ASTM F 2702 to estimate thermal protective performance.

Fabric

TPP sensor

Flame

Radiant heat

Meker burner Meker burner

Quartz tube

Fig. 5.14 Laboratory-simulated flame exposures tests in ASTM F 2703.

Similar to ASTM F 2703, the ASTM F 2700 standard was developed to evaluate the performance of fabrics used in thermal protective clothing. This test standard mea- sures the unsteady state of thermal energy transfer through a fire-resistant/retardant fabric specimen (150 mm× 150 mm) with or without a 6.4 mm air gap, which is subjected to continuous exposure. As with ASTM F 2703, this test standard does not predict second-degree burn injuries. Instead, this standard calculates the heat transfer perfor- mance (HTP) value to determine thermal protective performance. The HTP value is

measured according to the RHR calculation procedure discussed at the ASTM F 1939 in the previous section—“*Evaluation of thermalprotectiveperformance under radiant heat exposure*.” Additionally, a method described in the ASTM D 7140 standard can measure the thermal energy transfer through a fabric under an open flame exposure, within a spec- ified period of time. Here, a fabric specimen (133 mm× 133 mm) is exposed to an open flame exposure for 60 s, and then thermal energy transferred through the specimen can be measuredasthermalprotectiveperformance. This test standardismainlyusedforthermal protective fabric specimens to determine their endurance by an open flame exposure. However, these protective fabrics cannot be used alone to determine their endurance. In this test standard, the fabrics are always used in conjunction with materials that dem- onstrate any of the following behaviors when exposed to a highly intensive open flame: breakage, charring, dripping, brittleness, ignition, melting, and shrinkage. As these behaviors are not prominent in composite fabrics (shell fabrics, thermal liners, and mois- ture barriers) used for thermal protective clothing, this test standard cannot be accurately used in the context of thermal protective clothing. Nevertheless, this test standard may be used to differentiate/grade/rank between various thermal protective composite fabrics based on their relative performance.

*Assessment of thermal protective performance under flame exposures*: Many

researchers [25,75,100,101,167,200,350] have studied the thermal protective perfor- mance of inherently and/or chemically modified fire-retardant synthetic fabrics (organic and/or inorganic) in flame exposures using the previously discussed ASTM standards. Because in flame exposures mainly convection and radiant modes of heat transfer dominate, these researchers evaluated the thermal protective performance under different ratios (70:30 and/or 50:50) of convective to radiant modes. These dif- ferent ratios were chosen because these closely represent the actual environment faced by firefighters. In order to simulate the 70:30 convective to radiant mode, Shalev and Barker [25,75] and Torvi and Dale [350] used the ASTM D 4108 standard test ([Fig. 5.13](#_bookmark28)); in the same context, Behnke [100], Shalev and Barker[25], and Lee and Barker [167] used the ASTM F 2703 standard test to simulate the 50:50 convec- tive to radiant mode ([Fig. 5.14](#_bookmark29)). Shalev and Barker [25] found that the performance of thermal protective fabrics is similar under both ratios of convective to radiant modes; however, the thermal energy transfer characteristics through fabrics under the two modes are quite different. In the convective mode, thermal energy imposes on a fab- ric’s surface and blows through it; whereas, in the radiant mode, thermal energy directly penetrates through a fabric [36,38]. Shalev and Barker [25] corroborated that thermal energy transfer through fabric under both modes can be a complex combina- tion of absorption, re-radiation, conduction, and perhaps forced convection. In this context, Lee and Barker [167] further found that a 100% radiant mode significantly lowers the performance of thermal protective fabrics in comparison to a combined 50:50 ratio of convective to radiant modes, with the lowest performance observed under high heat flux. This is because actual thermal energy emitted through fabric is different under both modes. It was also observed that the thermal energy transmis- sions through fabric in convective modes are different at high and low heat flux. This is because thermal energy more readily escapes in the air gap between a tested fabric and heat sensor at low heat flux. Additionally, the thermal energy does not directly

contact the fabric at low heat flux, which results in a lower convective heat transfer coefficient through fabric. In contrast, the thermal energy directly contacts the tested fabric at high heat flux; in this situation, turbulent hot air movement on the fabric enhances the thermal energy absorptivity of the fabric. Lee and Barker [167] also con- cluded that the convective mode accelerates the thermal oxidation in the fabric in comparison to the radiant mode. As a result, fabric chars more in the convective mode than the radiant mode. Furthermore, Shalev and Barker [25] found that the configu- ration of testers in ASTM D 4108 and ASTM F 2703 standards are quite different in terms of the fabrics’ surface exposure area, angle of flame impingement, flame tur- bulence, and distance of the exposed fabrics from burner top; however, these different configurations have a negligible effect on the performance of thermal protective fabrics.

Barker and Lee [101], Shalev and Barker [25,75], and Mandal et al. [76] further observed that thermal protective performance in the combined flame and radiant heat exposure depends on fabric qualities [167,350]. Shalev and Barker [25] found that fab- ric thickness has a positive association with performance under flame exposure with different ratios of convective to radiant modes. They identified the thermal resistance of thicker fabrics, which ultimately increases the performance of fabrics to be much higher than thinner fabrics’ thermal resistance [75,100,167]. However, the combined flame and radiant heat exposures store a significant amount of thermal energy inside multilayered thicker fabrics, which ultimately reduces the performances of the fabrics [351]. Furthermore, Shalev and Barker [25] and Torvi and Dale [350] stated that fabric attributes such as air permeability, density, weight, surface transfer coefficient, sur- face optical properties, heat capacity, conductivity, fiber to air ratio, and air void dis- tribution mainly affect thermal energy transfer through fabrics under combined flame and radiant heat exposures, which ultimately affects the performance of thermal pro- tective fabrics [167]. In this context, Lee and Barker [167] explained that a fabric with high density possesses higher performance than a fabric with low density, if the weights of these fabrics are similar. This is because high-density fabric indicates a high fiber-to-air ratio, thus leading to more conductive thermal energy transfer through the fabric. On the other hand, low-density fabric increases the air void distri- bution or air volume fraction, thus leading to less thermal energy transfer through the fabric. Recently, Mandal et al. [76] reported that a fabric with high emissivity absorbs more thermal energy than a fabric with less emissivity under flame exposures. Even- tually, most of the absorbed thermal energy transmits toward wearers’ bodies and generates burns.

Lee and Barker [167] investigated the impact of moisture on the thermal protective performance of fabrics in combined flame and radiant heat exposures and found that moisture affects performance in a complex way. In low-intensity (approximately

<20 kW/m2) combined flame and radiant heat exposures, the absorbed moisture inside the fabrics increases their thermal conductivity; consequently, the performance

of the fabrics is reduced. On the other hand, in high intensity (approximately

>20 kW/m2) flame dominant combined exposures, the convective action of the flames has an ablative effect, carrying thermal energy away from the side of the fabric exposed to the flames, which ultimately increases the performance of the fabrics.

However, the absorbed moisture inside the fabrics becomes steam that may cause scalding on firefighters’ bodies. Furthermore, the differences in thermal protective performance among bone-dry condition fabrics and standard environment (65% relative humidity) condition fabrics was 10–20% in the 50:50 combined flame and radiant heat exposures at 84 kW/m2; the moisture-related increase in performance was significantly greater in fabrics that were soaked until they contained a significant amount of water [167].

*Evaluation of thermal protective performance under hot surface exposure*: In the ASTM D 7024 standard, the thermal protective performance of a fabric specimen (460 mm× 205 mm) is measured in both steady state and dynamic conditions of thermal energy transfer during contact with a hot surface. The fabric specimen is sand- wiched between a hot plate and two cold plates, one on either side of the hot plate. In order to measure the performance in a steady state, a constant controlled heat flux (250 W/m2) is maintained for the hot plate with a constant temperature (20°C) for cold plates. The thermal transmission coefficient or thermal resistance (*R*-value) is mea- sured after a steady state is reached. The heat flux of the hot plate is varied sinusoidally with a period of 15 min to evaluate the thermal protective performance in dynamic conditions. The midpoint of the sinusoid is typically kept at 150 W/m2, and the ampli- tude above as well as below the midpoint is typically kept at 100 W/m2. Here, the temperature regulating factor (TRF) can be measured for thermal protective perfor- mance; the TRF is defined as the amplitude of the temperature variation of the hot plate divided by the product of the amplitude of the hot plate flux variation and the steady-state *R*-value. This ASTM D 7024 standard can be used to determine the over- all thermal transmission coefficient due to conduction for dry specimens of textile fab- rics and battings. This coefficient can be used to establish criteria for thermal parameters of textiles particularly used in the clothing industry. In Mar. 2013, this standard was temporarily withdrawn for further upgrading.

The ASTM F 1060 standard is widely used in order to evaluate the thermal protec-

tive performances of fabrics in a more realistic hot surface contact exposure ([Fig. 5.15](#_bookmark30)). This test standard measures the thermal insulation of a fabric specimen (100 mm× 150 mm) used in thermal protective clothing when exposed to a hot surface with a temperature up to 316°C. A TPP sensor with a weight load is placed on a fabric specimen, which in turn has been placed on a hot surface plate, to measure the thermal energy transferred through the fabric specimen during the exposure. The weight load is used to create a contact pressure up to 0.003 MPa in between the hot surface and the fabric specimen. This test standard predicts the amount of thermal energy and time required to cause second-degree burn injury. The limitation of this test standard is that it can only test the fabric specimen in a horizontal position (under a standard pressure) and does not involve any movement; hence, other test configu- rations (eg, testing the fabric specimen in vertical positions and/or movable condi- tions) need to be included in this standard [76,77,352]. The standard is also limited to short exposure because the model used to predict burn injury is limited to predic- tions of time-to-burn for up to 30 s. The use of this standard for longer hot surface exposures requires a different model for determining burn injury or a different basis for reporting test results. Furthermore, the thermal protection time as determined by

this test standard relates to actual end-use performance only to the degree that the end- use exposure is identical to the exposure used in this test standard; that is, the hot sur- face test temperature must equal the actual end-use temperature and the test pressure must equal the end-use pressure [352].

Weight load with TPP sensor



Fabric

Hot surface plate

Fig. 5.15 Laboratory-simulated hot surface contact exposure test in ASTM F 1060.

Recently, a few researchers [76,77] studied fabric performance using a modified ASTM F 1060 standard. Fabric specimens were placed on a hot surface plate (400°C) under a weight load of 1 kg, and a skin simulant sensor attached to a weight load measured the thermal energy transferred through the specimens. From this mea- sured energy, thermal protective performances provided by these fabric specimens were predicted in terms of time required to generate second-degree burns.

*Assessment of thermal protective performance under hot surface exposure*: According to Mandal et al. [76], fabrics become compressed in between hot surfaces and human bodies under hot surface contact exposure. Due to this compression, the gaseous air phases inside the fabrics are reduced and solid fiber phases predominate. As the thermal conductivity of a fiber is greater than air, most of the imposed thermal energy on fabrics is absorbed inside the fabrics and/or transmitted toward the human body. This transmitted thermal energy generates burns on human bodies. In this con- text, Mandal and Song [353] stated that the ratio of gaseous air phase to solid fiber phase inside the fabrics varies depending upon the compression characteristics of the fabrics. They observed that the ratio of gaseous air phase to solid fiber phase of compressible fabrics is lower than noncompressible fabrics. Consequently, the amount of thermal energy transfer toward human bodies is greater in compressible fabrics. As a result, thermal protective performance is reduced. Mandal et al. [76] also demonstrated that the surface frictional properties of tested fabrics have significant effect on the thermal protective performance. They confirmed that a fabric with high surface roughness can trap a good amount of dead air on the boundary layer of the fabric when coming into contact with a hot surface. This boundary air layer resists the transmission of thermal energy from the hot surface to the fabric and enhances the thermal protective performance of the fabric.

*Evaluation of thermal protective performance under molten metal substances exposure*: The molten metal substances contact test is conducted according to ASTM F 955 ([Fig. 5.16](#_bookmark31)). This test standard evaluates fabrics’ thermal resistance to molten metal substances (aluminum, brass, and iron) [354–358]. The specimen of a protec- tive fabric (305 mm × 460 mm) is mounted over a vertically inclined (70 degree) sen- sor board. The sensor board (250 mm× 406 mm) is fabricated from a flame- and

heat-resistant material with a thermal conductivity value of <0.15 W/m K, and this board is attached with two TPP sensors (copper slug sensors), upper and lower. Then a molten metal substance of sufficient quantity for the test is heated—the temperature

of this molten substance is measured by an appropriate device, such as an optical pyrometer or any other heat-measuring device with an accuracy of at least 14°C. Subsequently, the molten substance is poured on the fabric specimen from a pouring crucible. The pouring crucible is aligned with the specimen at a height of 305 mm, so that the majority of the molten substance stream is applied to the fabric specimen directly above the center of the upper sensor. The amount of thermal energy transmit- ted through the specimen, during and after molten substance exposure, is measured using the two TPP sensors. The obtained thermal energy to cause a second-degree burn injury is interpreted as the thermal protective performance under molten sub- stances. This test standard rates fabrics which are intended for clothing protective against potential molten substance contact, for their thermal insulating properties and their reaction to the test exposure.

Pouring crucible

Metal substance

Data aquisition system

Upper sensor (TPP)

Sensor board

Lower sensor (TPP)

Fig. 5.16 Laboratory-simulated molten metal substances exposure test in ASTM F 955.

Although the ASTM F 955 standard is used to evaluate thermal protective perfor- mance under exposure to molten metal substances, this standard is very sensitive to variations in experimental variables, including the temperature of the metal, the dura- tion of the pour, the configuration of the test stand, and the type and sensitivity of the used sensor. Thus, the results obtained from this test may not be applicable in real life exposures; however, the results can be used as a first screening to choose fabrics for

thermal protective clothing. Moreover, this test is elaborate and expensive; therefore, only a few researchers have assessed protective performance under molten metal sub- stance exposure [69,200,359–361].

*Assessment of thermal protective performance under molten metal substances exposure*: Benisek and Edmondson [359] evaluated the performance of fabrics used in thermal protective clothing against various molten metal substances: cast iron, three different types of steel, copper, aluminum, zinc, lead, and tin. In their study, the performance of fire-retardant/resistant wool, cotton, novoloid, aramid, glass, and asbestos fabric were evaluated. The results showed that fire-retardant wool fabric had the best performance against any molten metal substances and that fabric attributes significantly affected thermal protective performance [360]. It has been identified that a fabric with high thermo-plasticity, high thermal conductivity, high air permeability, low softening temperature, and high flamma- bility has low thermal protective performance; whereas, a fabric with high weight and thickness will demonstrate high thermal protective performance [361]. In this context, it is evident that a fabric possessing char formation features can provide better protection than a fabric with no char formation features. Additionally, a fabric with high smoothness cannot trap molten metal on its surface and possesses a higher thermal protective performance. As a consequence, Barker and Yener

[361] concluded that aluminized smooth fabrics, including fabrics made with fire-retardant cotton, rayon, glass, or carbon as base fibers perform particularly well in deflecting the molten metal, resulting in a higher thermal protective per- formance. It was also found that heavier fabrics made from inorganic materials such as ceramic and silica fibers may have equivalent performance levels to alu- minized smooth fabrics [361].

*Evaluation of thermal protective performance under hot liquid exposure*: The performance of thermal protective fabrics under hot liquid exposure can be mea- sured according to the ASTM F 2701 standard ([Fig. 5.17](#_bookmark32)). This standard is used to measure thermal energy transmission through thermal protective fabrics (woven or knit fabrics, battings, sheet structures with permeable or impermeable coating) used in firefighters’ clothing and gloves that are exposed to a hot liquid splash. In this standard, a fabric specimen (355 mm × 560 mm) is exposed to a hot liquid pour at a determined temperature, volume, pour rate, and height above the spec- imen. The amount of thermal energy transmitted through the fabric specimen dur- ing and after the hot liquid exposure are measured using two TPP sensors (copper slug sensors). The amount of transmitted thermal energy to cause a second-degree skin burn injury is measured as the performance of the fabric specimen. Although this is a standard method, the fabric specimen is exposed to hot liquids only at one position (45 degree); to improve results, it is suggested to conduct the test at dif- ferent fabric positions (horizontal, vertical, etc.) [76,353]. This test method is also limited to the hot liquid temperatures 40°C below the flash point of the specific hot liquid used for testing. The intent of specifying the maximum temperature at 40°C below the flash point is to reduce the chances of a hot liquid fire hazard, which increases significantly at temperatures equal to or above the flash point of the liquid [362].

Funnel

Data aquisition system

Upper sensor (TPP)

Sensor board

Lower sensor (TPP)

Fig. 5.17 Laboratory-simulated hot liquid exposure test described in ASTM F 2701.

Recently, Mandal and Song [353], Mandal et al. [76], and Ackerman et al. [22] evaluated the thermal protective performance of inherently fire-retardant fabrics (eg, Nomex, Kevlar/PBI) under a hot liquid splash using a modified ASTM F 2701 standard ([Fig. 5.18](#_bookmark33)). In both studies, a fabric specimen was placed on a sensor board (aligned at a 45 degree angle) made up of nonconductive, liquid and heat-resistant material. Hot water was prepared in a circulating bath, and its temperature was maintained at 85°C using a temperature control device. The hot water was moved through a circulation system attached with a flow-control valve. This circulation process helped to warm up the water pipe to regulate water

Tap

Sensor board



Flow-controlled valve

Lower sensor (skin simulant)

Upper sensor (skin simulant)

Hot liquids

Sensor wire

Fig. 5.18 Laboratory-simulated hot liquid exposure test in modified ASTM F 2701.

temperature at 85°C. Using a tap, the hot water was passed through the water out- let. By employing a thermocouple at the front of the outlet, water temperature was constantly monitored. It was observed that the temperature at the outlet reached close to 85°C within 0.5 s immediately after opening the water tap, after which point the fabric specimen was continuously exposed to the hot water. The thermal energy transferred through the specimen was measured at direct and indirect con- tact points between the hot liquid and the fabric specimen using two skin simulant sensors (upper and lower sensors). This measured energy was used to calculate the time required to generate second-degree burns, which was interpreted as the thermal protective performance.

*Assessment of thermal protective performance under hot liquid exposure*: Ackerman et al. [22] and Mandal and Song [353] studied the performance of layered fabrics under hot liquid exposure. It was identified that fabrics’ air permeability is the most crucial aspect that affects thermal protective performance under a hot liquid splash. The researchers found that permeable fabrics have a lower performance than nonpermeable fabrics. This is because the permeable fabrics allow a rapid transfer of mass (hot liquid) through fabrics toward human bodies, which generates quick burns on the bodies. On the other hand, nonpermeable fabrics allow a negligible amount of mass transfer through fabrics toward human bodies, for a high performance of these fabrics against hot liquid [76].

It was also identified that the thermal protective performance of fabrics is depen- dent on the properties of hot liquids [22]. Data indicates that the thermal protective performance of fabrics is least effective when exposed to hot water among a compar- ison of three types of liquids: hot water, canola oil, and drilling mud. They inferred that the viscosity of water is the lowest among all these liquids; as a result, hot water easily transfers through fabrics toward firefighters’ bodies. Furthermore, the heat capacity of water is the highest among all these liquids; as a result, transferred hot water mass comprises more thermal energy than the other liquids (canola oil and dril- ling mud). This high thermal energy content of water generates more burns on fire- fighters’ bodies than the other liquids.

*Evaluation of thermal protective performance under steam exposure*: Although it is important to evaluate the thermal protective performance of fabrics in the presence of steam, to date no internationally recognized standard test methods exist for this eval- uation purpose. Many researchers have developed their own customized instruments to evaluate the performance of fabrics in the presence of steam [22,81–83,114]. For example, researchers from the University of Alberta developed an instrument to eval- uate the performance of fabrics under steam exposure ([Fig. 5.19](#_bookmark34)) [22]. By using this instrument, Mandal and Song [353] and Mandal et al. [76] compared the performances of inherently fire-retardant fabrics (eg, Nomex, Kevlar/PBI). In their study, they gen- erated steam at 150°C temperature and directed this steam through a nozzle (at a pres- sure of 200 KPa) onto a fabric specimen placed on a specimen holder. During this exposure, the amount of thermal energy transferred through the fabric was measured by a skin simulant sensor. From this measured energy, the time required to generate the second-degree burns on firefighters’ bodies was calculated as the fabric’s thermal protective performance.

Sample holder

Skin simulant sensor

Sensor wire

Boiler

Nozzle

Fig. 5.19 Laboratory-simulated steam exposure test using the University of Alberta steam tester.

*Assessment of thermal protective performance under steam exposure*: Keiser, Becker, and Rossi [81], Keiser and Rossi [82], Keiser, Wyss, and Rossi [83], Mandal and Song [353], and Shoda, Wang, and Cheng [85] have suggested that imposed high- pressurized steam inserts into fabrics’ structure and gradually condenses. After the condensation phase, all the steam converts into hot water. This hot water generates burn injuries when it comes into contact with human bodies. These researchers iden- tified that permeable fabrics allow more steam transfer toward human bodies than impermeable fabrics. As a result, these researchers suggested that thermal protective clothing should be impermeable in nature to effectively protect from steam exposures. Mandal and Song [353] stated that it is essential to place a moisture barrier in the fab- ric system in order to effectively protect from steam. This impermeable moisture bar- rier will immediately stop steam insertion inside the fabric system, which will ultimately decrease the chances of burns on human bodies [76].

### Evaluation of thermal protective performance using full-scale stationary manikin systems

Many bench-scale tests have been developed to evaluate fabric protective perfor- mance. These tests are a convenient, precise, and inexpensive means of evaluating performance [24,25,76,353]. Although previous researchers evaluated performance using bench-scale tests, these studies were limited with respect to the configuration of thermal exposure tests and the simulation of hazards. The bench-scale tests focused on fabric materials and did not provide accurate information on spatial effect

(microclimate or air gaps between human body and clothing), an important factor to predict clothing performance. As a result, the effects of garment design and construc- tion on thermal protective performance of clothing in current use were not fully stud- ied. Therefore, a great deal of research has been initiated to evaluate the performance of clothing using full-scale manikin systems [131,363,364].

In the early half of the 20th century, Baker and Smith used a full-scale nonin- strumented manikin to evaluate the burning rate of a shirt; similarly, Colebrook used a noninstrumented manikin to test clothing in a wire body form. Although these non- instrumented manikins were extensively used until 1962, the predictions made from these tests were not accurate or realistic [364]. In 1962, Stoll first conducted a test for the United States Navy using a full-scale instrumented manikin [364]. This instrumented manikin was leather-covered and equipped with temperature detector paper and a melting point indicator. By 1972, all these efforts resulted in a full-scale instrumented stationary flash fire manikin system. Recently, a full-scale instrumented stationary hot water spray manikin system was also developed [113]. The development of full-scale instrumented stationary flash fire and hot water spray manikin systems to evaluate thermal protective clothing performance are sig- nificant because they can realistically simulate real flame and hot water exposures, respectively. Additionally, these manikin tests provide information regarding the impact of clothing design, fit, and construction (seams, closures, pockets, or vents) on clothing performance, along with the impact of fiber and fabric properties. Although the flash fire and hot water spray manikin tests are complex and expensive processes, they provide more useful information about the thermal protective perfor- mance of clothing.

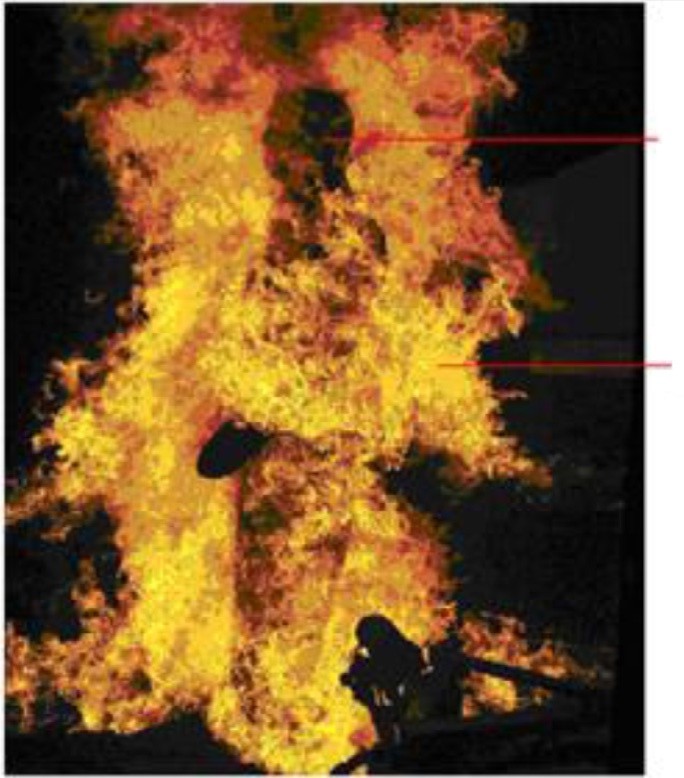
*Working principles of flash fire manikin systems*: Instrumented flash fire man- ikins exist in several research institutes; these include DuPont and North Carolina State University in the United States, University of Alberta in Canada, National Institute of Advanced Industrial Science & Technology in Japan, Swiss Federal Laboratories for Material Science & Technology in Switzerland, and British Tex- tile Technology Group in United Kingdom. Presently, three instrumented flash fire male manikin types—Thermo-Man of DuPont, PyroMan of North Carolina State University (NCSU), and Harry Burns of University of Alberta—are extensively used in protective clothing performance evaluation all over the world. The testing procedure of these three manikin systems to evaluate thermal protective perfor- mance is explained in ASTM F 1930 and ISO 13506, the standard test methods for evaluation of flame-resistant clothing for protection against flash fire simula- tions using an instrumented manikin [365,138] ([Fig. 5.20](#_bookmark36)). The Thermo-Man, developed by DuPont, is a size 40 regular manikin made of a high-temperature flame-resistant polyester [365]. This is a thermally instrumented manikin suspended from the ceiling of a burn chamber equipped with a system capable of generating the equivalent of fuel flash fire in a controlled exposure. This man- ikin is equipped with 122 embedded sensors distributed uniformly over the front and back side of the entire body, each one representing 0.82% of the body area. These sensors possess the capability of measuring incident heat fluxes in a range of 63–126 kW/m2 and have a response time of ≤0.1 s; however, for the

experimental purposes the average heat flux level is set up to 84 kW/m2. The flame is applied to the manikin through eight propane torches for at least 5 s. During flame application, sensors measure the thermal energy transferred through the clothing. The measured thermal energy data is used to evaluate thermal protective performance in terms of time required to generate second- and third-degree skin burn injury using a software package.

NCSU’s PyroMan at the College of Textiles is a size 42 regular manikin made of a high-temperature flame-resistant polyester resin reinforced with fiberglass; this manikin is suspended from the ceiling of a flame-resistant burn chamber (11 in. × 18 in.) [35,334]. Previously, this manikin system was operational with embedded sensors; however, this system was recently upgraded to include a new sensor technology and data acquisition system, as well as a new software package. Now, this manikin is set with 122 PyroCal sensors distributed uniformly over the entire manikin surface. The flame is impinged on this PyroMan manikin up to 84 kW/m2 heat flux for typically 3–5 s from eight propane gas torches that are attached in the surrounding of the manikin; the gas supply line is insulated and electrically heated to provide a constant supply of fuel throughout changes in weather. The manikin is also surrounded by several fans to permit testing under wind conditions, with velocities up to 5 mph. The thermal energy transferred to the sen- sors during testing are measured in both clothed and unclothed (nude) manikin con- ditions, and this measured thermal energy is interpreted in terms of time required to generate second- and third-degree burn injuries to evaluate thermal protective per- formance using the newly developed software.

The flame manikin Harry Burns is located at the Department of Human Ecology of

the University of Alberta, Canada [35,334]. This size 40 manikin is made of fiberglass and can be used in both clothed and unclothed conditions [23]. The manikin is housed in a flame-resistant room with large viewing windows on one wall. The fire chamber is equipped with supply and exhaust ducts, which are automatically controlled to provide safe startup of the system and rapid removal of the products of com- bustion/degradation after a test exposure. Flame is applied to the manikin through 12 propane gas torches. These torches are carefully positioned to create a large volume of fire that can fully engulf the manikin. The propane gas is supplied to the torches through a series of valves and reducers, and pressure-sensitive switches monitor the system to maintain safe operating conditions. The burner of each torch has a pilot flame, which is lighted before the gas is supplied to the torch. The gas control panels monitor the state of each pilot flame and do not open the exposure torch valve if pilot flame is not present. This feature provides both safety and control over the position and number of torches used in each test. The gas control panel also monitors the sta- tus/condition of the gas supply line and safety devices, and will shut the system down and vent the gas in the supply line in case of a malfunction. The flame is applied to the manikin for typically 3–4 s, and heat flux values can be monitored up to 84 kW/m2. The thermal energy transferred to 110 skin simulant sensors attached to the manikin gathers data to measure the time required to generate second- and third-degree burns on firefighters’ bodies using programmable software. This second-degree burn time is used as a thermal protective performance of the clothing.

Manikin

Flame

Fig. 5.20 Full-scale flash fire manikin tests in ASTM F 1930 and ISO 13506.

Based on the above discussion, it can be inferred that the three active flash fire man- ikin systems (Thermo-Man, PyroMan, Harry Burns) work on the same principle and generate a thermal protective performance report in real time on second- and third- degree burn injuries. This report can be further extended using a sophisticated com- puter system that allows a comprehensive analysis of test garment performance, including determination of the percentage of the body area receiving second- and third-degree burns, the total predicted burn injuries of the entire body by percentage, the total accumulated heat received by the sensors, a table of the individual sensor’s response, a plot of burn injury versus time, and a manikin diagram showing burn inten- sity distribution over the body surface. Furthermore, as described, these three flash fire manikin systems possess different operating features; hence, there is a need to tabulate these features to obtain a holistic comparison between them ([Table 5.2](#_bookmark37)). This insight can help apparel engineers to select a particular manikin system for thermal protective performance evaluation as per their requirements.

*Assessment of thermal protective performance using flash fire manikin systems*: Behnke, Geshury, and Barker [365] evaluated the thermal protective performance of clothing made from inherently fire-resistant (Kevlar, Nomex) and chemically mod- ified fire-retardant (Proban cotton, Zipro wool) fabrics. All fabrics had a similar weight of 260–280 g/m2. The coveralls made from these fabrics were worn by the size 40 regular flame manikin “Thermo-Man.” In this study, the authors identified that clothing design has a significant effect on the thermal protective performance.

Dale et al. [366] investigated the thermal protective performance of Nomex-IIIA and Kevlar/PBI fabrics. They evaluated thermal protective performance using the flame manikin developed by the University of Alberta at varying intensified thermal environments. In their study, they concluded that the percentage of body burns increases in higher-intensity thermal environments. Crown et al. [367] mentioned that fabrics used to manufacture underwear have significant effects on burn injuries. In this

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Thermal Protective Clothing for Firefighters

## Table 5.2 Features of Thermo-Man, PyroMan, and Harry Burns

|  |  |  |  |
| --- | --- | --- | --- |
| Features | Thermo-Man | PyroMan | Harry Burns |
| Size | 40 | 42 | 40 |
| Materials | Flame-resistant polyester resin | Flame-resistant polyester resin | Fiberglass |
|  |  | reinforced with fiberglass |  |
| Sensor type | Embedded | PyroCal | Skin simulant |
| Number of sensors | 122 | 122 | 110 |
| Type of torches | Propane | Propane | Propane |
| Number of torches | 8 | 8 | 12 |
| Incident heat flux  Thermal exposure duration | Up to ~126 kW/m2  At least 5 s | Up to ~84 kW/m2  Typically 3–5 s | Up to ~84 kW/m2  Typically 3–4s |

study, they used different garments with different types of underwear to evaluate the thermal protective performance using the manikin. They identified that underwear made from inherently fire-resistant fabrics can provide better protection than the underwear made from chemically modified fire-retardant fabrics.

Pawar [368] evaluated the impact of garment size on thermal protective perfor- mance using the PyroMan manikin. In his study, three different sized garments (40, 42, and 44) made from Nomex and Kevlar/PBI fabrics were selected for the controlled manikin tests. Results showed the clothing made of Nomex fabric displayed more sig- nificant effects on burn injuries than Kevlar/PBI, because Nomex fabric shrinks at the time of flame exposure, which ultimately reduces clothing performance, while a neg- ligible amount of shrinkage occurs in the case of Kevlar/PBI fabric. Pawar concluded that garment size is not a significant concern in thermal protective performance for Kevlar/PBI clothing because no shrinkage is visible in the case of Kevlar/PBI. How- ever, garment size is an important consideration in the case of Nomex fabric due to shrinkage, and a size 42 garment could provide a better protection than sizes 40 or 44. Pawar [368] compared the thermal protective performance of the same set of fab- rics between full-scale manikin tests and bench-scale tests, considering both with and without a spacer (air gap). He found that some sensors distributed over a clothed man- ikin test reveal results similar to the sensor without a spacer in bench-scale tests, while some sensors distributed over the manikin show a similar result to the sensors in bench-scale tests with a spacer (6.4 mm air gap). These observations suggest that it is necessary to evaluate thermal protective performance using the bench-scale test both with and without a spacer to achieve results with an accuracy approaching find-

ings reported in the manikin tests.

Crown et al. [23] evaluated the thermal protective performance of eight garments made from the inherently fire-resistant fabric meta-aramid and its blend. In their study, they developed all the garments in a size 42. These garments were tested by the size 40 Harry Burns manikin at the University of Alberta under 80 kW/m2 heat flux. In this test, it was identified that viscose/meta-aramid fabric-based clothing shows less shrinkage than carbon/meta-aramid fabric-based clothing. Interestingly, this study also indicated that clothing size; fit and style; and amount and number of closures have significant effects on thermal protective performance.

Song et al. [369] developed a numerical model to simulate the flash fire manikin evaluation system. The heat transfer from the simulated flash fire, the clothing, and the air gap between clothing and manikin body were categorized, and clothing perfor- mance was predicted under flash fire exposure conditions. In Song’s study, it was iden- tified that the air gap between the human body and clothing is a key factor for thermal protective performance. This air gap acts as a thermal insulator and slows down heat transfer to the skin. However, Song et al. [369] concluded that if the size of the air gap becomes large, it cannot properly trap the dead air. This situation causes a natural con- vection in the air gap between the human body and clothing, which reduces the thermal protective performance. Mah and Song [370] investigated the impact of garment design on thermal protective performance. In this study, they used the female flash fire man- ikin system to study clothing performance under different designs and sizes. The study demonstrated that clothing size, fit, and style are important for clothing performance. It has been identified that air gap size is also an important factor for thermal protective

performance because it is positively correlated with the time required for second- degree burn injury. Additionally, the air gap size is negatively correlated with energy absorption. A small air gap in between a human body and clothing can absorb little energy, and most of the thermal energy transmits toward the body and generates burn injuries. In this context, a new procedure for calculating the thermal energy transmis- sion was recently proposed by Rossi, Schmid, and Camenzind [86], which is currently being considered in the ISO standardization (ISO CD 13506.1).

*Working principles of a hot water spray manikin system*: Thermal protective perfor- mance against hot water spray was tested using a size 40 instrumented manikin system ([Fig. 5.21A](#_bookmark38)) [113,371]. In this study, each clothing specimen was put on the manikin. Then, the clothed manikin was hung from its head and fastened at the feet by two fetters to keep an upright posture. Hot water (85°C) was sprayed at a pressure of 250 KPa on the manikin for 10 s by four groups (each with three nozzles) of automatically controlled cylindrical spray jets ([Fig. 5.21B](#_bookmark38)). During and after the spray, thermal energy transmit- ted through the clothing specimen in 60s was measured by the sensors. This measured energy was used to evaluate the amount of second-degree scalding/burn injuries to dif- ferent body parts. These second-degree scalding/burn percentages of a particular spec- imen determined the thermal protective performance value of the clothing. A specimen that resulted in lower second-degree scalding/burn percentages had a higher perfor- mance than a specimen that resulted in higher second-degree scalding/burn percentages.



(A)



(B)

Fig. 5.21 Full-scale hot water spray manikin test - A) instrumented manikin system,

B) cylindrical spray jets.

Adapted from S. Mandal, Y. Lu, F. Wang, G. Song, AATCC J. Res. 1 (5) (2014) 7–15.

*Assessment of thermal protective performance using the hot water spray man- ikin system*: Research showed that different sizes of clothing have distinct thermal protective performances under hot water spray, and minimizing mass transfer through clothing is a prime concern to provide effective protection to firefighters [371]. The thickness and layered structure of fabrics used, along with the design features of clothing (pockets, closures, vents), significantly affect the thermal pro- tective performance of impermeable or semipermeable clothing. However, the effect of fabric weight on performance is minimal. Here, fabric thickness had less impact on performance in comparison to clothing design. It was also reported in earlier literature that impermeable clothing demonstrates better performance than semipermeable/permeable clothing, and a proper air gap between the garment and a firefighter’s body is a crucial aspect of improving thermal protective performance [113]. In this context, it has been found that heavy hot water spray and water flow may compress the clothing into firefighters’ bodies, significantly reducing the air gap between them. This situation results in a lower thermal protective performance from the clothing. In this context, a notable point is that the addition of reflective tape on clothing may enhance the clothing’s performance and can provide some extra protection to firefighters [113].

### Evaluation of thermal protective performance using full-scale dynamic manikin systems

In the earlier-mentioned test procedures, the manikins remain stationary, and the flame or hot water is directed onto the clothed manikin system at prescribed loca- tions to evaluate the thermal protective performance. Hence, these procedures do not accurately simulate the firefighters’ activity at the site of a fire. These tests are also limited to garments and do not evaluate the thermal protective performance of other Personal Protective Equipment including helmet, gloves, boots, and self contained breathing apparatus (SCBA). In actual fire hazard scenarios, firefighters are active and move through thermal exposures. During this movement, different parts of the clothing may compress with firefighters’ bodies. At the point of compression, the air gap between clothing and firefighters’ bodies diminishes. This situation ultimately lowers the insulation property of clothing. It seems that use of a dynamic manikin system may provide a better understanding of clothing performance [334,365]. To date, dynamic flame manikin systems have not been fully explored to evaluate cloth- ing performance.

*Working principles of a few dynamic flame manikin systems*: There is a dynamic flame manikin system available in Alden Research Laboratories [supported by the Navy Clothing and Textile Research Facility (NCTRF), and operated by faculty and students of Worcester Polytechnic Institute (WPI)] in Massachusetts to evaluate the thermal protective performance of firefighters’ clothing [334]. Additionally, DuPont also has a full-scale leg manikin system available, Thermo-Leg, to evaluate the thermal protective performance of trousers [365].

Alden Research Laboratories provides a facility to evaluate the thermal protective performance of clothing using a dynamic instrumented life-sized manikin system ([Fig. 5.22](#_bookmark39)). This movable manikin is constructed from fiberglass (its outer surfaces are coated with a high-temperature polymer) and can be equipped with up to 124 black-painted sensors. The experiment is conducted in a 2.4 m × 2.4 m × 3.6 m room, which is a modified ISO 9705 standard room [334,372,373]. This room com- prises two doors (0.81 m × 2.4 m), one facing the other on two opposite walls. These two doors allow the manikin to completely pass through the room, without having to stop its motion inside the room. The movement of the manikin is controlled by a transverse chain driven track mechanism attached to the ceiling. The speed of the movement is monitored by a variable frequency drive (VFD) motor that comprises a forward/backward/off-switch to control the speed of the manikin up to ~0.9 m/s. In this test, the fire scenario is created by using the eight (30 cm) square-size propane torches, and the torches can be arranged in four different configurations to create four various fire scenarios: Configuration A applies even distribution of flames over the manikin’s surface; Configuration B provides intense radiation to the manikin, while limiting flame contact; Configuration C creates flashover conditions over the man- ikin and Configuration D represents wildfire scenarios with low flame heights up to the waist of the manikin. The torches are attached with a propane gas flow (0–70 g/s) controller to deliver a consistent and reproducible fire with accuracy within 1–3%. These torches can give an effective fire HRR in a range of 0–3.08 MW; however, for experimental purposes the average HRR can be set up to 1.6 MW. In this context, Woodward [372] measured the temperature and heat flux on the centerline of the flame at various locations of the room where the manikin’s sensors are expected to be during testing, and he concluded that Configurations A and C have the potential to expose the manikin to a heat flux of 84 kW/m2. Fay [373] also determined that a 1 MW fire can produce heat fluxes of at least 80 kW/m2 at a height ranging from 0.71 to 1.1 m of the room. During testing, sensors attached to the manikin can measure the amount of thermal energy transferred to the manikin (in unclothed and clothed con- ditions) from the fire scenarios to evaluate the time required to generate the second- and third-degree burns on firefighters’ bodies using a software package. In clothed conditions, the time to burn injury can be interpreted as the thermal protective performance of the clothing. Previously, this manikin system allowed for the appli- cation of jackets, pants, gloves, and boots with embedded sensors; recently, this man- ikin system has been upgraded for the application of helmet and SCBA, also with PyroCal sensors. It is noteworthy to mention that it is very difficult to maintain a con- stant heat flux in this type of testing. As a result, it is difficult to repeat the test. In the case of quick movement of the manikin, the sensors also may not get enough time to provide accurate performance readings. Presently, many sensors on this manikin are inoperable and need suitable replacements. It seems that this manikin system needs further development to properly evaluate the performance of thermal protective clothing.



Fig. 5.22 Dynamic flame manikin of Alden Research Laboratories.

Adapted from J.E. Sipe, Development of an instrumented dynamic manikin test to rate the thermal protection provided by the protective clothing (M.Sc. thesis), Worcester Polytechnic Institute, Worcester, MA, 2004.

Similar to the Thermo-Man discussed in [Section 5.2.3](#_bookmark35), the Thermo-Leg was also developed by DuPont. This Thermo-Leg is used to evaluate the thermal protective per- formances of trousers [365]. The Thermo-Leg is a size 40 instrumented fiberglass- epoxy molded leg that simulates human running motion. The motion of the leg is designed based on biomechanical and kinesiology studies to simulate the path of the ankle of a running person. The Thermo-Leg can move at a frequency stride of

1.11 cycle/s (0.9 s/cycle) with an average stride length of 4.43 ft (1.35 m) and can pro- duce a running speed of 9.8 ft/s (3.0 m/s). During this movement, a flame is admin- istered to the leg from four large propane torches at a maximum heat flux value of 84 kW/m2. For the running motion spans of 5.5, 6.5, 7.5, and 8.5 s time intervals, the fire exposure can last for 3, 4, 5, and 6 s, respectively. As the Thermo-Leg is cov- ered with 18 embedded sensors, it can measure the thermal energy transferred through the trousers. The measured thermal energy is used to calculate thermal protective per- formance in terms of time required to generate burn injuries. Although Thermo-Leg can contribute additional useful information regarding the impact of tested trousers’ material performance and design on thermal protective performance, more research is needed to validate the Thermo-Leg test protocol, to refine test procedures, and to develop guidelines for the analysis and interpretation of test results [334,365].

*Assessment of thermal protective performances using dynamic flame manikin systems*: Sipe [334] evaluated the thermal protective performance of PBI clothing using the dynamic manikin system of Alden Research Laboratories. The author

evaluated the thermal protective performance of clothing in two positions: (1) when the manikin is stationary outside of the burn room, and (2) when the manikin is moving through the burn room. It has been identified that radiant heat predominates in the first position. However, when the manikin moves through the flame, a mixture of convec- tive and radiant heat exposure predominates. It has been further identified that the clothing performance is greater when the test is carried out outside the room; the per- formance of the clothing was also higher in the case of quick movement of the manikin in comparison to the slow movement. This is because the intensity of thermal exposure is lower outside the room than the intensity of thermal exposure inside the room. Fur- thermore, Ellison et al. [374] evaluated the thermal protective performance of four different types of fabric-based clothing (A–D): fabrics of clothing A (100% Nomex outer shell, Goretex-laminated 100% Nomex moisture barrier, 100% Nomex quilt thermal liner), fabrics of clothing B (60% Kevlar/40% PBI outer shell, 100% Nomex moisture barrier, 100% Kevlar batt thermal liner), fabrics of clothing C (100% Nomex-IIIA outer shell, laminated Nomex moisture barrier, Sonatara E89 thermal liner), and fabrics of clothing D (100% wool outer shell, 100% cotton thermal liner). The clothing materials of A and B are very common for firefighters in North America; whereas, the clothing materials of C and D are mainly used by firefighters in Victoria, Australia. In this test, three different types of exposures at 1.5 MW were considered:

(1) the manikin was stationary at the doorway of the burn room and exposed to fire for 30 s, (2) the manikin ran through the room at a speed of 0.27 m/s, and (3) the manikin ran through the room at a speed of 0.16 m/s. In this study, the thermal protective per- formance of the clothing was measured in terms of second-degree burn percentages on the manikin’s body as predicted by the sensors attached to the manikin. Clothing with second-degree burn percentages ≥10% on the manikin would not be recommended for use by firefighters, based on the medical profession’s definition of life-threatening burns. It has been found that all four clothing types possessed highest performance values in the case of exposure 1, whereas performance was lowest for exposure 3. Additionally, all four types of clothing generated ≤10% second-degree burns under the three different types of exposure; hence, they are all suitable for use by firefighters in actual fire hazards.

Behnke, Geshury, and Barker [365] evaluated the thermal protective performance of trousers made from inherently fire-resistant (Kevlar, Nomex) and chemically mod- ified fire-retardant (Proban cotton, Zipro wool) fabrics. In the study, they evaluated the thermal protective performance at 84 kW/m2 using the Thermo-Leg developed by DuPont, and it was found that the performance of inherently fire-resistant fabrics-based trousers are higher than the performance of chemically modified fire- retardant fabrics-based trousers. They also compared the thermal protective perfor- mance values obtained from the dynamic Thermo-Leg manikin tests with the thermal protective performance values obtained from the stationary Thermo-Man manikin tests. Both tests used sophisticated heat sensors to provide substantial information on the performance of the trousers’ materials to protect against second- and third- degree burn injuries. It was found that the dynamic Thermo-Leg predicts more burns than the nonmovement legs in Thermo-Man. This is because the dynamic legs have less insulative air gap between the sensors and trousers in comparison to the non- dynamic legs; as a consequence, the dynamic legs demonstrate more burns than

the nondynamic legs. Additionally, the dynamic legs comprise more burns in between the knee and hip area because the back side of the heated trousers comes in direct con- tact with the sensors in this area and enhances the conductive transfer of heat to the sensors for generating more burns. In this study, it was inferred that the dynamic Thermo-Leg can more accurately simulate the actual thermal environments that are faced by running firefighters in a flash fire accident; however, the Thermo-Leg can represent only a part of the human body. It was also concluded from this study that it is necessary to maintain the strength and integrity of the garment in dynamic test configurations. As a lot of stretch occurs during movement, it is difficult to get a good thermal protective performance without maintaining the proper integrity of the tested garments.

# Clothing comfort (physiological) evaluation

As mentioned before, clothing can provide physiological comfort to its wearers by properly transmitting the metabolic heat and sweat-vapor from wearers’ bodies to their ambient environment [306–311]. Various fabric attributes are important for the physiological comfort provided by any clothing; these attributes are: thermal resistance; evaporative resistance; air permeability; and water (liquid sweat) wickability/absorptivity (rate of water wicking and absorbency, and total water absorbent capacity) [375–378]. Although fabrics’ air permeability and/or water wickability/absorptivity can be important attributes for the physiological comfort provided by regular clothing, these are not as important for the physiological com- fort provided by thermal protective clothing. This is because an air-permeable and/ or water absorbent fabric may lower the thermal protective performance of the clothing under various thermal exposures (eg, radiant heat, hot liquids), which can be detrimental for wearers (firefighters) [24,29,75,76]. Thus, thermal resis- tance and evaporative resistance are the two key fabric attributes for the physio- logical comfort provided by protective clothing. Furthermore, a combined attribute of the thermal and evaporative resistance of a thermal protective fabric, called the THL capacity of the fabric, can be important for the physiological com- fort provided by the clothing [31,379–381]. In this context, the thermal resistance of a fabric can be defined as the resistance provided by the fabric to the flow of dry metabolic heat from wearers’ bodies to the nearby environment; the evaporative resistance of a fabric is the resistance provided by the fabric to the flow of sweat-vapor from wearers’ bodies to the nearby environment; and THL is the total amount of metabolic heat transferred through a fabric by the combined dry and evaporative heat exchanges [377,382]. A fabric with a low thermal/evaporative resistance and a high THL value generates lower heat stress for wearers, resulting in higher physiological comfort. Related research at the Hohenstein Institute in Germany has established an association between rain suit fabrics’ intrinsic evap- orative resistances and the comfort perceptions of human subjects wearing the suit under different environmental conditions and level of activity. This is shown in [Table 5.3](#_bookmark40). Similarly, the European standard EN 469 suggested that the intrinsic

fabric evaporative resistance of firefighters’ protective clothing should not be

>30 m2 Pa/W for providing an effective physiological comfort to firefighters. Additionally, the NFPA 1971:2007 standard suggested that the THL of the fabric used in thermal protective clothing should be at least 205 W/m2 in order to provide

physiological comfort to working firefighters.

## Table 5.3 Association between intrinsic fabric evaporative resistances and clothing comfort perception

|  |  |
| --- | --- |
| Comfort perception | Intrinsic fabric evaporative resistances (m2Pa/W) |
| Very good | <6 |
| Good | 6.1–13.0 |
| Satisfactory | 13.1–20.0 |
| Unsatisfactory | >20 |

Overall, it can be inferred that a thorough understanding of thermal resistance, evap- orative resistance, and/or THL is essential to properly evaluate clothing’s (physiolog- ical) comfort [380]. The following section discusses in detail the evaluation/calculation and assessment of thermal resistance, evaporative resistance, and/or the THL of fabric and clothing ([Sections 5.3.1](#_bookmark41) and [5.3.2](#_bookmark54)). Some researchers have directly evaluated the physiological comfort provided by clothing using human subjects [383,384]; therefore, the evaluation of clothing comfort through human trials is thoroughly discussed in [Section 5.3.3](#_bookmark66).

### Evaluation/calculation and assessment of thermal resistance, evaporative resistance, and THL of fabrics

In the late 1990s, the ISO 5085-1 and BS 4745:2005 standards (guarded hot plate and Togmeter method) were widely used to evaluate the thermal resistance of fabrics, and the CGSB 1977 standard (control dish method) was highly acceptable for evaluating fabrics’ evaporative resistance. In order to evaluate both thermal and evaporative resistance, the ISO 11092 standard (Measurement of Thermal and Water Vapor Resistance under Steady-State Condition using Sweating Guarded Hot Plate) was developed in 1993 by the scientists at the Hohenstein Institute in Germany. Then, the NFPA developed a method to determine THL through thermal protective fabrics or fabric systems using the ISO 11092 stan- dard. Later, this THL evaluation method was added to several NFPA standards (NFPA 1971, NFPA 1977, NFPA 1951, NFPA 1999) [380]. Next, the members

of the ASTM F23 committee decided to compile the evaluation procedures of thermal resistance, evaporative resistance, and THL in one document, which

resulted in the ASTM F 1868 standard: Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate [379–381,385]. This ASTM F 1868 standard is widely used to evaluate/calculate thermal resistance, evapora- tive resistance, and THL.

The ASTM F 1868 standard covers the evaluation/calculation of thermal resis- tance, evaporative resistance, and THL of fabrics, films, coatings, foams, leathers, and multilayer fabric assemblies used in clothing, under steady-state conditions [386]. The “sweating guarded hot plate” that acts as a human body is used to evaluate the thermal and evaporative resistances of a fabric or a multilayered fabric system ([Fig. 5.23](#_bookmark42)) and is housed in a closed chamber so that the experimental parameters (hot plate temperature, ambient air temperature, ambient air relative humidity, ambi- ent air velocity) can be controlled manually and effectively. This guarded plate is composed of a test plate, guard section, and bottom plate; each can be electrically con- trolled at a constant temperature in the range of human skin temperature (33–36°C), and the temperature control may be achieved by independent adjustment to the voltage, current, or both, supplied to the guarded plate using solid-state power sup- plies, solid-state relays (proportional time on), adjustable transformers, variable impedances, or intermittent heating cycles. Here, the guard section is designed to pre- vent the lateral loss of heat from the test plate; and the bottom plate is maintained to prevent the downward loss of heat from the test plate and guard section. The guard section and bottom plate force all the heat generated in the test plate to flow in an upward direction [387]. The temperature of the guarded plate and its ambient air can be measured with an accuracy of 0.1°C using temperature sensors (thermistors, thermocouples, resistance temperature devices (RTDs), or equivalent sensors). The relative humidity can be measured with an overall accuracy of 4% using either a wet-and-dry bulb psychrometer, a dew point hygrometer, or any other electronic humidity measuring device. And, the air velocity can be measured with an accuracy of 0.1 m/s using a hot wire anemometer attached at 15 mm from the plate surface [385,386].

The following sections discuss individually and in detail the procedures of ther- mal resistance evaluation, evaporative resistance evaluation, and THL using the ASTM F 1868 standard. Although the ASTM F 1868 standard is the best way to isolate and evaluate thermal resistance and evaporative resistance individually, some researchers feel that it is not realistic, as dry and evaporative heat losses occur simultaneously from a human body to the ambient environment, and there may be interactions between the dry and evaporative heat flows which this test does not capture [385]. Additionally, the devices used in ASTM F 1868 for deter- mining clothing properties ignore the physiological state of the wearer and are inadequate to evaluate the transient thermal properties of clothing. Keeping this point in mind, Psikuta, Wang, and Rossi [30] developed a thermo-physiological human simulator that can provide more realistic measurement of comfort proper- ties of clothing. By using this human simulator, ISO is currently developing a stan- dard (ISO CD 18640) that can evaluate the physiological comfort properties of clothing.

Water reservoir

Air-flow hood

Test plate

Fabric specimen

Guard section

Bottom plate

Guard section

Fig. 5.23 Thermal and evaporative resistance evaluation tester.

### Thermal resistance evaluation

In order to evaluate the thermal resistance of a fabric or a multilayered fabric sys- tem under steady-state condition, the temperature of the test plate (shown in [Fig. 5.23](#_bookmark42)) is kept at 35 0.5°C (without fluctuating more than 0.1°C during test- ing) to simulate human body temperature. The ambient air of the plate can be set at 04–25°C temperature (without fluctuating more than 0.1°C during testing) and 20–80% relative humidity (without fluctuating more than 4% during testing); and the air flow over the plate can be controlled at a speed of 0.5–1 m/s (without fluctuating more than 0.1 m/s during testing). The air temperature is selected such that it will generate a power level in the middle range of the instrument while maintaining a plate temperature of 35°C, and thicker fabrics always need to be tested at lower air temperatures; any relative humidity can be selected (within the range of 20–80%) as it has the least impact on the thermal resistance of a fabric or a multilayered fabric system under steady-state conditions. After setting the experimental parameters (the temperature of the plate and ambient air, relative humidity of the ambient air, and the ambient air velocity) as per requirements, a fabric or a multilayered fabric system specimen is placed on the test plate with the side normally facing the human body towards the plate; in the case of multiple layers, it is necessary to arrange the specimens on the plate as on the human body. When the specimen reaches the steady-state condition, the temperature at the plate surface and the ambient air temperature on the specimen’s surface are determined. Using the temperature values of the plate surface (*T*s) and the air temperature (*T*a), the total thermal resistance (*R*ct) provided by the specimen and the plate boundary air layer is calculated using Eq. [(5.19)](#_bookmark43) given in the ASTM F 1868 standard, where, *R*ct =total thermal resistance provided by the specimen and air layer (K m2/W); *A* =area of the plate (m2); *T*s =surface temperature of the plate (°C); *T*a =air temperature (°C); and *H*c =power input (W).

Here, it seems that a significant amount of trapped air on the boundary of the bare hot plate surface contributes to the *R*ct. Thus, the intrinsic thermal resistance (*R*cf) of the specimen can be determined by subtracting the thermal resistance (*R*cpb) of the bare plate from the *R*ct (Eq. [5.20](#_bookmark44)). This *R*cf determination process was developed based on the assumption that the air layer resistance measured on the bare plate is the same as the air layer resistance on the surface of the tested specimen. Although this *R*cf deter- mination process is easy, the assumption is not always true. This is because the heat flux from the bare plate is often greater than the heat flux from the surface of the tested fabric specimen, particularly for thick specimens, unless the temperature difference between the plate surface and the air is adjusted to compensate for the added thermal resistance of the tested specimen. Additionally, the emissivity of the plate may not be comparable to the emissivity of the tested specimen, and this may affect the radiant heat flux through the air layer [385]. One point of note: the *R*ct/*R*cf value obtained from the Eq. [(5.19)](#_bookmark43) or [(5.20)](#_bookmark44) is an SI-unit; these values needs to be multiplied by 6.45 to convert the SI-unit to a more commonly used thermal resistance unit “*clo*” [386]. Here, 1 “*clo*” is equivalent to 0.155 K m2/W, and the value of the “*clo*” was selected as roughly the thermal resistance (insulation) value of typical indoor clothing that can keep a resting man (producing heat at the rate of 58 W/m2) comfortable in an envi- ronment at 21°C with air movement at 0.1 m/s.

*R*ct = (*T*s — *T*a)*A*/*H*c (5.19)

*R*cf = *R*ct — *R*cpb (5.20)

Although the ASTM F 1868 standard is widely used to evaluate the thermal resistance, this standard possesses several limitations [377,385,386]. For example, the tested specimen should be large enough to cover the surface of the test plate and the guard section completely in order to prevent any heat loss; a specimen thicker than 0.5 cm should be tested on a plate with a large guard section to prevent any heat loss through the fabrics’ edges (if a large guard is not used, a lower thermal resistance value will be measured); the tested specimen should be free from any undesirable wrinkles or bub- bles, and there should be no unwanted air gap between the plate and the specimen, as well as within the specimen, to accurately evaluate the thermal resistance value. The ASTM F 1868 standard method is unsuitable to accurately evaluate the thermal resis- tances of very thin fabric specimens because they do not adhere to the plate well. Air tends to become trapped under the specimens, which erroneously enhances the eval- uated thermal resistance values, while the standard is limited to evaluating thermal resistance values within a range of 0.002–0.5 K m2/W.

Similar to the ASTM F 1868 standard, the ISO 11092 standard can be used to eval- uate the thermal resistance of any fabrics/films/battings using the following experimen- tal parameters under steady-state conditions: a test plate temperature of 35°C, an ambient air temperature of 20°C, an ambient air relative humidity of 65%, and an ambi- ent air velocity of 1 m/s (horizontal air flow with a 5–10% level of turbulence). In this ISO 11092 standard, the horizontal air flow may contribute to the nonuniformity in the ambient air temperature or humidity (or both) across the plate, particularly when the

heat flux from the plate is high (ie, the test is performed on the bare plate and/or thin fabrics). This is because the hot test plate is exposed to the air stream first and the air gains heat or humidity or both as it crosses the test section. This kind of problem may not be prominent in the case of vertical air flow, and vertical air flow can realistically sim- ulate real life conditions when clothing is worn; however, only a few labs have a hood capable of generating vertical air flow [385]. Another standard is available to evaluate thermal resistance: ASTM D 1518. This standard evaluates the thermal resistance of a batting or a batting/fabric system’s specimen, under steady-state conditions. It mea- sures the heat transfer from a warm, dry, constant-temperature, horizontal flat-plate up through a layer of the test specimen to a cool atmosphere and calculates the thermal resistance of the specimen; the measurements are made under still air over the speci- men. It seems that the ASTM D 1518 standard is mainly limited to testing fabric used in cold-weather protective clothing, sleeping bags, and bedding systems, along with sev- eral other limitations. The standard is restricted to determinations on specimens of bat- tings and layered batting/fabric assemblies having an intrinsic thermal resistance from

0.1 to 1.5 K m2/W and thicknesses not in excess of 50 mm; it is also limited to evalu- ating the thermal resistance of fabric under a still air condition, which is not acceptable in all scenarios, Additionally, this standard was developed with a conception of fabric as a homogeneous material, although most fabrics have heterogeneous structures (ie, mixtures of fiber and air, composite) [385,388].

Despite differing parameters, all the above-mentioned standards (ASTM F 1868, ISO 11092, ASTM D 1518) evaluated thermal resistance using a single hot test plate. This single-plate method can simulate a test in which tested fabrics are exposed to ambient environment. However, this type of simulation is not always acceptable; sometimes, there is a need to test a fabric that is shielded from the ambient environ- ment by an outer layer. For example, the thermal battings/liners in firefighters’ cloth- ing are always shielded from the ambient environment by the shell fabrics. In order to evaluate the thermal resistance of a fabric in a shielded condition, a two-plate method is required [377]. In this test method, a fabric specimen is placed on a hot plate (rep- resenting the human body) and then a cold plate (representing the outer layer) is placed on the specimen—this method utilizes heat flow principle from the hot plate towards the cold plate through the specimen, and measurement of the temperature gradient through the tested specimen is made using thermocouples ([Fig. 5.24](#_bookmark45)) [377,389,390]. Presently, the ASTM C 177 standard test method is also available to evaluate the thermal resistance of any material under steady-state conditions using a wide range of experimental parameters; however, this method is not specifically designed for textile materials [385,391].

Fabric specimen

Thermocouples

Fig. 5.24 Schematic diagram of the two-plate test method to evaluate thermal resistance.

### Evaporative resistance evaluation

In order to evaluate the evaporative resistance, two circumstances are preferred: isothermal and nonisothermal [387]. In isothermal circumstances, the temperatures of the test plate and its ambient air are set at 35 0.5°C (without fluctuating more than 0.1°C during testing) and the relative humidity of the ambient air is set at 40 4% (without fluctuating more than 4% during testing) by maintaining an air velocity in between 0.5 and 1 m/s (without fluctuating more than 0.1 m/s during testing). The plate temperature is the same as the ambient air temperature, so no dry heat exchange occurs between the plate and the ambient air. In nonisothermal circumstances, various experimental parameters (the temperature of the test plate and ambient air, relative humidity of the ambient air, and the ambient air velocity) can be set the same as the experimental parameters of the thermal resistance (*R*ct/*R*cf) evaluation (discussed in the previous section). Here, the ambient air tem- perature is lower than the plate’s temperature, so the dry heat loss can occur simul- taneously with evaporative heat loss. In nonisothermal circumstances, the ambient air temperature, relative humidity, and velocity can be set as per researchers’ requirements. After setting up the isothermal or nonisothermal circumstances as per requirements, water is fed to the surface of the plate (to simulate the sweat- vapor on wearers’ bodies) and the guard section; then, the plate and guard section are covered with a liquid barrier (eg, untreated cellophane film, microporous poly-

tetrafluoroethylene film) having a permeability index >0.7. Thereafter, a fabric or a multilayered fabric system specimen is placed on the liquid barrier-covered plate

with the side normally facing the human body towards the plate; in the case of multiple layers, it is necessary to arrange the specimens on the plate as on the human body. When the fabric or fabric system specimen reaches the steady-state condition, the temperature at the plate surface (*T*s) and the ambient air temperature (*T*a) on the fabric surface are determined. By using the *T*s and *T*a, the water vapor pressure at the plate surface (*P*s) and air (*P*a) are recorded, respectively, by employing internationally recognized water vapor saturation tables. Then, Eqs. [(5.21), (5.22)](#_bookmark46) are used to evaluate the total evaporative resistance (*R*et of the specimen, the liquid barrier, and the plate boundary air layer) in isothermal and nonisothermal circumstances, respectively. Here, it seems that the (*T*s — *T*a)· *A*/*R*ct in Eq. [(5.22)](#_bookmark47) can be substituted with *H*c (power input) according to Eq. [(5.19)](#_bookmark43); thus, the simplified form of Eq. [(5.22)](#_bookmark47) is shown in Eq. [(5.23)](#_bookmark48) and can be used to evaluate the total evaporative resistance (*R*et). Similar to intrinsic thermal resistance (*R*cf), intrinsic evaporative resistance (*R*ef) of the specimen is also determined by subtracting the evaporative resistance of the liquid barrier- covered plate (*R*ebp) from the *R*et (Eq. [5.24](#_bookmark49)).

*Note*: The total evaporative resistance (*R*et) of the specimen under nonisothermal

circumstances can also be called apparent total evaporative resistance (*RA*). Here, the apparent term is used as a modifier to total evaporative resistance (*R*et) to reflect the fact that condensation may occur within the tested fabric specimen, and the *RA* values of fabrics can only be compared to those of other fabrics measured under the same nonisothermal conditions.

et

et

*R*et = (*P*s — *P*a)*A*/*H*E (5.21)

*R*et/*RA* = [(*P*s — *P*a)*A*]/[*H*E — (*T*s — *T*a)*A*/*R*ct] (5.22)

et

*R*et/*R*A = [(*P*s — *P*a)*A*]/[*H*E — *H*c] (5.23)

et

*R*ef = *R*et — *R*ebp (5.24)

where *R*et =total evaporative resistance provided by the fabric specimen, liquid barrier, and air layer (kPa m2/W); *A* =area of the test plate (m2); *P*s =the water vapor pressure at the plate surface (kPa); *P*a =the water vapor pressure in the air (kPa); and *H*E =power input (W) to keep the plate heated at 35 0.5°C when water vapor evaporates from the surface of the plate and diffuses through the test specimen into the ambient environ- ment. The ASTM F 1868 standard is widely used to evaluate evaporative resistance because this standard can accurately simulate the metabolic heat and sweat-vapor trans- fer conditions present in a skin/clothing system [32]. However, this standard possesses several limitations/challenges [377,385,386]. In order to obtain consistent and accurate evaporative resistance results, it is important that the tested specimens be large enough to cover the surface of the test plate and the guard section completely to prevent any moisture transport through the edges of the specimens; the specimens must also remain flat against the plate during testing. This flat configuration will minimize the occur- rence of unwanted air layers between the plate and specimens as well as within the spec- imens; eventually, the impact of air layers on the evaluated results of evaporative resistance can be minimized to obtain a consistent/accurate result. Some fabric spec- imens have a tendency to ripple, swell, or curl, or otherwise not lie flat during testing. This tendency is frequently visible in hydrophilic coating or laminated fabric speci- mens when they absorb water from the test plate during testing [385]. In this case, it is necessary to eliminate bubbles, wrinkles, curls, and so on, by smoothing the speci- mens by hand without compressing or stretching them. Thereafter, the tested speci- mens’ leading edges need to be carefully secured, using water vapor impermeable adhesive tapes or other devices (metal bars, magnets, etc.,) in order to consistently/ accurately evaluate evaporative resistance [386]. Additionally, water condensation may develop between the plate and the tested fabric specimen, or within the tested fab- ric specimen, or both; this condensation may significantly affect the evaluated results of evaporative resistance [385]. The ASTM F 1868 standard is also limited to evaluating the evaporative resistance within a range of 0.0–1 kPa m2/W [386].

Similar to the ASTM F 1868 standard, another standard, ISO 11092, is also

frequently used to evaluate the evaporative resistance of any fabrics/films/battings using the following experimental parameters under steady-state condition: test plate and ambient air temperature of 35°C (isothermal circumstances), an ambient air relative humidity of 40%, and an ambient air velocity of 1 m/s (horizontal air flow with a 5–10% level of turbulence) [377]. However, the unit of evaluated evaporative resistance by the ISO 11092 standard is m2 Pa/W, which is different from the unit (m2 kPa/W) mentioned in ASTM F 1868; simply multiply the ASTM based evaporative resistance by 1000 to convert it into ISO based evaporative resistance. Both standards (ASTM F 1868 and ISO 11092) only evaluate the evaporative resistance of a fabric or a fabric system that represents the resistance provided by the fabric or fabric system to the flow of

sweat-vapor from wearers’ bodies to their nearby environment. However, the sweat- vapor evaporative resistance and sweat-vapor permeability of a fabric or a fabric system are inversely related [377,385]; thus, the sweat-vapor permeability can be directly eval- uated to indirectly calculate sweat-vapor evaporative resistance using Eq. [(5.25)](#_bookmark50), where, *R* =sweat-vapor resistance of the fabric or fabric system (cm); *Q* =weight change of the tested fabric or fabric system during test period *t* (g); *t* =test period (s); *A* =area of the exposed test fabric or fabric system (cm2); *D* =diffusion coefficient

of the tested fabric or fabric system (cm2/s); Δ*C* =difference in water vapor concentra- tion across the tested fabric or fabric system (g/cm3); and *Q*/*At* =sweat-vapor perme-

ability that can be evaluated directly [376]. To directly evaluate the *Q*/*At*, many standard test methods (ASTM E 96, JIS L 1099, CGSB 49, and BS 7209) are available, which evaluate the water vapor permeability (WVP) or moisture vapor transmission rate (MVTR) of a fabric or a fabric system. These test standards evaluate the water flow in a unit of time through the unit area of a fabric or a fabric system under a specific con- dition of temperature and relative humidity [387]. In general, the WVP or MVTR can be evaluated using Eq. [(5.26)](#_bookmark51), where, *M*0 =weight of the fabric or fabric system before the test (g); *M*1 =weight of the fabric or fabric system after the test (g); *t* =time between successive weighing of the fabric or fabric system (h); and *A* =area of the exposed test fabric or fabric system (m2) [377]. In this context, a notable point is that these standards (ASTM E 96, JIS L 1099, CGSB 49, and BS 7209) did not consider that convective water vapor flows through the pores existing in the structure of a fabric or a fabric sys- tem. This convective flow can be more prominent when the pressure gradient across the fabric or fabric system is very high, or the structure of the fabric or fabric system is highly porous; this situation can affect the MVTR [392]. Keeping this point in mind, the ASTM F 2298 standard was developed in 2003; this standard covers the measure- ment of moisture vapor transport and gas flow properties of fabrics, membranes, or membrane laminates that are usually used in protective clothing [387]. For comparison purposes, McCullough, Kwon, and Shim [387] evaluated the WVP or MVTR using the ASTM E 96, ASTM F 2298, and JIS L 1099. They found that the evaluated WVP or MVTR from the ASTM E 96 is highly correlated (regression coefficient value 0.97) with the evaluated WVP or MVTR from the ASTM F 2298. Thus, both standards (ASTM E 96 and ASTM F 2298) can be used for the evaluation of WVP or MVTR. However, the ASTM F 2298 standard method is much faster to perform than the ASTM E 96 standard method. Furthermore, McCullough, Kwon, and Shim [387] found that the evaluated WVP or MVTR from the ASTM E 96, ASTM F 2298, or JIS L 1099 is neg- atively correlated with the evaluated *R*et/*R*ef value from the ASTM F 1868 (isothermal). This negative correlation is expected because the WVP or MVTR and the *R*et/*R*ef are conceptually opposite parameters. It has also been identified that the WVP or MVTR from the JIS L 1099 is highly correlated with ASTM F 1868. Thus, both standards (JIS L 1099 and ASTM F 1868) can be a substitute for each other, However, the JIS L 1099 standard method is often preferred by fabrics/clothing manufacturers because it is quick, less cumbersome, and more cost-efficient than the ASTM F 1868. Additionally, the JIS L 1099 is also the basis for the new ISO 15496 standard, Measurement of Water Vapor Permeability of Textiles for the Purpose of Quality Control; as a consequence, the JIS L 1099 standard is more acceptable in the industry than the ASTM F 1868 standard [387].

*Note*: The ASTM E 96, ASTM F 2298, and JIS L 1099 standards only measure the WVP or MVTR; none of these standards evaluate the dry thermal resistance as the ASTM F 1868 standard does. Thus, any conclusion on the heat exchange between a clothed body and the ambient environment derived from the ASTM E 96, ASTM F 2298, or JIS L 1099 standards needs to be employed with caution, because both fab- ric attributes (*R*et/*R*ef/WVP and *R*ct/thermal transmission) are needed for characteriz- ing the heat exchange [387].

1

*R* = *QD*(Δ*C*)*At* (5.25)

WVP/MVTR g/m2/day = (*M*0 — *M*1)24

*At*

(5.26)

### THL calculation

In order to evaluate the THL of a thermal protective fabric or fabric system, first the intrinsic thermal and evaporative resistances of the fabric or fabric system are eval- uated under steady-state conditions using the earlier-mentioned procedures. In this evaluation process, the following experimental parameters are considered as per the NFPA guideline: the test plate temperature (35 0.5°C), the ambient air temper- ature (25 0.5°C), the ambient air relative humidity (65 4%), and the ambient air velocity (as per requirements). After evaluating the thermal and evaporative resis- tances, the THL is calculated according to Eq. [(5.27)](#_bookmark52) given in the ASTM F 1868 stan- dard, where, *Qt*/THL is total heat loss, *R*cf is the average intrinsic thermal resistance of the fabric or fabric system in K m2/W, and *R*ef is the average apparent intrinsic evap- orative resistance of the fabric or fabric system in m2 kPa/W [24,31–33]. According to Eq. [(5.27)](#_bookmark52), *R*cf and *R*ef are denominators to calculate the *Qt* and are inversely related to the *Qt*. This means that a fabric with high intrinsic thermal and evaporative resistance possesses a lower THL.

10°C

ef

3.57kPa

*Qt*/THL =

*R*cf

+ 0.04 + *RA* + 0.0035 (5.27)

The ASTM F 1868 standard is extensively used to calculate the THL of a thermal pro- tective fabric or fabric system due to its convenient reproducibility. In 2001, the THL of a set of fabrics was calculated using the ASTM F 1868 standard in five different laboratories: Kansas State University, Underwriters Laboratories Inc., Navy Clothing and Textile Research Facility, W.L. Gore & Associate Inc., and North Carolina State University [387]. The interlaboratory THL test results were compared according to ASTM E 691 to evaluate the repeatability (the variability between independent test results obtained within a single laboratory by the same operator using the same equip- ment) and reproducibility (the variability between independent test results obtained from different laboratories) of the ASTM F 1868 standard. It has been confirmed that ASTM F 1868 possesses a high reproducibility and repeatability [387]. However, this

ASTM F 1868 test standard does have some shortcomings and limitations [377,386,387]. For example, reaching the steady-state condition of the thermal pro- tective fabric or fabric system is often quite difficult during the evaluation of thermal and evaporative resistances; the tested fabric or fabric system may lift off from the plate, especially when tested under an ambient air velocity of 1 m/s, which can result in an abnormally high thermal and evaporative resistance (resulting in a low THL); the standard does not specify the direction of the ambient air flow or the level of air tur- bulence to evaluate the thermal and evaporative resistance; and, not least, the overall THL calculation procedure is very tedious and time-consuming. Furthermore, the THL value of a thermal protective fabric or fabric system in this standard is calculated in the normal ambient environment (see experimental parameters); thus, the calcu- lated THL value of thermal protective fabrics may not be applicable in actual fire haz- ard scenarios as faced by firefighters. It is also necessary to remember that the thermal exchange between firefighters and their ambient environment is an extremely compli- cated subject that involves many factors in addition to the steady-state thermal and evaporative resistance values of thermal protective fabrics. Therefore, the THL values calculated using this standard may or may not indicate the relative merit of a particular thermal protective fabric or fabric system for a given clothing application [386].

Given the above context, the NFPA 1971 standard set a guideline in 2007 that the THL value of a thermal protective fabric used in firefighters’ clothing should be at least 205 W/m2, which is much higher than that of 130 W/m2 in the NFPA 1971–2000 standard. It seems that the importance of the accurate/systematic/realistic evaluation of the THL is increasing [379]. To accurately evaluate the THL, it is essen- tial to understand the various common advantages and disadvantages of the thermal and evaporative resistance evaluations employing the universally used sweating guarded hot plate method described in various standards ([Table 5.4](#_bookmark53)). According to [Table 5.4](#_bookmark53), the sweating guarded hot plate method has several disadvantages; thus, con- stant development of the method for an accurate/systematic/realistic evaluation of the thermal and evaporative resistance is essential to design thermal protective clothing for firefighters with a proper THL.

## Table 5.4 Advantages and disadvantages of the sweating guarded hot plate method

|  |  |  |  |
| --- | --- | --- | --- |
| Sweating guarded hot plate method | | | |
| Advantages | | Disadvantages | |
| l | Best laboratory method | l | Expensive |
| l  l  l  l | Reproducible and repeatable Same specimen can be used for thermal and evaporative resistance evaluations  Layered fabrics can be tested  Compatible with the human/clothing thermal balance theory | l  l  l | Complex to use  Does not account for impact of air layers within layered fabrics or air flowing through fabrics  Difficult to use under transient thermal conditions of the fabric sample |

### Assessment of thermal resistance, evaporative resistance, and THL

Many researchers evaluated the thermal resistance, evaporative resistance, and THL of fabrics using the equipment/methods described in various standards (eg, ASTM F 1868, ISO 11092, ISO 5085-1, BS 4745:2005, CGSB 1977, ASTM D 1518) or

by employing their own customized instruments/procedures. To further understand evaporative resistance, a group of researchers also evaluated the WVP or MVTR of fabrics using standardized (eg, ASTM E 96, JIS L 1099, CGSB 49, BS 7209, ASTM 2298) or nonstandardized equipments/methods [393–424]. These studies have iden- tified that fabric features (eg, fiber types, weaves, design, weight, thickness, porosity) and ambient environmental variables (air, temperature, relative humidity) affect heat and/or moisture/water vapor transfer (convective/conductive/radiative/diffusive) through fabrics, which ultimately affect thermal resistance, evaporative resistance, and/or THL. However, it was very difficult to obtain a clear relationship between the individual fabric features and thermal resistance, evaporative resistance, and/or THL This is because most of these features are so profoundly interrelated it is impos- sible to separate them.

Black and Matthew [396] and Rees [397] studied the thermal resistance of fabrics. They examined the effect of environmental air relative humidity on the thermal resis- tance of fabrics, and found that thermal resistance is highly dependent upon relative humidity. They concluded that fabrics gain different levels of moisture under different levels of humidity, and this gained moisture affects thermal resistance. Black and Matthew [396] proved through experimentation that a marked reduction of thermal resistance takes place when the moisture content increases from 0% to 75% of the dry weight of fabrics. Furthermore, Farnworth [393] evaluated the thermal resistance of several commercial synthetic fabrics at a compression of 0.16 kPa under varied air temperatures. He found that the fiber used to manufacture the fabrics, along with the fabrics’ thickness and weight, has a significant effect on thermal resistance; a fabric which comprises a high percent fiber volume, a small fiber diameter, or a low thermal conductive fiber will possess high thermal resistance. Additionally, a fabric with high thickness and weight always traps air inside the fabric structure; as this air prevents heat transfer through fabrics, a fabric with high thickness and weight possesses higher ther- mal resistance than a fabric with low thickness and weight (when the same fiber is used to manufacture both the fabrics). For the same reason, heat transfer through a low- density fabric is reduced, and this type of fabric has a higher thermal resistance than high-density fabric. Hes, Araujo, and Djulay [398] analyzed the thermal resistance of multilayered woven fabric assemblies under steady-state and transient-state thermal conditions. In this study, two types of woven fabric assemblies were used: in the first, each layer of woven fabric was free from its subsequent layer(s), and in the second each layer of woven fabric was spot-bonded with its subsequent layer(s) by thermal fusion with polymer dots. They found that the free air layers (caused by raised surface fibers) between fabrics in the first type of assembly have a significant effect on thermal resis- tance. In fact, the free air layer-based fabric assembly exhibited up to 50% higher ther- mal resistance than the spot-bonded fabric assembly. For the spot-bonded fabric

assembly, the thermal absorptivity increased up to 32% when compared to the free air layer-based fabric assembly. Similarly, Matusiak [399] investigated the thermal resis- tance of single and multilayered fabrics of woven and/or nonwoven structures. In this study, it was found that a highly porous nonwoven fabric possesses greater thermal resistance than a less porous and tightly woven fabric; this is because the tightly woven structure possesses less air than the nonwoven structure; as a consequence, the heat flow through the woven fabric is much higher than the nonwoven fabric. Additionally, the configuration of each layer in a multilayered fabric has an impact on the thermal resis- tance. A multilayered combined woven and nonwoven fabric assembly generally has higher thermal resistance than a multilayered woven fabric assembly, because the com- bined woven and nonwoven assembly possesses higher amounts of air than the woven fabric assembly alone. Moreover, Bhattacharjee and Kothari [400] modeled the thermal resistance of woven fabrics by considering conductive and radiative heat transfer through the fabrics in normal ambient environments. They considered that the basic weaves in the woven fabrics can be represented as a repeating unit consisting of stacked yarn, unsupported yarn between interlaced warp and weft, and air pores. In this study, it was found that the air pores affect both the conductive and radiative heat transfer through the fabrics, which, in turn, affect the thermal resistance of the fabric. Addition- ally, the stacked yarn and unsupported yarn mainly affect the conductive heat transfer through the fabrics or the thermal resistance of the fabrics [395]. In another paper, Bhattacharjee and Kothari [401] modeled the thermal resistance of woven fabrics by considering natural and forced convective heat transfer through the fabrics. It was observed that the fabric thickness and porosity mainly control convective heat transfer through the fabrics or the thermal resistance of the fabrics. Here, a fabric with high thickness and porosity trapped a large amount of air inside its structure and enhanced its thermal resistance [402]. Based on this result, it was found that the size of the air pores in a fabric is also important for its thermal resistance. If the size of the air pores is smaller, the fabric will not trap sufficient air in its structure, which will reduce thermal resistance. Additionally, Bhattacharjee and Kothari [400] concluded that the surface heat transfer coefficient of a fabric is not significant to thermal resistance, especially in the case of natural convection. Barker and Heniford [394] evaluated the thermal resis- tance of various inherently fire-resistant woven/nonwoven fabrics or multilayered fab- ric systems. In these studies, it has been found that fabric weight and thickness definitely affect thermal resistance; however, some other fabric features (eg, air permeability, porosity, surface area) are also equally important for thermal resistance [403,404]. Shekar et al. [405] found that environmental air velocity may cause the thermal resis- tance loss in a fabric system; however, the presence of an impervious outer layer in the fabric system helps to reduce the loss in thermal resistance under high wind velocity conditions. They also found that the thermal resistance of a fabric system is independent from the nature of the outer layer (pervious or impervious) under normal environmental conditions. Additionally, it was determined that nonwoven fabrics possess high thermal resistance due to their bulkiness, compression recovery, and porosity compared to woven fabrics [24,29]. However, wet nonwoven fabrics possess lower thermal resis- tance than dry nonwoven fabrics; this is because the thermal conductivity of the wet fabric is much higher than that of the dry fabric. Barker and Heniford [394] stated that

the construction and thickness of fire-resistant nonwoven fabrics mainly affect thermal resistance. This study demonstrated that the effective layering of fiber web in nonwoven fabrics is a potential means to enhance thermal resistance because it contributes air layers and thickness without any increase in weight to the nonwoven fabrics.

Many fire-resistant fabrics are used in thermal/cold-weather clothing. One of the main requirements for thermal/cold-weather clothing is that it must possess a high thermal resistance in order to provide protection to wearers from thermal/cold expo- sures. However, it is necessary to remember that there must be a balance in thermal resistance to provide protection and comfort to wearers [28,406,379]. Recently, Matusiak and Sikorski [407] examined the impact of fabric structures (different types of weaves, linear densities of weft yarn, different weft densities) on thermal resistance. It has been found that the weave of woven fabrics significantly affects thermal resis- tance; plain weave fabrics were characterized by a lower thermal resistance than twill, rep, and hopsack weave fabrics, with the same linear and nominal densities of warp and weft yarn. It was also revealed that the linear density of weft yarn significantly affects thermal resistance, and the influence of the weave on the thermal resistance of woven fabric can be modified by the influence of the linear density of the weft yarn [399]. Additionally, a strong and statistically significant correlation exists between the thickness/weight of fabrics and their thermal resistance; similarly, the correlation between the fabric cover factor and thermal resistance is weaker than the correlation between the fabric structural factor and thermal resistance. This is because the fabric structural factor is an integrated parameter (by considering the average percentages of weft or weft densities) of the fabric cover factor; eventually, it has more correlation with thermal resistance. Dias and Delkumburewatte [408] found that thermal resis- tance of a knitted fabric is inversely related to its thermal conductivity; hence, a thorough study on thermal conductivity may develop an understanding regarding ther- mal resistance. They established that thermal conductivity can be calculated by considering (1) thermal conductivity of the fibers used to manufacture the fabric,

(2) the porosity of the fabric structure, and (3) water content in the fabric pores depending upon fabric hygroscopicity and environmental relative humidity. Dias and Delkumburewatte [408] concluded that the thermal conductivity of fabric increases due to three reasons: (1) the thermal conductivity of the fibers increases,

(2) the fabric porosity decreases, and (3) the water content in the fabric pores is high. This is because (1) a highly thermal conductive fiber enhances the thermal conduc- tivity of the solid yarn phase of a fabric; (2) a less porous fabric can trap less amounts of highly insulative air; and (3) water has a very high thermal conductivity. Bogaty, Hollies, and Harris [409] concluded that the thermal conductivity of a fabric is depen- dent on its bulk density. It is insensitive when the fibers/yarn are arranged parallel to the surface at higher bulk density, but becomes sensitive to this arrangement when fiber conductivity and bulk density are very high. In Ozcelic, Cay, and Kirtay’s

[410] study of thermal resistance in structured knitted fabrics, interlock knitted fabrics produced with air-jet textured, false-twist textured, and nontextured filament yarns were compared. It was found that the thermal resistance of textured fabrics is higher than fabrics produced with nontextured filaments, due to increased interfiber pore

dimensions and consequent thickness. Additionally, false-twist textured fabrics con- tain higher thermal resistance compared to air-jet textured fabrics. This is because the false-twist textured fabrics have more crimps and surface roughness, which ultimately enhances the thermal resistance by trapping more air on the boundary layer of the fabric.

Farnworth and Dolhan [411] described the evaporative resistance or water vapor transport behavior of cotton and polypropylene fabrics. In this study, it was established that there is no significant difference in the evaporative resistance of cot- ton and polypropylene fabrics under cold temperatures. It was also evident that water vapor transport through fabrics is mainly affected by their water absorptivity and wickability. A fabric with high moisture absorptivity and low wickability transports less water vapor, resulting in high evaporative resistance. Farnworth, Lotens, and Wittgen [412] analyzed the evaporative resistance of textiles under variable condi- tions of relative humidity. In most clothing applications, when the wearer is sweating, or when the ambient air temperature is low, or if it is raining on the garment, a high average relative humidity value is likely to be appropriate; whereas, if the wearer is only perspiring minimally in warm, dry conditions, a low average relative humidity is appropriate. Farnworth, Lotens, and Wittgen [412] found that the evaporative resis- tance of microporous polytetrafluoroethylene and polyurethane fabrics/films varied insignificantly with relative humidity; however, fabrics/films with hydrophilic coat- ing showed a strong variation of evaporative resistances under different relative humidity conditions. In the hydrophilic case, evaporative resistance decreases sub- stantially with increasing relative humidity.

Gibson [32] explored the evaporative resistance of various woven and nonwoven fabric materials. These materials included the permeable and impermeable types tested as single-layered, laminates, and composites. It has been found that the evap- orative resistance of permeable materials is very low, while the evaporative resistance of impermeable materials is significantly higher. This is because impermeable mate- rials do not allow the transfer of moisture vapor through their structure, whereas per- meable materials allow moisture vapor-transfer through their structure at a high rate. Here, the evaporative resistances of permeable materials were evaluated in a variety of conditions: (1) under the varying directions and velocity of airflow over the materials, and (2) by providing an air gap between the material sample and the sweating skin simulant hot plate. It has been found that airflow conditions have a significant effect on evaporative resistance, and the open structure of the material becomes particularly important for evaporative resistance, especially when an air gap exists between the material sample and the sweating skin simulant hot plate. Gibson [32] concluded that the correlation of the open structure and evaporative resistance can be altered by vary- ing the thickness of the materials at an air velocity of 1–2 m/s [32]. McCullough [413] studied the evaporative resistance of fabrics used in various types of regular clothing. It was found that evaporative resistance is dependent upon the porosity and bulk den- sity of fabrics. If any fabric is less porous or has a low bulk density, it may not allow for transfer of moisture vapor, which causes high evaporative resistance. However, evap- orative resistance can be altered by using different types of fibers and finishing

processes while manufacturing the fabrics. For example, the use of hydrophilic fibers and coatings in/on fabrics results in lower evaporative resistance than fabrics with hydrophobic fibers and coatings. Additionally, the ambient air velocity can also dras- tically lower evaporative resistance. Wang and Yasuda [414] investigated the evap- orative resistance of layered fabrics. They concluded that the modification of fabric surfaces can change evaporative resistance, and the wicking ability of fabric turned out to be the dominant factor governing evaporative resistance. Generally, a fabric with high wicking ability has lower evaporative resistance. Additionally, Wang and Yasuda [414] found that the temperature of the air gap between two layers of fab- rics increased when water vapor transport was present, and the temperature growth was almost proportional to the water absorption rate of the fabric; this temperature growth can change the evaporative resistance of fabric. Gretton et al. [415] studied the moisture vapor transmission through waterproof breathable fabrics under several temperature gradients along the fabric thickness. It was found that the presence of an accurate temperature gradient reduces the differences between the transmission rates of the hydrophilic fabrics and microporous waterproof breathable fabrics. Incorpora- tion of a highly insulating fabric system with microporous breathable fabric may sig- nificantly lower the moisture transmission rates through microporous fabric. The fabric thickness of microporous waterproof breathable fabric also maintains a higher temperature gradient compared to hydrophilic fabric at a particular vapor pressure. This high-temperature gradient enhances the relative humidity gradient across the microporous fabrics so less condensation occurs.

Gibson [416] determined the WVP of different polymer membranes and mem- brane/textile laminates under different ambient air temperatures. It was found that the changes in water vapor flux through the membranes and laminates over the tem- perature range of 30–40°C were primarily due to the fundamental physical relation- ship between temperature and saturation vapor pressure of water; in this case, fabric structure does not play an important role. Here, the WVP was mainly influenced by the water concentration gradient along the thickness of the membrane and laminates, and the water vapor mainly transferred through the gas phases present in the membrane and laminate structures. Zhou, Wang, and Yuan [417] analyzed the evaporative resis- tance of conventional tightly woven, microporous film, and hydrophilic film-fabrics. It has been found that these fabrics generally possess a high evaporative resistance, and increase the temperature and water vapor pressure inside the fabric structure under certain environmental condition. The water vapor condensation is more prominent within a fabric with high evaporative resistance than a low evaporative resistance fab- ric at a particular relative humidity. Fukazawa et al. [418] studied the evaporative resistance of textiles under the combined influence of temperature and pressure sim- ulating high altitude. In this study, it has been found that temperature and pressure have an impact on the moisture vapor transport through textiles, hence, the evapora- tive resistance of textiles; however, temperature has less effect on evaporative resis- tance than pressure. Fukazawa et al. [418] also observed that evaporative resistance decreases with increasing simulated altitude, due to an increase in the water vapor dif- fusion coefficient with increasing altitude. Additionally, the water vapor condensation in the fabrics tended to increase with increasing simulated altitude; as a consequence,

the evaporative resistance appreciably decreases in the long run. Rossi and Gross

[419] studied the water vapor resistance of multilayered fabric systems at several mod- erately cold temperatures. It was evident that the evaporative resistance increased in cold environments because the moisture partly condensed within individual layers of the fabric systems. Here, the evaporative resistance and moisture condensation rates strongly depended upon the ambient temperature and hydrophilicity of the outer layer of the system. The differences in effective evaporative resistance between the systems were small at an ambient climate of 20°C and 65% relative humidity, but the differ- ence became larger with decreasing ambient temperature. The formation of moisture condensation was the smallest for the fabric systems with a hydrophilic membrane laminated on the inside of the systems, and the moisture condensation occurred more when the hydrophilic layers were placed underneath the outer layer of the systems. Weder et al. [420] studied the evaporative resistance of various synthetic fiber-based fabrics under different relative humidities of ambient air. It has been found that the evaporative resistance of a fabric becomes lower in the presence of low relative humid- ity and vice-versa. This is because low air humidity causes a higher water vapor pres- sure gradient across fabric thickness; due to this gradient, the water vapor can transfer efficiently through the fabric. In this context, it was evident that the water vapor can be stored within the fabric structure in the presence of high relative humidity, which can affect the evaporative resistance of the fabric. Havenith, Hartog, and Martini [421] compared the evaporative resistance of the membrane and woven fabrics used in pro- tective clothing. It has been found that a membrane fabric possesses higher evaporative resistance than a woven fabric; this is because the openness/porosity of the membrane fabric is much lower than the openness/porosity of the woven fabric. As a consequence, the protective clothing made by incorporating the membrane fabric systems can cause heat stress/strain to wearers. However, a membrane is always required in protective clothing to provide protection from various hot liquids, chemicals, etc. Thus, the mem- brane should be designed in such a way that it can be impermeable to liquids/chemicals, but breathable/permeable to water vapor to provide better comfort to wearers [422]. In this context, Bartels and Umbach [422] quantified the MVTR through an ordinary membrane and a breathable membrane used in protective textiles at low ambient tem- peratures. It was found that moisture vapor transmission through the breathable mem- brane is usually higher than the ordinary membrane. There is also no relationship identified between the ambient air temperature and moisture vapor transport through the breathable membrane; it was observed that moisture vapor transmission through the breathable membrane remained the same in between the normal ambient temperature and —20°C temperature. Ding et al. [403] modeled the evaporative resistance of single- layered fabrics used in thermal/cold-weather protective clothing. In this study, it was found that moisture diffuses in fabrics through the air spaces between fibers or yarn and it is affected by yarn and fabric structures as well as size and number of interstices (with warp and weft) developed in a certain area of the fabric; here, fabric count, yarn twist, and yarn linear density are the main features that affect the size and number of inter- stices. Ding et al. [403] also found a decreasing trend in evaporative resistance with increasing air velocity for all fabrics, with a relatively large decrease occurring in a range of 0–5m/s air velocity [403]. It was observed that evaporative resistance

decreases at a faster speed in the presence of turbulent air than laminar air, and evap- orative resistance can be greatly increased by increasing fabric thickness at a particular air velocity. In this study, a small (4.54%) increase in evaporative resistance was observed when relative humidity varied from 0% to 100%; and, the smallest evapora- tive resistance was observed when the fabric porosity approached unity at a particular thickness [404]. Additionally, it was found that the surface diffusivity of the fabric determines the rate of moisture transfer through the fabric; thus, the evaporative resis- tance of the fabric. Wang et al. [379] investigated the WVP of the multilayered thermal protective fabric systems (composed of shell fabrics, moisture barriers, thermal liners, and comfort liners) used in firefighters’ protective clothing. The experimental results demonstrated that thermal liner played a different role in the WVP of the multilayered fabric system; however, the shell fabrics, moisture barrier, and comfort lining showed no distinct dissimilarity. In this study, the WVP of the multilayered fabric system were correlated with the WVP of the systems’ individual layer (shell fabrics, moisture bar- rier, thermal liner, and comfort liner); and it was found that the WVP of the multilayered fabric system was highly correlated with the WVP of the moisture barrier, meaning that moisture barriers have the greatest effect on the WVP. Additionally, a combined inter- action between the shell fabric and thermal liner also moderately affected the WVP. Prahsarn, Barker, and Gupta [423] evaluated the evaporative resistance and MVTR of synthetic fiber-based open knitted fabrics in the steady-state and transient condi- tions. They observed that evaporative resistance and MVTR through largely open knit- ted fabrics are predominantly controlled by the fiber, yarn, and fabric variables that determine the thickness and permeability of the fabrics. It was also found that evapo- rative resistance and MVTR can be controlled by a moisture vapor concentration gra- dient, coupled with a temperature gradient along the fabric thickness. It seems that fabric thickness governs the magnitude of the gradient, which is the main driving force for controlling evaporative resistance and MVTR. In the case of transient conditions, the openness of the fabric is most important, and in this condition the researchers con- cluded that a fabric with thin and open structure possesses high MVTR. In related research, Yoon and Buckley [424] showed the importance of knitted fabric construc- tional variables on evaporative resistance. They reported that evaporative resistance is dependent on fabric thickness, optical porosity, and water vapor diffusivity of the ambi- ent air. Their findings indicate that steady-state moisture vapor transport through fab- rics is controlled by a diffusion process that is strongly influenced by fabric structure, especially fabric thickness and openness.

Based on the preceding discussion, it is confirmed that thermal and evaporative resistance are affected by many direct or indirect parameters: namely, fabrics’ construc- tional (eg, fiber types, weaves, design) and physical (eg, weight, thickness, porosity) features, and/or ambient environmental variables (eg, air, temperature, relative humidity) [393–424]. These parameters can also be important for THL because it is a combined interpretation of thermal and evaporative resistance. Many researchers cor- roborated that heat loss through fabrics may occur through combined heat and moisture/ water vapor transfer by conduction, convection, radiation, evaporation, and/or diffu- sion [24,31,307,379,403,404,425]. Farnworth [307] studied heat loss by modeling the combined heat and water vapor transfer through multilayered fabrics. The heat

transfer was administered by conduction and radiation; whereas, the water vapor trans- fer was delivered by diffusion. In this study, it was evident that hygroscopic and non- hygroscopic fabrics behave differently to transfer heat and water vapor. Thicker fabrics do not allow the transfer of heat and water vapor through their structure, which ulti- mately reduces heat loss. Additionally, hygroscopic fabrics absorb vapor and transfer it to the ambient environment; this phenomenon ultimately enhances heat loss through the fabrics. It was also found that the water-impermeable but vapor-permeable fabrics possess an excellent heat loss characteristic at high ambient temperature; however, this characteristic is not prominent at low ambient temperature. Farnworth [307] concluded that a layered fabric may not allow the transfer of heat and water vapor through its struc- ture, which ultimately reduces heat loss. Ghali, Ghaddar, and Jones [31] studied heat loss by heat and moisture transfer through thin cotton fibrous media. They inferred that heat and moisture transfer mainly occurs through fabric by convection. Heat and mois- ture transfers are controlled by air pores present in any fabric. The air trapped in the pores may not allow the transfer of heat through the fabric and the heat loss is reduced; however, air passing through the pores may significantly enhance the moisture transfer through the fabric so that heat loss is increased. In this study, it was concluded that ambi- ent air temperature and humidity mainly control heat and moisture transfer through clothing. Generally, high temperature and relative humidity may lower heat and mois- ture transfer through fabrics and reduce heat losses through fabrics. However, this heat and moisture transfer and/or heat loss through fabrics can be altered by changing mois- ture regain and absorptivity of the fabric. Cao et al. [425] investigated heat loss by study- ing the heat and moisture transfer through various synthetic woven and knit fabrics. It was evident that knitted fabrics possess higher wicking than woven fabrics; as a con- sequence, moisture transfer through knitted fabrics is significantly higher than in woven fabrics. However, knitted fabric possesses air loops within its structure, which ulti- mately resist the transfer of heat through the fabric and lower heat loss. Cao et al.

[425] also stated that contaminating metal (if any) within a fabric structure may not sig- nificantly affect the heat and moisture transfer through the fabrics; as a result, heat loss will not be significantly affected. They suggested that the attachment of a liquid cooling device to the fabric may enhance its heat and moisture transport features, which can significantly enhance heat loss through fabrics. Weder et al. [420] studied wet heat loss through different underwear fabrics under different ambient air relative humidity. They confirmed that heat loss through fabrics is mainly dependent upon sweat-vapor gener- ated by wearers. For low sweat rates (50–70g/h), the heat loss difference was insignif- icant under different relative humidities in the ambient air. With high-relative humidities and low-sweat rates, the sweat did not fully transfer through the fabrics and stored inside the fabrics thus inducing a higher heat loss by wet thermal conductiv- ity. Wet thermal conductivity was also a dominant factor and caused higher amounts of heat loss through fabrics for high-sweat rates in high relative humidities. At low relative humidity, wet heat loss increased proportionally to the increase in sweat rate. However, wet heat loss increased with a much lower rate in dependency of the sweat rate when the relative humidity in the environment was raised.

Fanglong, Weiyuan, and Minzhi [426] analyzed heat loss through chemically mod- ified fire-retardant and inherently fire-resistant fabrics used in firefighters’ clothing.

In this study, heat and moisture transfer through multilayered fabric systems (shell fabrics, moisture barrier, thermal liner) was observed. It was reported that the heat transfer through the shell fabric occurred at a much higher rate than for the thermal liner because the shell fabric did not trap as much air as the thermal liner did. It seems that heat loss can occur at greater rates through the shell fabric than thermal liner; hence, there is a need to design the thermal liner in such a way that it can balance the heat protection and metabolic heat loss. Additionally, it was observed that a fabric system with high thickness and weight causes a high evaporative resistance, which in turn lowers heat loss through the fabric system [379]. In this context, Ding et al. [404] studied heat loss through single-layered thermal/cold-weather protective fabric by analyzing heat and moisture transfer through the fabrics. Results indicated that the heat and moisture transfer through fabric can be controlled, depending upon the thick- ness and porosity of the fabric. A highly thick fabric did not allow the transfer of heat and moisture through the fabrics, so that eventually, the heat loss is lower. Further- more, a fabric with high porosity transfers the moisture (by diffusion) and heat (by radiation) through the fabrics, which may cause heat loss through fabrics [403]. Recently, Tian et al. [427] analyzed the heat loss behavior of multilayered fabric sys- tems used in thermal protective clothing. As usual, the multilayered fabric systems were composed of three different fabrics in this study; however, the composed fabrics were used in different layering sequences. Altogether, six different three-layered fab- ric systems were prepared using the different layer stacking sequences. In this study, it was observed that heat loss occurred through three-layered fabric systems mainly in transient condition, and the stacking sequence of the three-layered fabric systems played an important role in heat loss. It was found that the layer in contact with the heat source is the most important layer for the heat loss; here, the volumetric heat capacity of the layer contacting the heat source is the prime parameter for heat loss through three-layered fabric systems.

### Evaluation/calculation and assessment of thermal and evaporative resistance of clothing

The previous section highlighted that many researchers evaluated and assessed the thermal and evaporative resistances of fabrics using various standardize hot plate test methods [393–424]. These studies can provide only the thermal and evaporative resis- tance results associated with a fabric; these results might also be a possible indicator for the thermal and evaporative resistances of clothing manufactured by using that fabric [24,31–33]. However, the results obtained for the fabric cannot be directly applicable to any corresponding clothing without considering the amount of body sur- face area covered by the clothing, the distribution of the fabric and air layers on the wearers’ bodies, the looseness or tightness of fit of the clothing, and the increase in surface area for heat loss in the clothing form. In this regard, some researchers at inde- pendent laboratories have developed models for predicting the thermal and evapora- tive resistances of clothing from the hot plate data on fabrics [428–430]. For example, researchers at Kansas State University used the hot plate fabrics data and clothing

circumference data to predict the thermal and evaporative resistances of clothing layers and air layers on different parts of the body [428]. Researchers at the Hohenstein Institute of Germany conducted several studies where they used the hot plate data of fabrics to predict the intrinsic evaporative resistance of clothing ensem- bles based on the fraction of the body surface area covered by each fabric [428,430]. However, these prediction models provided no information associated with the cloth- ing design, fit, and construction; additionally, these models showed no proven corre- lation to the thermal and evaporative resistances of the actual clothing systems worn by people in different ambient environments [386]. It is obvious that clothing attri- butes (eg, fit, design) and ambient environmental conditions have a significant effect on thermal and evaporative resistances of clothing. As a consequence, a great deal of research directly evaluated the thermal and evaporative resistances of clothing using full-scale manikin tests [431–433].

For evaluating the thermal and evaporative resistances of clothing using full-scale manikins, an ISO 9920 standard was developed in 1995 and later modified in 2007; in 2010, ASTM F 1291 and ASTM F 2370 standards were developed and modified to evaluate the thermal and evaporative resistances of clothing using full-scale manikins, respectively [432–434]. In both of these ASTM standards, a standing manikin is used that is built in the shape and size of an adult male or female. This manikin is con- structed to simulate the body of a human being; hence, the manikin consists of a head, chest/back, abdomen/buttocks, hands (can be with fingers), legs, and feet. The total body surface area of the manikin is 1.8 0.3 m2, and its height is 170 10 cm. This manikin is constructed in such a way that it can maintain a constant temperature dis- tribution over the nude manikin body surface, with no local hot or cold spots. The average skin temperature of the manikin is maintained at 35°C; here, the local skin temperature deviation must be within 0.3°C of the average skin temperature. The temperature uniformity of the nude manikin can be evaluated using an infrared ther- mal imaging system or an equivalent method, and it is required to evaluate the tem- perature uniformity annually or after repairs or alterations (eg, replacement of a heating element). The skin temperature of the manikin can be measured by point sen- sors or distributed temperature sensors with an accuracy of 0.15°C. The point sen- sors can be thermocouples, RTDs, thermistors, or equivalent sensors; nearly 15 thick (2 mm) point sensors (at least one sensor is placed on the head, chest, back, abdomen, buttocks, and both the right and left upper arms, lower arm, hand, thigh, calf, and foot) are bonded mechanically as well as thermally to the manikin surface, and the lead wires of each sensor are bonded to the surface or pass through the interior of the man- ikin, or both. In the case of distributed sensors (eg, resistance wire), all sensors of

<1 mm diameter are placed uniformly over the manikin and firmly bonded to the manikin surface at all points. The sensors-equipped thermal manikin is placed in a

1.5 m× 1.5 m× 2.5 m environmental control chamber to provide uniform ambient conditions over the manikin, both spatially and temporarily. Here, the spatial variations should not exceed the following conditions: ambient air temperature

1°C, ambient relative humidity 5%, and ambient air velocity 50%; additionally, temporal variations shall not exceed the following conditions: ambient air temperature

0.5°C, ambient relative humidity 5%, and ambient air velocity 20%.

The ambient relative humidity of the environmental chamber can be measured by any humidity sensing device (eg, dry-bulb/wet-bulb, dew point hygrometer) with an accu- racy of 5% and a repeatability of 3%; similarly, the ambient air velocity in the environmental chamber can be measured by an omnidirectional anemometer with an accuracy of 0.5 m/s. Furthermore, it is required that the sensor-equipped thermal manikin must have the ability to generate sweat in different body parts (head, chest, back, abdomen, buttocks, arms, hands, legs, and feet) and also evaporate sweat from its surface, especially in the case of an evaporative resistance evaluation. Here, sweat can be generated by different technologies in the sweating thermal manikin. For exam- ple, the sweating system can be a water-fed capillary body suit worn over the thermal manikin; the sweating can also be simulated by supplying water and maintaining it at the inner surface of a waterproof, but moisture-permeable fabric skin. Additional tech- nologies exist that deliver water to the thermal manikin surface with a valve delivery system. The average power required to run the manikin over the period of a test can be calculated with an accuracy of 2% using a variety of devices and techniques for power measurement. In this context, a notable point is that the thermal and evaporative resistance values of thermal protective clothing in the ISO 9920, ASTM F 1291, and ASTM F 2370 standards are evaluated in the normal ambient environment (relatively calm and cooler than the manikin body); thus, the evaluated values of thermal protec- tive clothing may not be applicable in actual fire hazard scenarios as faced by firefighters.

### Thermal resistance evaluation

In order to evaluate the thermal resistance of a fabric or a multilayered fabric system under steady-state conditions (according to ASTM F 1291 standard), the average tem- perature of the thermal manikin skin is controlled at 35 0.2°C during a 30 min test. The ambient air temperature is kept at least 12°C lower than the manikin’s body tem- perature (that is 23°C) with preferably 50% (can vary from 30–70%) ambient relative humidity and 0.4 0.1 m/s ambient air velocity. After setting these experimental parameters the manikin is dressed in the garment to be tested. The skin temperature of the clothed manikin is stabilized, and the clothed manikin system is allowed to reach steady-state (that is, the mean skin temperature and power input remain constant

3%). After the system reaches the steady-state, the manikin’s skin temperature and the ambient air temperature are measured every 1 min. The average of these measure- ments is taken over a period of 30 min to determine the thermal resistance value; the power input to heat the manikin is also measured every 1 min or continuously over the test period. Then, the thermal resistance of the clothing with the manikin’s surface (boundary) air layer is measured according to Eq. [(5.28)](#_bookmark55), where, *R*t =total thermal resistance of the clothing ensemble and surface air layer around the manikin (°C m2/W); *A* =area of the manikin’s surface (m2); *T*s =temperature at the manikin’s surface (°C); *T*a =temperature of the ambient air flowing over the clothing (°C); *H* =power required to heat the manikin (W). Here, it seems that a significant amount of trapped air on the boundary of the manikin’s surface (or around the manikin) contributes to *R*t. Thus, the intrinsic thermal resistance (*R*cl) of the clothing ensemble

can be determined by subtracting the thermal resistance (*R*a) of the nude manikin from the *R*t [Eq. [5.29](#_bookmark56), where, *R*cl =intrinsic thermal resistance of the clothing (°C m2/W); *R*t =total thermal resistance of the clothing ensemble and surface air layer (°C m2/W); *R*a =thermal resistance of the air layer on the surface of the nude manikin (°C m2/W); *f*cl =clothing area factor (dimensionless) estimated using the ISO 9920 standard, or a photographic method described by McCullough, Jones, and Huck [435]]. In Eq. [(5.29)](#_bookmark56), *f*cl is defined by the ratio of the clothed body surface area to the nude body surface area, and the value of *f*cl is usually measured by taking photographs of the man- ikin (nude and clothed) from different angles and comparing the projected areas (dif- ference in circumference between nude and clothed body). It seems that *f*cl can be an indicator of the increase in surface area for heat loss from the clothed body (in com- parison to the nude body) towards the ambient environment. The *R*cl determination process described in Eq. [(5.29)](#_bookmark56) was developed based on the assumption that air layer resistance measured on the nude manikin is the same as air layer resistance on the surface of the tested clothing. Although this *R*cl determination process is easy, the assumption may not always be true. This is because the heat flux from the nude man- ikin is often greater than the heat flux from the surface of the tested clothing, partic- ularly for thick clothing, unless the temperature difference between the manikin’s surface and the air is adjusted to compensate for the added thermal resistance of the tested clothing. Additionally, the emissivity of the manikin may not be comparable to the emissivity of the tested clothing, and this may affect the radiant heat flux through the air layer. Note: *R*t and *R*cl value obtained from Eqs. [(5.28), (5.29)](#_bookmark55) are in SI-units; these values need to be multiplied by 6.45 to convert the SI-unit to a more commonly used thermal resistance unit “*clo*” [436]. If the values are expressed in “*clo*” units, the symbol *I* is used instead of *R* in Eqs. [(5.28), (5.29)](#_bookmark55).

*R*t(*I*t) = (*T*s — *T*a)*A*/*H* (5.28)

*R*cl(*I*cl

) = *R* — *R*a

t *f*cl

(5.29)

The ASTM F 1291 standard is widely used to quantify and compare thermal resistance values provided by clothing ensembles with different designs, fabrics, garment layers, closures, and fits; the thermal resistance value of clothing ensembles can also be used in models to predict the physiological responses of people in different environmental conditions. However, the ASTM F 1291 standard possesses several limitations [436]. For example, this is only a static test that provides a baseline clothing measurement on a standing manikin, hence, the effects of body positions and movement are not addressed; the obtained thermal resistance values apply only to the particular clothing evaluated and for the specified environmental conditions of each test, particularly with respect to ambient air velocity; the measurement of thermal resistance provided by clothing ensembles is a complex process and depends on the apparatus and technique used; and technical knowledge concerning the theory of heat transfer, temperature, air motion measurement, and testing practices are essential for an operator to evaluate thermal resistance.

Along with the ASTM F 1291 standard, there are a few other standards to evaluate thermal resistance: ISO 15831, EN 342, and ASTM F 1720. The ISO 15831 describes the test protocol for measuring the thermal resistance of clothing worn in a relatively calm environment by a standing or walking thermal manikin; EN 342 prescribes the test methods for thermal resistance evaluation of clothing ensembles and of single gar- ments against a cold environment by a standing or moving thermal manikin; ASTM F 1720 specifies the test protocol to measure the thermal resistance of a sleeping bag in a cold environment by a supine manikin. Although the ISO 15831, EN 342, and ASTM F 1720 standards use the same measurement technique for thermal resistance evaluation as described in the ASTM F 1291 standard, these four standards have dif- ferent scopes associated with (1) manikin features, (2) test conditions, (3) methods for calculating the thermal resistance, and (4) parameters for test results ([Table 5.5](#_bookmark60)) [33]. Referring to [Table 5.5](#_bookmark60), columns (1), (2), and (4) are self-explanatory; however, col- umn (3) requires some explanation. It is clear from column (3) that all the standards use distinct methods to evaluate the thermal resistance of the clothing tested. The most-used method is the parallel method, which sums up the heat loss from all body segments, area-weighted skin temperatures, and body segment areas before calculat- ing the total thermal resistance [Eq. [5.30](#_bookmark57), where, *I*tp =total thermal resistance of the clothing with surface air layer around the manikin (clo), *Ai* =surface area of the seg- ment *i* of the manikin (m2), *A* =area of the manikin’s surface (m2), *T*si =local surface temperature of the segment *i* of the manikin (°C), *T*a =temperature in the air flowing over the manikin (°C), *H*c*i* =local heat loss from segment *i* of the manikin (W)]. The alternative method, ie, the serial method, calculates local thermal resistances first, which are then averaged in terms of segment area [Eq. [5.31](#_bookmark58), where, *I*ts =total thermal resistance of the clothing with surface air layer around the manikin (°C m2/W)]. It has been found that these two methods yield thermal resistance values as long as uniform clothing insulation occurs over the manikin body; however, the serial method can give a higher value than the parallel method if uneven clothing insulation is distributed over the manikin. It seems that the serial method can provide false information (over- estimated thermal resistance) [433]; thus, the parallel method is more promising. In this context, the ISO 9920 standard suggested that a global method is more generalized and accurate instead of the parallel or serial methods [437]. In the global method, the area-weighted skin temperature and heat loss of each body part are summed up before calculating total thermal resistance (*I*t) (Eq. [5.32](#_bookmark59), where, *I*t is in °C m2/W). In a recent study, Oliveira, Gasper, and Quintela [437] compared the thermal resistance values of cold-weather protective clothing calculated from the global, parallel, and serial methods. This study showed that the serial method always leads to highest thermal resistance values, while the parallel method generates the lowest values. Here, the dif- ferences between the calculation methods were significant for some clothing ensem- bles, and greater discrepancies were evident when the distribution of the clothing became less uniform on the manikin’s body. Oliveira, Gasper, and Quintela [437] also suggested that the global method can be simplified for two specific conditions of tem- perature or heat loss distribution over manikin’s body. If one makes an assumption that skin temperature is uniform over the manikin’s body, the global method becomes simplified and turns into summation of resistances according to the parallel method;

otherwise, if the assumption is that the local heat flux is uniform over the manikin’s body, the global method turns into summation of resistances according to the serial method. In addition, Oliveira, Gasper, and Quintela [437] suggested that the global method is the only suitable method for all manikin regulation modes, while the two other methods (parallel and serial) are suitable only in specific situations. The ISO 9920 standard underlines that the global method shall always be used whenever there is a doubt about which calculation method to choose [439]. Overall, it can be concluded that the thermal resistance obtained from the global method can be used as a reference despite the common use of parallel or serial methods.

" X*Ai* × *T* !— *T* # × *A*

*A*

s*i*

a

*I*tp =

*i*

0.155 × X*H*c*i*

(5.30)

*i*

*I* = X*Ai* × (*T*si — *T*a) × *Ai* (5.31)

ts

*A*

0.155 × *H*c*i*

*i*

X *Ai* × *T* — *T*a

*I*t = *A*  (5.32)

X *i* × *H*

*A*

*A* c*i*

s*i*

### Evaporative resistance evaluation

In order to evaluate the evaporative resistance of a fabric or multilayered fabric system under steady-state conditions (according to ASTM F 2370 standard), two circum- stances are preferred: isothermal and nonisothermal [387]. In isothermal circum- stances, the temperature of the sweating thermal manikin’s skin surface and its ambient air are set at 35 0.5°C (without fluctuating more than 0.2°C during test- ing), and the relative humidity of the ambient air is set at 40 5% by maintaining an air velocity in-between 0.4 1 m/s at the surrounding of the manikin. As the mani- kin’s temperature is the same as the ambient air temperature, no dry heat exchange occurs between the manikin and the ambient air. In nonisothermal circumstances, var- ious experimental parameters (the temperature of the manikin and ambient air, rela- tive humidity of the ambient air, and the ambient air velocity) can be set as equivalent to the experimental parameters of the thermal resistance (*R*t/*R*cl) evaluation (discussed in the previous section). Because the ambient air temperature is lower than the man- ikin’s temperature, the dry heat loss can occur between the manikin and the ambient air simultaneously with evaporative heat loss. In nonisothermal circumstances, the ambient air temperature, relative humidity, and velocity are set as per researchers’ requirements. After setting up the isothermal or nonisothermal circumstances as per requirements, water of 35 0.5°C is sprayed on the manikin until it is saturated;

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## Table 5.5 Differences between ASTM F 1291, ISO 15831, EN342, and ASTM F 1720 standards

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Standards | Scopes | | | |
| Manikin features | Test conditions | Method for calculating thermal resistance | Parameters for test results |
| ASTM F 1291  ISO 15831 | Manikin height: 1.7 0.1 m Manikin body area:  1.8 0.3 m2  Manikin posture: Standing  Manikin height:  1.7 0.15 m  Manikin body area:  1.7 0.3 m2  Manikin posture: Standing or walking at 45 2 double steps/min | Average manikin skin temperature: 35 0.3°C Ambient air temperature: At least 12°C<average skin temperature  Ambient air velocity: 0.4 m/s Relative humidity: 30–70% Average manikin skin temperature: 34 0.2°C Ambient air temperature: At  least 12°C<average skin temperature  Ambient air velocity: 0.4 m/s Relative humidity: 30–70% | Parallel  Parallel or serial | Total thermal resistance of clothing ensembles: *R*t(*I*t)  Intrinsic thermal resistance of clothing: *R*cl(*I*cl)  Unit: °C m2/W  Total static thermal resistance of clothing ensembles (with standing manikin): *I*t  Resultant total thermal resistance of clothing ensembles (with walking manikin): *I*tr  Unit: m2 K/W |

*Continued*

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|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 5.5 Continued | | | | |
| Standards | Scopes | | | |
| Manikin features | Test conditions | Method for calculating thermal resistance | Parameters for test results |
| EN 342  ASTM F 1720 | Manikin height:  1.7 0.15 m  Manikin body area:  1.7 0.3 m2  Manikin posture: Standing or walking at 45 2 double steps/min  Manikin height: 1.8 0.1 m Manikin body area:  1.8 0.3 m2  Manikin posture: Supine | Average manikin skin temperature: 34 0.2°C Ambient air temperature: At least 12°C<average skin  temperature  Ambient air velocity: 0.4 m/s Relative humidity: 30–70%  Average manikin skin temperature: 32—33 0.3°C Ambient air temperature: At least 20°C<average skin temperature  Ambient air velocity: 0.3 m/s Relative humidity: 30–70% | Parallel or serial  Parallel | Total thermal resistance of clothing ensembles (with standing manikin): *I*t  Effective thermal resistance of clothing ensembles (with standing manikin): *I*cle  Resultant thermal resistance (with walking manikin): *I*tr  Resultant effective thermal resistance (with walking manikin): *I*cle, r  Unit: m2 K/W  Total thermal resistance of sleeping bag: *I*t  Unit: Clo |

then, the water is continuously delivered to the manikin to keep it saturated for evap- oration throughout the test period. Saturation is usually detected visually by a color change (surfaces that are wet are darker than those that are dry) but an IR camera can also be used to ensure that the surface is completely saturated. Next, the manikin is dressed up in the garment to be tested. The skin temperature of the dressed manikin is stabilized, and the clothed manikin system is allowed to reach steady-state (that is, the mean skin temperature and power input remain constant 3%). After the system reaches steady-state, the manikin’s skin temperature and the ambient air temperature are measured every 1 min. The average of these measurements is taken over a period of 30 min to determine the evaporative resistance value of the clothing ensemble. The evaporative resistance (*R*et) of the clothing ensemble with manikin’s surface (boundary) air layer can be determined by measuring the power consumption of the manikin (option 1) or by measuring the evaporation rate of the water through the tested garment (option 2). In option 1, the *R*et can be calculated according to Eq. [(5.33)](#_bookmark61), where, *R*et =total evaporative resistance provided by the clothing ensemble with surface air layer around the manikin (kPa m2/W); *A* =area of the manikin’s sweating surface (m2); *P*s =the water vapor pressure at the manikin’s sweating surface (kPa); *P*a =the water vapor pressure of the air flowing over the clothing (kPa); *H*e =power required for sweating area (W); *T*s =temperature at the manikin’s surface (°C); *T*a =temperature of the air flowing over the clothing (°C); and *R*t =total thermal resistance of the clothing ensemble with manikin’s surface air layer measured by ASTM F 1291 (°C m2/W). In option 2, the *R*et can be calculated according to Eq. [(5.34)](#_bookmark62), where, *R*et =total evaporative resistance provided by the clothing ensemble and air layer around the manikin (kPa m2/W); *P*s =the water vapor pressure at the manikin’s sweating surface (kPa); *P*a =the water vapor pressure of the ambient air flowing over the clothing (kPa); *A* =area of the manikin’s sweating surface; *λ* =heat of vaporization of water at *T*s (W); and *dm*/*dt* =evaporation rate of moisture leaving the manikin’s sweating surface (g/min). Here, the total mass loss due to evaporation from the clothed manikin is measured by two balances (one balance is used to measure the amount of water being fed to the manikin, while the other balance measures the weight change of the manikin) to give an accurate average over the period of the test. Furthermore, the water dripping from the manikin is captured (by a pan large enough to retain all water drippings) and measured at the end of the test with a calibrated bal- ance having a resolution to the nearest gram, and the water loss from dripping is sub- tracted from the total mass loss to calculate the actual *dm*/*dt*. However, both options ignore the absorption of water vapor in the clothing, and several researchers have established that the water vapor from the manikin/human body would be absorbed or condensed within the clothing and influence the total evaporative resistance [311,440,441]. Additionally, the evaporative resistance in option 1 is calculated from the thermal resistance (*R*t), where, *R*t is calculated from the dry manikin test. However, the manikin is in a wet condition during the evaporative resistance test; and this wet manikin can change the *R*t. It has been found that water vapor condensation may occur within the clothing ensembles during the wet manikin test, which can lower the ther- mal resistance of clothing during the evaporative resistance test; this phenomenon is more prominent in thicker clothing than the thinner clothing [311]. Thus it can be

inferred that the evaporative resistance obtained from option 1 can be lower than the actual one. Because the water vapor absorption or accumulation within the clothing releases heat and changes the thermal properties of clothing ensembles, the measure- ment of both thermal and evaporative resistance needs to be taken after the stabiliza- tion of water vapor accumulation within the clothing in options 1 and 2. Similar to intrinsic thermal resistance (*R*cl), intrinsic evaporative resistance (*R*ecl) of clothing ensembles is also determined by subtracting the evaporative resistance of the air layer on the surface of the nude manikin’s sweating surface (*R*ea) from the *R*et [Eq. [5.35](#_bookmark63), where, *R*ecl =intrinsic evaporative resistance of the clothing ensemble (kPa m2/W); *R*et =total evaporative resistance of the clothing ensemble with surface air layer (kPa m2/W); *R*ea =the evaporative resistance of the air layer on the surface of the nude manikin’s sweating surface (kPa m2/W); *f*cl =clothing area factor (dimensionless) estimated using the ISO 9920 standard, or a photographic method described by McCullough, Jones, and Huck [435]]. Note: The total evaporative resistance (*R*et) of the garment under nonisothermal circumstances can also be called apparent total evaporative resistance (*AR*et). Here, the “apparent” term is used as a modifier to the total evaporative resistance (*R*et) to reflect the fact that condensation may occur within the garment, and the *AR*et values of the garment can only be compared to those of other garments measured under the same nonisothermal conditions.

*R*et = [(*P*s — *P*a)*A*]/[*H*e — (*T*s — *T*a)*A*/*R*t] (5.33)

*R*et = [(*P*s — *P*a)*A*]/[*λ*(*dm*/*dt*)] (5.34)

*R*ecl

= *R*et

— *R*et

*f*cl

(5.35)

The ASTM F 2370 standard is widely used to quantify and compare evaporative resis- tances provided by clothing ensembles having different designs, fabrics, garment layers, closures, and fits; the evaporative resistance values of clothing ensembles under isothermal circumstances can also be used in models to predict the physiolog- ical responses of people in different environmental conditions. However, the ASTM F 2370 standard does have several limitations [442]. For example, this is a static test that provides a baseline clothing measurement on a standing manikin, and the effects of body positions and movement are not addressed; the obtained evaporative resis- tance values applies only to the particular ensembles evaluated and for the specified environmental conditions of each test, particularly with respect to ambient air velocity and sweating simulations; the measurement of evaporative resistance provided by clothing ensembles is a complex process and dependent on the apparatus and tech- nique used; and technical knowledge concerning the theory of heat transfer, moisture transfer, temperature, air motion measurement, and testing practices is essential for an operator, who evaluates evaporative resistance. Furthermore, the ASTM F 2370 stan- dard has been developed based on the premise that the vapor pressure at the manikin’s skin surface is 100% and the sweating rate should be high enough to saturate the skin. However, this premise is not true in unstaged scenarios, in which optimal sweating

rates of human beings vary due to many factors, such as their ambient environmental conditions, activities performed, and type of clothing worn. It has been observed that if the sweat rate is low and the clothing is thin, all of the water vapor dissipates through the clothing towards the ambient environment. In this situation, 100% water vapor pressure at the skin surface cannot be attained. It seems that the ASTM standard should measure the exact water vapor pressure near the skin surface, although this is very difficult.

At this time, ASTM F 2370 and ISO 9920 are the only standards to evaluate the evaporative resistance of clothing. The testing protocols of these standards are almost the same; however, ISO 9920 standards also provide a method for estimating the evap- orative resistance of permeable clothing ensembles [Eq. [5.36](#_bookmark64), where, *R*et =total evap- orative resistance of clothing with manikin surface air layer (m2 kPa/W); *R*t =total thermal resistance of the clothing with manikin surface air layer (clo); *i*m =moisture permeability index (dimensionless), and LR =Lewis Relation (16.5°C/kPa)]. Although Eq. [(5.36)](#_bookmark64) is for permeable clothing ensembles, this equation is only appli- cable to normal indoor clothing, it cannot be applied to protective clothing, which is usually made of materials with low moisture permeability.

*R*et

*R*t

= *i* × LR

m

(5.36)

### Working principles of various manikins to evaluate thermal and evaporative resistance

Based on the preceding discussion, ASTM F 1291 and ASTM F 2370 standards are available to evaluate the thermal and evaporative resistance, respectively, of clothing ensembles using a full-scale manikin. By using these standards, different laboratories evaluated the thermal and evaporative resistances of various clothing ensembles (warm weather clothing, cold weather clothing, chemical protective clothing, surgical clothing, flame-resistant protective clothing, and firefighters’ protective clothing) on different sweating thermal manikins [436,442]. The interlaboratory thermal and evap- orative resistance test results were compared according to ASTM E 691 in order to evaluate the repeatability (the variability between independent test results obtained within a single laboratory by the same operator using the same equipment) and repro- ducibility (the variability between independent test results obtained from different laboratories) of ASTM F 1291 and ASTM F 2370 standards. It has been confirmed that there is a variability of 10% in the test results obtained from various laborato- ries. It was inferred that the variability from laboratory to laboratory is probably due to the complex nature of the apparatus and the fact that most manikins are one-of-a-kind instruments. It was recommended that the thermal and evaporative resistances of the clothing ensembles need to be measured on the same manikin for comparison unless prior agreement has been established regarding the use of different manikins at dif- ferent laboratories. It seems that it is essential to understand the working principles of various sweating thermal manikins available in different laboratories in order to accurately evaluate evaporative and thermal resistance.

In the last century, many researchers put their efforts into their individual labora- tories to develop the thermal manikin that can evaluate the thermal and evaporative resistances of clothing. The earliest thermal manikin was developed in 1945 by the US Army Research Institute on Environmental Medicine. This was a manually controlled one-segment copper manikin for the measurement of thermal resistance of a complete garment. From 1945 to date, the development of all manikins can be categorized into three generations [306]. In the first generation, the developed thermal manikins were standing (not walkable) and nonperspiring [428]; the second generation thermal man- ikins were movable (walkable) but nonperspiring, such as the manikins developed by University of Farnborough in England, Technical University of Denmark in Denmark, Hohenstein Institute in Germany (the copper manikin “Charlie”), and Kansas State University in the United States [428]. Among these second generation manikins, “Charlie” has been widely used. The Charlie manikin is made of copper and is divided into 15 segments that can be independently heated and temperature controlled; the manikin has movable joints at shoulders, elbows, hips, and knees and is driven by an external driving mechanism to simulate walking. At this stage, many workers tried to simulate sweating on nonperspiring manikins—in order do so, they put underwear of highly absorbent fabrics on the manikin, and supplied water to the underwear by sprinkling or water pipes. However, this wet underwear technique had the disadvan- tage that it was not possible to continuously generate sweat as occurs in human beings. As a consequence, the third generation of thermal manikins were developed, which can simulate true perspiration and/or body motions [306,431].

Since 1980, many sweating thermal manikins (standing or movable) have been developed in different laboratories all over the world. Some of these manikins are

(1) the Finnish sweating thermal manikin, Coppelius, (2) the Japanese sweating ther- mal manikin, Taro, (3) the Swiss sweating thermal manikin, SAM, (4) the Hong Kong sweating thermal manikin, Walter, (5) the United States sweating thermal manikin, ADAM, (6) the United States sweating thermal manikin, Newton, and (7) the Japanese sweating thermal manikin, KEM [306]. In this context, it is notable that ISO 9920, ASTM F 1291, and ASTM F 2370 standards designate a test protocol for determining the thermal and evaporative resistance of the clothing; however, these standards do not specify anything about the movability of the manikin. Additionally, ISO 9920 and ASTM F 2370 standards do not stipulate a specific design for sweating simulation and leave the sweating mechanism open to interpretation [436,442]. These unspecified freedoms encouraged the development of manikins in different laborato- ries with different sweating systems, sweat rate evaluation techniques, moving tech- niques, and so on. [306,431]. A brief description on the working principles of these manikins, mainly related to sweat generation, sweat rate evaluation technique, and/ or movement is presented here.

*Finnish sweating thermal manikin “Coppelius”*: The sweating thermal manikin “Coppelius” was developed based on the nonperspiring thermal manikin “Tore,” to which an additional sweating mechanism has been added [431]. The basic concept for this manikin (Coppelius) was to produce heat and moisture in a similar way to the human body. Coppelius was the first sweating thermal manikin developed (in 1980), which could deliver a controlled amount of water (200 g/m2/h) onto the surface of the manikin. This manikin has 18 individually controlled body sections. Its skin is

made up of two layers: an inner nonwoven material that transfers water via 187 arti- ficial sweat glands to the second, outer layer, which is microporous.

The manikin is housed in a chamber that can control the room temperature as per the requirements of the experiment. This manikin is hung from an electronic balance to constantly measure its weight. In order to evaluate evaporative resistance, the clothed manikin body is saturated with water. This water is supplied from a reservoir, and the amount of water supplied to the manikin is measured by an electronic balance attached to the reservoir. The amount of moisture vapor evaporation from the mani- kin’s body can be evaluated by calculating the difference between the weight of water supplied to the manikin, and the weight increase of the clothed manikin. The amount of moisture condensation in the clothing is measured by weighing the testing garments before and after the test. The amount of moisture condensation in the skin material of the manikin is measured by deducting the moisture condensed in the clothing from the increased weight of the clothed manikin.

*Japanese sweating thermal manikin “Taro”*: Dozen et al. [443] reported on the development of a sweating thermal manikin called “Taro”. This bronze manikin is equipped with pores that enable moisture vapors to flow from inside the manikin to the skin’s surface to simulate the body’s gaseous perspiration heat loss. The man- ikin’s body is divided into several segments, and the water supply in each segment can be individually controlled. The sweating quantity in each segment of the manikin is calculated by Eq. [(5.37)](#_bookmark65), where, *Qi* =sweat rate of a segment (g/m2/h); *qi* =the amount of air supply in the segment (L/min); *T*s*i* =skin temperature (°C); *T*a =ambient tem- perature (°C); *Di* =saturated absolute humidity (g/m3); *Ai* =the segment area (m2). The sweat rate can be altered by regulating the air flow rate. However, moisture vapor may not penetrate the garment to the ambient environment but rather escape from the opening of garment, especially in the case of increasing air flow rate.

*Q* = 60.10 — 3 · *q* · 273 + *T*s*i* · *Di*

(5.37)

*i i* 273 + *T*a *Ai*

*Swiss sweating thermal manikin “SAM”*: Richards and Mattle [444] introduced the Swiss “Sweating Agile Manikin,” or “SAM,” which has 26 individually controlled body parts with temperature sensors attached. Each body part can be heated sepa- rately. One hundred twenty-five artificial sweat glands are distributed all over the manikin’s body, which can simulate perspiration. The sweat rate of this manikin is 0–41 g/m2/h. The manikin can walk at the speed of 3 km/h in order to simulate real- istic human motion, and the wrists and ankles of this manikin are connected through an external drive assembly. Due to this, this manikin can move through various curves under computer control.

*Hong Kong sweating thermal manikin “Walter”*: The previous three manikins (Coppelius, Taro, SAM) were developed towards the end of the last century; however, their usability was very limited due to high cost. At this point, Fan [445] successfully developed a prototype of a low-cost fabric manikin in 1989 at the University of Leeds. However, the manikin developed by Fan was nonperspiring because the skin of the manikin was made up of a nonbreathable neoprene coated waterproof fabric. This

low-cost fabric manikin concept was further improved at Hong Kong Polytechnic University by Fan and Chen to develop the perspiring fabric thermal manikin called “Walter” [306]. Walter has a breathable fabric skin made of polytetrafluoroethylene (PTFE) Goretex membrane. The pores in this fabric are too small to allow water mol- ecules to pass through but large enough to allow the passage of molecules of water vapor [375]. Sweat glands present inside the manikin control the sweat. This manikin can maintain a constant body temperature by circulating water from its center to its extremities, and can move at a speed of 2.48 km/h to simulate actual human move- ment. As noted by the researchers, the strength of the membrane and seams used to construct the manikin must possess high strength in order to make the manikin dura- ble in the moving condition [306].

The Walter manikin is also hung in a controlled chamber similar to Coppelius. However, the technique used to measure evaporative resistance in the Walter manikin is different from the technique used with the Coppelius manikin. As previously explained, in the case of Coppelius, evaporative resistance is evaluated indirectly by calculating the difference between the weight of water supplied to the manikin and the weight increase of the clothed manikin. However, in the case of Walter, evap- orative resistance is measured directly. In this case, water is supplied to the Walter manikin as per the rate of sweating. During sweating, the water in the manikin reduces. As a consequence, water automatically flows to the manikin from a water reservoir through siphon action at the same atmospheric pressure. Therefore, the amount of water reduction in the water reservoir is proportional to the sweat rate of the manikin or the evaporative resistance of the clothing. It seems that the sweat rate in the Walter manikin is dependent on the type of clothing being tested. In real life, the perspiration of human beings is also dependent on their worn clothing; thus, Walter can simulate the real life perspiration of human beings. However, Walter cannot simulate real life situations in all contexts. It has been found that the sweating rate in different parts of a real human body is not equal. For example, the sweat rate for foreheads and underarms is much higher than other body parts. However, the Walter manikin cannot generate different sweat rates at its different parts. Furthermore, liquid sweats are formed at the skin surface of a real human body, whereas the Walter manikin can only allow the water vapor to pass through the skin. In real life, most sweat is also initially moved by liquid transport, then evaporates, transmits through moisture vapor, and at is last absorbed or condensed within the clothing worn by human beings; liquid transport further takes place when the condensed water exceeds a certain amount, and so on. This situation is somewhat different in the perspiring Walter manikin. Here, the mois- ture vapor from the skin surface of the manikin is initially transmitted through mois- ture vapor, and then is absorbed by or condensed on the tested garment; liquid transport further takes place, and so on. It seems that there is a difference in the initial liquid transport (immediately after sweat generation) between human beings and the manikin.

*United States sweating thermal manikin “ADAM”*: The United States sweating thermal manikin is called ADvanced Automotive Manikin (“ADAM”) and was devel- oped by Measurement Technology Northwest for the National Department of Renew- able Energy (NDRE) [446]. ADAM has a 175 cm height and 61 kg weight, which is

designed to match the 50th percentile of American males. ADAM has completely human-like geometry and weight with prosthetic joints to simulate the human range of motion. The manikin is equipped with sophisticated surface sensors that interact with its ambient environments. Not only does it respond to thermal inputs such as radi- ation and convection, but it also is affected by the environmental flow field and tem- perature field. There are 126 individually controlled segments in this manikin, each with a typical area of 120 cm2. Each segment is a stand-alone device with integrated heating, a temperature sensor, sweat distribution and dispensing, a heat flux gauge, and a local controller to manage the closed loop operation of the segment. Here, dis- tributed resistance wires provide uniform heating across each segment surface; the temperature of each segment is determined by an array of thermistors, typically four, on each segment; the sweat rate of each segment is controlled by a fluid control valve; and the heat flux gauge measures the heat loss in the manikin interior from each seg- ment. The sweating surface is an all-metal construction, optimized for thermal unifor- mity and temperature response speed (temperature response time that approximates human skin); and the variable porosity within the surface provides lateral sweat distribution and flow regulation across the segment. A breathing system was installed in this manikin in 2004 to permit inhalation and exhalation at a rate of 5 L/min; the breathing system can also permit a continuous high level of exhalation at 15 L/min. This manikin can generate realistic and uniform sweating as well, as it is rugged, dura- ble, and requires low levels of maintenance. Most importantly, this manikin is self-contained, with enough battery power, wireless data transfer capability, and inter- nal sweat reservoirs for at least 2 h of use with no external connections. Presently, this manikin with different postures is mainly used in transient and nonuniform thermal environments of automobiles (vehicles, aircrafts, etc.) to evaluate the thermal and evaporative resistance of clothing. This manikin can proficiently evaluate the thermo- regulatory response of a person who is wearing (1) a moisture impermeable suit used by first-responder personnel such as Hazmat, (2) a flight suit, (3) a battle dress suit, and (4) others [extra vehicular activity (EVA) suit, and personal cooling systems used with such suits].

*United States sweating thermal manikin “Newton”*: The thermal manikin “Newton” was produced by the Measurement Technology Northwest Company in the United States. This manikin is constructed of a thermally conductive aluminum-filled carbon-epoxy shell with embedded heating and sensor wire elements. The Newton body form (height 175 cm, surface area 1.8 m2, weight 30 kg) is available as either a 50th percentile western or Asian male, in either dry or sweating format. At present, this manikin body can be divided into 20 segments, 26 segments, or 34 seg- ments. This manikin is attached to a breathing machine with a nose/mouth manifold or filter. Newton was developed using advanced CAD digital modeling to ensure repeat- ability in manufacturing. This manikin is fully jointed, and can perform motorized walking motion at ankles, elbows, knees, and hips to allow virtually any possible body pose. The sweat rate of this manikin can be controlled manually.

*Japanese sweating thermal manikin “KEM”*: According to Fukazawa et al. [434], the manikin “KEM” was developed by the Kyoto Electronic Manufacturing of Japan. This manikin has 17 segments with movable joints and 17 sweat glands under the

water vapor permeable skin which distribute the water. The sweat rate produced by this manikin is 0–1500 g/m2/h, and the sweat rate of each gland can be individually controlled using pistons. The sweating mechanism of KEM is not a new technique; it is similar to that of the Finnish sweating thermal manikin Coppelius, developed in the 1980s, in terms of sweating sources and water vapor permeable skin.

Although the previously mentioned sweating thermal manikins (Coppelius, Taro, SAM, Walter, Newton, ADAM, KEM) are very popular for evaluating the thermal and evaporative resistance of regular clothing under normal ambient environments, these manikins have rarely been used to evaluate the thermal and evaporative resistance of thermal protective clothing [444]. This may be due to the unavailability of the man- ikins to researchers who usually focus on the resistance provided by thermal protective clothing. However, although most of the manikins are used to assess the thermal and evaporative resistance of regular clothing, the findings from these studies can be par- tially applied to thermal protective clothing. Furthermore, the sweat generation rates of these thermal manikins are also very limited compared to the sweat generated by firefighters in actual fire hazard scenarios. Thus, the evaluation of evaporative resis- tance of thermal protective clothing using sweating thermal manikins may not be accurate for real situations. Additionally, these sweating manikins are expensive and can only be operated by a skilled and trained operator. As a consequence, these manikins are exclusively used for high-end research and development purposes [445].

### Assessment of thermal and evaporative resistance

Many researchers evaluated the thermal and evaporative resistance of clothing, using the equipment/methods described in various standards (eg, ASTM F 1291, ISO 15831, EN 342, ASTM F 1720, ASTM F 2370, ISO 9920) or by employing their own cus- tomized instruments/procedures [440,441,447]. These studies have identified that fab- ric features (eg, fiber types, weaves, design, weight, thickness, porosity), clothing attributes (eg, fit, design, construction), and/or ambient environmental variables (air, temperature, relative humidity) mainly affect heat and/or moisture/water vapor transfer (convective/conductive/radiative/diffusive) through clothing, which ulti- mately affect the thermal and evaporative resistance of the clothing.

Lotens and Hevenith [440] studied the thermal resistance of clothing having a lay- ered structure and different thickness/weights. It was found that thermal resistance is mainly dependent upon ambient air velocity and clothing weight. Generally, an increase in air velocity can decrease thermal resistance, with a lesser effect on heavy clothing than on light clothing. It was also determined that layered structure clothing may trap larger amounts of air within its structure, which can enhance the thermal resistance of this clothing [447]. Researchers also found that thermal resistance is affected by the tightness of the fit of clothing and the clothing area factor (ratio of clothed body surface to the nude body surface). Here, highly tight-fitting clothing has a lower clothing area factor than loose-fitting clothing, which ultimately lowers the thermal conductivity of the tight-fitting clothing and increases its thermal resis- tance. Bouskill et al. [447] analyzed the thermal resistance of air-impermeable and

-permeable clothing having layered structures. Here, air-impermeable clothing had

a one-layered structure and air-permeable clothing had a three-layered structure. In this context, it was found that air-permeable clothing allows for transfer of the rela- tively cool air from the environment toward the manikin; as a consequence, the ther- mal resistance of this clothing becomes lower. In this study, it was also found that air layers trapped in between the clothing and manikin body (clothing microenvironment) plays an important role in clothing insulation; any exchange of air between the trapped air layers and the cooler ambient environment results in a change in thermal insula- tion. It was concluded that the exchange of air increases the heat transfer from the manikin surface to the ambient environment; consequently, the thermal resistance of the clothing decreases. In addition, the movement of the manikin allows the exchange of air and affects thermal resistance. If the speed of the movement is high, it will help to exchange a high amount of air between the clothing microenvironment and the ambient environment; eventually, the thermal resistance of the clothing decreases. Chen, Fan, and Zhang [441] corroborated that the thermal resistance of clothing is mainly evaluated in dry conditions. However, clothing can be wet due to perspiration from wearers’ bodies, and this accumulated water in clothing has a sig- nificant effect on thermal resistance. In this study, the thermal resistance of slightly wet (due to low perspiration) and highly wet (due to high perspiration) clothing are compared and analyzed. It has been found that the thermal resistance of wet clothing is significantly lower than the thermal resistance of dry clothing, and the thermal resis- tance of wet clothing can vary between 2% and 8% depending upon the accumulated water within the clothing. This lower thermal insulation can provide a chilling effect to wearers. Chen, Fan, and Zhang [441] challenged many other studies (McCullough, Jones, and Tamura [428]; Mecheels and Umbach [429,430]), where THL through clothing was considered the combination of thermal and evaporative resistance, and thermal resistance was evaluated only in dry clothing conditions. Chen, Fan, and Zhang [441] suggested that clothing’s thermal resistance should be calculated in both dry and wet conditions in order to accurately evaluate the THL through cloth- ing. Xu et al. [448] studied the thermal resistance of liquid cooling garments. It was stated that only a portion of total liquid cooling garments can actually reduce thermal resistance by perfusate circulating within the garments. Here, the perfusate inlet tem- perature is lower than both manikin and ambient temperatures. As a consequence, per- fusate helps to absorb heat from both the manikin and ambient environments; this situation lowers the thermal resistance of the garments. In this study, it was also found that the placement of an outer clothing layer on a garment may enhance the thermal resistance of the garment. Contextually, Bogerd, Psikuta, Daanen, and Rossi [449] studied the cooling garments with a manikin. They found that the manikin overesti- mates the cooling effect due to the lack of vasoconstriction simulation. The human subjects had vasoconstriction in the skin, which limited the cooling effect of the cooling vests. Qian and Fan [450] evaluated the thermal resistance of clothing under various ambient air velocities and walking speeds of manikins. It has been found that ambient air velocity significantly affects the thermal resistance of clothing in combi- nation with walking. Here, it was evident that thermal resistance decreases with increasing air velocity and walking speed. This is because increased air velocity and walking speed enhance the transfer of heat from the manikin body to its ambient

environment, which helps to reduce the thermal resistance of clothing. The effect of walking speed on the total thermal resistance of a clothing system was equivalent to 180% of air velocity. Fan and Tsang [451] discussed the thermal resistance of a track- suit. They confirmed that fabric properties such as porosity and movement of the man- ikin have significant effect on thermal resistance. It was evident that highly porous fabric-based clothing may allow for transfer of convective heat from a manikin’s body to its ambient environment and can lower the thermal resistance of clothing.

Ho et al. [392] investigated the impact of clothing design on the thermal resistance of clothing. In order to do so, they chose 10 short sleeve T-shirts of varying opening styles and mesh styles. They found that the design has significant effect on thermal resistance in standing as well as walking conditions of the manikin. It was evident that the thermal resistance of all of the T-shirts was much lower in the walking condition of the manikin than the standing condition of the manikin. This is because more natural convection (ventilative cooling) occurs in the walking condition in between the cloth- ing and manikin body, which ultimately lowers thermal resistance. It was also found that the thermal resistance of a T-shirt with more openings or comprising mesh fabrics at two vertical side panels along the side seams is significantly lower than a T-shirt with less opening or one comprising no mesh fabrics; this was evident in both standing and walking conditions of the manikin. Additionally, it was found that the presence of mesh fabrics at the center back or center front (either horizontally or vertically) of the manikin body does not have much effect on thermal resistance. This is because the mesh fabrics at these locations tend to lay on the manikin’s surface due to garment draping, and do not allow for transfer of heat from the manikin’s body to the ambient environment (less ventilative cooling). In the walking condition, the drape of the gar- ment changed rapidly, which allowed the mesh fabrics to gain more contact with the manikin’s surface. Furthermore, Ho et al. [392] concluded that the thermal resistance of a T-shirt gradually increases with increased T-shirt size in standing or no wind con- ditions. This increasing trend of thermal resistance continued even in walking and windy conditions. This study showed that adding fullness to the T-shirt design to cre- ate a flared drape can significantly reduce the thermal resistance of T-shirts under walking or windy conditions. The reduction of thermal resistance can further be enhanced by creating small apertures in the T-shirt design for added fullness.

Zhou et al. [452] compared the thermal resistance of permeable and impermeable clothing in dry and wet conditions of the manikin. It was found that water condensa- tion occurs within clothing in wet conditions, and this condensation process affects thermal resistance. Due to water condensation, the thermal resistance of wet clothing is much higher than the thermal resistance of dry clothing. It has been found that con- densation occurs more in impermeable clothing than in permeable clothing; as a con- sequence, the difference between the thermal resistance in dry and wet conditions is greater for impermeable clothing than for permeable clothing. Wu, Fan, and Yu [453] evaluated the thermal resistance of various clothing under different postures (stand- ing, sedentary, supine) of the sweating thermal manikin Walter. In this study, it was evident that the thermal resistance of clothing is significantly higher in the sedentary posture than the standing posture. Here, the radiative heat transfer coefficient from manikin body to the ambient environment was lower in the sedentary posture than

the standing posture due to a reduction in the radiative body surface area in the sed- entary posture; this lower radiative heat transfer coefficient increases the thermal resistance of the clothing. The sedentary posture also creates a cavity over the hori- zontal knees and thighs of the manikin. As a consequence, natural convection reduces over the manikin body in the sedentary posture versus the standing posture; this reduc- tion in natural convection enhances the thermal resistance of the clothing. Further- more, it was evident that thermal resistance is significantly higher in the supine posture than the standing posture. This is because the manikin remains flat on a wooden bed in the supine posture, and this wooden bed enhances thermal resistance. In this study, it was evident that thicker clothing always has a higher thermal resis- tance than thinner clothing in all postures. However, the thickness of the clothing may be significantly reduced in the supine posture due to compression provided by the manikin body; this reduction in thickness significantly reduces the thermal resis- tance of the clothing.

Holmer [454] investigated the thermal resistance of protective clothing under hot environments. It has been found that thermal resistance is dependent upon the emis- sivity of clothing. If the emissivity of clothing is higher in a hot environment, it can reduce the thermal resistance of clothing. The emissivity is dependent upon the mate- rial and surface structure of the fabric used to manufacture the clothing. Here, a polished surface emits much less radiation at a given temperature (10–20%) in com- parison with painted, matte, varnished, or dark surfaces (80–100%). As a conse- quence, polished surface-based fabric causes less radiant heat-load on wearers under hot environments; eventually, the thermal resistance of this clothing is indi- rectly reduced. However, a polished surface may enhance the evaporative resistance of clothing, which can be detrimental to wearers. Similarly, Oliveira, Gasper, and Quintela [437] evaluated the thermal resistance of cold-weather protective clothing ensembles, both in static conditions and considering the effects of body movements. The results from this study showed that the dynamic thermal resistance of this clothing was always lower than the corresponding static resistance. This means that an effec- tive reduction in thermal resistance should always be expected in the presence of any kind of movement. It was evident that a reduction in thermal resistance mainly occurs in thick and layered clothing. Here, the thermal resistance of clothing was highly dependent upon the layered structure of the chosen fabric, fabric weight and thickness, and clothing area factor. Brien et al. [455] evaluated the thermal resistance of clothing designed to provide protection from chemical, biological, radiological, nuclear, and explosive hazards. In this study, it was inferred that the thermal resistance of protec- tive clothing is highly dependent upon the wind velocity present in the clothing’s sur- roundings. Here, wind speed has greater effect on clothing with high thermal resistance in normal ambient conditions, and an increase in wind speed significantly reduces the thermal resistance of this clothing. However, the effect of wind speed is significantly lower on low-permeable clothing than high-permeable clothing. It should be noted that the protective clothing used in this study needs a high thermal resistance to provide protection from outside thermal hazards; thus, there must be a balance on thermal resistance that can provide optimum protection to wearers as well as effectively transfer their metabolic heat to the surrounding environment [24,29].

McCullough [456] investigated the evaporative resistance of clothing using a standing sweating thermal manikin. This evaluation was carried out in a residential building and vehicles. It was identified that the heating, ventilating, and air condition- ing system of a building or vehicle have a significant effect on the evaporative resis- tance of clothing. It can be concluded that the consideration of ambient environmental conditions is highly significant when evaluating evaporative resistance. Wang et al.

[457] studied the intrinsic evaporative resistance of multilayered winter clothing ensembles. In this study, various individual clothing articles (underwear, garment, and jackets) were used to construct multilayer clothing ensembles. It was identified that the intrinsic evaporative resistance of the individual clothing articles is dependent upon clothing area factors (ratio of clothed body surface to the nude body surface); and the clothing area factor of thicker fabric-based clothing is much higher than for thinner fabric-based clothing. As a consequence, the evaporative resistance of thick and thin clothing is very different. It was also identified that the evaporative resistance of a clothing ensemble has a linear relationship to the combined evaporative resistance of the individual clothing used in the ensemble.

Wu, Fan, and Yu [453] evaluated the evaporative resistance of various clothing under different postures (standing, sedentary, supine) of the sweating thermal manikin Walter. They identified a high correlation of the evaporative resistance in standing and sedentary postures. It was observed that the evaporative resistance of the sedentary posture was about 20–97% higher than that of the standing posture. In this context, Havenith, Heus, and Lotens [458] mentioned that the evaporative resistance of the sedentary posture is about 16–38% higher than that of the standing posture. It seems that Wu and Havenith’s study provided a different range of difference of evaporative resistance between the sedentary and standing postures; nevertheless, Wu’s study may be more realistic because they used the sweating thermal fabric manikin Walter, a highly reliable testing method. Wu, Fan, and Yu [453] also stated that the evaporative resistance for the manikin’s supine posture was significantly higher than that of the standing or sedentary posture. This is because a large amount of water condensation occurs (within the clothing, in between the clothing and the bed, etc.,) in the supine posture, and this water condensation enhances evaporative resistance. In this study, it was found that evaporative resistance in nonisothermal conditions is generally lower than in isothermal conditions in both standing and sedentary postures. This is because the natural convection induced by the temperature gradient is much lower in isother- mal conditions than in nonisothermal conditions. It was also observed that a higher temperature gradient in between the manikin body and the ambient environment con- tributes to the accumulation of water within the manikin’s clothing; this situation dras- tically changes the evaporative resistance. In fact, the moisture accumulation in the isothermal condition was around 1% or close to zero, which is substantially lower than that in the nonisothermal condition. In the nonisothermal condition, some moisture vapor accumulated in the clothing ensemble instead of fully evaporating. The evap- orative resistance measured in the nonisothermal condition, therefore, is apparently substantially lower than that of the isothermal condition.

Wang et al. [459] analyzed clothing’s evaporative resistance on different local body parts. The individual and interactive effects of air and manikin’s body

movements on localized evaporative resistance were examined using a strict protocol. Localized evaporative resistance was measured on the sweating thermal manikin at three different air velocities (0.13, 0.48, and 0.7 m/s) and three diverse walking speeds (0, 0.96, and 1.17 m/s). This study showed that wind speed has a distinct effect on localized clothing’s evaporative resistance. In contrast, walking speed had a larger effect on evaporative resistance of limbs (eg, thigh, forearm) versus the torso (eg, back, waist). In addition, the combined effect of body and air movement on local- ized clothing’s evaporative resistance demonstrated that walking has more influence on body extremities than the torso. This study concluded that localized clothing’s evaporative resistance is important for providing better comfort to wearers.

Zuo and McCullough [460] extensively studied the evaporative resistance of a vari- ety of permeable and impermeable protective clothing ensembles used in certain sports, such as football, baseball, soccer, and tennis. It was observed that the evapo- rative resistance of these clothing ensembles depends upon the moisture permeability characteristics and wicking properties of the fabric materials used in the clothing, and the amount of skin surface covered by the fabric. In this context, it is notable that the fiber content of the fabric has little effect on moisture permeability; instead, the mois- ture permeability is usually dependent upon fabric structure and type of surface fin- ishes used on the fabric. Generally, the moisture permeability of fabric with more open structures is higher than fabric with less open structures. In this study, it was found that the permeability index of impermeable and permeable clothing varies between 0 and 0.5; clothing with a high permeability index possesses lower evaporative resistance. In addition, if an article of clothing covers more body parts than others, generally it has high evaporative resistance.

Endrusick, Gonzalez, and Gonzalez [461] researched the evaporative resistance of US military chemical and biological protective clothing. They corroborated that the thicker, multilayered, and impermeable nature of the fabrics used in protective cloth- ing are mainly responsible for evaporative resistance. It was identified that evapora- tive resistance can be proportionately decreased by decreasing the thickness of the fabrics and/or by increasing the permeability of the fabrics. Gao and Holmer [462] studied the evaporative resistance of impermeable protective clothing with respect to time on the manikin body. In this study, the impermeable protective clothing was used in combination with cotton underwear. The researchers identified that the evaporative resistance of the impermeable clothing is different in the initial, transient, and steady-state of moisture vapor transfer through the clothing. It has been found that evaporative resistance is more than two times higher in the initial phases of moisture vapor transfer than in the steady-state phase. Here, the moisture content increased exponentially with time in the clothing ensemble; on the contrary, mass loss directly from the wet manikin skin decreased exponentially with respect to time. Candas, Broede, and Havenith [463] explored the evaporative resistance of various protective clothing (more or less permeable or impermeable coveralls) in combination with single-layer dry and wet underwear using a static (no body movement) standing man- ikin with 34°C skin temperature. This study investigated the impact of clothing attri- butes, wet/dry underwear, and ambient environmental conditions on evaporative resistance. It was found that the evaporative resistance of the coveralls was very

different under the same testing conditions; this is because the permeability of the cov- eralls was different. In this case, the impermeable coveralls showed the highest evap- orative resistance—more than other more or less permeable coveralls. Additionally, it was observed that the evaporative resistance of the permeable or impermeable cover- alls is very different in combination with dry and wet underwear. It was found that in the initial phase (when the coverall immediately comes into contact with the wet underwear), the coveralls absorb water and their evaporative resistance decreases; however, after some time, the evaporative resistance increases due to condensation of water inside the coveralls. This phenomenon was more prominent in the imperme- able coveralls, and the evaporative resistance of the impermeable coveralls varied at three different temperatures (10, 20, and 34°C) with constant ambient air velocity (0.5 m/s) and water vapor pressure (1 kPa). Holmer [454] analyzed the evaporative resistance of protective clothing. He reported that the evaporative resistance of this clothing is dependent upon its permeability and thickness; generally, the evaporative resistance of impermeable and thick clothing ensembles is higher than for permeable and thin clothing ensembles. He explained that in impermeable or less permeable clothing, the saturation of the clothing microclimate and condensation within clothing ensembles occurs very quickly. This condensation occurs more effectively inside the outer layer and moisture barrier present in protective clothing, especially in temperate and warm ambient environments. Eventually, the heat is liberated due to condensation and raises the local temperature within the clothing. This increasing local temperature increases the evaporative resistance of the protective clothing. Richards et al. [464] investigated the effect of moisture and underwear on the evaporative resistance of cold weather protective coveralls in transient and steady-state conditions. The clothing materials used in this study had a range of different properties; the underwear clothes were hygroscopic, hydrophilic, or hydrophobic; and the coveralls had different per- meability and thermal insulation values. It was observed that the evaporative resis- tance of tight-fitting clothing is more dependent upon the hygroscopicity of underwear than that of loose-fitting clothing. This study established that moisture absorption and desorption occurs very frequently in transient conditions; as a conse- quence, the evaporative resistance of clothing varies continuously. As no moisture absorption and desorption occurs in the steady-state condition, it was observed that evaporative resistance does not change very frequently in this condition.

### Evaluation and assessment of physiological clothing comfort using human trials

The preceding discussion confirms that many researchers have evaluated and assessed the thermal resistance, evaporative resistance, and/or THL of fabrics or clothing using various laboratory tests (a sweating guarded hot plate, sweating thermal manikins, etc.). These studies can help to understand the physiological comfort provided by clothing to wearers without directly involving any real human beings. The thermal and evaporative resistance results obtained from the sweating thermal manikin tests can also be further modeled for indirectly predicting humans’ physiological comfort in

different clothing ensembles and ambient and metabolic conditions; in this case, the results obtained from the tests are entered into different types of computer modeling software to predict the desired output automatically related to humans’ physiological comfort [458,465]. For example, Havenith, Heus, and Lotens [458] used the thermal and evaporative resistance of clothing under different manikin movements, postures, and ambient wind velocities to explain the physiological comfort provided by clothing on a working human being. Ghaddar, Ghali, and Jones [465] thoroughly reviewed a variety of computer models developed based on thermal and evaporative resistance values of clothing to understand clothed humans’ physiological comfort responses in a particular situation, and they also developed an empirical model to predict the physiological comfort of a clothed human body at a particular ambient temperature with sensible/latent metabolic heat losses. The US Army Research Institute of Envi- ronmental Medicine (USARIEM) developed a human physiological comfort model by using the thermal and evaporative resistance values of clothing to predict the clothed working human body’s core temperature, maximum endurance time, optimal work/ rest cycles, etc. Similarly, the ISO 7933 standard explained a predicted heat strain (PHS) model (based on accurate measurements of clothing’s thermal and evaporative resistance according to the ISO 9920 standard) to evaluate clothed human physiolog- ical comfort in terms of skin temperature, rectal temperature, etc. The advantage of these models is that predictions can be made for a wide variety and combination of input variables; however, these models assume that all human beings possess uniform or constant metabolic rates. In reality, metabolic rates cannot be uniform for a group of people because individual differences in height, weight, and oxygen consumption are all determining factors. A higher level of metabolic rate is also observed in an indi- vidual with dynamic work when compared to static work, as muscles are required to flex and extend according to work demands. It seems that laboratory-based thermal resistance, evaporative resistance, and/or THL values obtained from thermal manikin tests may not be accurately modeled to predict the physiological comfort of a clothed person, as these values do not consider the real metabolic rates of human beings. Addi- tionally, the limitation of currently developed models is that not all conditions can be modeled, or they must be modeled with qualifications, because the existing used data bank is incomplete in some areas. Wang et al. [466] recently challenged predictions of physiological comfort of a clothed human body made using the PHS model (ISO 7933). Wang et al. [466] evaluated the PHS model using six human subjects, three clothing ensembles (clothing thermal resistance varied between 0.63 and 2.01 clo), and two ambient environmental conditions [466]. Rectal and skin temperatures predicted by the PHS model using set ambient conditions were compared to data gen- erated from clothed human trials with the same ambient conditions. It was found that the PHS model failed to accurately predict skin temperatures for all three clothing ensembles. In spite of this, the model’s prediction of rectal temperatures was within 1 standard deviation (SD) of observed rectal temperatures in human trials for two of the three clothing ensembles. The predicted versus observed rectal temperatures for the third ensemble (2.01 clo) was 3.75SD greater than the human subject average mean SD. Based on these findings, Wang et al. [466] suggested that it is necessary to directly evaluate the comfort provided by clothing from human subjects

[165,383,384]. Here, it is noteworthy to mention that the medical, cost, and time con- siderations, as well as biological variability can impose more limitations on human testing, compared with the sweating guarded hot plate, thermal manikin testing, or predictive model developments. However, the advantage of human laboratory testing is that data collected from real people are perceived to be, and can be, reliable and valid. Thus, human physiological testing should be included in clothing comfort eval- uation, if prediction modeling indicates that comfort differences between clothing ensembles are sufficient within the resolution of physiological measurements. Here, careful consideration should be given regarding appropriate test methodology, as the results obtained from human trials are often included to provide garment users with information from a more realistic perspective. Because even a homogeneous group of human test subjects displays considerable interindividual variability, every effort must be made to account for variables within the investigator’s control if meaningful com- fort data are to be collected. Investigators must also adhere to applicable regulations for protection of human research subjects and consult/comply with the recommenda- tions of their institutional ethics review boards. Although human trials are best done in a controlled laboratory environment, human trials can also be conducted in an actual working field environment for realism and clothing user acceptability. The following section discusses in detail a general procedure for evaluating physiological clothing comfort using human trials in controlled laboratory or field environments.

### Evaluation of clothing comfort using human trials

The ASTM F 2668 standard is available to evaluate clothing comfort in a controlled laboratory environment, but clothing comfort in a controlled laboratory environment can be carried out per an investigator’s discretion. Additionally, field trials can be car- ried out according to investigators’ requirements and objectives. The ASTM F 2668 standard is believed to be appropriate for the evaluation of a majority of protective clothing ensembles, especially where wearers need to walk or perform similar activ- ities; this practice utilizes a treadmill for the wearers’ exercise protocol. In certain situations, where a protective clothing ensemble is designed to be worn when the user is performing specialized functions (eg, sitting or standing with only arm movement), alternative exercise equipment (eg, arm cycle-ergonometers) or protocol should be considered for use in determining clothing comfort. Here, it is necessary to remember that it is ethically unacceptable to involve human beings for evaluating comfort in a thermal environment that firefighters face in an actual fire hazard. Thus, all researchers should use a temperate environmental chamber to evaluate the comfort provided by thermal protective clothing. During all human trials in a laboratory- controlled environment, a physician should be readily available; for human trials in a field environment, an ambulance service should be readily available in addition to a physician.

According to the ASTM F 2668 standard, first, a group of human subjects need to be selected by investigators as research participants. All the selected human subjects should be healthy, relatively fit, and must be medically screened (medical history and physical exam) to exclude those for whom the combined stress of exercise and