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SAE Aerospace Applied Thermodynamics Manual
Aerothermodynamic Systems Engineering and Design

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

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PREFACE

This document is one of 14 Aerospace Information Reports (AIR) of the Third Edition of the SAE Aerospace Applied Thermodynamics Manual. The manual provides a reference source for thermodynamics, aerodynamics, fluid dynamics, heat transfer, and properties of materials for the aerospace industry. Procedures and equations commonly used for aerospace applications of these technologies are included.

In the Third Edition, no attempt was made to update material from the Second Edition nor were SI units added. However, all identified errata were corrected and incorporated and original figure numbering was retained, insofar as possible.

The SAE AC-9B Subcommittee originally created the SAE Aerospace Applied Thermodynamics Manual and, for the Third Edition, used a new format consisting of AIR1168/1 through AIR1168/10. AIR1168/11 through AIR1168/14 were created by the SAE SC-9 Committee.

The AIRs comprising the Third Edition are shown below. Applicable sections of the Second Edition are shown parenthetically in the third column.

AIR1168/1	Thermodynamics of Incompressible and Compressible Fluid Flow	(1A,1B)
AIR1168/2	Heat and Mass Transfer and Air-Water Mixtures	(1C,1D,1E)
AIR1168/3	Aerothermodynamic Systems Engineering and Design	(3A,3B,3C,3D)
AIR1168/4	Ice, Rain, Fog, and Frost Protection	(3F)
AIR1168/5	Aerothermodynamic Test Instrumentation and Measurement	(3G)
AIR1168/6	Characteristics of Equipment Components, Equipment Cooling System Design, and Temperature Control System Design	(3H,3J,3K)
AIR1168/7	Aerospace Pressurization System Design	(3E)
AIR1168/8	Aircraft Fuel Weight Penalty Due to Air Conditioning	(3I)

AIR1168/9	Thermophysical Properties of the Natural Environment, Gases, Liquids, and Solids	(2A,2B,2C,2D)
AIR1168/10	Thermophysical Characteristics of Working Fluids and Heat Transfer Fluids	(2E,2F)
AIR1168/11	Spacecraft Boost and Entry Heat Transfer	(4A,4B)
AIR1168/12	Spacecraft Thermal Balance	(4C)
AIR1168/13	Spacecraft Equipment Environmental Control	(4D)
AIR1168/14	Spacecraft Life Support Systems	(4E)

F.R. Weiner, formerly of Rockwell International and past chairman of the SAE AC-9B Subcommittee, is commended for his dedication and effort in preparing the errata lists that were used in creating the Third Edition.

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SECTION 3A - AIR CONDITIONING LOAD ANALYSIS**1. INTRODUCTION****1.1 Scope**

This section presents methods and examples of computing the steady-state heating and cooling loads of aircraft compartments. In a steady-state process the flows of heat throughout the system are stabilized and thus do not change with time. In an aircraft compartment, several elements compose the steady-state air conditioning load. Transfer of heat occurs between these sources and sinks by the combined processes of convection, radiation, and conduction in the following manner:

1. Convection between the boundary layer and the outer airplane skin.
2. Radiation between the external skin and the external environment.
3. Solar radiation through transparent areas directly on flight personnel and equipment and on the cabin interior surfaces.
4. Conduction through the cabin walls and structural members.
5. Convection between the interior cabin surface and the cabin air.
6. Convection between cabin air and flight personnel or equipment.
7. Convection and radiation from internal sources of heat such as electrical equipment.

The subsequent paragraphs discuss methods of determining each of the heat transfer rates listed above, as well as the physiological considerations involved in the selection of proper cabin conditions that are to be maintained.

1.2 Nomenclature

A = Area, ft², in.²

a = Insulation thickness, ft

c = Velocity of sound, ft/sec

c_p = Specific heat capacity at constant pressure, Btu/lb-°F

E = Electrical equipment power consumption, watts

e_w = Skin emissivity, dimensionless

f = Friction factor, dimensionless

F_a = Configuration factor, dimensionless

F_e = Emissivity factor, dimensionless

$F_{v-skin/soil}$ = Fuselage view factor of the reflective ground, dimensionless

G_s = Total solar radiation (irradiation), Btu/hr-ft²

g = Gravitational acceleration, ft/sec²

h'_c = Equivalent conductance due to conduction and convection, Btu/hr-ft²-°F

h_i = Film conductance, Btu/hr-ft²-°F

h_o	=	External surface conductance, Btu/hr-ft ² -°F
h'_o	=	External surface conductance based on enthalpy, Btu/hr-ft ² -°F
h_r	=	Equivalent conductance due to radiation, Btu/hr-ft ² -°F
i^*	=	Reference enthalpy, Btu/lb
i_o	=	Enthalpy corresponding to free stream temperature, or enthalpy corresponding to temperature at edge of boundary layer, Btu/lb
i_r	=	Enthalpy corresponding to recovery temperature, Btu/lb
i_w	=	Enthalpy corresponding to skin temperature, Btu/lb
k	=	Thermal conductivity of air, Btu-ft/hr-ft ² -°F
k_i	=	Thermal conductivity of insulation, Btu-ft/hr-ft ² -°F
m	=	Mass, lb
M	=	Mach number, V_o/c , dimensionless
N_{Gr}	=	Grashof number, $x^3(\rho)^2 g\beta\Delta T/\mu^2$, dimensionless
N_{Nu}	=	Nusselt number, $h'_c x / k$, dimensionless
N_{Pr}	=	Prandtl number, $\mu c_p / k$ dimensionless
N_{Re}	=	Reynolds No., $V_o x \rho / \mu$, dimensionless
P	=	Pressure, lbf/ft ²
P_o	=	Ambient pressure, lbf/ft ²
q_c	=	Rate of heat flow, Btu/hr
q_{cb}	=	Total heat flow from cabin, Btu/hr
q_s	=	Total solar heat load transmitted through transparent areas, Btu/hr
r	=	Recovery factor, dimensionless
rf	=	Soil reflectance, dimensionless
t	=	Temperature, °F
ΔT	=	Difference in temperatures, °R
T_c	=	Cabin temperature, °R
T_k	=	Cargo compartment temperature, °R
T_{max}	=	Maximum allowable temperature of electrical equipment compartment, °R
T_r	=	Recovery temperature, °R
T_o	=	Outside ambient temperature, °R

T_{st}	=	Local ambient static temperature or static temperature at edge of boundary layer, °R
T_u	=	Effective temperature of outer space, °R
T_w	=	Outer skin (wall) temperature, °R
U	=	Overall conductance Btu/hr-ft ² -°F
V_o	=	Free stream velocity or velocity at edge of boundary layer, ft/sec
W	=	Amount of cabin air required to cool electrical equipment, lb/hr
x	=	Thickness or length, ft
Z	=	Compressibility factor, dimensionless
α_s	=	Solar absorptance, dimensionless
β	=	Volumetric thermal expansion coefficient, dimensionless
ρ	=	Density, lb/ft ³
τ	=	Overall solar transmissivity of transparent area, dimensionless
γ	=	Specific heat ratio, c_p/c_v , dimensionless
η	=	Efficiency or effectiveness, dimensionless
μ	=	Absolute viscosity, lb/ft-sec
σ	=	Stefan-Boltzmann constant, 0.171×10^{-8} , Btu/hr-ft ² -°R ⁴

1.3 Common Abbreviations

ARDC	—	Air Research and Development Command
ASME	—	American Society of Mechanical Engineers
ASHRAE	—	American Society of Heating, Refrigeration and Air Conditioning Engineers
Btu	—	British thermal unit
Eq.(Eqs.)	—	Equation(s)
°F	—	Degrees Fahrenheit
Fig.(Figs.)	—	Figure(s)
fpm, ft/min	—	Feet per minute
fps, ft/sec	—	Feet per second
ft	—	Feet
hr	—	Hour
in.	—	Inch
lb	—	Pound mass

lbf	— Pound force
lbf/ft ²	— Pounds force per square foot
lb/hr	— Pounds mass per hour
min	— Minute
mph	— Miles per hour
no.	— Number
%	— Percent
Par.(Pars.)	— Paragraph(s)
°R	— Degrees Rankine
Ref.	— Reference
sec	— Second
WADC	— Wright Air Development Center (U.S. Air Force)

2. PHYSIOLOGICAL REQUIREMENTS

The maintenance of a comfortable and safe environment for human occupancy involves the simultaneous control of the temperature, moisture content, movement, purity, and absolute pressure of the air in occupied areas. In many applications, consideration of cost and weight make it impractical to control all factors that maintain ideal conditions, but in all cases sufficient control must be maintained to provide for the safety of the occupants and to ensure that the mission of the aircraft can be accomplished. As this section is concerned with the calculation of air conditioning thermal loads, only the temperature and humidity requirements will be considered here. For a more detailed discussion of physiological requirements, refer to Refs. 2 and 4.

The conditions required for comfort in an occupied area depend to a large extent on the individual. Conditions that are comfortable for one person may be decidedly uncomfortable for another. However, certain conditions have been determined to be comfortable for a large number of persons. The combinations of temperature, humidity, and air movement that cause comfort or discomfort have been tabulated and are expressed as “effective temperature.”

2.1 Effective Temperature

The effective temperature is an experimentally determined index of the degree of warmth experienced by individuals on exposure to different combinations of temperature, humidity, and air movement. The numerical value of the effective temperature for a given set of conditions is the temperature of saturated, slowly moving (15-25 ft/min) air that results in the same feeling of warmth. The effective temperature cannot be measured directly, but must be obtained from charts (such as Fig. 3A-1) for various conditions of temperature, humidity, and air movement.

Lines of constant effective temperature show conditions that will produce equal sensations of warmth, but not necessarily equal sensations of comfort. Some degree of discomfort will be experienced at very high or very low relative humidity, high air velocity, or extreme temperatures, regardless of the effective temperature.

In summer the most popular effective temperature appears to be 71°F, and in winter, 68°F. However, the effective temperature index must be used with discretion since it is an experimentally determined index, based on tests of United States inhabitants who are normally clothed. Also, the tests that established the index were performed with convective type heating systems where radiation was not a factor. The summer index applies to persons completely adapted to artificial air conditions, which require from 1-1/2 to 3 hr exposures.

3. STATEMENT OF HEATING AND COOLING LOAD EQUATIONS

3.1 Heat Transfer Between the Air and Skin

The heat transfer between the air and the airplane skin is determined by an equation of the form

$$q_c = h_o A (T_2 - T_1) \quad (3A-1)$$

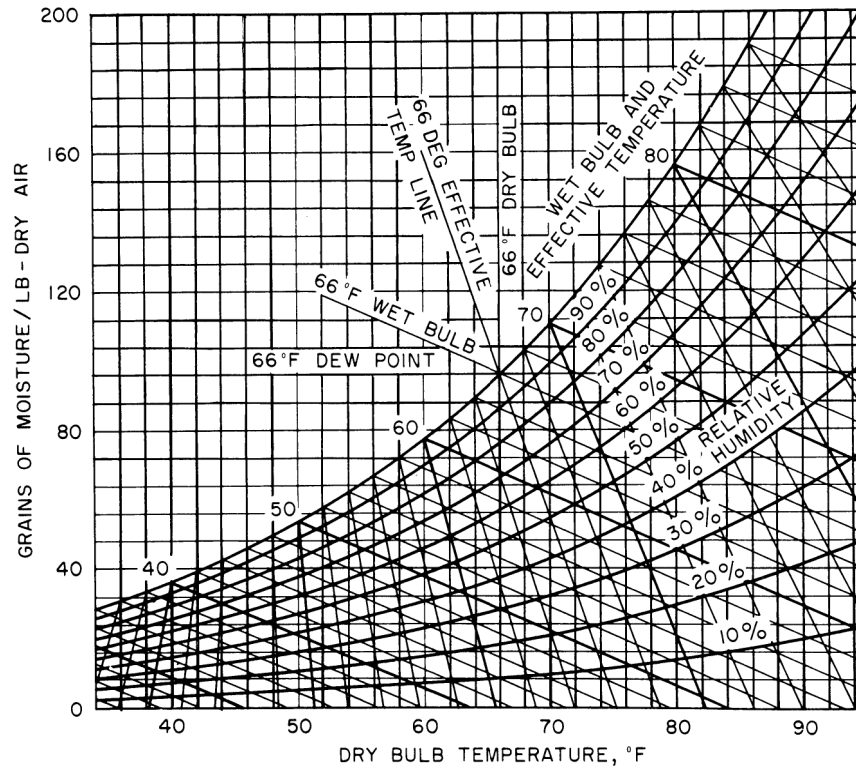


Figure 3A-1 - Psychrometric Chart, Persons at Rest, Normally Clothed, in Still Air

3.1.1 Ground Static Conditions

At ground static conditions, Eq. 3A-1 becomes:

$$q_c = h_o A (T_o - T_w) \quad (3A-2)$$

For this case, h_o may be evaluated in the same manner as the internal coefficient h_i discussed in Par. 3.2.2. The value of h_o may be obtained from Eq. 3A-25 at the design velocity. The outside wind velocity for design purpose is usually taken as 22 ft/sec unless it is known to be different for a particular application. For a velocity of 22 ft/sec, h_o has the value 8.9 Btu/hr-ft²-°F.

The evaluation of the skin temperature, T_w , necessary to solve Eq. 3A-2, is a tedious process, but as will be shown in Par. 3.2.1, it can be omitted by determining an overall coefficient of heat transfer from outside to inside. If it is necessary or desirable to determine the skin temperature, a heat balance at the skin must be formed as described in Par. 4.3.

3.1.2 Flight Condition

For flight conditions, Eq. 3A-1 takes the form

$$q_c = h_o A(T_r - T_w) \quad (3A-3)$$

$$\text{where } T_r = T_o \left[1 + r \left(\frac{\gamma - 1}{2} \right) M^2 \right] \quad (3A-4)$$

The recovery factor, r , has the value $\sqrt{N_{Pr}}$ for laminar flow and $\sqrt[3]{N_{Pr}}$ for turbulent flow. The determination of surface conductance for use in Eq. 3A-3 is more involved than for the ground static case and is the subject of the next paragraph.

3.1.2.1 Determination of Surface Conductance for the Flight Condition

In recent years (circa 1955-1965) much work has been done in the field of high velocity heat transfer, with most of it directed to the problem of aerodynamic heating. From this work, several methods of determining the film coefficient were evolved. The method given here is described in detail by Eckert in Ref. 5 and is known as the reference temperature method.

When the property values in the equations that describe the flow and heat transfer are evaluated at the reference temperature, the variation of the friction factor with Mach number and T_w/T_o vanishes. The equations required to evaluate the reference temperature and the surface conductance are as follows:

$$T^* = 0.5(T_o + T_w) + 0.22r \left[\frac{\gamma - 1}{2} \right] M^2 T_o \quad (3A-5)$$

$$\rho^* = \frac{P}{RT^*} \quad (3A-6)$$

$$N_{Re}^* = \frac{V_o \rho^* x}{\mu^*} \quad (3A-7)$$

$$\frac{f^*}{2} = \frac{0.332}{(N_{Re}^*)^{0.5}} (\text{laminar flow}) \quad (3A-8)$$

$$\frac{f^*}{2} = \frac{0.0296}{(N_{Re}^*)^{0.2}} (\text{turbulent flow}) \quad (3A-9)$$

$$Dh_o = \frac{\rho^* c_p^* (f^* / 2)}{(N_{Pr}^*)^{0.667}} (3600) V_o \quad (3A-10)$$

where T^* = Reference local static temperature, °R

x = Distance from origin of boundary layer, ft

In the preceding equations the asterisk superscript denotes the reference temperature and property values evaluated at the reference temperature. The equations are solved for a given flight condition as follows:

1. Assume a skin temperature T_w and solve Eq. 3A-5 for the reference temperature.
2. Solve the remaining equations, evaluating the fluid properties at the reference temperature. The resulting h_o , from Eq. 3A-10, is the surface conductance corresponding to the assumed skin temperature T_w .
3. Utilizing Eq. 3A-2 and the procedure described in Par. 4.2, determine by an iterative procedure the equilibrium skin temperature.

Note: See Par. 8 for a sample calculation.

Dissociation Effects — At air temperatures above about 3000°R, air begins to dissociate, and the specific heat increases rapidly, since dissociation energy as well as thermal energy is being absorbed. When this happens, temperature is no longer a correct measure of the energy content of the air, and it must be replaced by a corresponding enthalpy. Also, when dissociation occurs, the gas constant R changes.

This change is accounted for by introducing a compressibility factor, Z , which must be used in computations involving the gas constant. To allow for dissociation effects, certain of the equations in Pars. 3.1.2 and 3.1.2.1 must be modified as follows:

$$i^* = 0.5(i_w + i_o) + 0.22 \left(\frac{\gamma - 1}{2} \right) M^2 i_o r \quad (3A-11)$$

$$\rho^* = \frac{P}{RT^* Z} \quad (3A-12)$$

$$h_o' = \frac{\rho^* V_o (f^* / 2) c_p^*}{(N_{Pr}^*)^{0.667}} (3600) \quad (3A-13)$$

$$q_c = h_o' (i_r - i_w) \quad (3A-14)$$

The method of solution of Eqs. 3A-11 to Eq. 3A-14 combined with the unaffected equations of Par. 3.1.2.1 is essentially the same as when using the reference temperature method directly. An outer skin temperature is assumed and a corresponding i_w is determined. Eq. 3A-11 is then solved for i^* . A T^* corresponding to i^* is determined and the remaining equations evaluated, using fluid properties corresponding to T^* . An iterative procedure is then used to determine the equilibrium skin temperature.

3.2 Heat Transfer Between the Skin and Occupied Areas

The heat transfer between the skin and occupied areas occurs mainly by conduction, but the situation is complicated by the following factors:

1. The cabin wall usually consists of several layers of different material.
2. The construction throughout the structure is not the same; therefore, many parallel heat flow paths exist.
3. There may be dead air spaces that affect heat flow through a combination of conduction, free convection, and radiation.
4. The structural members, bulkheads, and floors usually act as fins to dissipate heat.
5. Heat transfer at the inner cabin walls is usually by convection.
6. Heat transfer may occur to or from adjacent nonconditioned compartments where the temperature is unknown or difficult to determine.

In order to simplify the calculations, it is assumed that heat flows in parallel paths and is one-dimensional; that is, the heat flows along radial lines with no circumferential or longitudinal pattern. For a discussion of methods that consider two- or three-dimensional heat transfer, refer to Ref. 6.

3.2.1 Combined Heat Transfer Through Composite Walls

The heat transfer equation for a simple composite wall as shown in Fig. 3A-2 can be written as

$$q = h_o A (T_o - T_w) \quad (3A-15)$$

$$q = \frac{k_1}{x_1} A (T_w - T_a) \quad (3A-16)$$

$$q = \frac{k_2}{x_2} A (T_a - T_b) \quad (3A-17)$$

$$q = \frac{k_3}{x_3} A (T_b - T_i) \quad (3A-18)$$

$$q = h_i A (T_i - T_c) \quad (3A-19)$$

For a steady-state process, the heat transfer is equal through each section of the wall; therefore, adding Eqs. 3A-15 to 3A-19 and solving for q gives

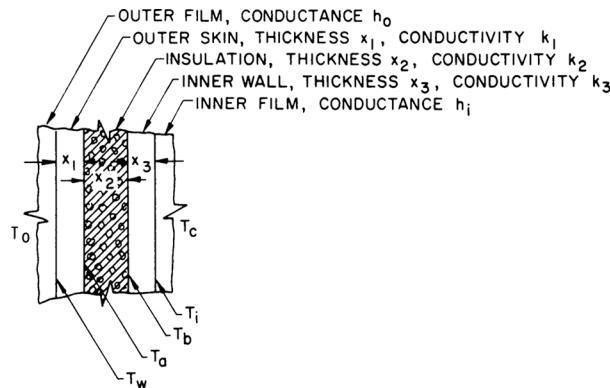


Figure 3A-2 - Simple Composite Wall

$$q = UA(T_o - T_c) \quad (3A-20)$$

where U , the overall conductance of the wall in Btu/hr-ft²-°F is given by

$$U = \frac{1}{\frac{1}{h_o} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \frac{1}{h_i}} \quad (3A-21)$$

or

$$U = \frac{1}{(1/h_o) + \left[\sum (x/k) \right] + (1/h_i)} \quad (3A-22)$$

3.2.1.1 Overall Conductance for Ground Static Heating

The maximum ground static heating load ordinarily occurs at night when solar radiation to the skin is not a factor. For this case, Eqs. 3A-20 and 3A-22 are valid as stated, with the overall conductance U based on total resistance from outside to inside.

The outside and inside film coefficients, h_o and h_i , can be evaluated from Eq. 3A-25 at the design velocity, ordinarily assumed to be 22 ft/sec for the outside and 3.3 ft/sec for the inside. The thermal conductivity values can be obtained from the tables in AIR1168/9.

3.2.1.2 Overall Conductance for Ground Static Cooling

The maximum ground static cooling load occurs during the day when solar radiation to the skin is a factor. For this case, Eqs. 3A-20 (see Fig. 3A-2) and 3A-22 take the form

$$q = UA(T_w - T_c) \quad (3A-23)$$

$$U = \frac{1}{\left[\sum (x/k) \right] + (1/h_i)} \quad (3A-24)$$

The difference is that, owing to solar radiation, the skin temperature may be higher than ambient temperature, thus requiring a heat balance at the skin to determine skin temperature, as shown in Par. 4.3. The overall conductance and heat transfer are determined from equations that apply from the outer skin to the cabin.

3.2.1.3 Overall Conductance for Flight Below Mach 2

In flight, at subsonic and low supersonic Mach numbers, the conductance of the outer film, h_o , is large in comparison with the conductance of the rest of the wall, and the effects of radiation to and from the skin are usually insignificant. Therefore, the skin temperature can be considered equal to the recovery temperature and can be determined as shown in Par. 4.1. The overall wall conductance and heat transfer can be determined using Eqs. 3A-23 and 3A-24.

3.2.1.4 Overall Conductance for Flight Exceeding Mach 2

In flight, at Mach numbers exceeding Mach 2, aerodynamic heating becomes significant and the skin temperature becomes hot enough to radiate considerable heat away from the skin to the atmosphere. The skin temperature is ordinarily lower than the recovery temperature and may be evaluated by the method shown in Par. 4.2. The overall conductance and heat transfer can be determined from Eqs. 3A-23 and 3A-24.

3.2.2 Internal Coefficient of Heat Transfer

Heat transfer between the inner walls and the air in the compartments occurs by forced convection due to cabin ventilating air or by free convection in unventilated spaces. Very little work has been done to determine accurate values of heat transfer coefficients under conditions directly applicable to aircraft cabins. However, experiments that have been conducted for commercial application provide an indication of values to be expected in aircraft applications.

An equation that fits a curve given in Ref. 2 for the surface film coefficient is

$$h_i = 2.0 + 0.314V_o \quad (3A-25)$$

The values from Eq. 3A-25 are actually reported for stucco from Ref. 2, but since these are the largest values reported, it is recommended that this equation be used unless better data are available. Generally, air velocities in an occupied compartment will be in the range 0 – 3.3 ft/sec. Therefore, h_i will have the range 2.0 – 3.04 Btu/hr-ft²-°F under ordinary conditions. It should also be noted that Eq. 3A-25 may be used to determine the outside surface conductance, h_o , for ground static conditions.

3.2.3 Heat Transfer Across an Enclosed Airspace

Often a composite wall includes an airspace between the outer skin and inner wall, as illustrated in Fig. 3A-3. The heat transfer across such an airspace occurs by a combination of conduction, radiation, and convection. It is convenient to lump the convective and conductive heat transfer together as an equivalent conductance and to consider heat transfer by radiation separately as an equivalent conductance due to radiation. The resulting equation for heat transfer across an airspace is (see Fig. 3A-3)

$$q = h'_c A(T_2 - T_3) + h_r A(T_2 - T_3) \quad (3A-26)$$

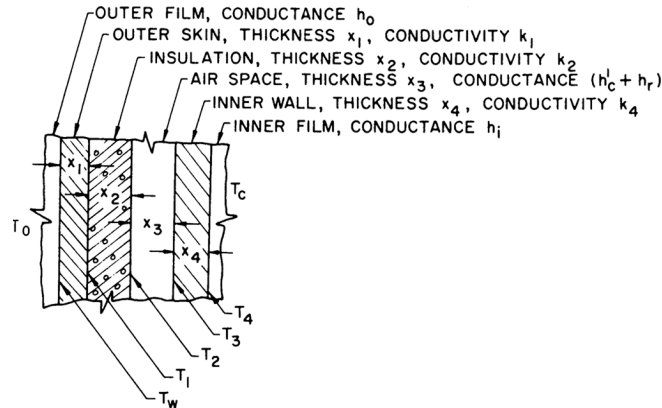


Figure 3A-3 - Simple Composite Wall Including an Air Space

To solve Eq. 3A-26, the surface temperatures T_2 and T_3 must be known. Also, as shown in Pars. 3.2.3.1 and 3.2.3.2, temperatures T_2 and T_3 are required to evaluate h'_c and h_r . This means that an iterative procedure is required to obtain an exact solution. A suggested procedure is as follows:

1. Estimate an equivalent conductance for the air space.
2. Compute the overall conductance of the wall from

$$U_{wc} = \frac{1}{\sum \left(\frac{x}{k} \right) + \left(\frac{1}{h'_c + h_r} \right) + \frac{1}{h_i}} \quad (3A-27)$$

(See Fig. 3A-3.)

3. Compute the surface temperatures T_2 and T_3 from

$$U_{wc}(T_w - T_c) = U_{w2}(T_w - T_2) \quad (3A-28)$$

$$U_{wc}(T_w - T_c) = U_{3c}(T_3 - T_c) \quad (3A-29)$$

where U_{wc} = Overall conductance of wall (wall-to-cabin), Btu/hr-ft²-°F

U_{w2} = Overall conductance from outer wall to inner surface of air space, Btu/hr-ft²-°F

$$U_{w2} = \frac{1}{(x_1/k_1) + (x_2/k_2)} \quad (3A-30)$$

U_{3c} = Overall conductance from inner surface of air space to cabin, Btu/hr-ft²-°F

$$U_{3c} = \frac{1}{(x_4/k_4) + (1/h_i)} \quad (3A-31)$$

4. Compute the equivalent conductance of the air space by the methods of Pars. 3.2.3.1 and 3.2.3.2.
5. With the computed conductance of the air space, return to step 2 and compute the overall conductance of the wall. For the desired accuracy, repeat this procedure until two successive values of the overall conductance agree.

3.2.3.1 Equivalent Conductance of an Air Space Due to Conduction and Convection

The equivalent conductance of an air space may be determined as a function of the Grashof number, Prandtl number, Nusselt number, and the length/width ratio of the air space, by using the following equations:

1. Vertical air spaces (walls enclosing air spaces are vertical):

$$\frac{h'_c x}{k} = 1 \text{ for } N_{Gr} \leq 2000 \quad (3A-32)$$

$$\frac{h'_c x}{k} = \frac{0.20}{(L/x)^{1/9}} (N_{Gr} N_{Pr})^{0.25} \text{ for } 2 \times 10^4 \leq N_{Gr} \leq 2.1 \times 10^5 \quad (3A-33)$$

$$\frac{h'_c x}{k} = \frac{0.071}{(L/x)^{1/9}} (N_{Gr} N_{Pr})^{0.333} \text{ for } 2.1 \times 10^5 \leq N_{Gr} \leq 1.1 \times 10^7 \quad (3A-34)$$

2. Horizontal air spaces (walls enclosing air spaces are horizontal):

$$\frac{h'_c x}{k} = 0.21 (N_{Gr} N_{Pr})^{0.25} \text{ for } 10^4 \leq N_{Gr} \leq 3.2 \times 10^5 \quad (3A-35)$$

$$\frac{h'_c x}{k} = 0.075 (N_{Gr} N_{Pr})^{0.333} \text{ for } 3.2 \times 10^5 \leq N_{Gr} \leq 10^7 \quad (3A-36)$$

where ΔT = Difference in surface temperatures, °R (used in N_{Gr})

L = Height of air space, ft

x = Width of air space, ft

3. Inclined air spaces - For air spaces inclined at an angle from the horizontal, it is satisfactory to interpolate between the values for horizontal and vertical air spaces.

The preceding equations are plotted for vertical and horizontal air spaces in Fig. 3A-4.

3.2.3.2 Equivalent Conductance of an Air Space Due to Radiation

Radiant heat exchange is proportional to the difference of the fourth power of the absolute temperature of the surfaces emitting and receiving the radiant energy:

$$q = \sigma A F_a F_e (T_2^4 - T_3^4) \quad (3A-37)$$

(see Fig. 3A-3) where

F_e = Emissivity factor, a function of the emissivities and the configuration of the surfaces, dimensionless

F_a = Configuration factor, a function of the configuration of the surfaces, dimensionless

Since the heat transfer due to convection and conduction is proportional to the difference of the first power of the temperature, it is convenient to determine an equivalent conductance due to radiation that can be used with the first power of the temperature. This can be done by setting the second term of Eq. 3A-26 equal to Eq. 3A-37 and solving for h_r (see Fig. 3A-3):

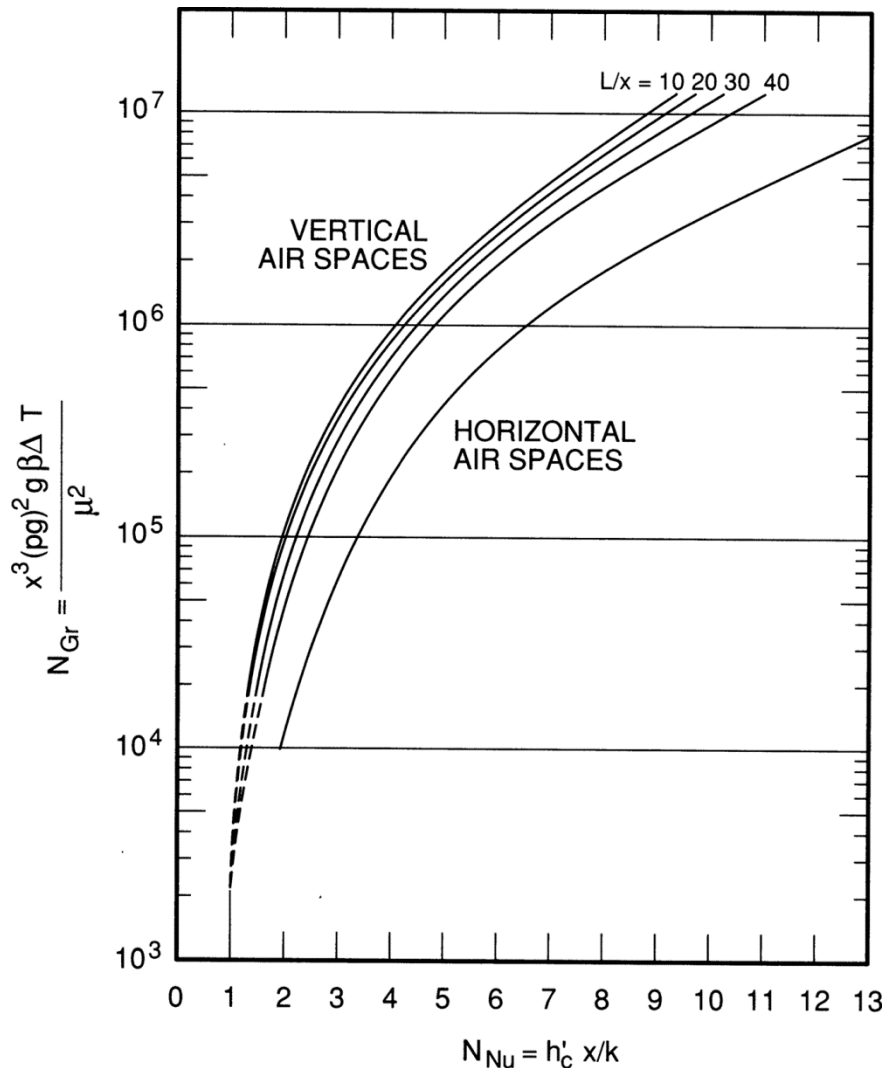


Figure 3A-4 - Nusselt Number versus Grashof Number for Vertical and Horizontal Air Spaces. Note: $N_{Pr} = 0.72$

$$h_r = \frac{\sigma F_a F_e (T_2^4 - T_3^4)}{(T_2 - T_3)} \quad (3A-38)$$

Values of h_r are plotted in Fig. 3A-5 for various values of surface temperature and for $F_a F_e = 1$. For other values of $F_a F_e$, the h_r obtained from Fig. 3A-5 must be multiplied by the correct $F_a F_e$. The configuration and emissivity factors for infinite parallel planes give a good approximation to those for dead air spaces. The configuration factor is 1, and the emissivity factor is:

$$F_e = \frac{1}{(1/e_2) + (1/e_3) - 1} \quad (3A-39)$$

(see Fig. 3A-3) where e_2 and e_3 are the emissivities of walls enclosing the air space.

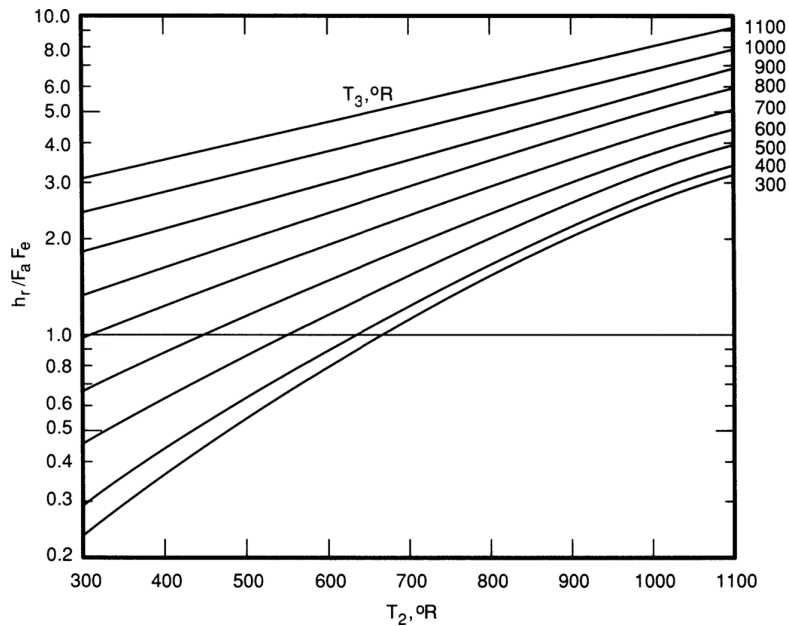


Figure 3A-5 - Equivalent Heat Transfer Coefficient for Radiation

3.2.4 Fin Effect of Structural Members

Structural members that are attached to the aircraft skin and protrude into the cabin interior, such as fuselage frames, can be considered as fins.

For the purpose of this analysis, it is assumed that the base of the frame is in contact with the skin and therefore is at skin temperature. The heat transfer from a plain fin in contact with the skin, as shown in Fig. 3A-6, can be determined using Eq. 3A-40:

$$q = Cu_c L \frac{\tanh m_f L}{m_f L} (T_w - T_c) \quad (3A-40)$$

where C = Perimeter of fin

$$= 2(b + \delta), \text{ ft (see Fig. 3A-6)}$$

L = Projection of fin into cabin, ft

$$m_f = \sqrt{u_c C / kA}, \text{ ft}^{-1}$$

u_c = Unit conductance of surface of fin, including insulation, Btu/hr-ft², given by $1/[(1/h_i) + (a/k_i)]$

and where, for u_c and m_f , respectively,

A = Conduction cross-sectional area of fin

$$= b\delta, \text{ ft}^2$$

a = Insulation thickness, ft

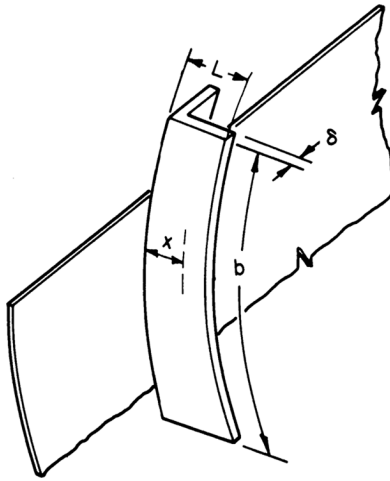


Figure 3A-6 - A Simple Fin

Eq. 3A-40 can be written as

$$q = Cu_c L \eta_f (T_w - T_c) \quad (3A-41)$$

where $\eta_f = \frac{\tanh m_f L}{m_f L}$ = Fin effectiveness, dimensionless

Fig. 3A-7 plots η_f as a function of $m_f L$.

Another factor to be considered, especially for noninsulated fins, is the temperature distribution along the fin. It is undesirable from a comfort standpoint to have very cold or very hot surfaces in occupied areas. The temperature distribution along a fin, shown in Fig. 3A-6, is solved by

$$\frac{T_x - T_c}{T_w - T_c} = \frac{\cosh m_f (L - x)}{\cosh m_f L} \quad (3A-42)$$

where T_x is the temperature of the surface of the fin at a distance x from the wall. Eq. 3A-42 is plotted in Fig. 3A-8 for various values of x/L and $m_f L$.

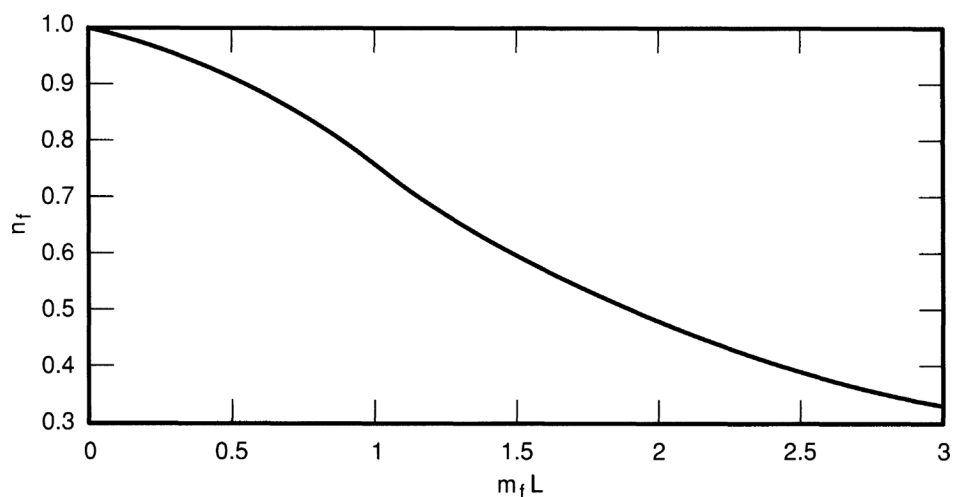


Figure 3A-7 - Fin Effectiveness Factor

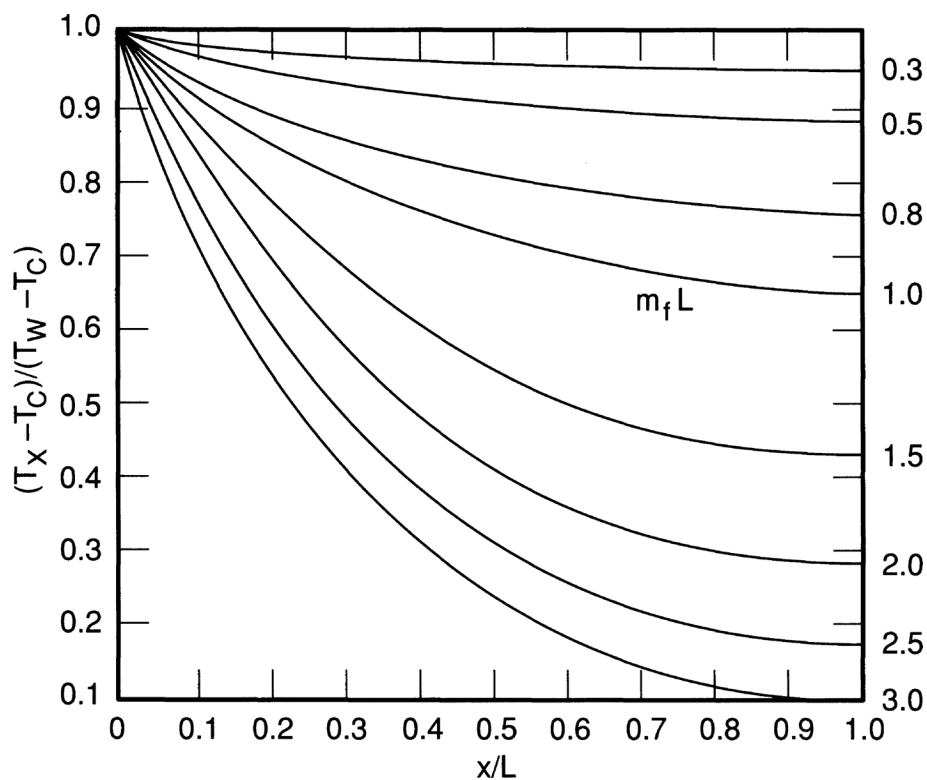


Figure 3A-8 - Temperature Distribution Along a Fin

4. SKIN TEMPERATURE COMPUTATIONAL METHODS

4.1 Skin Temperature at Flight Conditions Less Than Mach 2

In the flight range below Mach 2, it is satisfactory to assume that the skin temperature is equal to the recovery temperature:

$$T_w = T_r = T_o \left[1 + r \left(\frac{\gamma - 1}{2} \right) M^2 \right] \quad (3A-43)$$

When this assumption for skin temperature is used, the outside film conductance, h_o , is not to be included in the computation of the overall conductance, U , of the wall.

4.2 Skin Temperature at Flight Above Mach 2

At approximately Mach 2 the skin temperature becomes high enough for radiation from the skin to become significant. To determine accurately the skin temperature under these conditions, a heat balance at the skin must be written as follows:

$$h_o(T_r - T_w) = -\alpha G_s \frac{A_p}{A} - \alpha G_s (rf) F_{v-skin-soil} + U(T_w - T_c) + \frac{1}{2} \sigma F_e F_a (T_w^4 - T_u^4) + \frac{1}{2} \sigma F_e F_a (T_w^4 - T_e^4) \quad (3A-44)$$

where $h_o(T_r - T_w)$	= Heat transferred to the skin by aerodynamic heating, Btu/hr-ft ²
$\alpha G_s (A_p/A)$	= Heat gained by solar irradiation, Btu/hr-ft ²
$\alpha G_s (rf) (F_{v-skin/soil})$	= Heat gained by solar irradiation reflected from ground (Albedo), Btu/hr-ft ²
$U(T_w - T_c)$	= Heat lost by skin through cabin walls to cabin interior, Btu/hr-ft ²
$(1/2) \sigma F_e F_a (T_w^4 - T_e^4)$	= Heat radiated from lower half of airplane skin to earth's surface, Btu/hr-ft ²
$(1/2) \sigma F_e F_a (T_w^4 - T_u^4)$	= Heat radiated from upper half of airplane skin to atmosphere, Btu/hr-ft ²
α_s	= Solar absorptance, dimensionless
A_p/A	= Ratio of projected area of fuselage to the total area, dimensionless
T_e	= Mean temperature of earth's surface, °R
F_e	= Emissivity factor, dimensionless
F_a	= Configuration factor, dimensionless
rf	= Soil reflectance, dimensionless
$F_{v-skin/soil}$	= Fuselage view factor of the reflective ground, dimensionless

At high altitudes, the solar irradiation intensity is approximately 430 Btu/hr-ft² (from Ref. 7 or other sources). For a body of revolution, the value of A_p/A is $1/\pi$. The configuration factor for fuselage shapes is 1 and the emissivity factor is equal to the emissivity of the skin, e_w . The effective temperature of space is assumed to be 0°R and of the earth's surface to be 510°R. (At lower altitudes, T_{sky} values available on line should be used.) The albedo becomes insignificant at altitude. α_s is assumed to be 0.25 for white paint on aluminum. (See AIR1168/12 for additional values.) By substituting these numerical values into Eq. 3A-44 it can be seen that

$$h_o(T_r - T_w) = -0.25 \frac{430}{\pi} + U(T_w - T_c) + 0.173 e_w \left(\frac{T_w}{100} \right)^4 - 58.52 e_w \quad (3A-45)$$

The equilibrium skin temperature can be determined from Eq. 3A-45 in conjunction with the methods outlined in Par. 3.1.2 by an iterative procedure. Such a procedure is as follows:

1. Compute the overall wall conductance, U .
2. Determine the emissivity, e_w , of the skin and select the desired cabin temperature, T_c .
3. Assume a wall temperature, T_w .
4. Solve Eq. 3A-45 for the convective heat transfer rate, $h_o(T_r - T_w)$.

5. For the known flight conditions and the assumed wall temperature, compute, using the methods described in Pars. 3.1.2 and 3.1.2.1, the convective heat transfer rate from Eq. 3A-3.
6. If the skin temperature assumed in step 3 is correct, the convective heat transfer rate computed in steps 4 and 5 will be equal. If not, assume a new skin temperature and repeat the process.

4.3 Skin Temperature at Ground Static Conditions

For ground static conditions, the heat balance at the skin is identical to that determined by using Eq. 3A-44, but some of the numerical quantities used to establish Eq. 3A-45 are different for the sea level case. The solar irradiation intensity at sea level can be taken as 360 Btu/hr-ft², and the effective temperature of outer space is assumed to be 410°R.

Note: Typical values of the effective temperature of outer space (also known as T_{sky}) and ground temperature are assumed. There are many derivations of these temperatures available on line that may be available for specific applications.

Albedo is given as $\alpha G_s(\text{rf})(F_{\text{v-skin/soil}})$. rf is the soil reflectance and assuming light concrete ground is 0.8. $F_{\text{v-skin/soil}}$ is the fuselage view factor of the reflective ground is assumed to be 0.5 for a view factor between a cylinder and a plane.

Substitution of the numerical values used to establish Eq. 3A-45 with the above changes gives:

$$h_o(T_o - T_w) = -0.25 \frac{360}{\pi} - 0.25[-360 \times 0.8 \times 0.5] + U(T_w - T_c) + 0.173e_w \left(\frac{T_w}{100} \right)^4 - 82.96e_w \quad (3A-46)$$

Solving Eq. 3A-46 for T_w gives:

$$T_w = \frac{T_o h_o + (90/\pi) + 36 + UT_c}{U + h_o} + \frac{82.96e_w - 0.173e_w(T_w/100)^4}{U + h_o} \quad (3A-47)$$

Eq. 3A-47 can be written as

$$T_w = B - CT_w^4 \quad (3A-48)$$

where

$$B = \frac{T_o h_o + (90/\pi) + 36 + UT_c + 82.96e_w}{U + h_o}, ^\circ R$$

$$C = \frac{0.173 \times 10^{-8} e_w}{U + h_o}, ^\circ R^{-3}$$

Values of T_w for various values of B and C are given in Fig. 3A-9.

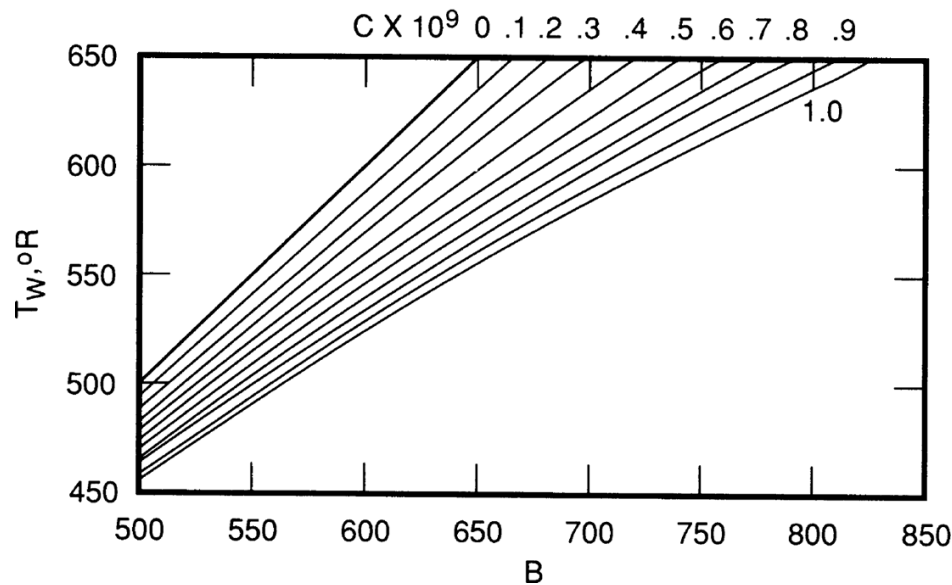


Figure 3A-9 - Average Equilibrium Skin Temperature at Ground Static Conditions

5. COOLING LOADS DUE TO RADIATION THROUGH TRANSPARENT AREAS

Solar radiation is transmitted directly through transparent areas to the cabin interior. The reradiated energy from the interior surfaces does not pass through the transparent areas because they are nearly opaque to these longer wavelengths. The solar radiant heat transmitted through transparent areas is

$$q_s = \tau G_s A_p \quad (3A-49)$$

where A_p = Projected area of transparent surface normal to sun's rays, ft²

Often a window or canopy is constructed of several layers of material in series. Sometimes these layers consist of different materials and sometimes there is an air space between the layers. In any case, the overall transmissivity is the product of the transmissivities of the individual layers:

$$q_s = (\tau_1 \cdot \tau_2 \dots \tau_n) G_s A_p \quad (3A-50)$$

6. HEATING AND COOLING LOADS DUE TO INTERNAL SOURCES

6.1 Sensible and Latent Heat Emission by Occupants

In densely occupied areas, such as the cabin of transports, the heat produced by the occupants can be a substantial factor in the total cooling load. Fig. 3A-10 shows the sensible heat production of human beings at various activity levels versus dry bulb temperature, and Fig. 3A-11 shows the latent heat production for the same conditions. The total heat production is the sum of the two. The latent heat emission is in the form of evaporated moisture (perspiration) and has no effect on the dry bulb temperature of the space.

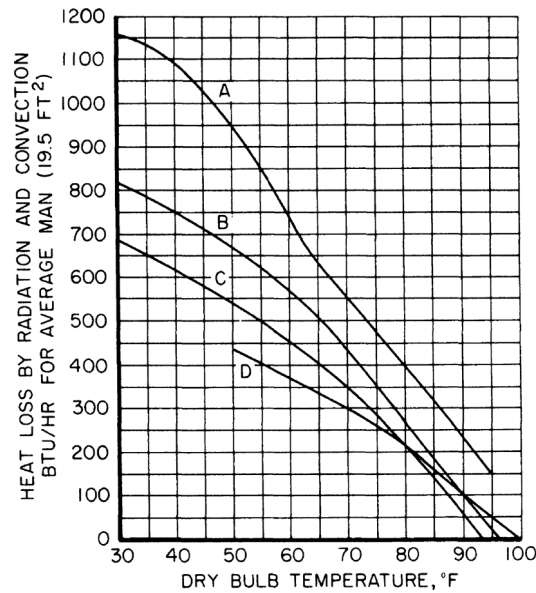


Figure 3A-10 - The Relationship between Radiation and Convection Loss from the Human Body and Dry Bulb Temperature for Still Air. (Ref. ASHRAE Guide)

For a system that uses 100% fresh air (no recirculation), the latent heat production of the occupants does not enter into the calculation of the cooling load, but does enter into a calculation of the relative humidity of the cabin. If some of the cabin air is recirculated, the latent heat production must be included in a moisture balance for the cabin and cooling equipment. Some of the moisture released by the occupants will be condensed in the cooling equipment, and this heat of condensation is a part of the total cooling load.

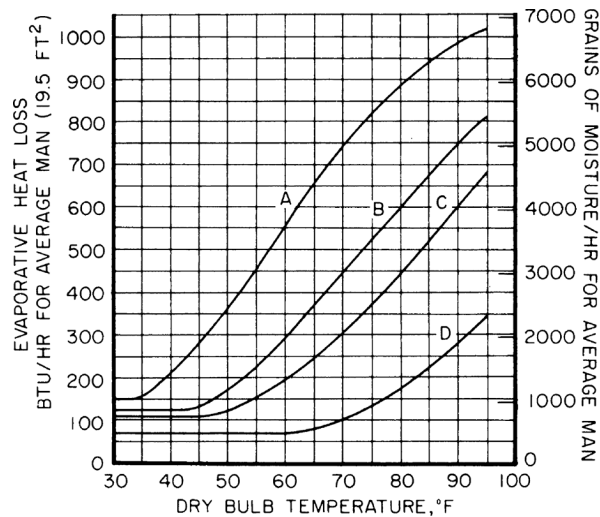


Figure 3A-11 - Evaporative Heat and Moisture Loss from The Human Body in Relation to Dry Bulb Temperature for Still Air Conditions. (Ref. ASHRAE Guide)

Fig. 3A-10 shows:

1. Curve A, persons working, metabolic rate 1310 Btu/hr.
2. Curve B, persons working, metabolic rate 850 Btu/hr.
3. Curve C, persons working, metabolic rate 660 Btu/hr.
4. Curve D, persons seated at rest, metabolic rate 400 Btu/hr.

Fig. 3A-11 shows:

1. Curve A, persons working, metabolic rate 1310 Btu/hr.
2. Curve B, persons working, metabolic rate 850 Btu/hr.
3. Curve C, persons working, metabolic rate 660 Btu/hr.
4. Curve D, persons seated at rest, metabolic rate 400 Btu/hr.

6.2 Electrical Load

The wattage rating of electrical equipment installed in modern aircraft is large. A conservative, but not unrealistic, estimate of the cooling load introduced by the electrical equipment can be obtained by assuming that the electrical equipment converts all of its energy to heat and that all of the heat is released to the cabin:

$$q_e = 3.415E \quad (3A-51)$$

where q_e = Electrical load, Btu/hr

E = Power input to electrical equipment, watts

Usually all or a portion of the cabin air is exhausted overboard at cabin temperature. Also, the electrical equipment usually can operate in an ambient atmosphere warmer than the cabin. If it is possible to enclose the electrical equipment in a compartment isolated from the cabin and to pass a portion of the cabin air through this compartment before exhausting it overboard, the contribution of the electrical load to the cabin cooling load can be reduced. The amount of cabin air required to completely absorb the electrical load is

$$W = \frac{q_e}{0.24(T_{max} - T_c)} \quad (3A-52)$$

where W = Amount of cabin air required to cool electrical equipment, lb/hr

The contribution of the electrical equipment to the cabin cooling load in this case is the transmission heat gain through the equipment compartment walls to the cabin. If the amount of cabin air required by Eq. 3A-52 is not available, the cabin air must be supplemented by additional air, or the cabin air must be cooled before passing it through the equipment compartment.

7. PRACTICAL CONSIDERATIONS IN THE DETERMINATION OF OVERALL HEATING AND COOLING LOADS

An exact analysis of aircraft cooling and heating loads would result in equations and methods of solution that would be impractical to handle except by large digital and analog computers. The prediction of skin temperature alone has been the subject of dozens of technical papers and possibly by as many computer programs.

The temperature distribution in the structure as a result of aerodynamic heating is more complicated than the methods of predicting skin temperature. Usually, in high performance aircraft and missiles, the cooling problem is transient and never reaches a true steady-state condition. Therefore, it must be recognized that the methods presented here have been simplified considerably to reduce the problem to one that can be handled by a hand calculator. This is not to suggest that the methods presented here are of limited value or that a computer must be used to obtain acceptable results.

For subsonic and low supersonic applications, the methods presented here usually are adequate. For missile or high supersonic applications, the methods presented can serve as a preliminary or "first approximation" to the final answer. Usually some preliminary design calculations must be made to estimate system weight and envelope before the design becomes firm enough to conduct a more exact analysis.

7.1 Conditions that Establish Heating and Cooling Loads

Since aircraft operate over a wide range of altitudes, speeds, and ambient conditions, it is necessary to compute the loads for several conditions to establish a complete envelope. The usual procedure is to compute the loads for several altitudes at the maximum and minimum speeds of the aircraft and at the maximum and minimum temperatures expected.

7.1.1 Maximum Flight Condition Requiring Heating

The maximum flight condition requiring heating may be defined as follows:

1. Minimum airplane speed.
2. Cold day.
3. Minimum electrical load.
4. Zero solar load.
5. Minimum crew and passenger load.
6. Minimum temperatures in adjoining compartments.
7. Maximum passenger compartment temperature required for the condition under consideration.

7.1.2 Maximum Flight Condition Requiring Cooling

The maximum flight condition requiring cooling can be defined as follows:

1. Maximum airplane speed.
2. Hot day.
3. Maximum electrical load.
4. Maximum passenger and crew load.
5. Maximum solar load.
6. Maximum temperature in adjoining compartments.
7. Minimum passenger compartment temperature required at the condition under consideration.

7.2 Example of Cooling and Heating Load Calculation

7.2.1 Flight Compartment Details

The flight deck of a hypothetical aircraft to be air conditioned is shown in Fig. 3A-12. The flight compartment is located in the forward section of the upper fuselage and accommodates a total of 12 persons. The fuselage construction in the area of the flight compartment consists of a skin with frames located approximately every 18 in. in station planes. The floor beams run laterally across the fuselage, attaching to the frames. The nominal insulation thickness is 5 in. on the fuselage walls and 3 in. under the floor and attached to the aft bulkhead.

Typical construction details are shown in Figs. 3A-13 through 3A-18. The areas have been computed from detail drawings not shown here for reasons of simplification and space limitations.

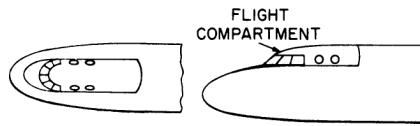


Figure 3A-12 - Flight Compartment to be Air Conditioned

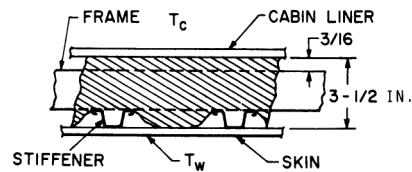


Figure 3A-13 - Construction Details: between Fuselage Frames

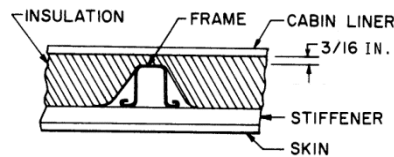


Figure 3A-14 - Construction Details: through Fuselage Frames

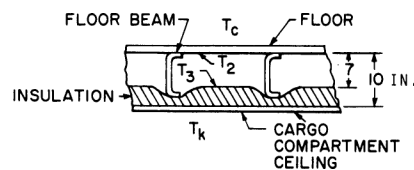


Figure 3A-15 - Construction Details: between Floor Beams

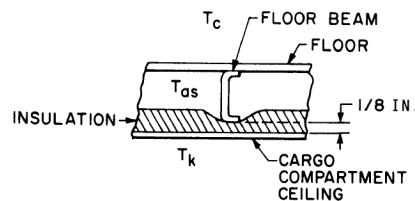


Figure 3A-16 - Construction Details: through Floor Beams

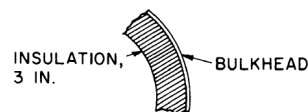


Figure 3A-17 - Construction Details: through Pressure Bulkhead

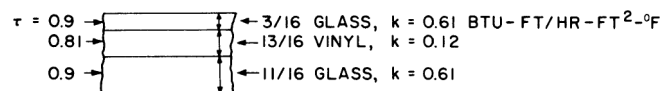


Figure 3A-18 - Construction and Thermal Details: Windshield

7.2.2 Flight and Ambient Conditions

The loads will be computed at the sea level static condition and at the 20,000 ft flight condition (see Table 3A-1). In a complete analysis, the loads would be computed at several altitudes as noted in Par. 7.1.

7.2.3 Determination of Overall Heat Transfer Coefficients

The values of conductivity, emissivity, and other physical properties used to compute overall values of heat transfer coefficients may be obtained from AIR1168/9. However, when the loads were computed, that AIR was not available, so values were obtained from various sources and may not agree with values included in AIR 1168/9.

7.2.3.1 Between Fuselage Frames

This construction is detailed in Fig. 3A-13. The 5 in. blanket is compressed to a maximum of 3.5 in. with an average of 3.25 in. (0.271 ft), considering the stiffeners. The inside coefficient, h_i , is computed from Eq. 3A-25 at an assumed inside velocity of 3.3 ft/sec:

$$h_i = 2.0 + 0.314V_o = 3.04 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

The resistance to heat flow of the metal cabin liner and outer skin in flight can be neglected in comparison with the resistance of the film and insulation. The overall conductance may be computed from Eq. 3A-24:

Table 3A-1 - Load Values at Sea Level and 20,000 Ft

Case	Condition	Altitude Ft	T_o , °R (1)	Mach No.	T_r , °R (2)	T_w , °R (2)
A	Heating	20,000	407.7	0.28	412.4	412.4
B	Heating	0	400	0	---	(3)
C	Cooling	20,000	488.3	0.89	558.5	558.5
D	Cooling	0	560	0	---	580.0 (4)

NOTES:

1. T_o = Ambient static temperature, assumed to be Standard less 40°F for heating and Standard plus 40°F for cooling except sea level heating, which is -60°F.
2. T_r = Recovery temperature = T_w = skin temperature computed from Eq. 3A-43 with $r = 0.90$.
3. For sea level heating conditions, skin temperature is not required (Par. 3.2.1.1).
4. Skin temperature for ground static cooling computed by methods of Par. 4.3. (See Par. 7.2.6.)
5. k assumed to be .0185 typical of a glass fiber insulation. Specification sheet of insulation to be used should be consulted. Note that "k" will vary with density, so that compressed insulation will have a different value than the same insulation that is not compressed.

$$\begin{aligned}
 U &= \frac{1}{(x/k) + (1/h_i)} \\
 &= \frac{1}{(0.271/0.0185) + (1/3.04)} \\
 &= 0.067 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$

7.2.3.2 Through Fuselage Frames

Details are shown in Fig. 3A-14. The insulation is compressed to 3/16 in. (0.0156 ft) over the frame. The frame is assumed to be at the skin temperature T_w :

$$\begin{aligned}
 U &= \frac{1}{(0.0156/0.0185) + (1/3.04)} \\
 &= 0.853 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$

7.2.3.3 Between Floor Beams

Fig. 3A-15 represents details of this construction.

$$U_{ck} = \frac{1}{\frac{1}{h_i} + \frac{x}{k} + \frac{1}{h'_c + h_r} + \frac{1}{h_i}} \quad (3A-53)$$

Since there is a dead air space between the floor and the cargo compartment ceiling, the conductance is a function of the surface temperature of the air space and may be computed by the methods described in Par. 3.2.3.

For the 20,000 ft heating case (case A) the cabin is maintained at 70°F and the cargo compartment at 45°F. Assume $h'_c + h_r = 0.32$. Then

$$\begin{aligned} U_{ck} &= \frac{1}{\frac{1}{3.04} + \frac{0.25}{0.0183} + \frac{1}{0.32} + \frac{1}{3.04}} \\ &= 0.0575 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \end{aligned}$$

$$U_{c2} = \frac{1}{(1/h_i)} = 3.04 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}, \text{ ignoring floor resistance}$$

$$\begin{aligned} U_{k3} &= \frac{1}{\frac{1}{3.04} + \frac{0.25}{0.0183}} \\ &= 0.0717 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \end{aligned}$$

(ignoring frame fin effect which is accounted for in Par. 7.2.3.4).

The surface temperatures may be computed from Eqs. 3A-28 and 3A-29.

$$\begin{aligned} T_2 &= T_c - \frac{U_{ck}}{U_{c2}} (T_c - T_k) \\ &= 530 - \frac{0.0575}{3.04} (530 - 505) \\ &= 529.5^\circ\text{R} \end{aligned}$$

$$\begin{aligned}
 T_3 &= T_k + \frac{U_{ck}}{U_{k3}}(T_c - T_k) \\
 &= 505 + \frac{0.0575}{0.0717}(530 - 505) \\
 &= 525^\circ\text{R} \\
 T_{av} &= 527.25^\circ\text{R} \\
 \Delta T &= (T_2 - T_3) = 4.5^\circ\text{R} \\
 \rho &= .0765 \text{ lb/ft}^3 \text{ (for cabin air density, a sea level cabin is assumed here)} \\
 N_{Gr} &= \frac{x^3 \rho^2 g \beta \Delta T}{\mu^2} \\
 &= \frac{(0.583)^3 (0.0765)^2 (32.2) \left(\frac{1}{527.25} \right) (4.5)}{(12.2 \times 10^{-6})^2} \\
 &= 2,141,000
 \end{aligned}$$

$$\frac{h'_c x}{k} = 8.7 \text{ (for horizontal air spaces; from Fig. 3A-4)}$$

$$\begin{aligned}
 h'_c &= \frac{(0.0147)(8.7)}{0.583} \\
 &= 0.219 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$

The radiation coefficient, h_r , is obtained from Fig. 3A-5 as a function of the surface temperatures and $F_a F_e$:

$$\frac{h_r}{F_a F_e} = 1 \text{ for } T_2 = 529.5^\circ\text{R and } T_3 = 525^\circ\text{R}$$

For this case, $F_a = 1$, $e_2 = 0.10$, $e_3 = 0.8$, and

$$\begin{aligned}
 F_e &= \frac{1}{(1/e_2) + (1/e_3) - 1} \\
 &= \frac{1}{(1/0.10) + (1/0.8) - 1} \\
 &= 0.098
 \end{aligned}$$

$$\begin{aligned}
 \text{Then } h_r &= (1)F_a F_e = (1)(1)(0.098) \\
 &= 0.098 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$

$$\begin{aligned}
 h'_c + h_r &= 0.219 + 0.098 \\
 &= 0.3165 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$

This is close enough to the assumed value of 0.32; therefore, the overall conductance is

$$U_{ck} = 0.0575 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

For the 20,000 ft cooling case (case C), the cabin is maintained at 70°F and the cargo compartment is assumed to be at the skin temperature of 98.5°F. The difference in cabin and cargo compartment temperature is 28.5°F for this case, compared with 25°F for the heating case. Therefore the values of h'_c , h_r , and the overall conductance are the same for each case. For the sea level heating case (case B), the cabin is maintained at 70°F and the cargo compartment is assumed to be at the outside ambient temperature of -60°F. Computations for this case show that

$$h'_c + h_r = 0.474 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

$$\text{and } U_{ck} = 0.061 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Note that an increase of ($h'_c + h_r$) of 48% results in an increase of U_{ck} of only 6%. Therefore, the larger value of $U_{ck} = 0.061$ will be used in all calculations.

7.2.3.4 Through the Floor Beams

For construction details, see Fig. 3A-16. Heat transfer through the floor beams is complex, since the beam ends are attached to the outer skin and are therefore at approximately skin temperature. Heat is transferred through the beam ends to or from the cargo compartment and the cabin.

In the following analysis, the beam extends to the centerline of the airplane and is considered as a fin with one end at skin temperature. Weighted averages are used to determine the equivalent temperature at which heat transfer takes place, the conductance of the fin surface, and the percentage of heat transferred from the cabin.

Table 3A-2 shows the average temperature and heat transfer coefficients to use in the fin equation.

In addition to values of Table 3A-2, other considerations are

- (1) Cabin temperature $t_c = 70^\circ\text{F}$, or $T_c = 530^\circ\text{R}$ (case A)
- (2) Cargo compartment temperature $t_k = 45^\circ\text{F}$, or $T_k = 505^\circ\text{R}$
- (3) Skin temperature $t_w = -47.6^\circ\text{F}$

The weighted average temperature t_{eff} and the conductance h_{eff} to use in the fin equation are

$$t_{eff} = \frac{UA t}{UA} = \frac{1018}{18.69} = 54.6^\circ\text{F}$$

$$h_{eff} = \frac{UA t}{At} = \frac{1018}{513.9} = 2 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Table 3A-2 - Values for Temperature and Heat Transfer Coefficient

	Area (1) ft ²	U	$t(4)$ °F	$UA t$	UA	At
Beam Top	0.468	3.04	70	100	1.42	32.8
Beam Bottom	0.468	0.86 (2)	45	18	0.40	21.1
Beam Sides	8.430	2.00 (3)	53.3 (5)	<u>900</u>	<u>16.87</u>	<u>460</u>
Total				1018	18.69	513.9

NOTES:

(1) Areas obtained from detail drawings.

$$(2) U = \frac{1}{(1/3.04) + (0.0104/0.012)} = 0.86 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

(3) $h = 2.0 + 0.314V_o = 2.0$ (Eq. 3A-25 at zero velocity).

(4) Temperature to which heat transfer takes place.

(5) Initially assumed and checked during analysis.

From Eq. 3A-41 (modified), the total heat transfer from the beam end is

$$q_t = Ch_{eff}L\eta_f(t_w - t_{eff})$$

where

$$\eta_f = \frac{\tanh m_f L}{m_f L}$$

and

$$m_f = \left[\frac{h_{eff}C}{kA} \right]^{1/2}$$

Substituting the following information obtained from detail drawings:

C = Perimeter of fin, ft = 2.16

L = Projection of fin into cabin, ft = 4.5

A = Conduction cross-sectional area, ft² = 0.00812

Using $k = 70$ Btu-ft/hr-ft²-°F,

$$m_f L = (2.79)(4.5) = 12.52$$

$$\eta_f = \frac{\tanh 12.52}{12.52} = \frac{1}{12.52} = 0.0798$$

$$\begin{aligned} q_t &= (2.16)(2)(4.5)(0.0798)(t_w - t_{eff}) \\ &= 1.55(t_w - t_{eff}) \end{aligned}$$

To check the initial assumption of 53.3°F for the temperature of the airspace, assume that the heat transferred from the air space to the beam came initially from the cabin, since the insulation limits heat transfer between the cargo compartment and the air space. Assume also that the ratio of heat flow from the air space to the total heat flow is the ratio of the UA_t value of the sides of the beam to the total UA_t value (see values in Table 3A-2).

$$\frac{q_{as}}{q_t} = \frac{900}{1018} = 0.884$$

$$q_{as} = (0.884)(1.55)(-47.6 - 54.6)$$

$$q_{as} = -142 \text{ Btu/hr-beamend}$$

Since this heat must first pass through the floor to the air space, the required air space temperature to transfer the heat may be computed. The area between the beams is 6.75 ft².

$$\begin{aligned}
 U_{\text{floor}} &= \frac{1}{(1/3.04) + (1/2)} \\
 &= 1.204 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \\
 UA &= (1.204)(6.75) = 8.15 \\
 q_{as} &= UA(t_c - t_{as}) \\
 \text{or } t_{as} &= 70 - \frac{142}{8.15} = 52.6^\circ\text{F}
 \end{aligned}$$

which is close enough to the assumed temperature of 53.3 °F.

The total heat flow from the cabin, including that through the top of the beam, may be determined from the UA ratio:

$$\begin{aligned}
 \frac{q_{cb}}{q_t} &= \frac{1000}{1018} = 0.982 \\
 q_{cb} &= (0.983)(1.55)(-47.6 - 54.6) \\
 &= -157.3 \text{ Btu/hr-beam end}
 \end{aligned}$$

Since there are 44 beam ends, the total heat flow from the cabin is

$$\text{Total } q_{cb} = 44(-157.3) = -6922 \text{ Btu/hr}$$

A similar analysis for all design points considered in this example problem gives the results summarized in Table 3A-3.

Table 3A-3 - Results of Analysis

Case	Condition	Altitude, ft	q , Btu/hr
A	Heating	20,000	-6922
B	Heating	0	-7709
C	Cooling	20,000	1633
D	Cooling	0	2838

7.2.3.5 Through the Pressure Bulkhead

For the bulkhead shown in Fig. 3A-17, the following equation is used:

$$\begin{aligned}
 U &= \frac{1}{(1/h_i) + (x/k) + (1/h_o)} \\
 &= \frac{1}{\frac{1}{3.04} + \frac{0.25}{0.0183} + \frac{1}{3.04}} = 0.07 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$

7.2.3.6 Through the Windshield

Fig. 3A-18 gives the data applicable to the windshield computation:

$$\begin{aligned}
 U &= \frac{1}{(1/h_i) + \sum (x/k)} \\
 &= \frac{1}{\frac{1}{3.04} + \frac{0.0729}{0.61} + \frac{0.0673}{0.12}} \\
 &= 0.99 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
 \end{aligned}$$