Designation: F2732 – 16

Standard Practice for Determining the Temperature Ratings for Cold Weather Protective Clothing[1]

This standard is issued under the fixed designation F2732; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

INTRODUCTION

Manufacturers of cold weather protective clothing want consumers to be thermally comfortable when wearing their products. Therefore, they want to indicate the amount of warmth (that is, insulation) their products will provide to consumers at the point of sale. This is often expressed as a temperature rating on product labels and in product descriptions in catalogs. A temperature rating is commonly understood to mean the lowest air temperature at which the average adult person will have an acceptable level of thermal comfort when wearing the product. Although it is not always stated on labels or in catalogs, manufacturers are assuming that consumers will wear the appropriate amount of clothing with the cold weather garments.

Heated manikins are used to measure the thermal resistance (insulation) and evaporative resistance of clothing ensembles in accordance with Test Methods F1291 and F2370, respectively. The thermal insulation value of a cold weather protective ensemble are used in heat loss models to estimate the thermal comfort of people in cold environments. This approach has already been used for sleeping bags (see EN 13537).

1. Scope

1.1 This standard practice covers the determination of the temperature rating of cold weather protective clothing ensembles. It involves measuring the thermal resistance (insulation) value of a clothing ensemble with a heated manikin in accordance with Test Method F1291 and using a heat loss model to predict the lowest environmental temperature for comfort.

1.2 The predictive model used in this standard estimates the evaporative heat loss from a person wearing cold weather clothing as opposed to measuring the evaporative resistance on a sweating manikin. If a person is active and gets overheated in a cold environment, he/she is usually able to adjust the garments in order to dissipate excess heat.

1.3 The temperature ratings estimated by this standard practice are guidelines for thermal comfort that are designed to protect people from hypothermia when wearing cold weather protective garments. However, localized cooling, discomfort, and even frostbite could still occur at extremely low temperatures because clothing insulation is not evenly distributed over the body surface. In addition, some body parts (for example, ears, fingers, toes) have a high surface area relative to their mass, and consequently lose heat at a faster rate than other parts of the body.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

F1291 Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin

F2370 Test Method for Measuring the Evaporative Resistance of Clothing Using a Sweating Manikin

2.2 *Other Standards:*

EN 13537 Requirements for Sleeping Bags[3]

[1] This practice is under the jurisdiction of ASTM Committee F23 on Personal Protective Clothing and Equipment and is the direct responsibility of Subcommittee F23.60 on Human Factors.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

ASHRAE 55-2013 Thermal Environmental Conditions for Human Occupancy[4]

3. Terminology

3.1 *Definitions:*

3.1.1 *clo, n*—a unit of thermal resistance (insulation) equal to 0.155 K-m^2/W.

3.1.1.1 *Discussion*—The value of the clo was selected as roughly the insulation value of typical indoor clothing, which should keep a resting man (producing heat at the rate of 58 W/m^2) comfortable in an environment at 21°C, air movement 0.1 m/s.

3.1.2 *clothing ensemble, n*—a group of garments worn together on the body at the same time.

3.1.3 *temperature rating, n*—the lowest environmental temperature at which a person can remain thermally neutral while wearing a particular clothing ensemble.

3.1.4 *thermal comfort, n*—that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation (see ASHRAE 55-2013).

3.1.5 *thermal insulation, n*—the resistance to dry heat transfer via conduction, convection, and radiation.

3.1.5.1 *Discussion*—The following insulation values can be determined with a thermal manikin using clo units:

I_a = thermal resistance (insulation) of the air layer on the surface of the nude manikin.
I_t = total thermal resistance (insulation) of the clothing and surface air layer around the manikin.
I_{cl} = intrinsic thermal resistance (insulation) of the clothing.

Total insulation values are measured directly with a manikin. Intrinsic clothing insulation values are determined by subtracting the air layer resistance around the clothed manikin from the total insulation value for the ensemble.

4. Significance and Use

4.1 This practice is used to measure the insulation provided by different cold weather clothing systems using a heated manikin (see Test Method F1291) and to predict the temperature rating for comfort at two activity levels using whole body heat loss models.

4.1.1 The temperature rating is for an ensemble—not an individual garment. However, manufacturers want to label cold weather garments with a temperature rating to help consumers select the product that will best meet their needs. Therefore, the standard is limited to garments that cover a substantial amount of body surface area such as jackets, coats, and insulated pants, coveralls, or snow suits. The temperature ratings of head wear, footwear, and hand wear cannot be determined with this practice.

4.1.2 The temperature predictions determined by this standard practice are for adults only. The physiology of children is significantly different from that of adults, so a modified heat loss model needs to be used to predict the comfort of children wearing outdoor clothing.[5]

4.1.3 The temperature ratings determined by this standard practice and listed on garment labels are only guidelines for comfort and will be affected by the garments consumers wear with them, their activity level during wear, and individual differences in the physiological characteristics of people (for example, gender, age, body mass, etc.).

5. Calibration of Manikin

5.1 *Manikin*—Use a thermal manikin as described in Test Method F1291.

5.2 *Calibration*—Calibrate the manikin using the procedures in Test Method F1291.

5.2.1 The intrinsic clothing insulation value of the Test Method F1291 calibration ensemble (I_{cl}) needs to be 0.79 clo, ±10 % before proceeding with this method.

6. Base Ensembles

6.1 Cold weather garments are worn with other garments as part of an ensemble. Therefore, they need to be tested that way on the manikin in order to determine the temperature for comfort. All cold weather jackets, coveralls, and jacket/pant sets (where the garments are designed to be worn together) shall be tested with a lightweight base ensemble that represents the minimum amount of clothing that a reasonable person might wear with the cold weather clothing (Base Ensemble #1). Cold weather pants shall be tested with a base jacket added to the base ensemble (Base Ensemble #2). The size of the garments shall be selected based on the measurements of the manikin.

6.2 The garments used in Base Ensemble #1 are:

6.2.1 *Shirt*—Long-sleeve mock turtle neck shirt, interlock knit, 100 % cotton, 214 g/m^2 (6.3 oz/yd^2); worn with shirttail over jeans.

6.2.2 *Jeans*—Denim 5-pocket jeans, 100 % cotton 397 g/m^2 (11.7 oz/yd^2).

6.2.3 *Men's Underwear Briefs*—Jersey knit briefs, 100 % cotton, 180 g/m^2 (5.3 oz/yd^2); jockey style that fits snugly at the waist and legs (from Test Method F1291).

6.2.4 *Men's Socks*—Basic knit sock that covers foot and extends up the calf no more than 25.4 cm (10 in.) from the bottom of the heel. Each individual sock shall be composed of at least 75 % cotton and shall weigh 33 ± 5 g (from Test Method F1291).

6.2.5 *Athletic Shoes*—Fabric/soft leather and soft sole.

6.2.6 *Gloves or Mittens*—Insulated knitted fleece gloves or mittens, 100% polyester, all layers 454 g/m^2 (13.4 oz/yd^2); cuffs worn under jacket sleeves.

6.2.7 *Hat*—Knitted fleece hat, 100 % polyester 129 g/m^2 (3.8 oz/yd^2); worn pulled down to eye brows.

6.2.8 The intrinsic thermal resistance (insulation) value (I_{cl}) of Base Ensemble #1 needs to be 0.80 clo, ±10 %.

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[4] Available from American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329, http://www.ashrae.org.

[5] McCullough, Elizabeth A., Eckels, Steve, and Harms, Craig. "Determining Temperature Ratings for Children's Cold Weather Clothing," *Applied Ergonomics*, Vol. 40, 2009, pp. 870-877.

6.2.8.1 The insulation value of the cold weather ensembles would be higher (and the predicted temperature ratings lower) if a thicker base ensemble was used. However, many people will not wear more clothing with the cold weather garments, and some people might not wear gloves, or a hat, or both. Consequently, this standard practice is specifying a lightweight base ensemble only. It is acceptable for other garments such as thermal underwear to be substituted for the knit shirt and jeans as long as the intrinsic insulation value is 0.80 clo, ±10 % and the head, hands, and feet are covered in the same way.

6.3 The garments used in Base Ensemble #2 are:

6.3.1 All of the garments in Base Ensemble #1.

6.3.2 A quilted fiberfill jacket, 100 % nylon shell and lining, 100 % polyester fiberfill insulation, all layers 339 g/m^2 (10.0 oz/yd^2). The stow-away hood shall not be placed on the head during the test; it needs to be stowed in the collar.

6.3.3 The intrinsic thermal resistance (insulation) value (I_{cl}) of Base Ensemble #2 needs to be 1.35 clo, ±10 %.

7. Sampling and Test Specimens

7.1 *Sampling*—It is acceptable to test one sample (that is, specimen) of each garment type. However, there will be some variability in garments made of fiberfill or down insulations, so it is recommended to test two or three specimens and average their insulation values prior to modeling.

7.2 *Specimen Size and Fit*—Select the size of garments that will fit the manikin appropriately (that is, the way the manufacturer designed them to be worn on the human body during their intended end use).

8. Manikin Procedure

8.1 *Environmental Test Conditions*—The test conditions given below shall be standard for all tests unless otherwise stated.

8.1.1 *Air Temperature*—The air temperature shall be at least 12°C lower than the mankin's mean surface temperature (that is 23°C) during a test. When emsembles with high insulation values are tested (for example, cold weather clothing), the air temperature shall be lowered so the that a minimum heat flux of 20 W/m^2 form the manikin's segements is maintained. A temperature around 20–23°C will be needed for the nude test and the base ensemble test. A lower air temperature (for example, 5°C) will be needed for heavy cold weather ensembles.

8.1.2 *Air Velocity*—The air velocity shall be 0.4 ± 0.1 m/s during a test.

8.1.3 *Relative Humidity*—Select a level between 30 and 80 % relative humidity ±5 %, preferably 50 %. The relative humidity has no effect on measurements of insulation under steady-state conditions.

8.2 *Mean Surface (Skin) Temperature of Manikin*—The manikin's surface temperature shall be maintained at 35 ± 0.5°C for all tests. The mean surface temperature shall not be allowed to drift more than ± 0.2°C during a 30 min test.

8.3 *Nude Test*—Measure the thermal resistance (insulation) (I_a) provided by the air layer surrounding the nude manikin by conducting a test using the same procedures given for the cold weather ensemble tests (see 8.5).

8.3.1 A new nude test shall be conducted for every series of cold weather clothing tests since this value (I_a) is used to calculate the standardized total thermal resistance of each clothing ensemble.

8.4 *Base Ensemble Test*—Measure the total thermal resistance (insulation) (I_t) provided by Base Ensemble #1 (and Base Ensemble #2 if cold weather pants will be evaluated) by conducting a test using the same procedures given for the cold weather ensemble tests (see 8.5).

8.4.1 The base ensemble tests shall be conducted periodically to document that the intrinsic thermal resistance values for these ensembles meet the requirements given in the standard within ±10 % (see 6.2 and 6.3).

8.5 *Cold Weather Ensemble Test*—Dress the standing manikin in Base Ensemble #1 or #2 and the cold weather garment (such as a jacket, coverall, or pants) or garments (such as a work jacket and pants set) to be tested. Garments with a hood need to be tested with the hood drawn up over the hat and tightened around the face. Position the manikin so that it is hanging vertically a few inches off the floor with its arms at its sides. Take a photograph of the ensemble on the manikin for the report (optional).

8.5.1 Conduct the test in accordance with procedures given in Test Method F1291.

8.5.2 *Replication of Tests*—Conduct three replications of the test, with at least 15 minutes in between test periods. If more than one sample is available of each garment type, test each separately one time.

9. Insulation Calculations

9.1 The parallel method of calculating the total thermal resistance (insulation) of the clothing ensemble shall be used, where the area-weighted temperatures of all body segments are summed and averaged, the power levels to all body segments are summed, and the areas are summed before the total resistance is calculated. Calculate the total thermal insulation of the clothing ensemble (I_t) to the nearest 0.01 clo, using Eq 1: (6.45 is a units constant).

$$I_t = (T_s - T_a) A \cdot 6.45 / H \quad (1)$$

where:

I_t = total thermal resistance (insulation) of the clothing and surface air layer around the mankin (clo),
A = manikin's surface area (m^2),
T_s = mankin's surface temperature (°C),
T_a = air temperature (°C), and
H = power required to heat the manikin (W).

9.1.1 It is **not** valid to use only the zones of the manikin covered by the cold weather garment in the calculation of insulation. The total thermal resistance value for the whole body is used to determine the temperature ratings for comfort.

9.2 Determine the average total insulation value (I_t) of the ensemble by averaging the values from the three replications of the test.

9.3 Determine the average intrinsic insulation value of the clothing alone (I_{cl}) to the nearest 0.01 clo, using the mean I_t value and Eq 2:

$$I_{cl} = I_t - (I_a/f_{cl}) \quad (2)$$

where:

I_{cl} = intrinsic thermal resistance (insulation) of the clothing (clo),
I_t = total thermal resistance (insulation) of the clothing and surface air layer around the manikin (clo),
I_a = thermal resistance (insulation) of the air layer on the surface of the nude manikin (clo), and
f_{cl} = clothing area factor (dimensionless).

9.3.1 Use the value of 1.25 for the f_{cl} of Base Ensemble #1.

9.3.2 Use the value of 1.30 for the f_{cl} of Base Ensemble #2.

9.3.3 Use the value of 1.35 for the f_{cl} of cold weather clothing ensembles. It is possible to determine the f_{cl} value for each ensemble using a photographic method, but it is very time consuming. Therefore, an average value for cold weather clothing ensembles is used here.

9.4 Calculate the standardized total insulation value ($I_{t,s}$) of the cold weather clothing ensembles to the nearest 0.01 clo, using a standard air layer resistance of 0.5 clo in Eq 3:

$$I_{t,s} = I_{cl} + (I_{a,s}/f_{cl}) \quad (3)$$

where:

I_{cl} = intrinsic thermal resistance (insulation) of the clothing (clo),
$I_{t,s}$ = standardized total thermal resistance (insulation) of the clothing and surface air layer around the manikin (clo),
$I_{a,s}$ = standard thermal resistance (insulation) of the air layer on the surface of the nude manikin, 0.5 clo, and
f_{cl} = clothing area factor (dimensionless).

9.4.1 The thermal resistance of the air layer measured with a nude manikin (I_a) varies from lab to lab based on the air velocity and the air flow patterns in the chamber. Therefore, each lab needs to use their own I_a value to determine I_{cl} and use the standard $I_{a,s}$ of 0.5 clo to calculate a standardized total thermal resistance (insulation) value $I_{t,s}$ for each cold weather ensemble.

10. Temperature Ratings

10.1 The heat exchange between the body and the environment depends upon the environmental conditions, the clothing worn, and the activity of the person. All of these factors vary each time a person dons cold weather protective clothing and goes outdoors.

10.1.1 *Environment Conditions*—Air temperature, relative humidity, radiant temperature (for example, solar load), and air velocity (that is, wind) affect thermal comfort. These conditions vary from day to day and throughout the day and night.

10.1.2 *Clothing Worn*—Resistance to dry heat transfer from the body to the environment (that is, insulation value), resistance to evaporative heat transfer (that is, vapor permeability), and pumping during movement are clothing variables that affect thermal comfort. The garments that a person wears with a cold weather garment will change each time he/she wears it – causing the insulation value for the clothing system to vary. People also vary the way that they wear the cold weather garment (for example, hood down, zipper open, without liner, etc.), and these changes will affect insulation and comfort. In addition, if the garments get wet or penetrated by wind, the insulation value will decrease.

10.1.3 *Metabolic Heat Production*—Metabolic heat production is directly affected by a person's activity level. A person's activity level will vary from sleeping/resting to running or working hard.[6] As a person's activity level increases, the amount of metabolic heat produced by the body increases, and less insulation is needed for comfort. If the clothing insulation stays the same, the preferred temperature for comfort will be lower when a person is active. However, it is difficult to remain active for long periods of time while wearing thick, protective clothing. If a person is active and begins to feel too warm, he/she will adjust the clothing to dissipate the heat.

10.1.4 *Other Human Factors*—A person's gender, age, body surface area to mass ratio, muscle mass, and perceptions of comfort vary among people and affect thermal comfort also.

10.2 The average total thermal resistance (insulation) value for a cold weather clothing ensemble is used in a heat loss model to estimate the lowest temperature for comfort. (See Annex A1 for equations.) The assumptions for the model are:

10.2.1 Radiant temperature is assumed to be equal to air temperature in the model. In outdoor environments, the radiant heat from the sun provides warmth to a person during the day, and it is possible that he/she will lose more radiant heat to the environment on a clear night.

10.2.2 The effect of wind was not used in the model. Wind will reduce the insulation of a clothing system by decreasing the resistance provided by the external air layer around the body and by penetrating the clothing layers (creating convection currents inside the ensemble). Cold weather garments vary in their wind resistance properties. However, it is possible to use wind-chill temperature tables to roughly estimate the equivalent temperature for heat loss at different levels of air velocity.[7]

10.2.3 An average 50 % relative humidity was used in the model. This parameter varies widely within a 24 hour period and from day to day.

10.2.4 The permeability index for the clothing was set at 0.4. This value was used with the insulation value for each clothing ensemble to determine the evaporative resistance of the clothing. The permeability index might be lower for ensembles that are very thick, or are made with shell fabrics that impede moisture vapor transport, or both. However, if a person gets overheated in the cold, he/she will adjust garment closures or open the garment to provide cooling.

10.2.5 The pumping effect was not taken into account in the model. The pumping effect refers to the decrease in clothing insulation during body movement. It occurs because convection heat transfer increases as air is pumped between garment layers and in and out of garment openings during movement.

[6] *The Compendium of Physical Activities Guide*, available at: http://prevention.sph.sc.edu/tools/docs/documents_compendium.pdf

[7] Go to: http://www.weatherimages.org/data/windchill.html

The decrease in clothing insulation varies widely from 10-50 % depending upon the design and fit of the clothing. It is typically about 15-20 % for outdoor ensembles since garment openings are usually restricted at the wrists, neck, ankles, etc. to prevent cold air from getting inside the ensemble.

10.2.6 The model uses physical and physiological data for an average man. Since human variability affects thermal comfort, the temperature rating predictions need to be considered rough estimates of the air temperature that will result in comfort.

10.2.7 The model predicts a temperature rating for low activity (2 MET) and for moderately high activity (4 MET). A person who is lying down or sitting perfectly still produces about 1 MET of heat. A person who is walking very slowly produces about 2 MET of heat, whereas, a person who is walking very fast produces about 4 MET. At higher levels of activity, a person will need less insulation and will begin to sweat in the clothing unless he/she adjusts the clothing.

10.2.8 This is a whole body heat loss model that predicts overall comfort for the body under steady-state conditions. The model treats the insulation of the ensemble as if it were evenly distributed over the body surface. In reality, some parts of the body are better insulated than others in outdoor ensembles. It is possible for localized cooling and discomfort to occur on different parts of the body like the hands, feet, and face – particularly if they are exposed to the environment and/or the air temperature is below freezing.

11. Temperature Rating Calculations

11.1 Total insulation values ranging from 1.0 to 4.0 clo were used in the model to predict the corresponding temperature ratings for 2.0 MET and 4.0 MET of activity. The resulting regression equations were created.

$$TR_2 = -23.78\, I_{t,s} + 89.83 \quad (4)$$

$$TR_4 = -48.61\, I_{t,s} + 86.7 \quad (5)$$

where:

TR_2 = temperature rating (°F) for 2 MET of activity,
TR_4 = temperature rating (°F) for 4 MET of activity, and
$I_{t,s}$ = standardized total thermal resistance (insulation) of the clothing and surface air layer around the manikin (clo).

11.2 *Temperature Rating Range*—Use Eq 4 to predict the temperature rating for 2 MET of activity to the nearest 0.1°F from the standardized total insulation value ($I_{t,s}$) for the cold weather clothing ensemble. Use Eq 5 to predict the temperature rating for 4 MET of activity to the nearest 0.1°F from the standardized total insulation value ($I_{t,s}$). For example, a jacket ensemble with a standardized total thermal resistance (insulation) value of 2 clo will have a temperature rating range of -10.5°F at high activity to 42.3°F at low activity.

11.2.1 Convert the temperature rating in °F to °C.

11.3 *Single Temperature Rating*—If only one temperature rating is given for a garment, the comfort temperature predicted from Eq 4 for 2 MET of activity shall be used.

12. Report

12.1 State that the clothing ensembles were tested as directed in F2732.

12.2 Report the following information:

12.2.1 Describe the garments used in the ensembles (for example, fiber content, design features, fabric structure) and provide dressing details.

NOTE 1—It is recommended to include a photograph of the manikin dressed in each clothing ensemble in the report.

12.2.2 Report the thermal resistance (insulation) value of the air layer on the surface of the nude manikin (I_a).

12.2.3 Report the intrinsic thermal resistance (insulation) value (I_{cl}) for the base ensemble used with the cold weather garments. Indicate whether the clo value was within ±10 % of the value specified in the standard.

12.2.4 Report the standardized total thermal resistance (insulation) value ($I_{t,s}$) of the cold weather clothing ensembles (calculated using the standard air layer resistance of 0.5 clo).

12.2.4.1 Although it is necessary to calculate the intrinsic thermal resistance (insulation) values for the clothing ensembles in order to calculate the standardized total thermal resistance values, the intrinsic clo values do not have to be reported.

12.2.5 Report the predicted temperature ratings for 2 MET and 4 MET of activity for the cold weather clothing ensembles in °F and °C.

12.2.6 Specify the environmental test conditions listed in 8.1.

12.2.7 Explain any departures from the specified apparatus or procedure.

13. Product Labeling and Advertising

13.1 A temperature rating estimated using this standard practice needs to be referred to as an "ASTM F2732 Temperature Rating" or "ASTM F2732 Temperature Range" on product labels and in advertisements and catalogues only if all procedures were followed exactly as specified in this document. If a base ensemble with more than 0.80 clo ± 10 % of intrinsic insulation was used with jackets, coveralls, and jacket/pant sets, the term "ASTM F2732 Temperature Rating" is not permitted to be used. If a base ensemble with more than 1.35 clo ± 10 % of intrinsic insulation was used with pants, the term "ASTM F2732 Temperature Rating" is not permitted to be used.

13.1.1 It is recommended that manufacturers explain to consumers in their product literature that the temperature ratings are for ensembles and provide a description of the garments worn with the cold weather clothing.

13.2 Temperatures need to be rounded to the nearest whole degree on product labels and advertising.

14. Keywords

14.1 clothing insulation; outdoor clothing; temperature rating; thermal insulation; thermal manikin

ANNEX

(Mandatory Information)

A1. CALCULATIONS FOR TEMPERATURE RATINGS

INTRODUCTION

A thermally neutral condition is one in which the body generates the same amount of energy as it dissipates. The heat loss model estimates the lowest environmental temperature at which adults can remain thermally neutral while wearing a particular ensemble. The environmental temperature is the air temperature—assuming the radiant temperature is the same as the air temperature. The heat loss from the body consists of two components: *1*) heat loss from the surface of the body (skin) and *2*) heat loss from respiration. Each of these components in turn has two sub-components: *1*) dry (sensible) heat loss and *2*) evaporative (latent) heat loss. Evaporative heat loss occurs from the cooling effect of evaporation of moisture from the skin or in the respiratory passages.

The dry heat loss is the sum of the conduction, convection, and radiation from the body or the respiratory passages.

When the heat generated by the body is equal to total body heat loss, a person will be thermally comfortable (neutral). This relationship is expressed in the classic heat balance equation as

$$Q_{met} = Q_{sk,d} + Q_{sk,e} + Q_{res,d} + Q_{res,e} \quad \text{(A1.1)}$$

where:

Q_{met} = the body metabolic energy generation per unit surface area (W/m^2)
$Q_{sk,d}$ = dry convective heat transfer from the body (W/m^2)
$Q_{sk,e}$ = evaporative heat transfer from the body (W/m^2)
$Q_{res,d}$ = the dry energy loss due to breathing (W/m^2)
$Q_{res,e}$ = the evaporative loss due to breathing (W/m^2)

The general approach for determining the temperature rating is as follows. For a given type of activity, the Q_{met} can be determined for an adult. In this practice, metabolic rates of 2 MET (116.4 W/m^2) and 4 MET (232.8 W/m^2) are used in predicting a temperature rating range. The environmental temperature at which heat loss from the body exactly equals the Q_{met} is determined through a spreadsheet application. The following sections give detailed information on the methods used to calculate heat transfer and energy generation.

A1.1 **Dry Heat Loss from the Skin**

$$Q_{sk,d} = \frac{(T_{sk} - T_e)}{R_{t,d}} \quad \text{(A1.2)}$$

where:

$Q_{sk,d}$ = the dry heat loss from the skin (W/m^2)
T_{sk} = the average skin temperature (°C)
T_e = the temperature of the environment (°C)
$R_{t,d}$ = the total thermal resistance provided by the clothing (m^2 • °C/W)

Note that this parameter is entered as a "clo value" in a spread sheet and converted to proper SI units the program (1 clo = 0.155 m^2 • °C/W).

A1.2 **Evaporative Heat Loss from the Skin**

$$Q_{sk,e} = \frac{(P_{sk} - P_e)}{R_{t,e} + R_{sk,e}} \quad \text{(A1.3)}$$

where:

$Q_{sk,e}$ = the evaporative heat loss from the skin (W/m^2)
P_{sk} = the average vapor pressure for the skin (kPa)
P_e = the vapor pressure of the environment (kPa)
$R_{t,e}$ = the total evaporative resistance of the clothing which is a measure of the ability of water vapor to pass through the clothing (m^2 • kPa/W)
$R_{sk,e}$ = the evaporative resistance of the skin (m^2 • kPa/W)

Eq A1.3 is based on the premise that the person will not be actively sweating. Since we are concerned with determining the cold temperature ratings, this is a reasonable assumption. Even though sweating is ignored within the model, it can still be an important confounding factor especially in localized areas of the body that are under heavy insulation. If activity levels are high initially, sweating will occur, and once the clothing is wet, the temperature ratings will no longer provide accurate environmental temperature ratings. Even though we ignore sweating, moisture diffuses through the skin causing some evaporative losses. The skin vapor pressure, P_{sk}, is then equal to the saturation pressure at the skin temperature. The vapor pressure of the environment is set at the value corresponding to 50 % relative humidity. Thus,

$$P_{sk} = P_{sat}(T_{sk})$$
$$P_e = \frac{P_{sat}(T_e)}{2}$$

where:

P_{sat} = the saturation pressure for water vapor (kPa)

The total evaporative resistance, $R_{t,e}$, is estimated from the total thermal resistance, $R_{t,d}$, using the Lewis relation:

$$R_{t,e} = \frac{R_{t,d}}{L_r \cdot i_m}$$

where:

L_r = the Lewis relation and is approximately equal to 16.5°C / kPa for a wide range of conditions

i_m = the permeability index for the clothing and is approximately 0.4 for typical clothing materials

The value of the evaporative resistance of the skin, $R_{sk,e}$, is 0.33 $m^2 \cdot kPa/W$ for typical conditions (Fanger, 1970[8]).

A1.3 **Dry Heat Loss from Respiration**

$$Q_{res,d} = m_{res} \cdot c_{p,a} \cdot (T_{ex} - T_e) \quad (A1.4)$$

where:

$Q_{res,d}$ = the dry heat loss from respiration (W/m^2)

m_{res} = the respiration rate per unit body surface area ($kg/m^2 \cdot s$)

$c_{p,a}$ = the specific heat of air, approximately 1006 J/kg K at typical conditions

T_{ex} = the temperature of the exhaled air (ºC)

T_e = the temperature of the environment (ºC)

The respiration rate in this case shall account for differences based on age and activity level. ASHRAE (2005)[9] suggests the respiration rate is directly related to the total energy generation in the body and that the following equation can be used to estimate m_{res}.

$$m_{res} = K_{RES} \cdot M$$

where:

K_{RES} = a proportionally constant $\left(1.43 \times 10^{-6} \frac{kg}{J}\right)$

M = the metabolic output (W/m^2)

The exhaled air temperature, T_{ex}, can be estimated according to (Holmer, 1984[10]):

$$T_{ex} = 29 + 0.2 \cdot T_e$$

A1.4 **Evaporative Heat Loss from Respiration**

$$Q_{res,e} = m_{res} \cdot h_{fg} \cdot (W_{ex} - W_e) \quad (A1.5)$$

where

$Q_{res,e}$ = the evaporative heat loss from respiration (W/m^2)

h_{fg} = the heat of vaporization of water, approximately 2,430,000 J/kg

W_{ex} = the humidity ratio of the exhaled air (n.d.)

W_e = the humidity ratio of the environment (n.d.)

The humidity ratios can be calculated from the vapor pressures according to:

$$W_{ex} = 0.622 \frac{P_{ex}}{P_t - P_{ex}}$$
$$W_e = 0.622 \frac{P_{ex}}{P_t - P_e}$$

where:

P_t = the total atmospheric pressure (101.325 kPa)

A1.5 **Skin Temperature and Environmental Temperature**

The heat loss can be calculated from Eq A1.1-A1.5 if two more variables are specified. The first is the average skin temperature over the body (T_{sk}) which is set at 34°C.

$$T_{sk} = 34°C \quad (A1.6)$$

The final variable is the environmental temperature. This temperature is determined through a trial and error solution in a spread sheet application.

[8] Fanger, P.O. (1970). *Thermal Comfort: Analysis and Application in Environmental Engineering*. New York: McGraw-Hill Book Company.

[9] *ASHRAE Handbook 2005 Fundamentals*. Available from American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. (ASHRAE), 1791 Tullie Circle, NE, Atlanta, GA 30329, http://www.ashrae.org.

[10] Holmer, I. (1984). Required clothing insulation (IREQ) as an analytical index of cold stress. *ASHRAE Transactions, 90*: pp. 1116 -1128.