Mar 7th, 8:00 AM

# Transient Thermal Study of a Space Suit Clad Astronaut on the Moon

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# TRANSIENT THERMAL STUDY OF A SPACE SUIT CLAD ASTRONAUT ON THE MOON

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A transient thermal analysis of a space suit clad man on the moon is presented. No refrigeration system is considered for his suit, and it is assumed that the only evaporative cooling is that achieved through the saturation of the occupant's exhalation. These restrictions are imposed because the primary concern is to determine whether useful mission times are possible without recourse to special cooling devices. Practicable exposure times are demonstrated for the lunar day. The analysis also shows that extended mission times are easily feasible for the lunar night side.

## Introduction

The heating effect from exposure on the moon's day side poses a serious problem for the lunar explorer. The purpose of this study is to see what can be achieved with regard to temperature control through suitable selection of radiation emissivities for the space suit surfaces. From the standpoint of operation simplicity it is desirable that no refrigeration of the suit be required.

Since it is possible that there are systems which will heat slowly enough to allow a practicable exposure time, and yet would overheat if exposed until steady state conditions were approached, the study must be a transient one.

The suit considered here is assumed to be similar to the present full pressure suits used for Projects Mercury and Gemini. The oxygen tank is considered to be located under the suit but against the man's undergarment.

## Nomenclature

$A$ = maximum cross section area - $ft^2$.

$C$ = solar constant at moon - btu/hr $ft^2$.

$G$ = thermal gradient in the sole, at the inner boundary - °R/ft.

$K$ = thermal conductivity - btu/hr ft °R.

$Q$ = mean volumetric rate of helmet oxygen into man - $ft^3$/hr.

$R$ = radius - ft.

$S$ = surface area - $ft^2$.

$T$ = temperature - °R.

$a$ = thickness - ft.

$c$ = specific heat - btu/lb °R.

$e$ = base of natural logarithms.

$f$ = heat flux density - btu/hr $ft^2$.

$m$ = mass - lb.

$p$ = proportion of helmet obscured by man's body - none.

$q$ = heat flux - btu/hr.

$t$ = time from start of exposure - hr.

$\alpha$ = absorptivity of a surface for infrared radiation - none.

$\bar{\alpha}$ = absorptivity of a surface for solar spectrum - none.

$\beta$ = mean hydraulic radius of gas flow path in cavity - ft.

$\epsilon$ = emissivity of a surface for infrared - none.

$\rho$ = density of oxygen in helmet - $lb/ft^3$.

$\sigma$ = Stefan-Boltzmann radiation constant- btu/hr. $ft^2$ $°R^4$.

$\Delta h$ = heat increment exchanged during $\Delta t$ time - btu.

$\Delta t$ = computation time increment - hr.

$dq_{dA_L}$ = radiation flux to helmet from area increment on moon - btu/hr.

### Subscripts

$C$ = convection.

$F$ = refers to conduction between moon and feet.

$G$ = expiration gas between suit and man's body.

H = helmet.

HX = oxygen in helmet.

K = conduction.

L = luna.

M = refers to heat from metabolic processes.

R = radiation.

s,S = body of suit, as distinct from helmet.

T = oxygen tank.

TS = tank to suit contact.

ST = refers to radiation between suit and tank.

Tm = man's undergarment to tank contact.

TG = tank exposed to suit gas.

u = undergarment.

v = refers to vertical emitted heat flux from moon at a specified elevation, r.

vf = refers to vertical reflected heat flux from moon at a specified elevation, r.

x = oxygen.

b = refers to expired breath.

env = ambient environment to man-suit system.

h = head.

i = inner surface.

m = man.

o = outer surface.

ref = refers to reflected radiation from moon.

§ = refers to heat transfer between man and oxygen inhaled.

1 = the beginning of a time increment.

2 = the end of a time increment.

(NOTE: All figures in this paper follow the text.)

## Analysis

The block diagram, Figure 1, is the system considered. The components shown as squares are those upon which heat balances were made. The wavy lines represent radiation transfer, the dash lines convection, the solid lines conduction. The solid line studded with dots represents transfer by mass flow. The arrows indicate the direction of heat transfer during the major time of the process. Heat exchanges not shown were deemed negligible.

The radiant energy received by the helmet from the sun is

$$\Delta h_{(sol\ -\ H)R} = A_H C\, \bar{\alpha}_{Ho}\, \Delta t \qquad (1)$$

Radiation from helmet to surroundings is

$$\Delta h_{(env\ -\ H)R} = -\sigma\, \epsilon_{Ho} S_H T_{H1}^4\, \Delta t \qquad (2)$$

As a model for treating radiation from the lunar surface to the helmet, consider a sphere set on a post, the post representing the man's body below the head. The post and sphere stand on a plane, since the curvature of the lunar surface is only important here insofar as it provides a horizon, the location of which limits the extent of lunar surface seen by the helmet. In the model this is taken care of by making the surface a disc, with a radius determined by the distance of the horizon from the helmet. Equations determined are (3) and (3a). Use of two equations is to discriminate between direct radiation from the moon and reflected solar radiation. See Appendix A.

$$\Delta h_{(L-H)R} = 2\sigma\, \epsilon_L \alpha_{Ho} y_H A_H T_L^4\, \Delta t \cdot \left\{ \frac{1}{\sqrt{R_m^2 - y_H^2}} - \frac{1}{\sqrt{2R_L y_H + y_H^2}} - e^{\left(\frac{0.69\, R_m}{y_H - R_m}\right)} \int_{r_{xz} = R_m}^{\sqrt{2R_L y_H}} \frac{r_{xz}\, e^{\left(\frac{0.69\, r_{xz}}{R_m - y_H}\right)}}{\left(r_{xz}^2 + y_H^2\right)^{3/2}}\, dr_{xz} \right\} \qquad (3)$$

$$\Delta h_{(L-H)ref} = \left(\frac{C(1 - \bar{\alpha}_L)\bar{\alpha}_{Ho}}{\sigma \epsilon_L \alpha_{Ho} T_L^4}\right) \Delta h_{(L-H)R} \qquad (3a)$$

It should be noticed that (3) is not an expression for net radiation exchange between the helmet and the moon. It takes no account of the radiation from the helmet to the moon. This, however, is included in equation (2).

The heat transfer coefficient for laminar flow between helmet and head may be approximated as $1.3K_x/\beta_H$. The equation for convection heat transfer between the helmet and the oxygen in the helmet is

$$\Delta h_{(HX-H)C} = (1.3K_X/\beta_H)\, S_H(T_{T1} - T_{H1})\, \Delta t \tag{4}$$

In equation (4) the temperature of the oxygen in the helmet is considered the same as the temperature of the tank metal, $T_T$.

The radiation transfer between the man's head and the helmet is a situation where one of two surfaces is completely enclosed by another. Thus

$$\Delta h_{(m-H)R} = \frac{\sigma S_h (T_{m1}^4 - T_{H1}^4)\ \Delta t}{\frac{1}{\epsilon_h} + \frac{S_h}{S_H}\left(\frac{1}{\epsilon_{Hi}} - 1\right)} \tag{5}$$

The total heat gained by the helmet in a small time interval is

$$\Delta h_H = \Delta h_{(sol - H)R} + \Delta h_{(env - H)R} + \Delta h_{(L - H)R} + \Delta h_{(L - H)ref} + \Delta h_{(HX - H)C} + \Delta h_{(m - H)R} \tag{6}$$

A heat balance on the helmet gives the temperature of the helmet at the end of a time increment.

$$T_{H2} = T_{H1} + (\Delta h_H/m_H c_H) \tag{7}$$

Similar to equations (1) and (2) there are

$$\Delta h_{(sol - S)R} = C\, \bar{\alpha}_{so} A_s\, \Delta t \tag{8}$$

$$\Delta h_{(env - S)R} = -\sigma\, \epsilon_{so} S_s\, T_{s1}^4\, \Delta t \tag{9}$$

For the radiation from the lunar surface to the suit, the shape of the man was approximated by a rectangular parallelepiped. See Appendix B.

$$\Delta h_{(L-S)R} = 1.5\, \sigma\, \epsilon_L \alpha_{so}\, w_s\, y_n\, T_L^4\ \Delta t \tag{10}$$

Analogous to equation (3a):

$$\Delta h_{(L - S)ref} = \left(\frac{C(1 - \bar{\alpha}_L)\bar{\alpha}_{so}}{\sigma \epsilon_L \alpha_{so} T_L^4}\right) \Delta h_{(L - S)R} \tag{10a}$$

Similar to equation (4):

$$\Delta h_{(G-S)C} = (1.3K_G/\beta_s)\, S_s\, (T_{m1} - T_{s1})\ \Delta t \tag{11}$$

In equation (11) the temperature of the man is used for the temperature of the gas in the suit.

Radiation between the suit and the man is a case where one surface is entirely enclosed by another. So:

$$\Delta h_{(m-S)R} = \frac{\sigma S_m (T_{m1}^4 - T_{S1}^4)\ \Delta t}{\frac{1}{\epsilon_m} + \left(\frac{S_m}{S_s}\right)\left(\frac{1}{\epsilon_{si}} - 1\right)} \tag{12}$$

The temperature drop in the low conductivity suit will be much larger than that in the high conductivity tank wall. Therefore, the entire drop between the mean temperature of the suit and the tank temperature is assumed to be in one half the suit wall thickness. Thus

$$\Delta h_{(T-S)K} = 2K_S\, S_{TS}\, a_S^{-1}(T_{T1} - T_{SI})\ \Delta t \tag{13}$$

For radiation between the suit and the tank, since contact between the suit and the tank will be loose, the tank surface not in contact with the man is assumed to be involved in radiation to the suit. The total enclosure radiation expression is used, but is reduced by virtue of the one third of the tank surface assumed in contact with the man's body.

$$\Delta h_{(T-S)R} = \frac{0.67\sigma\, S_T(T_{T1}{}^4 - T_{S1}{}^4)\,\Delta t}{\frac{1}{\epsilon_T} + \left(\frac{S_T}{S_{ST}}\right)\left(\frac{1}{\epsilon_{si}} - 1\right)} \quad (14)$$

Similar to equations (6) and (7) for the helmet, a heat balance on the suit will provide the mean temperature of the suit at the end of a time interval.

In conduction between the astronaut and the oxygen tank, the controlling resistance would be the undergarment. Thus--

$$\Delta h_{(m-T)K} = K_u a_u^{-1} S_{Tm} (T_{m1} - T_{T1})\,\Delta t \quad (15)$$

Convection between the gas in the suit and the oxygen tank is--

$$\Delta h_{(G-T)C} = (1.3K_G/\beta_S)\, S_{TG} (T_{m1} - T_{T1})\,\Delta t \quad (16)$$

where the $1.3K_G/\beta_S$ is the transfer coefficient.

Together with relations developed previously, equations (15) and (16) complete the set of equations needed to set up a heat balance on the tank.

Ignoring edge effects, conduction through the shoe soles may be treated as one dimensional heat flow,

$$\Delta h_{(L-m)K} = K_F S_F G_1 \;\Delta t \quad (17)$$

where $G_1$ is the thermal gradient in the sole, at the inner boundary of the sole, and at the beginning of the time interval for which $\Delta h_{(L-m)K}$ is being sought. For simplicity there is assumed a conductive barrier of sole, sock and skin, which has thermal properties that are the thickness weighted means of these components. The $G_1$ in (17) is determined by solving the problem of conduction in a slab whose sides are held at the lunar surface temperature and the man's body temperature. Schmidt's method was used. A one-inch thick leather sole was assumed. The moon's surface temperature was taken as 250°F, and the initial temperature of the sole as 70°F. The results are closely approximated by the exponential function--

$$G_1 = 1500 - 3180\, e^{-3.27t_1} \quad (18)$$

Convection between the oxygen in the helmet and the man is similar to equation (4).

$$\Delta h_{(HX-m)C} = (1.3K_x/\beta_H)\, S_h (T_{T1} - T_{m1})\Delta t \quad (19)$$

Heat is transferred between the man and the inhaled oxygen.

$$\Delta h_{(HX-m)\S} = c_x Q \rho\, (T_{HX1} - T_{m1})\,\Delta t \quad (20)$$

Metabolic heat from the man is

$$\Delta h_{(M-m)} = q_m \Delta t \quad (21)$$

There is evaporative cooling involved in saturating the gases expired.

$$\Delta h_{(b-m)} = -q_b \Delta t \quad (22)$$

The temperature of the man at the end of a time interval may be found by a heat balance on the man.

## The Specific System

Values used for our specific system follow.

**Geometrical Parameters**

$a_H$ = 0.01 ft.

$\beta_H$ = 0.014 ft.

$y_n$ = 5.0 ft.

$R_L$ = 5,280,000 ft.

$S_H$ = 2.598 ft$^2$.

$S_m$ = 19.0 ft$^2$.

$S_{ST}$ = 2.1 ft$^2$.

$S_F$ = 0.514 ft$^2$.

$a_S$ = 0.005 ft.

$\beta_S$ = 0.019 ft.

$w_S$ = 1.75 ft.

$A_H$ = 0.786 ft$^2$.

$S_h$ = 2.1 ft$^2$.

$S_T$ = 3.14 $ft^2$.

$S_{Tm}$ = 1.05 $ft^2$.

$a_U$ = 0.0027 ft.

$y_H$ = 5.5 ft.

$R_m$ = 1.0 ft.

$A_S$ = 7.33 $ft^2$.

$S_S$ = 20.2 $ft^2$.

$S_{TS}$ = 1.05 $ft^2$.

$S_{TG}$ = 1.05 $ft^2$.

Thermal Parameters

C = 430 btu/hr $ft^2$

$\bar{\alpha}_L$ = 0.93 (albedo = 0.07)

$\epsilon_T$ = 0.5

$K_G$ = 0.0154 btu/hr ft °R

$K_U$ = 0.024 btu/hr ft °R

$c_T$ = 0.12 btu/lb °R

$T_L$ = 710 °R

$\sigma$ = 0.174 x $10^{-8}$ btu/hr $ft^2$ $°R^4$

$\epsilon_h$ = 0.9

$K_X$ = 0.0167 btu/hr ft °R

$K_S$ = 0.1 btu/hr ft °R

$c_H$ = 0.4 btu/lb °R

$c_m$ = 1.0 btu/lb °R

$\epsilon_L$ = 0.93

$\epsilon_m$ = 0.9

$K_H$ = 0.1 btu/hr ft °R

$K_F$ = 0.092 btu/hr ft °R

$c_S$ = 0.4 btu/lb °R

$c_X$ = 0.225 btu/lb °R

Mechanical Parameters

$m_H$ = 4.37 lb.

$m_T$ = 45.0 lb.

$m_S$ = 9.0 lb.

$\rho$ = 0.0267 $lb/ft^3$

$m_m$ = 180.0 lb.

Physiological Parameters

Q = 19.1 $ft^3/hr$.

$q_M$ = 1000 btu/hr. (This corresponds to moderately heavy activity)

$q_b$ = 117.0 btu/hr.

## Numerical Results

The set of equations formed by substituting the specific values into the general equations was explored for different cases. For each case computations were made until the man's body temperature reached 104.5 °F, which was considered to be the extreme tolerable limit. The results show that the suit surface condition is important for controlling heating. See Figure 2.

Two surface finishes were considered: an aluminized surface and a special B.F.Goodrich finish. The special finish has an infrared absorptivity and emissivity of 0.34, and an absorptivity for solar radiation of 0.12. The data for the aluminized surface is $\alpha = \epsilon = 0.05$, and $\bar{\alpha} = 0.16$.

Notice that advantage is gained by finishing both outside and inside surfaces of suit and helmet.

Figure 3 is typical of the kind of temperature-time curves obtained. It corresponds to case 6 of Figure 2, which gave the longest safe exposure time; 1.28 hr. The maximum suit material temperature found for any case is a tolerable 160 °F.

## Exposure During Lunar Night

Suit number 5 of Figure 2 was considered for night time exploration. This was calculated from the above system by omitting the heating from the lunar surface and the sun. In this case net heat flux is from the man to his suit. However, the heat flux to the ambient is not adequate to dissipate the metabolic heat, which is assumed to be forming at 1000 btu/hr. Therefore, overheating occurs. The overheating is slow, as the safe exposure time found is 2.25 hr. Probably eliminating the aluminized surface on the suit interior would increase the heat loss to the point where night time stay out time could be indefinite.

## Concluding Remarks

Allowable exposure times determined here are not binding. They indicate what may be achieved by controlling radiation transfer by selective surfaces. Exposure times could be extended by the use of a dry gas flush between the man and his suit. Also, improvement for dayside conditions could be had through the use of a loose "Tuareg" style cloak worn outside the suit.

## Acknowledgement

The author appreciates the ready response of the Navy, granting permission to publish this paper. The bulk of the work on which this paper is based was done on the U.S. Navy, Bureau of Naval Weapons, contract NOW 61-0554- C.

## Appendix A
## Radiation From Lunar Surface to Helmet

Refer to Figure A-1. From elementary geometrical considerations the total hemispherical flux from $dA_L$ is found. (NOTE: Symbols whose meanings are clearly indicated on Figures A-1 and B-1 in the appendices are not also defined in the Nomenclature.)

$$2\pi r^2 f_v \int_0^{\pi/2} (\sin\theta)(\cos\theta)\, d\theta \tag{A1}$$

The total hemispherical flux from $dA_L$ is also given directly from the Stefan-Boltzmann Law.

$$\epsilon_L \sigma T_L^4 \, dA_L \tag{A2}$$

(A1) and (A2) are equated and solved for $f_v$.

$$f_v = \sigma \epsilon_L T_L^4 \, dA_L / \pi r^2 \tag{A3}$$

From any $dA_L$ the entire helmet surface seen by the increment is assumed equidistant. Thus the helmet may be likened to a great circle area normal to r. All rays reaching this from $dA_L$ are considered parallel. With these two assumptions, we can dispense with double integration over the helmet surface.

Proceeding from (A3) it follows that the flux on the helmet from $dA_L$ is

$$\sigma \epsilon_L T_L^4 \, dA_L (\sin\theta) A_H / \pi r^2 \tag{A4}$$

For double integration over the radiating plane, the geometrical variables in (A4) must be in terms of $r_{xz}$ and $\phi$.

$$\sigma \epsilon_L y_H A_H T_L^4 r_{xz} dr_{xz} d\phi / \pi (y_H^2 + r_{xz}^2)^{(3/2)} \tag{A5}$$

The obscuring effect of the man's lower body on radiation from the moon to the helmet is approximated by an exponential decay function.

$$p = e^{\left[\frac{0.69(r_{xz} - R_m)}{R_m - y_H}\right]} \tag{A6}$$

(1 - p) is the proportion unobscured. From this, equation (A5), and the helmet absorptivity, we may write--

$$dq_{dA_L} = \frac{\sigma \alpha_{Ho} \epsilon_L y_H A_H T_L^4 \left[1 - e^{\left(\frac{0.69(r_{xz} - R_m)}{R_m - y_H}\right)}\right] r_{xz} dr_{xz} d\phi}{\pi (y_H^2 + r_{xz}^2)^{(3/2)}} \tag{A7}$$

The radius of the plane radiating to the helmet is the distance between the helmet and the horizon. This is approximately $\sqrt{2R_L y_H}$.

Double integration of (A7) over the radiating plane, and some simplification, yields equation (3).

Equation (3) applies to emission from the lunar surface. Additionally, there is reflected radiation. As far as the helmet is concerned, diffusely reflected radiation looks like emitted radiation. The total hemispherical flux of reflected radiation from $dA_L$ is

$$C(I - \bar{\alpha}_L)\, dA_L \tag{A8}$$

Referring to (A1), another expression is obtained for the total reflected hemispherical flux from $dA_L$; viz. $\pi f_{vf} r^2$. Equating this to (A8) and solving for $f_{vf}$ yields--

$$f_{vf} = C(1 - \bar{\alpha}_L) dA_L/\pi r^2 \qquad (A9)$$

The radiation received by the helmet from the moon from the two sources will be directly proportional to the ratio of vertical flux densities, if the absorptivity of the helmet were the same for solar radiation as it is for infrared. Since this is not so, a factor ($\bar{\alpha}_{Ho}/\alpha_{Ho}$) applies. From this factor, (A3), and (A9), equation (3a) is derived.

## Appendix B
## Radiation From Lunar Surface to Suit

Figure B-1 shows the front (or back) of the man. For simple conformance to the rectangular body approximation, the radiating surface is considered to be a square. The distance from the origin to the sides of the square is the distance to the horizon from the place on the man that is looking at the radiating surface. The fact that we treat as radiating surface a region too large, in the proportion that a square exceeds its inscribed circle, is of little significance, because the corners of the square will contribute a trivial part of the total radiation. Referring to Figure B-1

$$\sin \gamma = x/\sqrt{y^2_s + x^2 + z^2} \qquad (B1)$$

From Appendix A may be written the flux density at $dS_s$ due to $dA_L$. This is $f_v \sin \theta$. The projected area of $dS_s$ normal to r is $dS_s(\sin \gamma)$. The product of these two terms and the surface absorptivity is the flux into the suit at $dS_s$ from $dA_L$.

$$\alpha_{so} f_v (\sin \theta)(\sin \gamma) dS_s \qquad (B2)$$

It is apparent from the figure that

$$\sin \theta = y_s/\sqrt{y^2_s + x^2 + z^2} \qquad (B3)$$

Substituting (B1) and (B3) above, and (A3) from Appendix A, into (B2), yields

$$\alpha_{so} \epsilon_L \sigma T_L^4 \, x y_s dS_s dA_L/\pi(y^2_s + x^2 + z^2)^2 \qquad (B4)$$

Assume that the z extent of $dS_s$ is the width of the man, $w_S$, divided by some large number, n. Then

$$dS_s = (w_s/n)dy_s \qquad dA_L = dxdz \qquad (B5)$$

Substituting (B5) into (B4), and then integrating over the entire radiating surface, provides the expression for the total flux into $dS_S$ from the lunar surface. Then integrating with respect to $y_S$ between the ground and shoulder level, and multiplying by the time increment, gives the heat increment into a vertical strip. Multiplying the result by 3n yields the heat increment into the entire man, if he is assumed to be half as thick as his width.

$$\Delta h_{(L-S)R} = \left(\frac{6}{\pi}\right)\sigma \alpha_{so} \epsilon_L w_S T_L^4 \Delta t \cdot \int_0^{y_n} \int_0^{\sqrt{2R_L y_S}} \int_0^{\sqrt{2R_L y_S}} \frac{x y_s dxdzdy_s}{(y_s^2+x^2+z^2)^2} \qquad (B6)$$

With a minor approximation involved, all integrations may be performed, resulting in equation (10).

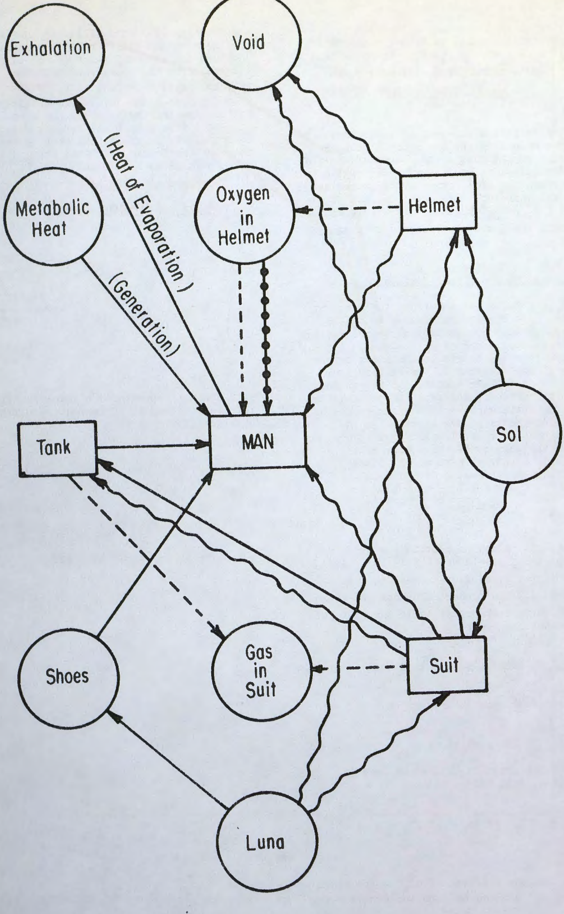


Fig. 1 - Heat Exchange Relations Between Components of System.

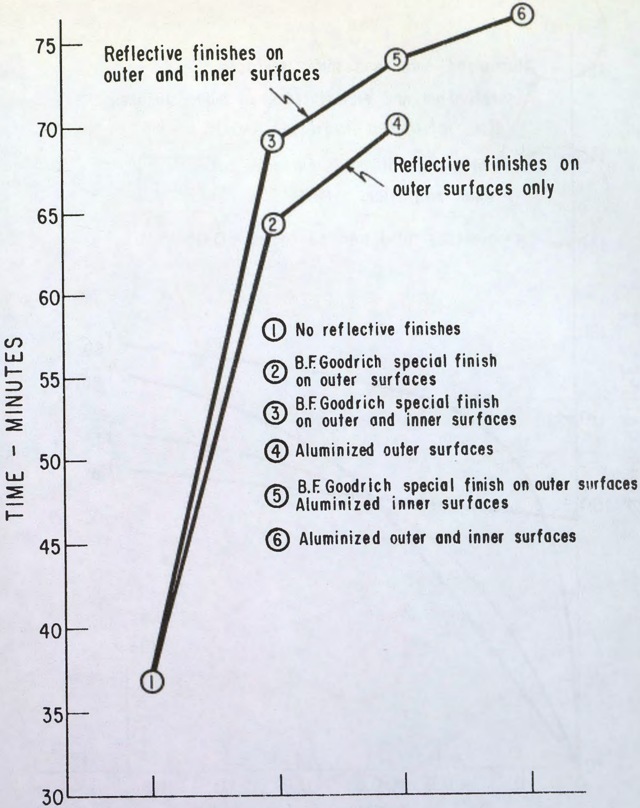


Fig. 2 - Astronaut Exposure Times on Lunar Dayside, in Relation to Suit Surface Finishes.

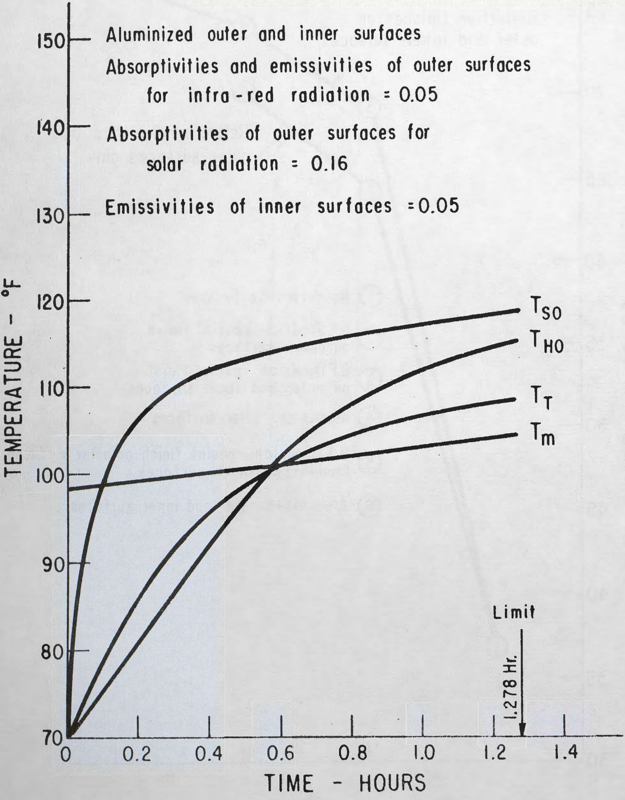


Fig. 3 - Temperature Time Curves for Case (6) of Figure 2.

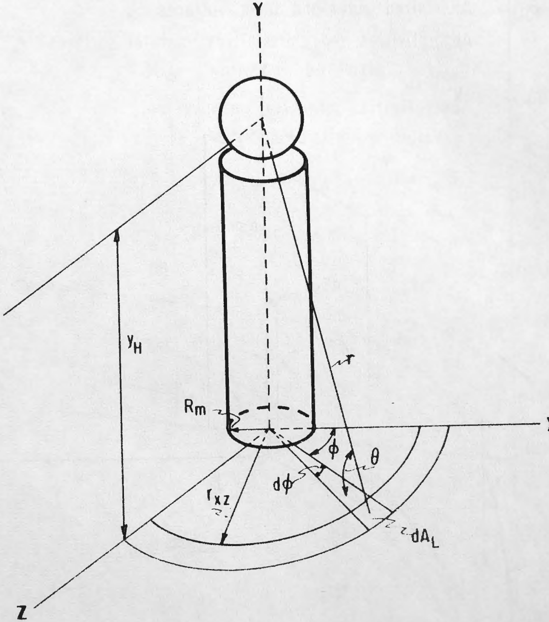


Fig. A-1 - Stylized Representation for Radiation Between Helmet and Ambient.

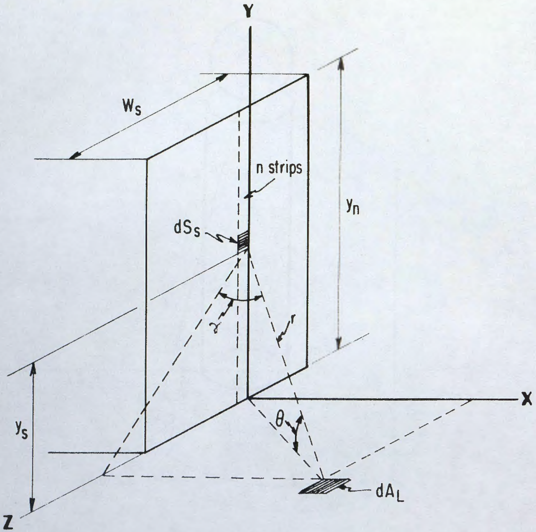


Fig. B-1 - Stylized Representation for Radiation Between Body of Suit and Ambient.