Analytic Model for Assessing the Thermal Performance of Scuba Divers

Leslie D. Montgomery*
NASA Ames Research Center, Moffett Field, Calif.

An analytic model is developed to simulate the thermoregulatory system in man under immersed conditions. The biothermal model is divided into two distinct subsystems: the physical-controlled system and the dynamic-controlling system. Two types of experimental data are used to substantiate the analytic model: neck immersed, seminude subjects in cool to temperate water, and neck-immersed "wet-suited" subjects in cold water. These types of data encompass a wide range of water temperatures, protective clothing, breathing gas mixtures, and durations of immersion. From the Law of Propagation of Errors,† influence coefficients are developed for 16 major parameters and initial conditions that may be used to enhance man's performance in cold water. A standard set of parameter values and initial conditions is used in the sensitivity analysis so that each case investigated has a common basis for comparison. Influence equations are derived that may be used to predict body temperatures for various dive conditions represented by small variations in the standard set of parameters and to assess proposed life-support system designs.

Nomenclature

$ATAIR$	= ambient water temperature
AV	= ambient relative water velocity
$AWORK$	= work load of diver
$BF(N)$	= total effective blood flow to compartment N
BM	= basal metabolic rate
BP	= dive depth
C	= heat capacity of body
$CHILM(I)$	= total shivering heat generation in muscles of segment I
E_r	= respiratory heat exchange
H_a	= convective heat loss
H_c	= conductive heat loss
H_e	= evaporative heat loss
H_r	= infrared radiation from the body
$HO(I)$	= water/wet suit surface heat transfer for segment I
$HSS(I)$	= thermal conductance between skin and wet suit of segment I
HT	= height of diver
$K(3)$	= thermal conductivity of wet suit material
M	= metabolic heat production
$QB(N)$	= basal metabolism of compartment N
QWS	= external heat input to wet suit
$RHEAT$	= respiratory heat generation
RHL	= respiratory evaporative heat loss
$SBFD$	= local skin blood flow factor
T	= temperature
t	= time
$T_{BACK}{}^{-A}$	= analytical back skin temperature
$T_{BACK}{}^{-E}$	= experimental back skin temperature
T_{FIN}	= finger skin temperature
$T_{FIN}{}^{-A}$	= analytical finger skin temperature
$T_{FIN}{}^{-E}$	= experimental finger skin temperature
T_{FINI}	= initial finger temperature
T_{REC}	= rectal temperature
$T_{REC}{}^{-A}$	= analytical rectal temperature
$T_{REC}{}^{-E}$	= experimental rectal temperature
T_{RECI}	= initial rectal temperature
T_{TOE}	= toe skin temperature
$T_{TOE}{}^{-A}$	= analytical toe skin temperature
$T_{TOE}{}^{-E}$	= experimental toe skin temperature
T_{TOEI}	= initial toe temperature
T_{TR}	= trunk skin temperature
T_{TRI}	= initial trunk temperature
TB	= breathing gas temperature
$TC(N)$	= thermal conductance between compartment N and $N+1$
$THWS$	= thickness of wet suit
$WORKM(I)$	= work done by muscles in segment I
WT	= weight of diver

I. Introduction

AS man increases his exploration of the oceans, he will find it necessary to dive to greater depths for longer periods of time. A major limiting factor of the diver's performance in cold water is the lack of adequate thermal protection. The life-support system of the diver must provide the thermal protection he needs during all combinations of diver activity, dive depth and duration, and ambient water temperature. Before protective clothing is designed, a method must first be developed to assess the body thermal state during various dive conditions.

The object of this study was to develop a mathematical model of man's thermoregulatory system which may be used to predict body thermal response under immersed conditions.

Under ordinary conditions, the thermal balance of man in air is described by

$$M - CdT/dt = \pm H_a - H_e \pm H_c \pm E_R \pm H_r \tag{1}$$

where $T \triangleq$ temperature, $t \triangleq$ time, $M \triangleq$ metabolic heat production, $C \triangleq$ body heat capacity, $H_r \triangleq$ infrared radiation, $H_a \triangleq$ convective heat loss, $H_e \triangleq$ evaporative heat loss, both insensible and sweating, $H_c \triangleq$ conductive heat loss, and $E_r \triangleq$ respiratory heat exchange. For the diver, H_r, H_a, and H_e can be eliminated from Eq. (1) since there are essentially no heat losses due to radiation, pure convection, or evaporation from the body in water.[1-3]

The basic thermal balance for man under water then becomes

$$M - CdT/dt = H_c + E_r \tag{2}$$

where the heat-loss mechanisms are simply 1) respiratory evaporation and 2) heat transfer through the shell of the

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*National Research Council Associate, Environmental Control Research Branch. Member AIAA.

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†The Law of Propagation of Errors may be simply stated: for small finite increments about a particular reference case, changes in a dependent parameter is a linear sum of the products of the changes in each of the independent parameters and the derivative of the function with respect to the given parameter at the reference point.

body to the ambient water. Respiratory, evaporative heat loss E_r is limited to the amount lost by evaporation from the lungs plus the heat required to warm the inspired air to body temperature, and the heat required to increase the water-vapor content of the air toward 100%. E_r is greatly affected by changes in gas composition, density, and temperature, all of which can occur in the life-support systems of divers.

The rate of conductive-convection loss from the body (H_c) is proportional to the temperature gradient between the skin and the surrounding water and is expressed mathematically for a given body segment as

$$H_c = h_c A_s (T_s - T_w)$$

where $H_c \triangleq$ heat flux, $h_c \triangleq$ body segment—water heat-transfer coefficient, $A_s \triangleq$ body segment surface area, $T_s \triangleq$ body segment surface temperature, and $T_w \triangleq$ ambient water temperature. This heat loss is controlled by the insulative value of the body shell, the rate at which heat is conducted to the skin via the underlying vascular system, the presence of protective clothing, and the thermal and physical characteristics of the environment.

The body surface, heat-transfer coefficient, h_c, depends on the geometrical shape of the body segment; the ambient temperature and pressure; the viscosity, thermal conductivity, heat capacity, and density of the surrounding water; and the water velocity relative to the body segment.

The metabolic heat production, M, is affected not only by the swimming and working effort of the diver, but at large depths, increased heat production results from the work of breathing because of the increased density and viscosity of the inspired gas. Thus, a term must be added for respiratory heat production, Q_r. Also, since heated garments for divers are becoming fashionable, the inclusion of a term (Q_s) that enables the addition of artificial heat to the diver's skin is beneficial.

The complete thermal balance for the man under water then becomes

$$Q_r + E_r + \sum_{i=1}^{n\text{-body segments}} \left(M_i + Q_{s_i} - C_i \frac{dT_i}{dt} - H_{c_i} \right) = 0$$

II. Critical Body Regions Affected by Cold-Water Thermal Stress

The temperatures of certain critical portions of the human body will limit the performance of the diver in cold water. Several studies[3-6] have shown that these critical regions are the head and the extremities of the body, i.e., hands and feet. Because of the limited vasomotor constriction in the skin of the head, a large amount of thermal energy may be lost from this body region upon exposure to cold. This will strongly influence the thermal state of the body. The skin temperatures of the hands and feet are important as they have been shown to be the limiting factors that determine the psychomotor performance of a diver.

Thus, it may be concluded that any model of the body heat transfer under diving conditions must be capable of predicting temperatures of the extremities and head skin to be of any practical use.

III. Mathematical Model

Introduction

Figure 1 is a simplified block diagram of the thermoregulatory system to be modeled. The system may be divided into two distinct subsystems: the physical-controlled system and the dynamic-controlling system. The controlled system consists of the physical portions of the body and the interacting thermal exchange patterns (solid lines in the figure). The positions of influence for all terms in the heat balance equation for the body on the controlled system are illustrated in Fig. 1.

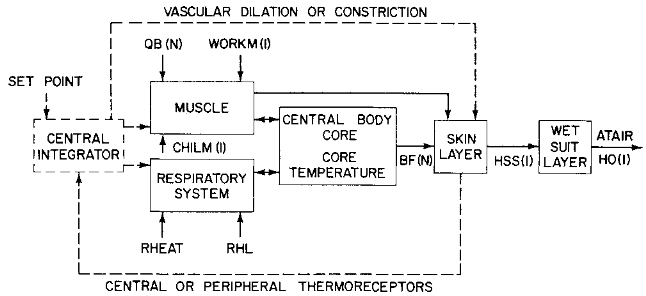

Fig. 1 Simplified block diagram of human thermoregulatory system during immersion.

The controlling system contains the central hypothalamic thermointegrator, the central set point temperature, and signal pathways (dashed lines in the figure). The controlling system receives afferent signals from all portions of the body, integrates the received signals, compares the result to the central set point, and distributes the appropriate effector command signals to all portions of the body.

The analytic model is adapted from an earlier mathematical model of the physiological temperature regulation in man[7-9] developed to represent a nude man in air.

The controlled system in the analytic model is simulated by the SIZE program. The controlling system is modeled by the WETMAN computer program. The SIZE program is used to develop the basic thermal network with initial conditions and input parameters. The WETMAN program uses the output of the SIZE program to determine the thermal response of the diver to a given environment.

Description of SIZE Computer Program

The thermal model simulated by the SIZE program consists of the head which is considered to be a sphere and cylinders that represent the trunk, arms, hands, legs, and feet. Both arms, hands, legs, and feet are represented by one cylinder each. Each body segment is composed of 11 concentric layers—four representing the body core, four representing the muscle layer, and one each representing the body layers of fat and skin, and one representing the outer wet-suit layer. A central blood compartment simulates the central blood pool of the body and exchanges heat with all other body compartments via the convective heat transfer through simulated blood flow to each body compartment. Each of the 61 body compartments is represented by a thermal balance equation that accounts for internal heat generation, conductive heat transfer between adjacent compartments, and convective heat exchange with the central blood compartment. Where applicable, respiratory heat generation and heat loss are included in the body compartment, heat-transfer equations. Additional heat balances represent the six wet-suit compartments which include the effects of conductive heat transfer with the body skin layers and conductive-convection with the ambient water. Each of the 67 heat balance equations includes the thermal capacitance of the compartment that enables the transient response of the compartment to be simulated.

Figure 2, a schematic diagram of a typical body segment, shows the interrelations between the 11 concentric layers. Each compartment represents a lumped thermal capacitance with appropriate modes of heat production and heat transfer to other compartments. Each body layer generates metabolic heat at a basal level and exchanges

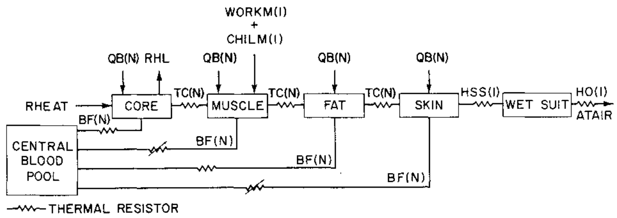

Fig. 2 Block diagram of the controlled system for one segment. *BF(N)* to muscle is dependent upon work load and shivering. *BF(N)* to skin is dependent upon vascular response. Core and muscle compartments are each representative of four compartments in analytic model.

convective heat with the central blood pool. The 11 compartments of each segment exchange heat via conductive transfer with adjacent compartments as a function of layer geometry and tissue thermal conductivity. Each wet-suit segment exchanges heat with the environment as a function of wet-suit properties and ambient water conditions.

Description of WETMAN Program Computer Program

The Stolwijk biothermal model[10] was chosen to form the basis of the WETMAN program because it is a digital simulation of man's complete thermoregulatory system and is capable of predicting the temperatures of the extremities and head skin. A complete description of the simulation of the physical portions of the body may be obtained from Refs. 7–10.

The core and muscle portions of each segment in the WETMAN program were divided into four compartments, each having ¼ of the core or muscle mass of the given segment. An additional compartment was also provided to represent the wet suit covering each body segment. The water/wet-suit surface, heat-transfer coefficient for each body segment in the WETMAN program depends on the geometrical shape of the segment, the ambient temperature and pressure, and the thermophysical properties of the surrounding water.

The equation used by Stolwijk[10] to calculate the ventilatory evaporative heat loss was felt to be inadequate for use in the WETMAN program under immersed conditions. The quantity of heat lost from the respiratory tract in the WETMAN program is calculated as a function of the physical properties of the gas mixture breathed and

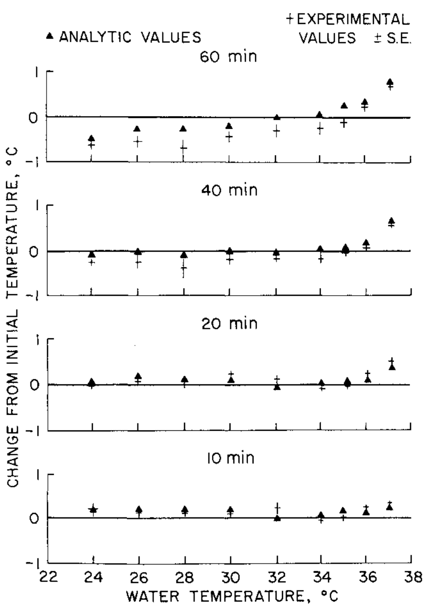

Fig. 3 Changes in ear temperature from initial temperature at times indicated vs. water temperature.[11] Neck immersed, seminude, rest.

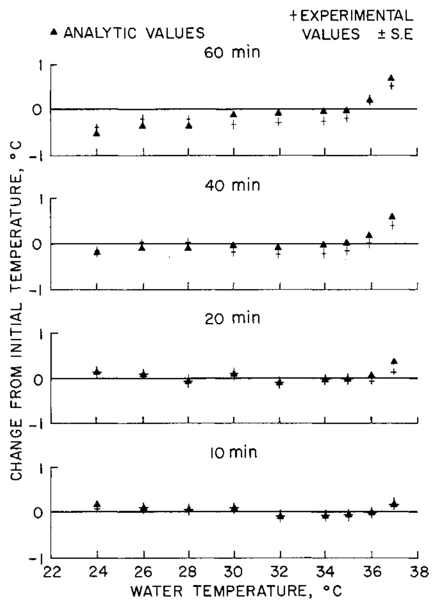

Fig. 4 Changes in rectal temperature from initial temperature at times indicated vs. water temperature.[11] Neck immersed, seminude, rest.

the dynamic characteristics of the respiratory system. The respiratory heat loss is proportional to the respiratory minute volume which is, in turn, a function of the amount of oxygen required to provide energy for metabolic needs during rest and exercise.

IV. Substantiation of the Analytic Model

Experimental Data Used to Substantiate the Model

Two types of experimental data were used to substantiate the analytic model that simulates the thermoregulatory system of man under immersed conditions.

Type I: neck immersed, seminude subjects in cool to temperate water.

Type II: neck immersed, wet-suited subjects in cold water.

These types of data encompass a wide range of water temperatures, protective clothing, breathing gas mixtures, and durations of immersion.

Neck Immersed, Seminude Subjects in Cold to Temperate Water

A head-out immersion study[11] using subjects clothed in light swim trunks was used to check the physiologic response mechanisms incorporated into the biothermal model.

This experiment was conducted with the subjects completely at rest. Ten subjects were immersed for 1 hr in each of nine different water temperatures ranging from 24° to 37°C. During the tests, the room temperature varied from 25° to 28°C. During immersion, rectal, external auditory canal, middle finger, and chest wall temperatures were measured.

The average temperatures of all 10 subjects were given for each body segment and water-bath temperature as a function of time. These temperature vs time values form the basis for comparison between the experimental results and the analytic calculations made to simulate the given test conditions. The extensive physical and physiologic data that represent the average values for the experimental group were used as the initial conditions and input parameters for the analytic model.

A detailed comparison between the experimental and analytic results for resting subjects is presented in Figs.

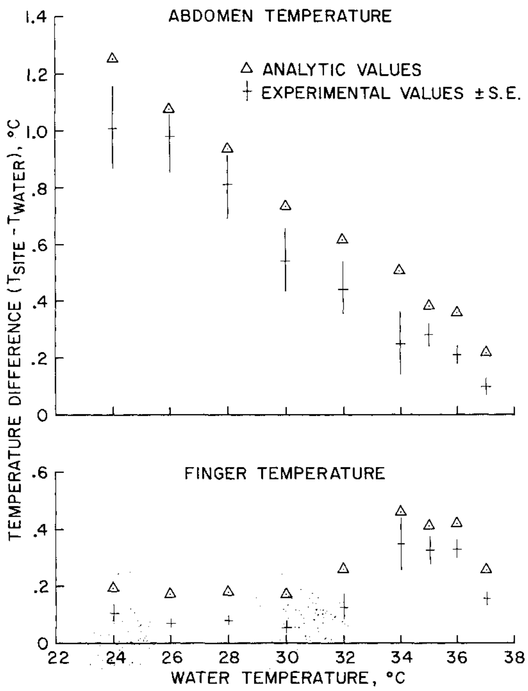

Fig. 5 Temperature difference between skin site and ambient water.[11] Neck immersed, seminude, rest.

3-5. Figures 3 and 4 show the changes in ear and rectal temperatures, respectively, during the times indicated as functions of water temperature. The experimental values in Figs. 3 and 4 are shown as the horizontal bars at the specified times. Vertical bars indicate the plus and minus sample error for each experimental value. The calculated temperatures are shown as ▲-points in Figs. 3 and 4.

Figure 5 presents the average difference in the temperature of the covered abdominal and finger skin sites from the water temperature during the last 40 min of immersion. The horizontal bars indicate the experimental temperature at each water temperature. As in Figs. 3 and 4, vertical bars show the sample error limits and the analytic values are given as △-points.

In Figs. 3 and 4, the calculated ear and rectal temperatures agree well with the measured values for all water temperatures during the first 20 min of immersion. During the last 40 min of immersion, the difference between measured and calculated temperatures tends to increase. The maximum difference between calculated and experimental ear or rectal temperatures occurs for the ear after 60 min of immersion in 28°C water. This difference is ~0.40°C. All other calculated ear and rectal temperatures are within ~0.35°C of the corresponding experimental values. In general, the over-all agreement is better for the rectal temperatures than for the ear temperatures. The maximum difference between a calculated and a measured rectal temperature is 0.20°C, which occurs after 60 min of immersion in 32°C water.

The average calculated finger temperature during the last 40 min of immersion at each water temperature is within approximately 0.1°C of the corresponding average experimental value. The maximum difference between the average calculated abdominal temperatures and the experimental values is less than 0.3°C (as shown in Fig. 5).

Neck Immersed, Wet-Suited Subjects in Cold Water

The second type of experiment[12] established the average tolerance times of a large number of subjects clothed in 3⁄16-inch wet suits. These subjects were immersed to neckline level in ambient water temperatures of 4.44°, 10.0°, and 15.56°C. The tolerance times for these water

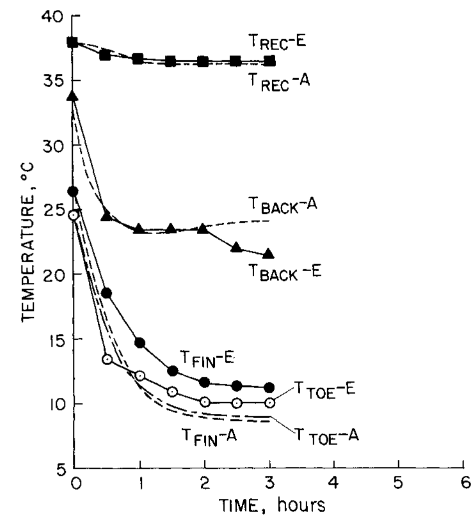

Fig. 6 Temperature vs time.[12] Conditions: neck immersed, 3⁄16-inch wet suit, rest; water temperature, 4.44°C.

temperatures ranged from 2.5 hr for the 4.44°C water to 6 hr for the 15.56°C water. Rectal temperature and 16 skin temperatures were measured.

The average rectal, midline back, left great toe, and left index finger temperature vs time values given for this experiment were used in comparing the analytic results to the experimental results for the given test conditions. Temperature vs time results of the three series of tests are given in Figs. 6-8.

Ten subjects demonstrated an average tolerance time of 2½ hr when immersed to neckline level in 4.44°C water. The average rectal, back, finger, and toe temperatures are given as solid lines in Fig. 6.

A second group of 10 subjects had an average tolerance time of 4 hr when immersed in 10°C water. The same temperature traces are given for this series of experiments in Fig. 7. Four subjects were immersed in 15.56°C water for 6 hr. This series of experiments was terminated after 6 hr because skin temperatures stabilized at the end of the fourth hour and rectal temperatures stabilized at the end of the fourth hour; rectal temperatures were nearly constant after 3 hr. The average results of this series of experiments are given in Fig. 8.

The broken lines in Figs. 6-8 illustrate the calculated results from the analytic model made to simulate the various test conditions. In all three water bath temperatures, the calculated trunk skin and rectal temperatures closely approximate the measured values. The theoretical finger

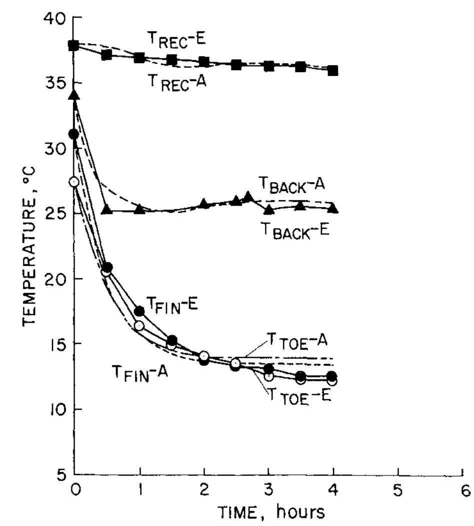

Fig. 7 Temperature vs time.[12] Conditions: neck immersed, 1⁄16-inch wet suit, rest; water temperature, 10.0°C.

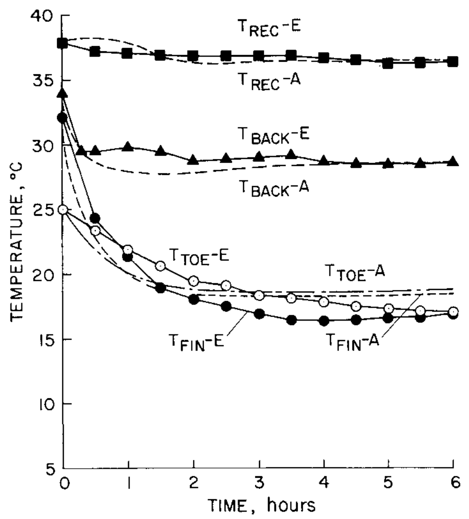

Fig. 8 Temperature vs time.[12] Conditions: neck immersed, 3/16-inch wet suit, rest; water temperature, 15.56°C.

and toe temperatures agree well with the experimental temperatures in all three test situations.

V. Sensitivity Study

Outline and Method

The specific objectives of the sensitivity analysis are: 1) To determine the change in the resulting analytic temperatures due to a perturbation in any given input. 2) To identify and tabulate those parameters that most strongly influence the analytic solutions. 3) To calculate the composite range of deviation in the selected position temperatures due to the range of deviation in each input. 4) With the results achieved from objectives 2 and 3, to determine

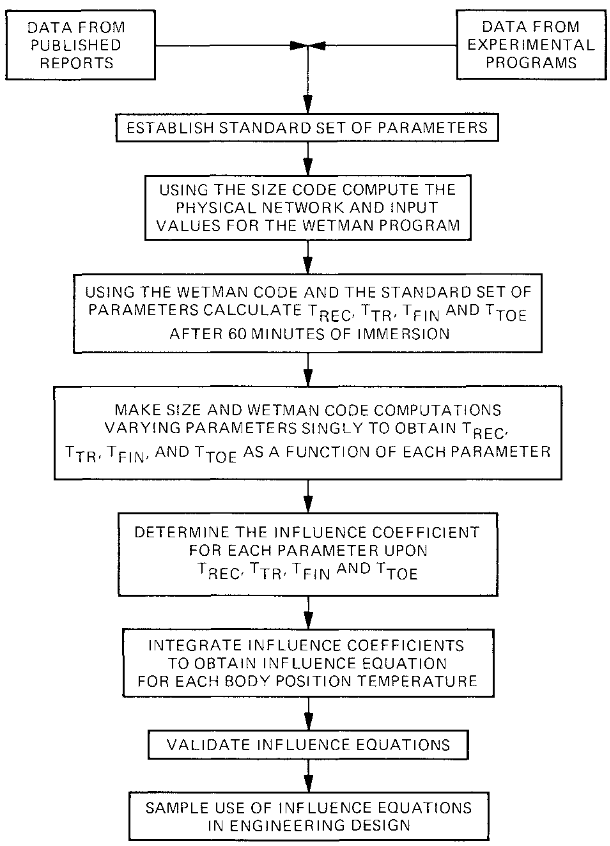

Fig. 9 Flow diagram of sensitivity study.

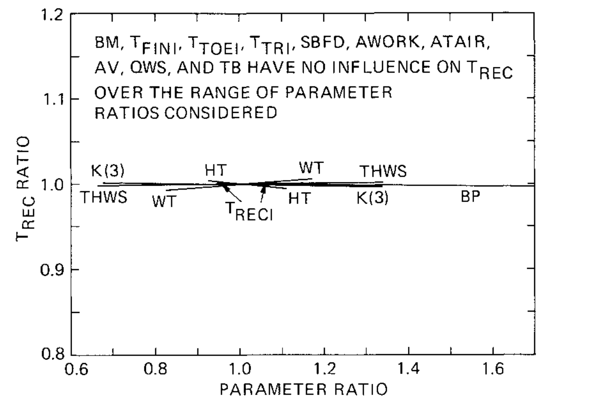

Fig. 10 Influence coefficients of those parameters that determine rectal temperature.

engineering design criteria or physiologic factors that may be used to enhance man's capability under water.

Figure 9 is a flow chart of the over-all sensitivity study. The focal point of the study is the derivation of parameter influence coefficients and the subsequent determination of design criteria, although the objectives listed above are also of interest. The results of this sensitivity study will be used to illustrate various techniques that may be used to lengthen the functional time of a diver in cold water.

The format of this sensitivity study and the derivation of an over-all influence equation that incorporates the effects of all the parameters investigated are based on a previous study by Barsell et al.[13] which uses the Law of Propagation of Errors.[14]

For this process, consider

$$F_{BPT} \triangleq f[BM, HT, WT, T_{FINI}, T_{TOEI}, T_{RECI}, T_{TRI}, SBFD, AWORK, ATAIR, AV, THWS, K(3), QWS, BP, TB] \quad (4)$$

to be the functional relation between a selected body position temperature F_{BPT} and the parameters upon which the calculated value of F_{BPT} depends.

If it is assumed that f can be expanded in a Taylor's series and if products of errors are neglected in comparison with the errors themselves, its differential is

$$dF_{BPT} = (\partial F_{BPT}/\partial BM)dBM + (\partial F_{BPT}/\partial HT)dHT + (\partial F_{BPT}/\partial WT)dWT + \ldots \quad (5)$$

where $\partial F_{BPT}/\partial BM$, etc., are the differentials of $T_{BPT} = f$.

Table 1 Standard set of parameters used in the sensitivity study

Parameters used in the SIZE program
Wet suit thickness, $THWS$ = 0.00474 m
Wet suit thermal conductivity, $K(3)$ = 0.046 kcal/m-hr°C
Diver height, HT = 172 cm
Diver weight, WT = 74400 gm
Diver basal metabolic rate, BM = 39.4 kcal/m²-hr
Parameters used in the WETMAN program
Ambient water temperature, $ATAIR$ = 5°C
Relative water velocity, AV = 122 m/hr
Total metabolic power due to external work, $AWORK$ = 0.0($REST$)
Initial rectal temperature, T_{RECI} = 37.7°C
Initial trunk skin temperature, T_{TRI} = 34°C
Initial finger skin temperature, T_{FINI} = 34.5°C
Initial toe skin temperature, T_{TOEI} = 32.8°C
Halving and doubling temperature for skin blood flow, $SBFD$ = 6.0°C
Temperature of inspired gas, TB = 5.0°C
Barometric pressure due to depth, BP = 1 atm
External heat input to wet suit, QWS = 0.0 kcal/m²-hr

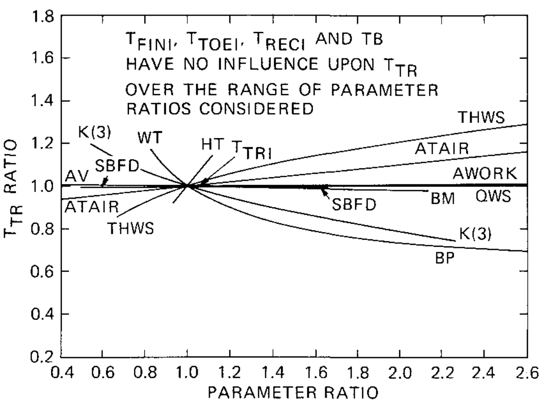

Fig. 11 **Influence coefficients of those parameters that determine trunk skin temperature.**

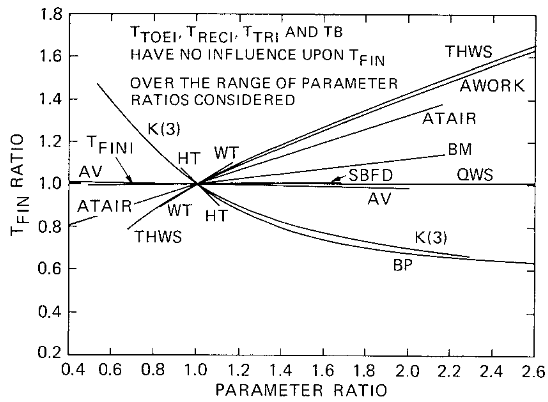

Fig. 12 **Influence coefficients of those parameters that determine finger skin temperature.**

In Eqs. (4) and (5), $\partial F_{BPT}/\partial BM$, $\partial F_{BPT}/\partial HT$, $\partial F_{BPT}/\partial WT$, etc., are the influence coefficients for the given parameters.

For each parameter listed in Table 1, several computer runs were made in which the given parameter was varied over a range of probable values, with all other initial parameter values remaining the same as in the standard case. After a 60-min simulated dive using the standard set of parameters, $T_{REC} = 36.10°C$, $T_{TR} = 21.97°C$, $T_{FIN} = 11.90°C$, and $T_{TOE} = 12.22°C$. These four temperatures form the basis for comparing the various computer runs made during the sensitivity analysis.

From the results of the various computer runs in which the parameters were varied singly, it was possible to obtain each of the four body position temperatures at the end of the 60-min simulated dive as a function of the individual parameters, i.e., $T_{FIN} = f$ (given parameter).

1) Basic physiologic variables; basal metabolic rate *BM*, diver height *HT*, diver weight *WT*, initial finger T_{FINI}, toe T_{TOEI}, rectal T_{RECI}, and trunk T_{TRI}, temperatures and local skin blood flow denominator *SBFD*.

2) Variation of workload, *AWORK*.

3) Variation of ambient water conditions; temperature, ATAIR, and relative velocity *AV*.

4) Variation of wet-suit parameters; thickness *THWS*, thermal conductivity *K*(3), and external heat input *QWS*.

5) Variation of dive conditions; depth *BP*, breathing gas temperature *TB*, and breathing gas composition.

To maintain consistency in Eq. (5), ratios or factors were used for all properties and the calculated values of T_{REC}, T_{TR}, T_{FIN}, and T_{TOE}. The factor for a given parameter is defined as

$$F_{(\text{given parameter})} = \frac{\Delta \text{ given value of parameter for each case}}{\text{standard parameter value}}$$

In terms of parameter ratios, $F_{BPT} = f$ (given parameter). The latter equation is then differentiated with respect to the parameter ratio in question to obtain the influence coefficients to be substituted in Eq. (5).

Figures 10–13 show $F_{T(REC)}$, $F_{T(TR)}$, $F_{T(FIN)}$, and $F_{T(TOE)}$, respectively, as functions of the ratio of each parameter investigated to its corresponding standard value. Equation (5), in terms of the parameter ratios, was then integrated from F_{standard} to the F value of the parameter in question for each of the four body positions to obtain the general influence equation for all parameters. The influence coefficient equations for $F_{T(REC)}$ and $F_{T(TR)}$, after integration, are shown in Tables 2 and 3. Similarly, the influence of all parameters on $F_{I(FIN)}$ and $F_{T(TOE)}$ are shown in Tables 4 and 5.

Table 2 Influence coefficient equation for the rectal temperature factor, $F_{T_{REC}}$ after integration

Term in the equation	Corresponding parameter
$F_{T_{REC}} - 1.0 = -0.129925\ (F_{HT} - 1.0)$	*HT*
$+0.032764\ (F_{WT} - 1.0)$	*WT*
$-0.0307547\ (F_{T_{RECI}} - 1.0)$	T_{RECI}
$+0.00245756\ (F_{THWS} - 1.0)$	*THWS*
$-0.00259094\ (F_{K(3)} - 1.0)$	*K*(3)
$+0.999862\ (F_{BP}{}^{-0.00414874} - 1.0)$	*BP*

Table 3 Influence coefficient equation for trunk skin temperature factor, $F_{T_{TR}}$, after integration

Term in the equation	Corresponding parameter
$F_{T_{TR}} - 1.0 = -0.0144796\ (F_{BM} - 1.0)$	*BM*
$+1.67256\ (F_{HT} - 1.0)$	*HT*
$+1.02038\ (F_{WT}{}^{-0.676704} - 1.0)$	*WT*
$+0.00802469\ (F_{T_{TRI}} - 1.0)$	T_{TRI}
$+0.00415122\ (F_{SBFD} - 1.0)$	*SBFD*
$+0.0028718\ (F_{AWORK} - 1.0)$	*AWORK*
$+0.103061\ (F_{ATAIR} - 1.0)$	*ATAIR*
$-0.0140484\ (F_{AV} - 1.0)$	*AV*
$+0.993661\ (F_{THWS}{}^{0.283911} - 1.0)$	*THWS*
$+0.987493\ (F_{K(3)}{}^{-0.319919} - 1.0)$	*K*(3)
$+0.0011957\ (F_{QWS} - 1.0)$	*QWS*
$+\dfrac{0.70413}{1.69704}\left[\dfrac{1.0}{-0.70413 + 1.69704\ F_{BP}} - \dfrac{1.0}{(-0.70413 + 1.69704)}\right]$	*BP*

Use of Influence Coefficients

To predict a value of body temperature for a given change in one or two parameters, the values of the param-

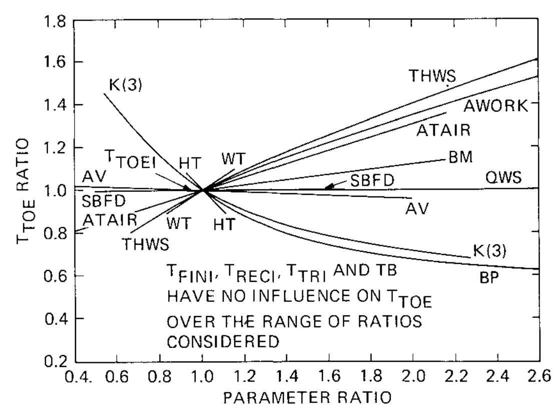

Fig. 13 **Influence coefficients of those parameters that determine toe skin temperature.**

Table 4 Corresponding influence equation for finger skin temperature factor, $F_{T_{FIN}}$, after integration

Term in the equation	Corresponding parameter
$F_{T_{FIN}} - 1.0 = +0.128922\ (F_{BM} - 1.0)$	BM
$-0.980451\ (F_{HT} - 1.0)$	HT
$+0.997641\ (F_{WT}{}^{0.599802} - 1.0)$	WT
$+0.0586308\ (F_{T_{FINI}} - 1.0)$	T_{FINI}
$+0.0123483\ (F_{SBFD} - 1.0)$	$SBFD$
$-\frac{0.636353}{0.363534}\left[\frac{1.0}{0.636353 + 0.363534\ F_{AWORK}} - \frac{1.0}{(0.636353 + 0.363534)}\right]$	$AWORK$
$+0.334429\ (F_{ATAIR} - 1.0)$	$ATAIR$
$-0.0558336\ (F_{AV} - 1.0)$	AV
$+0.992675\ (F_{THWS}{}^{-0.570655} - 1.0)$	$THWS$
$+1.02112\ (F_{K(3)}{}^{-0.570655} - 1.0)$	$K(3)$
$+0.003590\ (F_{QWS} - 1.0)$	QWS
$+\frac{0.910188}{1.91177}\left[\frac{1.0}{-0.910188 + 1.91177\ F_{BP}} - \frac{1.0}{(-0.910188 + 1.91177)}\right]$	BP

eter factors: given parameter value/standard parameter value must be substituted in the corresponding terms in the four general influence equations. All other terms on the right-hand side of each general equation become zero and may be neglected. The four body temperature ratios are then evaluated. The temperature for a given body position for the given case is then obtained by multiplying the standard body temperature by the appropriate temperature factor.

The influence equations derived in this section may be used to predict body temperatures for various dive conditions represented by small variations in the standard set of parameters. They may also be used to illustrate the approximate influence of proposed engineering designs that may alter some of the standard parameter values.

Use of Sensitivity Study in Engineering Design

The results of the sensitivity study have been used to identify those parameters that may be effectively controlled to improve the performance of man under water in cold water. These results have also shown other parameters to be ineffective in preventing rapid cooling of the diver.

Table 5 Influence coefficient equation for toe skin temperature factor, $F_{T_{TOE}}$, after integration

Term in the equation	Corresponding parameter
$F_{T_{TOE}} - 1.0 = 0.126329\ (F_{BM} - 1.0)$	BM
$-1.04962\ (F_{HT} - 1.0)$	HT
$+0.996751\ (F_{WT}{}^{0.619116} - 1.0)$	WT
$+0.060557\ (F_{T_{TOEI}} - 1.0)$	T_{TOEI}
$+0.00599982\ (F_{SBFD} - 1.0)$	$SBFD$
$-\frac{0.558823}{0.441953}\left[\frac{1.0}{0.558823 + 0.441953\ F_{AWORK}} - \frac{1.0}{(0.558823 + 0.441953)}\right]$	$AWORK$
$+0.318469\ (F_{ATAIR} - 1.0)$	$ATAIR$
$-0.100278\ (F_{AV} - 1.0)$	AV
$+0.991123\ (F_{THWS}{}^{0.518205} - 1.0)$	$THWS$
$+1.01591\ (F_{K(3)}{}^{-0.55364} - 1.0)$	$K(3)$
$+0.00343278\ (F_{QWS} - 1.0)$	QWS
$+\frac{0.913327}{1.91396}\left[\frac{1.0}{-0.913327 + 1.91396\ F_{BP}} - \frac{1.0}{(-0.913327 + 1.91396)}\right]$	BP

The parameters investigated may be divided into three groups to be used for the benefit of man. The first group is composed of those parameters that can be controlled by appropriate engineering design; wet-suit thickness, wet-suit thermal conductivity, diver work level, heated wet suits, and warming of the inspired air.

The second parameter group may be described as those physiologic variables that may be altered by the application of proper drugs. It may be possible to increase the basal metabolic rate of a diver, thereby producing more internal energy. Vasoconstrictive drugs may be used to limit the convective thermal loss from the central core to the various skin regions. Conversely, vasodilative drugs may be used to increase thermal transport to the skin regions to help maintain extremity temperatures or to increase skin temperatures before immersion.

The third group consists of parameters such as height and weight that may be controlled by diver selection techniques. Increased body fat provides more effective thermal insulation and therefore tends to conserve internal thermal energy in cold environments.

This study has shown that various body temperatures are relatively insensitive to changes in the second group of parameters. Increased basal metabolism, body temperatures, or altered vasomotor response have little or no effect on rectal and skin temperatures after a 60-min dive in 5°C water. Diver selection has been shown to be a possible means of increasing a diver's duration time in cold water. However, selection may not always be practical and the benefits gained may be small compared to other considerations.

For the above reasons, it is felt that work should be concentrated on developing the improving engineering designs that may decrease a diver's thermal loss to the marine environment. The group of variables open to engineering control has been used to show how the analytic model and influence coefficients may be used to evaluate proposed engineering designs.

The various influence coefficients may be used to determine the approximate rectal and skin temperatures that result from a proposed design altering the standard set of parameters. The analytic model may then be used to determine the transient body response to the proposed design under dive conditions different from those represented by the standard set of parameters.

VI. Conclusion

A biothermal model of the immersed man has been presented and, from the Law of Propagation of Errors, influence coefficients have been derived for 16 parameters that affect the skin and rectal temperatures. These influence coefficients were integrated to obtain four general influence equations for the parameters considered upon rectal and trunk, and finger and toe skin temperatures. It has been demonstrated that these equations may be used to predict rectal and skin temperatures for various dive conditions represented by small parameter changes around the standard set of values.

Those parameters that can be controlled by appropriate engineering design to improve the underwater performance of man in cold water have been identified. Other parameters have been shown to be ineffective in preventing rapid cooling of the diver.

The influence equations and the analytic model may be used to evaluate proposed engineering designs. Any design could be analyzed in detail by use of the various influence coefficients and the analytic model without requiring system construction or human testing. The model may also be used to assess the endurance and performance of a diver in cold water.

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Thermal Protection for Divers

W. W. McCrory*

Naval Coastal Systems Laboratory, Panama City, Fla.

Providing proper heat balance for divers in cold water requires adding distributed heat to an insulated garment. A garment consisting of a heat distribution network, a pump, and an outer dry suit with helmet was developed and evaluated. A modified Apollo cooling garment was used to distribute the heat. A problem area concerns the outer suits, which are dry in their original state but difficult to keep dry and to maintain a practical fit when required modifications are made. Pressure compensation techniques are not adequate in flexible expanded neoprene foam dry suits.

Introduction

CONDUCTIVE and conductive/convective heat exchange from the immersed diver are two processes that cause subnormal body temperatures. Direct conductive heat transfer from the diver's body to the water constitutes the bulk of the loss. However, under certain conditions, conductive/convective heat exchange within the diver's lungs can account for a significant part of the loss. Difference in body and water temperatures, body area exposed to the water, film coefficients, respiration rate, gas density, specific heats, and material conductance provide classic engineering parameters for solving these problems. One must understand what the term "thermal protection" is intended to mean. It should be clear that ideal thermal protection is an ideal thermal insulator; one that would allow an acceptable heat exchange between the diver's body and surrounding water. An acceptable heat exchange is one in which the diver's body temperatures, skin, and deep core, remain in a comfortable range under all conditions, with no subnormal or abnormal physiological readings.

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*Senior Project Engineer, Diving and Salvage Department.

Providing adequate thermal insulation to the diver's body is a difficult task because of the operating environment. Insulation of clothing worn by man in a gaseous atmosphere is provided, to a large extent, by trapped gas. Once in the water, the trapped gas is lost from clothing or the stagnant layer of gas is lost from the unclothed diver's bare skin. Since 32°F water has a thermal conductivity 24.5 times more than air at the same temperature, the immersed diver will lose body heat 24.5 times faster in 32°F water than in 32°F air. Thus, if he is in water, the diver's garments must provide him with thermal insulation that is much more effective than the best available for use in his normal gaseous environment, i.e., in air. A material that can be practically fashioned into a diver's garment and provide adequate thermal insulation is not available. With this stumbling block in the way of providing adequate thermal protection, techniques other than insulation must be employed.

A satisfactory alternate solution is to provide a dry atmosphere with a uniform insulative gas layer and supplemental heat between the diver's body and the surrounding water. The supplemental heat should be sufficient to offset the heat the diver would lose if he had no protection. No attempt should be made to force extra heat into him because his physiological processes will maintain proper body temperature if the supplemental heat balances what he would lose to the water.

Turning to body heat loss from the lungs, the problem is not so severe from an engineering standpoint. The breathing gas must be warmed to slow the conductive/