ALTITUDE EFFECTS ON HEAT TRANSFER PROCESSES IN AIRCRAFT ELECTRONIC EQUIPMENT COOLING

by

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Abstract

Altitude dependent changes of aircraft heat transfer processes in electronic equipment boxes in equipment bays were investigated to examine the compatibility of current specifications for avionics thermal design with the thermal environment encountered in high performance aircraft.

Steady state equipment and bay air temperature were analyzed as a function of altitude based on known sea level thermal conditions and design parameters, by using standard atmospheric models and aircraft altitude Mach number flight envelope. This analysis was used to generate temperature-altitude envelopes which give the temperature of the equipment and the bay air as a function of altitude, based on typical altitude profiles of the bay wall temperature. Analysis of an unconditioned bay, containing ambient cooled equipment, was conducted. The optimal temperature difference between the equipment and the bay wall was identified. Analysis of a conditioned bay, containing both ambient and forced-air cooled avionics, showed a tendency towards isothermal bay air temperature-altitude profiles as the fraction of forced-air cooling was increased. The results showed that the temperature difference between the equipment and the bay wall grows exponentially with altitude in natural convective cooling and can be approximated as a function of the external pressure only. Radiation heat transfer was shown to serve as a ''thermal pressure relief valve'' and to improve the thermal performance of the system at high altitude.

The isothermal tendency of the bay air in a conditioned bay implies that ambient cooled equipment designed in accordance with MIL-E-5400 would not be compatible with the bay environment and additional cooling would be required. The results of this thesis provide guidance in determining the thermal design parameters which improve altitude performance of the avionics cooling system and in identifying the flight conditions resulting in critical thermal conditions.

Thesis Supervisor: Professor R. John Hansman
Title: Associate Professor of Aeronautics and Astronautics

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I would like to express my appreciation to my parents, Rachel and Avigdor, who have had their fingers crossed for the past several months while waiting "in the dark" across the sea. To my wife Edna: there is not enough space to express the gratitude you deserve for being so patient, understanding, and most of all for caring. Last but certainly not least, to our children Liron and Zohar, who have left their little friends behind and come to see the big world: I hope that the huge pile of scrap paper will give you a chance to express your artistic talents.

Table of Contents

List of Figures

Nomenclature

a	Local velocity of sound, [m/sec]
A	Surface area, [m^2]
C	Constant
C_p	Specific heat at constant pressure, [J/Kg°K]
d	Diameter,[m]
F_r	Radiation heat transfer factor, defined by equation (3.13), [W/°K^4]
g	Acceleration of gravity, [m/s^2]
h_c	Average convective heat transfer coefficient, [W/m^2°C]
h_r	Average radiative heat transfer coefficient, [W/m^2°C]
H = hA	Heat transfer conductance factor (1/*R*), [W/°C]
k	Thermal conductivity, [W/m°C]
L	Length, [m]
m	mass, [Kg]
$\dot{m}$	Mass flow rate, [Kg/sec]
M = u/a	Mach number
n	Exponent - used for Rayleigh number in free convection =1/4 for laminar flow =1/3 for turbulent flow
P	Pressure - absolute, [N/m^2]
p	Pressure - atmospheres, [dimensionless]
q	Heat transfer rate, [W]
q" = q/A	Heat flux, [W/m^2]
r	Recovery factor, defined by equation (2.5), [dimensionless]
R	Thermal resistance, [°C/W]
s	A characteristic dimension (in conduction path), [m]
t, T	Absolute temperature, [°K]
y	Elevation - altitude, [Ft]

Dimensionless Groups

$Bi = \frac{hs}{k}$	Biot modulus
$Gr_x = \frac{\rho^2 g \beta \Delta T x^3}{\mu^2}$	Grashof number
$Gr_* = \frac{\rho^2 g \beta q'' x^4}{\mu^2 k}$	Modified Grashof number for uniform heat flux (q")
$N_F = \frac{\dot{m} C_p}{h_w A_w}$	Forced-air cooling influence number
$Nu_x = \frac{h_x x}{k}$	Local Nusselt number
$Nu_L = \frac{h_L L}{k}$	Average Nusselt number

$Pr = \frac{C_p \mu}{k}$	Prandtl number
$Ra_L = \frac{g\beta\rho\Delta T L^3}{\alpha\mu}$	Rayleigh number
$Ra_{*L} = \frac{g\beta q'' L^4}{\alpha\nu k}$	Modified Rayleigh number for uniform heat flux (q")

Greek

$\alpha = \frac{H_r}{H_c}$	Radiation factor, Eq. (3.7)
$\alpha = \frac{k}{\rho c}$	Thermal diffusivity, [m²/sec]
β	Volumetric expansion coefficient, [°K⁻¹],(= 1/T for ideal gasses)
γ	Convection balance factor, Eq. (3.7)
$\delta = \left(\frac{h_{e,alt}}{h_{e,sl}}\right)$	Normalized convective heat transfer coefficient, Eq. (3.7).
δ_T	Thermal boundary layer thickness, [m]
ΔT	Temperature difference, [°C]
μ	Dynamic viscosity of air, [Nsec/m²] = [Kg/msec]
ρ	Density of air, [Kg/m³]
ν	Kinematic viscosity of air, [m²/sec]
σ	Stefan - Boltzmann constant

Superscripts

$(\dot{\ })$	Per unit time, [sec⁻¹]
$()''$	Per unit area, [m⁻²]
$(\tilde{\ })$	Normalized parameter, $\tilde{P} = \frac{Parameter\ at\ altitude}{Parameter\ at\ sea\ level}$

Subscripts

$()_{alt}$	Evaluated at altitude
$()_a, ()_{amb}$	Refers to ambient temperature
$()_{aw}$	Adiabatic wall conditions
$()_b$	Evaluated at bulk temperature
$()_{cond}$	Conduction
$()_c, ()_{conv}$	Convection
$()_d$	Based on diameter
$()_e$	Refers to equipment surface temperature
$()_{ext}$	Refers to the external air
$()_f$	Evaluated at the film temperature, given by equation (3.20)
$()_i, ()_{in}$	In
$()_i$	Summation convention
$()_L$	Based on length of plate
$()_m$	Mean flow conditions
$()_{out}$	Out

$()_r$	Radiation
$()_{sl}$	Evaluated at sea level
$()_w$	Refers to wall temperature
$()_x$	Local value
$()_0$	Denotes reference conditions (usually ambient pressure and temperature at sea level)
$()_0$	Denotes stagnation flow conditions
$()_\infty$	Evaluated at free stream conditions

Chapter 1

Introduction

1.1 Overview

The objective of this thesis is to examine the compatibility of the current specifications for avionics thermal design with the thermal environment encountered in modern high performance jet aircraft. A subsequent goal is to examine the possibility of improving the environmental control system (ECS) effectiveness by tailoring avionics specifications to meet actual environmental conditions.

Two types of aircraft bays are examined. The first type is an unconditioned bay where the internal environment (temperature, pressure, humidity) is not actively controlled and ECS cooling air is not supplied to any of the equipment in the bay. The second type is a conditioned bay where cooling air is provided by the ECS for controlling the environment, or as a cooling fluid. The electronic equipment is also separated into two categories by the cooling method used. The two cooling techniques considered in this thesis are ambient cooling (where heat is transferred by free convection and radiation) and forced air cooling (where heat is transferred to cold air supplied by the aircraft ECS).

The analyses are presented in two chapters, distinguished by bay type. Chapter 3 includes the analysis of the unconditioned bay. In this type of bay, only ambient cooled avionics equipment are considered. Chapter 4 includes the analysis of the conditioned bay. For this type of bay, both ambient and force cooled avionics are examined.

For each bay type the effects of altitude variation on equipment and internal bay temperatures are analyzed. Temperature-Altitude performance curves are generated, and discussed in light of the requirements found in existing military and aircraft manufacturers specifications for avionics thermal design of recent aircraft (e.g. MIL-E-5400 [21] and F-15 [6]).

Chapter 2

Avionics Cooling

2.1 Background

The demand for avionics cooling in aircraft has increased in recent years, as the quantity and complexity of electronic equipment installed aboard has increased. This is brought about mainly by the rapid development of new electronic systems, and the trends towards more sophisticated aircraft and engine electronic control systems. Furthermore, increases in aircraft performance have resulted in increased aerodynamic (kinetic) heat loads due to the higher speeds flown by modern aircraft.

The increased heat load imposed on aircraft requires larger and heavier cooling equipment. At the same time aircraft mass has reduced, resulting in cooling systems comprising a higher fraction of the vehicle mass. The total mass of cooling equipment in a modern high performance aircraft can be as much as 300 Kg (660 lb) [14] [18]. The ECS mass is undesirable for the following reason: if the performance of the aircraft (range, maneuverability, payload) are to be maintained, additional wing area, thrust, and fuel are required to compensate for the added weight. Thus, the actual weight penalty of an aircraft can be 1.5 - 7 times larger than the basic increase in the specific system weight, as shown in Fig. 2-1 [16]. It can also be seen from Fig. 2-1 [16] that the smaller aircraft with higher performance are typically the most sensitive.

The other aspect concerning aircraft mass is the limited use of the airframe as a potential heat sink due to the reduction in airframe mass. The importance of airframe as a heat sink is mainly for transient conditions where temporary high heat loads can be absorbed by the airframe and thus moderate the effects of transient heating extremes.

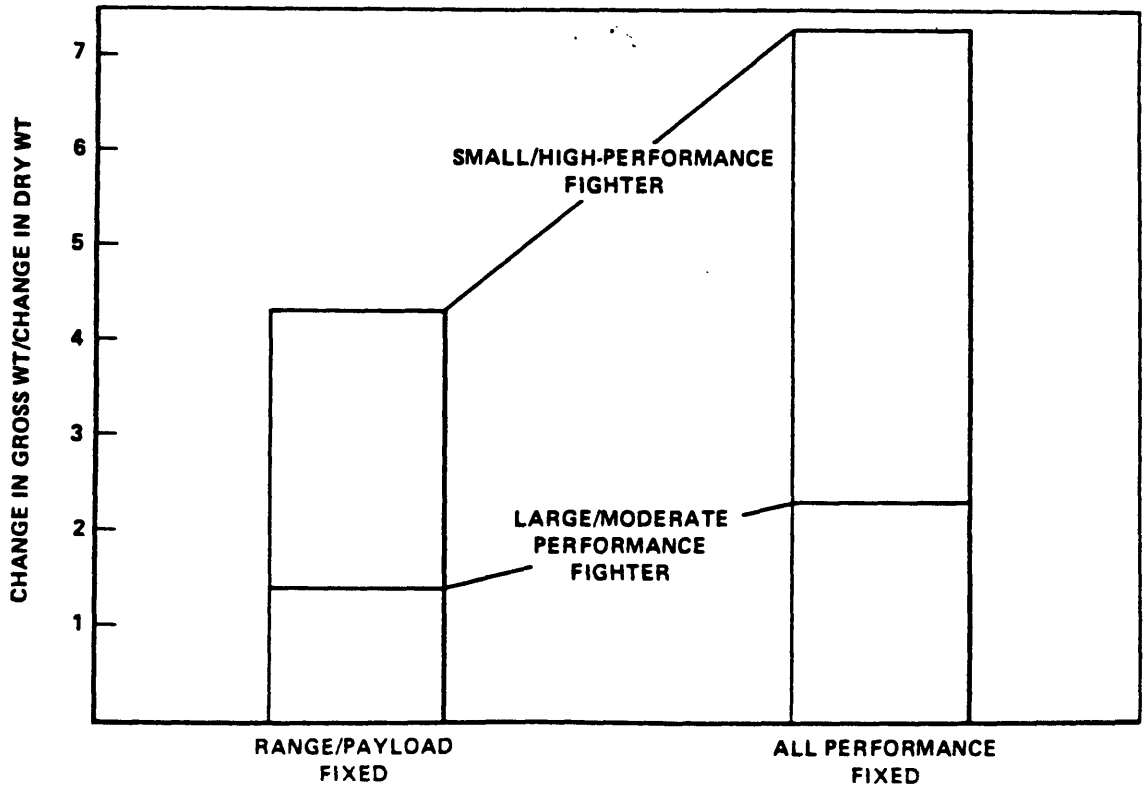

Figure 2-1: Aircraft growth curve magnifies effects of weight increments [16]

A summary of the trends in avionics and aircraft design compiled from a broad selection of American and European combat aircraft over the years 1955-1976 is shown in Fig. 2-2 [14]. It can be seen that avionics and cabin heat loads have been increased by a factor of 3 while aircraft mass has reduced by a factor of approximately 3.

In addition to the weight penalty there are two other major performance penalties resulting from the use of engine bleed air as a conditioning fluid by most environmental control systems. The first penalty is associated with the direct reduction of engine thrust which results from bleeding off engine compressor air. The second penalty is due to the drag which results from cooling the high pressure, high temperature bleed air through a ram-air heat exchanger before it is used as a conditioning fluid. The magnitude of the combined penalty of using engine bleed air

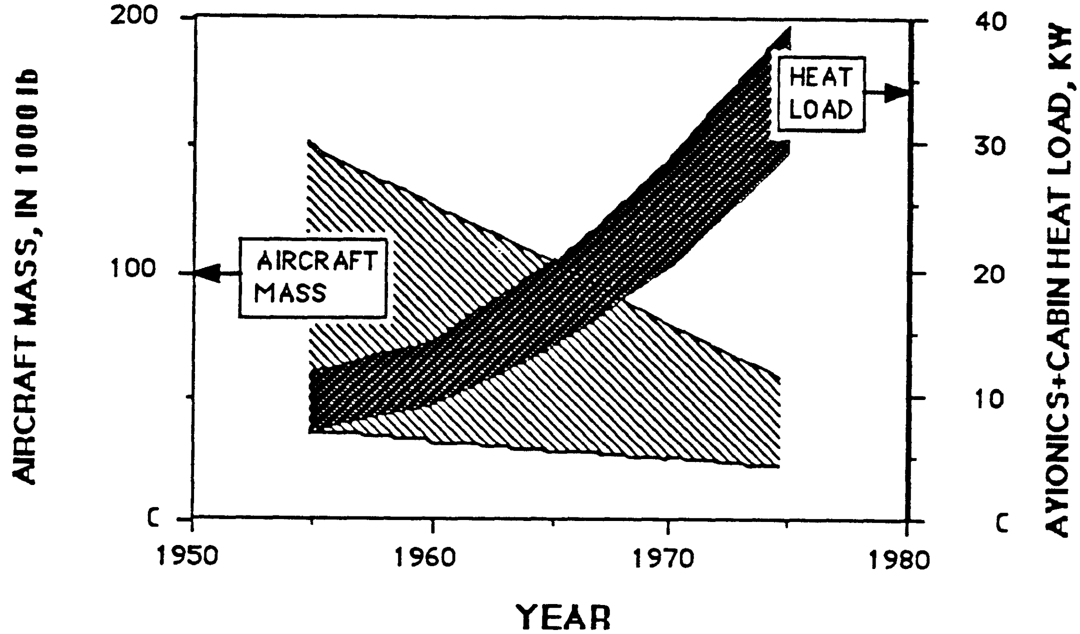

Figure 2-2: Trends in cabin and avionics heat load and aircraft mass [14].

is typically in the order of 20 KW per 1 KW of power being cooled, which represents a system coefficient of performance of 5 percent, as depicted in Fig. 2-3 [14], but can be much higher (more than 200 KW per KW extracted) for the more advanced engines at high speeds [16]. The conclusion is straightforward: engine bledded cooling air is extremely expensive and therefore should be used efficiently.

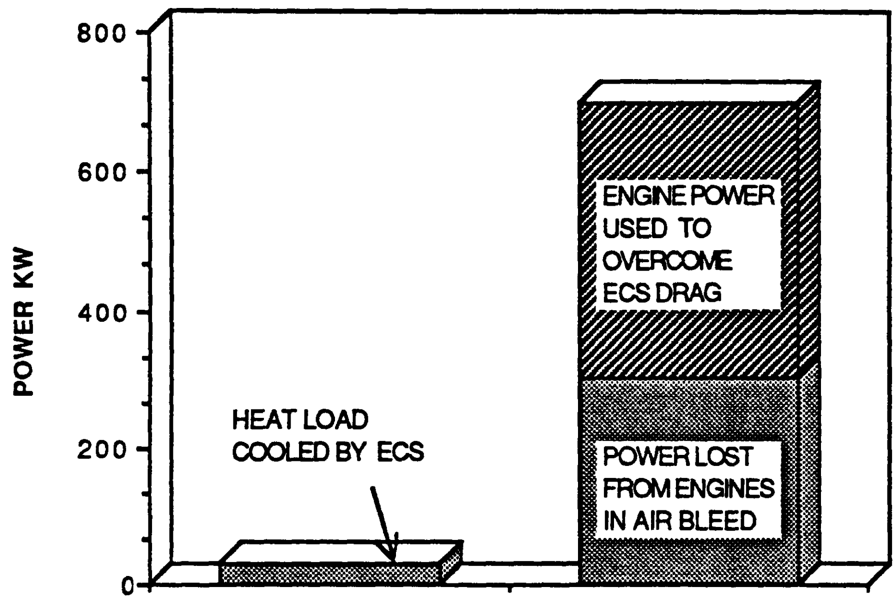

Figure 2-3: Illustration of order of aircraft penalty of an E.C.S. designed to cool 30 KW [14]

2.2 The Importance of Avionics Thermal Control

As the aircraft dependence on avionics has increased, electronic component reliability has become one of the most significant factors which determines satisfactory aircraft operation. The relationship between individual component temperature level and reliability is considered to be understood [22]. Failure rate is typically assumed to increase exponentially with temperature. Example is shown in Fig. 2-4 [1].

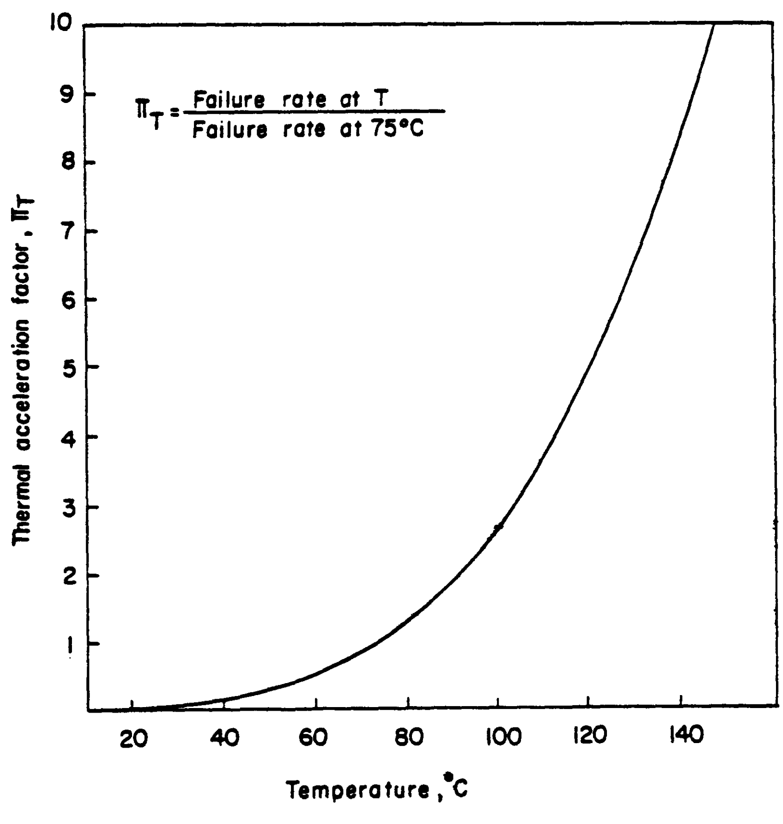

Figure 2-4: Thermal acceleration factor for bipolar digital devices [1].

The effect on reliability is seen in Fig. 2-5 which presents reliability curves of PNP Silicon transistor for two different temperatures. It can be seen that reliability of the specific component decreases with increasing temperature.

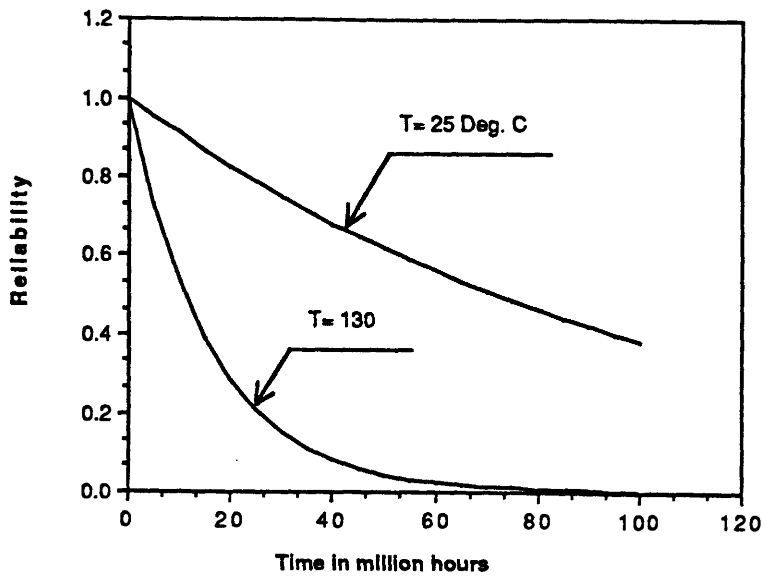

Figure 2-5: Example - The influence of temperature on component reliability (PNP Silicon transistor)

Temperature cycling has also been found to reduce reliability, almost independently of the influence of the average temperature level. Increased failure rates, by a factor of 8 were reported by Hilbert and Kube [12] for temperature cycling in excess of $\pm 15^{o}C$.

In addition to thermal factors vibration, moisture, humidity, and altitude are also known to degrade electronic components reliability [25].

2.3 The Optimization Problem

Since avionics reliability is very sensitive to the operating temperatures, and aircraft penalties are very sensitive to the avionics cooling requirements, it is important to optimize the integrated avionics/ECS system. The goal of such an optimization is to maintain desired level of avionics reliability while minimizing ECS cooling air requirements. The important parameters which are required for the optimization process are the bay internal environment, ECS cooling air temperature, and the electronic components temperatures. Unfortunately, the decision about avionics heat loads and operating temperatures, as well as ECS cooling capacity and operating temperatures, has to be made in an early stage of the development phase of both the aircraft and the avionics [14] [20] [21] [22]. It is therefore essential that information about the aircraft thermal environment and component temperatures are available as accurately as possible, and as early in the design process as possible.

In this thesis these two points are addressed, first, a method is developed to model the integrated equipment/aircraft system and to analyze bay and equipment temperatures. The results can be used in identifying the critical points for thermal design purposes. The method helps in predicting the maximum or worst case temperature that may be expected during flight conditions at altitude based on known performance of the system at sea level. The thermal predictions may also be applicable for reliability prediction purposes as well.

The second point is addressed by analyzing the expected change of the environment within the aircraft bay as a function of flight envelope and altitude by assuming standard atmospheric models. The result of such an analysis are presented as temperature-altitude environment curves.

2.4 The Cooling Problem

Since individual electronic components (e.g. diodes or transistors), are the heat sources within the electronic boxes, they will be the hottest points. The component temperatures depend on two major factors: first, the environment in which the equipment operates and the ability to transfer heat to the external air, and second, the thermal control design of the equipment.

While the first establishes the heat sink temperature, the second determines the temperature difference (ΔT) between the heat sink temperature and the specific component temperature, as shown in Fig. 2-6.

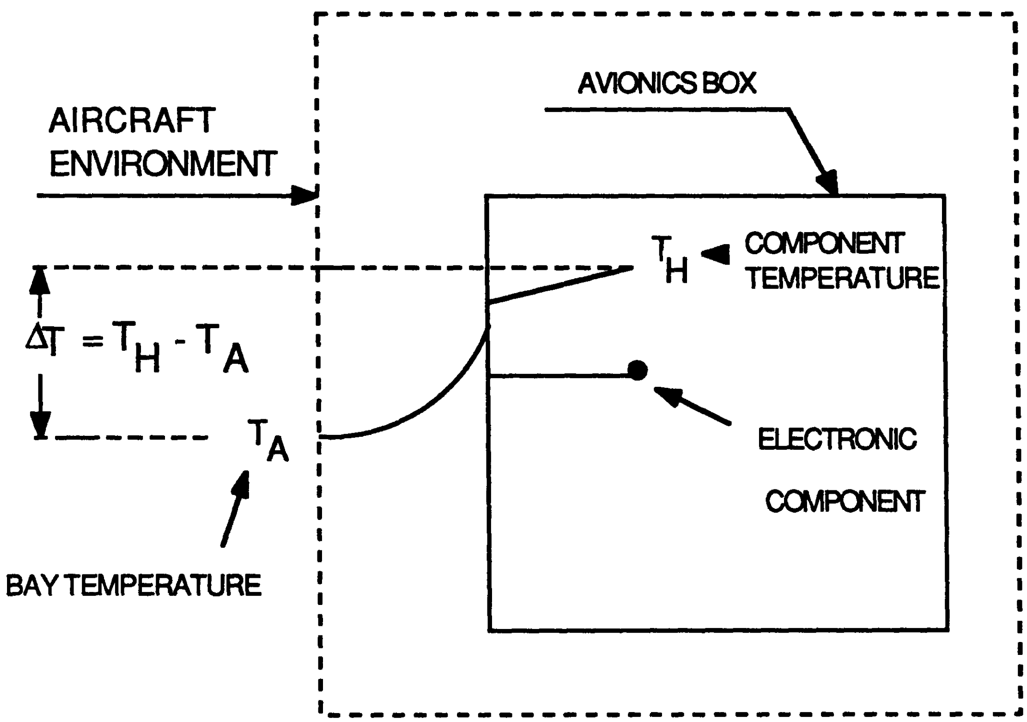

Figure 2-6: Electronic component temperature buildup

The relation between the the electronic component temperature, T_H, and the environment (heat sink) temperature, T_A, is given by:

$$q_{component} = H_{overall}(T_H - T_A) \tag{2.1}$$

where $q_{component}$ is the heat dissipated from the component, and $H_{overall}$ is the overall heat transfer coefficient which includes geometry factors and reflects an equivalent heat transfer coefficient for the combined coefficients of the various heat transfer modes that take place in this process (e.g. conduction, convection, radiation). Thus, for a given heat dissipation, $q_{component}$, to be removed from the component, both $H_{overall}$ and T_A have a direct effect on the component temperature T_H.

In practice, equipment thermal control design and the environment lie under separate responsibilities, i.e. the avionics designer is responsible for transferring heat from power dissipating components within the box to a suitable heat sink, and the aircraft designer has to provide an aircraft atmosphere or cooling services compatible with the equipments needs to transfer heat from the box, as shown schematically in Fig. 2-7. Therefore, it is convenient to separate between the environment and the thermal control design of the avionics box, and to analyze them independently. The physical interface between the equipment and the aircraft replaced for design purposes by specifications (interface control documents) to enable each party to pursue independent designs. The thermal environment which is used both as an input to the avionics thermal control design, and as a requirement for the ECS design, is one of the most important elements of such a specification.

Furthermore, during the past few decades, many of the specifications from different applications have been grouped into design standards. This is mostly the case for military aviation and in many cases for civilian aviation as well [1] [18] [21] [25] [30]. MIL-E-5400 [21], for example, is one of the most common used specifications for defining environment temperatures as function of altitude.

2.5 The Avionics Bay Environment

The avionics bay environment including temperature, pressure (density), and humidity, is of primary importance for the design of airborne electronic equipment. These parameters are strongly dependent on the altitude, which therefore is also an important parameter in the determination of the thermal environment. As was explained in the previous section, the bay and the cooling fluid (environmental factors) temperatures, T_A, are related to the electronic component temperature (avionics thermal design factors), T_H by the following equation:

$$q_{component} = H_{overall}(T_H - T_A) \qquad (2.2)$$

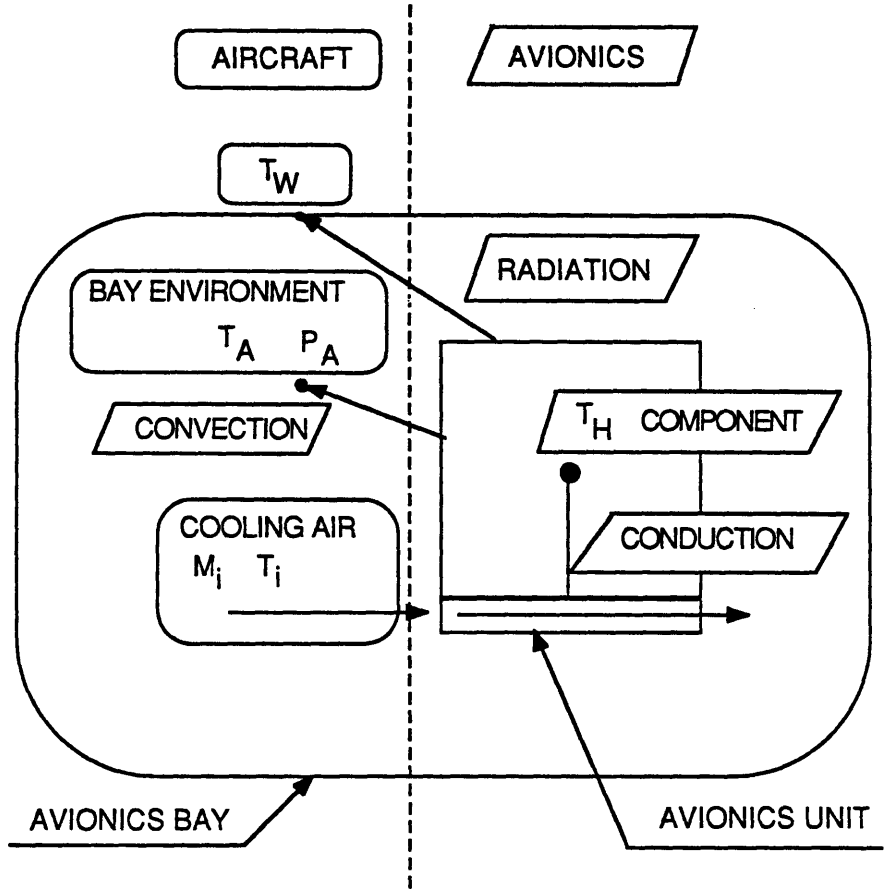

Figure 2-7: Illustration of responsibilities of aircraft and avionics designers for thermal design

Hence, the bay temperature or the cooling fluid temperature set the datum line for the electronic component temperature. The contribution of pressure and humidity is explained below. The primary importance of density is in heat transfer by natural convection where buoyancy forces are the fluid driving forces. Since air may be considered as an ideal gas, there is a direct relation between its absolute pressure (P) and its density (ρ) for a given temperature (T):

$$P = \rho R T \tag{2.3}$$

were R is the gas constant. Thus, since pressure reduces with increasing altitude the density also decreases. This in turn, results in a reduction of the effectiveness of natural convective heat transfer with altitude.

Humidity, on the other hand affects the integrated ECS/avionics system design problem differently. Moisture and humidity have been found to have a significant adverse effect on equipment performance and reliability [1] [18] [30] and therefore should be avoided. Condensation can occur when atmospheric air is cooled below its dew point. This condensation typically determines the lowest temperature used by the environmental control system if no other means (such as water separators) are introduced. It is worth mentioning here that humidity is also a function of altitude, and hence there is an additional coupling between temperature and altitude.

Three factors influence the parameters which drive the bay environment. The first is the external ambient environment which constitutes the ultimate heat sink for the aircraft. The second factor is the aerodynamic heating which should be added on the basic environment. High speed flight combined with high external atmospheric temperature may result in aircraft skin temperatures above 100 °C due to energy recovery in the boundary layer. The third component to be considered is the effect of the specific configuration of the aircraft/avionics system which includes bay location, internal heating by equipment dissipation, or cooling by the environmental control system if used. These three aspects of the environment are described in the following paragraphs. Other factors such as solar radiation and engine heat may affect the bay thermal environment as well.

2.5.1 The External Atmospheric Environment

Several atmospheric models exist for various applications, however, for the purpose of this thesis the models of MIL-STD-210 [23] which are included in many military specification and standards are being used.

2.5.1.1 Atmospheric Temperature Model

Two atmospheric models are given, cold and hot, which provide probable extreme minimum and probable extreme maximum temperature-altitude data.

The model is presented in Fig. 2-8. It can be seen that highest temperatures (hot atmosphere) are expected at sea level (40 °C), and temperature decreases at a rate of about 2 °C/1000 ft up to an altitude of 40,000 feet then rather constant temperature levels are encountered (-43 to -20 °C).

2.5.1.2 Atmospheric Pressure Model

The pressure - altitude model given in MIL-STD-210 [23] for the hot atmosphere is used in this thesis and it is presented in Fig. 2-9. Fig. 2-9 shows that pressure decreases in an exponential manner with increasing altitude.

2.5.1.3 Atmospheric Humidity Model

Fig. 2-10 describes the design humidity conditions to be considered for the design of the environmental control system. Absolute content of water in external atmospheric air decreases exponentially with altitude and therefore at higher altitude the air temperature can be reduced to lower temperature without condensation. This enables cooling temperature of the environmental control system to be set at a lower value at higher altitude resulting in increased cooling capacity of the system.

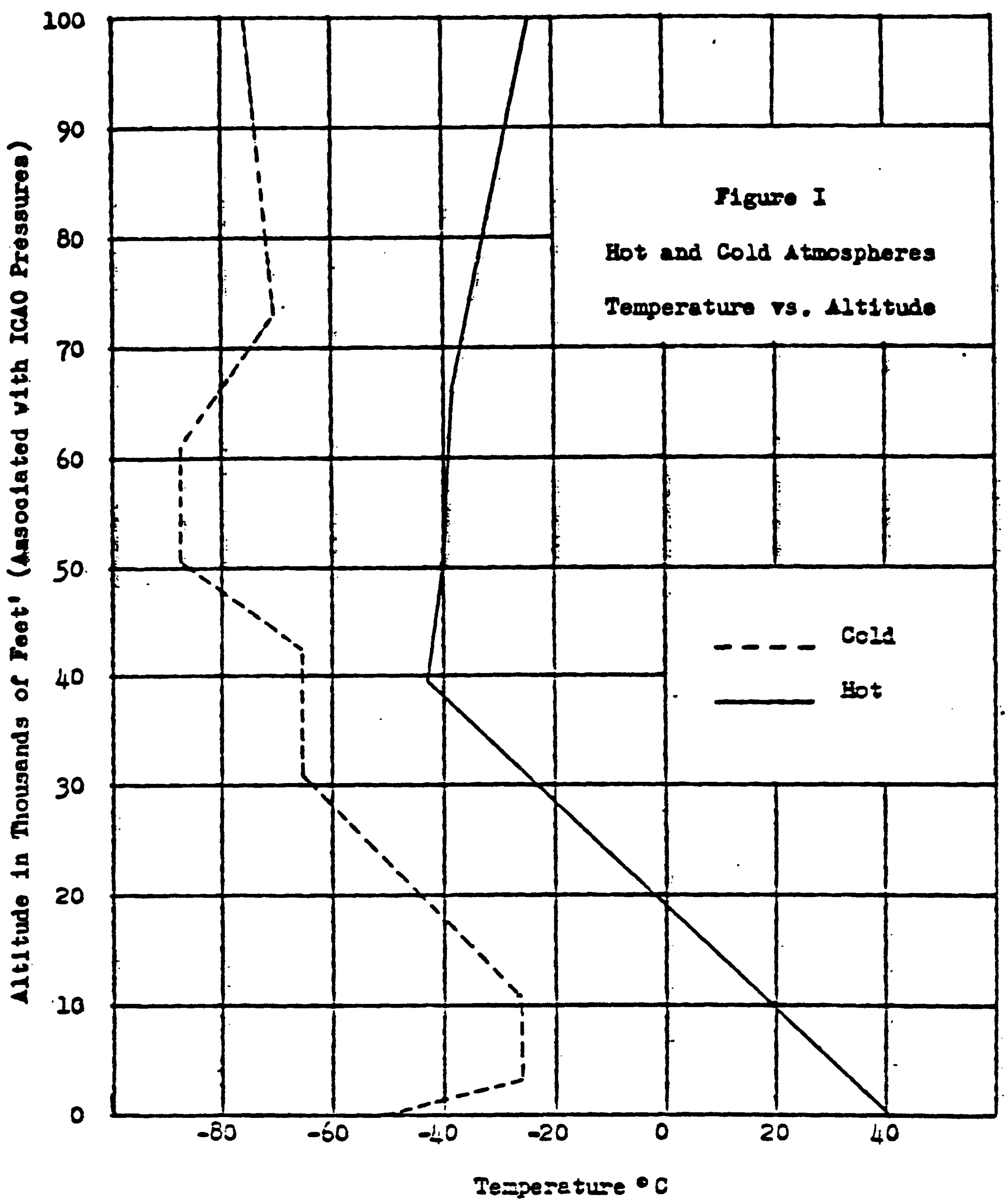

Figure 2-8: Hot and cold atmosphere models - Temperature vs. altitude [23]

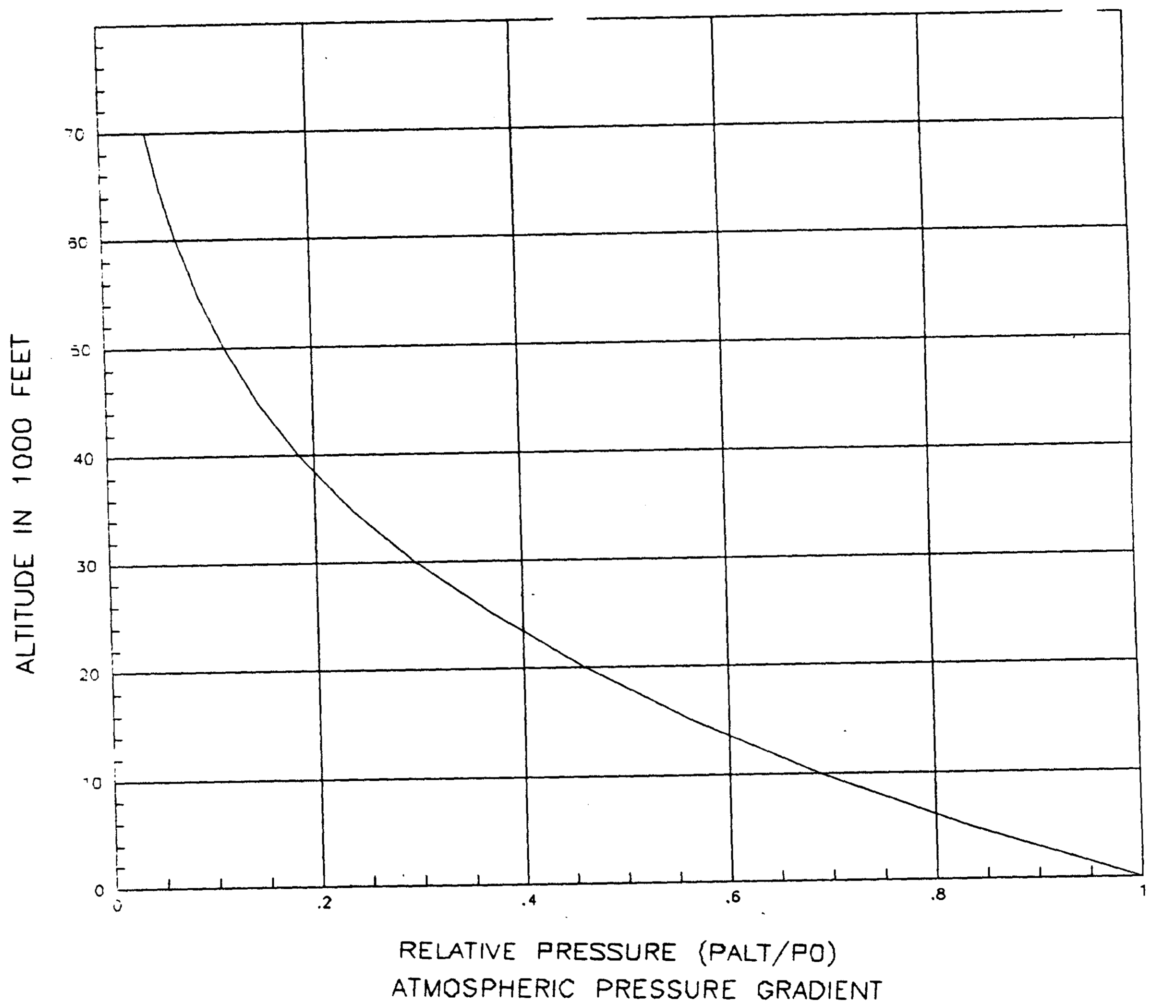

Figure 2-9: Atmospheric model - Pressure vs. altitude [23]

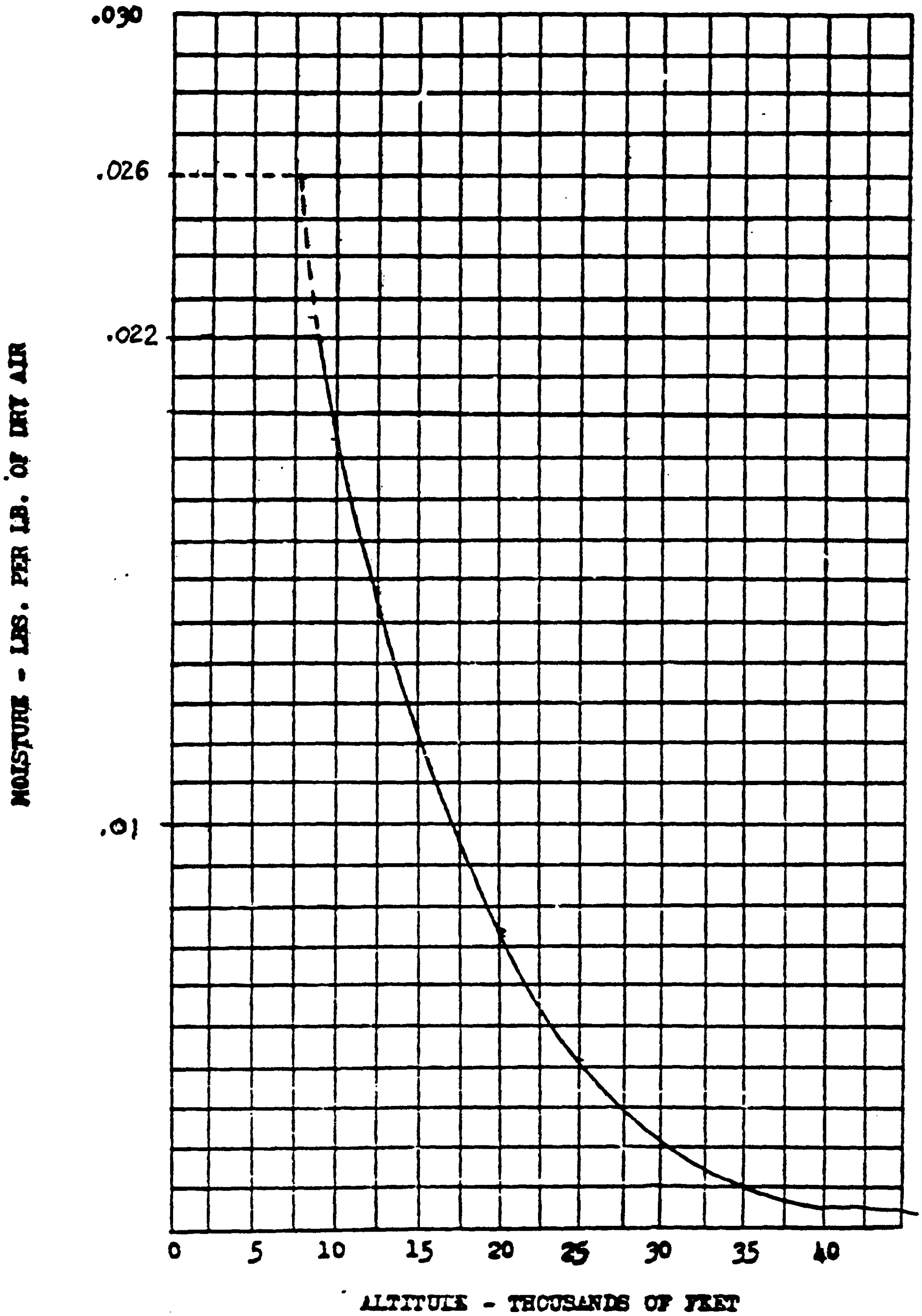

Figure 2-10: Atmospheric model - Design moisture conditions [23]

2.5.2 Aerodynamic Heating

The most important external aerodynamic effect relevant to the bay thermal environment is the heating of the air in the boundary layer surrounding the aircraft resulting from conversion of kinetic energy to internal energy, and from viscous dissipation.

Considering the conversion of kinetic energy to internal energy, and assuming an adiabatic reversible process then the following relation expresses the increase in the air temperature :

$$\frac{T_0}{T_\infty} = 1 + \frac{\gamma - 1}{2} M_\infty^{\ 2} \qquad (2.4)$$

where, T_0 is the stagnation temperature, T_∞ is the external atmospheric free-stream temperature, and M_∞ is the Mach number defined as $M_\infty = \frac{U_\infty}{a}$, where a is the speed of sound at the free stream temperature (T_∞).

When taking reversibility into account, and considering heat loses in the boundary layer, a recovery factor is used to express the ratio of actual heating to the maximum heating available [13]:

$$r = \frac{T_{aw} - T_\infty}{T_0 - T_\infty} \qquad (2.5)$$

where T_{aw} is the actual adiabatic wall temperature. r can be found experimentally, or in some cases, analytically. However, for air, the following relations for the recovery factor are generally used [13]:

$$r = Pr^{1/2} = 0.84\ , \quad \textit{laminar flow} \qquad (2.6)$$

$$r = Pr^{1/3} = 0.89\ , \quad \textit{turbulent flow} \qquad (2.7)$$

where Pr is the Prandtl number and is taken as 0.7 for air. At the high Reynolds numbers typically encountered the aircraft boundary layer around most of the aircraft is turbulent and the later value is typically used.

Combining Eq. (2.4) and Eq. (2.5) results in the following relation for the adiabatic wall temperature

$$T_{aw} = T_{\infty}[1 + r\frac{\gamma-1}{2}M_{\infty}^{2}] \tag{2.8}$$

Thus the air temperature increases with the square of the Mach number, and the absolute temperature depends on the free stream temperature T_{∞}. This dependence is demonstrated in Fig. 2-11 using standard external atmospheric temperatures from Fig. 2-8. It can be seen that a combination of moderate Mach number (~ 1) and high external atmospheric temperature at low altitudes [A] produce similar adiabatic wall temperatures ($\sim 100^oC$) as higher Mach numbers (~ 1.7) with lower external atmospheric temperature at higher altitudes [B].

Aerodynamic heating is sensitive to the Mach-altitude flight envelope of the aircraft and the external atmospheric temperatures. A typical flight envelope[1] of a modern fighter aircraft is depicted in Fig. 2-12. Such data in conjunction with the external atmospheric models can be used in developing an adiabatic wall temperature envelope. Fig. 2-13 shows an example of an adiabatic wall temperature profile, for the continuous flight envelope described in Fig. 2-12 and the hot atmosphere given in Fig. 2-8. It can be seen from Fig. 2-13 that the wall temperature is maximum at sea level (approximately 65 ^oC) and reduces with altitude.

When the wall is not adiabatic, i.e. there is heat exchange between the wall and the air, the following expression defines the heat flow (q_{ext}) transferred from the wall to the air:

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[1]Flight envelope such as in Fig. 2-12 is compiled from the basic flight envelope to reflect the duration parameter

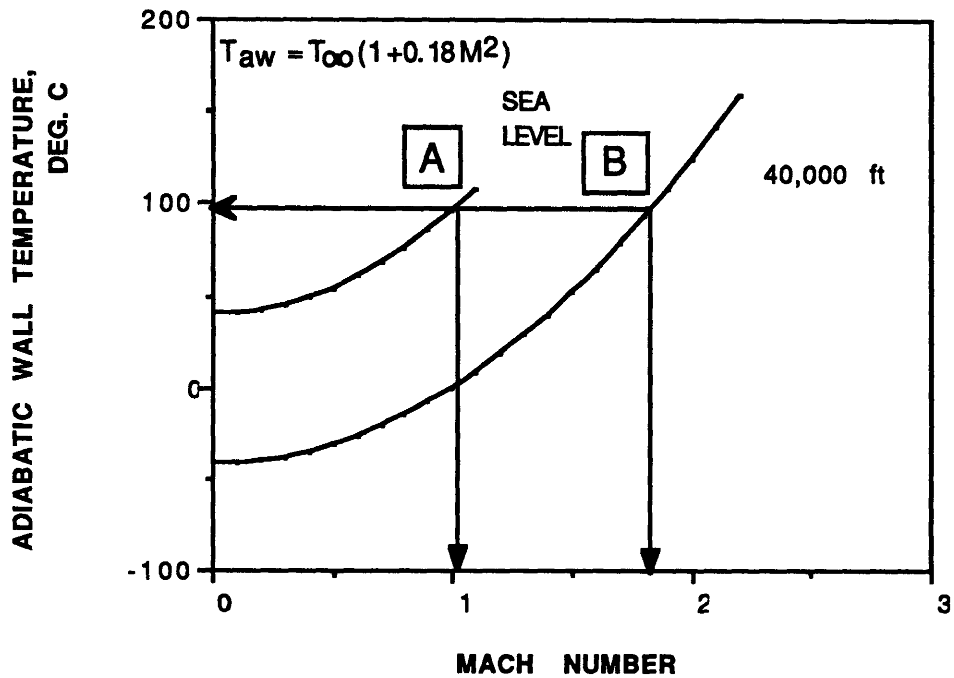


Figure 2-11: Adiabatic wall air temperature versus Mach number and altitude

$$q_{ext} = h_{ext}A_{ext}(T_w - T_{aw}) \tag{2.9}$$

where T_w is the wall temperature, A_{ext} is the surface area and h_{ext} is the average heat transfer coefficient to the external air associated with the surface.

2.5.3 Aircraft Thermal Zones

Electronic equipment boxes are typically installed in various designated bays in the aircraft or large equipment cabinets in many transport aircraft. The thermal environment of each bay may be different and depends on factors such as the location, or the environmental control system. Aircraft are typically divided into several groups of thermal zones an example of which is shown in Fig. 2-14. These thermal zones reflect areas within the aircraft with distinct thermal environments.

There are two basic types of thermal zones, which are associated with the bay

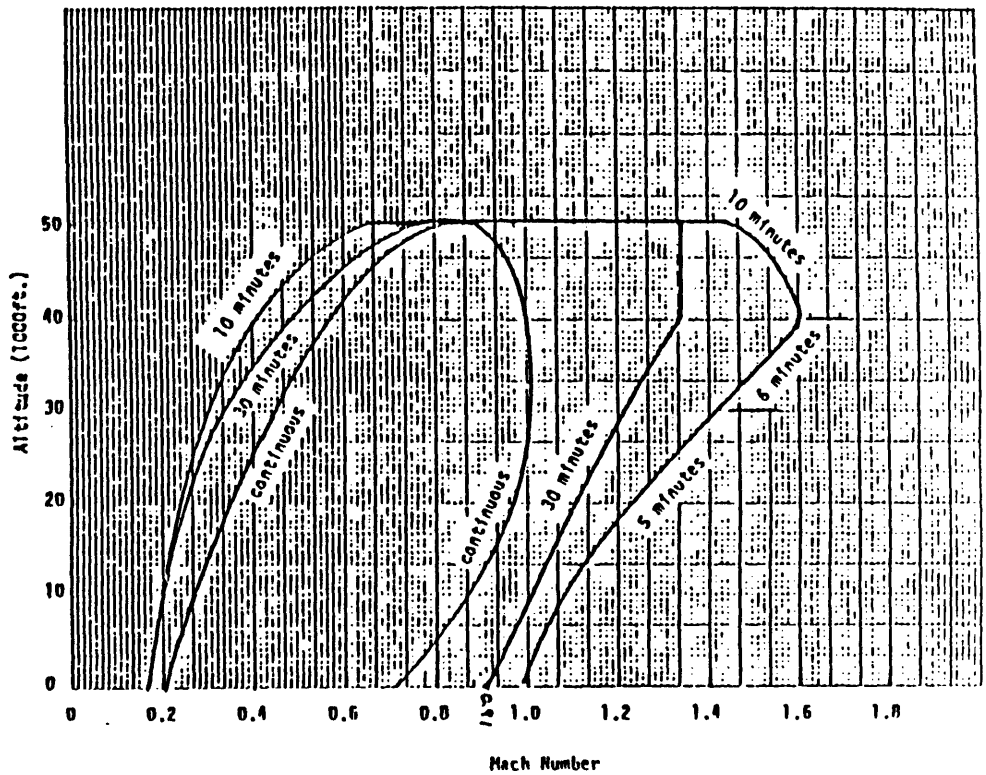


Figure 2-12: Typical flight envelope of modern fighter aircraft

types shown in Fig. 2-15. The first type is an <u>unconditioned bay</u> where no active cooling is used. The thermal environment in the bay is a result of the external atmospheric conditions, the aerodynamic effects, and internal heat loads. The equipment cooling inside these bays relys on heat transfer by natural convection and radiation.

The second type is a <u>conditioned bay</u> where cooling air is provided by the environmental control system to the bay. This cooling air is typically used to increase the cooling of specific components by forced-air cooling and to control the ambient thermal environment inside the bay to minimize undesirable effects of external atmosphere and aerodynamic conditions.

Other zones may also exist. For example, zones 7 and 8 in Fig. 2-14 are the

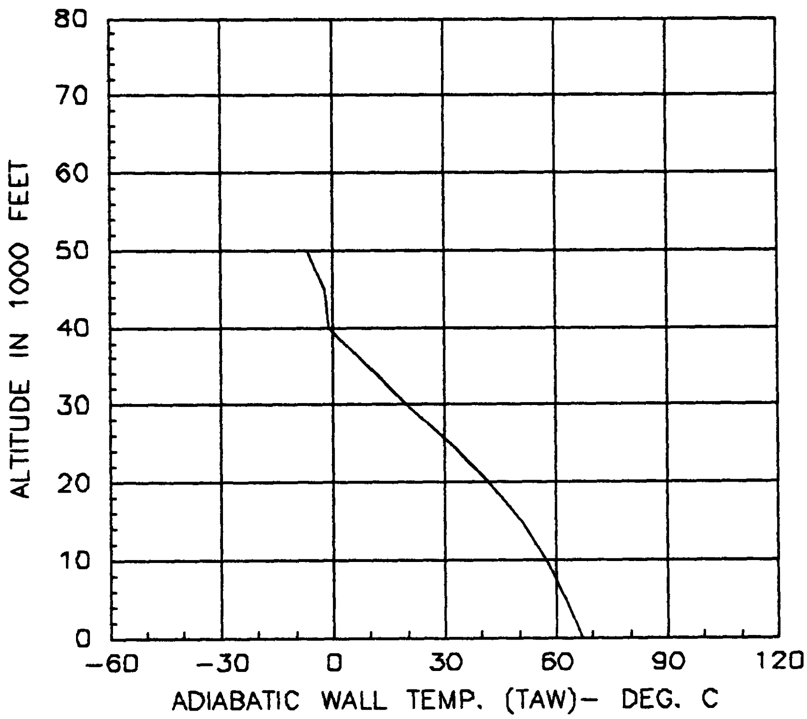


Figure 2-13: Typical adiabatic wall temperature profile of modern fighter aircraft

engine bays and are affected primarily by the engine heating, or zone 4 in Fig. 2-14 which is the pilots cockpit and is conditioned by the ECS to meet human thermal requirements.

The following section introduces the techniques most commonly used for avionics cooling.

2.6 Avionics Cooling Techniques

Air cooling is the most common technique used in aircraft avionics systems [15]. Other techniques such as liquid cooling can be used for applications where heat densities are high (e.g radar transmitters - order of 2 kw/cm ^{2}) or where volume is a major constraint (e.g. pod mounted avionics). In this thesis only air cooled avionics are considered.

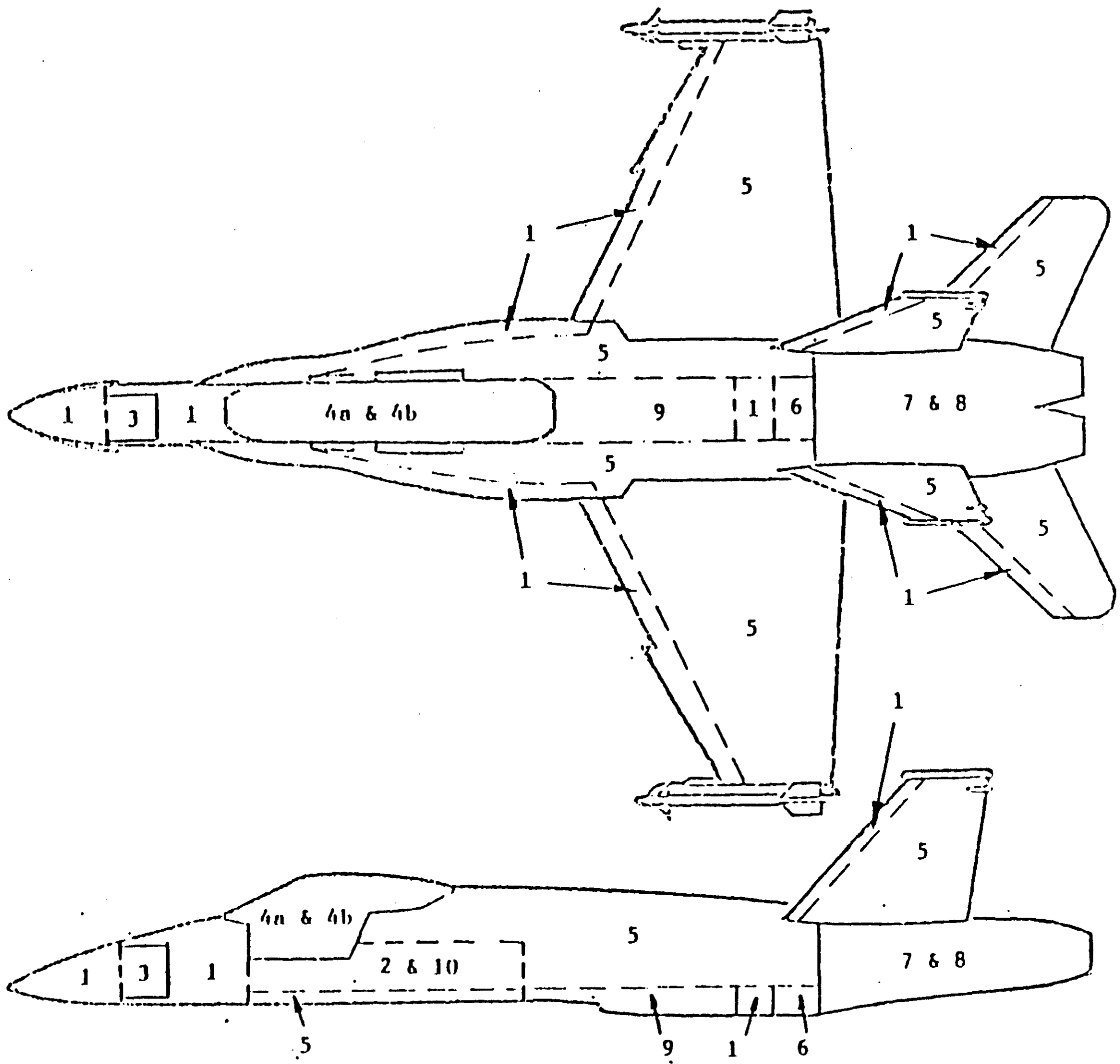
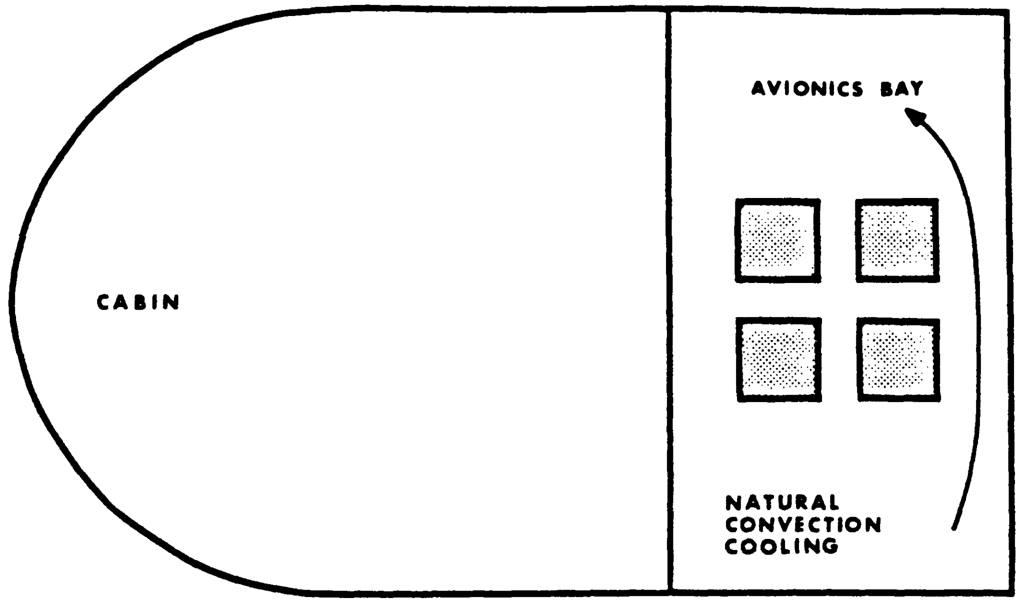
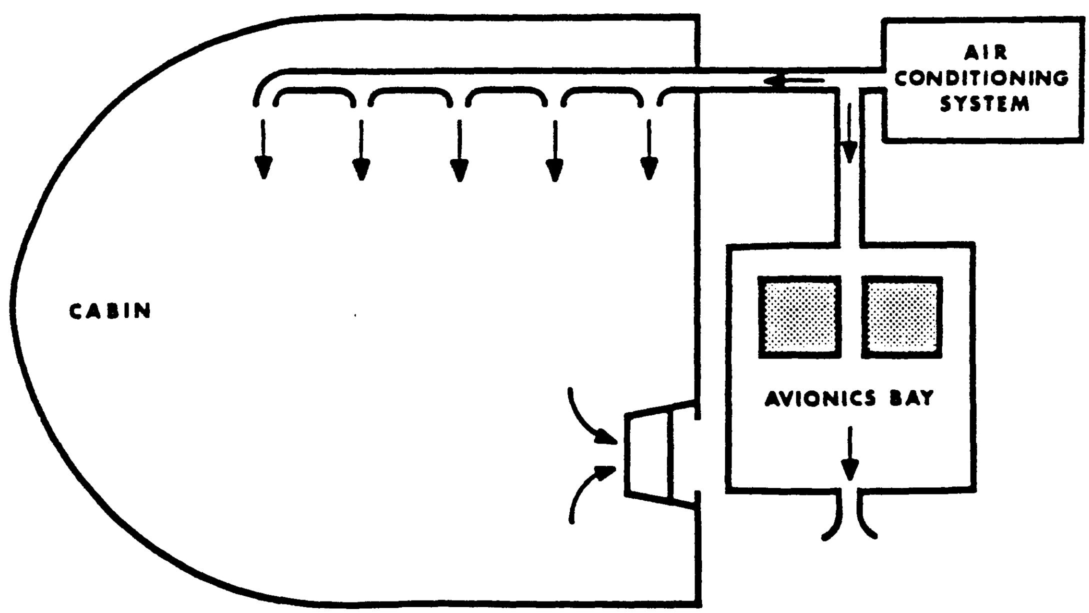


Figure 2-14: Typical aircraft thermal zones [7]



(a) Unconditioned Bay Configuration (Ambient Cooled Equipment)



(b) Conditioned Bay Configuration (Forced Air and Ambient Cooled Equipment)

Figure 2-15: Typical electronic equipment bay arrangements [10]

The equipment bays of most military aircraft contain equipment which can be either "off the shelf" or designed specifically for that aircraft. Furthermore, in addition to thermal constraints the allocation of equipment to the various avionics bays also reflect considerations of size and maintenance requirements. Because of these, it is frequently necessary to install equipment using different cooling methods, side by side.

For the purpose of cooling, the air cooled equipment can be separated into two basic types :

1. **Ambient cooled** - Equipment relying on convection and radiation from the outer case to the surrounding air and walls, as described in Fig. 2-16(a);
2. **Forced-air cooled** - Equipment which is cooled by a supply of air from the aircraft system blown through a "cold plate"/heat exchanger, see Fig. 2-16(b);

There are also combinations and variations of the above cooling types. Examples of such are :

- Equipment whose heat loss is assisted by supply of airflow blown through the box from the aircraft supply system ;
- Equipment which uses fans to induce a supply of cooling air from the surrounding ambient. This fan induced air is then used for either direct or indirect component cooling in the black box ;
- Equipment which uses buoyancy induced air circulation to directly cool the components inside the box (also called *passive cooling*).

In this thesis, however, only the two basic types - **ambient cooled** and **forced-air cooled** as defined above will be considered.

2.6.1 Ambient Cooled Equipment

Two heat transfer modes are involved in the cooling of ambient cooled equipment. The first mode is heat transfer by natural convection, where heat is

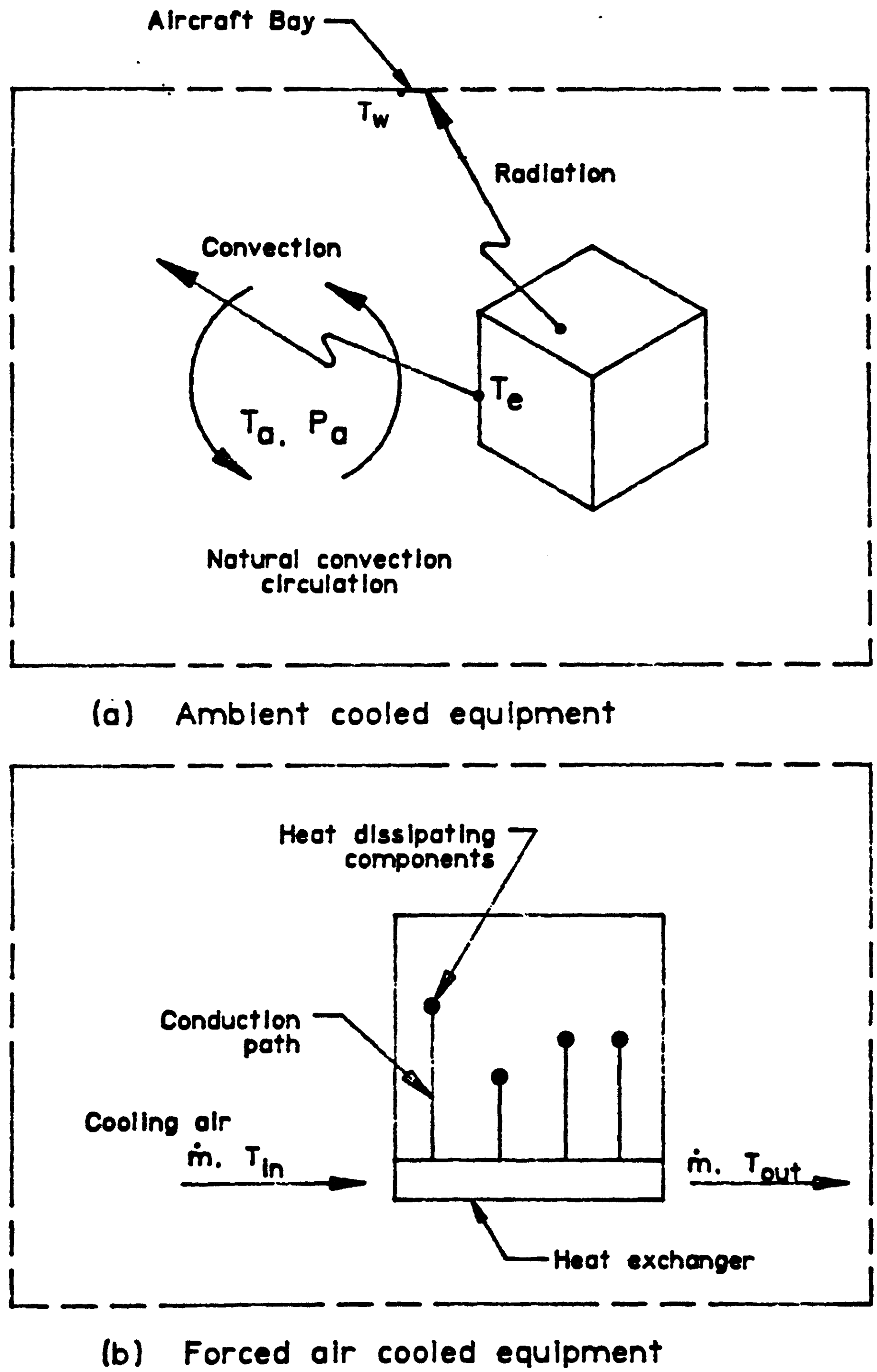


Figure 2-16: Ambient cooled and forced-air cooled avionics

transferred from the equipment box outside surfaces to the bay ambient air. The temperature difference between the equipment surface temperature and the surrounding air temperature causes buoyancy driven circulation of the air in the bay as shown in Fig. 2-16(a). The second mode of heat transfer involved in ambient cooling is radiation, where heat is exchanged between the surface of the equipment and the surrounding airframe or adjacent equipment surfaces[2]. Heat transfer by conduction, is not considered, since conduction heat paths between the equipment and the airframe are normally not provided. Inside the equipment, however, heat from the electronic components is transferred to the surface mainly by conduction.

2.6.1.1 Cooling Requirements

Since the bay ambient air constitutes the primary heat sink for the ambient cooled equipment heat dissipation, the cooling requirements of the ambient cooled equipment are defined primarily in terms of the bay environment.

The general expression which defines the heat transfer by convection is:

$$q_{A,c} = h_c A\,(T_e - T_a) \tag{2.10}$$

where, $q_{A,c}$ is the amount of heat convected, h_c is the average convective heat transfer coefficient, A is the surface area involved in the process, and $(T_e - T_a)$ is the temperature difference between the equipment surface temperature (T_e) and the ambient bay air temperature (T_a). Solving Eq. (2.10) for T_e gives:

$$T_e = T_a + \frac{q_{A,c}}{h_c A} = T_a + (\frac{1}{h_c})q''_{A,c} \tag{2.11}$$

where $q''_{A,c} = \frac{q_{A,c}}{A}$ is the heat flux from the surface. It can be seen from Eq. (2.11) that if a specific amount of heat ($q_{A,c}$) is to be convected from a given surface area

[2]Note: air is practically transparent to thermal radiation.

(A), then there are two parameters which determine the equipment temperature (T_e). The first parameter is the ambient temperature (T_a) which sets the datum line for the temperature. The second parameter is the convective heat transfer coefficient (h_c), which determines the temperature difference between the equipment surface and the bay air. Small values of h_c result in higher increase in the equipment temperature (T_e) above the ambient temperature (T_a) and vice versa as illustrated in Fig. 2-17.

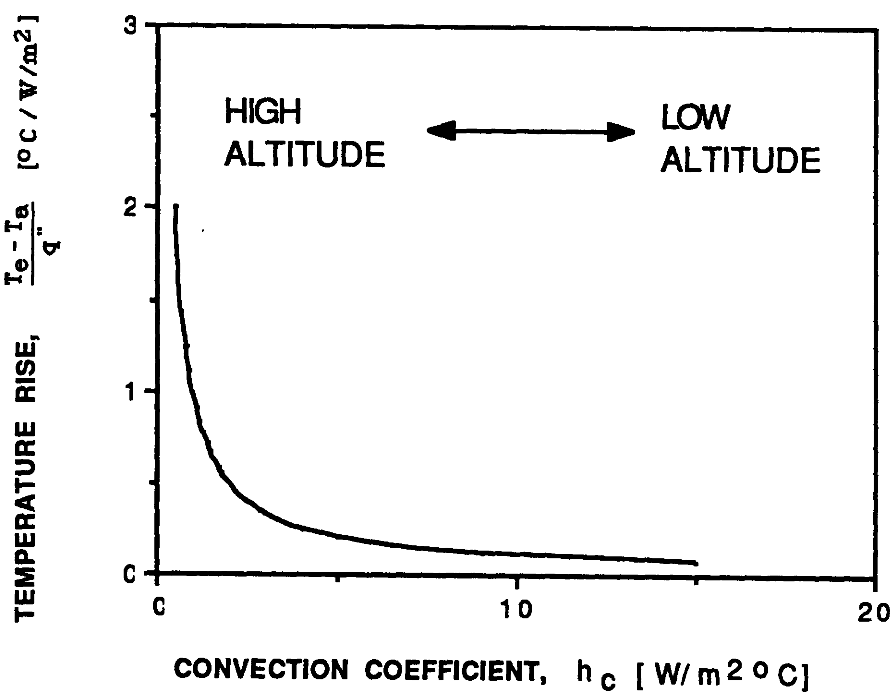
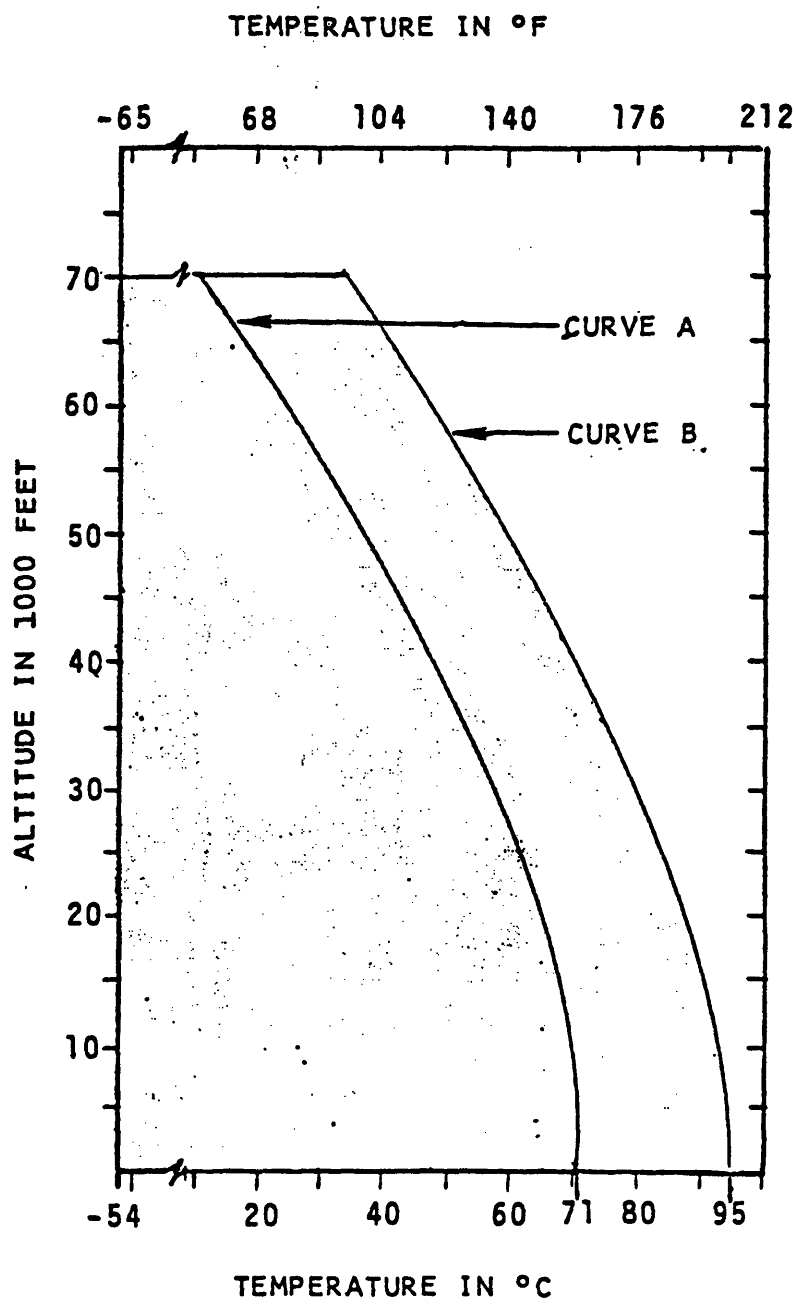


Figure 2-17: Temperature rise per unit heat flux vs. convective heat transfer coefficient

The convective heat transfer, h_c, depends on the air density and reduces as pressure reduces with altitude. Therefore, the cooling requirements for an ambient cooled equipment are typically specified in terms of a temperature-altitude envelope, example of which is shown in Fig. 2-18. Fig. 2-18 serves as the thermal interface definition between the equipment and the aircraft, discussed in Section 2.4. The avionics designer has to design the avionics to operate in the specified environment (Fig. 2-18), and the aircraft designer has to provide the specified environment.



NOTES:

1. *Curve A - Design and test requirements for continuous operation.*
2. *Curve B - Design and test requirements for intermittent operation.*

Figure 2-18: Temperature-altitude operational requirements -- bay air temperature versus altitude, MIL-E-5400 Class II [21]

Radiation heat transfer is usually being neglected in the thermal analysis of the ambient cooled equipment. Furthermore, aircraft manufacturers specifications for avionics thermal design typically require that the thermal design of the ambient cooled avionics equipment rely only on natural convection to "do the job". In this thesis, however, the effects of the radiative heat transfer on the thermal performance of the ambient cooling as a function of altitude are shown to be important. They are examined, and presented in Chapter 3.

2.6.2 Forced-Air Cooled Equipment

Forced-air cooled avionics use ECS supplied cooling air. Typically, the cooling air enters the unit at one end passes through heat exchanger/cold plate, and exits the box at another end (see Fig. 2-16(b)). Inside the box, heat is transferred mainly by conduction from the components through the printed circuit board (PCB) to the heat exchanger.

2.6.2.1 Cooling Requirements

Since ECS cooling air constitutes the main heat sink for the forced-air cooled equipment, the cooling requirements of the box are defined mainly in terms of cooling air mass flow and temperatures needed to remove the heat dissipated by the equipment. The following expression gives the relation between the heat dissipation removed from the equipment q_F, and the cooling air mass flow $\dot{m}$ and temperatures:

$$q_F = \dot{m} C_p (T_{out} - T_{in}) \tag{2.12}$$

where C_p is the specific heat of the cooling air, T_{out} and T_{in} are the cooling air outlet and inlet temperatures.

For any practical combination of $\dot{m}$, T_{in}, and T_{out} which satisfies the cooling capacity relation (2.12), the most important parameter for the thermal design of the equipment is T_{out} which is the hottest temperature of the heat sink. Typically, the electronic components will be 30-50 °C above the temperature of the heat sink [18] [30].

As a common design practice, T_{out} is limited to 71°C (160 °F) [6] [7] [30]. After T_{out} is defined, the cooling airflow requirements for the electronic box can be determined using Eq. (2.12), as depicted in Fig. 2-19.

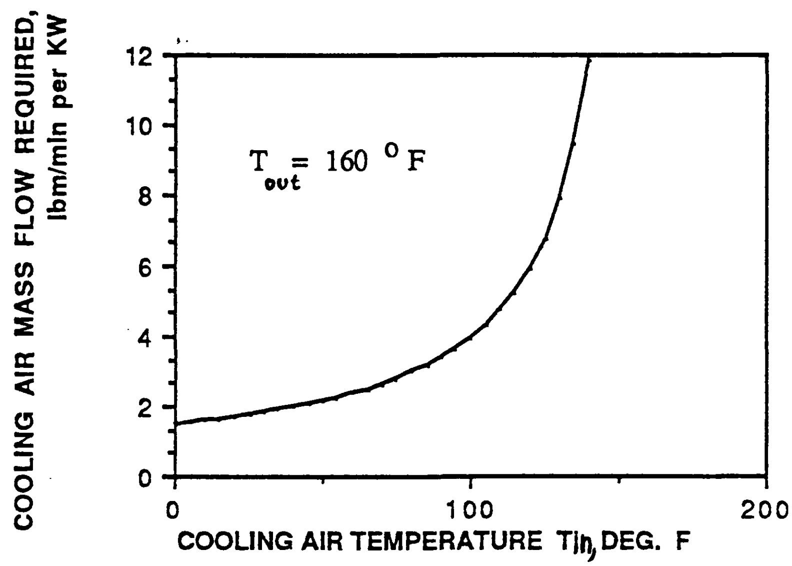


Figure 2-19: Forced-air cooled avionics cooling requirements - airflow vs. cooling air temperature

The amount of conditioned air required to cool an electronic equipment will vary with temperature of cooling air, less air is required when the cooling air temperature is low, and more air is required when the cooling air temperature is high, as shown if Fig. 2-19.

In addition to the cooling air requirements, there are requirements regarding the bay thermal environment. Temperature-altitude envelopes similar to those of ambient cooled equipment Fig. 2-18, are typically used. However, it should be noted that the forced-air cooled equipment does not rely on the bay air as a heat sink and, therefore, it is typically thermally insulated from the surrounding air. Thus, the bay environment have only a small effect on the cooling of the forced-air cooled equipment. The important conclusion that can be drawn from the above is that the cooling requirements of the forced-air cooled equipment do not depend directly on altitude.

2.7 Environmental Control System

Fig. 2-20 shows the general arrangement of a typical environmental control system (ECS) in an aircraft. The ECS supplies cooling air to control avionics bays and electronic equipment temperatures. Since the cooling air has to pass through the distribution system and the equipment boxes, a source of high pressure air is required. Therefore, engine compressor air is typically used. Before it is used as a conditioned fluid, the bleed air is cooled as much as possible by an ambient (ram) air cooled heat exchanger, and then expanded through a turbine to achieve maximum cooling.

The cooling air temperature is controlled as a function of altitude, and is kept above its maximum expected dew point temperature. Fig. 2-21 shows an example of such scheduling: at low altitude (up to 25,000 ft), where humidity can be high, the ECS controls the temperature of avionics cooling air to 30 °C. But since humidity decreases with altitude, as was presented in Fig. 2-10, avionics supply air temperature can be reduced to 5 °C at 32,000 ft. When the cooling air is supplied at lower temperatures, smaller amounts of cooling air mass flow are required, as depicted in Fig. 2-19. This in turn, reduces overall mission use of engine bleed air which results in better aircraft performance. When water separators are used the temperature of the cooling air can be reduced below the dew point temperature without condensation. This will result in an increased cooling capacity of the ECS.

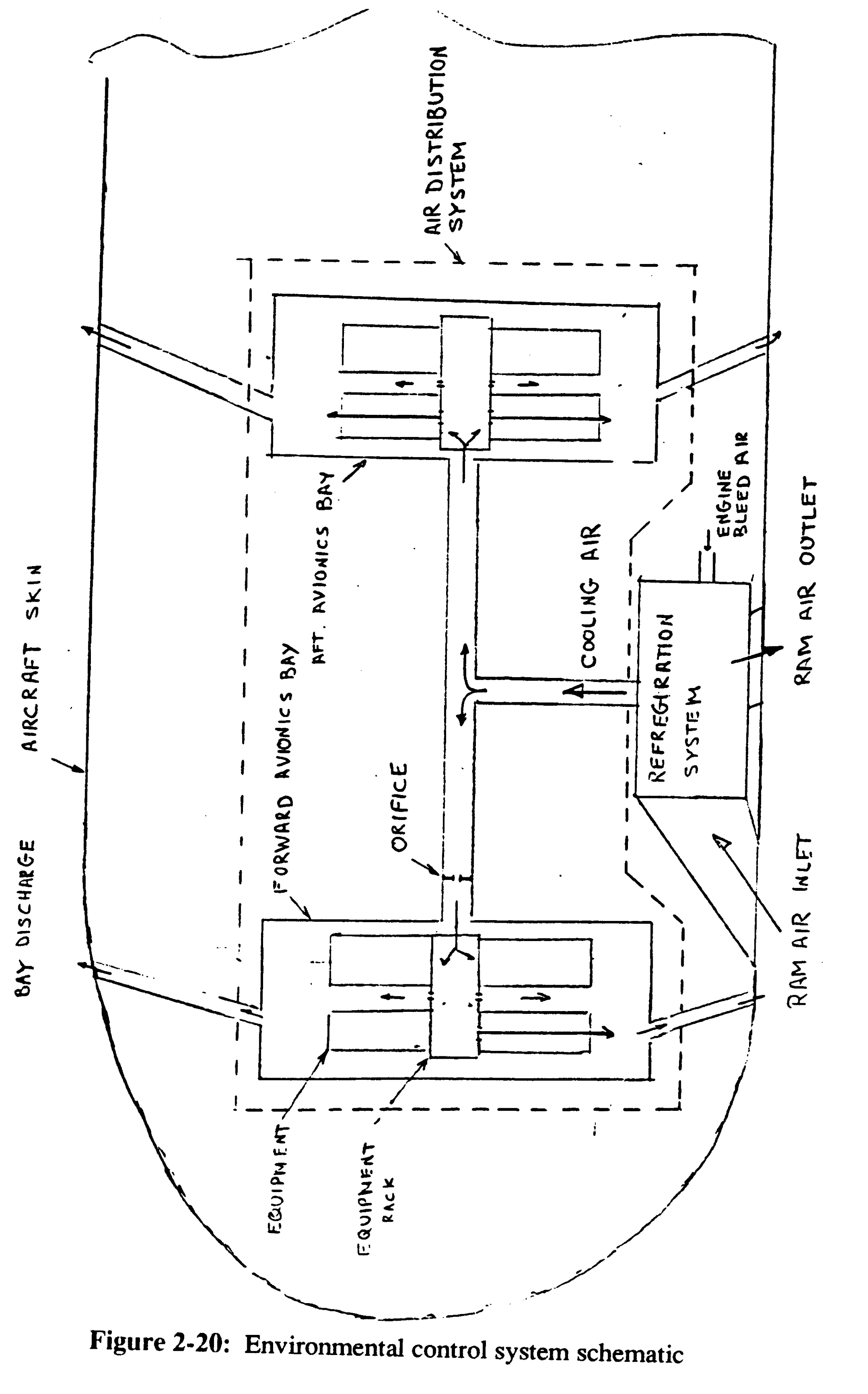


Figure 2-20: Environmental control system schematic

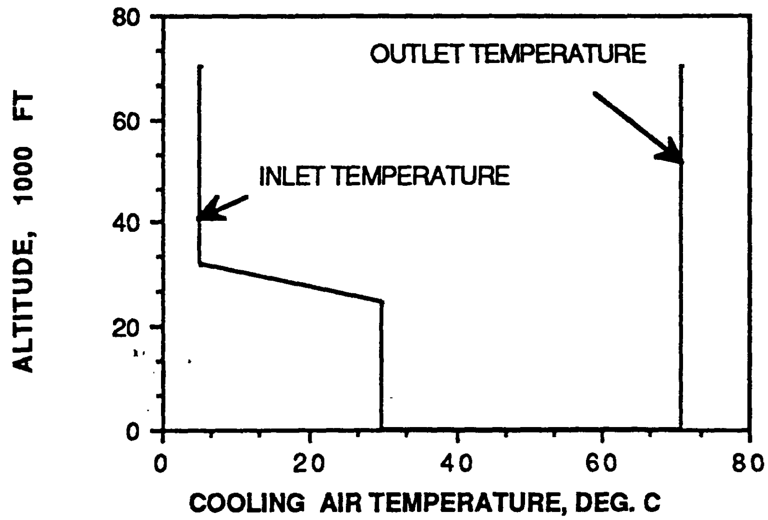


Figure 2-21: Typical ECS cooling air temperature control schedule

The conditioned air is distributed to the various pieces of equipment in the avionics bays, by a set of ducts and valves. Fig. 2-20 shows the general configuration of an air distribution system. Each equipment box may receive a different amount of cooling air as determined by its heat load. The cooling air typically passes through the forced-air cooled equipment boxes entering at a temperature T_{in} and exiting at a higher temperature T_{out} after absorbing the heat dissipated within the forced-air cooled equipment boxes. The cooling air, after exiting the forced-air cooled equipment box, is discharged overboard.

Chapter 3

Unconditioned Bay Configuration - Ambient Cooled Avionics

3.1 Introduction

This chapter describes the modeling approach used to study the heat transfer problems of an unconditioned avionics bay. For this type of bay only ambient cooled equipment is considered. In Section (3.2), the physical situation is described and the mathematical model is developed and discussed. The effects of both radiation and natural convection are studied for various bay temperature conditions in Section (3.3).

3.2 Modes of Heat Transfer

Fig. 3-1(a) shows a generic installation of ambient cooled equipment in an unconditioned bay. In steady state, the heat generated by the equipment ($q_{A,T}$) has to be removed. Two primary heat paths between the equipment and the aircraft skin are considered as depicted in Fig. 3-1(a). The first is the natural convection path. Since the convected heat ($q_{A,c}$) is transported from the equipment surface to the bay walls by the internal bay air, this path is divided into two segments. In the first, heat ($q_{A,c}$) is transferred from the equipment to the air by natural convection. The temperature difference between the equipment surface temperature (T_e) and the bay air temperature (T_a) is determined by the equipment geometry (A_e), the heat being transferred ($q_{A,c}$), and by the equipment heat transfer coefficient (h_e):

$$q_{A,c} = h_e A_e (T_e - T_a) \tag{3.1}$$

The natural convection heat transfer coefficient h_e is also a function of the temperature difference between the equipment and the bay air.

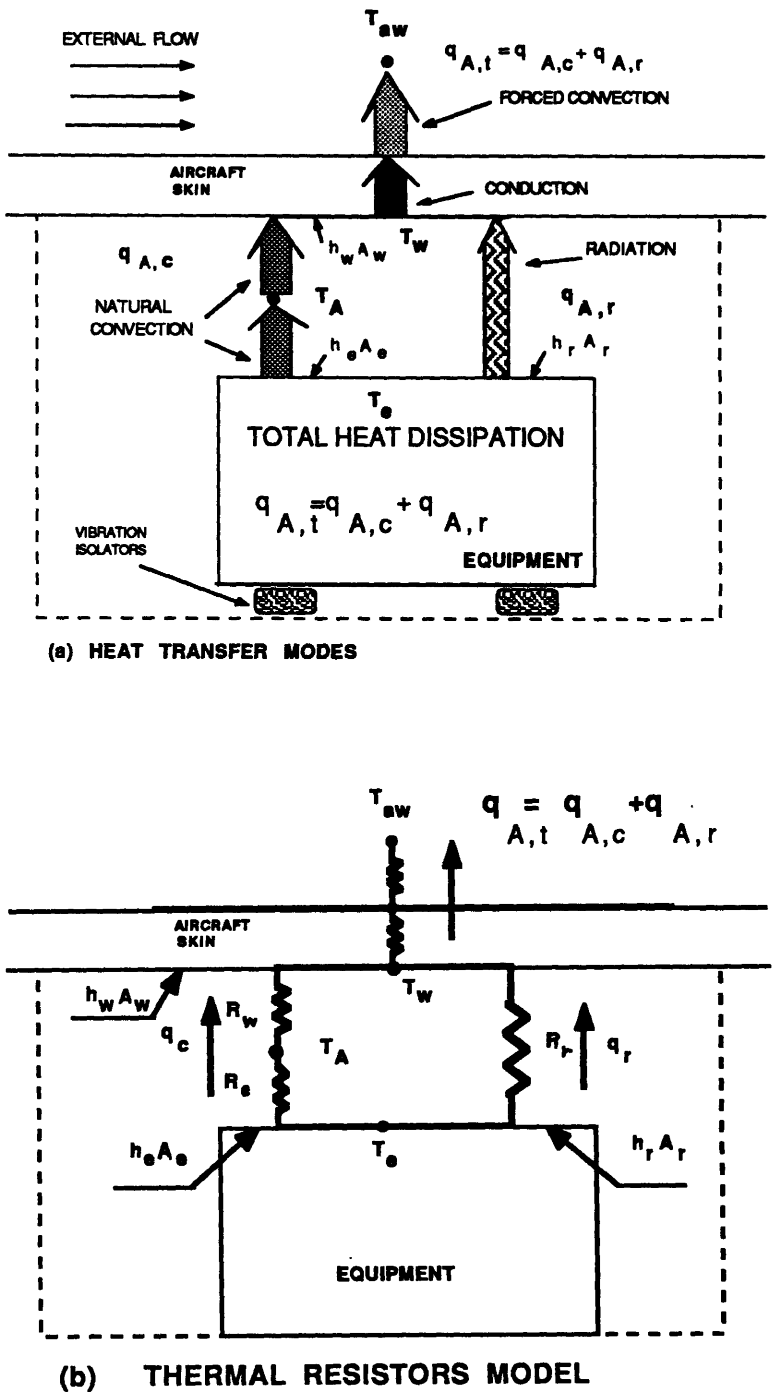


Figure 3-1: Ambient cooled equipment: modes of heat transfer and thermal resistors model

In the second segment, the same heat rate ($q_{A,c}$) is transferred from the air to the aircraft walls also by natural convection. At this side, the temperature difference between the the air (T_a) and the aircraft skin temperature (T_w) is determined by the bay wall geometry (A_w), the heat being transferred ($q_{A,c}$), and by the bay wall heat transfer coefficient (h_w):

$$q_{A,c} = h_w A_w (T_a - T_w) \tag{3.2}$$

The wall heat transfer coefficient, (h_w), is determined by the bay wall geometry and the difference between the air temperature, which is considered to have a mean bulk temperature (T_a), and the aircraft skin temperature (T_w).

The second path shown in Fig. 3-1(a) is the radiation path. Since air is a nonparticipating gas, heat ($q_{A,r}$) is exchanged directly between the equipment surfaces and the bay walls. The radiative heat transfer coefficient, h_r, is determined by the geometry and temperature of both the equipment box surface and the bay wall:

$$q_{A,r} = h_r A_r (T_e - T_w) \tag{3.3}$$

These two heat paths are combined to one in the aircraft skin. The total heat flow ($q_{A,T} = q_{A,c} + q_{A,r}$) is then conducted through the aircraft skin and rejected to the external air by forced convection.

In most cases the equipment is mounted on vibration or shock absorbers usually made of materials with poor thermal conductivity; therefore, conduction heat transfer between the equipment and the aircraft structure is neglected in this model.

The most important parameter in the thermal design of the avionics unit is the equipment box surface temperature (T_e). The temperature of the external air (T_{aw}) is a function of factors such as the outside atmospheric temperature and the flight Mach number. Furthermore, the wall temperature (T_w) will typically be very close to the external air temperature, T_{aw}, due to the high forced convective heat transfer that takes place between the aircraft skin and the external air. If needed, T_w can be calculated from the total heat dissipation ($q_{A,T}$) and the external convection heat transfer coefficient (h_{ext}) by using Eq. (2.9). Also, the temperature gradient across the aircraft skin is usually negligible. While the bay wall temperature (T_w) depends on external factors, the equipment box temperature (T_e) is determined by the wall temperature (T_w) and by bay internal factors. It is therefore convenient to express the equipment temperature (T_e) in terms of the reference wall temperature T_w and the overall internal temperature difference ($\Delta T_{ew} = T_e - T_w$). This approach is used in this thesis.

After the temperature difference between the equipment and the bay wall is defined, it is analyzed as functions of altitude. This is done by expressing each of the elements which are involved in the process, i.e. the radiation and the convection heat transfer coefficients as a function of altitude.

Since steady state conditions are assumed, the electrical resistor analogy may be used to relate the temperature and the heat flow in the system. Fig. 3-1(b) shows the resistor model for the problem defined in Section (3.2). It should be noted that R_e and R_w depend on the natural convection heat transfer coefficients (h_e and h_w) which depend on the temperature differences between the surfaces and the air. Since the temperature of the equipment (T_e) and the air (T_a) also depend on the convective heat transfer coefficients (h_e and h_w) they are not known a priori. Thus, R_e and R_w cannot be replaced with an equivalent resistance until the temperatures of the equipment (T_e) and the air (T_a) are evaluated iteratively.

The objective is to express the temperature difference between the equipment box and the aircraft wall ($\Delta T_{ew} = T_e - T_w$) in terms of the system resistances. This overall temperature difference is given by

$$\Delta T_{ew} = q_{A,T} R_T \tag{3.4}$$

where $\Delta T_{ew}=T_e-T_w$, $q_{A,T}$ is the total heat dissipation of the equipment, and R_T is the total thermal resistance of the system between the equipment box and the bay wall and is given by:

$$R_T = \frac{R_e+R_w}{1+\frac{R_e}{R_r}+\frac{R_w}{R_r}} \tag{3.5}$$

where R_e, R_w and R_r are defined in Fig. 3-1(b).

If the resistors in Eq. (3.5) are replaced with their reciprocal values ($1/R_e$; $1/R_w$; $1/R_r$), the following expression is obtained by combining (3.4) and (3.5) :

$$\Delta T_{ew} = q_{A,T} \frac{\left[\frac{1}{H_e}+\frac{1}{H_w}\right]}{\left[1+\frac{H_r}{H_e}+\frac{H_r}{H_w}\right]} \tag{3.6}$$

where: $H_e=h_eA_e=\frac{1}{R_e}$; $H_w=h_wA_w=\frac{1}{R_w}$; $H_r=h_rA_r=\frac{1}{R_r}$ are the total heat conductances of the different paths $[W/^oC]$. In order to study altitude dependent effects, Eq. (3.6) can be normalized by the sea level value. Assuming the total heat dissipation of the equipment ($q_{A,T}$) is constant during all flight conditions, the result is the following nondimensional general parametric equation:

$$\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}} = \left[\frac{1}{\delta}\right]\left[\frac{1+\gamma}{1+\gamma_0}\right]\left[\frac{1+\alpha_0+\alpha_0\gamma_0}{1+\alpha+\alpha\gamma}\right]$$

$$\textit{where} \quad \delta=\frac{(H_e)_{alt}}{(H_e)_{sl}}=\left(\frac{h_{e,alt}}{h_{e,sl}}\right) \quad \alpha=\left(\frac{H_r}{H_e}\right) \quad \gamma=\left(\frac{H_e}{H_w}\right)$$

$$0 = \textit{sea level value} \tag{3.7}$$

The three resistances of Eq.(3.5) and (3.6) were replaced here by three dimensionless factors. The first and the most important factor, δ, reflects the altitude dependent changes of the convective heat transfer coefficient between the equipment surface and the bay air. The second is the radiation factor, α, which represents the balance between radiation and convection heat transfer path in the system. Small values of α mean that convection is dominant in the process, and large values of α mean that radiation is dominant. For example, $\alpha=0$ means that there is no radiation involved in the process and only the convective heat path exists. On the other hand, large values of α mean that most of the heat is transferred from the equipment by radiation.

The third factor, γ, results from having two segments in the convection path. This parameter reflects the ratio between the convective heat transfer coefficient from the equipment to the bay air (H_e) and the convective heat transfer from the air to the bay wall (H_w). These two parameters α and γ can take any value from 0 to infinity. The value of γ may be interpreted as a measure of how close the bay ambient temperature T_a is to the wall temperature T_w ($\gamma << 1$) or to the equipment temperature T_e ($\gamma >> 1$).

3.2.1 Dependence of Radiation and Convection Parameters on Altitude and Configuration

In this section expressions for the factors (δ, α, γ) are developed. It should be noted that the definitions of these three factors are based on three basic components of the heat transfer process -- h_e, h_w, and h_r. Both h_e and h_w are convective heat transfer coefficients and, therefore, have the same general form, which is different from that of the radiative heat transfer coefficient h_r.

3.2.1.1 Convective Heat Transfer Coefficient

Typically, the convective heat transfer coefficient is expressed in terms of the dimensionless Nusselt number (Nu), which is defined by

$$Nu_L = \frac{h_L L}{k} \tag{3.8}$$

where h_L is the heat transfer coefficient averaged over the length L of the surface, and k is the thermal conductivity of the fluid. In natural convection, the Nusselt number is typically correlated to the dimensionless Rayleigh number which represents the balance between the buoyancy forces (the driving forces) and the inertia and viscous forces. The Rayleigh number group (Ra_L) is defined as :

$$Ra_L = \frac{g\beta\rho\Delta T L^3}{\alpha\mu} \tag{3.9}$$

where, g is the acceleration of gravity, ρ is the density of the fluid, β is the volumetric expansion coefficient, ΔT is the temperature difference between the surface and the fluid, L is the characteristic length scale of the circulation (e.g. the height of a vertical plate or the diameter of a horizontal cylinder), α and μ are the thermal diffusivity and the viscosity of the fluid respectively.

A typical correlation of the average Nusselt number in natural convection problem with air as a fluid is of the form:

$$Nu_L = C\,(Ra_L)^n = C\left(\frac{g\beta\rho\Delta T L^3}{\alpha\mu}\right)^n \qquad (3.10)$$

where C is a constant which depends on the geometry, and the exponent n depends on the type of flow, i.e. laminar ($n=1/4$) or turbulent ($n=1/3$). The type of flow is determined primarily by the Rayleigh number. For example, in the case of an isothermal vertical plate:

$10^4 < Ra_L < 10^9$, laminar flow.

$10^9 < Ra_L < 10^{13}$, turbulent flow.

Using these relationships for the heat transfer coefficient (Eq. (3.8), (3.10)) and normalizing by the sea level value, assuming constant geometry and gravity, allow the changes of h_L with altitude to be written as:

$$\boxed{\left(\frac{h_{alt}}{h_{sl}}\right) = \left[\frac{\rho(P_{alt})}{\rho(P_{sl})}\right]^{2n}\left[\frac{\Delta T_{alt}}{\Delta T_{sl}}\right]^{n} F(T_{sl},T_{alt}) = \delta} \qquad (3.11)$$

where $\left(\frac{h_{alt}}{h_{sl}}\right)$ reflects the changes in the average heat transfer coefficient at a given altitude in respect to the value at sea level. $\rho(P)$ is the density of air as a function of ambient pressure only (i.e. with a constant temperature), ΔT_{alt} is the equilibrium temperature difference which will produce the proper natural convective circulation necessary to remove the heat ($q_{A,c}$) which is the same both from the equipment to the bay air and from the air to the bay wall. The exponent n, again, is determined by the flow type and may take typical values of 1/4 for laminar flow and 1/3 for turbulent flow. The function F introduced in Eq. (3.11) is defined as:

$$\boxed{F(T_{sl},T_{alt}) = \left(\frac{k_{alt}}{k_{sl}}\right)^{1-n}\left[\left(\frac{\beta_{alt}}{\beta_{sl}}\right)\left(\frac{\mu_{sl}}{\mu_{alt}}\right)\left(\frac{C_{P_{alt}}}{C_{P_{sl}}}\right)\left(\frac{\rho(T_{alt})}{\rho(T_{sl})}\right)^2\right]^n} \qquad (3.12)$$

This function reflects the changes in the properties of the air due to temperature changes between the two states, where k is the thermal conductivity, β is the volumetric expansion coefficient, μ is the viscosity, and C_p is the specific heat.

Dimensions of avionics units are typically less than 0.5 *m*, and the temperature difference between the equipment and the ambient bay air is typically less than 75 °C. Fig. 3-2 shows the transition line from laminar to turbulent natural convective circulation for a vertical plate situated in atmospheric air at 71 °C. It can be seen that avionics units typically will experience laminar natural convection; therefore, all numerical results presented in this thesis are based on n=1/4.

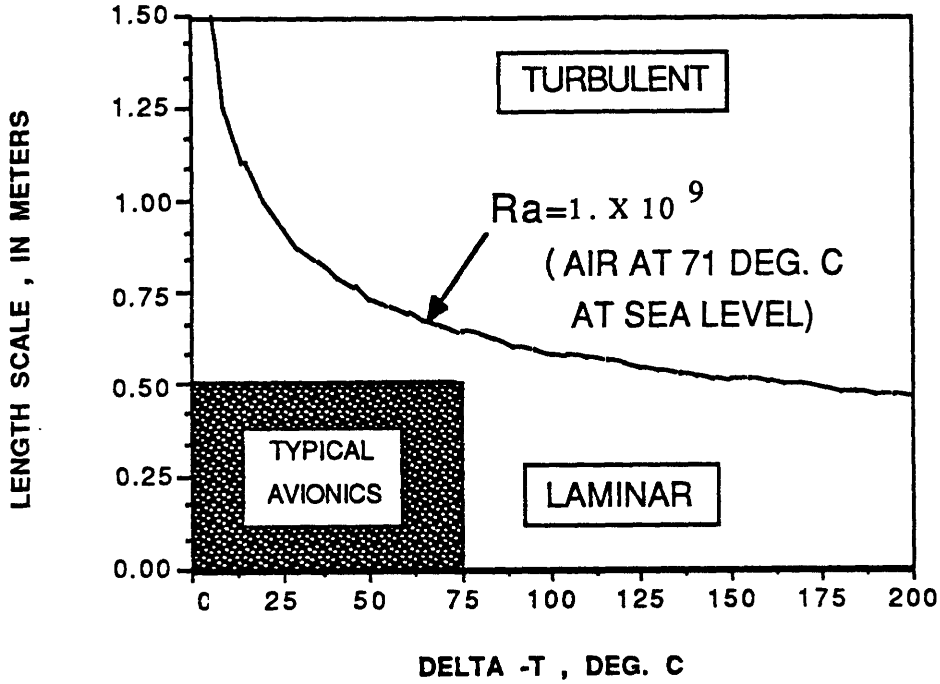


Figure 3-2: Natural convection - avionics units vs transition to turbulent

3.2.1.2 Radiative Heat Transfer Coefficient

Radiation heat transfer, unlike convective heat transfer, depends on the forth power of the temperature as shown in Eq. (3.13)

$$q_{A,r}=F_r(T_e^4-T_w^4) \tag{3.13}$$

where F_r is a constant which depends on the properties of the two bodies involved in the thermal radiation exchange, and on geometry.

The radiative heat transfer coefficient, h_r, on the other hand, is defined by the following relation

$$q_{A,r}=h_r A_r (T_e - T_w) \tag{3.14}$$

combining (3.13) and (3.14) and eliminating $q_{A,r}$, the following expression is used to evaluate the heat transfer coefficient h_r

$$h_r=\left(\frac{F_r}{A_r}\right)(T_e^2+T_w^2)(T_e+T_w) \tag{3.15}$$

Using this relationship for the heat transfer coefficient (Eq. (3.15)) and normalizing by the sea level value, assuming constant geometry, allow the changes of h_r with altitude to be written as:

$$\left(\frac{h_{r,alt}}{h_{r,sl}}\right)=\frac{\left[1+(\theta)^2_{alt}\right]\left[1+(\theta)_{alt}\right]}{\left[1+(\theta)^2_{sl}\right]\left[1+(\theta)_{sl}\right]}\left(\frac{T_{w,alt}}{T_{w,sl}}\right)^3$$
$$\text{where } \theta=\left(\frac{T_e}{T_w}\right) \tag{3.16}$$

From Eq. (3.16) it can be seen that the radiative coefficient does not depend on altitude directly. Furthermore, when radiation is the only mode of heat transfer in the system, and if the wall temperature (T_w) is constant the temperature difference between the equipment and the wall (ΔT_{ew}) will remain constant at any altitude. However, when convective heat transfer is involved, the box equilibrium temperature will change with altitude and thus the radiation coefficient h_r will be indirectly dependent on altitude.

3.3 Results

The effect of natural convection and radiation factors on the temperature difference between the equipment and the bay wall as a function of altitude are presented in the following paragraphs. These effects are studied for various wall temperatures and different values of sea level temperature difference $(\Delta T_{ew})_{sl}$. The effects of convection and radiation heat transfer modes, are isolated and examined for various combinations of convection and radiation factors. It is shown that the changes of convective heat transfer with altitude are determined primarily by the changes of external atmospheric pressure with altitude. It is also shown that radiative heat transfer is an important factor at high altitude.

3.3.1 Equipment Temperature Versus Altitude For a Single Segment Convection Path System Configuration

In this section, the changes of temperature difference between the equipment and the bay wall temperatures as a function of altitude for a single convective segment configuration are presented and compared for different temperature conditions. Then, the actual equipment temperature is simulated by using the MIL-E-5400 temperature altitude envelope.

The increase of temperature difference between the equipment and the wall, ΔT_{ew}, with altitude is shown to grow exponentially. External atmospheric pressure is shown to be the primary factor responsible for that increase. The sea level temperature difference between the equipment and the bay wall, $(\Delta T_{ew})_{sl}$, on the other hand, has only a small effect on the altitude dependent changes of ΔT_{ew}. The reference wall temperature T_w is shown to have no effect on the altitude dependent changes of ΔT_{ew}.

The simulation based on the MIL-E-5400 temperature - altitude envelope shows regions of convergence, stability, and divergence of the equipment temperature with altitude depending on the value of temperature difference at sea level, $(\Delta T_{ew})_{sl}$. This suggests the introduction of an optimal design sea level value of $(\Delta T)_{opt}$ which will result in relatively constant equipment temperature at all altitudes.

i) Configuration

Results presented in this section are for the configuration shown in Fig. 3-3. It is assumed that the total heat dissipation of the equipment $(q_{A,T})$ is transferred to the bay wall by natural convection. It is further assumed that the bay air temperature is the same as the wall temperature ; therefore, only one convective segment is considered in this model. Results for situations where the temperature difference between the bay ambient air temperature (T_a) and the wall temperature (T_w) cannot be neglected, are presented in Section (3.3.3).

ii) Analysis

The expression for the changes of temperature difference between the equipment and the bay wall with altitude, $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, for the configuration shown in Fig. 3-3 is based on Eq. (3.7) which was derived for the more general case. However, since radiation is not considered (α=0) and only one segment in the convection path is included (γ=0), the general form given by Eq. (3.7) for the altitude dependent changes of temperature difference between the equipment and the bay wall, $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, is reduced to the following:

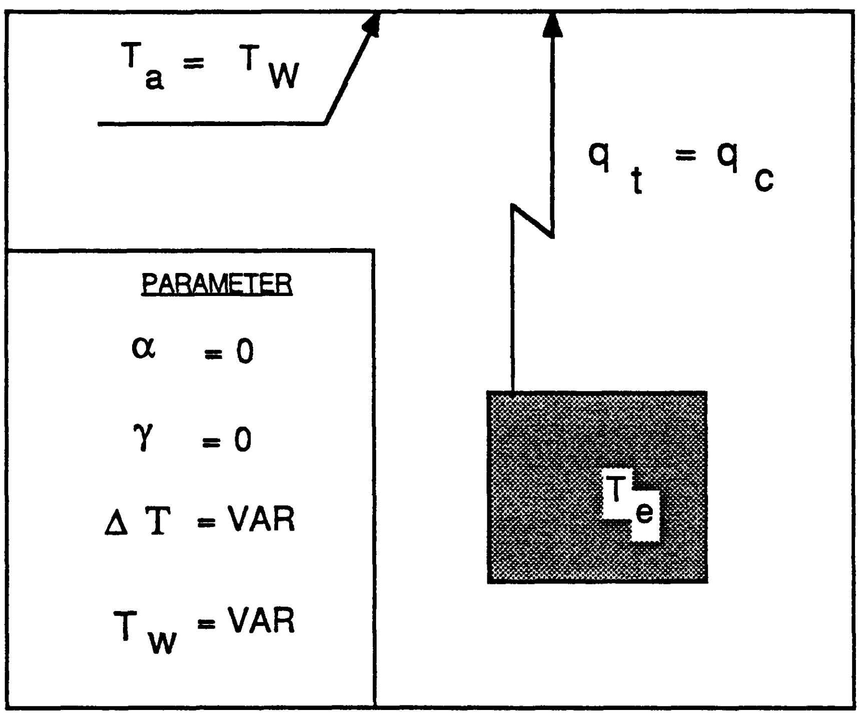


Figure 3-3: Single convection segment configuration schematic

$$\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}} = \left[\frac{1}{\delta}\right] \quad where \quad \delta = \frac{(H_e)_{alt}}{(H_e)_{sl}} = \frac{(h_e)_{alt}}{(h_e)_{sl}} \tag{3.17}$$

and from Eq. (3.11) with $n=1/4$ as explained in Section (3.2.1.1) the changes of the equipment convective heat transfer coefficient with altitude, $\frac{(h_e)_{alt}}{(h_e)_{sl}}$, are given by

$$\frac{(h_e)_{alt}}{(h_e)_{sl}} = \left[\frac{\rho(P_{alt})}{\rho(P_{sl})}\right]^{1/2}\left[\frac{\Delta T_{ew,alt}}{\Delta T_{ew,sl}}\right]^{1/4} F(T_{sl},T_{alt}) \tag{3.18}$$

where $\left[\frac{\rho(P_{alt})}{\rho(P_{sl})}\right]$ is the external atmospheric air density changes as function of pressure only. The function F which reflects the changes in air properties between the two states was defined in Eq. (3.12):

$$F(T_{sl},T_{alt}) = \left(\frac{k_{alt}}{k_{sl}}\right)^{3/4}\left[\left(\frac{\beta_{alt}}{\beta_{sl}}\right)\left(\frac{\mu_{sl}}{\mu_{alt}}\right)\left(\frac{c_{p_{alt}}}{c_{p_{sl}}}\right)\left(\frac{\rho(T_{alt})}{\rho(T_{sl})}\right)^2\right]^{1/4} \tag{3.19}$$

The volumetric expansion coefficient , β, is typically approximated by the ideal gas relation to give $\beta = 1/T_a$, where T_a is the bay ambient air temperature.

Since in each state, sea level or altitude, there are two different temperatures in the system, the equipment temperature T_e and the bay air temperature, T_a, the thermal and the thermodynamic properties in Eq. (3.19) are typically evaluated at the average temperature T_f which is defined as:

$$T_f = \frac{T_e + T_a}{2} \tag{3.20}$$

The numerical analysis follows the procedure shown schematically in Fig. 3-4, using the pressure profile shown in Fig. 2-9, and correlations for the properties of air as a function of temperature in the range 250 - 600 ^{o} K. There were no problems of convergence.

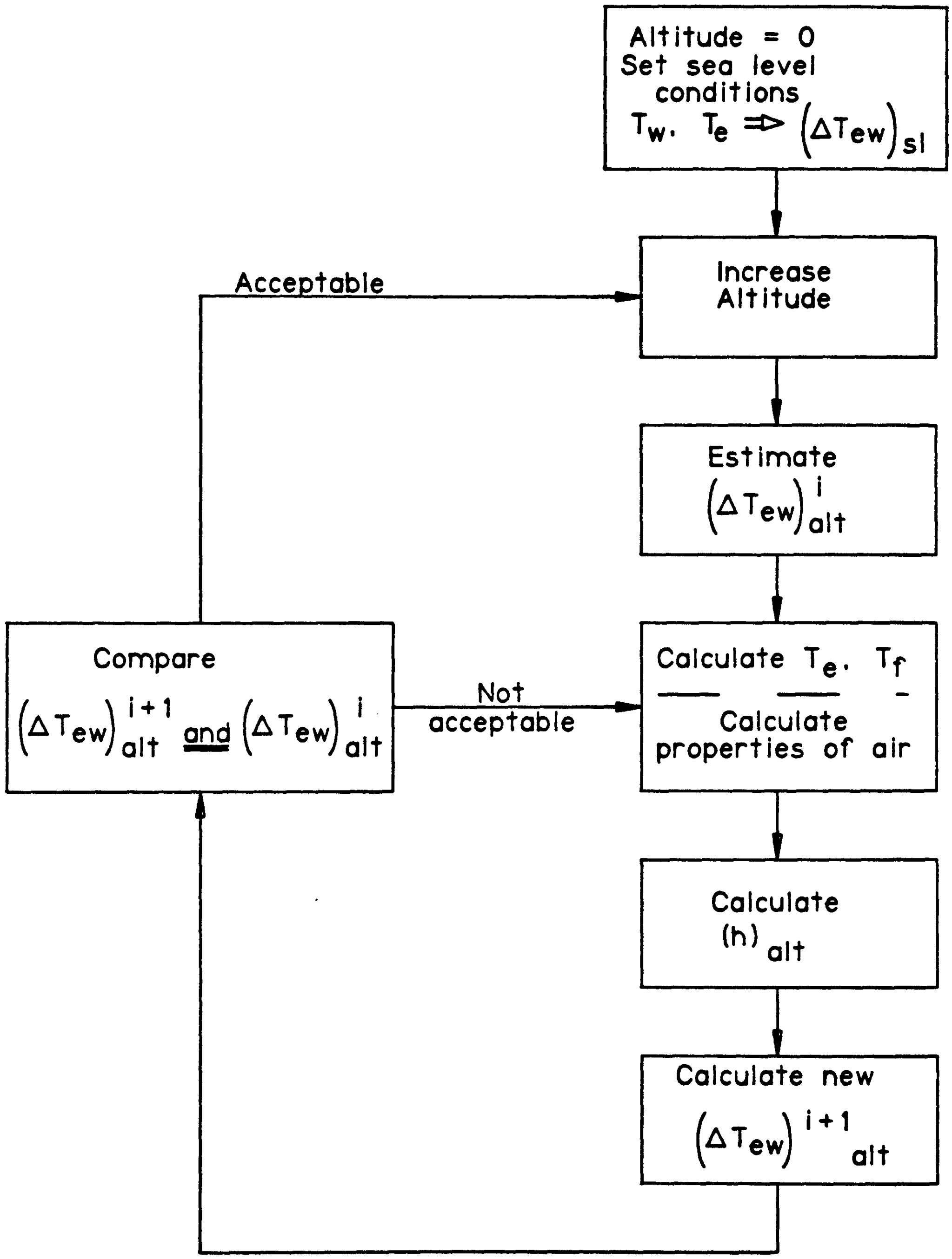


Figure 3-4: Numerical analysis flow diagram

iii) Results: The Effects of Pressure and Temperature on Changes of ΔT_{ew} With Altitude

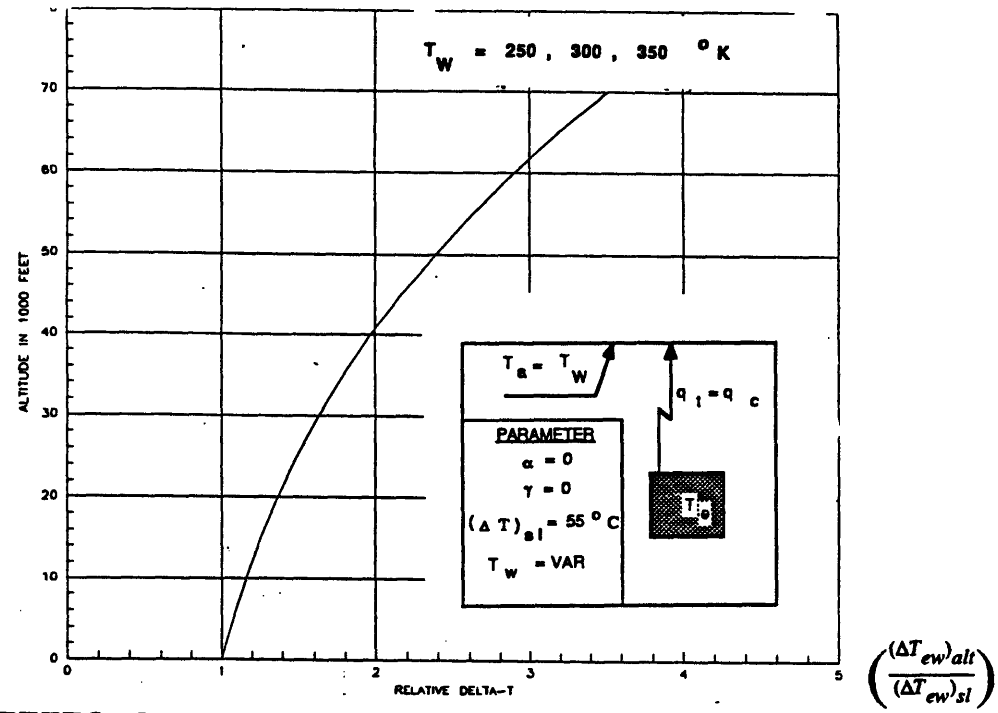
Fig. 3-5 shows the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude for three different values of bay wall temperature, T_w, and three different sea level values of temperature difference between the equipment, T_e, and the bay wall T_w, $(\Delta T_{ew})_{sl}$. It can be seen that $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ grows exponentially with altitude. The value at sea level is 1, and at an altitude of 70,000 ft it is approximately 3.5. The single curve in Fig. 3-5(a) represents three different cases of wall temperature. In each case the wall temperature, T_w, was held constant throughout the altitude range from sea level to 70,000 ft. The temperature difference between the equipment and the bay wall at sea level $(\Delta T_{ew})_{sl}$ was the same, 55 ^{o} C, in the three cases. It is clear from Fig. 3-5(a) that the changes in the wall temperature do not have any effect on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude.

Fig. 3-5(b) shows the small effect that the temperature difference between the equipment and the wall has on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude. The three close curves in Fig. 3-5(b) represent three different cases of $(\Delta T_{ew})_{sl}$. In all cases the wall temperature was the same (250 ^{o} K) and kept constant throughout the altitude range. It can be seen that larger values of $(\Delta T_{ew})_{sl}$ cause a shift of the $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ curve towards somewhat higher values.

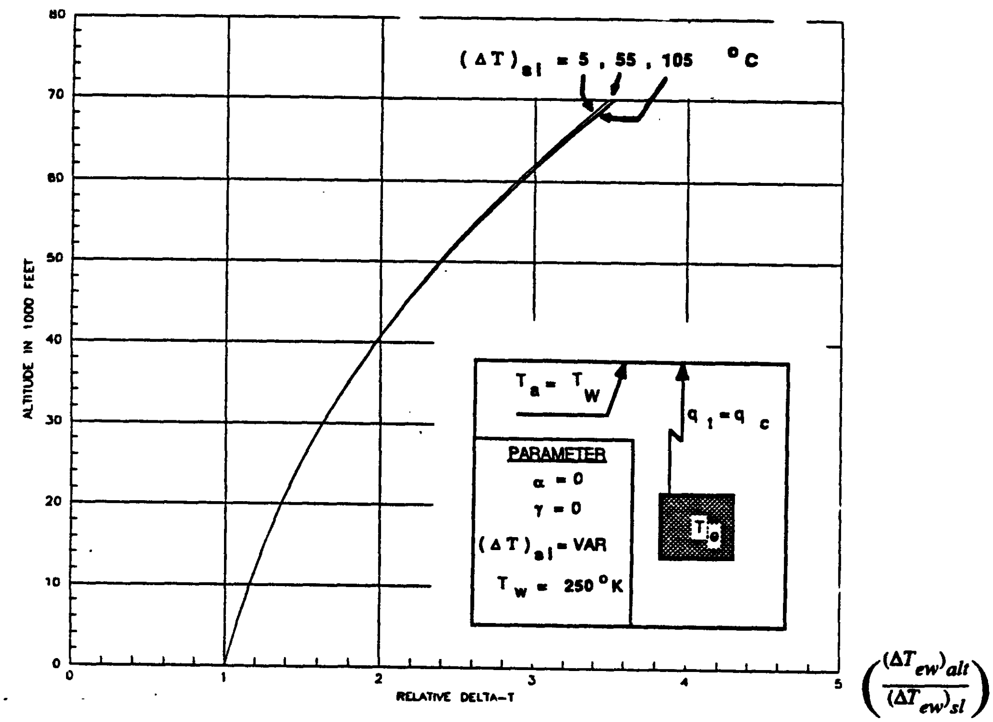
Since equipment temperature, T_e, is a result of the wall temperature, T_w, and the temperature difference between the equipment and the bay wall, ΔT_{ew}, it can be expressed in terms of these two factors as follows:

$$T_e = T_w + (T_e - T_w) = T_w + \Delta T_{ew} \tag{3.21}$$

and also as



(a) EFFECTS OF WALL TEMPERATURE



(b) EFFECTS OF TEMPERATURE DIFFERENCE

Figure 3-5: Effects of bay wall temperature and temperature difference on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude in a single segment convection path configuration

$$(T_e)_{alt} = (T_w)_{alt} + (\Delta T_{ew})_{sl}\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right) \tag{3.22}$$

The positive growth of the temperature difference between the equipment and the bay wall with altitude means that if the wall temperature T_w, is kept constant, T_e, will be at a maximum at the highest altitude. For example, a system with the configuration shown in Fig. 3-3 that is designed to operate at sea level at a bay air temperature, T_a, of 70 °C with an equipment temperature, T_e, of 90 °C, will experience equipment temperature of approximately 140 °C at an altitude of 70,000 ft if the wall temperature is the same as at sea level.

The fact that $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ is effectively insensitive to temperature conditions in the range presented, suggests that the primary factor which determines the shape of the curve is the density which is the only term in Eq. (3.18) that does not depend on temperature alone but also on pressure. This may be confirmed by examining the dependence of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ on pressure which can be derived from Eq. (3.17) and (3.18) by dropping terms that are a function of temperature only ($F(T_{alt}, T_{sl})$):

$$\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right) = \left[\frac{\rho(P_{sl})}{\rho(P_{alt})}\right]^{2/5} = \left[\frac{P_{sl}}{P_{alt}}\right]^{2/5} \tag{3.23}$$

This relationship is plotted in Fig. 3-6. By comparing Fig.3-6 to Fig. 3-5 it can be seen that the curves are approximately the same. Hence, the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude for the single segment convection path without radiation may be described very well by considering the changes in external atmospheric pressure only (Eq. (3.23)). This means that the temperature difference between the equipment and the wall at any altitude, $(\Delta T_{ew})_{alt}$, can be estimated from the sea level value, $(\Delta T_{ew})_{sl}$, simply by using Eq. (3.23) even when the wall temperature, T_w, is not kept constant with altitude.

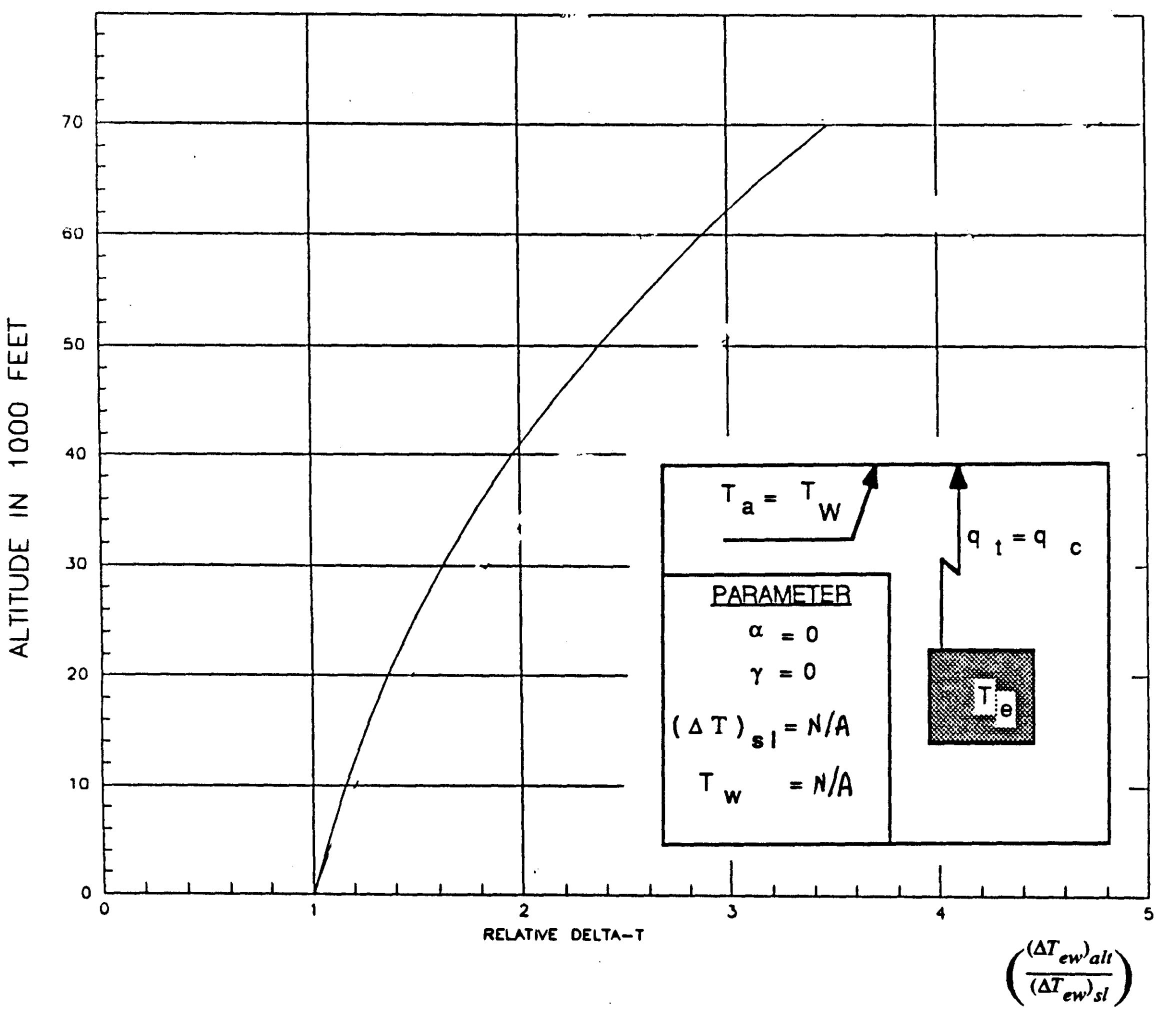


Figure 3-6: $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ versus altitude, as a function of pressure only

iv) Results of Equipment Temperature Simulation for MIL-E-5400 Temperature-Altitude Envelope

Fig. 3-7 shows the changes of equipment temperature, T_e, as a function of altitude obtained by simulating the bay air temperature with the temperature-altitude envelope of MIL-E-5400 Class II. The MIL-E-5400 Class II envelope specifies the air temperature in the bay as shown in Fig. 3-7, as a dashed line which starts from 71 ^oC at sea level and drops continuously as altitude increases to a value of 10 ^oC at an altitude of 70,000 ft. The other curves in Fig. 3-7 represent the equipment temperature, T_e, as a function of altitude for different values of temperature difference between the equipment and the wall at sea level, $(\Delta T_{ew})_{sl}$.

There are three regions shown in Fig. 3-7 which represent the following behaviors of the curves: convergent , stable, and divergent

The most important is the <u>stable</u> region, in between the convergent and the divergent regions. The stable region contains curves that have relatively constant equipment temperature, T_e, at all altitudes, which means optimal design for all altitudes. Other design conditions (lower or higher values of the temperature difference at sea level) result in equipment temperatures decreasing or increasing with altitude. These design conditions have one critical point, either at sea level, or at high altitude. Typically, the equipment has to be designed to operate at that critical temperature and, therefore, at other altitudes the equipment will experience overcooling conditions.

Since the heat flux transferred from the equipment, $q''_{A,c}$, is proportional to the temperature difference between the equipment and the wall, ΔT_{ew}, as can be seen from the following relationship

$$q''_{A,c} = \frac{q_{A,c}}{A_e} = h_e \Delta T_{ew} \tag{3.24}$$

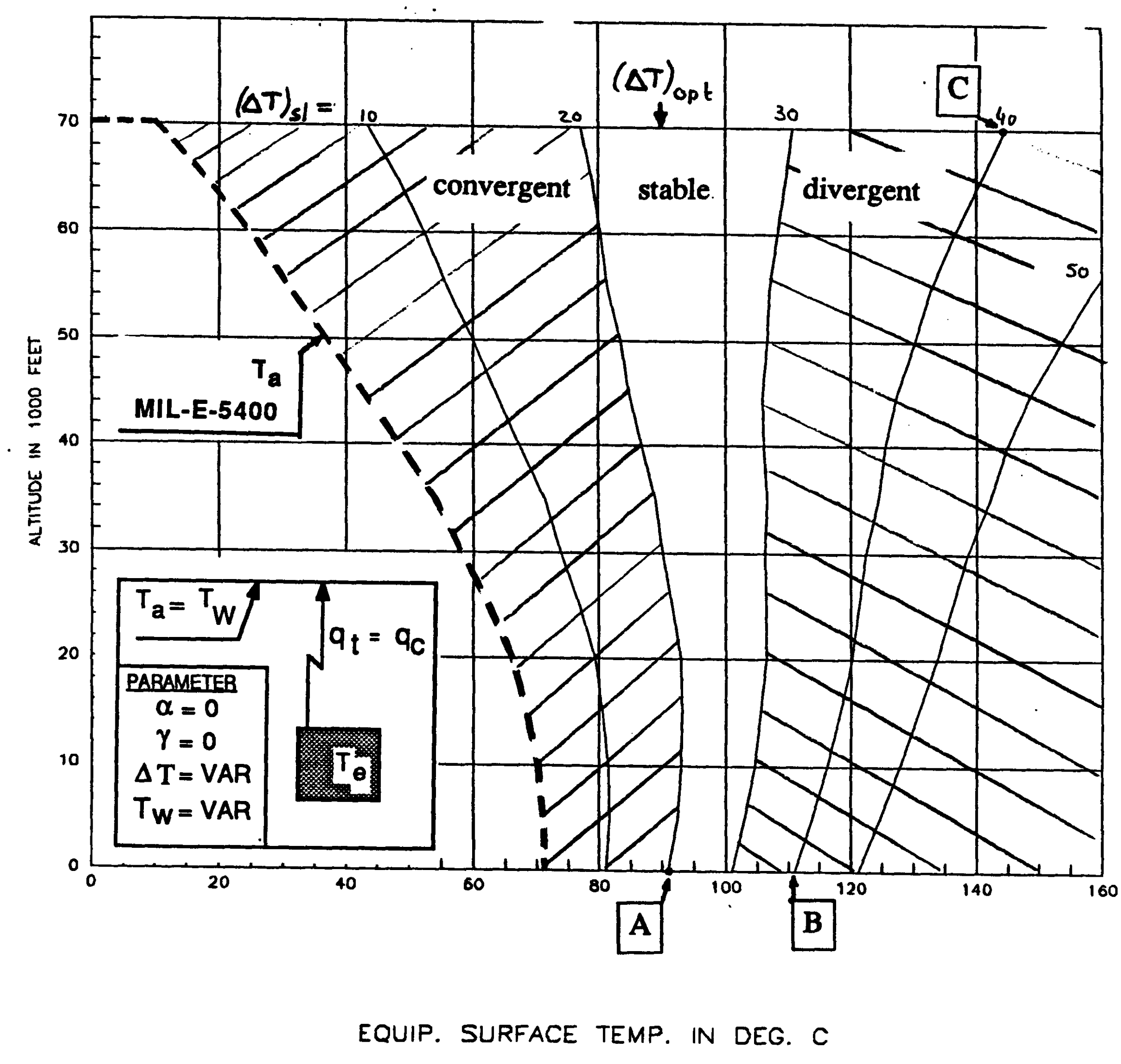


Figure 3-7: Equipment temperature simulation based on MIL-E-5400 class II temperature altitude envelope for a single segment convection path

ΔT_{ew} is, in a sense, a measure for the amount of heat that can be removed from the equipment. The temperature difference between the equipment and the wall, ΔT_{ew}, cannot be increased without increasing the equipment temperature, T_e, as can be seen from Eq. (3.21). However, it is desirable to achieve maximum increase in ΔT_{ew} with minimum increase in the equipment temperature, T_e. This maximum value of ΔT_{ew} is represented by the $(\Delta T_{ew})_{opt}$ which is located in the stable region shown in Fig. 3-7. Further increase in ΔT_{ew} will cause penalty in terms of increasing equipment temperature (at altitude), T_e, by an amount which is greater than the increase in the temperature difference, ΔT_{ew}, itself. For example, referring to Fig. 3-7, an increase of 20 °C in $(\Delta T_{ew})_{sl}$, from the line of $(\Delta T_{ew})_{sl}$=20 °C, point [A], to the line of $(\Delta T_{ew})_{sl}$= 40 °C, point [B], will increase maximum equipment temperature, T_e, from 91 °C, point [A], to 145 °C, point [C], at high altitude (increase of 54 °C).

The two shaded regions shown in Fig. 3-7 represent convergent and divergent behaviors of the curves. The convergent curves are characterized by the fact that the equipment temperature, T_e, at high altitude is lower than the sea level value for the given curve. In this group there are curves for $(\Delta T_{ew})_{sl}$ from 0 to 20 ° C. The meaning of this is that the worst case equipment temperature, T_e, for that group is determined at sea level. For example, a system which is designed to operate at sea level with $T_e = 80°C$ will experience lower temperature of approximately $T_e = 45°C$ at an altitude of 70,000 ft.

The divergent curves, on the other hand, are characterized by the fact that the equipment temperature, T_e, at high altitude is higher than the sea level value. This means that the worst case equipment temperature is expected at the highest altitude. The curves in the divergent group represent equipment temperature, T_e, for temperature difference with values above 30 °C between the equipment and the bay wall, $(\Delta T_{ew})_{sl}$.

3.3.2 Equipment Temperature Versus Altitude for a Single Segment Convection and Radiation Paths System Configuration

In this section, the changes in the temperature difference between the equipment and the bay wall temperatures as a function of altitude for a system with combined, radiation and single segment convection, heat transfer modes are presented and compared for different values of radiation heat transfer factor α. The actual equipment temperature is then simulated by using the MIL-E-5400 temperature-altitude envelope.

The changes of temperature difference between the equipment and the bay wall with altitude $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, are shown to be at a maximum when radiation heat transfer is not included (radiation factor, α=0) and to decrease when the radiation heat transfer factor increases.

The simulation based on the MIL-E-5400 temperature-altitude envelope shows regions of convergence, stability, and divergence of the equipment temperature with altitude for small values of radiation factor α ($\alpha < 1.0$) similar to the regions discussed in the previous section. When radiation factor α, increases, the curves of equipment temperature for different sea level values tend to be shifted towards the convergence region. This means that higher heat fluxes could be attained without increasing the equipment temperature at altitude, as was explained in the previous section.

i) Configuration

The results presented in this section are for the configuration shown in Fig. 3-8. In this configuration two heat transfer modes are considered: convection and radiation. It is assumed that the bay air temperature is the same as the wall temperature and, therefore, only one segment in the convective path is considered.

ii) Analysis

The derivation of the expressions for the changes of temperature difference between the equipment and the bay wall with altitude, $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, for the configuration shown in Fig. 3-8, follows a procedure similar to that presented in the previous section; it results in the following relations:

$$\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}} = \left[\frac{1}{\delta}\right]\left[\frac{1+\alpha_0}{1+\alpha}\right]$$
$$where \quad \delta = \frac{(H_e)_{alt}}{(H_e)_{sl}} \quad \alpha = \left(\frac{H_r}{H_e}\right)$$
$$0 = sea\ level\ value \tag{3.25}$$

The expressions relevant to the convective heat transfer coefficient, h_e, were presented in the previous section and they are also used here (Eq. (3.18); (3.19); (3.20)). The expression for the changes of the radiative heat transfer coefficient with altitude, $\left(\frac{h_{r,alt}}{h_{r,sl}}\right)$, is

$$\left(\frac{h_{r,alt}}{h_{r,sl}}\right) = \frac{\left[1+(\theta)^2_{alt}\right]\left[1+(\theta)_{alt}\right]}{\left[1+(\theta)^2_{sl}\right]\left[1+(\theta)_{sl}\right]}\left(\frac{T_{w,alt}}{T_{w,sl}}\right)^3$$
$$where \ \theta = \left(\frac{T_e}{T_w}\right) \tag{3.26}$$

The numerical analysis here is similar to that presented in the previous section, and it follows the procedure shown schematically in Fig. 3-9.

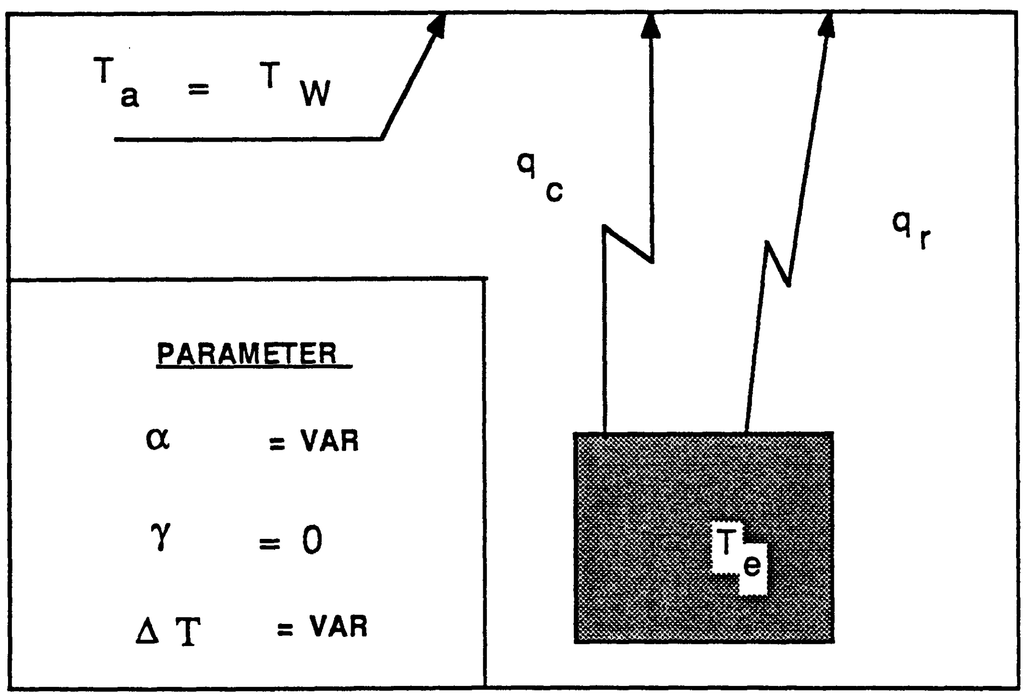


Figure 3-8: Single convection segment and radiation configuration schematic

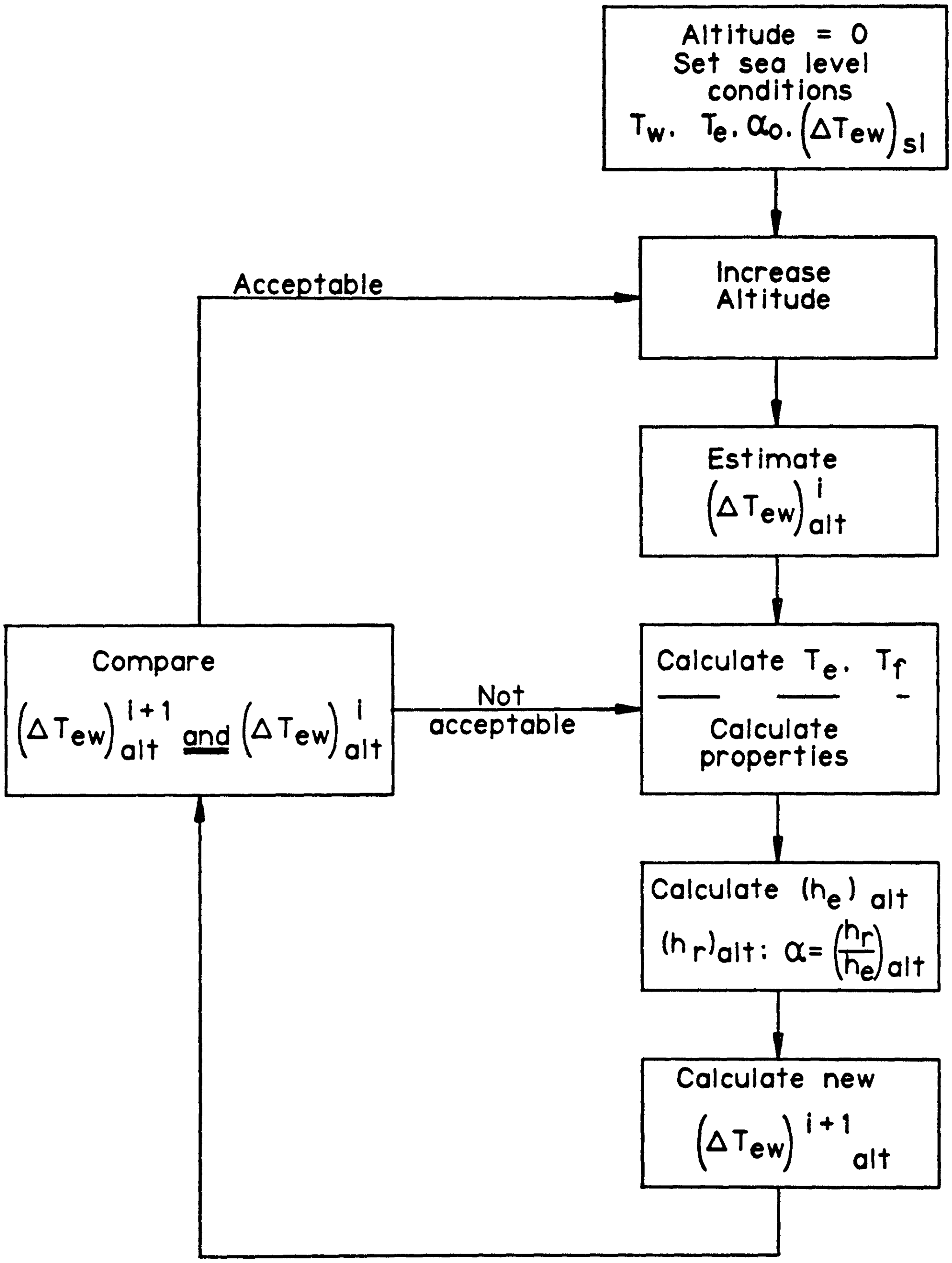


Figure 3-9: Numerical analysis flow diagram for single convection and radiation system

iii) Results: The Effects of Radiation on Changes of ΔT_{ew} With Altitude

Fig. 3-10 shows the changes of the temperature difference between the equipment and the bay wall, $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, with altitude for 6 different values of the radiation factor, α. It can be seen that $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ grows exponentially with altitude for small values of the radiation factor ($\alpha < 0.01$). This growth is moderated by increasing the radiation factor. The following observations may be made regarding the results. Radiation is shown to have an important effect. The sensitivity of the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude to the radiation factor is the strongest when $0.01 < \alpha < 10$. Otherwise, when the radiation factor is small ($\alpha<0.01$) the effect is negligible. When radiation factor is large ($\alpha>10$), the increase in $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude is bounded (less than 1.1). Thus the temperature difference between the equipment and the bay wall will be relatively constant with altitude, and, hence, the equipment temperature will also be constant with the altitude as can be seen from Eq. (3.22). Radiative heat transfer does not depend on the air to transfer heat from the equipment to the bay wall, and, therefore, changes in the air density do not affect the radiation heat transfer. As a result, the radiative heat transfer serves the role of a thermal "pressure" relief valve. Whenever the convective resistance increases with altitude due to the reduced pressure (Eq. (3.23)), the fraction of heat which is transferred by radiation increases while the fraction of heat transferred by convection decreases. This in turn helps to maintain the temperature difference ΔT_{ew} at stable values.

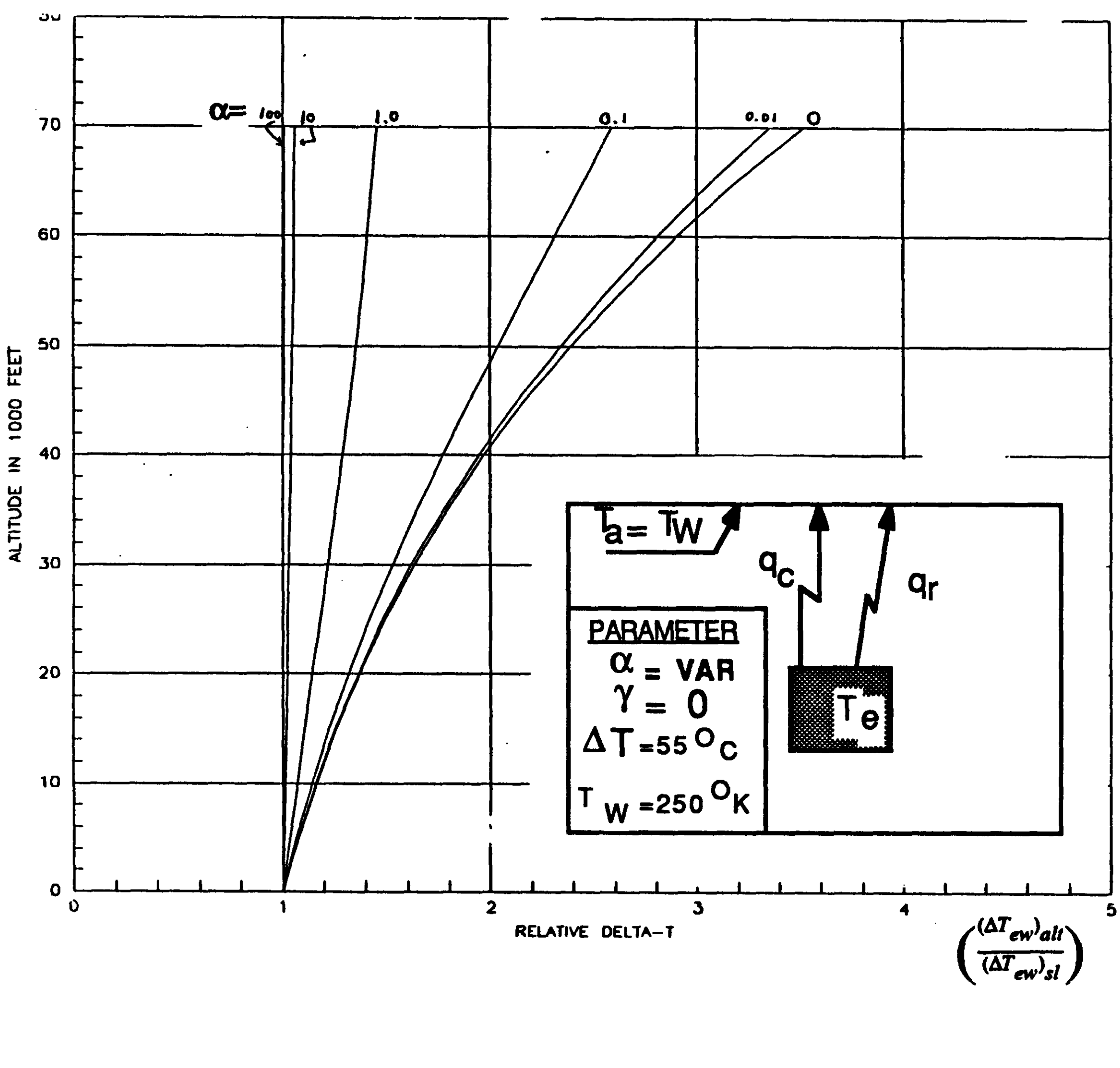


Figure 3-10: Effects of radiation factor α, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude

iv) Results of Equipment Temperature Simulation for MIL-E-5400 Temperature-Altitude Envelope

Fig. 3-11 through 3-15 show the changes of equipment temperature, T_e, as a function of altitude for different values of radiation factor, α, obtained by simulating the bay air temperature with the temperature-altitude envelope of MIL-E-5400 Class II.

By comparing Fig. 3-7 to Figures 3-11 through 3-15 it can be seen that the three regions which are presented in Fig. 3-7, namely: convergent, stable, and divergent, can be recognized only in Fig.3-11 and 3-12, where radiation factor is small ($\alpha < 0.1$). In the other Figures, 3-13 through 3-15, all the curves are shifted towards the convergent region. This is simply because the values of $(\Delta T_{ew})_{opt}$, which was discussed in the previous section are larger for higher values of radiation factor. The increase of $(\Delta T_{ew})_{opt}$ with increasing radiation factor, α, is shown in Fig.3-16. This means that a system with a configuration similar to that shown in Fig. 3-8 which is designed for $(\Delta T_{ew})_{sl}$ *LtE* $(\Delta T_{ew})_{opt}$ is expected to experience lower equipment box temperatures, T_e, at high altitude than the sea level value. Hence, the thermal design of such a system is determined by the sea level conditions.

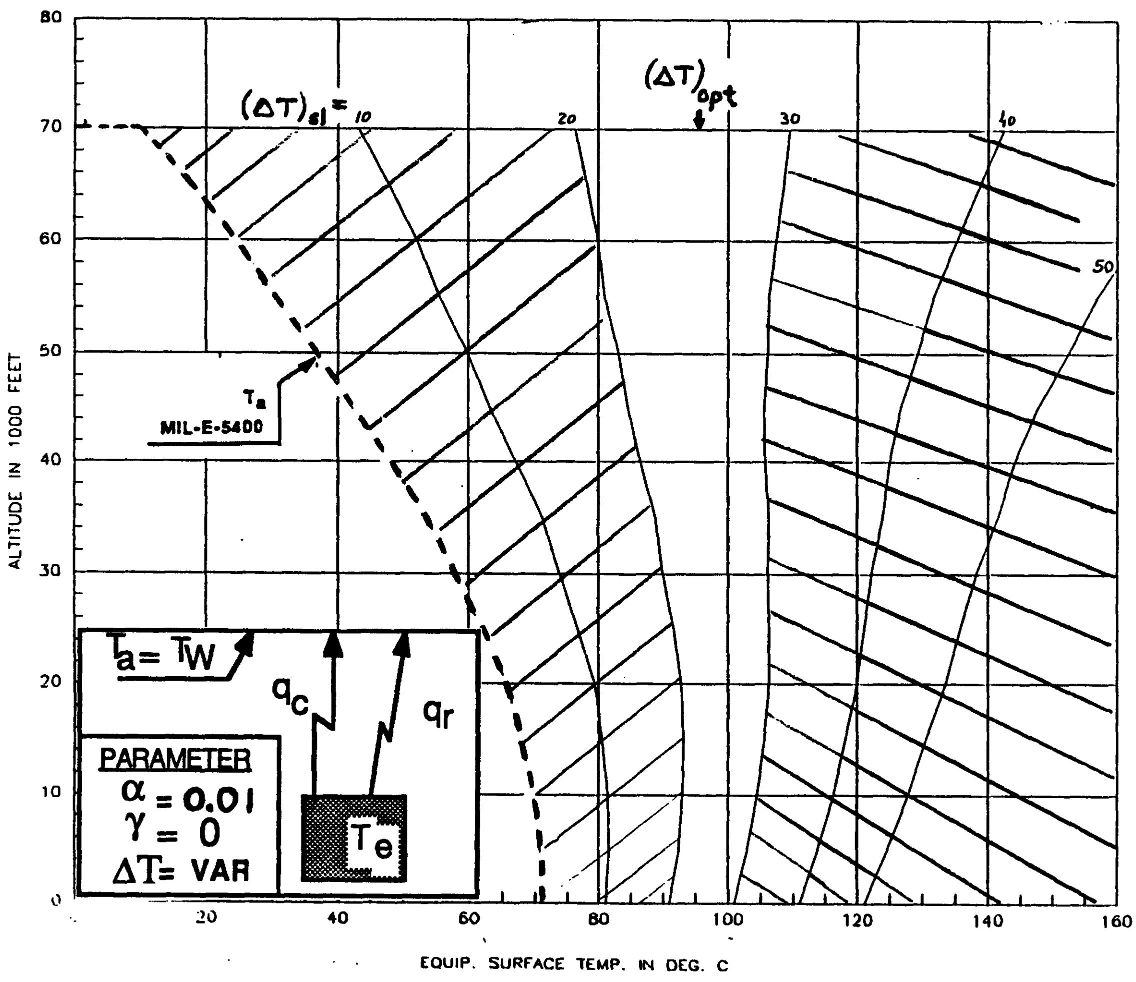


Figure 3-11: Equipment temperature simulation based on MIL-E-5400 class II temperature altitude envelope for a single segment convection path and radiation, radiation factor α=0.01

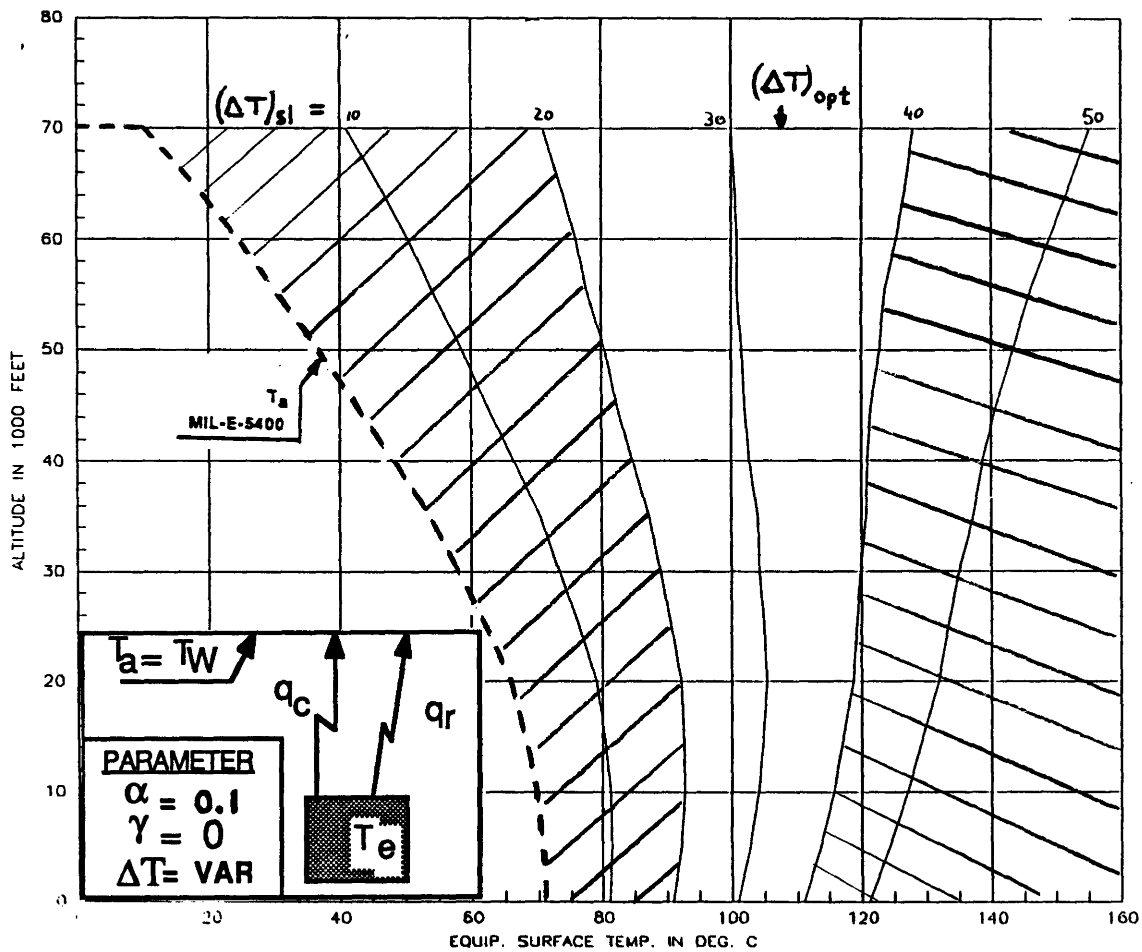


Figure 3-12: Equipment temperature simulation based on MIL-E-5400 class II temperature altitude envelope for a single segment convection path and radiation, radiation factor α=0.1

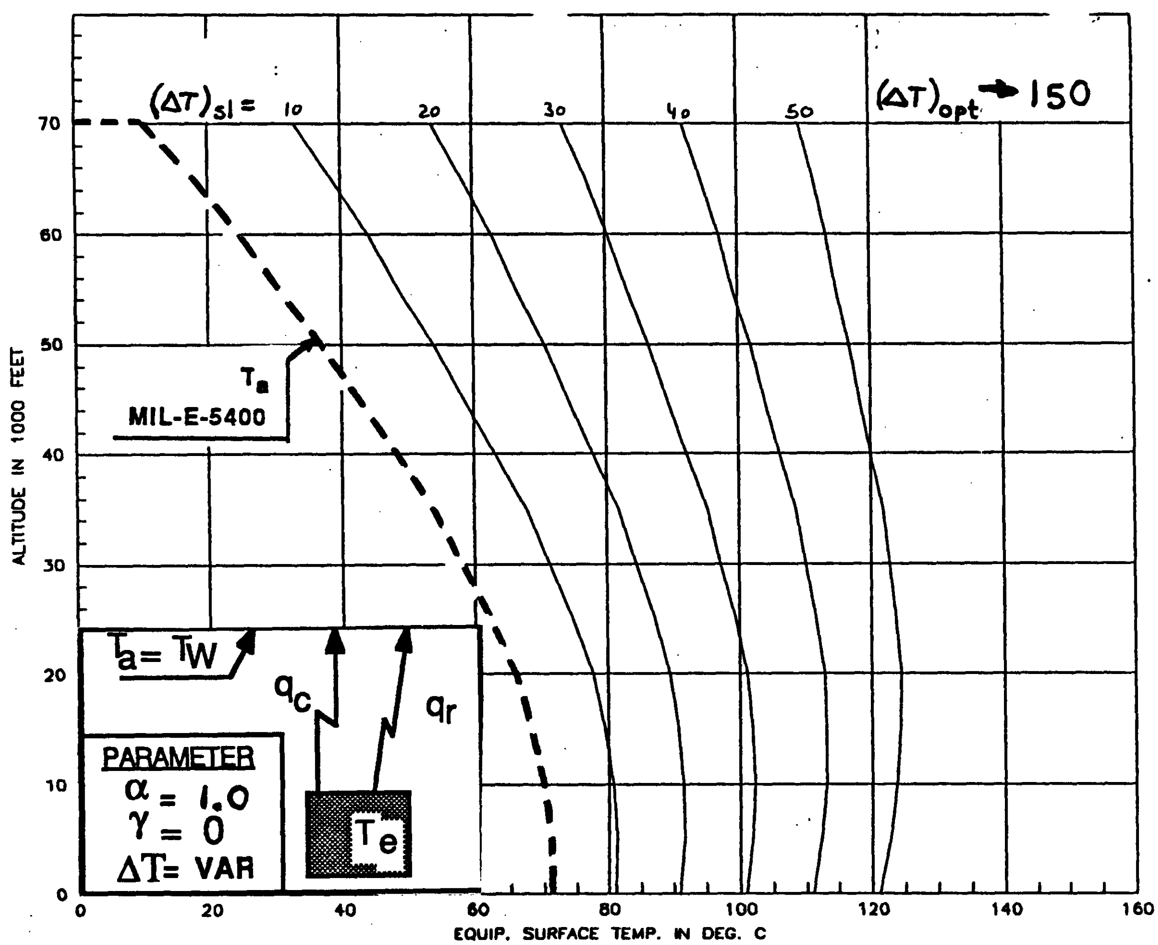


Figure 3-13: Equipment temperature simulation based on MIL-E-5400 class II temperature altitude envelope for a single segment convection path and radiation, radiation factor α=1.0

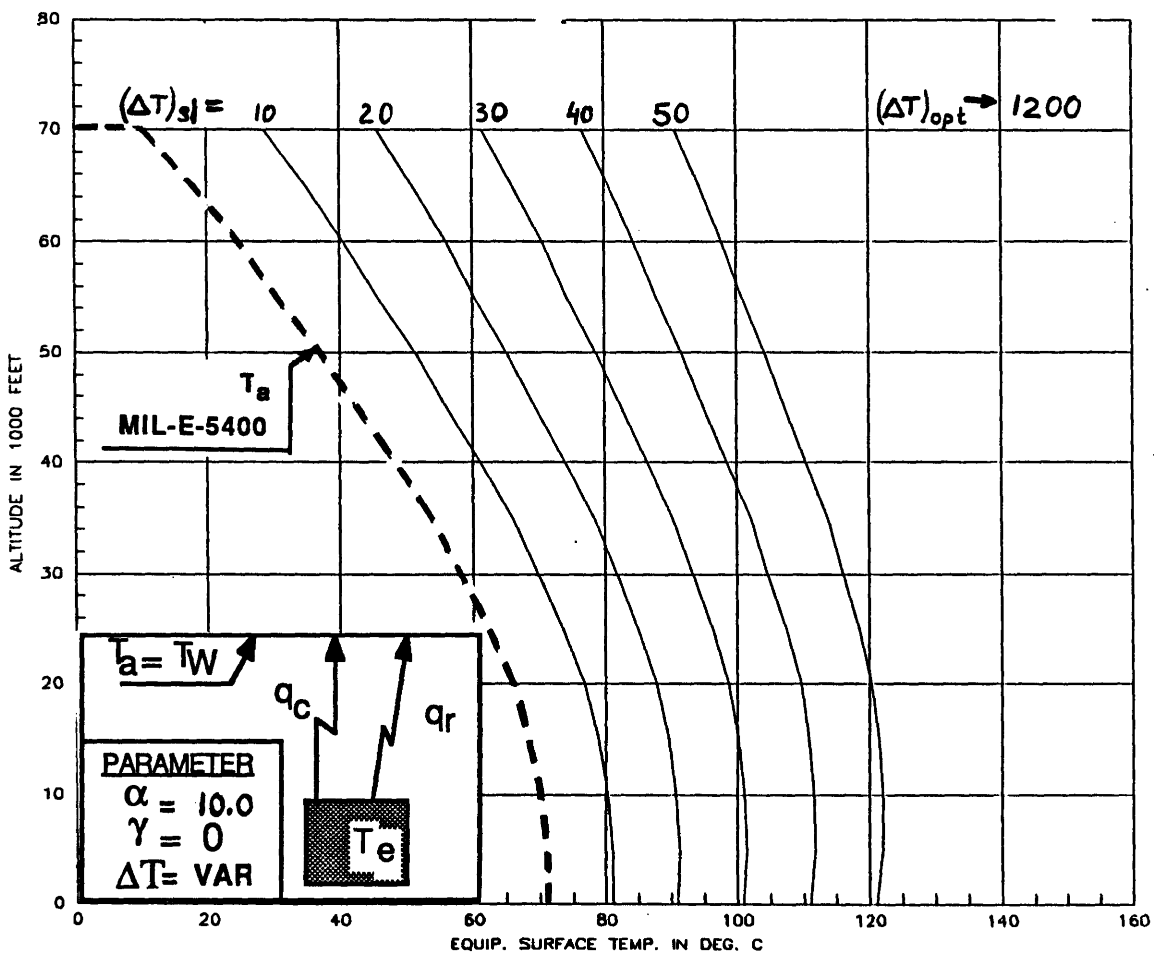


Figure 3-14: Equipment temperature simulation based on MIL-E-5400 class II temperature altitude envelope for a single segment convection path and radiation, radiation factor α=10.0

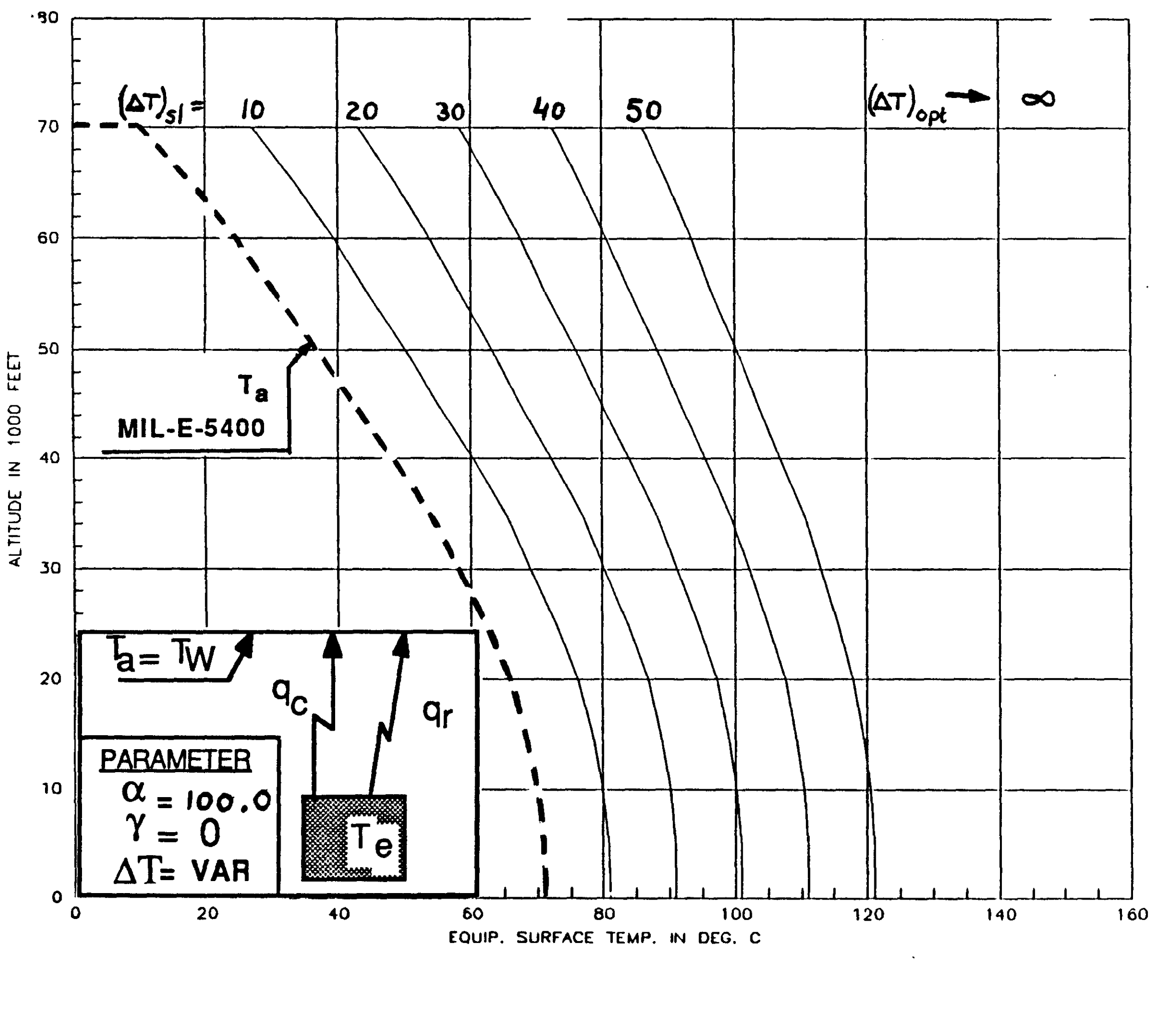


Figure 3-15: Equipment temperature simulation based on MIL-E-5400 class II temperature altitude envelope for a single segment convection path and radiation, radiation factor α=100.0

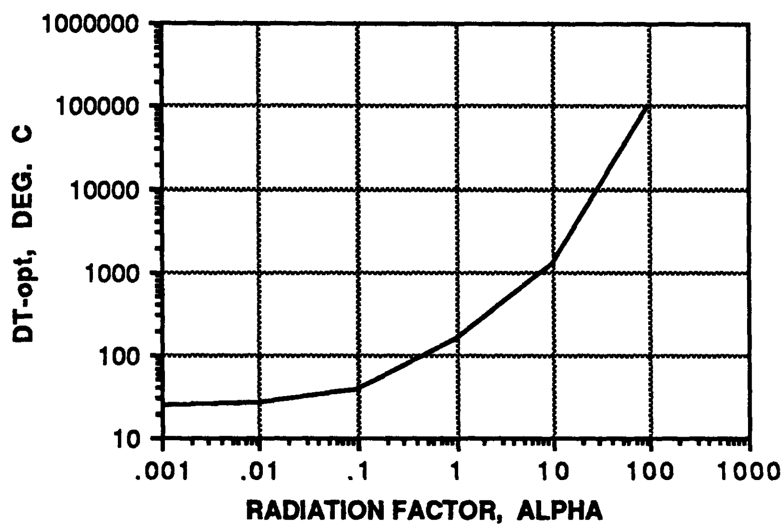


Figure 3-16: Optimal temperature difference versus radiation factor α

3.3.3 Equipment Temperature Versus Altitude for a Double Segment Convection and Radiation Paths System Configuration

In this section, the changes of temperature difference between the equipment and the bay wall temperatures as a function of altitude for a system with combined, radiation and double segment convection, heat transfer modes are presented and compared for different values of radiation heat transfer factor (α) and for various values of the convection balance factor (γ). The effects of radiation factor, α, and convection balance, γ, are isolated and examined for various combinations of convection and radiation factors. It is shown that the effects of radiation factor α in this configuration (Fig. 3-17) are similar to those observed in the previous section. It is also shown that, when isolated, the convection balance factor γ has little effect on the altitude dependence of the changes in temperature difference $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ that is, when radiation is not included (α=0). On the other hand, the product of the dimensionless parameters $\alpha\gamma=\frac{H_r}{H_w}$ has effects here similar to that which the radiation factor $\alpha=\frac{H_r}{H_e}$ has on the system with the configuration presented in the previous section.

i) Configuration

The results presented in this section are for the configuration shown in Fig. 3-17. In this configuration two heat transfer modes are considered: convection and radiation. The general situation in which the bay ambient air temperature, T_a, is different from the wall temperature, T_w, is considered here; therefore, two convective segments, as depicted in Fig. 3-17, are analyzed.

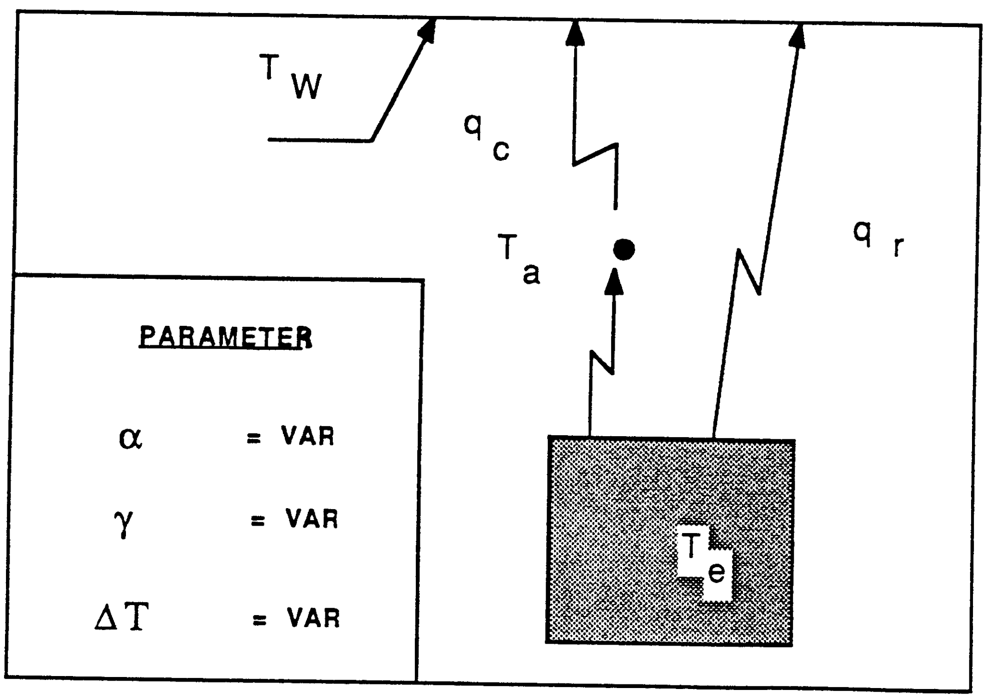


Figure 3-17: Double convection segment and radiation configuration schematic

ii) Analysis

The expressions for the changes of the temperature difference between the equipment temperature and the bay wall temperature with altitude, $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, for this configuration were derived in Section (3.2), and they are repeated here:

$$\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}} = \left[\frac{1}{\delta}\right]\left[\frac{1+\gamma}{1+\gamma_0}\right]\left[\frac{1+\alpha_0+\alpha_0\gamma_0}{1+\alpha+\alpha\gamma}\right]$$

$$\text{where} \quad \delta = \frac{(H_e)_{alt}}{(H_e)_{sl}} \quad \alpha = \left(\frac{H_r}{H_e}\right) \quad \gamma = \left(\frac{H_e}{H_w}\right)$$

$$0 = \text{sea level value} \qquad (3.27)$$

$$\left(\frac{h_{alt}}{h_{sl}}\right) = \left[\frac{\rho(P_{alt})}{\rho(P_{sl})}\right]^{1/2}\left[\frac{\Delta T_{alt}}{\Delta T_{sl}}\right]^{1/4} F(T_{sl},T_{alt}) \qquad (3.28)$$

$$F(T_{sl},T_{alt}) = \left(\frac{k_{alt}}{k_{sl}}\right)^{3/4}\left[\left(\frac{\beta_{alt}}{\beta_{sl}}\right)\left(\frac{\mu_{sl}}{\mu_{alt}}\right)\left(\frac{c_{P_{alt}}}{c_{P_{sl}}}\right)\left(\frac{\rho(T_{alt})}{\rho(T_{sl})}\right)^2\right]^{1/4} \qquad (3.29)$$

$$\left(\frac{h_{r,alt}}{h_{r,sl}}\right) = \frac{\left[1+(\theta)^2_{alt}\right]\left[1+(\theta)_{alt}\right]}{\left[1+(\theta)^2_{sl}\right]\left[1+(\theta)_{sl}\right]}\left(\frac{T_{w,alt}}{T_{w,sl}}\right)^3$$

$$\text{where} \quad \theta = \left(\frac{T_e}{T_w}\right) \qquad (3.30)$$

The numerical analysis here is similar to that conducted in the two previous sections, and it follows the procedure shown schematically in Fig. 3-18.

iii) Results: The Effects of Convection Balance and Radiation on Changes of ΔT_{ew} With Altitude

Fig. 3-19 shows the changes of the temperature difference between the

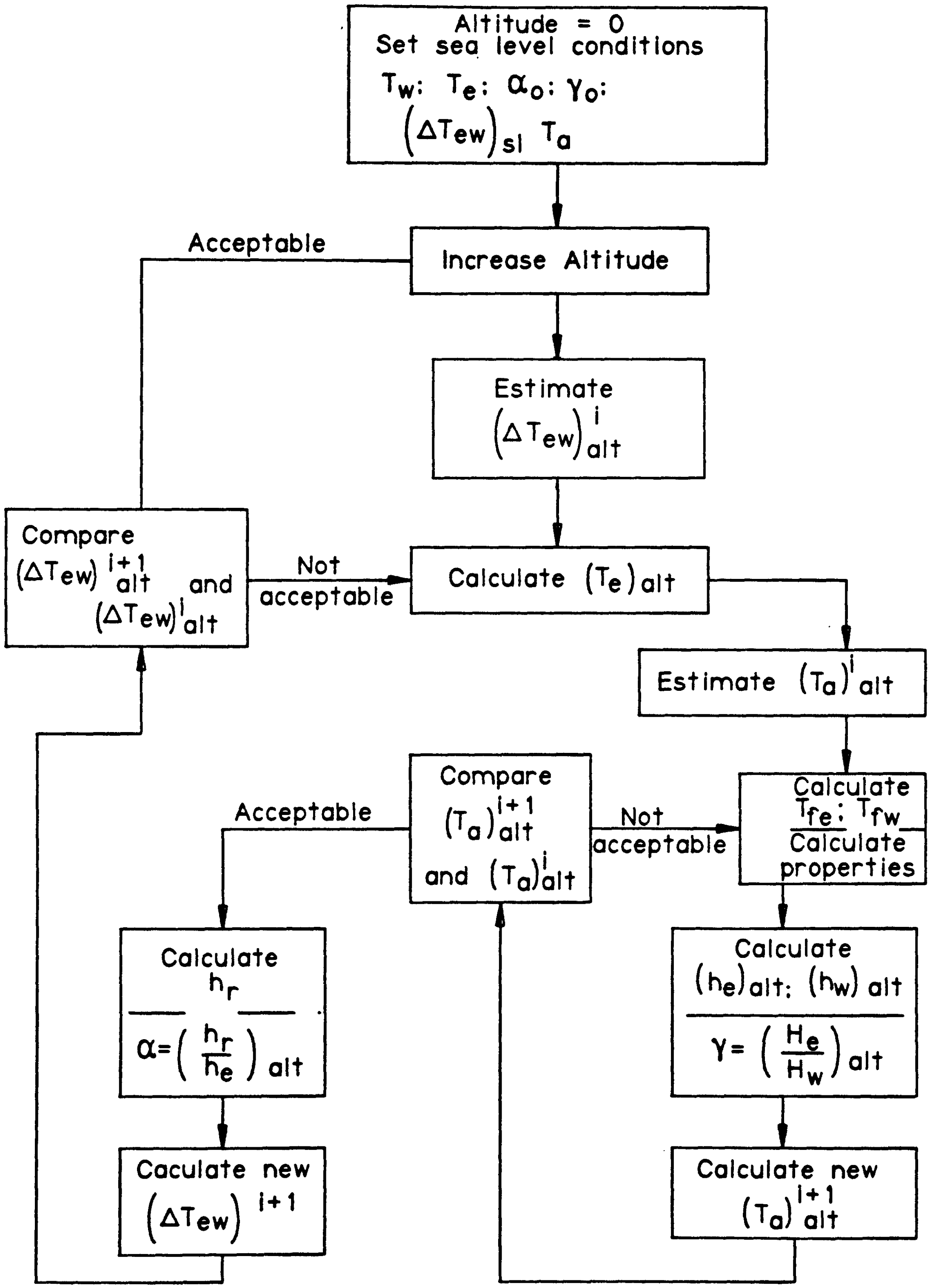


Figure 3-18: Numerical analysis flow diagram for double convection and radiation system

equipment and the bay wall,. $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, with altitude for a double segment convective path and when radiation is not considered (α=0). The various curves shown in Fig. 3-19 represent different values of the ratio between the two resistance factors in the convection path, represented by the convection balance factor, $\gamma=\frac{H_e}{H_w}$. All the cases were run with constant wall temperature, $T_w=250^oK$, and the same $(\Delta T_{ew})_{sl}=105^oC$. It can be seen from Fig. 3-19 that the changes of the temperature difference between the equipment and the bay wall, $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$, in general, grow exponentially with altitude. The changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude are maximum when γ=0, which represent a situation in which the thermal resistance at the bay wall, R_w, is much smaller than the resistance at the equipment surface (R_e). R_w, thus is negligible and the system becomes similar to the single segment convection path presented in Section 3.3.1. This can be confirmed by comparing Fig. 3-19 (for $\gamma=0$) to Fig. 3-5.

The changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude are moderated by increasing γ down to a convergence limit represented by the leftmost curve in Fig. 3-19. This behavior is attributed to the fact that in this model, in contrast with the single segment convection model of Section 3.3, the bay air temperature, T_a, is allowed to change (only the wall temperature is constant) with altitude. This in turn changes the value of the term $\left(\frac{\beta_{alt}}{\beta_{sl}}\right)^{1/4}$ in equation (3.29) which was approximated as $\left(\frac{T_{a_{sl}}}{T_{a_{alt}}}\right)$, and was otherwise constant (=1) in the previous analysis in Section 3.3.1. The dependence of the term $\left(\frac{\beta_{alt}}{\beta_{sl}}\right)^{1/4}$ on γ is presented in Fig 3-20, and demonstrates the rate at which $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ in Fig. 3-19 is moderated by the increasing value of γ.

For example, referring to Fig.3-19, the point A for the case of $\gamma=0$, with a value $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)=3.5$ is shifted to the point B when γ is increased ($\gamma=100$). At

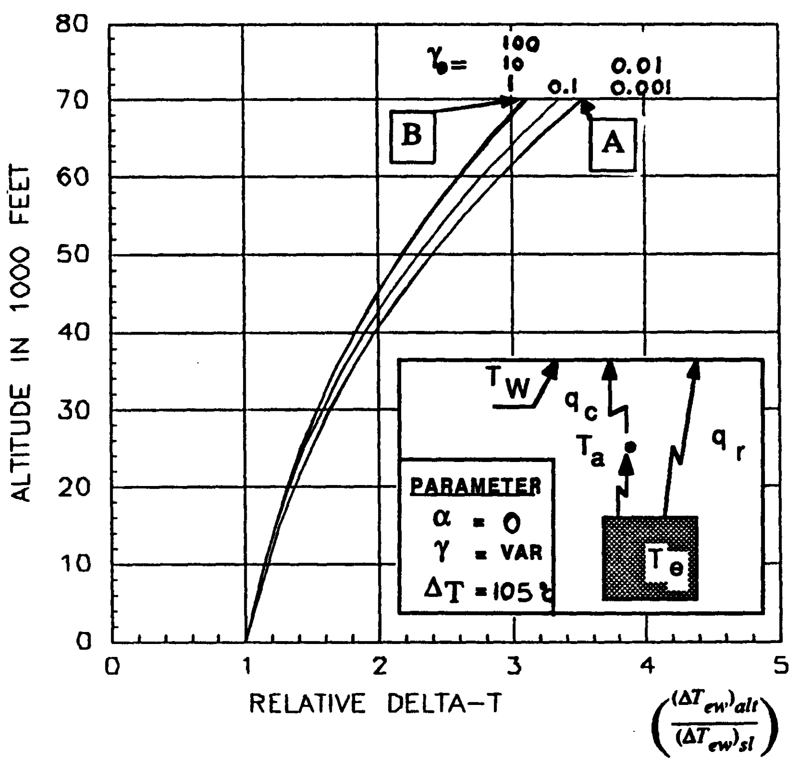


Figure 3-19: Effects of convection balance factor, γ, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude (without radiation)

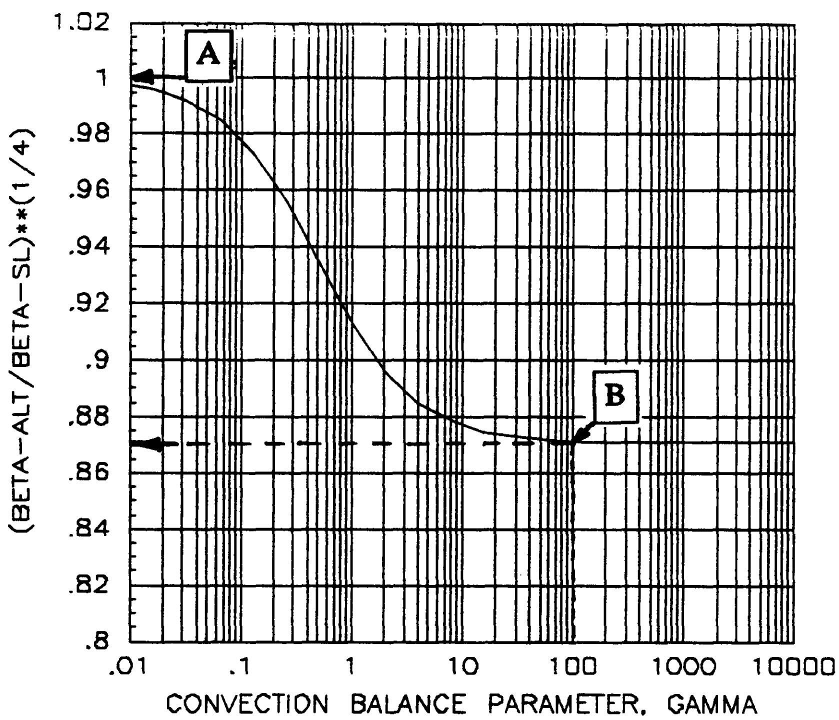


Figure 3-20: The changes in $\left(\frac{\beta_{alt}}{\beta_{sl}}\right)^{1/4}$ versus γ for the system considered in Fig. 3-19

point **B** the value of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ is approximately 3.1. The ratio between the values of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ in these two points is 3.1/3.5 = .885 . Now, referring to Fig. 3-20, the point **B** have a value of .87 which is different from the value obtained from Fig.3-19 by 1 percent only.

Fig. 3-21 through 3-24 show the effects of the combined factors, the radiation factor α and the convection balance factor γ, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$. It can be seen that increasing either the radiation factor α, or the convection balance factor γ, has a moderating effect on the altitude dependent changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$. Since in this case, both, α and γ are not equal to zero, there is the contribution of the cross product term $\alpha\gamma$, as can be seen in Eq. (3.27). Physically, the cross product term $\alpha\gamma=\frac{H_r}{H_w}$ reflects the balance between the convective resistance at the bay wall surface,

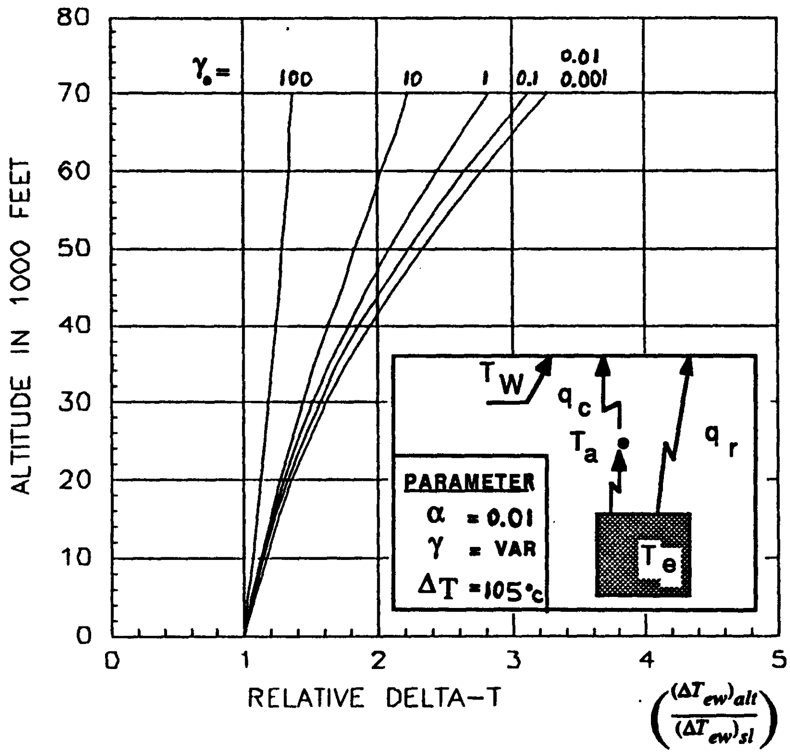


Figure 3-21: Effects of convection balance factor, γ, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude in a system with radiation factor $\alpha=0.01$

and the radiative resistance between the equipment box and the bay wall. This is parallel to the meaning of the radiation factor α which is the balance between the convective resistance at the equipment box surface, and the radiative resistance between the equipment box and the bay wall. Therefore, it is expected that the contribution of $\alpha\gamma$ will be similar to that of the radiation factor α.

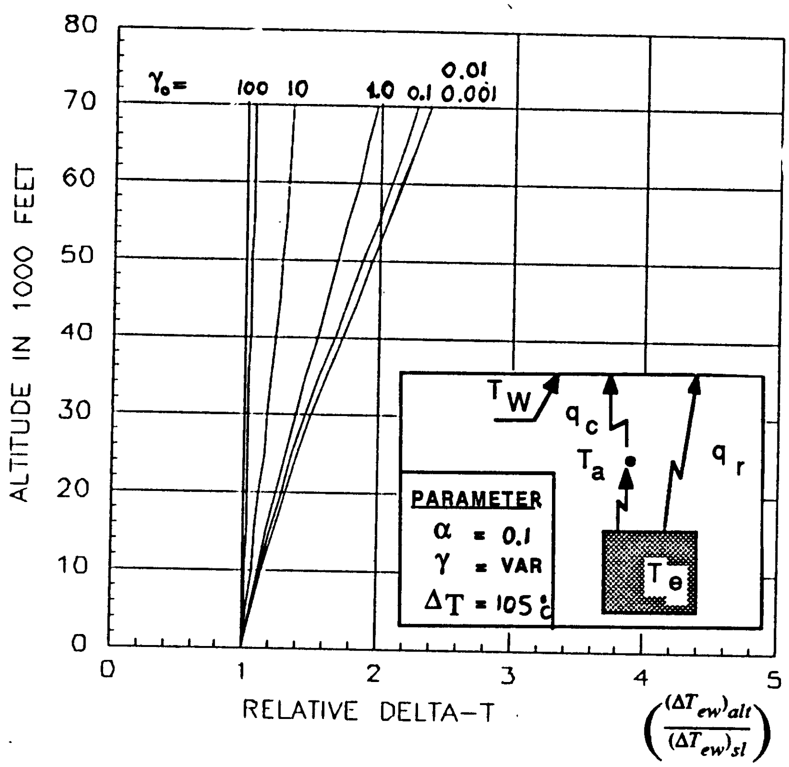


Figure 3-22: Effects of convection balance factor, γ, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude in a system with radiation factor $\alpha = 0.1$

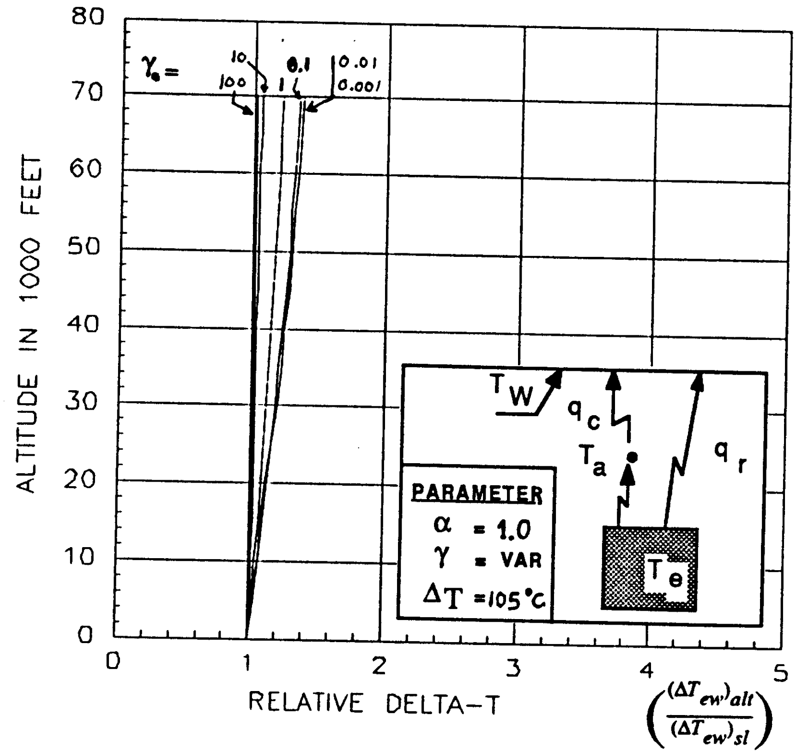


Figure 3-23: Effects of convection balance factor, γ, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude in a system with radiation factor $\alpha = 1.0$

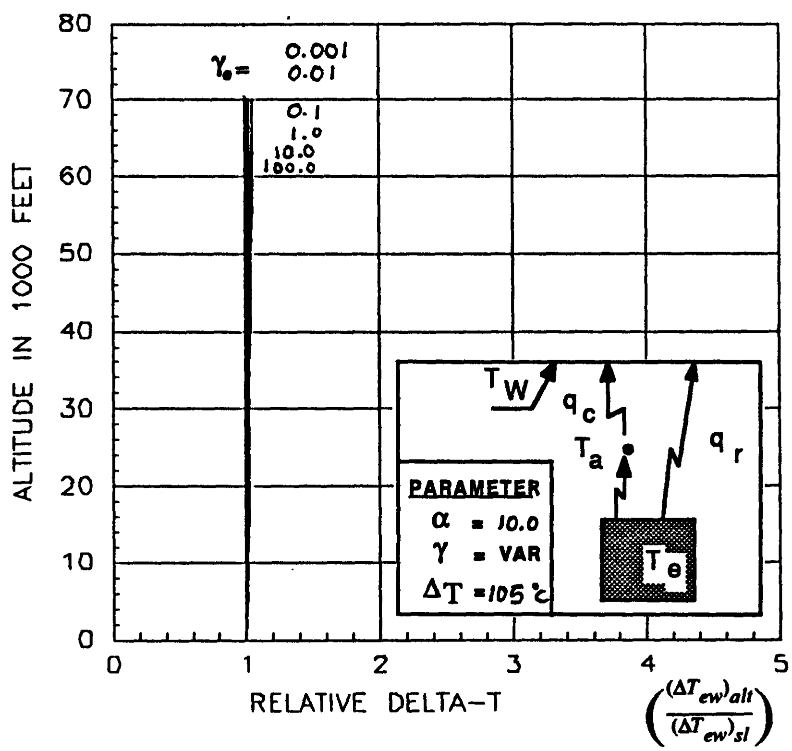


Figure 3-24: Effects of convection balance factor, γ, on the changes of $\left(\frac{(\Delta T_{ew})_{alt}}{(\Delta T_{ew})_{sl}}\right)$ with altitude in a system with radiation factor $\alpha = 10.0$

Chapter 4

Conditioned Bay Configuration - Ambient and Forced-Air Cooled Avionics

4.1 Introduction

This chapter describes the modeling approach used to study the heat transfer problems of a conditioned avionics bay. For this type of bay, both ambient and forced-air cooled equipment are considered. In Section 4.2, the physical situation is first described, and then the mathematical model for a well mixed bay air is developed and discussed. The effects of the forced-air cooled avionics on the bay thermal environment, as a function of altitude, are studied for various combinations of ambient and forced-air cooled avionics configurations (Section 4.5)

4.2 Thermal Configuration of a Conditioned Avionics Bay

Fig. 4-1 shows a generic configuration of a conditioned avionics bay. The bay includes both ambient and forced-air cooled avionics which may be installed side by side within the bay. In steady state the forced-air cooled equipment box transfers its heat to the cooling air supplied by the aircraft environmental control system. The cooling air enters the forced cooled equipment box at temperature T_{in}. It then flows through the equipment box and is typically exits into the bay at temperature T_{out} after absorbing the heat q_F from the forced-air cooled equipment. The heat transfer process for the forced-air cooled box is described by the following relationship, initially described in Section 2.6.2:

$$q_F = \dot{m} C_p (T_{out} - T_{in}) \tag{4.1}$$

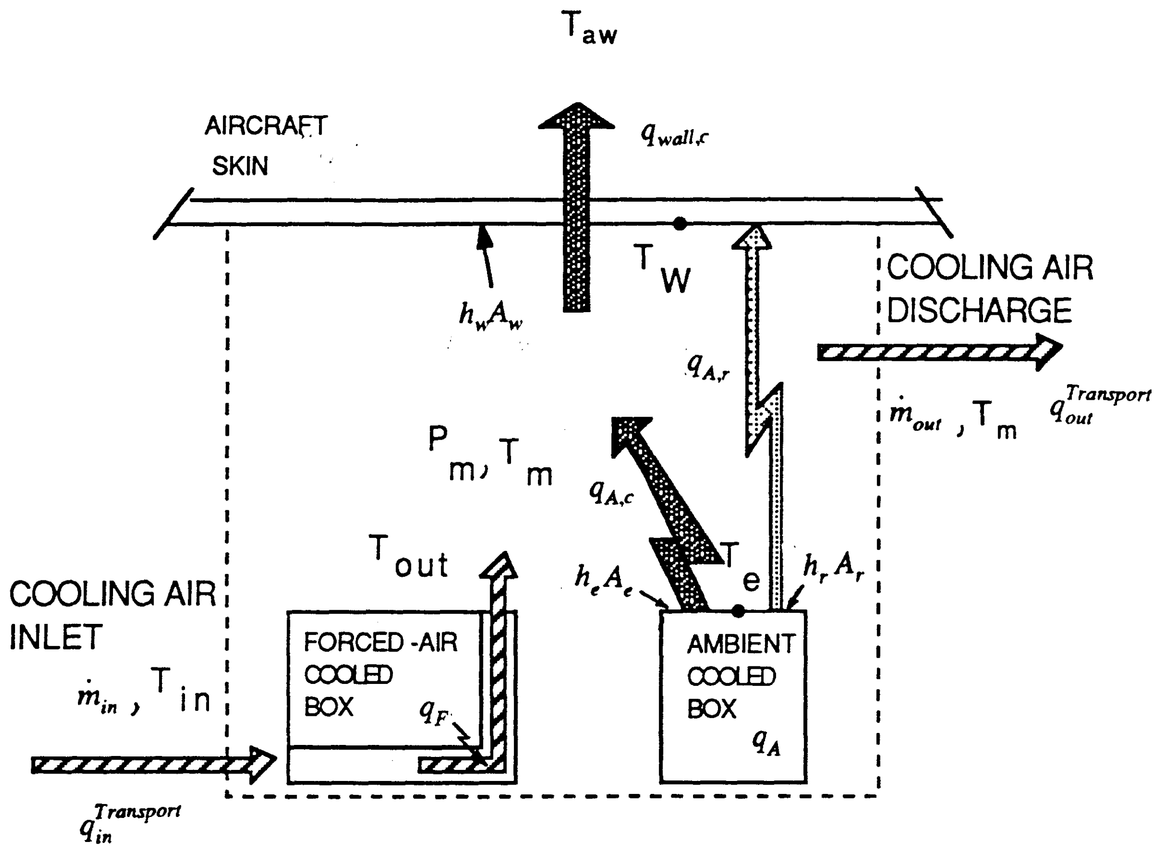


Figure 4-1: Thermal configuration of a conditioned bay -- Ambient and forced-air cooled avionics

where q_F is the heat dissipated within the forced-air cooled equipment box, $\dot{m}$ is the mass flow rate of the cooling air, C_p is the specific heat of the cooling air, and $(T_{out}-T_{in})$ is the temperature increase of the cooling air as it passes through the equipment box. It should be noted that this relationship (Eq. (4.1)) is based on the assumption that the equipment box is designed to transfer all of its heat to the cooling air.

The cooling air, after exiting the forced-air cooled equipment box, travels inside the bay where its temperature may increase or decrease depending on heat loads from the ambient cooled equipment, and heat exchanged with the bay wall. It is assumed that the air in the bay is well mixed and its temperature can be represented by a mean value T_m. The cooling air then leaves the bay at a temperature T_m.

The ambient cooled equipment dissipates its heat, q_A, by convection $(q_{A,c})$ to the bay air and by radiation $(q_{A,r})$ to the bay wall. As explained in Chapter 3, the convective heat $q_{A,c}$, transferred from the ambient cooled equipment box to the bay air, is given by the following relationship:

$$q_{A,c} = h_e A_e (T_e - T_m) \tag{4.2}$$

where h_e is the average convective heat transfer coefficient between the equipment surface and the bay air, A_e is the surface area where the heat transfer takes place, and (T_e-T_m) is the temperature difference between the equipment (T_e) and the bay air (T_m), respectively.

The radiative heat exchange $q_{A,r}$ between the equipment box surface (at T_e) and the bay wall (at T_w) is given by the following relationship:

$$q_{A,r} = h_r A_r (T_e - T_w) \tag{4.3}$$

where h_r is the average radiative heat transfer coefficient, A_r is the surface area of the equipment where radiation is exchanged with the wall, and $(T_e - T_w)$ is the temperature difference between the equipment surface and the bay wall. It is assumed that the sum of the radiative heat $q_{A,r}$ and the convective heat $q_{A,c}$ is equal to the total heat dissipation of the ambient cooled equipment box q_A.

The difference between the model which was presented in Chapter 3 and the situation here is in the convective path. In the unconditioned bay configuration presented in Section 3.2 the same amount of heat was transferred from the equipment to the bay air and from the bay air to the bay wall. In the conditioned bay configuration presented here, the convective heat from the equipment, $q_{A,c}$ is first convected to the bay air, and then is split into two parts. Some of the heat $(q_{wall,c})$ is convected from the bay air to the bay wall and from the bay wall to the external air. This convective heat transfer is determined by the heat transfer coefficient between the bay air and the bay wall, h_w, the bay wall surface area A_w, and the temperature difference between the bay air (T_m) and the bay wall (T_w) :

$$q_{wall,c} = h_w A_w (T_m - T_w) \tag{4.4}$$

The rest of the convective heat $(q_{A,c} - q_{wall,c})$ is absorbed by the bay air as internal energy and exits the bay as the air leaves the bay $(q_{out}^{Transport})$.

The most important parameter in this system for the thermal design of the avionics equipment boxes, is the temperatures of the boxes. In the case of the ambient cooled equipment box this parameter is the surface temperature T_e. In the case of the forced-air cooled box the important parameter is the temperature of the cooling air as it exits the equipment T_{out}.

The temperature of the cooling air as it exits the forced-air cooled equipment box (T_{out}) is determined by the relation given in Eq.(4-1). Typically the the cooling air inlet temperature T_{in}, and mass flow rate $\dot{m}$, are controlled to maintain the cooling air exit temperature T_{out} within desired limits, a maximum value of 71 °C (160 °F) is typically used as a common design practice [6] [7] [30].

The ambient cooled equipment box temperature, T_e, is determined by the heat dissipation from the equipment, and by both the radiative (h_r) and the convective (h_e) heat transfer coefficients (Eq. (4.2), (4.3)), as well as the bay air temperature T_m, and the bay wall temperature, T_w. The bay wall temperature, T_w, as explained in Section 3.2, is a function of external factors such as the outside atmospheric temperature and the flight Mach number. The bay air temperature, on the other hand, depends on the convective heat transferred from the ambient cooled equipment box, and on the forced-air cooled equipment heat dissipation.

Comparing the ambient cooled equipment boxes in the cases of conditioned and unconditioned bay configurations, the bay air temperature is the primary internal parameter which will be different. Therefore the approach used here is to analyze the bay air temperature T_m, and to use the results obtained in Chapter 3 to infer the changes in the equipment temperature with altitude.

It is worth noting that the additional forced cooling may have an effect on the convective heat transfer coefficient between the equipment and the bay air, as well as between the bay air and the bay wall. However, in this thesis a conservative approach was taken, and only natural convection was assumed.

Also, since radiative heat is exchanged between the surfaces of the equipment and the bay wall, it does not affect the bay air temperature directly. Therefore, radiation is not included in the analysis.

4.3 Control Volume Analysis For a Conditioned Bay

Fig. 4-2 shows the control volume used to evaluate the bay air temperature T_m.

Two mass flow components are shown in Fig. 4-2: the one entering the control volume is the inlet flow of the cooling air, $\dot{m}_{in}$, and the one leaving the control volume, is the outlet flow, $\dot{m}_{out}$.

Five energy transfer paths to and from the control volume are considered: three paths convey heat to the control volume, the first two of which are the heat sources generated by the forced-air cooled equipment, q_F, and the ambient cooled equipment, q_A; the third is the enthalpy that enters with the cooling air, $q_{in}^{Transport}$. The two heat paths which leave the control volume are the heat convected by the bay air to the bay wall, $q_{wall,c}$, and the enthalpy leaving with the air, $q_{out}^{Transport}$.

Since steady state conditions are assumed, the rate at which mass and energy are added to the control volume equals the rate at which they are removed. Thus the mass balance and the energy balance equations for the control volume are:

$$\dot{m}_{in} = \dot{m}_{out} \tag{4.5}$$

$$q_F + q_{A,c} + q_{in}^{Transport} = q_{wall,c} + q_{out}^{Transport} \tag{4.6}$$

Again, it is assumed that the air in the bay is well mixed and therefore T_m represents the bulk mean temperature. Conduction between the equipment and the airframe is neglected, and the radiative heat exchange between the equipment surface and the bay wall is omitted.

With these assumptions and definitions, Eq. (4.6) can be expanded as:

$$q_F + q_{A,c} + \dot{m} C_p T_{in} = q_{wall,c} + \dot{m} C_p T_m \tag{4.7}$$

or

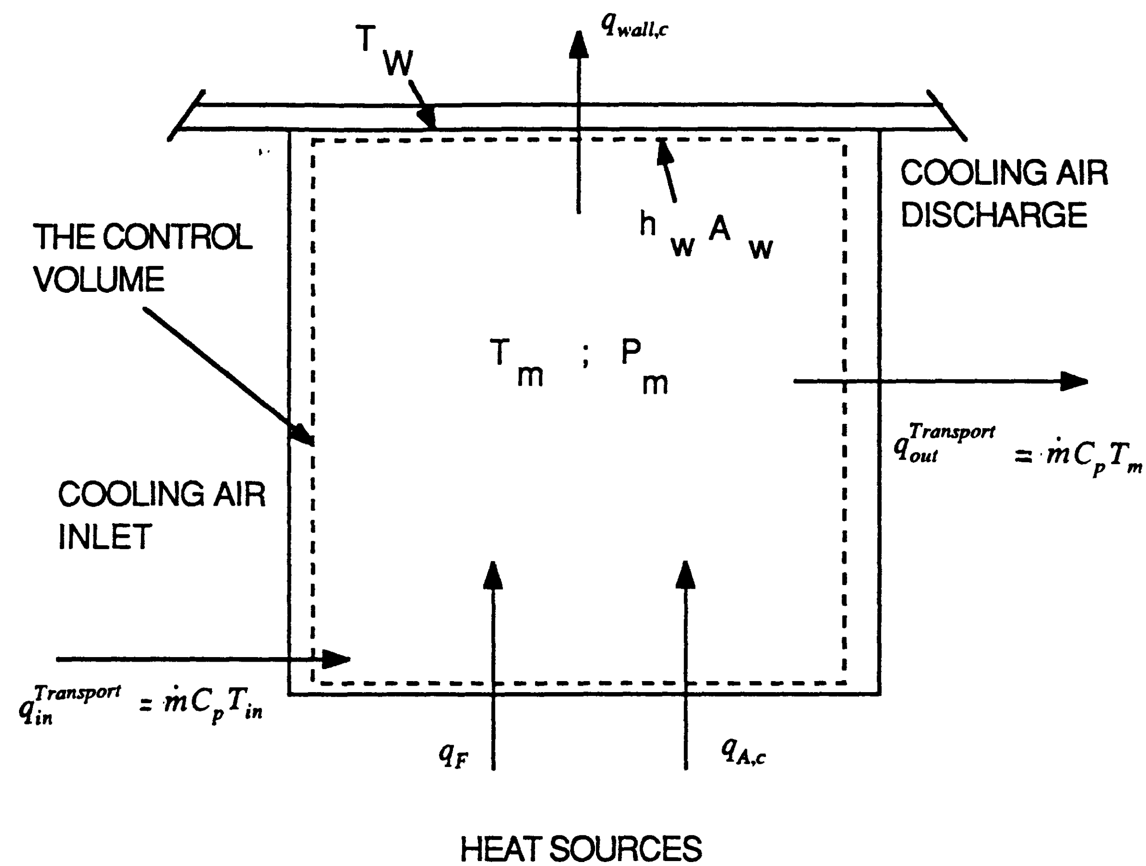


Figure 4-2: Control volume analysis for a conditioned avionics bay.

$$\dot{m}C_p(T_m-T_{in}) + h_wA_w(T_m-T_w) = q_F+q_{A,c} \tag{4.8}$$

Solving Eq. (4.8) for the bay air temperature, T_m, results in

$$\boxed{T_m = \frac{T_w+N_F(T_{out}-T_{in})(\frac{q_{A,c}}{q_F}+1)+N_FT_{in}}{1+N_F}} \tag{4.9}$$

where the dimensionless term N_F introduced in Eq. (4.9) is the forced-air cooling influence number, which is defined by

$$\boxed{N_F = \frac{\dot{m}C_p}{h_wA_w}} \tag{4.10}$$

The physical meaning of N_F is the balance between the the forced cooling and the natural convective heat transfers which are the two paths rejecting heat out of the bay.

In view of this meaning, the dependence of ΔT_{mw} of N_F is demonstrated in the following two limiting cases.

<u>Case</u> <u>I:</u> $N_F \to 0$

This case reflects the situation where $\dot{m}C_p \to 0$ (from Eq.(4.10)) which will typically occur when there is only a small amount of forced-air cooling heat in the bay. Thus

$$\Delta T_{mw}=T_m-T_w=\frac{q_{A,c}+q_F}{h_wA_w} \tag{4.11}$$

Since $\dot{m}C_p \to 0$, it can be seen from Eq (4.1) that $q_F \to 0$ in this case, therefore

$$\boxed{\Delta T_{mw}=T_m-T_w=\frac{q_{A,c}}{h_wA_w} \quad ;limit\ as\ N_F \to 0} \tag{4.12}$$

This equation says that the temperature difference between the bay air T_m, and the bay wall temperature T_w, depends only on the convective heat transferred $q_{A,c}$ and on the convective resistance between the bay air and the bay wall $\frac{1}{h_w A_w}$. This result is identical to Eq. (3.2) which was obtained for the unconditioned bay configuration. The conditioned bay configuration, thus reduces to the unconditioned configuration when $N_F \rightarrow 0$, because cooling air mass flow to the bay is small $\dot{m} \rightarrow 0$.

<u>Case II:</u> $N_F \rightarrow \infty$

This case reflects the situation where $\dot{m}C_p >> h_w A_w$, which will typically occur when most of the avionics boxes within the bay are forced-air cooled. Eq. (4.9) reduces to the following

$$T_m = (T_{out} - T_{in})\left(\frac{q_{A,c}}{q_F} + 1\right) + T_{in} \qquad (4.13)$$

which can be simplified to the following (assuming $q_F >> q_{A,c}$)

$$\boxed{T_m = T_{out} \quad ; \textit{limit as } N_F \rightarrow \infty} \qquad (4.14)$$

This means that the large amounts of cooling air which exit the forced-air cooled equipment boxes, at a higher temperature T_{out}, "floods" the bay with hot air, which determines the mean temperature of the air in the bay.

Results for other values of N_F are demonstrated in the following sections.

4.4 Analysis of Altitude Dependent Effects on Bay Temperature

In order to study altitude dependent effects on the bay air temperature T_m, Eq. (4.9) can be normalized by the sea level value:

$$\frac{(\Delta T_{mw})_{alt}}{(\Delta T_{mw})_{sl}}=\frac{[N_{F_0}+1]}{[N_{F_0}+\delta_w]}\left[\frac{[(T_{out}-T_w)+(T_{out}-T_{in})(\frac{q_{A,c}}{q_F})]_{alt}}{[(T_{out}-T_w)+(T_{out}-T_{in})(\frac{q_{A,c}}{q_F})]_{sl}}\right]$$

$$Where\ ,\ N_F=\frac{\dot{m}C_p}{h_w A_w}\ \ ;\ \ \delta_w=\left(\frac{h_{w,alt}}{h_{w,sl}}\right)$$

$0=$ *sea level value.* (4.15)

The factor δ_w represents the altitude dependent changes of the convective heat transfer coefficient between the bay air and the bay wall, and is given by Eq. (3.11) and (3.12). There are two parameters in Eq. (4.15), the first of which is the forced-air cooling influence number N_F and the second is the ratio of forced-air cooled heat loads to ambient cooled heat loads $\frac{q_F}{q_{A,c}}$.

The numerical analysis here is similar to that presented in Chapter 3, and it follows the the procedure shown schematically in Fig. 4-3.

4.5 Results

The effects of the forced-air cooled heat loads on the altitude dependence of the bay air temperature are presented in the following paragraphs. It is shown that large amounts of forced-air cooling in the bay stabilize the bay air temperature with altitude, and this stabilized temperature is approximately the temperature of the cooling air as it exits the forced-air cooled boxes.

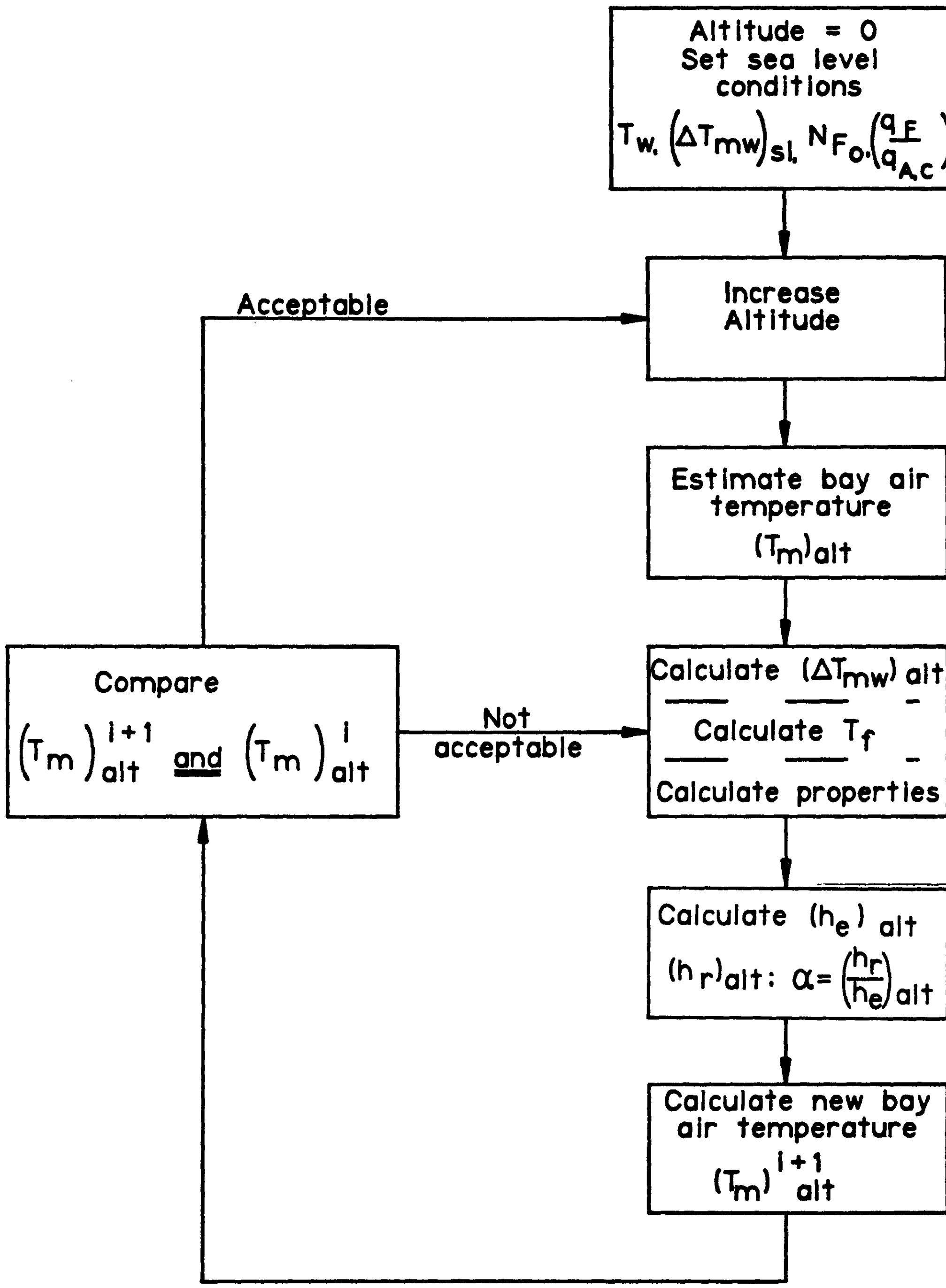


Figure 4-3: Numerical analysis flow diagram for conditioned bay configuration

i) The Changes of The Bay Air Temperature With Altitude for Constant Wall Temperature

Fig. 4-4(a) shows the changes of the bay air temperature with altitude for five different values of the forced-air cooling influence number N_F. It can be seen that the bay temperature T_m, grows exponentially with altitude for small values of N_F ($N_F <$ 1). This growth is moderated by increasing N_F. For larger values of N_F the bay air temperature T_m is relatively constant (within 5 °C). This is in agreement with the conclusion obtained in Section 4.3 when the limiting cases of Eq. (4.9) where studied. In order to have a common basis for comparison with the results obtained in the previous sections, Fig. 4-4(b) shows the changes with altitude of the normalized temperature difference between the bay air and the bay wall. It can be seen that at an altitude of 70,000 ft, when $N_F=0$ the maximum increase in the temperature difference is approximately 3.8 which is similar to the results obtained for the unconditioned bay configuration, as was predicted (Eq. (4.12)).

The sensitivity of the altitude dependent changes of the bay air temperature to the forced-air cooling influenced number, is the greatest when $0 < N_F < 1$.

ii) The Changes of The Bay Air Temperature With Altitude for a Wall Temperature-Altitude Profile

Fig. 4-5 shows the changes of the bay air temperature with altitude when the wall temperature is not constant, but also changes with altitude. As observed in

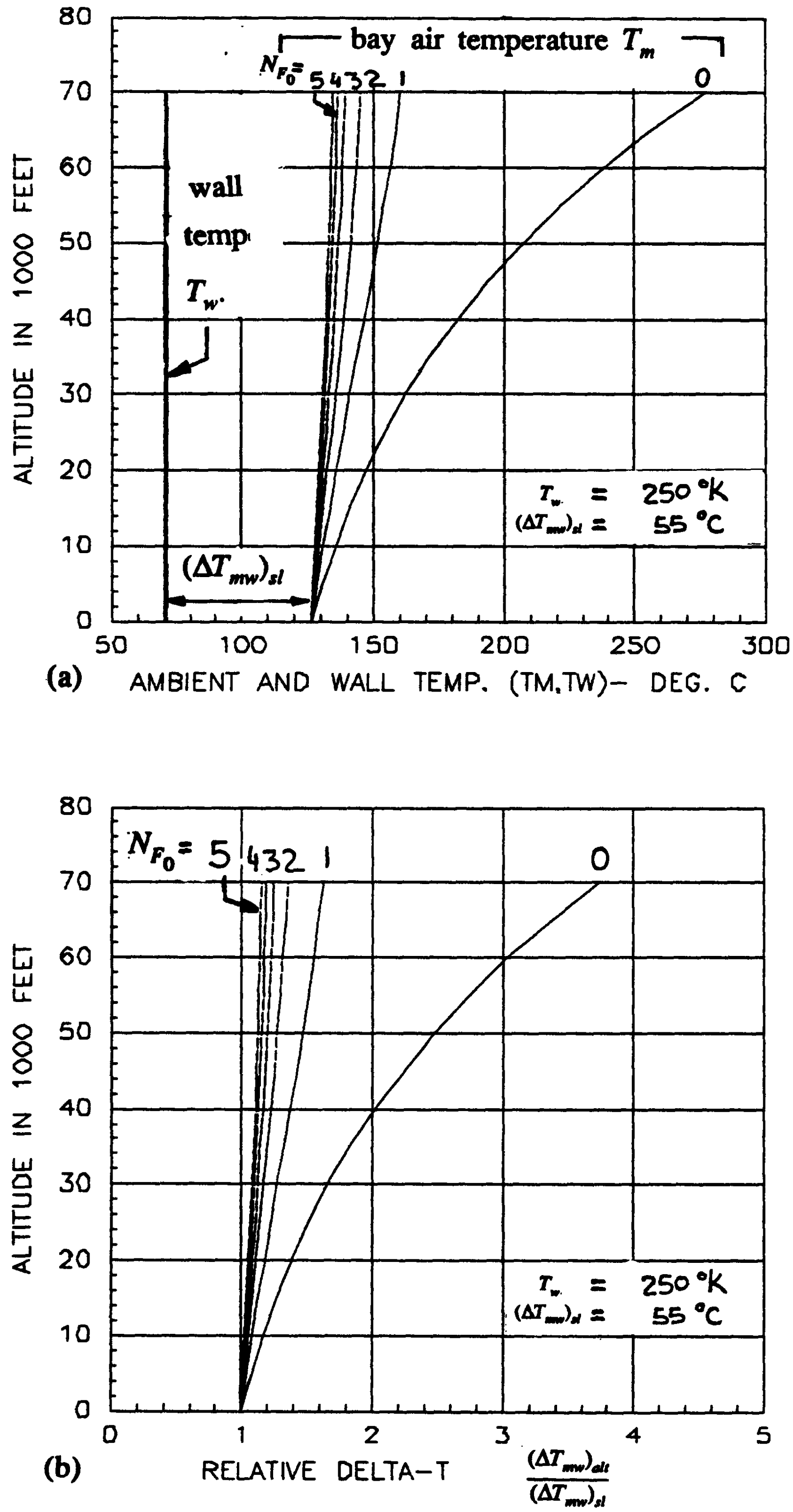


Figure 4-4: The changes of bay air temperature with altitude for constant wall temperature

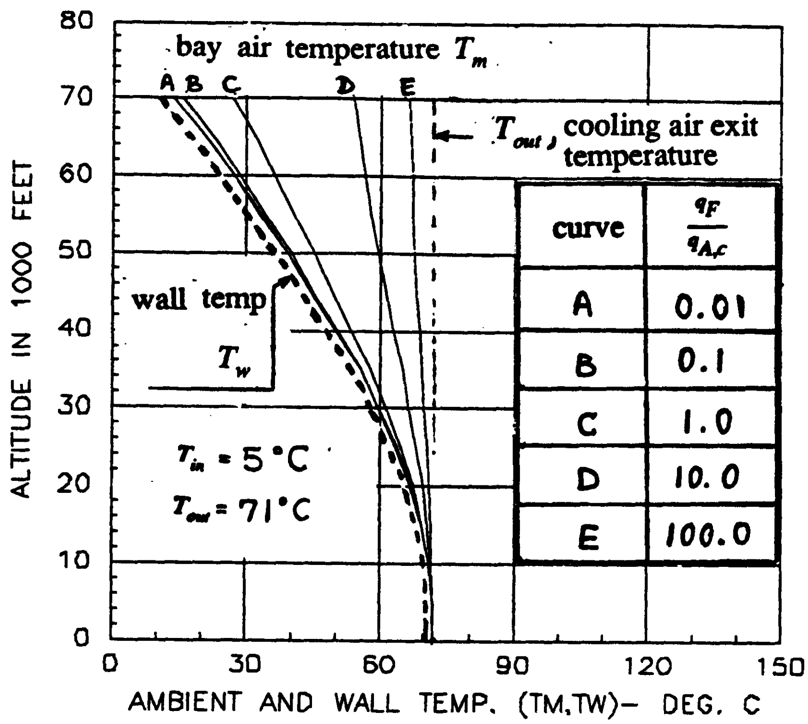


Figure 4-5: Bay air temperature vs. altitude for a simple temperature-altitude profile as the wall temperature

Chapter 2, the bay wall temperature typically drops with increasing altitude. In Fig. 4-5 a simple temperature-altitude profile is used as the wall temperature. The altitude dependence of the bay air temperature is presented for five different values of the ratio between the forced-air cooled heat loads and the ambient cooled heat loads, $\frac{q_F}{q_{A,c}}$. In all cases, an initial sea level temperature difference of 1 °C between the air temperature and the bay wall temperature was assumed. It can be seen from Fig.4-5 that for small values of the forced-air cooled heat load ratio (curves A, B, and C) the changes of the bay air temperature with altitude are similar to the unconditioned bay configuration presented in Chapter 3. However, for larger values of forced-air cooled heat loads ratio, $\frac{q_F}{q_{A,c}} > 10$, the temperature of the bay air stays relatively constant with altitude. The constant value of that temperature is approximately the temperature of the cooling air as it exits the forced-air cooled equipment boxes, T_{out}, as was estimated in Section 4.3 above, for the limit value of T_m when $N_F \rightarrow \infty$.

Fig. 4-6 is another example showing a similar analysis but with an altitude dependence of the wall temperature typical for a modern high performance aircraft. The temperature-altitude envelope of the adiabatic wall temperature which was presented in Fig. 2-13 is used.

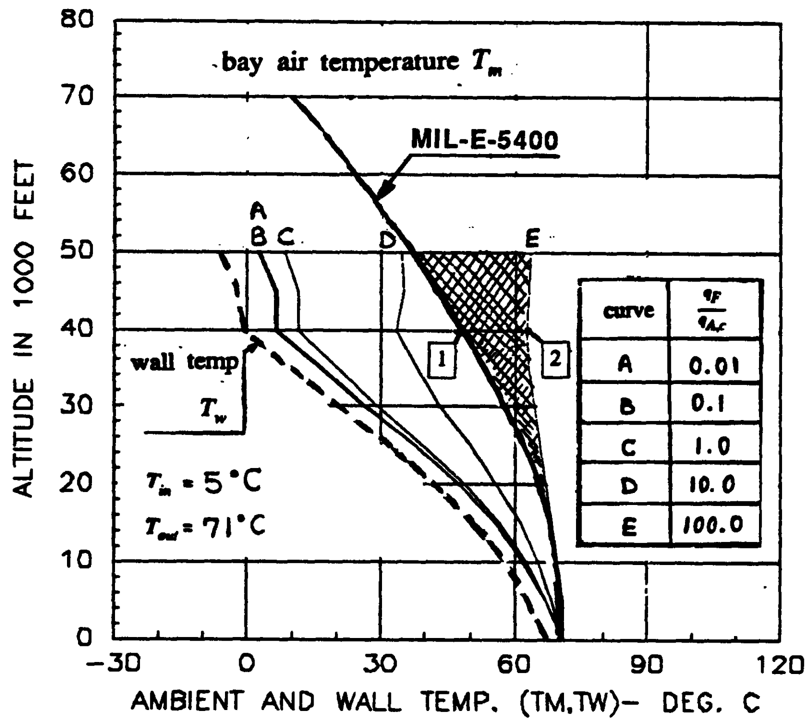


Figure 4-6: Bay air temperature vs. altitude and forced-air cooled heat load ratio in comparison with MIL-E-5400

The behavior is similar to that presented for the simple case. An important feature in Fig. 4-6 is the comparison given between the simulated bay air temperature with altitude and the MIL-E-5400 Class II bay air temperature-altitude envelope. The shaded area in Fig. 4-6 represents conditions where the expected bay air temperature of that typical aircraft, is higher than the temperature specified by MIL-E-5400. For example, in referring to Fig.4-6, at an altitude of 40,000 ft the MIL-E-5400 specifies a maximum bay air temperature of approximately 45 °C (point 1), while the expected bay air temperature can be as high as 62 °C (point 2) for large value of forced-air cooled heat load ratio $\frac{q_F}{q_{A,c}}$. Clearly, this may create a cooling problem in that bay in these conditions for an ambient cooled equipment which was designed to meet the temperature-altitude envelope of MIL-E-5400.

Chapter 5

Summary and Conclusions

5.1 Summary

The increasing penalty on aircraft and engine performance due to larger and heavier cooling equipment which modern aircraft carry for the cooling of the growing avionics heat loads, has motivated attempts to reduce aircraft performance penalties. This thesis sought to examine the possibility of improving the environmental control system (ECS) effectiveness by tailoring avionics design specifications to meet actual environmental conditions, and thereby reducing ECS cooling air requirements.

A method was developed which enables the analysis of the avionics bay thermal environment as well as equipment box temperatures as a function of altitude, based on sea level performance. The technique uses standard atmospheric models and aircraft altitude-Mach number flight envelopes. In order to study the effects of altitude on equipment box temperatures, equations were derived which relate the altitude dependence of equipment box and bay air temperature to the bay wall temperature. Thermal design parameters such as convective and radiative heat transfer coefficients, as well as temperature "potentials" (to reflect the avionics heat loads), were included.

Two different configurations of aircraft bays were examined. The first type was an unconditioned bay where the internal environment (temperature, pressure, humidity) is not actively controlled. The second type was a conditioned bay where cooling air is provided by the ECS for controlling the bay environment, or as a cooling fluid for forced-air cooled equipment. The electronic equipment within the avionics bay were also separated by cooling method into two categories. The cooling techniques considered in this thesis were ambient cooling (where heat is transferred by free convection and radiation) and forced-air cooling (where heat is transferred to cold air supplied by the aircraft ECS).

The results of the analysis of the unconditioned bay (Chapter 3) showed that of the environmental parameters, pressure has the most significant effect. The changes in temperature difference between the equipment box and the bay wall were shown to grow exponentially with altitude. The temperature conditions of the equipment box and the bay wall, on the other hand, were found to have only a small effect on the altitude dependent of the changes in the temperature difference between the equipment box and the bay wall in the range examined. Of the design parameters, radiation heat transfer was found to be very effective in moderating the undesirable growth of the temperature difference with altitude. At high altitude where convective resistance increases due to reduced air pressure in the avionics bay, radiative heat transfer takes over and a larger fraction of the heat dissipation is transferred by radiation. Thus, radiation heat transfer in this system may be regarded as a "thermal pressure relief valve".

An interesting result was found when actual equipment box temperatures were obtained by simulating the bay wall temperature with the temperature-altitude envelope of MIL-E-5400 Class II. The equipment box temperature was plotted as a function of altitude for different sea level values of the temperature difference between the equipment box and the bay wall. It was observed that there was an optimal design value for the sea level temperature difference between the equipment box and the bay wall. At the optimal value, the equipment temperature stays relatively constant at all altitudes. Lower values result in decreasing equipment box temperature with altitude, and therefore sea level conditions will be the critical case for the equipment thermal design. Higher values of temperature difference result in increasing equipment box temperature with altitude, and therefore the critical point for the thermal design of the equipment will be the highest expected altitude.

The simulation of the conditioned bay (Chapter 4) showed that, with the assumption of constant inlet and outlet cooling air temperatures (i.e. appropriate balance between the cooling air mass flow and the associated forced-air cooled heat load), the bay air temperature depends on the relative amount of forced-air cooling and ambient cooling. When the ambient cooling was the dominant one, the bay air temperature-altitude envelope exhibits a behavior similar to that of the unconditioned bay (i.e. the temperature of the bay air decreased with altitude, for small temperature difference between the bay air and the bay wall). However, when the forced-air cooling increased, the bay air temperature tended to be isothermal at all altitudes. As expected, the isothermal temperature was close to the temperature of the cooling air as it exited the forced-air cooled equipment.

5.2 Conclusions and Implications

The following are the conclusions and implications which were drawn from this thesis:

1. Convective heat transfer resistance, and thus the temperature difference across such a resistance, increased exponentially with altitude and is well approximated by considering only the pressure dependence.

2. Radiation heat transfer serves as a "thermal pressure relief valve" and significantly helps in maintaining a relatively constant temperature difference between the equipment box and the bay wall. Therefore, the common procedure of neglecting radiation heat transfer, which is clearly stated in many aircraft manufacturer

specifications for avionics and is implicit from the design requirements of MIL-E-5400, causes built-in overdesign in both avionics equipment boxes and in aircraft ECS. It would be beneficial to both avionics and aircraft manufacturers, as well as to aircraft operators, if these specifications were expanded to allow incorporation of radiation heat transfer in the thermal design.

3. In an unconditioned bay configuration, where the bay air temperature decreases with altitude (e.g. MIL-E-5400), it is possible to design the avionics such that the equipment box temperature is relatively constant at all altitudes. This can be achieved by choosing the optimal value of temperature difference between the equipment and the bay air. In this case, the thermal design of the equipment is not determined by only one flight condition.

4. The requirements specified by MIL-E-5400 do not cover the case of a conditioned bay which contains large percentage of forced-air cooling and small percentage of ambient cooling. In this case, the bay air will be relatively isothermal as a function of altitude. Ambient cooled equipment boxes which were designed to meet only the MIL-E-5400 requirements will result in unnecessary cooling demands from the ECS. It would be beneficial, therefore, for the ECS design if the isothermal temperature-altitude envelope was reflected in the specifications of the avionics systems intended to be installed in a conditioned bay of this type. This requirement would impose a more severe requirement on thermal design of the ambient cooled equipment but would result in a major benefit to the ECS.

5. If ambient cooled equipment could be designed to meet an isothermal

temperature-altitude envelope, the configuration would carry additional savings in ECS cooling air. In the case of isothermal bay air temperature the critical design temperature of the equipment is at the highest expected altitude, therefore, the equipment is overcooled at low altitude. This overcooling at low altitude can be beneficial to aircraft which experience higher aerodynamic heat loads during certain transient conditions (e.g. high speed dash at low altitude) which would normally require that additional cooling air be supplied to the bay.

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