Development of the METMAN Thermal Desktop Human Model for System Integration

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Human thermal analysis and model development inform NASA's space suit development, vehicle/habitat design, and survivability studies. Historically, human thermal models such as the 41-node metabolic man (METMAN) and the Wissler model have been standalone software tools developed with FORTRAN, a programming language known for its high performance in computationally intensive applications. Though efficient, these standalone programs pose challenges to coupled human-system analysis with detailed life support and thermal control subsystem models in other commercial software. This paper describes the conversion of the METMAN human thermal model from a standalone FORTRAN program to a model in Thermal Desktop (Ansys), a commonly used CAD-based simulation software for engineering that specializes in heat transfer, thermal radiation, and fluid flow analysis. This format was chosen to best facilitate model sharing and compatibility, enabling the direct integration of METMAN human thermal analysis with subsystem models across NASA programs and commercial partners.

Acronyms and Nomenclature

AR	=	Radiative Area
ATCS	=	Active Thermal Control System
BF	=	Blood flow rate to a given segment
BMR	=	Basal Metabolic Rate
CBZ	=	Heat capacitance of a given tissue layer
$CONFAC$	=	Conversion factor from Kcal/°C to BTU/°F
C_{pg}	=	Specific heat of an inspired gas
$Dilat$	=	Vasodilation factor for blood flow rate
ECLSS	=	Environmental Control and Life Support System
EMU	=	Extravehicular Mobility Unit
F	=	Radiation interchange factor
HTM	=	Human Thermal Modeling
K_{ms}	=	Shiver distribution coefficient
K_s	=	Skin surface area distribution coefficient
K'_s	=	Sweat distribution coefficient
LCG	=	Liquid Cooling Garment
METMAN	=	41-node metabolic man
METMAN TD	=	Metabolic Man, Thermal Desktop version
NESC	=	NASA Engineering and Safety Center
P_{cab}	=	Cabin pressure
Q_{basal}	=	Basal metabolic rate
Q_{Dif}	=	Diffusion latent heat loss
$Q_{int.conv}$	=	internal convection heat transfer
Q_{lat}	=	Latent heat rejection
Q_{met}	=	Metabolic heat generation
Q_{rad}	=	Radiation heat transfer
Q_{rlat}	=	Latent component of respiratory heat transfer
Q_{rsen}	=	Respiratory sensible heat transfer

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Q_{sens}	=	Sensible heat transfer
Q_{shiv}	=	Rate of shiver heat generation
Q_{stor}	=	Total body heat storage
Q_{work}	=	Heat produced through muscle work
RM	=	Metabolic rate
S	=	Total Sweat Signal in BTU/hr
σ	=	Stefan-Boltzmann constant
$Strict$	=	Vasoconstriction factor for blood flow rate
SWT	=	Total segment weight
TA	=	Adipose tissue weight
T_c	=	Temperature of a given segment core
T_{cab}	=	Cabin temperature
TD	=	Thermal Desktop
TNA	=	Nonadipose tissue weight
T_r	=	Temperature of the respiratory tract
T_s	=	Skin temperature of a given segment
T_{set}	=	Setpoint temperature of a given component
T_w	=	Wall temperature of the environment
$Ueff$	=	Muscle efficiency
VPT_{dewc}	=	Vapor pressure of the ambient air
VPT_r	=	Vapor pressure of the respiratory tract
$WTFACT$	=	Segment weight scaling factor

I. Introduction

Human Thermal Modeling (HTM) is the computational simulation of heat transfer between a human and the environment. The human thermoregulatory system dynamically responds to environmental changes to maintain a thermal homeostasis. Within the context of spaceflight, the analysis and modeling of these complex human-system interactions are utilized in vehicle/habitat design, spacesuit development, and human survivability studies with respect to system sizing and human thermal health. A human model currently in-use at NASA is the 41-Node Metabolic Man (METMAN) model, a computational stand-alone tool evolved from the Apollo program. While METMAN has been in continuous use and refinement, the stand-alone nature has posed integration challenges with modern analysis software for coupled simulations. As spacecraft systems become increasingly intricate, and vehicle architecture expands across multiple organizations, a need was identified to create an interface between the human stand-alone model and vehicle thermal models to couple the human-system analyses and to provide modularity and versatility. Through a collaboration between the human thermal analysis team at NASA Johnson Space Center and the NASA Engineering and Safety Center (NESC), the METMAN computational model has been adapted to the Thermal Desktop (TD) analysis software. This format allows for the standardization of human thermal analysis across programs, institutions, and commercial partners.

This work will provide an overview of the human thermoregulatory system as modeled in METMAN, the development process of subdividing the METMAN FORTRAN 77 code into a Thermal Desktop model/submodules, verification against existing METMAN thermal analyses, and potential use cases as spacecraft systems continue to evolve. Updating the original METMAN model to a modern adaptable platform enhances model usability and enables the direct integration of human thermal metabolic loads with the Environmental Control and Life Support Systems (ECLSS).

II. Background

A. Human Thermoregulation

The human thermoregulation system can be logically subdivided as the passive system of anthropometry and internal conduction frameworks and the active system of muscular, circulatory, and vasomotor responses. Passive system parameters are assumed to remain constant throughout a given simulation; examples of passive system parameters include body geometry and tissue composition [1]. The active system consists of parameters that dynamically respond to environmental factors and subsequently adjust thermoregulatory components. Examples of active system parameters include sweating, shivering, and blood flow [2].

The thermoregulatory system attempts to maintain homeostasis of the core body temperature [3]. As the core temperature falls below the comfort setpoint, the body responds by constricting blood vessels to conserve heat and contracting muscles to enable heat generation through shivering. Conversely, if the body temperature rises above thermal comfort, the blood vessels dilate to transport body heat outward to the skin, and the thermoregulatory system dissipates that heat to the environment through latent heat rejection. When the thermoregulatory system is unable to reject as much heat as is generated by the body or introduced through the environment, the resultant heat load is referred to as “heat storage” [4] and causes an increase in core temperature.

At NASA, HTM is utilized for a variety of systems and programs, and each application has a unique set of requirements for thermal performance. HTM is a critical aspect of verification of these requirements and ensuring that the thermal systems designed to support human spaceflight can support the thermal requirements of the human body. Figure 1 below outlines the NASA standards and integration requirements [5, 6, 7, 8, 9, 10] that are commonly evaluated through human thermal modeling.

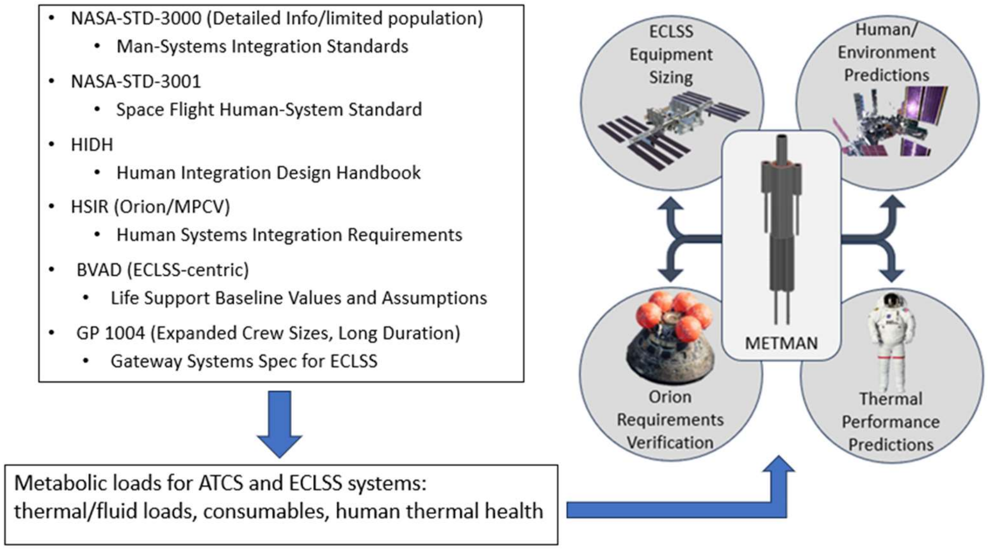


Figure 1. Usage of HTM in NASA Thermal System Requirements Verification

These requirements define metabolic loads applied to the Active Thermal Control Systems (ATCS) and Environmental Control and Life Support Systems (ECLSS). In addition to broader system level studies, human thermal models can provide the necessary analytical insight for contingency operations and failure scenarios, as these are often not feasible for human subject testing due to complexity, cost, and/or safety.

B. METMAN Functionality

Fundamentally, METMAN is a 41-node model that approximates the human body as layered, concentric cylinders [11]. METMAN categorizes those cylinders into 10 body segments: the head, torso, arms, hands, legs, and feet. Each of those segments is further deconstructed into 4 layers: the core, muscle, fat, and skin. Figure 2 shows a visualized layout of segment positioning as given in the METMAN code documentation. These 10 segments and 4 layers equate to 40 nodes. The 41st node refers to the central blood node, a distinct component of the torso that contains the internal convective heat transfer of the blood. Model subroutines within the FORTRAN code break down the different but interconnected functions of thermoregulation that output human thermal information such as core temperature and heat storage.

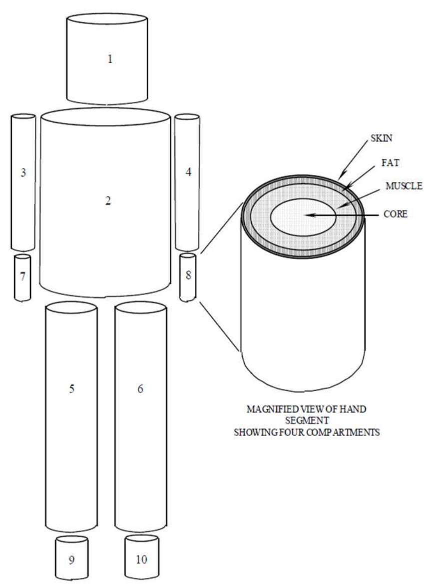


Figure 2. Diagram of Segment Layout within METMAN Totaling 10 Segments with 4 Layers Each [11]

III. Model Framework

A. Goals of METMAN Modernization

Results from METMAN analysis are frequently used to inform design specifications of human spaceflight hardware to properly manage the metabolic loads of the human; many modern missions contain thermal performance requirements that explicitly designate the METMAN model to evaluate crew thermal health [12]. Therefore, this developmental effort prioritizes the translation of METMAN from FORTRAN to the Thermal Desktop format to maintain the same functionality while modernizing the capabilities of analysis integration.

As vehicle models and mission architecture become increasingly intricate, there is a growing need for a transition in how HTM is utilized. While previous models were typically adapted for specific systems, the discipline of human analysis has evolved to support multiple programs, systems, and thermal architectures. A standard baseline format is a key consideration of this model development effort to fit the varied use cases of mission scenarios that stretch beyond the original METMAN design.

Software compatibility challenges arise from the decoupled vehicle and human models including fidelity differences and the limited capability for 3D human analysis [13]. Environmental and vehicle thermal models used at NASA are typically CAD-based within Thermal Desktop (TD) and can contain thousands of nodes with nonuniform thermal loads in a 3D space, and this creates a fidelity mismatch with METMAN assumptions of uniformity and limited nodalization.

The model development effort described in this work aims to strategically port the METMAN human thermal model from FORTRAN 77 to Thermal Desktop to modernize human thermal modeling and provide the foundation for future integration with modern thermal systems and models in a standardized software. As the METMAN model has been validated against human test data and has a longstanding history of use within NASA, equivalent functionality in the new TD format will be demonstrated. Additionally, the development of METMAN TD will separate the program-specific ATCS and ECLSS domains from the human model itself, allowing for more versatile future use cases across any system's thermal architecture.

B. High Level Structure

At a high level, the development of METMAN TD involves deconstructing the METMAN thermoregulatory subroutines into Thermal Desktop modules. Each subroutine has been categorized into either the passive system or the active system. The passive system is implemented through an outer geometry framework with TD cylindrical elements and conductive ties between nodes. The active system contains modularized thermoregulatory subroutines in TD logic blocks that execute each time step of the simulation. These two systems are coupled through a TD schematic shown in Figure 3 that represents the 41-node METMAN model. This nodal network passes resulting heat loads to each node through convective ties that link back to the central blood node.

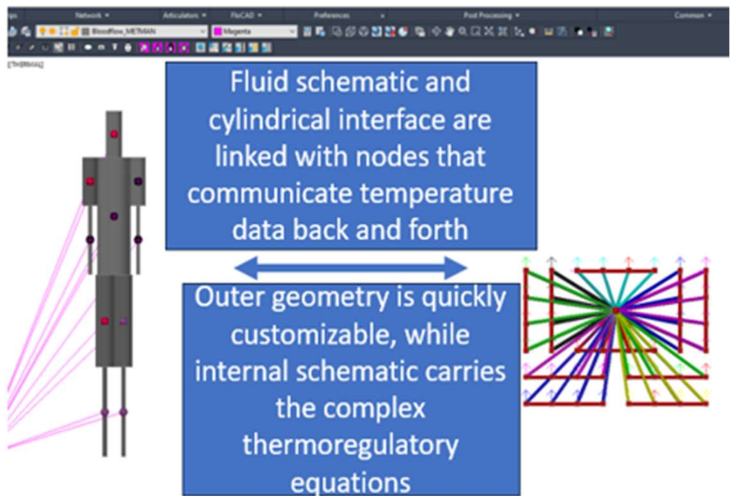


Figure 3. Physical Geometry Model (left) and Active System Fluid Schematic (right)

The primary benefit to graphically separating the outer geometry from the thermoregulatory schematic is that the skin layer functions as an interface between the internal heat transfer of the human and external environmental heat transfer (such as air flow convection, radiation, and external conduction). This enables the geometry to be completely customizable and easily integrated with other thermal models through a nodalized interface. When tied to external sources of heat transfer, the geometry model will pass those heat loads back to the schematic for calculation of the active system response.

IV. Submodel Overview

One primary objective of a human thermal model is to output the total heat storage of the human in the form of a net heat balance. For a full body heat balance, the 41-node METMAN model considers metabolic, radiative, latent, sensible (external convective) and internal convective heat transfer components. Each component is summed as shown below [4]:

$$Q_{stor} = Q_{met} - Q_{rad} - Q_{lat} - Q_{sens} - Q_{int.conv} \quad (1)$$

Q_{stor} refers to the total heat storage of the human in BTU/hr, Q_{met} is the total metabolic heat production rate inclusive of muscle work and shivering in BTU/hr, Q_{rad} is the heat loss due to radiation to the environment in BTU/hr, Q_{lat} is the latent heat rejection to the environment through sweating, diffusion, and respiration in BTU/hr, Q_{sens} is the sensible heat transfer to the environment through convection and respiration in BTU/hr, and $Q_{int.conv}$ refers to the internal convection carried out by blood flow to each segment in BTU/hr. A visual depiction of these heat storage components is shown in Figure 4.

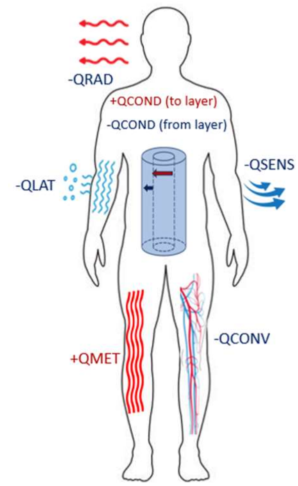


Figure 4. Components of a Full Body Heat Balance; a Summation of these Elements Equates to Total Heat Storage

While heat storage is an output that computes the full body heat balance, each layer of the body (core, muscle, fat, and skin) has its own heat balance that contributes to the overall heat storage and core temperature. Detailed descriptions of each component of heat storage, as well as their implementation in the active thermoregulatory schematic, are discussed in the following sections. It should be noted that the presentation of units follows the METMAN convention of English units (unless otherwise specified), as many of the equations and constants within the METMAN code base are empirical and specific to the units contained therein.

A. The Passive System

1. Anthropometry

In the base METMAN FORTRAN code, a human's height and weight are provided as inputs for the calculation of concentric cylinder dimensions for conductance calculations and blood flow paths [11]. In METMAN TD, each cylinder dimension is saved as a symbol within the Thermal Desktop Symbol Manager, and the cylindrical geometry graphical output dynamically scales with height and weight of the subject as shown in Figure 5.

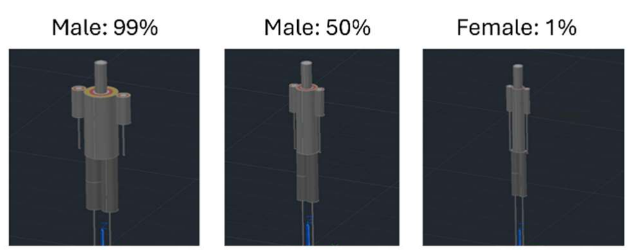


Figure 5. Examples of Scaled Geometry with Inputs of Height and Weight

Prior to the calculations of cylindrical dimensions, METMAN first computes the total body surface area given a height and a weight. An important assumption within METMAN is that all subjects are scaled proportionally; based on the total skin surface area of a standard reference person, the total surface area will scale along with height and weight [14]. After the calculation of body surface area, METMAN computes weights and volumes of each segment compartment. Height and radius of body components are calculated from each individual volume. Graphical geometry in Thermal Desktop is automatically drawn with these symbol dimensions. A detailed flow of each calculation step is given in Figure 6.

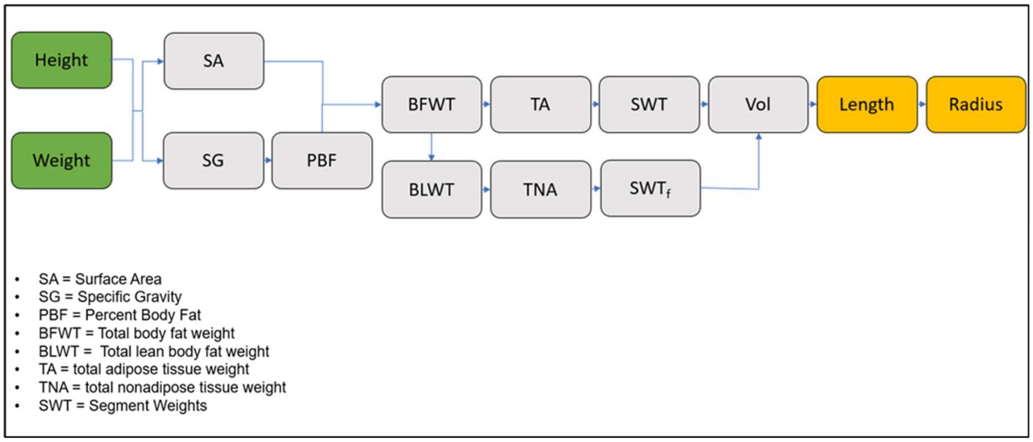
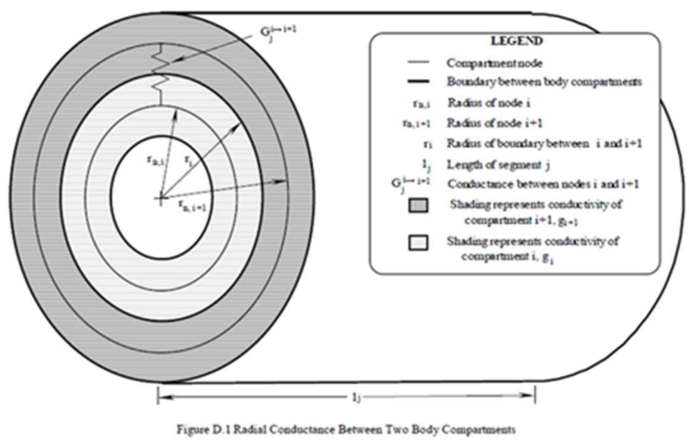


Figure 6. The Process of Body Geometry Calculation for Each Segment in METMAN and Thermal Desktop

To enable the geometry submodel to function as an interface between the thermoregulatory schematic and the external environment, a nodalization technique within Thermal Desktop was utilized to convert the geometry nodes into "clone nodes" of the schematic. A clone node is a special node type that allows for a copy of the original node to exist in a new geometry framework, while still preserving the thermal information passed between them. Functionally, this means that any heat loads applied to the cylindrical model from the environment (such as convection or radiation) will be passed back to the schematic in calculation of final nodal temperatures. This perceived separation by the model user allows for the complete customization of outer body geometry, as any nodal geometry can be corresponded and cloned back to the schematic.

2. Internal Conduction

Internal conduction refers to the heat transfer between tissue layers in a given segment, acting as a method of thermal communication between the core and the skin to enable an active system response to temperature differentials. The internal conduction of METMAN TD is computed in the Symbol Manager and applied graphically as node-to-node conductors in the thermoregulatory schematic. Conductivities for each body layer are given as material property constants in the Symbol Manager, and conductances between each layer are calculated based on body geometry using the given equation [11] for the radial conductance between two cylindrical components.



$$G_j^{i \rightarrow i+1} = \frac{2 š l_j}{\frac{\ln\left(\frac{r_i}{r_{n,i}}\right)}{g_i} + \frac{\ln\left(\frac{r_{n,i+1}}{r_i}\right)}{g_{i+1}}}$$

Figure 7. Radial Conductance between Cylindrical Segment Layers [11]

3. Thermal Capacitance

For all 40 segment nodes within METMAN and METMAN TD, the thermal capacitance is calculated as the product of body compartment weight (computed in the anthropometric segment dimensions) and specific heat (given as 0.5, 0.6, and 0.9 Kcal/kg-°C respectively for skeletal, fat, and all other material properties as designated in the Symbol Manager) [11]. Heat capacity of the central blood node is given as a constant 2.25 Kcal/kg-°C and does not scale with body size, as METMAN assumed a constant blood volume of 2.25 liters within the central node [11]. For each body layer, the final capacitance is calculated as follows [15] and applied to each respective node in the thermoregulatory schematic:

$$SWT = WTFACT * (TA \text{ or } TNA) \tag{2}$$

$$CBZ_{Core} = (0.5SWT_{Core} + 0.9SWT_{Musc}) * CONFAC$$
$$CBZ_{TrunkCore} = CBZ_{Core} - 2.25 * CONFAC$$
$$CBZ_{Musc} = 0.9SWT_{Musc} * CONFAC \tag{3}$$
$$CBZ_{Fat} = 0.6SWT_{Fat}CONFAC$$
$$CBZ_{Skin} = 0.9SWT_{Skin} * CONFAC$$

Where SWT is the total segment weight in kg, WTFACT is the compartment weight factor for a standard man in kg (for proportional scaling from the reference weight), TA is the adipose tissue weight in kg, TNA is the nonadipose tissue weight in kg, CBZ is the thermal capacitance for each body layer in BTU/°F, and CONFAC is the conversion factor from Kcal/°C to BTU/°F. Note that the thermal capacitance for the trunk core has been calculated separately from other tissue layers; because the central blood is contained within the core of the trunk and is assigned its own capacitance, the central blood capacitance is subtracted from the total capacitance of the trunk. Each capacitance is individually assigned to all 41 nodes in the thermoregulatory schematic and are automatically symbol driven for each instance of new geometry parameters.

B. The Active System

1. Heat Production in the Body

Metabolic heat generation in METMAN is comprised of muscle work and the response of shivering to cold temperatures [11]. A baseline rate of metabolic heat generation is referred to as the basal metabolic rate and maintains the body temperature in ideal, at-rest conditions. This basal rate is calculated for each segment as the product of surface area and a constant 14.26 BTU/hr-ft^2 defined as the basal metabolic rate per unit surface area [15]. This value is added to muscle work and shivering at the muscle layer to solve for the resultant metabolic heat generation.

Muscle work is the amount of heat generated at a given metabolic rate based on muscle efficiency. Muscle work is calculated as:

$$Q_{work} = RM - BRM - \frac{Ueff}{100} * (RM - 278.0) \tag{4}$$

Where RM is the metabolic rate of the individual (given as a model input in BTU/hr), BRM is the basal metabolic rate in BTU/hr, and Ueff is the muscle efficiency of mechanical work [11]. 278.0 is the basal metabolic rate for an "average sized male" [11] and is contextualized as a constant and does not scale with respect to body size.

As an additional means of producing heat, shivering is the involuntary contraction of muscles in response to cold temperatures, increasing metabolic heat generation to stabilize body temperature. In METMAN, each muscle node produces heat as described in the equation below:

$$Q_{mshiv} = K_{ms} * Q_{shiv} \tag{5}$$

Where Q_{mshi} is the heat generation for the given muscle compartment in BTU/hr, K_{ms} is the percentage of shiver allocation to each muscle compartment (based on segment contribution to total heat generation), and Q_{shiv} is the total heat generated by full body shivering in BTU/hr [15]. Q_{shiv} is calculated by the equation:

$$Q_{shiv} = 12.22\left(T_{set,c} - T_c\right)[\sum_{segments} K_s(T_{set,s} - T_s) \tag{6}$$

Where $Tset_c$ is the core temperature setpoint in °F, or the comfort body temperature of the individual when designated as the head core temperature. T_c is the core temperature of the given body segment in °F; in this case, the head core temperature deviance from the setpoint is calculated to determine whether shivering should take place. K_s refers to the skin distribution coefficient for surface areas, and $T_{set,s}$ and T_s are the setpoint temperatures in °F and calculated temperatures of each skin compartment [11].

Within TD, the resulting shiver heat load for each muscle compartment is applied to each associated node in the thermoregulatory schematic. The value of that heat load is either 0 BTU/hr (if either the core temperature is elevated or the given segment does not contribute to full body shivering) or the value of Q_{mshiv} for each segment if the skin temperature deviance is greater than 0. To implement this logic within TD Logic Objects, a full body shiver flag is enabled for core temperatures below the setpoint, and a logic object designated to calculate setpoint deviances of each segment determines whether the thermoregulatory schematic heat loads are activated.

For the core, fat, and skin layers, the total heat load applied to each node in the thermoregulatory schematic is equal to the basal metabolic rate. For the muscle layer of each segment, the heat load also accounts for Q_{work} and Q_{msh} for the total body heat generation.

2. Sensible Heat Transfer

In the context of HTM, sensible heat transfer refers to the transfer of heat throughout the body driven by segment and environmental temperature differentials. Specifically, sensible heat transfer is driven by convection, radiation, and respiration [15]. The METMAN FORTRAN code groups these three methods of heat transfer together into one combined heat load, but due to the model structure in TD, these three types of sensible heat transfer are calculated and applied as three different heat loads to their respective nodes.

Convection equations calculate both free and forced convection based on temperature differentials, gravity, and air velocity. The larger of the two heat transfer coefficients is used in the final convection calculation, functioning as a method of prioritizing the convective heat transfer with the most thermal impact (for example, calculations in microgravity would rely on forced convection rather than free convection) [4]. In METMAN TD, this heat load is modeled as a convective tie between the outer geometry skin node and the ambient environment with the magnitude of the tie equating to the heat transfer coefficient of either free or forced convection.

Radiation heat transfer is calculated based on the following equation [11]:

$$Q_{rad} = A\sigma f[(Ts + 460.0)^4 - (T_w + 460.0)^4] \tag{7}$$

Where A is the radiative surface area of the body (dependent on position/posture) in ft^2, σ is the Stefan-Boltzmann constant, f is the “interchange factor” (product of view factor and emissivity), and T refers to the temperatures of the skin and wall, respectively. All temperatures are given in Fahrenheit and converted to Rankine for heat flow units of BTU/hr. Similar to the implementation of convection heat transfer, the radiation heat transfer is modeled as a tie between the outer skin layer and the environment with the heat transfer coefficient computed for each segment. For the purposes of this work to demonstrate and maintain equivalent functionality, the radiation calculations as originally developed in the METMAN FORTRAN code override the Thermal Desktop radiation calculations. If desired for future integration efforts and complex geometries, the METMAN radiation calculations represented through the environmental convective tie can be disabled and replaced with built-in Thermal Desktop calculations.

Respiration is also a component of sensible heat transfer, as cool air enters the body and is warmed by convection. The heat rejected due to respiratory sensible heat transfer is given by the empirical equation [11]:

$$Qr_{sen} = Q_{met}C_{pg}\left[\frac{0.0418(144.0 * P_{cab})}{48.3(T_{cab} + 460)}\right] * (T_r - T_{cab}) \tag{8}$$

Where Q_{met} represents the metabolic heat generation in BTU/hr, C_{pg} is the specific heat of the inspired gas in BTU/lbm-°F, P_{cab} is the cabin pressure in psia, T_{cab} is the cabin temperature in °F, and T_r is the temperature of the respiratory tract in °F. The bracketed term is a combined empirical factor to characterize ventilation and mass flow given by the METMAN code documentation [11]. Because respiratory heat transfer is considered a form of internal heat transfer, the computed heat load for respiratory sensible heat transfer is applied directly to the nodal components of the respiratory tract: the head core, muscle, and fat layers, and the trunk core and muscle layers.

3. Latent Heat Rejection

Latent heat transfer, or the dissipation of heat through phase change, consists of diffusion, respiration, and sweat [15]. METMAN calculates the total latent heat loss of each segment through a summation of these three components, then applies Q_{lat} as a heat load to that segment’s total heat balance [11]. METMAN TD assumes a similar approach and applies a TD heat load to each schematic skin node; latent heat transfer is controlled by active system temperature differentials and is best integrated directly with the thermoregulatory schematic. The passive system geometry model functions as a boundary between the environment and the active system response.

Diffusion is the latent heat loss caused by vapor pressure differences at the boundary layer of the skin. Since the skin is porous and the concentration of water inside the body is typically greater than the external environment, there is an assumed constant rate of diffusion modeled as an applied heat load from the skin layer. METMAN calculates heat loss through diffusion as the product of surface area and vapor pressure difference between the skin and the surrounding air [11]:

$$Q_{dif} = 6.66A(VPT_s - VPT_{Dewc}) \tag{9}$$

Respiration includes a component of latent heat rejection as the dry inspired gas flows over a moist respiratory tract. Similar to sensible respiratory heat rejection, METMAN uses an empirical equation to calculate the heat lost to respiration [11]:

$$Qr_{lat} = q_{met}\left[\frac{0.0418(144.0 * P_{cab})}{48.3(T_{cab} + 460)}\right][\frac{18.0(1040.0)}{32.0P_{cab}}] * (VPT_r - 0.8VPT_{Dewc}) \tag{10}$$

Where VPT_r is the vapor pressure of the respiratory tract in psia, and VPT_{Dewc} is the vapor pressure of the surrounding air in psia. Bracketed terms encompass empirical data fitting and unit standardization to characterize evaporative mass flow, while the vapor pressure differential compares the respiratory tract and environmental vapor pressures. The resulting respiratory heat rejection is placed as a heat load from the respiratory tract including the head core, muscle, and fat and the trunk core and muscle.

Sweating is the latent heat loss caused by the evaporation of perspired liquid from the skin. Since sweating is a physiological response to elevated core temperatures, the sweat rate is dependent on the positive temperature deviance between the core and comfort body temperatures and the skin and skin setpoint temperatures. The METMAN FORTRAN code includes a subroutine that loops through all skin nodes with the equation [11]:

$$Q_{swt} = SK_s' * 2.0^{\left(\frac{T_s - T_{sets}}{7.2}\right)} \tag{11}$$

Where S is the full body sweat signal calculated by an equation involving the product of the core temperature differential and the summation of skin temperature and setpoint differentials across each body segment. K_s' denotes the sweating distribution coefficient for each segment. In TD, the latent heat loss due to sweating is calculated in three parts and applied as a heat load from the skin node in the thermoregulatory schematic.

The first part of sweat rate calculations involves the creation of sweat signal flags; body segments only contribute to the overall rate of sweating heat rejection if the core temperature is elevated *and* the calculated deviance from their skin setpoint temperatures is greater than 0.

The second component of the sweating submodule is the calculation of the full body sweat signal. This value acts as a control of sweat rate in BTU/hr based on the individual sweat signal flags passed by each segment. The total sweat signal is given by [11]:

$$S = \left(T_{c,head} - T_{set,c}\right) * [884.0 + 73.4 * \sum_{10} K_s(T_s - T_{set,s})] \tag{12}$$

The last step in the TD logic involves calculating Q_{swt} for each segment and passing the heat load from the Logic Manager to the TD applied heat loads to each skin node. For the contribution of latent heat rejection to the full body heat storage, each segment is summed to a total Q_{lat} and subtracted from the rest of the segment heat balance.

4. Internal Convection

Internal convection refers to the heat exchange between flowing blood and each respective segment in the body. Basal blood flow is the flow required to maintain baseline metabolic requirements; this is given as a symbol input for each node as a constant (and does not change with varying anthropometry) [4]. From this basal rate, flow can increase or decrease based on demand from muscle work and the ambient environment. When muscles are performing mechanical work during periods of exercise, a higher rate of flow is required to support the increased metabolic loads.

The ambient environment also plays a role in determining blood flow. In cold environments, blood vessels will tighten to conserve heat in a phenomenon called vasoconstriction. By contrast, vasodilation is the widening of blood vessels to reject heat.

The total blood flow to each node is dependent on the tissue layer. For the core and fat body layers, the total blood flow rate in lbm/hr is assumed to be constant at the basal rate [4]. Blood flow in lbm/hr to each muscle layer is defined as [11]:

$$BF_{musc} = basal + 0.554(Q_{met,musc} - Q_{basal,musc}) \tag{13}$$

Where the blood flow to each muscle node is increased as a function of muscle work and metabolic rate. As the level of exercise intensity increases, more blood flow is required to support the metabolic activity.

The blood flow rate to each skin layer is defined as [11]:

$$BF_{skin} = \left(\frac{basal + Dilate}{1.0\ + Strict}\right) \tag{14}$$

Essentially, the blood flow to the skin layer is environmentally dependent and calculated as a function of either an increase to the basal rate by a dilation factor or a decrease to the basal rate by a constriction factor. If either the dilation or constriction factors are activated, the other is set equal to 0 in the model logic.

Once each blood flow rate is calculated, the nodes in the thermoregulatory schematic are convectively tied to the central blood node as seen in Figure 8. The values of each of these internal convective ties are equal to the product of the blood flow rate and temperature difference from the central blood.

C. The Complete Heat Balance

When each heat load is summed per segment, the resultant value is the total heat storage for that segment. Subsequently, when each segment heat storage is summed together, this culminates in the final full body heat storage as shown in Figure 8 [4]. The final change in nodal temperatures for each time step are then computed as the quotient of segment heat storage (in BTU) and heat capacitance as defined in the passive system model.

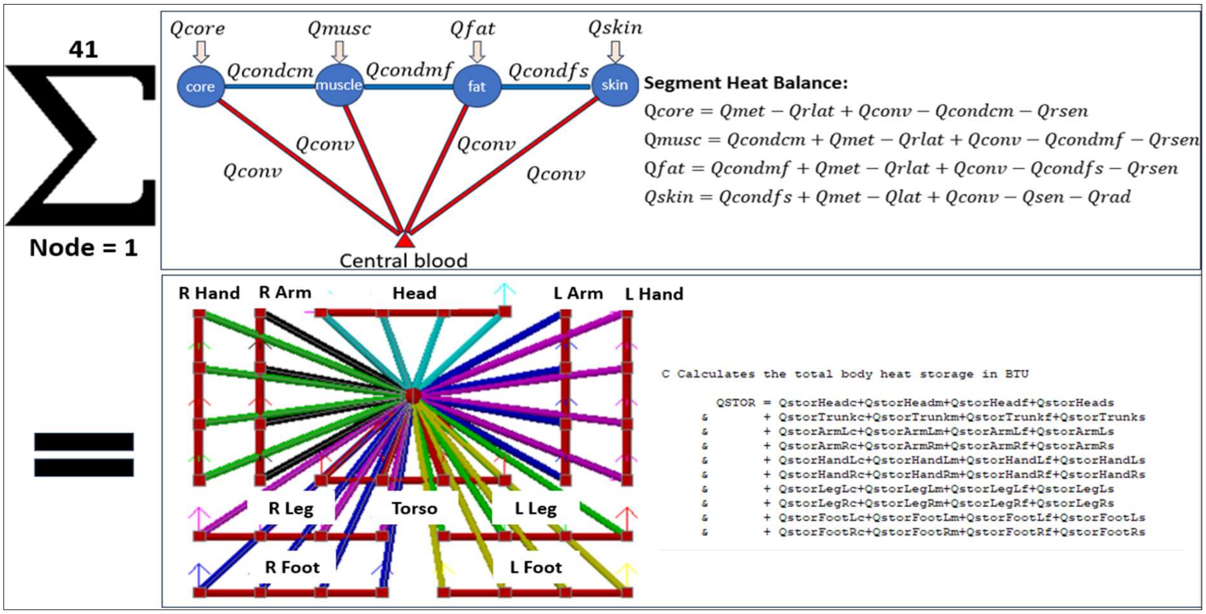


Figure 8. The Structure and Final Logic Calculation of the Total Body Heat Storage in BTU

V. Comparison Results and Verification

A. Model Verification: Steady State

For comparison between the METMAN FORTRAN code and METMAN TD, both models were run at similar environmental conditions, input parameters, and metabolic rates to analyze steady state nodal temperatures. As an example, results from an 85°F ambient environment run are seen in Table 1. At this elevated temperature, the active system was engaged to cool the body and maintain a thermal homeostasis, so the results encompass all subroutines that converge on final temperatures.

Core temperature is a primary point of comparison, as the calculation of nodal temperatures involves both the active system model (through heat storage calculations and thermoregulatory response) and the passive system model (through geometry and heat capacitance). METMAN TD outputs a steady state core temperature of 98.77°F, the same core temperature computed at the end of an original METMAN FORTRAN run. The original METMAN FORTRAN code and METMAN TD output similar temperatures for each segment and layer, with the highest temperature difference between formats to be 0.01°F.

Table 1: Node Temperature Comparison Between METMAN and METMAN TD at Steady State

Nodal Temperatures (°F) at Steady State				
Head	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	98.77	96.07	94.30	93.21
METMAN TD	98.77	96.08	94.30	93.21
Trunk	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	99.07	98.90	93.64	89.38
METMAN TD	99.07	98.90	93.64	89.38
Left Arm	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	97.13	96.36	93.50	92.17
METMAN TD	97.13	96.36	93.50	92.17
Right Arm	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	97.13	96.36	93.50	92.17
METMAN TD	97.13	96.36	93.50	92.17
Left Leg	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	99.22	98.81	95.59	93.48
METMAN TD	99.22	98.81	95.59	93.48
Right Leg	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	99.22	98.81	95.59	93.48
METMAN TD	99.22	98.81	95.59	93.48
Left Hand	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	91.69	91.51	90.79	90.09
METMAN TD	91.69	91.51	90.79	90.09
Right Hand	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	91.69	91.51	90.79	90.09
METMAN TD	91.69	91.51	90.79	90.09
Left Foot	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	90.69	90.41	89.84	89.12
METMAN TD	90.69	90.41	89.83	89.12
Right Foot	**Core**	**Muscle**	**Fat**	**Skin**
METMAN	90.69	90.41	89.84	89.12
METMAN TD	90.69	90.41	89.83	89.12
Central Blood Node				
METMAN	98.7			
METMAN TD	98.7			

B. Model Verification: Transient Analysis

Following model verification at steady state, a new capability for transient analysis was implemented with METMAN TD. The desirement for customizable transient analyses enables mission profiles to be tested in one continuous run. An example of such a case is a metabolic profile of a theoretical full mission day. To complete a full METMAN analysis of nominal metabolic rates, aerobic exercise, resistive exercise, and recovery, multiple METMAN cases were generated at the different metabolic rates as consistent inputs. These cases were run sequentially, and the results were appended together to be considered a continuous run. In METMAN TD, the functionality has been added to customize input parameters directly in the Logic Manager. In this case, a metabolic profile was imported into the Logic Manager as an array, and results are seen in Figure 9. The core temperature profile is similar to what is expected at the given array of metabolic rates, with the core temperature beginning to reach steady state before a spike in metabolic rate leads to an initial dip in core temperature (as blood flow increases as a function of metabolic rate) before a rapid spike in core temperature. Resistive exercise causes a decline in core temperature due to the reduced metabolic rate, and in the recovery phase, core temperature returns to steady state. METMAN FORTRAN runs were conducted at the same metabolic rates as the transient TD analysis, and the core temperature at notable time steps are recorded in the table below. In this comparison, all environmental parameters are held constant such as ambient temperature (75.2 °F) and pressure (10.2 psia).

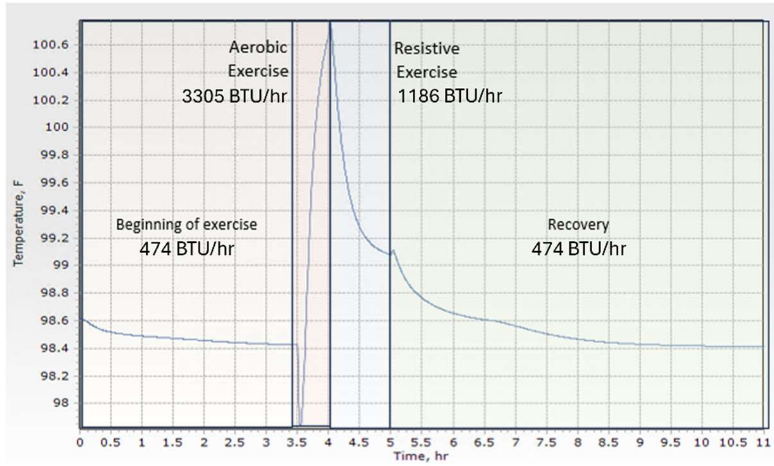


Figure 9. Transient Analysis of Core Temperature with a Varied Metabolic Profile

Table 2: Transient Analysis of Core Temperature with METMAN FORTRAN and METMAN TD Model Formats

Time (hr)	METMAN FORTRAN (°F)	METMAN TD (°F)
0	98.6	98.6
1	98.49	98.49
2	98.46	98.45
3	98.43	98.43
3.5	98.42	98.42
4	100.67	100.67
5	99.08	99.08
11.5	98.41	98.41

Results appear to be nearly identical between METMAN FORTRAN and METMAN TD, demonstrating equivalent functionality between model formats. METMAN TD contains the added capability of continuous analysis, even with inputs that change over time. In this example, metabolic rate changed with time, while previous METMAN analysis would require the execution of multiple cases for each changing input parameter.

VI. Conclusion

As a result of the NESC HTM discipline-advancing effort, the METMAN human model has been modernized from the base FORTRAN 77 code to the new format of a 3D Thermal Desktop model. Thermal Desktop was chosen as a common standard of analysis software across NASA centers and commercial partners, enabling the integration of human thermal analysis with vehicle, system, and spacesuit analyses. Use cases range from the baseline METMAN functionality to updated geometry customization and logic customization to run more advanced simulations.

To replicate baseline METMAN steady state analysis, input parameters are initialized in the Symbol Manager within Thermal Desktop, and the default case can be run to output results such as the nodal temperatures seen in Table 1. To perform more advanced transient analysis with parameters that change throughout a given run, these updated parameters can be input as arrays such as the metabolic profile example shown in Figure 10. An additional capability of the translation of METMAN to a 3D modeling format is the increased fidelity of geometry. A modeling technique in Thermal Desktop has been tested to map the functionality of METMAN to any given mesh. This can be accomplished through TD "Node Cloning" (the same technique used to couple the thermoregulatory node network with the outer geometry shown in Figure 3) and "Node Correspondence" (the mapping of a complex geometric nodal mesh to a singular SINDA node). Interfaces for these use cases and added capabilities are depicted in Figure 10.

As near identical functionality to METMAN has been demonstrated, forward work for METMAN TD integration will be implementing varied geometries with inline NASA human thermal analysis. The Thermal Desktop implementation enables streamlined, coupled analysis, and the standardization of modeling format allows direct human/system integration that was not previously accessible in decoupled analysis. As spaceflight aims to push the boundaries of human exploration, human thermal modeling can now be directly implemented with the systems designed to keep crew safe.

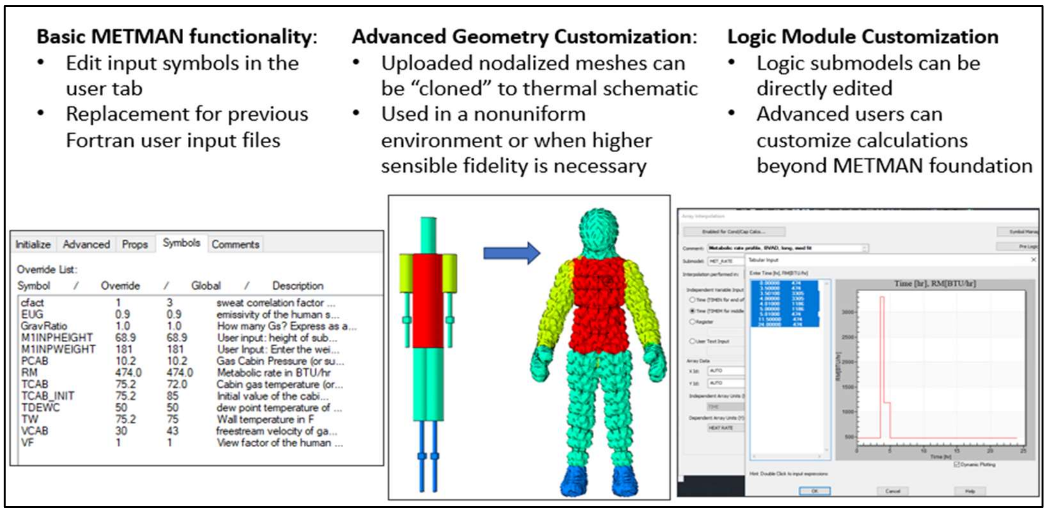


Figure 10. METMAN TD Model Use Cases with Modularity and TD Interfaces

Acknowledgments

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