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RE-EXAMINATION OF METMAN, RECOMMENDATIONS ON ENHANCEMENT OF LCVG, AND DEVELOPMENT OF NEW CONCEPTS FOR EMU HEAT SINK

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Prepared by: Amir Karimi, Ph.D.

Academic Rank: Associate Professor

University & Department: The University of Texas at San Antonio
                         Division of Engineering
                         San Antonio, Texas 78285

NASA/JSC

Directorate: Engineering

Division: Crew and Thermal Systems

Branch: Thermal Systems

JSC Colleague: Chin H. Lin, Ph.D.

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ABSTRACT

METMAN is a 41-node transient metabolic computer code developed in 1970 and revised in 1989 by Lockheed Engineering and Sciences, Inc. This program relies on a mathematical model to predict the transient temperature distribution in a body influenced by metabolic heat generation and thermal interaction with the environment. A more complex 315-node model (Wissler-model) is also available that not only simulates the thermal response of a body exposed to a warm environment, by-including-in-the-model the -perfusion rate in muscle and the magnitude of counterflow heat exchange between large -arteries-and-veins, but is also capable of describing the thermal response resulting from exposure to a cold environment . It is important to compare the the two models for the prediction of the body's thermal response to metabolic heat generation and exposure to various environmental conditions. Discrepancies between the two models may warrant an investigation of METMAN to ensure its validity for describing the body's thermal response in space environment.

The Liquid Cooling and Ventilation Garment is a sub-system of the Extravehicular Mobility Unit (EMU). Designed-by ILC-Dover in the 1960's, this garment, worn under the pressure suit, contains the liquid cooling tubing and gas ventilation manifolds; its purpose is to alleviate or reduce thermal stress resulting from metabolic heat generation. There is renewed interest in modifying this garment through identification of the locus of maximum heat transfer at body-liquid cooled tubing interface.

The sublimator is a vital component of the Primary Life Support System (PLSS) in the EMU. It acts as a heat sink to remove heat and humidity from the gas ventilating circuit and the liquid cooling loop of the LCVG. The deficiency of the sublimator is that the ice, used as the heat sink, sublimates into space. There is an effort to minimize water losses in the feedwater circuit of the EMU. This requires developing new concepts to design an alternative heat sink system.

We-directed-our efforts to review and verify the heat transfer formulation of the analytical model employed by METMAN. We-recommend a conceptual investigation of regenenerative non-venting heat-sink subsystem for EMU.

INTRODUCTION

Considerable effort has been made by physical scientists and engineers to develop mathematical models to describe natural phenomena through mathematical models. Those efforts include attempts to model the human thermal system. The models are designed to simulate the effects of heat generation, resulting from physical activities, and the heat exchange between the body and its environment on heat transfer within the body.

Although our understanding of many important physiological phenomena remains incomplete, it is important to use mathematical modeling for prediction of human response to a variety of stressful environmental conditions. These applications become essential in situations for which it is at least difficult, if not impossible, to conduct experiments on human subjects. Examples include the thermal effects on astronauts during lunar missions, or extravehicular activities (EVA), thermal response of humans while diving in cold water and the effect of thermal stress on workers who must perform their assigned duties under thermally hostile environments. Applications could be extended to various survival situations involving accidental immersion in cold water or military personnel who have to perform their duties under chemical or biological warfare environmental situations. The threat posed to humans by these conditions has long been recognized.

Mathematical modeling of human thermal systems dates back to 1947, when Machle and Hatch [1] introduced the concept of core and shell temperatures (rectal and mean skin temperatures, respectively). In their model the stored energy in the body was expressed as linear function of core. Pennes' cylindrical model [2] (1948) provided a reasonable temperature profile in the forearm. Wissler's first model [3] extended Pennes' model by employing six cylindrical elements to describe the entire human thermal system.

Extensive application of mathematical modeling of human thermal systems began with NASA's Apollo program. Stolwijh [4] developed a model to predict the astronauts' thermal response during the extravehicular activities (EVA). To achieve this a transient metabolic man computer program (METMAN) was developed to describe the temperature profile in the body. METMAN's initial construction was based on a two-model point model and later was extended to an eight-node, a 14-node, a 25-node and to the present 41-node model [5]. This model has been adequate to predict thermal behavior in the body resulting from thermal stress. Wissler's latest 250-node and 315-node physiological models [6,7] were mainly designed to describe the human thermal response resulting from exposure to cold environments. They have been used to analyze the performance of divers working in water as deep as 450 meters. In recent years they have also been used to describe human thermal experience working or exercising in a hot humid environment.

The advantage of Wissler's model over METMAN is that it has a wider range of applications. It can be used for predication of thermal response for humans exposed to hot or cold environments, while METMAN's range of application is limited to hot environments. Wissler's model considers factors which are important in cold subjects. They include the perfusion rate in muscle and counter flow heat exchange between large arteries and veins. This thermal model contains mass balances for oxygen, carbon dioxide, and lactic acid required in equations for perfusion and ventilation. However, Wissler's model is poorly documented and is difficult to use. METMAN's advantage over Wissler's

model is that it is well documented and easy to use. It also has been developed specifically for space application.

The problem of rapid increase in body temperature becomes significant when an individual has to wear special protective clothing to be isolated thermally and/or otherwise, from hazardous surroundings. Although such clothing protects the individual from a hostile environment, it also places additional thermal stress on the individual, as the generated metabolic heat cannot be directly dissipated into the environment by natural means. Therefore, to make such micro-environments habitable, fluid-conditioned suits have been designed to reduce thermal stress. A fluid-cooled garment is usually warn and is placed in direct contact with the skin.

A fluid-cooled garment may consist of cold liquid flowing in a network of flexible tubes which come in direct contact with the heat source (body), or conditioned air flowing against the body or a combination of both. A cold fluid (typically, in the range 5 to 20 °C) is used to remove a portion or all of the metabolically generated heat from the body. On return cycle, heat is rejected to a heat sink medium. The ILC Dover liquid cooled conditioned vest has been used in space applications. A modified (half-length) version of this suit is also been used by USAF for military application. In recent years USAF has directed its efforts in intermittent method of ambient air cooling. References [8-11] provide typical performances of liquid cooled garments and air conditioned suits.

A heat sink for a life support system may consist of an ice pack heat exchanger, a small vapor-compression cooling unit. A thermal heat sink is a vital component of the Primary Life Support System (PLSS) in the Extravehicular Mobility Unit (EMU). It is required to remove heat and humidity from the gas ventilating circuit, to cool the liquid cooling loop of the LCVG, and to eliminate other EMU equipment thermal load. The present heat sink subsystem in the EMU consists of a sublimator. The ice formed in the sublimator is used as the heat sink for heat removal and the vapor product is vented into space. To minimize the water losses in the feedwater circuit of the EMU, NASA has identified a need for developing a regenerable non-venting heat sink (RNTS) subsystem for advanced extravehicular activities (EVA). The subsystem must address the EMU thermal control requirements of the existing Shuttle Orbiter, the Space Station EVA mission, and the Man-Mars mission.

The Shuttle EVA missions require RNTS operations of up to four hours duration with a cumulative heat removal capacity of up to 7240 Btu. They require heat removal rates in the range 310-3445 Btu/hr, with an average rate of 1810 Btu/hr for the entire EVA mission. The liquid-cooling and ventilation garment (LCVG) inlet water temperature should not exceed 45°F at maximum thermal load during the Shuttle EVA mission. The Space Station EVA mission has a maximum duration of 8 hours with a cumulative heat removal capacity requirement of up to 11,680 Btu. It requires an RNTS operation with a heat removal rate in the range of 310-2695 Btu/hr, with an average rate of 1460 Btu/hr for the entire mission. The liquid-cooling and ventilation garment (LCVG) inlet water temperature should not exceed 60°F at maximum thermal load during the space station EVA mission.

A series of feasibility studies have been conducted [12-14] for the development of a RNTS thermal control for the EMU. The studies suggested a thermal control subsystem utilizing a water/alcohol phase change thermal storage for the Shuttle EVA mission and a thermal control subsystem consisting of a vapor compression heat pump/space radiator

integrated with a water/ethanol phase change medium thermal sink for the Space Station EVA mission. The proposed thermal control subsystems are heavy for the lunar and Mars EVA missions.

This report concentrates on a review of mathematical modeling and physical concepts used in the METMAN. Its purpose is to point out shortcomings of the model and, when possible, to make recommendations for improvement.

DESCRIPTION OF THERMAL MODEL

Both METMAN and Wissler's models are transient-state models which predict thermal and metabolic changes that occur during a certain period of time. Given initial values for all dependent variables and specification of independent variables, they both evaluate nodal temperatures at various time periods and compute thermal storage within the body. Each program is capable of predicting body-thermal behavior subject to different modes of operation. The modes of operation of METMAN include shirt-sleeve, normal-suited intravehicular activity (IVA), extravehicular activity (EVA) and helmet off. The METMAN and Wissler's models are based on similar descriptions of the human body. In METMAN, as shown in Figure 1, the human form is divided into 10 cylindrical elements: head, trunk, right and left arms, right and left legs, and right and left feet. Each element is further divided into four concentric compartments. They include a central core, muscle, fat layer and skin. Each compartment is represented by a nodal point. Therefore, including the central blood as a compartment, the METMAN model is constructed around 41 nodal points. The temperature throughout each compartment is assumed to be uniform, equaling its nodal point.

The Wissler model as shown in Figure 2 is based on 15 major cylindrical elements: head, upper torso, lower torso, right and left proximal arms, right and left medial arms, right and left distal arms, right and left proximal legs, right and left medial legs, right and left distal legs. Within each element there are 15 nodal points representing a conglomeration of tissue, bone, fat, skin and a vascular system containing arteries, veins and capillaries. The model includes up to six additional nodal points, external to the body, for computation of temperature and accumulation of sweat within clothing. Thus, the nodal points in this model may exceed 300, depending upon the mode of operation.

DISCUSSION

A human thermal model must account for the following factors. It should be capable of describing temperature as a function of position and time. It should account for the geometry of the human body. It should consider that properties vary with position throughout the body. It should account for metabolic heat generation resulting from various types of work and environmental conditions. It should account for heat and mass transfer in the respiratory tract. And it should account for all thermal interactions of body with its environment. Thus it is important that the physical modeling of thermal behavior in the body also include the effects of fluid-cooled garment-body interactions.
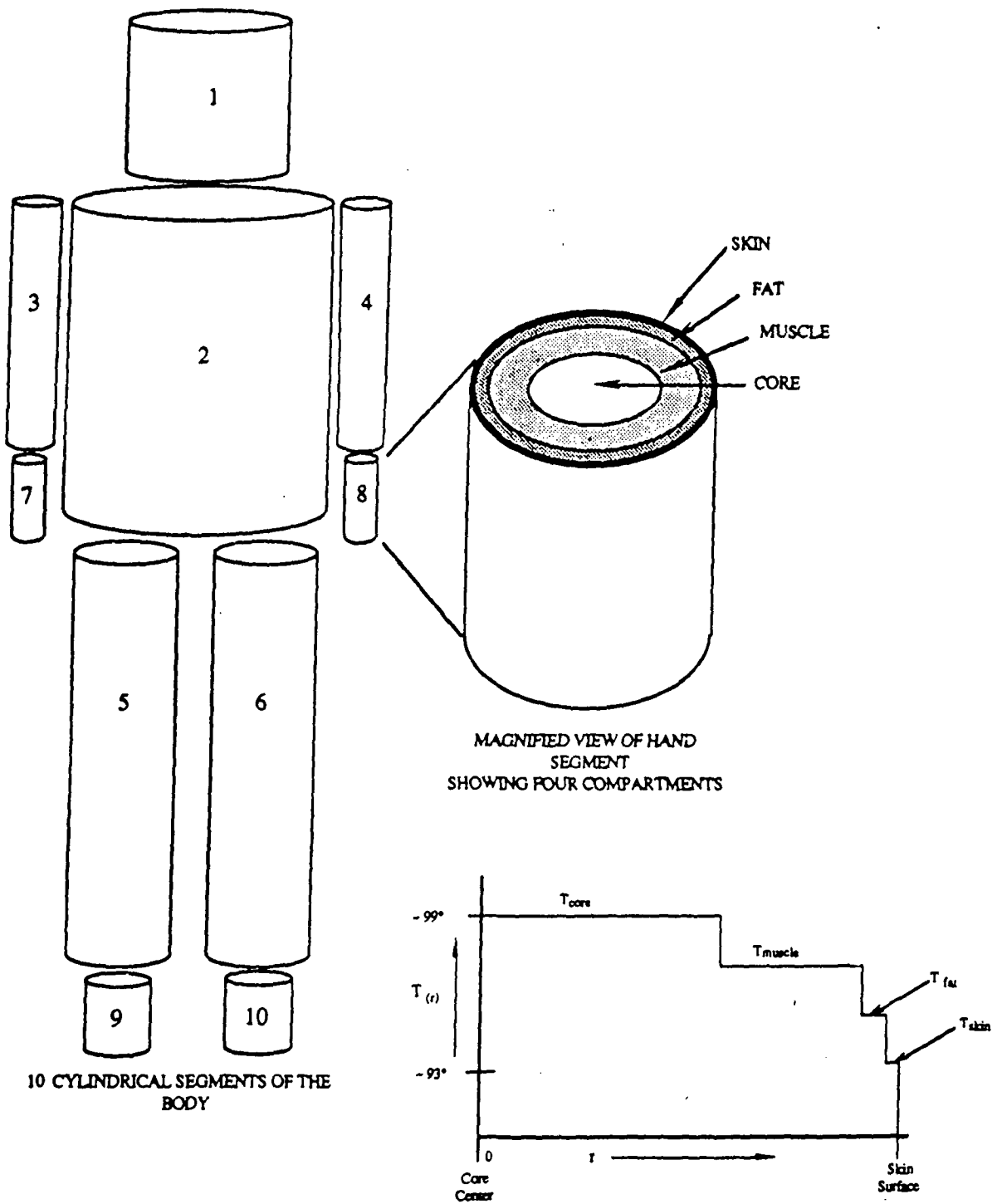
SKIN
FAT
MUSCLE
CORE

MAGNIFIED VIEW OF HAND
SEGMENT
SHOWING FOUR COMPARTMENTS

10 CYLINDRICAL SEGMENTS OF THE
BODY

T_{core}

T_{muscle}

T_{fat}

T_{skin}

$T_{(r)}$

~ 99°

~ 93°

0

r

Core
Center

Skin
Surface

Figure 1. Geometric Representation of Human Body by METMAN Model

HEAD

③

PROXIMAL LEFT ARM   MEDIAL LEFT ARM   DISTAL LEFT ARM   PROXIMAL RIGHT ARM   MEDIAL RIGHT ARM   DISTAL RIGHT ARM

⑮   ⑭   ⑬   ①   ⑩   ⑪   ⑫

UPPER TORSO

LOWER TORSO   ②

PROXIMAL LEFT LEG   ⑦   ④   PROXIMAL RIGHT LEG

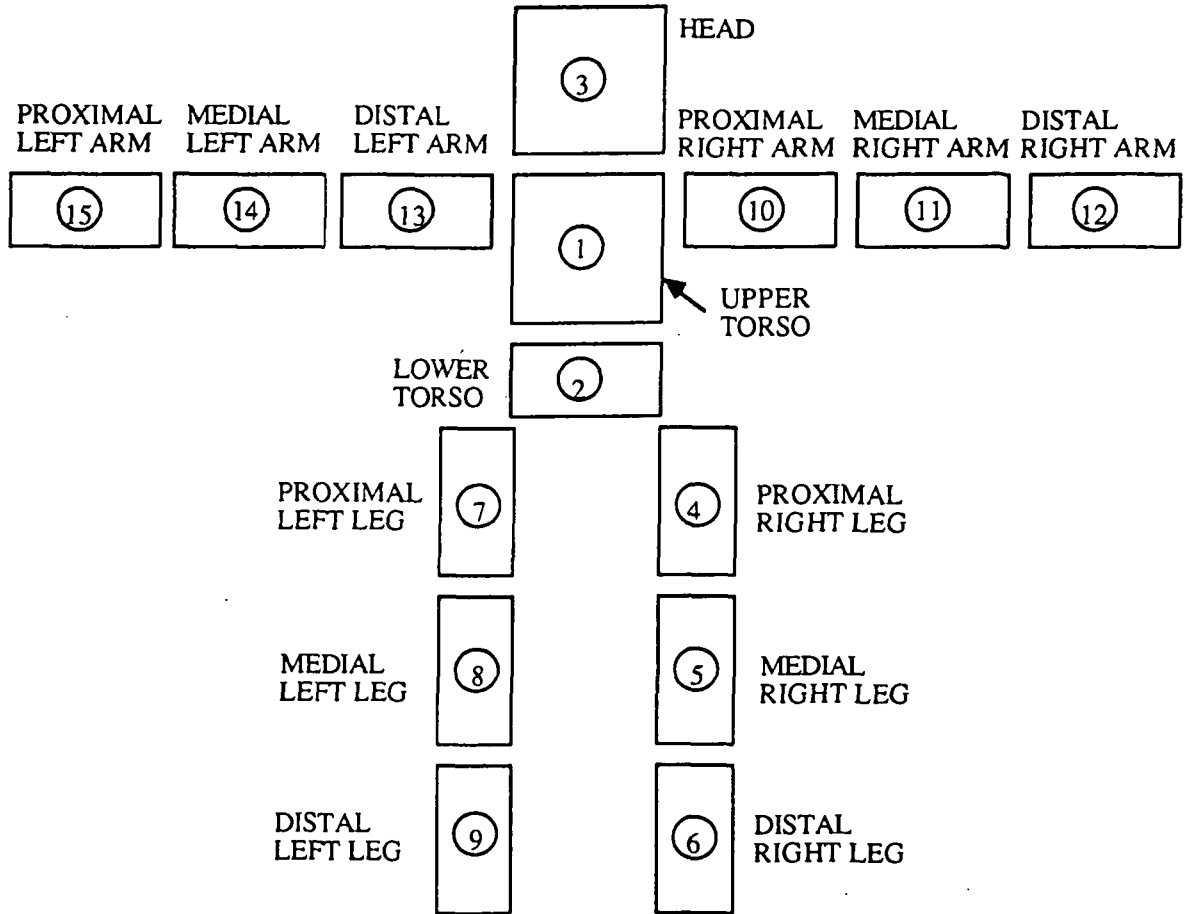MEDIAL LEFT LEG   ⑧   ⑤   MEDIAL RIGHT LEG

DISTAL LEFT LEG   ⑨   ⑥   DISTAL RIGHT LEG

Figure 2. Geometric Representation of Human Body by Wissler's Model

The heat transfer formulation of METMAN model is described in detailed in [5]. Therefore, we limit this report to few equations necessary, and refer the reader to this document for detailed description of thermal system.

The energy balance for each compartment is based on the following general relationship.

$$Q_{st} = Q_m \pm Q_c \pm Q_r - Q_e \pm Q_k \pm Q_{res} \pm Q_{LCG} \qquad (1)$$

Where Q_{st} is the rate of energy storage, Q_m is the metabolic heat generation, Q_c is convective surface heat transfer, Q_r is the radiation heat transfer at the surface, Q_e is the rate of evaporation losses, Q_k is the rate of conductive heat transfer, Q_{res} is the rate of heat transfer through respiratory tract and Q is the heat transfer with the liquid-cooled garment. It should be noted that Q_c, Q_r and Q_e are zero for internal compartments and they are important at skin compartment.

The rate of energy stored in each compartment can be expressed by:

$$Q_{st} = (m\, c_p \frac{\partial T}{\partial t}) \qquad (2)$$

The rate of heat generation, Q_m in the body is the sum of the basal metabolic rate and heat generated through work or shivering by muscles. METMAN model considers the effect of the height and the mass of an individual in evaluating the basal metabolic rate. The relations used in evaluation of heat generation are given in [5]. METMAN uses a distribution coefficient, K_{mw}, to evaluate the heat produced by work in each muscle compartment. These distribution coefficients are presented in Table 1. It indicates that the leg muscles' contribution to heat generation dominates all other body elements. These distribution coefficients are reasonable for work in a gravitation field. However, in a micro-gravity environment the major work is done by the arms. Therefore, it appears that the METMAN uses unreasonable distribution coefficients for the evaluation of heat production in the muscle compartments.

The heat transfer between internal body compartments occurs through conduction and vascular convection. The METMAN model assumes a uniform temperature, equal to the nodal point temperature, throughout each compartment. It employs the thermal resistant analogy, as shown in Figure 3, to evaluate the conductive heat transfer between two adjacent compartments. The internodal conductances are calculated based on the following relationship:

$$G_j^{i \to i+1} = \frac{2\pi l_j}{\dfrac{\ln (\frac{r_i}{r_{n,i}})}{g_i} + \dfrac{\ln (\frac{r_{n,i+1}}{r_i})}{g_{i+1}}} \qquad (3)$$

The variables in Equation (3) are defined in Figure 3.

Table 1. DISTRIBUTION COEFFICIENT, K_{mw}, OF HEAT PRODUCED BY WORK
AMONG THE MUSCLE COMPARTMENTS

Body Element	K_{mw}
Head	0.00
Trunk	0.30
Arms	0.08
Legs	0.60
Hands	0.01
Feet	0.01
	1.00

A uniform temperature distribution assumption for each compartment would present temperature discontinuities at the interface of two adjacent compartments. To improve the model we recommend the addition of appropriate boundary conditions for each compartment. Along the axis of each cylindrical element the boundary condition (central core) is

$$(\frac{\partial T_j}{\partial r})_{r=0} = 0 \qquad (4)$$

Equation (4) indicates that along the element's central axis the temperature is either a minimum or a maximum. Subscript j refers to j^{th} element. At the interface between the compartments, both temperature and thermal conduction must be continuous. This implies that

$$(T_j)_{r_i} = (T_j)_{r_{i+1}} \qquad (5)$$

and

$$(k_j \frac{\partial T_j}{\partial r})_{r_i} = k(\frac{\partial T_j}{\partial r})_{r_i} \qquad (6)$$

subscripts i and i + 1 refers to the ith and $(i + 1)^{th}$ compartment of the jth element.

Intrinsic convection is the result of heat transfer between the tissue compartments and the vascular system. The heat transfer between skin and environment depends on the micro or macro environments. The mechanism for this mode of heat transfer may include extrinsic convection, radiation, latent heat transfer (evaporation of sweat), heat transfer to the undergarment, heat transfer to the liquid-cooled garment and respiratory heat transfer. These modes of heat transfer are described in detail in [5].

Four active controllers are included in the METMAN model. These are sweat production, shivering, vasodilation and vascodilation. They play an important role in maintaining the body in an isothermal state. The relations used to describe the human thermoregulatory system are based on experimental results.
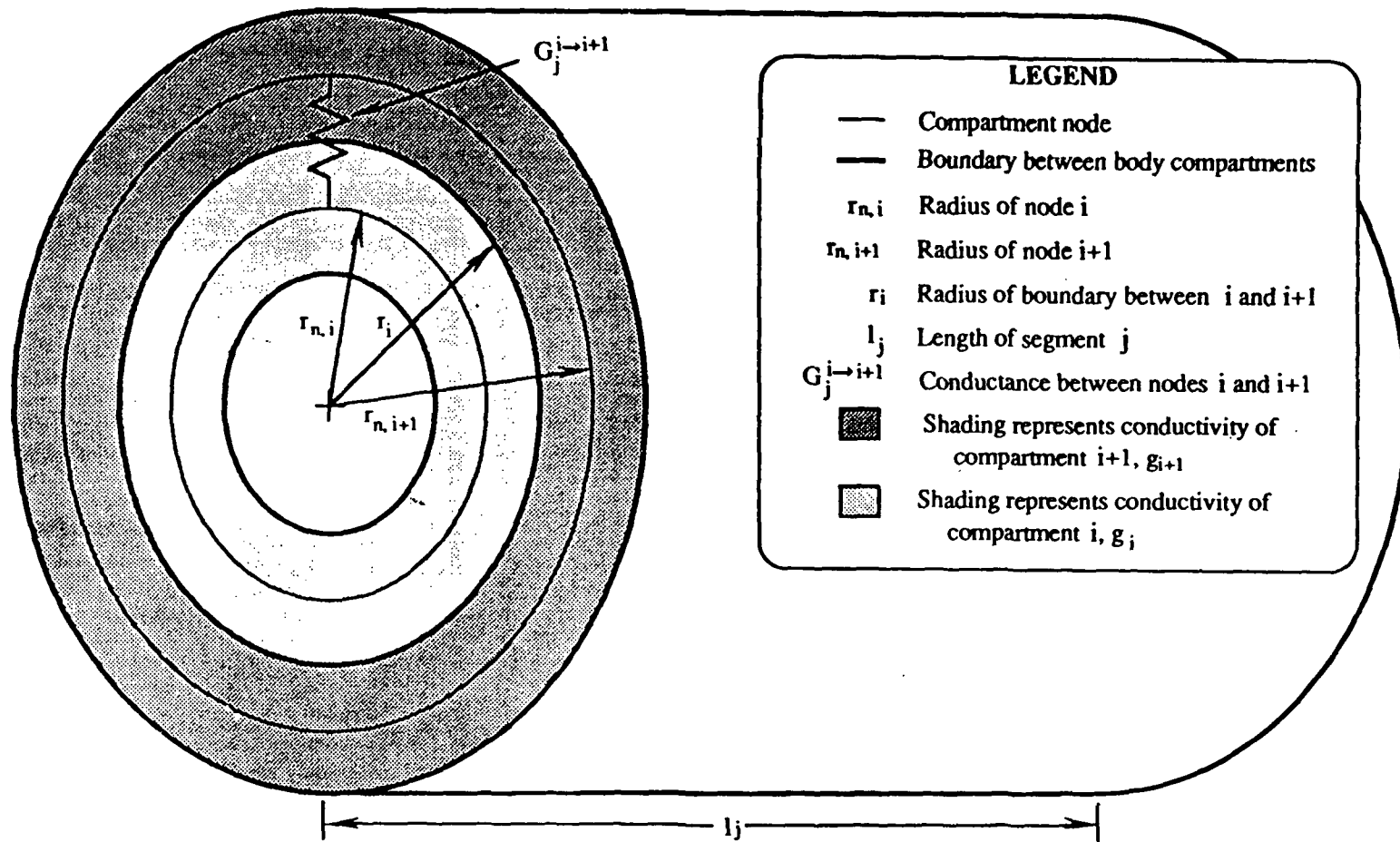
Figure 3. Radial Conductance Between Two Body Compartments

In various mode of operations METMAN compares the effect of natural convection with forced convection and chooses the greater value for convective heat transfer. The forced convection is presented by:

$$q_{senc} = 0.212 \, (P_{cab} \, V_{cab})^{1/2} \, \kappa_1 \, A_c \, (T_{ug} - T_{cab}) \qquad (7)$$

and the free convection is given as:

$$q_{senc} = 0.06 \, [\, G \, (P_{cab})^2 \, | \, T_{ug} - T_{cab} \, | \,]^{1/4} \, \kappa_2 \, A_c \, (T_{ug} - T_{cab}) \qquad (8)$$

However relation are available for combined effects of free and forced convection. The following relationship is used to establish the dominant regions of free and forced convection.

$$\frac{Gr}{Re^2} = \frac{g \, \beta \, (T_w - T_\infty) \, L}{U_o^2} \qquad (9)$$

When the LHS of Eq. 9 >> 1 then the free convection dominates. If the LHS of Eq. 9 << 1, then forced convection dominates. in all other cases forced and free convections are of comparable magnitude. References [15-23] describe the combined free and forced convections for various geometric configurations.

In general heat transfer between the skin and environment depends on the mode of operation. The METMAN model can be applied to various modes of operation. This includes the shirt-sleeve model which emulates a man in a cabin, or in any environment, wearing an undergarment, as well as the suited mode which describes a man in a space suit. The space suit model itself can be applied to several modes of operation. The EVA suited mode is used to model extravehicular activity. The IVA model is used to identify intravehicular activity. METMAN is also capable of modeling the suited modes of operation for both the helmet off and the purge flow activity.

The METMAN program utilizes a number of subroutines and functions which are generally used to determine physical parameters and thermophysical properties. Among these subroutines are Function DEWPT and Function VVP. Function DEWPT evaluates the saturation temperature for a given vapor pressure. Function VPP determines saturated vapor pressure for a given temperature. Both functions are based on old relations in which three separate equations are used to describe the vapor pressure curve. Each equation is valid only within a limited range of temperature and pressure. In addition, the equation used by METMAN for the evaluation of dewpoint at very low pressures ($0.0 < P < 0.0185$ Psia) is highly inaccurate.

There are modern equations of state and fundamental equations [23-27] available now that describe a wide range of thermodynamic regions with a single relation. The fundamental equation developed by Haar et. al [27] is the most recent and accurate relation for thermodynamic properties of water. A FORTRAN computer code is included in [14] for the evaluation of the thermodynamic properties of water. Inclusion of this computer code will enhance the METMAN model.

There are many parameters that should be considered in selection and design of a thermal control subsystem for the EMU. These include the size and the weight of the subsystem, thermophysical and thermal transport properties, and operational safety during an EVA mission. For example, the selection of a heat sink medium should not be based solely on the total heat capacity of the heat sink material, but should also consider the size of equipment required for the freezing and melting processes.

We must identify a heat sink concept that will minimize the size and the weight of the thermal control subsystem required for the EMU. To achieve this goal we must to re-examine and extend the existing alternative technologies for the heat sink medium. This includes a feasibility study of:

- o phase change materials with a suitable melting-freezing temperature
- o heat pipe technologies
- o eutectic binary solutions
- o thermoelectric technologies
- o heat of solution of mixtures
- o endothermic and exothermic heat of chemical reactions

CONCLUSIONS AND RECOMMENDATIONS

The METMAN thermal model in its present form is adequate to describe the heat transfer phenomena in a warm subject. However, there are deficiencies present in the current model. Following is a summary of the shortcomings of the present model and recommendations for improvement.

1. The distribution coefficients used by METMAN to evaluate the heat generation in the muscle compartments are unreasonable for space application. These coefficients should be adjusted for EVA missions in the microgravity environment. Further physiological study is recommended in this area.

2. The METMAN model can be further improved by including appropriate boundary conditions along the central axis of each cylindrical element and along the interface of two adjacent compartments. These boundary conditions are presented in Equations (4-6) in the text.

3. The present equations used by METMAN for the evaluation of dewpoint temperatures and water vapor pressures are inaccurate. We recommend that the FORTRAN computer code given in [14] for the evaluation of the thermodynamic properties of water be incorporated into the METMAN model.

4. Addition of external nodal points for the evaluation of temperatures and the amount of sweat accumulation will enhance the METMAN model

5. The heat transfer formulation of METMAN is based on old knowledge. We recommend that METMAN be revised to include advances in heat transfer research.

A conceptual investigation in desired to determine alternative heat sink for the EMU.

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