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## **DEVELOPMENT OF MATLAB<sup>®</sup> SCRIPTS FOR THE CALCULATION OF THERMAL MANIKIN REGIONAL RESISTANCE VALUES**

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**USARIEM TECHNICAL NOTE TN16-1**

**DEVELOPMENT OF MATLAB<sup>®</sup> SCRIPTS FOR THE CALCULATION OF THERMAL  
MANIKIN REGIONAL RESISTANCE VALUES**

Timothy P. Rioux, B.S.  
Anthony Karis, B.S.  
Xiaojiang Xu, Ph.D.

Biophysics and Biomedical Modeling Division

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U.S. Army Research Institute of Environmental Medicine  
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## **EXECUTIVE SUMMARY**

A software tool has been developed via MATLAB® scripts to reduce the amount of repetitive and time-consuming calculations that are performed by thermal manikin and modeling personnel. Steps to operate the scripts as well as the underlying calculations are outlined in detail, and a file organization structure is recommended to run the scripts efficiently. A feature in the thermal manikin software that performs similar calculations is acknowledged and compared to the scripts. The ultimate goal is to improve the accuracy and efficiency of preparing raw thermal manikin data for physiological modeling through an automated tool that performs all necessary calculations. The current version of the scripts is only semi-automated due in large part to an evolving method of determining the clothing area factor, which is a necessary parameter to calculate required input for the Six Cylinder Thermoregulatory Model (SCTM). Once a method is established, improvements detailed in this technical note should increase the level of automation of the script. The current scripts are customized for SCTM. However, similar automated tools could be developed for additional physiological models based on the framework developed with the current scripts.



## INTRODUCTION

The Biophysics Biomedical Modeling Division (BBMD) utilizes thermal manikins to measure total thermal resistance ( $R_t$ ) and total evaporative resistance ( $R_{et}$ ) of various clothing and individual equipment (CIE). Data collected from thermal manikin testing are one major component of the input parameters for physiological models. However, intermediate calculations are often necessary to prepare output data provided by the thermal manikin software, ThermDAC (Thermetrics, Seattle, WA) into the necessary format for modeling. Different physiological models require different variations of the two clothing parameters,  $R_t$  and  $R_{et}$ . The Six Cylinder Thermoregulatory Model (SCTM), the model of interest in this technical note, requires six regional values of both intrinsic thermal resistance ( $R_{cl}$ ) in clo units and the dimensionless intrinsic permeability index ( $i_{m,cl}$ ) for the head, torso, arms, hands, legs, and feet sections of the body (a more detailed discussion on the different clothing parameter units and their conversions is located in Appendix A) (7). In order to separate the whole-body thermal manikin data into six separate regions, the parallel weighted average of all the zones in each of the six regions must be calculated (7). This calculation is done with enough frequency that a programming solution using MATLAB<sup>®</sup> scripts was deemed necessary. Additionally, clothing designers and developers have recently shown interest in regional resistance values for the purpose of locating areas of garments where improvements can be made.

Prior to the development of MATLAB<sup>®</sup> scripts, macros were created with the Visual Basic for Application (VBA) editor in Microsoft Excel to eliminate the tedious calculations necessary to sectionalize thermal manikin data for SCTM. Two major deficiencies were observed with the VBA macros, 1) separate macros were required for  $R_t$  and  $R_{et}$  calculations and 2) it was necessary for the appropriate macro to be run for each individual steady state report. Steady state reports are the output files created by ThermDAC which summarize manikin and environmental data for the steady state period of an experiment. In accordance with ASTM standards, a minimum of six steady state reports are required for proper  $R_t$  and  $R_{et}$  measurements of a single garment configuration (1; 2). To improve upon these deficiencies, scripts collectively titled "SCTMprep" were developed in MATLAB<sup>®</sup>. Only a single script is required to prepare both  $R_t$  and  $R_{et}$  regional values with multiple steady state reports being easily selected via user interfaces (UI). As an example, a project with ten ensembles would require running the two VBA macros thirty times each as opposed to the MATLAB<sup>®</sup> scripts which would only need one script to run ten times to prepare the same data, minimizing the time required by the user.

BBMD has three whole-body thermal manikins, which are all twenty-zone Newton models, as well as thermal foot, hand, and head manikins (Thermetrics, Seattle, WA). Whole-body manikins are useful for testing complete configurations of CIE; while the thermal hand, thermal foot, and thermal head measure  $R_t$  and  $R_{et}$  of gloves, footwear, and headwear more accurately, due in part to the existence of more zones within those particular body regions. Additionally, the amount and type of CIE typically tested are semi- or completely impermeable materials with minimal simulated sweat

being transferred to the environment. This impermeability causes a significant amount of sweat to be collected in clothing of the extremities (e.g. gloves and boots) which often results in unrealistic  $R_{et}$  values of hands and feet. Therefore, glove or boot data is often collected on the thermal hand and thermal foot instead of the whole-body manikin. Data collected on the thermal hand and thermal foot can be used for SCTM, but it is still necessary to calculate the parallel average from the pertinent zones of these manikins as well. In addition to a SCTMprep script for the whole-body manikin, another script was developed for the thermal foot that separates clothing data into leg and foot sections. Only data from the upper and lower toe zones of the thermal foot currently comprise the SCTM foot section. Toe zones typically have the lowest thermal resistance, allowing for conservative predictions of time until cold injury. Future development of similar scripts for the thermal hand would be relatively simple to create using the current framework of the two existing scripts.

## METHODS

### CALCULATION STEPS

The first step in preparing thermal manikin results for SCTM is to average data for the six separate regions. Details of the zone groupings to be averaged are outlined in Table 1. The six regions required for SCTM modeling are listed in the first column and the ThermDAC names for the individual zones as well as their associated numbers are listed in the next two columns. Zone names and numbers apply to all three of BBMD's twenty-zone Newton manikins. Different model thermal manikins and Newton models with a different number of zones may not have the same zone naming and numbering combination.

Table 1. SCTM Zone Segmentation

SCTM Region	Newton Zone Names	Newton Zone Numbers
Head	Head, Face	1-2
Torso	Chest, Shoulders, Stomach, Back, R Hip, L Hip	9-14
Arms	R Upper Arm, L Upper Arm, R Forearm, L Forearm	3-6
Hands	R Hand, L Hand	7-8
Legs	R Thigh, L Thigh, R Calf, L Calf	15-18
Feet	R Foot, L Foot	19-20

\* The torso section is listed non-sequentially. The intention is to order the results in a consistent manner with SCTM regional clothing data input.

The weighted average of the six regional resistances are calculated using the parallel method (7), as:

$$R_{wtd.(parallel)} = \frac{A_{tot}}{\sum A_i/R_i} \quad (\text{Eq. 1})$$

where  $A_i$  and  $R_i$  are the surface area and resistance, respectively, of each individual zone within the SCTM regions, and  $A_{tot}$  is the total area of all zones within the SCTM region of interest. For example, when calculating the regional resistance for the SCTM head region,  $A_i$  are the two surface area values of the Newton head and face zones. In a similar fashion,  $R_i$  are the two resistance values of the Newton face and head zones.  $A_{tot}$  is the sum of the surface area for the Newton face and head zones. Equation 1 can be applied for either  $R_t$  or  $R_{et}$ .

Once the manikin resistances are averaged for the six regions, the next step is to calculate the intrinsic resistance for each of the six regions by:

$$R_{cl} = R_t - \left( \frac{R_a}{f_{cl}} \right) \quad (\text{Eq. 2})$$

where  $R_t$  is total thermal resistance of the SCTM region,  $R_a$  is the nude manikin resistance of the same region, and  $f_{cl}$  is the clothing area factor. Equation 2 is shown for calculating intrinsic thermal resistance ( $R_{cl}$ ), but can also be applied in the same manner to calculate intrinsic evaporative resistance ( $R_{ecl}$ ). The  $f_{cl}$  is the ratio of surface area of the clothed manikin region to surface area of the same region without clothing.

The most accurate way to calculate  $f_{cl}$  is by measuring the clothed surface area of the manikin with a three dimensional scanner. In the absence of a three dimensional scanner,  $f_{cl}$  can be estimated by an empirically derived formula (4):

$$f_{cl} = 1.0 + 0.3 \cdot R_{cl} \quad (\text{Eq. 3})$$

where  $R_{cl}$  is in SI units. However, this estimation has only been tested for ensembles with  $R_{cl}$  values between 0.031 and 0.264 ( $^{\circ}\text{C m}^2/\text{W}$ ) (3). In order to estimate  $f_{cl}$ , iterative techniques will need to be used along with Equations 2 and 3.

The next step is to calculate the intrinsic permeability index for each SCTM region by:

$$i_{m,cl} = \frac{k \cdot R_{cl}}{R_{ecl}} \quad (\text{Eq. 4})$$

where  $k$  is a constant value of  $60.6515 \frac{\text{Pa}}{^{\circ}\text{C}}$  when  $R_{cl}$  and  $R_{ecl}$  are in SI units.

The final step, if not already done so, is to convert the six  $R_{cl}$  values from SI units to clo units by dividing  $R_{cl}$  by  $0.155 \text{ m}^2\text{K}\cdot\text{W}^{-1}$ . Once the clothing parameters are in the correct form and units for SCTM, the twelve clothing parameters (six values for  $R_{cl}$  and

six values for  $i_{m,cl}$ ) are placed in a text file which will then be read by SCTM when the model runs.

The intrinsic calculation, estimation of  $f_{cl}$ , and calculation of  $i_{m,cl}$  are not currently included in the SCTMprep script, but are described in this technical note to provide a thorough explanation of the process of preparing thermal manikin data for SCTM as well as identifying the potential to include these calculation steps in a later version of the scripts.

## **PROCEDURE FOR RUNNING SCRIPTS**

### **Necessary files: Scripts and Functions**

If running the script for the first time, copy the folder titled “SCTMprep” to the default MATLAB<sup>®</sup> path (e.g., C:\Users\...\Documents\MATLAB). The SCTMprep folder should contain two scripts, “ManikinPrep\_SCTM.m” and “FootPrep\_SCTM.m”, which are used for calculating SCTM regional resistances for the whole-body thermal manikin and thermal foot manikin, respectively. There should also be four functions present in the folder, MSR.m, PRC.m, SnapCount.m, and WrH.m.

Manikin Sectional Resistance (MSR.m) groups the resistance and surface area values from the individual zones into the six separate SCTM regions and is only used with the whole-body manikin script. The remaining three scripts are used by both the whole-body manikin script and the thermal foot script. Parallel Resistance Calculation (PRC.m) calculates the parallel weighted average resistance of the zone groupings; SnapCount.m counts the number of steady state reports selected via the file browsing UI; and Write Headers (WrH.m) converts a cell array to a single string, adding commas in between what was formerly different cells.

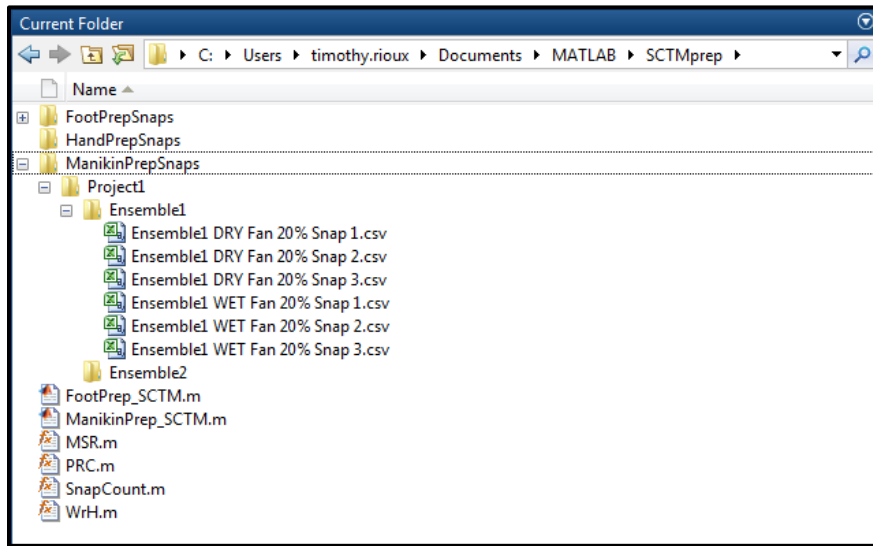
### **Transferring and Organizing Data**

The steady state reports used for calculation must be in the active MATLAB<sup>®</sup> path for the scripts to function. The scripts were created with the intention of preparing thermal manikin data for a large number of projects and ensembles. To improve clarity for sorting files and since the script was developed for a particular file organization system, it is recommended to use the file organization structure shown in Figure 1 which is also outlined by the following general guidelines:

- In the SCTMprep folder, create separate folders for whole-body manikin and thermal foot manikin data.
- At the next folder level, create a folder for the project that pertains to the manikin testing and modeling.
- Inside each project folder, create a folder for each ensemble or ensemble configuration.

- Transfer only valid steady state reports to the ensemble folder. Including out of tolerance steady state reports and experiment files will only cause confusion and increase likelihood of calculation error.
- $R_t$  and  $R_{et}$  steady state reports should be transferred into the same ensemble folder and be labeled with consistent, clear file names to avoid confusion and reduce the possibility of calculation error. Note: For common file naming terminology,  $R_t$ ,  $R_{et}$ , and snaps are synonymous with dry, wet, and steady state report, respectively.

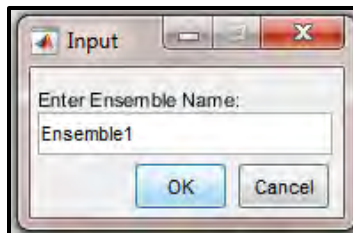
Figure 1. File organization structure



## Running Scripts

Once all the operational files and steady state reports are present and in proper locations, “ManikinPrep\_SCTM.m” or FootPrep\_SCTM.m scripts can be run. First, a text input UI will appear as in Figure 2 in which the name of the CIE is entered by the user.

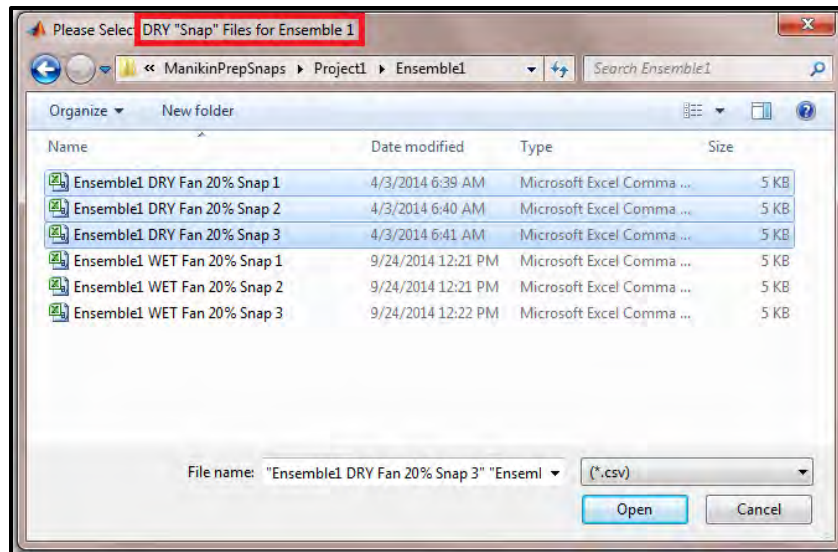
Figure 2. Ensemble Input UI



Once “OK” is clicked on the ensemble input UI, a file selection UI will appear. The title of the file selection UI window will request the user to select DRY snaps for the specific CIE entered in the previous UI, as highlighted by the red box in Figure 3. If valid files

were selected, an almost identical file selection UI to Figure 3 will appear, this time requesting WET snaps. The “cancel” button can be clicked on either dry or wet file selection UI and the script will continue to run, but there will be no values for the type of steady state report that was “canceled”. To reduce the likelihood of selecting the wrong files, the script determines if the snap is from dry or wet testing. If the type of file selected (dry or wet) is inconsistent with the type requested by the UI, then an error message is displayed and the script stops running.

Figure 3. File selection UI for steady state reports



Once the script finishes running, the results are written to a comma separated value (.csv) file, either ManikinOutput.csv or FootOutput.csv, depending on the script. A sample output file with three entry items is shown in Figure 4. The output units are  $R_t$  in clo units and  $R_{et}$  in SI units ( $m^2Pa/W$ ), which are not the proper units or form of SCTM clothing parameter input. Fully automated calculations from thermal manikin output to model input is incomplete, mostly due to the fact that our methods for estimating  $f_{cl}$  are evolving and best suited to be entered manually at this time. However, once an estimation of  $f_{cl}$  is complete, the calculations are fairly straightforward to convert the total resistance values to  $R_{cl}$  and  $i_{m,cl}$  as outlined in the “Calculation Steps” section. Additionally, although the whole-body resistance is not a required input for SCTM, the values may be useful for other applications and therefore are included in the output file.

Figure 4. Manikin output file for SCTM regional resistances

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1																
2	Ensemble Name	Entry Date	Whole Body	Head	Torso	Arms	Hands	Legs	Feet	Whole Body	Head	Torso	Arms	Hands	Legs	Feet
3	Nude	8/17/2015 14:58	0.66	0.75	0.83	0.64	0.54	0.57	0.57	12.92	18.54	17.46	12.32	9.30	11.02	9.25
4	Ensemble 1	8/17/2015 14:59	0.81	0.71	1.57	1.05	0.59	0.56	0.61	16.27	17.04	34.42	20.06	12.45	10.83	11.16
5	Ensemble 2	8/17/2015 15:00	2.51	0.79	5.05	3.09	1.55	3.11	1.48	63.94	16.11	132.45	72.74	38.85	80.37	89.21

## DISCUSSION

It is worth noting that there is a “Group Definition” feature within ThermDAC to calculate the parallel weighted average of  $R_{ct}$  and  $R_{et}$  for custom zone groupings. For example, the six regions of interest for the SCTM could be selected prior to running an experiment and the parallel weighted average of resistance for each of the six regions would appear in the steady state report. Nevertheless, SCTMprep scripts were developed due to a few compounding factors:

- Even if the SCTM group definitions were used as intended in ThermDAC, the user would still have to go through at least six individual steady state reports and compile regional data for each section whereas the SCTMprep script does all the compiling within the code.
- Often times, historical data is analyzed using steady state reports that have already been saved for the whole-body group definition which does not include data for the six regions of the SCTM group definitions. Additionally, the steady state reports are based on specific time periods selected during the experiment. It is possible to reopen the experiment in ThermDAC and retroactively save the steady state report for the same time period with new SCTM group definitions. However, the raw data file must exist, which is not always the case, and steady state times must be matched with previous reports, requiring a significant amount of time from the user. Additionally, the raw data file must be in the format created by the current version of ThermDAC or it will not be able to be opened at all. Whereas, the SCTMprep script may still be able to read in the necessary information, and if not, the framework is set up so the code can be modified with relative ease.
- MATLAB<sup>®</sup> is more likely to be installed on USARIEM computers than ThermDAC, which translates to having far more trained users of MATLAB<sup>®</sup> than ThermDAC. Even the few computers that have ThermDAC installed are very frequently running experiments and therefore SCTMprep scripts are more widely available and more likely to be used for calculating regional resistances of historical data.
- The SCTMprep scripts provide greater flexibility for data output. With minor changes to the code, output file format and parameters written to the file can be altered for different versions of SCTM or other applications where regional resistance values are of interests.

The SCTMprep scripts eliminate the need for raw data files and save the user from additional, unnecessary and time-consuming steps.

## RECOMMENDATIONS

When preparing thermal manikin data for SCTM, the ideal scenario would be to have as much of the data compiling and calculations as fully automated as possible. Our evolving method for estimating  $f_{cl}$  is one of the major hurdles in achieving an automated tool. BBMD has recently acquired a three dimensional scanner (Go!Scan 50, Creaform, Lévis, QC, Canada, <http://www.creaform3d.com/en>) which we intend to use for scanning the clothed surface area of the thermal manikin to obtain accurate  $f_{cl}$  values. Once a consistent method of estimating  $f_{cl}$  is established and integrated into the script, the next challenge will be to implement a method to include the nude manikin data for the calculation of intrinsic clothing parameters. BBMD has three manikins and typically two environmental chambers where the thermal manikins are tested. Occasionally, the manikins are moved to different chambers due to chamber or manikin maintenance. There are typically six manikin and chamber combinations and each combination requires specific nude values. Therefore, a method that allows the user to enter or select the appropriate nude values for the chamber and manikin combination will be necessary.

A potential way to incorporate the nude data into the script could be accomplished through a new UI which is displayed immediately after the script is run. This particular UI could allow the user to select one of the six manikin and environmental chamber combinations. The script could then be operated in a similar manner to how it is currently constituted, but with the addition of an option on the ensemble entry UI (Figure 2) to select whether the data calculation is being performed for nude or clothed manikin experiments. If the nude experiment option is selected, the user is allowed to select nude steady state reports in the typical manner, which separates the manikin data into the six SCTM regions. Once the calculation is complete, the regional nude data could be written to a text or .csv file that is similar but separate from the output file (Figure 4) for clothed experiments. It may also be beneficial to have separate files for each manikin and chamber combination. These separate output files may be necessary in order to easily read the nude values into the script for the purpose of calculating intrinsic values of ensembles. Additionally, these separate files could be an easy way of maintaining a record of all compiled regional nude data for a particular manikin and chamber combination, providing well-documented control values. New values could be appended to each database and the last entry could be easily accessed for calculating intrinsic resistance. With the inclusion of the two major steps of estimating  $f_{cl}$  and calculating intrinsic resistance into the script, the only step remaining to accomplish a virtually automated data preparation tool from manikin testing to SCTM would be to add the relatively simple calculation of  $i_{m,cl}$  (Eq. 4) into the script.

Potential supplementary improvements could be to include tolerance checks to ensure that resistance values of all regions for a particular clothing configuration are within  $\pm 10\%$  of their average, as specified in the ASTM standards (1; 2). These tolerance checks should already be performed by the thermal manikin operator, but it would be beneficial to provide a more efficient tool to assist the operator.



In addition to improvements of the currently existing scripts, there are a couple of evident possibilities for expanding the SCTMprep scripts into new, separate calculation tools. First, there could be an additional script created for separating the thermal hand data for use with SCTM. This script should be relatively easy to adapt from the framework already created in the FootPrep\_SCTM.m script. A script for the thermal head will not be necessary as the surface area and zone locations on the thermal head are very similar to the head on the whole-body thermal manikin. Other calculation tools could be developed to automate the preparation of manikin data for other physiological models (e.g., SCENARIO), as a lot of the similar methods from SCTMprep scripts can be used for extracting manikin data from steady state reports.

## **SUMMARY**

The SCTMprep scripts are a software tool developed for the purpose of creating a more streamlined process of applying the calculations necessary for preparing thermal manikin data for the SCTM model. The intent of this technical note is to educate the reader on how to operate the scripts as they are currently constituted. Planned improvements to SCTMprep scripts will improve efficiency. However, even in their current state, the SCTMprep scripts will reduce the amount of time required by thermal manikin and modeling personnel to prepare manikin data for SCTM. The eventual goal of these scripts is to have an automated tool that connects thermal manikin output to physiological model input. To accomplish this goal a clear objective and plan to improve the efficiency is laid out; underlying calculation steps as well as the obstacles to obtaining the ultimate goal are outlined in detail.

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## APPENDIX A

### 1. Definitions for clo and $i_m/\text{clo}$

Resistance to heat transfer by convection and radiation is combined into one general clothing property, insulation. Insulation is commonly expressed in an arbitrary unit, the clo. Clo is a unit of thermal insulation of clothing; a standard men's suit has an insulation of about 1 clo, the warmest have about 4 clo.

“A clo is a unit of thermal resistance defined as the insulation required to keep a resting man (producing heat at the rate of  $58 \text{ W/m}^2$ ) comfortable in an environment at  $21^\circ\text{C}$ , air movement  $0.1 \text{ m/s}$ , or roughly the insulation of a heavy business suit. Numerically one clo is equal to  $0.155 \text{ m}^2\text{K}\cdot\text{W}^{-1}$ ” (ASTM F1291-10).

“Resistance of clothing to evaporation is expressed by the water vapor permeability index ( $i_m$ ), a dimensionless index. Clothing slows the rate of vapor loss from the skin to the environment. If water vapor passes completely from the body to the environment, heat is transferred from the body to the environment. If water vapor recondenses on the skin or within the clothing, heat is not lost to the environment” (Woodcock, 1962).

The value of  $i_m$  is about 0.45 for normal indoor clothing and 0 for impermeable clothing.

The maximum potential for heat transfer through the clothing to the environment is a function of the ratio of the permeability index ( $i_m$ ) to the total insulation (clo). This ratio ( $i_m/\text{clo}$ ) approximates the percentage of the maximum potential for a given environment that may be realized when wearing specified clothing.