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CRITERIA FOR THERMAL REGULATION FOR MANNED SPACECRAFT CABINS

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SUMMARY

Use of man in space for observational, analytical, and experimental missions requires that a comfortable and as nearly stress-free environment as possible be provided. By use of results of engineering and physiological investigations, conditions are proposed for thermal comfort in spacecraft "shirt-sleeve" environments.

Air, cabin-wall, and skin temperatures are investigated for a range of clothing and interrelated to obtain essentially sweat-free conditions. This criterion establishes a basis for minimum individual stress and efficient design of atmospheric subsystems. Design methods are recommended in order to apply the minimal sweat condition to a wide range of work and rest levels.

Measurements are discussed that may be used to evaluate comfort conditions, taking into account airflow rate and temperature, surface temperature, and metabolic rates.

INTRODUCTION

With the advent of missions that require long-term spacecraft occupancy by man, environments that are consistent with mission objectives must be provided. These objectives are the performance and analysis of biomedical, scientific, and engineering experiments. For effective performance of these tasks, the astronaut requires a comfortable environment with as low a level of physical and mental stress as may reasonably be provided. The definition of this environment must account for physiological factors such as basic life support requirements and human thermal regulation which may be based on known or readily measured parameters. In addition, there are little-understood stresses - such as those due to the psychological and physical effects of tension, space environment, and confinement - which are receiving considerable attention but by their nature are not amenable to definitive evaluation from earth-based tests.

The purpose of this paper is to present an analysis of the engineering and physiological requirements for thermal regulation of man in space, with particular emphasis on a 0 g condition in the "shirt-sleeve" environment for long-duration missions. Criteria have been developed that are compatible with comfort over a wide range of activity (metabolic) levels and means are recommended whereby sweat rates may be limited. Although minimal sweat rate is a desirable objective, it is realized that this condition will not be attainable at all times. Minimal-sweat-rate conditions provide the basis for minimum individual thermal stresses and efficient design of atmospheric subsystems.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units (SI). Factors relating these two systems of units are presented in reference 1.

A	surface area of average man, taken as 19.35 foot^2 (1.80 meter^2)
B	rate of heat loss to environment in exhaled breath, Btu/hour (joules/hour)
C	rate of heat loss to environment by convection, Btu/hour (joules/hour)
E	rate of heat loss to environment by evaporation, Btu/hour (joules/hour)
G	unit mass flow rate, slugs/minute-foot^2 (kilograms/minute-meter^2)
I	insulating effect, $^{\circ}$F/Btu/hour-foot^2 ($^{\circ}$C/joules/hour-meter^2)
M	excess metabolic heat, Btu/hour (joules/hour)
p	partial pressure of water vapor in air, millimeter of mercury
R	rate of heat loss by radiation, Btu/hour (joules/hour)
S	rate of change of heat content of body, Btu/hour (joules/hour)
t	temperature, $^{\circ}$F ($^{\circ}$C)
V	velocity of air, feet/minute (meters/minute)
v	specific volume of air, foot^3/slug (meter^3/kilogram)

Subscripts:

a	air
cl	clothes
g	globe
max	maximum
req	required

s skin

std standard conditions, 68° F (20° C), 14.7 psia (101.4×10^3 N/m^2)

w wall

STATEMENT OF PROBLEM

Due to physiological requirements associated with long missions, astronauts in future spacecraft such as the Manned Orbital Research Laboratory or interplanetary-mission vehicles will use space suits only for extravehicular activity, emergency, or exploration of lunar or other surfaces. Cabins will be designed for "shirt-sleeve" environments which, with a limited range of clothing, will provide comfortable conditions for the range of activities from sleeping to routine desk work. However, in a limited-volume spacecraft there will also be exercise requirements and perhaps periods of relatively heavy work. Environmental factors include reduced total atmospheric pressures and a 0 g environment where heat transfer by natural convection does not apply. For the normal earth-surface environment, there have been extensive analytical and experimental investigations of comfort conditions by the air-conditioning and heating industries. Results of these studies are available in the literature of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, and its predecessor societies. In addition there have been extensive physiological investigations of man's external (skin) and internal (rectal, heart, brain, etc.) body temperatures with regard to comfort and acclimation for a wide range of activity levels.

However, there is a lack of specific information for the system designer who needs to optimize combinations of air temperature, airflow rate, and wall temperature in spacecraft cabins. These parameters and their effect on heat transfer may be predicted on the basis of known heat-transfer relations.

Many of the parameters concerned with personnel comfort in an Earth environment are those of interest in a spacecraft environment and include air temperature, airflow rate, humidity, wall temperature, clothes, and astronaut physiological factors. Other factors which must be considered and which are particularly significant in the design of spacecraft are (1) the absence of gravitational forces, (2) weight-power limitations, and (3) the relative freedom to control surface temperatures to meet overall design objectives. Thus, the problem is essentially one of providing design information on the parameters of interest for efficient human thermal regulation in manned spacecraft cabins.

In order to develop a basis for solutions in this problem area consider, first, man as the source of heat and, second, man's heat rejection to the spacecraft environment. Also, since the basic problem is one of providing conditions so that man is comfortable under a variety of activity (metabolic) rates, it is necessary to consider comfort criteria and how these vary over the conditions of interest. Each of these areas is discussed in the following paragraphs.

HEAT GENERATION

Man, as a constant-temperature machine, is a relatively inefficient source of energy based on an input-output analysis. There is no way to turn him "off" when not required, and even when sleeping he has a heat generation (excess metabolic heat rate). Excess metabolic heat rate in this paper means that rate at which heat must be rejected in order to maintain constant body temperature.

Man generates excess metabolic heat at rates from about 250 Btu/hr (2.64×10^5 J/hr) while sleeping to 4800 Btu/hr (50.68×10^5 J/hr) or higher at maximum work output. Typical rates for various activities at normal earth conditions are given in the following table (based on refs. 2 and 3):

Activity	Excess metabolic heat rate	
	Btu/hr	J/hr
Sleeping	250	2.64×10^5
Sitting quietly	350 to 400	3.70×10^5 to 4.22×10^5
Light desk work	500 to 600	5.28×10^5 to 6.33×10^5
Moderate work (standing and walking around)	800 to 1000	8.45×10^5 to 10.56×10^5
Heavy work (sustained)	1600 to 2400	16.89×10^5 to 25.34×10^5
Maximum exertion	3000 to 4800	31.68×10^5 to 50.68×10^5

The excess metabolic heat rates for the activities cited in the table may be different under reduced- or zero-gravity conditions. For instance, the results presented in reference 4 indicate higher metabolic rates for subjects performing certain tasks when reduced or zero gravity is simulated by using a low-friction environment (with the subject standing on roller bearings). The studies reported in reference 5 indicate that metabolic rates can be higher, lower, or unchanged relative to 1 g values, depending on the task, work efficiency, acclimation, and other factors. This area needs a great deal of detailed study before significant conclusions can be reached.

HEAT REJECTION

For a man who is sitting quietly and has an excess metabolic rate of 400 Btu/hr (4.22×10^5 J/hr), heat rejection is typically distributed, for the earth environment, as follows (ref. 3):

Heat-transfer rate	Body heat-loss rates	
	Btu/hr	J/hr
Radiation	190	2.00×10^5
Convection	120	1.27×10^5
Evaporation	90	0.95×10^5
Total	400	4.22×10^5

Under spacecraft conditions of 0 g, there is no natural convection, and convective heat transfer is supplied only by forced airflow. Thus, typically, radiative and evaporative heat transfer would be larger factors in a space environment.

It is important to recognize that heat rejection by convection and radiation is dependent on environmental conditions. Additional heat rejection is supplied by evaporation of sweat. Sweating rate is internally controlled. Except for cold conditions, there is a minimum sweat rate of about 0.1 lb/hr (45.4 g/hr) which accounts for heat rejection of 90 Btu/hr (0.95×10^5 J/hr). As other means of heat rejection vary or activity rate increases, the sweat rate is regulated in conjunction with moderate changes in skin temperature for thermal regulation.

The applicable heat-balance equation for man in any environment is

$$M = R + C + E + B + S \tag{1}$$

The excess metabolic heat rate M and the evaporation heat-loss rate E are always positive. The values of radiation R, convection C, and breath B are normally positive but may be negative, dependent on environmental conditions.

Heat exchange due to breath B is small and may be neglected as may the change in body heat content S if equilibrium conditions are assumed. Then

$$M = R + C + E_{req} \tag{2}$$

where E_{req} is the amount of heat transfer by evaporation needed to maintain body temperature.

Heat-transfer equations have been developed and reported by a number of investigators (e.g., refs. 2, 3, 6, and 7) for the applicable modes of heat transfer, convection, radiation, and evaporation.

From empirical equations developed by using theoretical and experimental correlation techniques for a nude man in the earth environment (ref. 2), the following equivalents are obtained:

$$R = 22\left(t_s - t_w\right) \tag{3}$$

$$C = 2\sqrt{V_{std}}\left(t_s - t_a\right) \tag{4}$$

or, for any atmospheric density, equation (4) is

$$C = 2\sqrt{Gv_{std}}\left(t_s - t_a\right) \tag{5}$$

Effective values for mean radiant (wall) temperature in equation (3) may be obtained by calculation from measured values of globe temperature obtained by using a globe thermometer, eupatheoscope, or thermal integrator (ref. 8). The commonly used instrument, a Vernon globe thermometer, may be a 6-inch-diameter (15.3 cm) copper sphere, painted flat black on the outside, and with a thermometer bulb or thermocouple at its center. The temperature measured at equilibrium is the result of a balance of radiant and convective heat transfer on the globe. Since the emissive and absorptive characteristics of the human skin and most clothes approach those of the black sphere, the resultant temperature balance of the globe is indicative of the net radiative heat transfer of man.

Evaporation of sweat as a further means of heat rejection from the body is dependent on environmental conditions. The ability of the environment to provide evaporative cooling, determined by the empirical equation from reference 2, is

$$E_{max} = 10(V)^{0.4}\left(p_s - p_a\right) \tag{6}$$

or, for any atmospheric density, may be written

$$E_{max} = 10\left(Gv_{std}\right)^{0.4}\left(p_s - p_a\right) \tag{7}$$

CLOTHES

In cold environments, clothes are used to keep man warm; however, in warm environments and under working conditions, clothing provides an insulating effect or a barrier to heat rejection. In any event, except for special conditions such as the high temperature and low humidity of the desert, lower environmental temperatures are required for comfort of clothed man than for nude man, but a minimum amount of clothing is desirable. In a spacecraft where the control of environmental temperatures will be limited, the addition or removal of clothing will be a significant factor in human thermal control. It would be anticipated that activities requiring maximum mental effort or manual dexterity (light desk work) would dictate the most comfortable clothes, with garments added or removed for other activities. Light-desk-work clothing as considered in this report consists of a lightweight shirt and trousers and appropriate underwear.

In order to study the effect of the probable range of clothing available to astronauts, environmental criteria are determined for both nude and clothed man. Of course, the temperature response of a man wearing few clothes, such as during exercise periods, would approach the temperature response of a nude man. However, primary emphasis is on the comfort criteria for the man doing light desk work and wearing light-desk-work clothing.

For a 1 g environment, a nude man sitting at rest is comfortable for air and wall temperatures of 86° F (30° C) with an air velocity of about 20 ft/min (6.1 m/min) (ref. 9). The addition of clothing requires lower temperatures for comfort. A standard clothing unit, the "clo," has been defined in reference 9 as that amount of clothing required to keep a resting individual comfortable for air and wall temperatures of 70° F (21° C) with an air velocity of 20 ft/min. The insulating effect of this clothing is (ref. 9)

$$I_{cl} = 0.88 \frac{^{\circ}\mathrm{F}}{\mathrm{Btu/hr\text{-}ft^2}} = 0.18 \frac{^{\circ}\mathrm{C}}{\mathrm{kg\text{-}cal/hr\text{-}m^2}} \tag{8}$$

By using this value of I_{cl} the effective average temperature of clothes and exposed skin for heat-rejection calculations may be expressed as

$$t_{cl} = t_s - \frac{MI_{cl}}{A} \tag{9}$$

where A is the surface area of an average man.

As developed in reference 9, the clo may also be related to temperature difference with 1 clo being equal to the insulation effect required for comfort for a 16° F (9° C) drop in environmental temperature (i.e., from 86° (30° C) to 70° F (21° C)), 2 clo for a 32° F (18° C) drop, and so forth. It is, of course, necessary to maintain the same metabolic rate and air movement rates.

The clo as defined relates to the earth environment where forced convection is supplemented by natural convection. For equivalent comfort in the spacecraft (0 g) environment, an air-velocity increase to 50 ft/min (15.2 m/min) was assumed to compensate for the loss of natural convection effects.

ASHRAE comfort chart (ref. 8) and additional unpublished validation tests made at Kansas State University by Ralph G. Nevins determined that 78° F (25° C) was a comfortable environmental temperature for clothed college students seated at rest. Air velocity was similar to that in the definition of the clo. Comfort sensations were determined after 3-hour exposure.

Subjects were clothed in cotton shirts and trousers plus underwear. Wool sweat socks were worn in lieu of shoes. Sixty subjects participated in the tests on a random basis.

It is interesting to note that these clothes are similar to those generally proposed for spacecraft simulation tests. By applying the temperature-difference concept of the clo, these clothes would have a value of 0.5 clo; that is, an 8° (4.5° C) drop for subject comfort.

Heat Stress

A man who is working or in a hot environment generally requires the evaporation of sweat in order to remain in thermal balance. Under these conditions two physiological requirements are important in fixing the limits of sustained heat exposure (ref. 2):

1. Body heat content should be limited so that the skin temperature does not rise above 95° F (35° C).

2. Thermal balance must be accomplished with a sweat rate not exceeding about 2.4 pounds (1.1 kg) of water per hour (2400 Btu/hr or 25.34×10^5 J/hr).

Thermal stress may be measured by relating the required sweat rate for thermal balance to the ability of the environment to evaporate the sweat. This relation, called the Heat Stress Index (HSI), is defined as follows:

$$HSI = 100 \times \frac{E_{req}}{E_{max}} \tag{10}$$

where E_{max} is determined from equation (6) or (7) and has an upper value of 2400 Btu/hr (25.34×10^5 J/hr) in this relation. E_{req} is defined in equation (2).

Physiological implications of exposure to stress represented by HSI values for an 8-hour working day are as follows (based on ref. 2):

HSI	Physiological and hygienic implication
-10 to -20	Mild cold strain
4 to 8	No thermal strain
10 to 30	Mild to moderate heat strain - impairs higher intellectual functions
40 to 60	Severe heat strain - requires physically fit and acclimatized individuals
70 to 90	Very severe heat strain - only small percentage of the population may qualify after medical examination and acclimation
100	Maximum strain tolerated daily by fit acclimatized young men

Introduction and definition of the heat stress index in this analysis is not meant to suggest that the design objective for spacecraft environments should be such that there will be a "design" thermal stress. However, it is recognized that because of the variation of activities of an astronaut there will be some periods of thermal stress.

Decreasing the sweat rates $\left(E_{req}\text{ reduced}\right)$ to the minimal value (about 0.1 lb/hr or 45.4 g/hr) will minimize thermal strain and thereby provide for more effective performance of the spacecraft occupants during periods requiring maximum mental activity. Potential methods for controlling sweat rate during periods of high work output are discussed subsequently.

An additional factor with regard to thermal stress is that of physiological acclimation or adaptation of man to environments. An important example is the substantial adaptation of man to cold or hot environments after some period of time - usually 7 to 10 days - as reported in references 10 and 11. This phenomenon has been extensively investigated and reported in physiological studies (i.e., refs. 10, 11, 12, and bibliography). The net effect of this acclimation is reduced sensitiveness to the warm or cold environment because of changes in blood flow patterns, sweat rates and salinity, and other automatic physiological changes. However, little quantitative information is presently available that could be used for design purposes.

MAN'S THERMAL CONTROL

Man is a round or oval heat-transfer body with cylindrical extremities - head, arms, and legs. The legs and arms are temperature-controllable extended surfaces. In a warm environment, the hands and feet sweat and the arms and legs are at about the same temperature as the body surface. However, in a cold environment, the surface temperatures of arms, hands, legs, and feet will remain only a few degrees above the ambient temperature and thus limit heat loss. For example, in tests reported in reference 7, men in a 15° C (59° F) environment for a month had foot temperatures of 17° C (63° F) with no ill effects. Thus, it should be recognized that the internal temperature regulatory system of the body has a number of unique automatic control methods that are not available in machine or equipment temperature control.

As mentioned previously, man is a variable-surface-temperature heat-transfer body incorporating a control system for temperature regulation. It is postulated in references 10, 12, and 13 that the basic thermal control mechanism is in the brain (hypothalamus) with a variation in the "set-point" of the human thermostat based on a weighted skin-temperature level. For example, at a given hypothalamic temperature an increase in skin temperature would increase sweating rate. Also, for a constant skin temperature an increase in activity (metabolic) rate, which increases hypothalamic temperature, will increase sweat rate. However, a need exists for a relation between activity levels and human thermostat temperatures in order to define required skin temperatures for high activity (metabolic) rates with minimal sweat rates.

Average skin temperatures of 93° F (34° C) with local variations of about 5° F (3° C) on the body and head and 8° F (4.5° C) on the hands and feet have been recommended in references 10, 13, 14, and 15 as suitable for a man in a shirt-sleeve environment. However, as recommended in references 10 and 13, it is necessary to lower skin temperatures several degrees in order to maintain minimal sweat rates for periods of high activity.

For physical comfort and physiological well-being, there are additional requirements to be met. For example, if a man were to stand with one foot in a bucket of ice water (32° F or 0° C) and the other foot in a bucket of hot water (132° F or 55° C), mathematically he should be comfortable since the "average" environmental temperature is 82° F (28° C), or comfortable. However, it is obvious that he will be uncomfortable. Thus, temperatures at particular locations must be held within limits regardless of "average values." The hands and feet are less temperature sensitive than other parts of the body.

A further means available for heat rejection is that of direct conduction of heat from the skin to cooling surface. Examples of this are the use of cool floors and other direct-contact surfaces such as flowing liquids in plastic tubes held to or worn on the body, legs, or arms. This concept is being developed in space-suit programs and would appear to have application in spacecraft cabin areas where there are high metabolic rates, such as in the exercise area.

The recommended course based on presently available information is to provide controllable environmental conditions to obtain a skin temperature of 93° ± 5° F (34° ± 3° C). The control range would allow for individual differences in desired temperatures as well as some downward adjustment for high metabolic periods.

SPACECRAFT CABIN DESIGN

As computed from the previously presented equations and the comfort criteria of a skin temperature of 93° F (34° C), figure 1 shows the relative values of air temperature, wall temperature, and air velocity required for comfort in a spacecraft (0 g) at a cabin pressure of 14.7 psia (101.4×10^3 N/m^2). Conditions are for a clothed individual seated at a desk, doing light work - metabolic rate of 550 Btu/hr (5.81×10^5 J/hr). The sweat rate was assumed to be the normal minimal rate of 90 Btu/hr (0.95×10^5 J/hr). Thus, heat rejection by radiation and convection is 460 Btu/hr (4.85×10^5 J/hr). Air velocities shown are for standard air density. For reduced-total-pressure atmospheres, air velocity would be increased to maintain convective heat-transfer rate. Actually, the airflow per unit area (unit mass-flow rate) must be maintained constant for constant convective heat transfer if air and skin temperatures are held constant, as shown in equation (5).

Although the curves of figure 1 are for air velocities up to 200 ft/min (61.1 m/min), air velocities in excess of about 50 ft/min (15.2 m/min) probably would not be used because of the increase in fan horsepower (increases as the cube of velocity) and potential draft sensation. Increasing air velocity from 50 to 100 ft/min (15.2 to 30.5 m/min) allows an increase of only about 2° F (1° C) when air and wall temperatures are equal.

There is a relatively larger effect of wall (mean radiant) temperature than of air temperature in the air-velocity range from about 25 to 50 ft/min (7.6 to 15.2 m/min) than in higher air-velocity ranges.

For example, at an air velocity of 50 ft/min a 10° F (6° C) change in wall temperature is about equivalent to a 15° F (8° C) change in air temperature. At lower air velocities, the effect of wall temperature is even more dominant.

Figure 2 shows the change in convective and radiative heat transfer for different air and wall temperatures. The results are based on an average skin temperature of 93° F (34° C), an air velocity (standard conditions) of 50 ft/min (15.2 m/min), and a lightly clothed (0.5 clo) individual doing light desk work.

The basic condition is for a clothed man with radiative plus convective heat transfer of 460 Btu/hr (4.85×10^5 J/hr); however, since convection and radiation occur independently the two parts of the curve also may be used independently. For example, for a 60° F (15° C) air temperature and 460 Btu/hr sensible (radiative plus convective) load, the required average wall temperature would be 73° F (22° C) as obtained by continuation of the 60° F air-temperature line horizontally to the wall-temperature scale. Also, for a 60° F air temperature (convective heat rejection equals 290 Btu/hr (3.06×10^5 J/hr)) and a total sensible load of 600 Btu/hr (6.33×10^5 J/hr), radiative heat rejection of 310 Btu/hr (3.27×10^5 J/hr) would require a wall temperature of about 67° F (19° C).

Figure 3 shows the effect of activity rates on required air and wall temperatures for clothed individuals. The clothed man at a desk ($M = 550$ Btu/hr or 5.81×10^5 J/hr) would be comfortable for air temperatures in a range from about 60° F (15° C) to 80° F (26° C) if the average wall temperatures surrounding him were varied from 73° F (22° C) to 60° F (15° C), respectively. If air temperature and mean radiant wall temperature were the same, they would be about 68° F (20° C). Note the difficulty in depressing a local radiant wall temperature sufficiently to cool a relatively active individual (a man dressed to 0.5 clo with a metabolic rate of 900 Btu/hr (9.50×10^5 J/hr), $R + C = 810$ Btu/hr (8.55×10^5 J/hr)) if the air temperature is maintained at 68° F. From figure 3, the required average wall temperature would be about 39° F (3° C). To prevent moisture condensation on the wall, a relative humidity of about 34 percent would be required. A lower relative humidity would be required if there were local surfaces below 39° F.

In space vehicles it is desirable to maintain a constant air temperature. Where light desk work and moderate activity may be carried on simultaneously in different areas, a constant but lower than usual air temperature (possibly about 60° F (15° C)) would be maintained. Average wall temperatures would be 80° F and 50° F (26° C and 15° C), respectively, for the light-desk-work and moderate-activity areas. A reduction in clothing would result in a decrease in the need for these relatively low wall temperatures. An additional factor to be considered is the favorable psychological effect of radiant heat on man. The qualitative "fireplace" and "sunshine" effects are recognized but little quantitative data are available. A method of expressing quantitatively the effects of high-intensity radiant heat on man's physiologic response and comfort is discussed in reference 16 as a part of a continuing research program.

Figure 4 shows the effect of the amount of clothing on the required air and wall temperatures in a spacecraft cabin for an individual doing light desk work. Clothing range is from 0 clo (a nude individual) to 1 clo of insulation. As would be expected, reduction of clothing requires higher temperatures for comfort. For example, removal of coat, tie, and shoes (a change from 1 clo to 0.5 clo) would allow an increase in air temperature from 48° F (8° C) to 81° F (27° C) at a constant wall temperature of 60° F (15° C). Referring again to figure 3 shows that air and/or wall temperatures could be increased for a decrease in activity rate.

CONCLUDING REMARKS AND RECOMMENDATIONS

Based on the present engineering and physiological state of the art with regard to thermal regulation of man, it is believed that with recognition of the potential problems, spacecraft may be designed for habitation with little or no thermal stress. For the astronaut doing light desk work, clothing of insulating value equal to light-desk-work clothes will be suitable for environmental temperatures of about 68° F (20° C) if the air velocity is about 50 ft/min (15.2 m/min). By using lighter clothing and/or removing part of the clothing for more active periods and adding clothing during rest, the man will be comfortable for a broad range of activities. Physiologically, it may be desirable to sweat during exercises or other periods of high activity. This would be acceptable, assuming odor and humidity were controlled. In the event that high activity periods are anticipated where profuse sweating is not desirable, control of local surfaces for radiant and conductive cooling may be applicable. Further, in rest or relaxation areas, warm panels may be used to take advantage of the pleasant sensation of radiant heat. Use of clothing and heated or cooled panels are significant factors in the thermal design of spacecraft cabins since zoning of air temperatures and flow rates may not be feasible.

In most cases, thermal regulation should maintain average skin temperature at a comfortable level so that the minimal sweat rate is maintained. Based on the best data presently available, during conditions of resting or light desk work, skin temperature should be maintained at about 93° F (34° C) with local skin temperatures not varying by more than about 5° F (3° C) from the average value. For higher work rates (which will tend to increase hypothalamic temperatures), the skin temperature must be lowered to provide minimal sweat conditions.

Design curves and parameters presented in this paper indicate the factors that must be considered and the type of calculations that must be made in the selection of air temperature, airflow rate, and wall temperatures for minimal sweat conditions in spacecraft. Environmental factors considered in the analysis are 0 g and normal or reduced atmospheric pressure levels.

Environmental conditions of normal (1 g) or reduced gravity levels may be treated in a conventional manner by using the skin-temperature comfort criteria presented in this analysis. However, testing will be required under spacecraft conditions to verify this extension of physiological comfort criteria to space environments.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 30, 1965.

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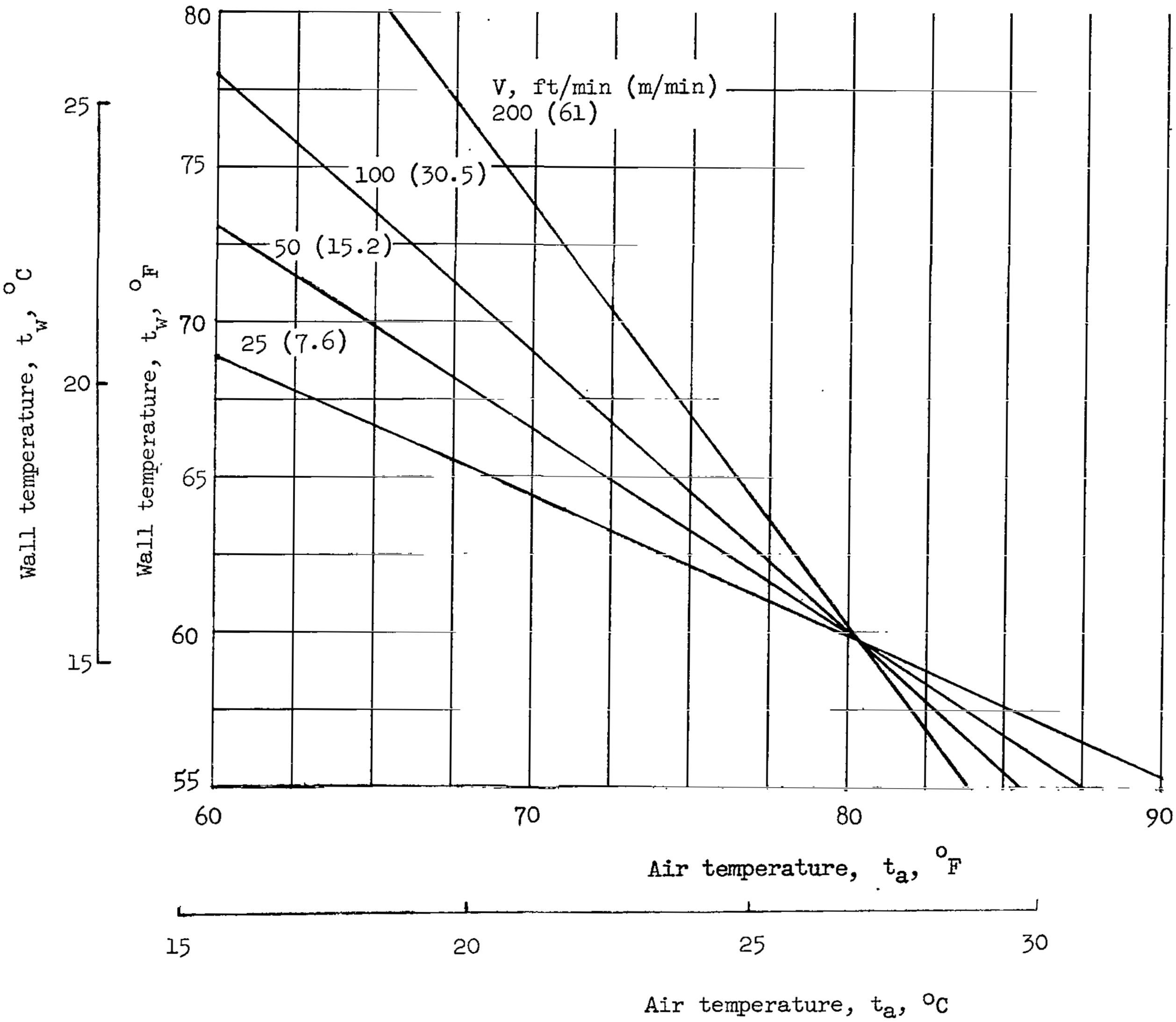

Figure 1.- Air and wall temperatures and air velocities for comfort conditions in manned spacecraft for clothed man doing light desk work. M = 550 Btu/hr (5.81×10^5 J/hr); R + C = 460 Btu/hr (4.85×10^5 J/hr); 0.5 clo.

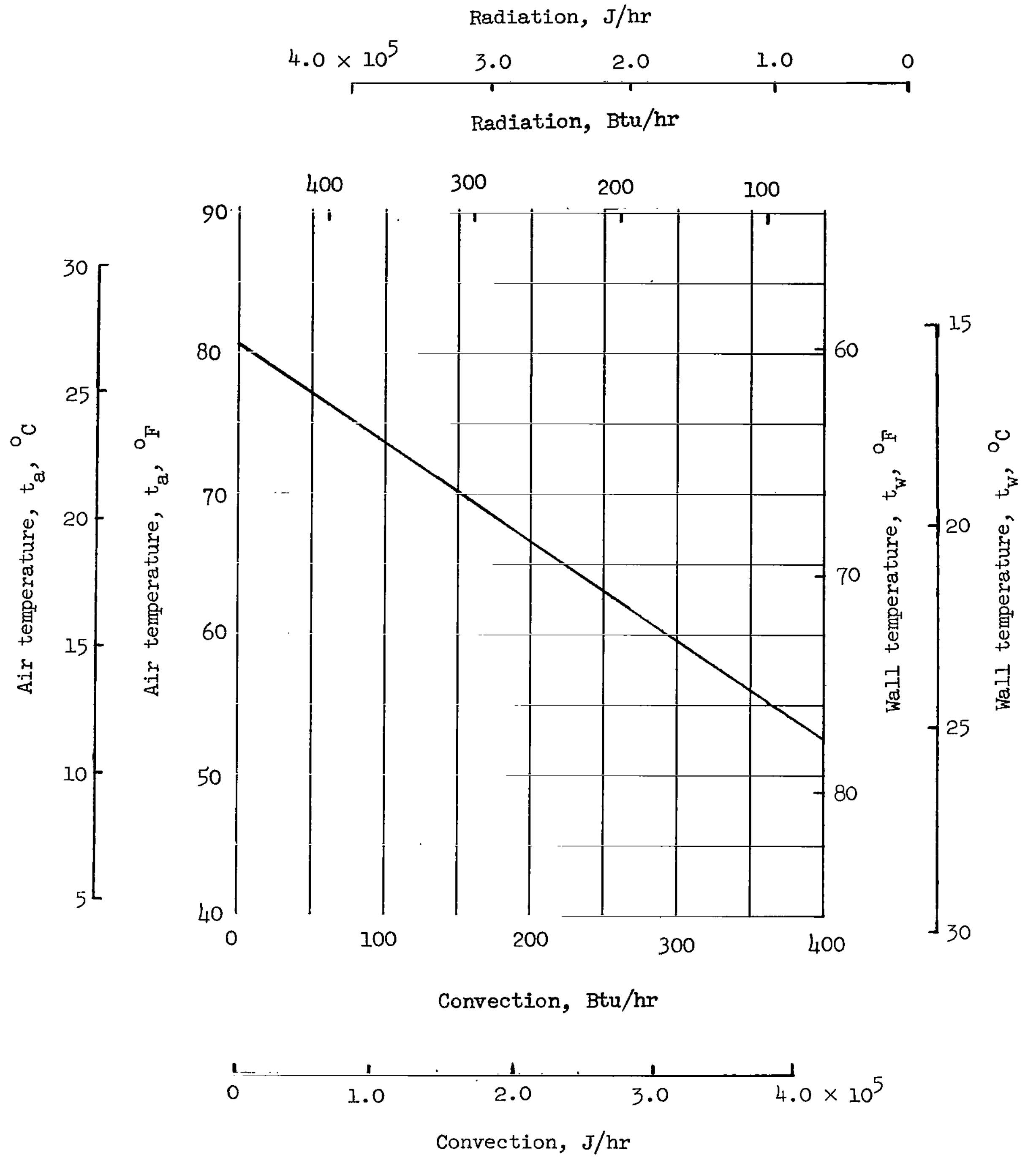

Figure 2.- Heat transfer by convection and radiation for clothed man doing light desk work in spacecraft cabins. M = 550 Btu/hr (5.81×10^5 J/hr); R + C = 460 Btu/hr (4.85×10^5 J/hr); V = 50 ft/min (15.2 m/min); 0.5 clo.

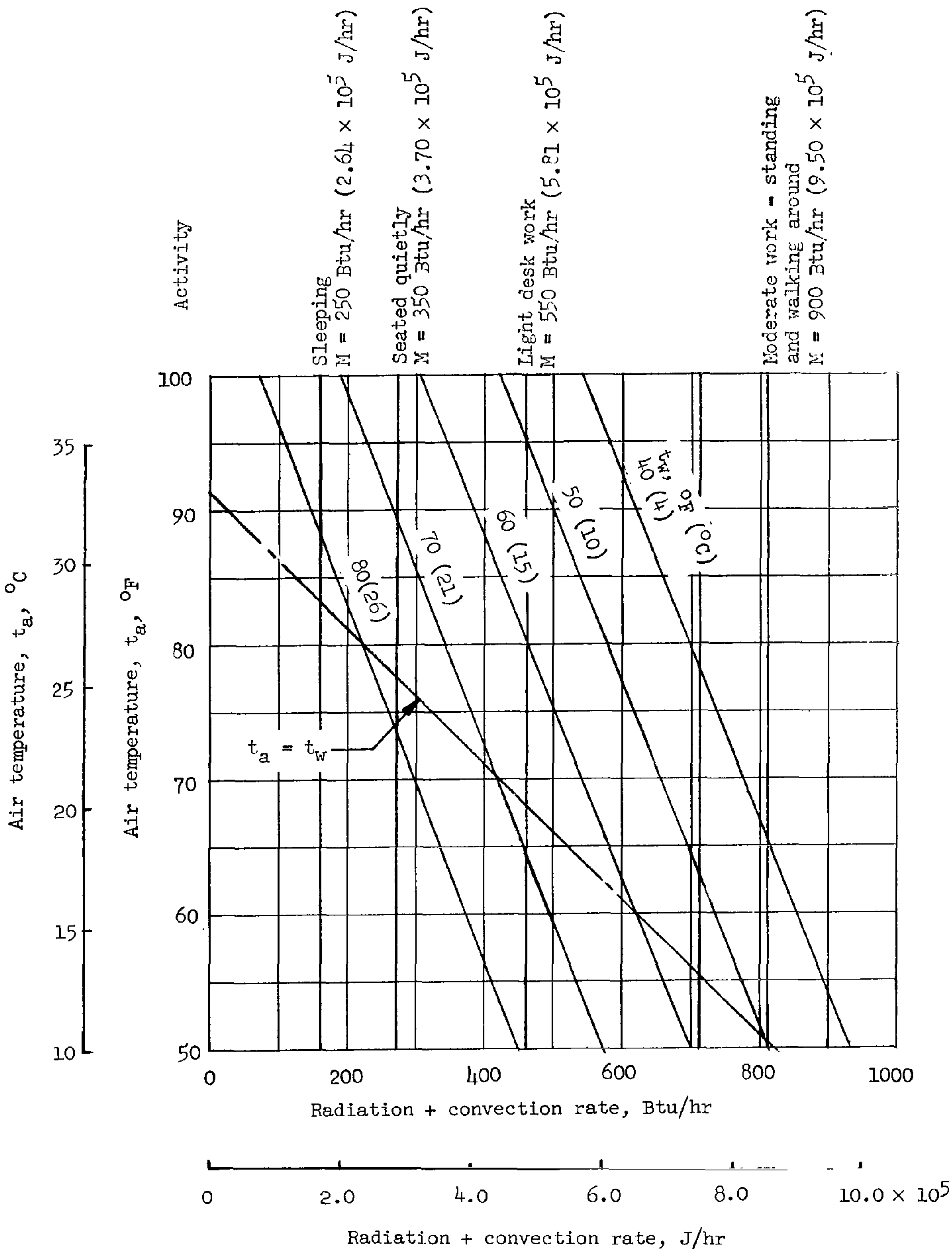

Figure 3.- Effect of activity rates on required air and wall temperatures for comfort of clothed man in spacecraft cabins. V = 50 ft/min (15.2 m/min); M = R + C = 90 Btu/hr (0.95×10^5 J/hr); 0.5 clo.

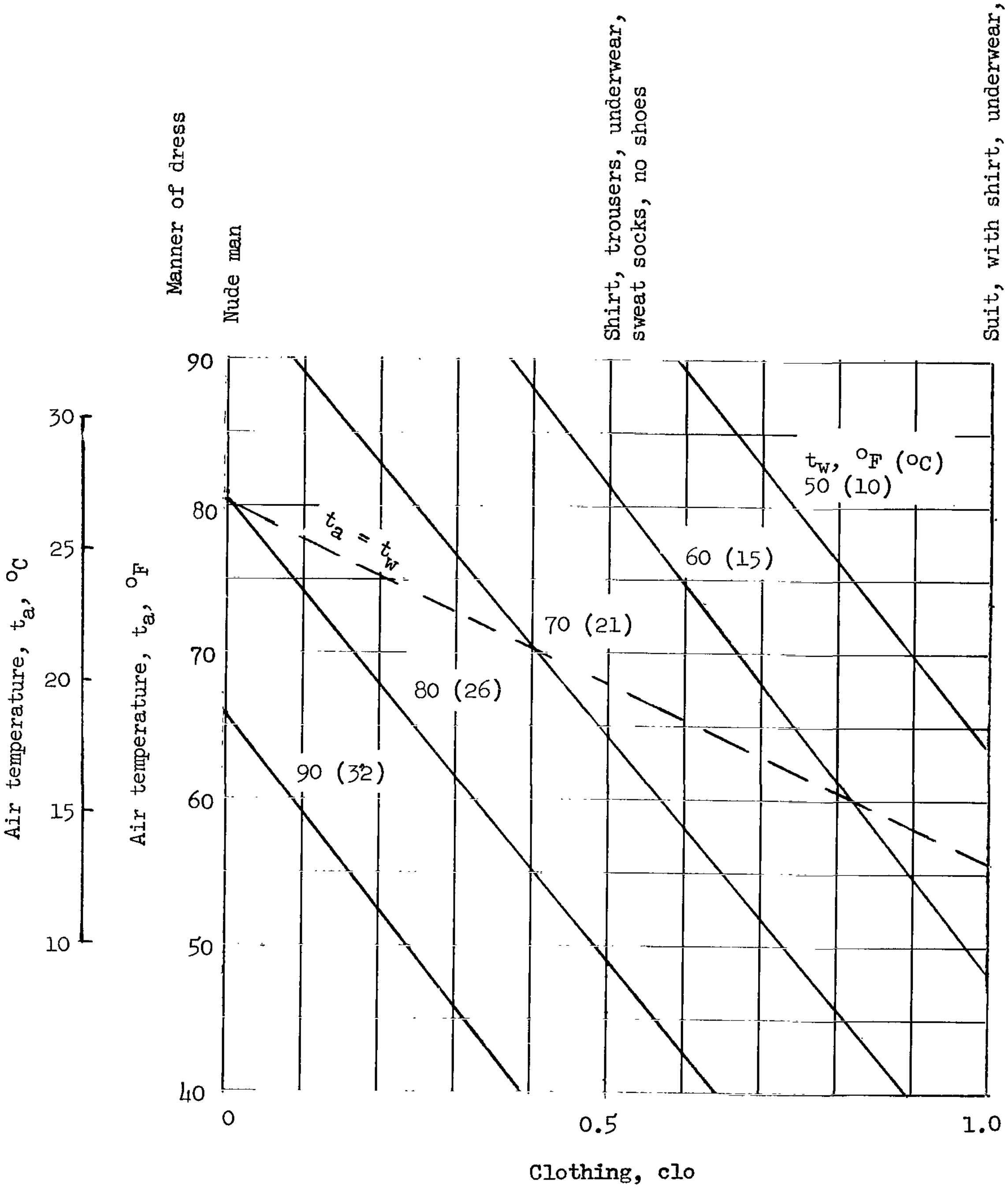

Figure 4.- Effect of amount of clothing on required spacecraft wall and air temperatures for light desk work in spacecraft cabins. M = 550 Btu/hr (5.81×10^5 J/hr); R + C = 460 Btu/hr (4.85×10^5 J/hr); V = 50 ft/min (15.2 m/min).