FOREWORD

This investigation was conducted by Dr. Thomas F. Irvine, Jr., Dean of Engineering, State University of New York, Stony Brook, New York, and Kenneth R. Cramer, Aerospace Research Laboratories, Office of Aerospace Research, Wright-Patterson Air Force Base, Ohio. The work was performed for the 6570th Aerospace Medical Research Laboratories, Aerospace Medical Division, between May 1959 and July 1963 in support of Project No. 6301, "Aerospace Systems Personnel Protection," Task No. 630104, "Space Protective Garments." Robert F. Witte, 1st Lt, USAF, and Mr. J.D. Bowen, Altitude Protection Branch, Physiology Division, Biomedical Laboratory, served as project advisors for the 6570th Aerospace Medical Research Laboratories.

The first phase of this investigation, conducted between May 1959 and November 1959, was reported by Irvine and Cramer in WADD TN 60-145, Thermal Analysis of Space Suits in Orbit, May 1960. The second phase, conducted between November 1959 and April 1961, was reported by Cramer and Irvine in MRL-TDR-62-8, Analysis of Nonuniform Suit Temperatures for Space Suits in Orbit, March 1962. The third phase, conducted between April 1961 and April 1963, was reported by Cramer and Irvine in AMRL-TDR-63-80, Attenuation of Nonuniform Suit Temperatures for Space Suits in Orbit, September 1963.

ABSTRACT

In this study, three thermal problems have been examined which occur in the design of space suits to be used when personnel are outside the parent vehicle. The first concerns the time-temperature variation of an infinite thermal conductivity suit exposed to extreme conditions of heating and cooling. The second is related to temperature differences which may occur from the top to the bottom of the suit, thereby causing physiological discomfort. Finally, the scheme was examined whereby these temperature differences might be ameliorated by circulating a fluid in passages behind the suit material.

PUBLICATION REVIEW

This technical documentary report is approved.

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ANALYSIS OF LIMITING THERMAL CONDITIONS ENCOUNTERED BY A MANNED SPACE SUIT IN ORBIT

by

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and

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INTRODUCTION

One of the difficult problems of protecting a man in space who is free of a shielding vehicle or structure is to preserve him from the adverse thermal environment. Without adequate temperature control, a man would readily freeze when shaded from the sun or burn when exposed to the sun. To provide a satisfactory temperature regimen, the parameters involved in this thermal problem must be defined and investigated. A general analysis of the problem is complicated by the changing types of thermal radiation fields to which he may be exposed and the influence of his orientation with respect to the solar system and with nearby objects.

In addition to his orientation and form, man, by reason of his physiological processes, influences the problem through body heat generation and respiration and perspiration processes. Thus, the number of free parameters in the problem becomes very large, and there is some doubt whether a completely general analysis accounting for all of these factors is feasible.

An approach which appears to offer more immediate progress is to divide the total problem into separate and manageable phases while remaining conscious of the interrelations among the various phases. This report concentrates on three of these phases (refs. 1,2,3).

In the first phase (ref. 1) we analyzed the equilibrium temperature history of a space suit assuming that the thermal conductivity of the suit is infinite and that no temperature control system exists. In the second phase (ref. 2) we analyzed the temperature difference which might be found from the top to the bottom of the space suit assuming a finite thermal conductivity of the suit material. In the third phase (ref. 3), we examined the effect of circulating a liquid coolant and its ability to reduce the top-to-bottom temperature differences calculated in the second phase.

GENERAL ORBIT CONSIDERATIONS

The reasons for the choice of orbits for this study may be illustrated by a brief discussion of the motion of the earth in the solar system. Figure 1 shows the important aspects of the earth's motion around the sun looking down on the ecliptic plane (the plane containing the earth's path around the sun).

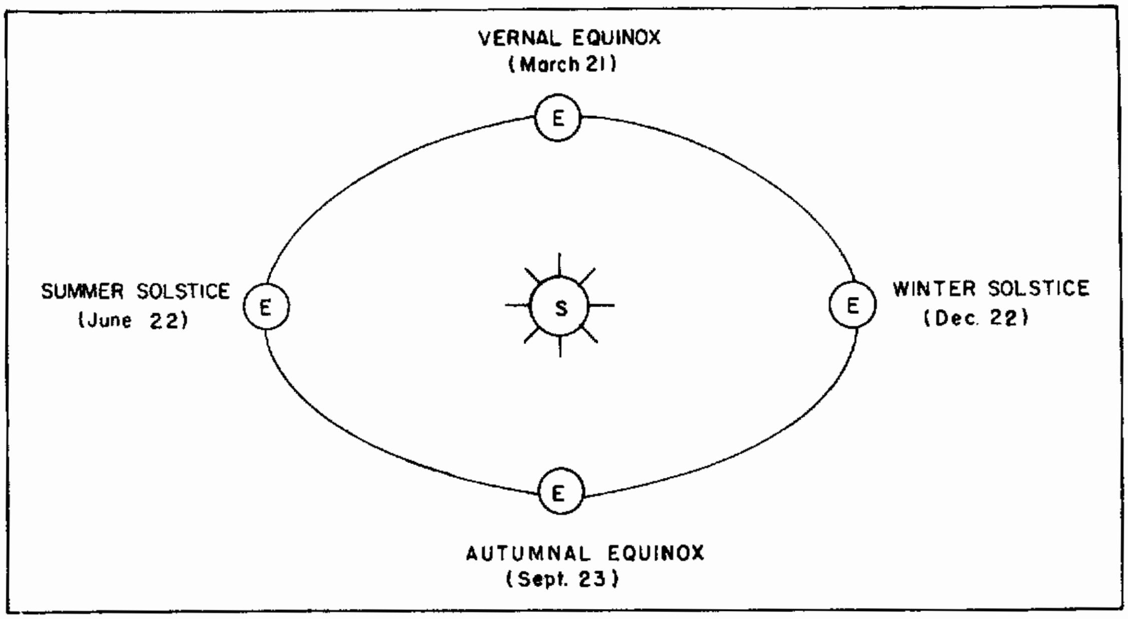

Figure 1. Earth-Sun Relation Looking Normal to Ecliptic Plane

The four important referenced locations of the orbit, the summer and winter solstices and the vernal and autumnal equinoctial points, are also shown in figure 1. Figure 2 is a side view looking parallel to the ecliptic, showing only the solstice points. It is important to note two things about the polar axis of the earth: (a) first, the polar axis is not perpendicular to the ecliptic but is tipped at an angle of about 23 degrees from the perpendicular, and (b) second, the polar axis remains fixed in its orientation in space as the earth travels around the sun. Thus, at the winter solstice the north polar axis points away from the sun and at the summer solstice it points toward the sun.

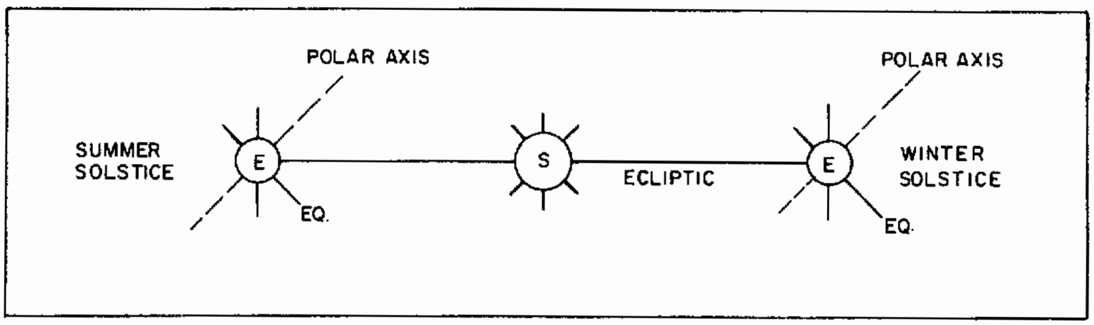

Figure 2. Earth-Sun Relation Looking Parallel to Ecliptic Plane

A close-up view of the earth at winter solstice (figure 3) is useful in our discussion of satellite orbits. If the satellite is moving in an orbit perpendicular to the plane of the paper, then only two numbers are needed to define its location with respect to the solar system. The satellite altitude, h, and the angle, β, between the perpendicular to the ecliptic and the radius vector to the satellite are convenient choices for this problem. For example, if $\beta = \gamma$ and h = H (figure 3), the satellite is traveling in a polar orbit at altitude, H, above the earth's surface.

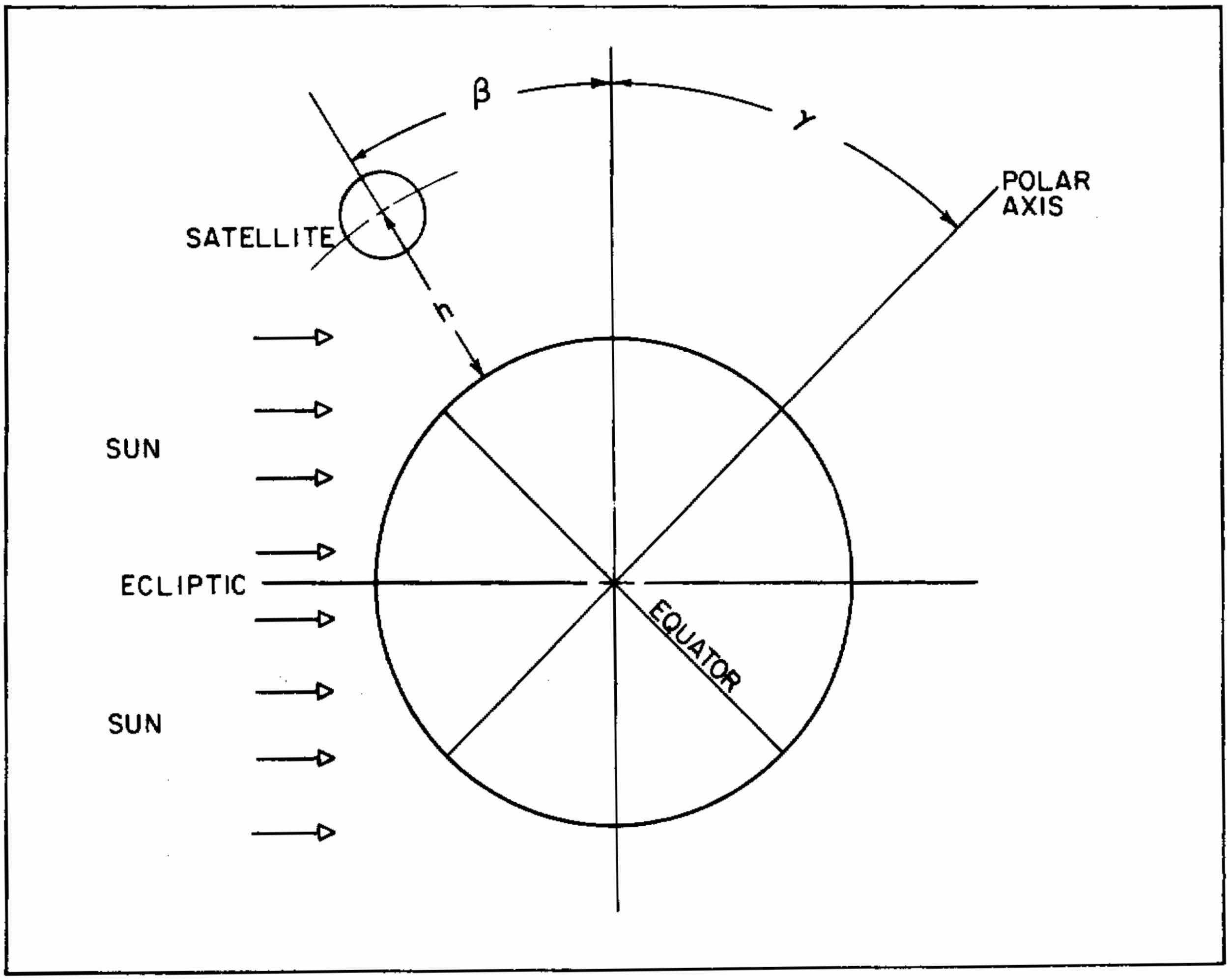

Figure 3. Relation between Polar Axes and Ecliptic Plane

Equilibrium satellite temperatures can be calculated for a wide variety of orbits. However, for our purposes we will examine only the extreme cases to which any design may be subjected: (a) when the satellite is continuously exposed to both the solar and earth's radiation fields ($\beta = 0$) and (b) when the satellite is shielded from the solar field by being in the shadow of the earth. These may be called the "hot" and "cold" cases and will be described in more detail in later sections.

HUMAN GEOMETRY

The orbital space suit in its final evolution may well bear a close resemblance to the general outlines of a man. The choice of the geometry for the purposes of this calculation has an important influence on the complexity of the calculations and the applicability of the final results; i.e., the more nearly manlike the geometry, the more difficult the calculations and the more useful the results. Since the final configuration of the space suit to be worn by a man in orbit is at present unknown, no attempt was made at this time to consider the geometry of a man wearing a space suit with its accompanying life support, stabilization, and locomotion equipment.

Possible geometric choices of space suit configurations have been investigated by Charles Clauser of the Behavioral Sciences Laboratory.* Some of the results of his investigations are shown in figures 4 and 5. These geometric forms are representative of the general size of a 50th percentile (height and weight) nude Air Force male. Total body surface area for such a man would be approximately 21 square feet. An important decision in our investigation was whether to consider geometrics which were singly cylindrical and everywhere plane or convex, such as in figure 5, or to include other geometrics, such as in figure 4, which would allow radiation exchange among various parts. The geometry described in figure 5 was chosen so as not to obscure the consideration of the thermal problem with the additional complicated geometric details of the analysis, if the geometry in figure 4 had been used.

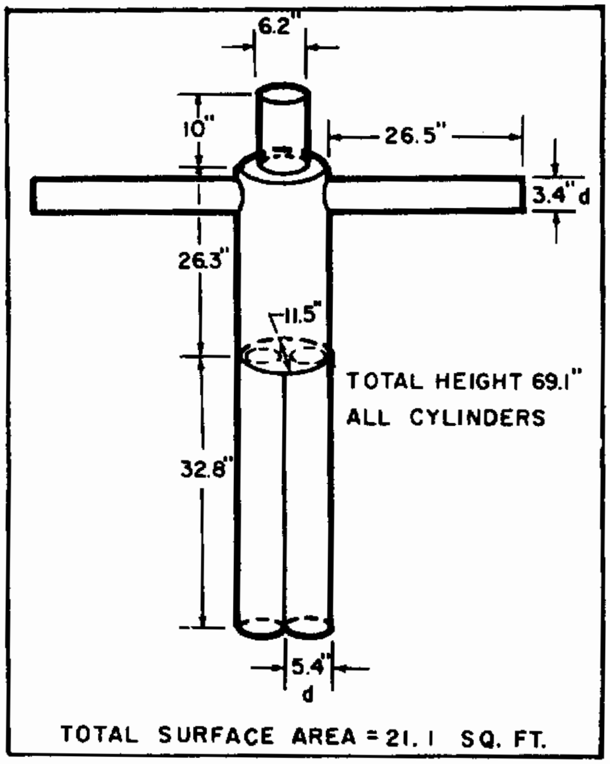

Figure 4. Geometric Model of Man, All Cylinders

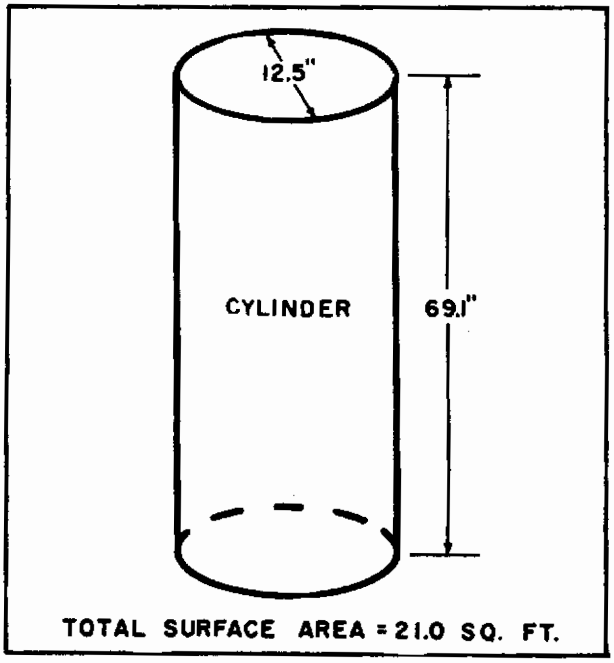

Figure 5. Geometric Model of Man, Cylinder

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PHASE I

INFINITE THERMAL CONDUCTIVITY SUIT

At any instant in time, a man wearing a space suit will be under the influence of a number of factors which will determine his thermal environment and, consequently, the average temperature of his thermodynamic system. Among these factors are the thermal radiation fields from the sun, earth, and nearby objects, the thermal properties of the suit, the man's own metabolic heat generation and other biological processes, and the previous history or variations of all these factors.

Much useful information and background knowledge should accrue from an analysis of a part of this complex system. For example, the temperature history of a space suit without a man inside (but with energy generation within the suit to model the metabolic heat rate) may be examined with reasonable sophistication. Such information, coupled with the present knowledge of man's physiological processes, serves as an excellent starting place for determining additional modifications necessary to a space suit before a man is placed inside.

The energy balance for determining the temperature-time history was based on the suit scheme in figure 6. Additional specifications were an adiabatic inside surface and a very high thermal conductivity for the space suit material so that no heat-transfer processes inside the cylinder would require consideration and no temperature differences would exist in the suit material.

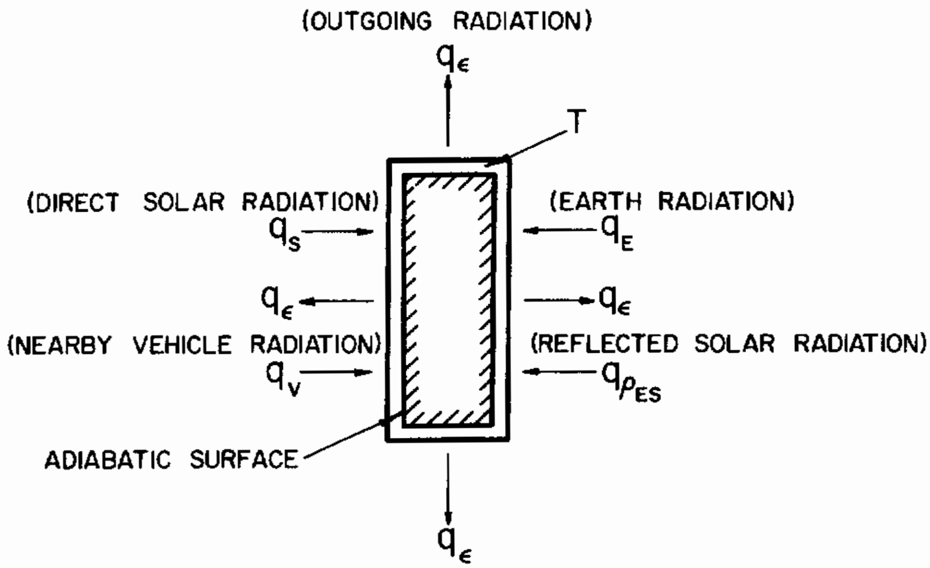

Figure 6. Model Chosen to Analyze Time-Temperature Variation in Orbit Suit

Under the conditions described above, the energy balance on the suit assumes the following form as applied to a unit of time:

$$Q_{\alpha_R} + Q_G = Q_{\epsilon_R} + \frac{dQ}{dt} \qquad (1)$$

The first term, Q_{α_R}, consists of a number of terms representing the separate radiation fields absorbed by the suit. These fields include direct and reflected solar radiation, earth radiation, and radiation from nearby objects such as the parent satellite or space ship. The second term allows for the internal generation of heat within the suit or on its boundaries. The third term describes the amount of thermal radiation which leaves the suit. The last describes the influence of the heat capacity of the suit. Implicitly, we assumed that any radiation leaving the suit does not return by reason of a reflection process.

Details of the energy balance are given in WADD TN 60-145 (ref. 1). The final equation in a dimensionless form is:

$$N_S + N_V + N_G + N_E = \theta^4 + 3.78\, t_c^{\Delta} \frac{d\theta}{dt^{\Delta}} \tag{2}$$

In equation 2, N_S and N_V are the dimensionless values of the absorbed solar and nearby vehicle radiation fields, N_G the dimensionless internal heat generation, and N_E the dimensionless absorbed earth radiation. The symbol θ represents a dimensionless suit temperature referred to the average temperature of the earth, i.e., $\theta = \frac{T}{T_E}$. The term $3.78\, t_c^{\Delta}$ is a dimensionless measure of the energy retention capacity of the suit material and t^{Δ} is a dimensionless time referred to the period of orbit of the suit.

Equation 2 is a first-order, nonlinear, differential equation which requires the specification of one boundary condition. The condition which has been chosen for all calculations is:

$$\theta = 1.2 \tag{3}$$

when:

$$t^{\Delta} = 0$$

Equation 3 states that the space suit temperature at the beginning of the calculation is 80° F. The calculation then predicts whether and how much the temperature of the suit increases or decreases under its environmental influences.

Calculation Results

The basic energy equation discussed above was solved on a computer for two extreme conditions. The first condition was when $\beta = 0$ and the space suit at 80° F was suddenly placed in the sunlight and remained there during subsequent time. Parametric values were chosen so that the solar and earth-radiation inputs as well as the radiation input from the nearby vehicle were maximum. The internal energy generation rate was chosen to approximate that normally found when a man is engaged in a mild activity. Thus, this calculation could be expected to predict the maximum temperatures that might be found in a space suit. Details of the choice of parametric values are given in WADC TN 60-145 (ref. 1).

As an illustration of the temperature control factors available to the designer, the calculation was then repeated for two additional cases. In one, the suit properties were chosen so that a minimum amount of outside radiation was absorbed and the internal heat generation rate was the same. The second condition considered the space suit at 80° F, suddenly placed in the earth's shadow (in a 300-mile orbit in the plane of the ecliptic) so that the only incident radiation field was the earth's. To represent the "coldest" case, the internal heat generation rate was taken as zero. The result of the calculations for these two conditions is discussed in detail below.

Case I - Hot (Maximum Radiation Input and Heat Generation Rate):

Figure 7 presents the computed variation of the nondimensional suit temperature with time, measured in multiples of the orbital period, for three values of $\frac{\alpha}{\epsilon}$. The extreme equilibrium values of θ = 3.23 and 1.13 or T = 993° F and 48° F reveal the wide variation of suit temperatures permitted by the choice of the suit's spectral properties. The heat retention parameter, t_c^{Δ}, is defined as:

$$t_c^{\Delta} = \frac{1}{3.78}\left[\frac{\rho CV}{\alpha_E A_T \sigma T_E^3 t_p}\right] = \frac{1}{3.78}\left[\frac{\rho C\tau}{\epsilon\sigma T_E^3 t_p}\right]$$

Thus, for a fixed orbital period, t_c^{Δ} is directly proportional to the specific heat per unit volume (ρC) and the suit material thickness, τ. Conversely, t_c^{Δ} is inversely proportional to the suit's emissivity, ϵ.

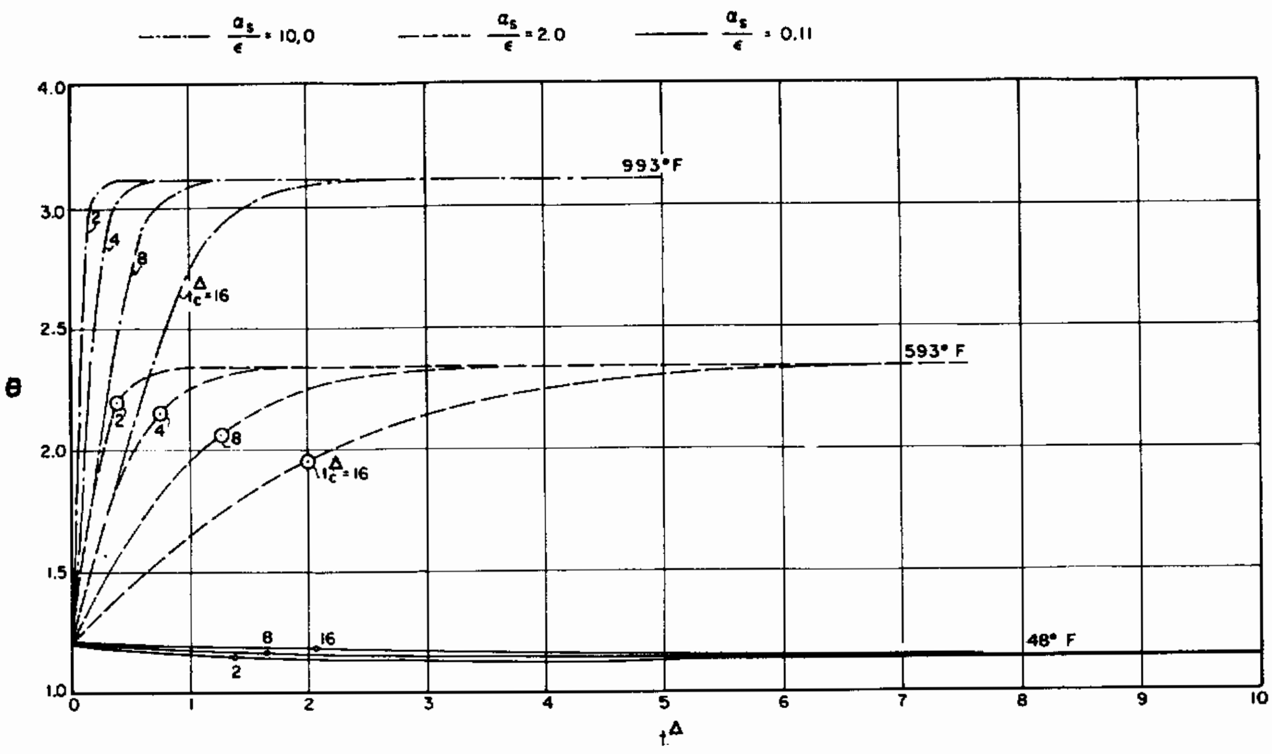

Figure 7. Variation of Suit Temperature with Time - Hottest Case

Figure 7 indicates that the suit designer must limit the external heat inputs by choosing a low $\frac{\alpha_s}{\epsilon}$ value to maintain comfortable suit temperatures. Also, the choice of a sufficiently large value for the heat retention parameter will lengthen the time in which the suit reaches its equilibrium temperature.

Case II - Cold (Earth Heating Only):

Figure 8 shows the results of the calculations for the coldest case. Judiciously chosen suit properties will inhibit rapid temperature changes when the suit is being heated by earth radiation alone. For example, when t_c^Δ is equal to 12, the suit temperature drops only 25° F from its original value of 80° F in one equivalent period (90 minutes). This slow decrease is interesting since the equilibrium (long-time) temperature for these conditions is -100° F and the suit can stay in the earth's shadow for only 34 minutes in a 300-mile orbit.

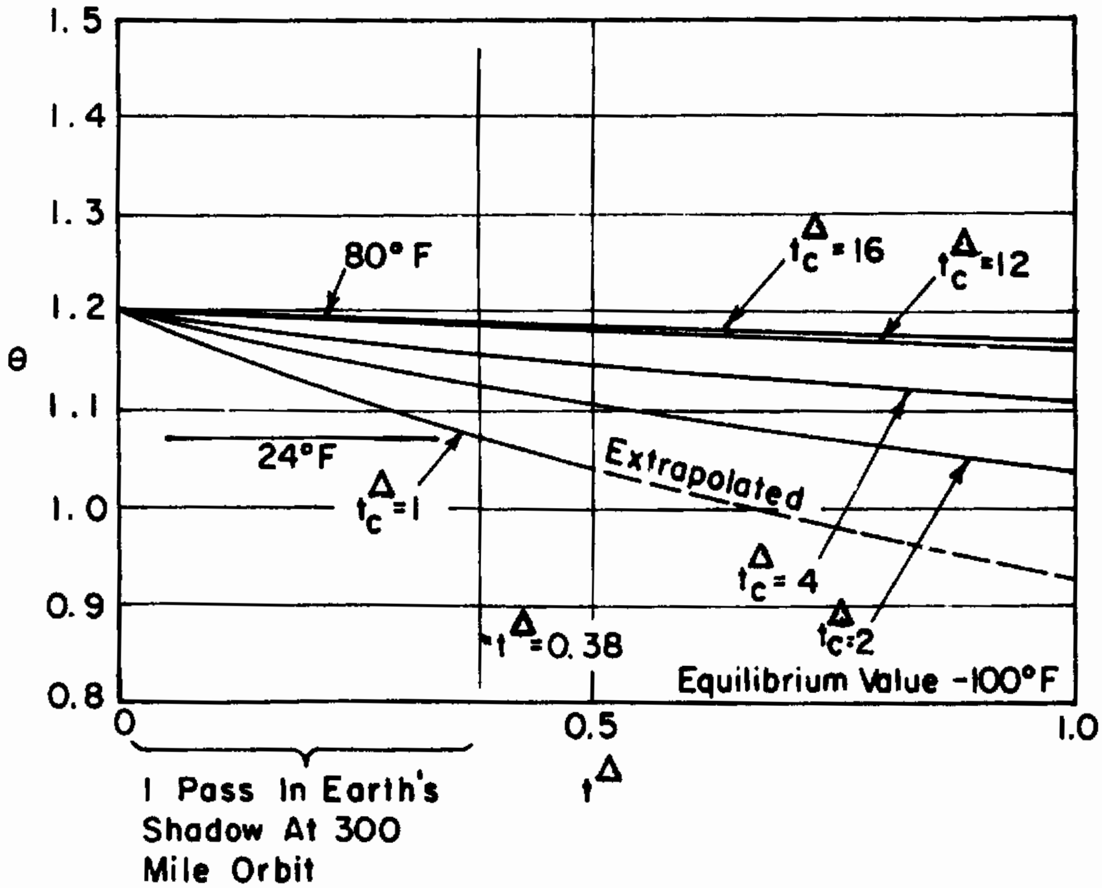

Figure 8. Variation of Suit Temperature with Time - Coldest Case, Earth Heating Only

Thus, controlling the thermal environment of a man in space under conditions of earth heating only through the selection of proper suit properties should be considered. This is true whether control is desired on the unsteady state temperature, the final equilibrium temperature, or both.

For applying the calculations, we examined the following "suit problem":

Design Requirements

A. Passive heat control

B. θ_{max} = 1.22 or 90° F

θ_{min} = 1.17 or 60° F

C. Exposure time: one 300-mile orbit

D. Lightweight suit material

E. Thin suit material to permit mobility

To Be Determined

A. Surface coating $(\frac{\alpha_s}{\epsilon})$

B. Suit material (C)

C. Suit's total mass (ρV)

D. Material thickness (τ)

A white $PbCO_3$ paint $(\frac{\alpha_s}{\epsilon} = 0.13)$ for the surface coating will maintain the maximum suit temperature below the required 90° F since $\frac{\alpha_s}{\epsilon}$ is only slightly larger than the 0.11 value plotted in figure 7. A low t_c^{Δ} value and a large ρC value must be selected if a small suit thickness is required. Thus, the material must have a high specific heat (C) to obtain a low total mass suit. If, for example, a water-filled five-eighths-inch-thick shell is chosen for the suit material, then:

$$\rho C = 60$$

and:

$$t_c^{\Delta} = 4$$

This value of t_c^{Δ} will limit the minimum suit temperature to θ = 1.16 or 62° F for a 300-mile orbit. The minimum temperature requirement of 60° F will thus be met. The resulting total mass of the water is then a reasonable 64 lbm.

PHASE II

SUIT WITH FINITE THERMAL CONDUCTIVITY

The preceding analysis assumed an infinite thermal conductivity of the space suit material so that no temperature gradients could exist in the suit. This restriction will now be relaxed to allow different suit thicknesses and thermal conductivities so that these temperature gradients may be examined. Since the maximum temperature difference which might be encountered is of primary interest, the heat input and the outgoing radiation have been chosen so that extreme temperature gradient conditions will be encountered. Figure 9 illustrates the model which was used. From figure 9 we see that the suit is to be subjected to a solar heat flux, q_s, only at one end. The remaining two surfaces of the suit are allowed to radiate into space at 0° absolute. In addition, the total heat absorbed by the end area is assumed to be concentrated uniformly around the circumference of the shell at its initial boundary, x = 0. The metabolic heat is uniformly distributed only along the inner cylindrical surface, and the entire heat-transfer process is assumed to be at steady state.

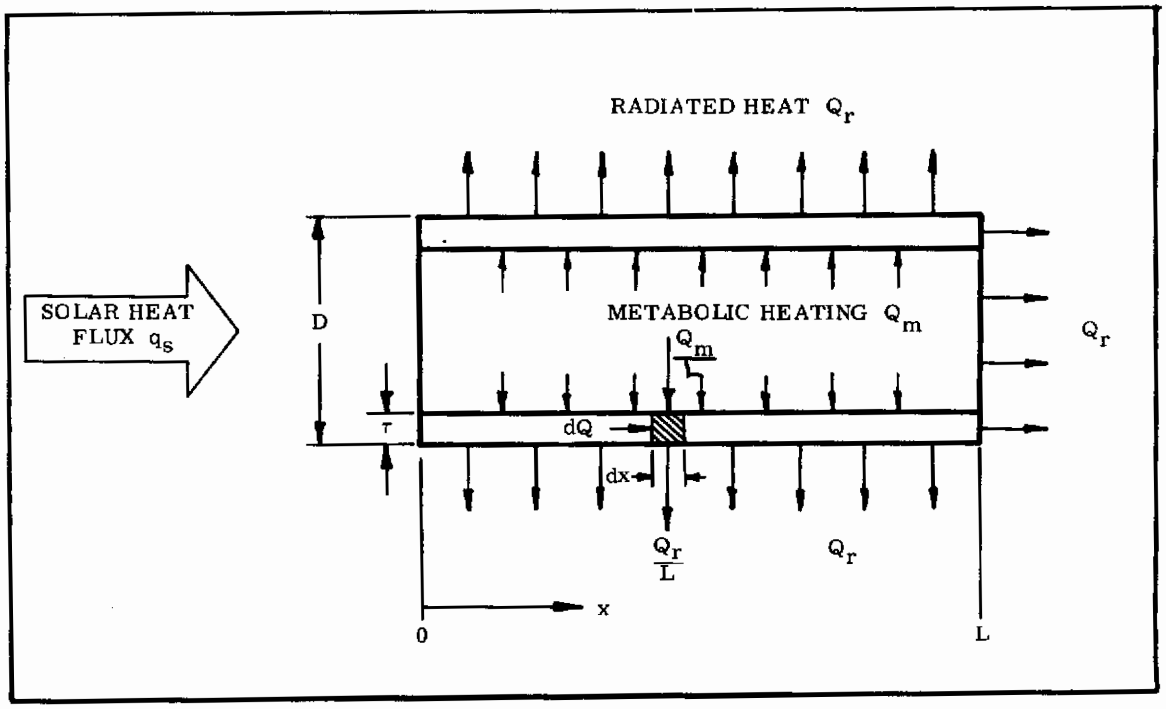

Figure 9. Analytical Suit Model for Phase II

With these assumptions and the suit geometry of figure 9, the heat balance for an elemental length of the cylindrical shell is expressed by:

$$\frac{dQ}{dx} + \frac{Q_m}{L} = \frac{Q_r}{L}$$

Substituting the defined expressions:

$$Q = - k\pi D\tau_2 \frac{dT}{dx}$$

$$Q_r = \sigma\epsilon\pi DLT^4$$

$$Q_m = \pi DLq_m$$

for the various heating rates, and nondimensionalizing:

$$\frac{d^2\theta}{d\eta^2} + A\theta^4 - \bar{q} = 0 \qquad (5)$$

The boundary conditions for this ordinary second order differential equation can be determined by considering the heat balance with the external environment at each end:

at $\eta = 0$:

$$Q = - k\pi D\tau_2 \frac{T_a}{L} \frac{d\theta}{d\eta} = \frac{\pi D^2 \alpha_s q_s}{4}$$

or:

$$\left.\frac{d\theta}{d\eta}\right|_{\eta = 0} = - \frac{LD\alpha_s q_s}{4k\tau_2 T_a} = - B \qquad (6)$$

at $\eta = 1$:

$$Q = - k\pi D\tau_2 \frac{T_a}{L} \frac{d\theta}{d\eta} = \sigma\epsilon \frac{\pi D^2}{4} T_L^4$$

or:

$$\left.\frac{d\theta}{d\eta}\right|_{\eta = 1} = - \frac{LDT_a^3\sigma\epsilon}{4k\tau_2} \theta_L^4 = \bar{C}\theta_L^4 \qquad (7)$$

Therefore, the solution of equation 5, subject to the boundary conditions of equations 6 and 7, will provide the temperature distribution along the cylindrical portion of the suit for various suit materials and thicknesses. The maximum temperature difference will then simply be the difference between the temperatures at the two ends.

Equation 5 was solved by a numerical integration scheme to provide the required longitudinal temperature distribution (ref. 2). The numerical work was greatly reduced by the use of the relations for the various parameters:

$$A = \frac{4\sigma T_a^4 \epsilon L}{q_s \alpha_s D} B$$

$$B = \frac{L D \alpha_s q_s}{4 T_a k \tau_2}$$

$$\overline{C} = \frac{\sigma T_a^4 \epsilon}{\alpha_s q_s} B$$

The following constants used in phase I (ref. 1) were also selected:

$L = 5.75$ feet
$D = 1.04$ feet
$\alpha_s = 0.12$
$\epsilon = 0.89$
$Q_m = 800$ Btu/hr
$A_T = 20.5$ ft^2

The number of arbitrary parameters is then reduced to one, the initial slope B, which is a function of the material thickness and thermal conductivity.

The required suit shell thickness and mass can then be determined from the relations:

$$\tau_2 = \frac{0.1397}{kB} \quad (8)$$

$$M = \frac{2.86}{B} \frac{\rho}{k} \quad (9)$$

In the first phase the suit temperature variation with time was determined from the balance of the metabolic heating with the external environment as influenced by the heat retention capacity of the material and the surface radiation properties. The shell thickness (τ_1) was determined as a function of the heat retention parameter, which was chosen as four in the sample problem, and the surface radiation properties to limit the minimum suit temperature to 62° F for a 300-mile orbit:

$$\tau_1 = \frac{\epsilon t_c^{\Delta}}{1.132 \rho C} \quad (10)$$

Therefore, with the various assumed constants, the ratio of the thicknesses or masses is a function of the material thermal diffusivity and the initial slope B:

$$\frac{\tau_1}{\tau_2} = \frac{M_1}{M_2} = 22.5\, \alpha\, B \quad (11)$$

When this ratio is greater than 1, the material thickness as required by the first analysis must be chosen to provide a proper thermal environment. Since this thickness is greater than that required by the present analysis, smaller equilibrium maximum temperature differences will exist. If the ratio is less than 1, then the thickness computed in equation 11 must be chosen to minimize the maximum temperature difference. This thickness is greater than that computed with equation 10 and this provides a greater thermal capacity which will lengthen the time for the suit to reach thermal equilibrium with its external environment. This ratio is useful only for the above type comparison since it compares the results of the time-dependent analysis of the first part with the results of this non-time-dependent study.

Finite Thermal Conductivity Results

Equation 5, as restricted by the boundary conditions and simplifying relations, was integrated numerically with the Runge-Kutta method on a digital computer for a range of initial slopes, B. Agreement with precomputed slopes at $\eta = 1$ was obtained to seven significant figures.

Figures 10 and 11 present in graphical form the numerical results for the temperature variation along the suit and the maximum temperature difference from $x = 0$ to $x = L$. The strong dependence of the temperature and maximum temperature difference on the parameter B is shown in the figures. A small value of B is desirable in any suit design problem. However, small values of B are obtained at the expense of increased shell thickness and mass for a given shell material. The shell thickness increases as the ratio $\frac{\rho}{k}$ increases and, therefore, it is desirable to have a low ratio. Aluminum and copper have the lowest ratio for metals while fabrics have ratios approximately 100 times as large.

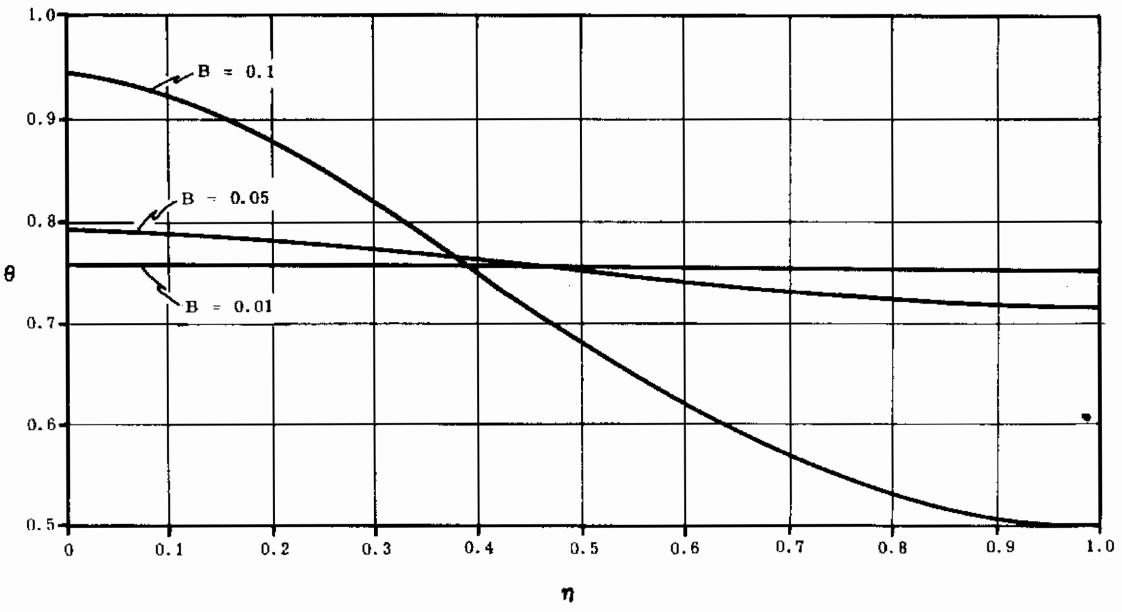

Figure 10. Suit Temperature Distribution

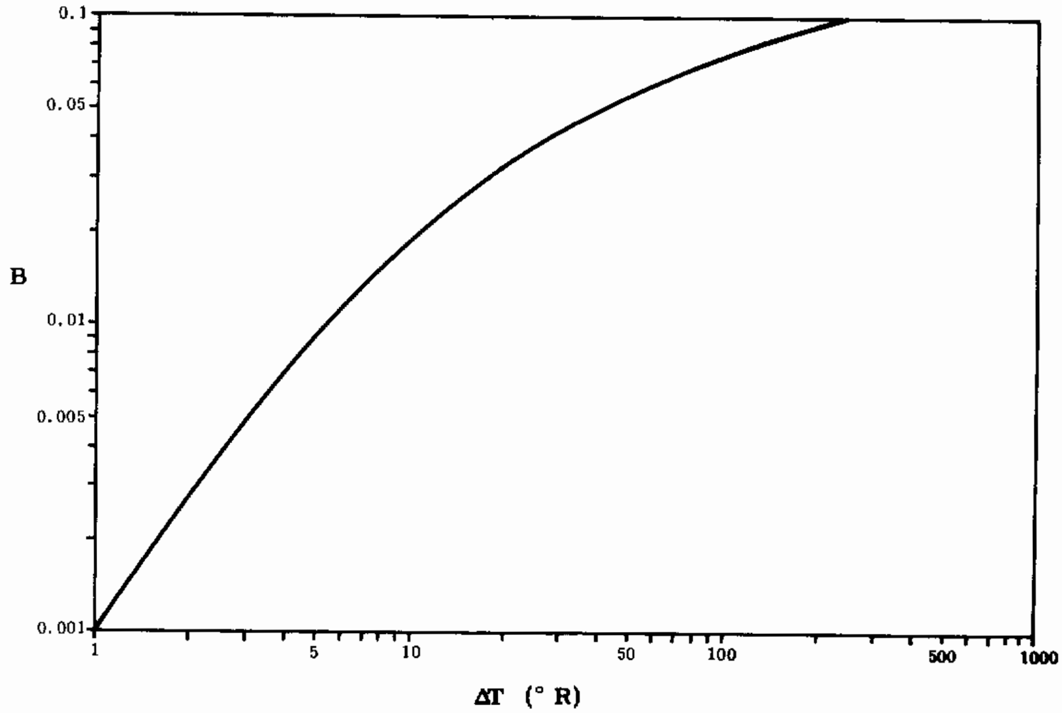

Figure 11. Maximum Suit Temperature Difference

The interlocking considerations of both the infinite and finite thermal conductivity analyses can be illustrated by:

Given: Maximum Tolerable $\Delta T = 30°$ F

To be determined: Material type, thickness, mass, and resulting maximum ΔT.

Solution:

1. With figure 11 and $\Delta T = 30°$ F, $B_2 = 0.043$
2. From equation 9 and $B_2 = 0.043$, $M_2 = 95$ lbm for aluminum
3. From equation 8 and $B_2 = 0.043$, $\tau_2 = 0.33$ inch for aluminum
4. From equation 11, $\frac{\tau_1}{\tau_2} = \frac{M_1}{M_2} = 3.7$ for aluminum
5. Since $\frac{\tau_1}{\tau_2} > 1$, then the thickness τ_1 and mass M_1 must be used. Therefore,

$$\tau_1 = 3.7 \times 0.33 = 1.22 \text{ inches}$$

and $M_1 = 3.7 \times 95 = 352$ lbm

6. With equation 9 and $M_1 = 352$ lbm,

   $B_1 = 0.011$ for aluminum

7. With figure 11 and $B_1 = 0.011$, $\Delta T = 5.8°$ F

Thus, a suit constructed with an aluminum shell 1.22 inches thick would have a mass of 352 lbm and a 5.8° F maximum equilibrium temperature difference.

Since the thermal diffusivity of most light metals is in the range of 3.6 to 4.4 ft^2/hr, the thickness ratio will be greater than 1 for $B > 0.01$. Therefore, most light-metal suit thicknesses computed with the results of the first analysis will develop small equilibrium temperature differences and be very thick and heavy. With this general conclusion the $\frac{5}{8}$-inch-thick, water-filled shell suggested previously becomes attractive since it would have a mass of 64 lbm. The very large equilibrium and nonequilibrium temperature difference that would exist, since $\left.\frac{\rho}{k}\right|_{H_2O} = 186 \frac{\text{lbm hr °R}}{\text{ft}^2 \text{ Btu}}$, could be reduced by circulating the water.

PHASE III

THE EFFECT OF CIRCULATING WATER

To examine the effect on the shell temperature difference of circulating water in passages just inside the outer wall, the model used in the second analysis will have to be modified as shown in figure 12. Since maximum temperature differences are of primary interest, the mathematical model is chosen to produce these extreme conditions. Thus, the solar flux is again assumed to be incident on one end of the cylinder while the other two surfaces are radiating to a zero temperature environment. The solar flux is also assumed to be concentrated uniformly around the circumference of the outer shell at its initial boundary. In addition, the metabolic heating is uniformly distributed along the inner shell surface and the suit is taken to be in thermal equilibrium with its environment.

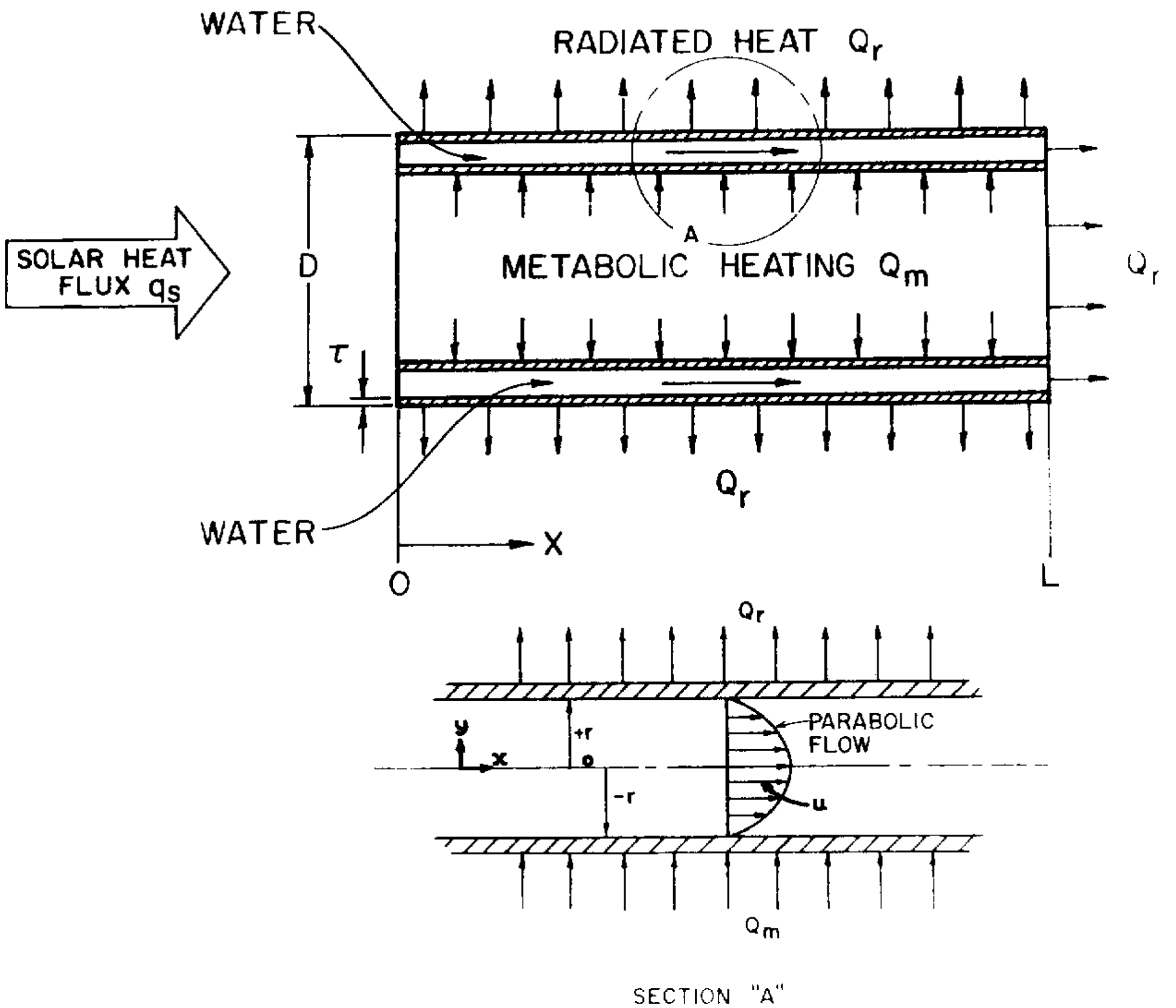

Figure 12. Analytical Suit Model for Phase III

If the fluid flowing through the passage is specified as being incompressible, laminar, and fully developed, and having constant physical properties, the energy equation describing the temperature field in the fluid may be written as:

$$u \frac{\partial T}{\partial x} = \alpha_w \frac{\partial^2 T}{\partial y^2}$$

The temperature boundary conditions are specified as:

$$T(0,y) = T_0 \qquad (13)$$

$$T(x,r) = ae^{-\ell x} \qquad (14)$$

$$\frac{\partial T}{\partial y}(x, -r) = \frac{Q_m}{k} \qquad (15)$$

Condition 14, as is explained more fully below, is taken from the results of the second analysis to give the maximum possible temperature difference along the inner shell.

Equation 12 may be put into dimensionless form by the following substitutions:

$$\eta = \frac{x}{L}$$

$$\xi = \frac{y}{r}$$

$$\theta = \frac{T}{T_0}$$

$$\frac{u_{max}}{u} \frac{\partial^2 \theta}{\partial \xi^2} - a \frac{\partial \theta}{\partial \eta} = 0 \qquad (16)$$

where $a = \dfrac{r^2 u_{max}}{\alpha_w L}$. The boundary conditions become:

$$\theta(0,\xi) = 1$$

$$\theta(\eta,1) = e^{-B\eta}$$

$$\frac{\partial \theta}{\partial \xi}(\eta, -1) = -\lambda$$

where $\lambda = q_m r / k_w T_0$ and the heat conducted along the inner wall is neglected.

In the above, we assumed that the solar heat is conducted only through the outer shell and is not influenced by the flowing fluid. The resulting temperature difference in the outer shell is then the one computed in the second analysis and is applied in this analysis as the boundary condition on that surface. Under these conditions the flow rates computed will be maximum since the flowing water would clearly produce a more moderate temperature distribution in the outer shell. Details of the solution of equation 16 are given in AMRL-TDR-63-80 (ref. 3). The results are discussed below.

Temperature differences in the inner shell and over the passage length are shown in figure 13. They are plotted against the dimensionless flow rate of the water (a) and for two values of the dimensionless metabolic heating parameter (λ).

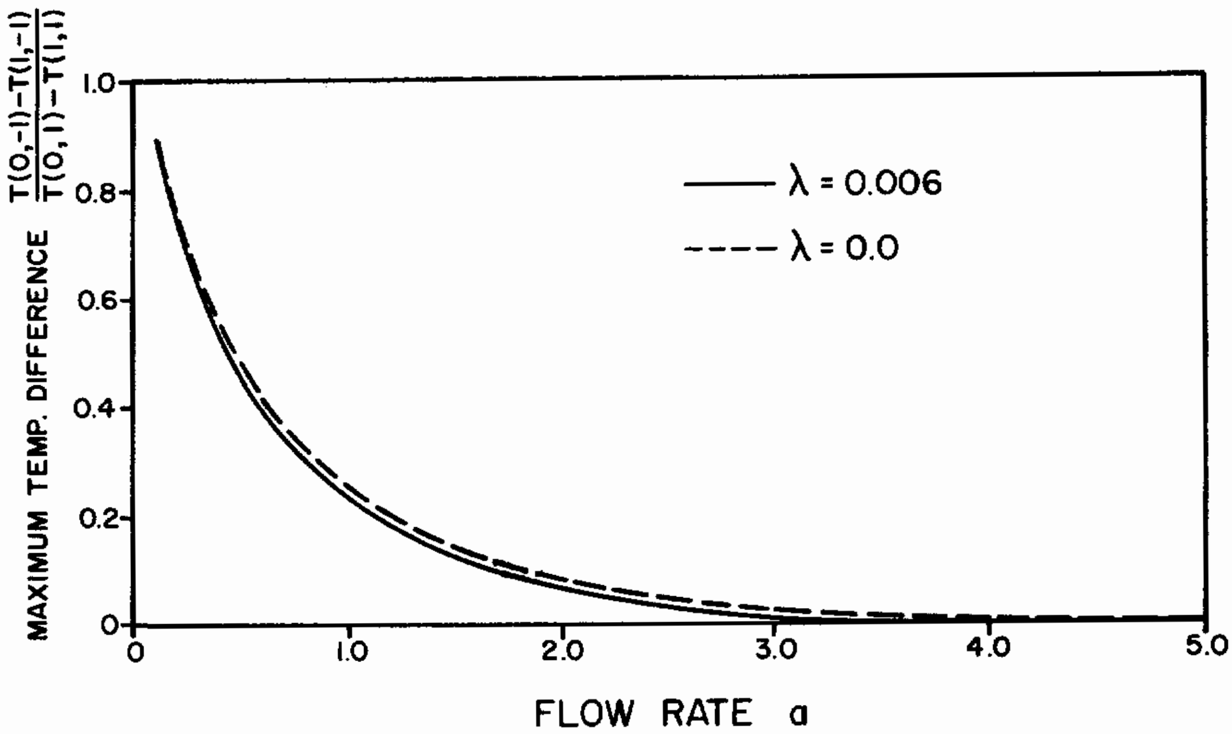

Figure 13. Nondimensional Flow Rate

Figure 13 illustrates the decrease in temperature difference with increasing water flow rate. This decrease is shown quantitatively in table 1 for particular values of the suit and water passage geometry; i.e., L = 5.76 ft, r = $\frac{5}{16}$ inch, $\alpha_w = 5.5 \times 10^{-3}$ ft^2/hr. The flow rates are for water flow around the complete suit circumference.

TABLE 1

WATER FLOW RATES

ΔT (° F)	Flow Rate (gal/min)	
	$\lambda = 0.0$	$\lambda = 0.006$
0	2.020	1.618
5	1.416	1.214
10	1.112	1.012
15	0.950	0.808
20	0.808	0.728
25	0.606	0.668

Figure 13 also indicates that changes in the metabolic heating rate do not have a great influence on the water flow required. The two values given on the curves are for zero metabolic heat rate and for a value of $\lambda = 0.006$ which corresponds to the metabolic heat rate found in a man engaged in mild activity.

We can conclude that temperature differences in a space suit under the conditions specified may be kept to reasonable values without excessive flow rates of the cooling fluid. Also, the variations in the distribution of metabolic heating over the body surface and those due to differences in physical activity do not seem important in their influence on the required flow rate for the cooling fluid.

SUMMARY AND CONCLUSIONS

An appropriately chosen analytical space suit model subject to environmental extremes has been examined to provide knowledge of the dominant heat transfer processes and to determine the suit temperature control requirements. Analytical results demonstrate that a wide range of temperatures may be produced by variation of the surface spectral properties and the external heating sufficiently limited by selection of low $\frac{\alpha_s}{\epsilon}$ ratios. High heat capacity materials are required to inhibit rapid temperature changes and prevent freezing temperatures when passing through the earth's shadow. A water liner is recommended as the highest capacity per pound suit construction.

Intolerable temperature differences can exist over the suit surface depending on its material and thickness. However, circulation of the water at small flow rates will prevent their occurrence.

Finally, a water-jacketed space suit appears practical and, when modified to satisfy the requirement of an astronaut's physiological processes, should result in a garment capable of protecting him outside a vehicle that is located in an orbit about the earth.

LIST OF REFERENCES

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