SAE

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AEROSPACE RECOMMENDED PRACTICE

ARP 89C

Issued 3-15-70
Revised

TEMPERATURE CONTROL EQUIPMENT, AUTOMATIC, AIRCRAFT COMPARTMENT

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REAFFIRMED
3/92

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PREPARED BY
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1. PURPOSE

1.1 The purpose of this Aerospace Recommended Practice is to outline the design considerations and criteria for automatic temperature control systems for use as a guide in the aircraft industry.

1.2 These recommendations are representative of present engineering practices, and necessarily subject to revision from time to time due to the rapid development of the industry.

2. SCOPE

The recommendations of this ARP are primarily intended to be applicable to temperature control of compartments, occupied or unoccupied, of civil aircraft whose prime function is the transporting of passengers or cargo. The recommendations will apply, however, to a much broader category of civil and military aircraft where automatic temperature control systems are applicable.

3. NOMENCLATURE

3.1 Terminology: The terminology of ARP 147B, or later revision, "Nomenclature, Aircraft Air Conditioning Equipment," should be used where applicable.

Further terminology may be found by reference to "American Standard Terminology for Automatic Control" (ASA C 85.1 - 1963) published by the American Society of Mechanical Engineers.

3.2 Definitions: The following definitions apply to the special items related to automatic temperature controls as used in this ARP.

3.2.1 Accuracy: The degree to which the controlled temperature approaches the set point value. It is usually expressed as ± a given amount.

3.2.2 Anticipation: A means of sensing that some modification of controller action is necessary before the main sensing element has specified such a need. This is usually accomplished by sensing the rate of change of the controlled temperature, either directly or indirectly.

3.2.3 Control Action: The act of changing some variable (position, power, etc.) to effect a correction of the controlled temperature.

3.2.4 Control Amplifier: The device which mixes the signals from the input and feedback devices, detects an error if there is one, and causes a correction to be made.

3.2.5 Control Point: The actual value of the controlled temperature at which the system is controlling.

3.2.6 Controlled Device: The final element which is under the direct control of the control amplifier, such as a valve, damper, programmer, or a resistance heater.

3.2.7 Cooling Effect: The ability of a fluid stream to carry away heat. For a given fluid, this is a function of temperature and mass flow.

3.2.8 Corrective Action: Controller output which results in a change in controlled temperature in the direction of the control point.

3.2.9 Dead Band: The complete range of values of the controlled temperature in which no corrective action will be taken by the controller.

3.2.10 Differential: When applied to two position control action, it is the difference between the value of the controlled temperature at which the controller operates to one position and that value of controlled temperature at which it operates to the other position. When applied to a control with a deadband, it is the difference between the value of the controlled temperature at which the controller action in a given direction is started and the value at which it is stopped. The differential is not necessarily the same on both sides of null.

3.2.11 Droop: The difference between the control point and the set point due to some inherent control characteristic. Also called offset or deviation.

3.2.12 Error: The difference between the set point and the control point.

3.2.13 Floating Control: A control which has no unique position of the final controlled device. In any given stable condition the control point and the set point are the same or within the deadband. When an error exists, continuous control action will be exercised until the error is eliminated at the control element(s) (i.e., cabin sensing element). The rate of corrective action may or may not be a linear function of error and is often modified by velocity feedback, pulse modulation or anticipation.

3.2.14 Integrating Control: A control system in which rate of change of valve position is proportional to temperature error, or valve position is the integral of temperature error.

3.2.15 Neutral Zone: Same as deadband.

3.2.16 Null: A situation of no input to the controller.

3.2.17 On-Off Control: Also called two position or cycling control. This type of control can assume only a maximum or minimum position. The differential of the controller and the system characteristics determine the rate of amplitude of controlled variable cycles.

3.2.18 Proportional Band: The total amount of change in the controlled variable required for the controller to move the controlled device through its complete stroke. That is, the amount that the control point of the system can be changed by varying the controlled device over its entire range. Also called throttling range.

3.2.19 Proportioning Control or Proportional Control: A control which has a unique stable position of the final control device for any given error. This may result in a difference between the control point and set point, known as droop. See also Proportional Band.

3.2.20 Pulse Band: That range of controlled variable over which the final control device is pulsed to take corrective action. That is, it is the range of controlled variable that falls between a "maximum on" condition in one direction and a "maximum on" condition in the other direction.

3.2.21 Pulse Modulation: A method of varying the rate of corrective action as a function of error by moving the final control device in discrete steps. See also Pulse Band.

3.2.22 Reset: Another term for an integrating control function. Also used for any control characteristics which eliminate droop in a system.

3.2.23 Response: A quantitative expression of the output as a function of the input under conditions must be explicitly stated.

3.2.24 Response Time: A measure of the time required to complete some part or all of a required action. The 63% point is commonly used; e.g. the time required for the cabin air temperature to reach 63% of the total change which results from a step change in the supply air temperature.

3.2.25 Sensing Element: A device which measures the value of a variable by providing an output that can be utilized by the controller.

3.2.26 Sensitivity: In a sensing element, the ratio of change in output to a specified change in input.

3.2.27 Set Point: That value of the controlled temperature to which the selecting device is adjusted, representing the desired value of controlled variable.

3.2.28 Threshold: In a system or component, the least signal input capable of causing an output signal having desired characteristics.

3.2.29 Transfer Function: The mathematical expression relating the output to the input of a control system or component thereof.

4. CONTROL SCHEMES

In the automatic control of temperature, various schemes are available, each one of which produces a different kind of controller output in the presence of a given error. It is the purpose of this section to briefly describe these various schemes or approaches to temperature control and to draw conclusions concerning each scheme.

4.1 On-Off Control: As its name implies, the final controlled device can assume only two positions as dictated by the controller output being either on or off.

The controller, for mechanical reasons, possesses a differential. For example, a bimetal actuated thermostat with an electric output will usually require a temperature change of at least 1.5 F to move the contacts from open to closed or vice-versa.

The controlled temperature will oscillate as the controller goes from on to off to on; and if the system has little or no thermal capacitance, the amplitude will be equal to the differential of the controller. The frequency depends on the differential and the time constant of the system. In a fast-responding system, a deliberately large differential may be necessary to prevent undue wear on valves, contactors or other elements in the control loop. If the system has thermal capacitance, e.g. an electric heating element plus the material in which it is imbedded, the capacitance will continue to emit heat to the controlled space and the temperature in the space will continue to rise even after the controller has turned to "off". This overshoot, when added to the amplitude caused by the differential, can produce objectionable swings in the controlled temperature. In order to reduce overshoot amplitude, a small heating element is sometimes incorporated into the controller and the heater is arranged to be energized whenever the controller calls for heat. The sensing element in the controller feels this additional heat and sets the controller to "off" before the upper limit of the differential is reached.

4.2 Floating Control:

4.2.1 Single Speed Floating Control: A reversible motor drives the final controlled device at a given speed in one direction when the temperature at the sensing element is above the set point and reverses when the temperature is below the set point. A dead band in the controller causes the motor to remain stationary when there is no load change or other disturbance to the system.

The speed of the motor (floating speed) relative to the time constants of the sensing element and the system is an extremely important factor in the application of floating control. A high floating speed coupled with a slow responding system and/or a slow responding sensing element may result in overshoots and departures from set point for unacceptable periods of time or sustained oscillation.

These considerations impose an upper limit on the floating speed. This in turn implies poor control in the presence of rapid load changes.

4.2.2 Proportional Speed Floating Control: A variation of floating speed control is proportional speed floating. Here the motor speed is proportional to the error. The speed is high for large errors and low for small errors.

4.2.3 Pulse Width Modulation Control: A control scheme wherein the controller output is a train of pulses of variable duration is called pulse width modulation. The width of the "on" pulse is varied relative to the width of the "off" pulse as some function of the error.

When the total effect on the final controlled device is observed over a period of time, it can be seen that the actual effect is that of one of the control schemes already described. For example, in a pulse width modulation system wherein the final controlled device is a motor driven valve, the motor may be driven by pulses whose width is proportional to the error. Therefore, the average speed of the motor is proportional to the error, which has already been defined as proportional speed floating control.

4.3 Proportional Control: In proportional control, there is a definite value of controller output (and a definite position of the final controlled device) for every value of the error. The range of error which causes full range of position of the controlled device is called proportional band or throttling range. The proportional band is usually adjustable within the controller.

In the presence of a load change, the controlled device must change its position to accommodate the new load. This results in droop (or offset), that is, the controlled temperature must depart from the set point in order to move the controlled device. Droop is a result of proportional control.

The amount of droop can be decreased by decreasing the proportional band, but this decrease in proportional band increases the tendency toward system instability (sustained oscillation of controlled temperature).

4.4 Reset Control: The characteristic of reset control is that the controller output (and position of final controlled device) will be changed at a steady rate in the presence of a given error. It is sometimes called integral control because its effect can be related to the integral of the error or the area under the curve of error plotted against time.

Reset control is sometimes added to proportional control for the purpose of eliminating the droop which would exist with proportional control alone. Reset control action continues to provide correction as long as there is any error and reset action stops only when the error is zero.

A controller containing proportional plus reset control will have adjustments for proportional band and reset rate. Reset rate is measured by the length of time it must persist to produce the same change that the proportional control alone would produce immediately. A slow reset rate (in the presence of a given error) would require a long time to produce the same change as that of the proportional control alone. Conversely, a fast reset rate would require a short time to produce the same change that proportional control alone would produce.

4.5 Rate Control: The characteristic of rate control is that the controller output (and position of final controlled device) is a function of rate of change of error. If an error is present, but not changing, rate control has no effect whatsoever on controller output. Because it produces no effect in the presence of a steady error, rate control is always used in combination with other forms of control action.

The advantage of adding rate control is that it permits the use of a narrow proportional band without inducing instability.

5. DYNAMIC ANALYSIS

5.1 General Considerations:

5.1.1 Mathematical Model: Formulating and evaluating the means of controlling the temperature of a duct or compartment is best accomplished by using a mathematical model of the temperature control system. The introduction of a mathematical model permits the use of servo analysis techniques for evaluation of the system stability.

The mathematical model is developed from equations that are written to describe the physical processes in the various parts of the system, and these equations are, understandably predominantly temperature relationship. Equations representing the valve-actuator are included so as to complete the definition of the system. The development of the mathematical model frequently proceeds along lines of reasoning similar to those followed in developing electrical analogues of physical processes.

The mathematical model defines the gain and dynamics of each significant component of the system. For example, the gain of an electrical temperature sensor would be defined as the change in resistance of the sensor per degree change in temperature. The dynamics of the sensor would define the time lag in the response of the sensor to a change in temperature.

Both the gain and dynamics of the components of a system are subject to change with changes in flight conditions. Becuase of this, stability analyses should be performed for a range of values representative of all significant flight conditions.

5.1.2 Bode Diagrams: Nominally, the stability analysis is made by means of either Bode diagrams or Root Locus plots and analog computer simulations. Since temperature control systems, for the most part, involve the cascading of simple leads and lags, the direct graphical method of accomplishing gain multiplication that is possible through the use of Bode diagrams recommends their application here.

A Bode diagram is a specialized plot that relates how the amplitude and phase response of a network (or of a system that the network simulates) varies with the frequency of excitation. The method of making and interpreting Bode diagrams will not be dealt with here.

5.1.3 Analog Simulation: An analog simulation is usually resorted to for a prediction of the transient response of a system. While the inverse LaPlace transform of a system transfer function can be evaluated to give the transient response, the labor and time involved normally dictates the use of a computer for all but the simplest of systems. The analog computer is especially useful in dealing with nonlinearities that may be encountered in a system. Here again, analytical techniques are available for handling nonlinearities without an analog computer, but they become quite cumbersome for multiple loop problems especially if more than one nonlinearity is present.

5.2 Generation of the Mathematical Model: To generate the mathematical model referred to above, it is necessary to be able to define numerically each element of the system. Included among the numerics that are required are the gains of the temperature sensor(s), air flow mixing or modulating valve, the compartment, the controller, and the gain of the valve actuator. The gain of the air modulating valve, usually referred to as the equipment gain (Ke) is understandably quite important. Ke relates the change in air temperature immediately downstream of the mix point to a unit change in valve angle.

When a compartment temperature control system is analyzed, the compartment characteristics must be accounted for in addition to developing an expression for the equipment gain. Briefly, this involves evaluating the expression for Ke and cascading it with a gain term that accounts for heat gains or losses in the compartment. The details of how this is accomplished are developed in Paragraphs 5.4 and 5.5.

A frequently encountered requirement is for a system to control the temperature of a compartment by means of controlling the total flow of air (as contrasted to controlling the temperature of mixed air) to the compartment with the sensor located in the exit air duct. In order to obtain sensed temperature as a function of valve area $\frac{dT_{out}}{dB}$ Ke must be augmented by an additional term which reflects changes in exit duct temperature caused by variations in weight flow across the heating load that may exist. Thus, Ke supplies the inlet air temperature as a function of incremental valve angle and then this is modified to account for the heat load in the compartment. Some compartments, particularly personnel compartments require steady state flows of such magnitude that the total flow is not influenced greatly by changes in valve angle.
In order to predict the temperature change at the sensor, it is only necessary to multiply the temperature change in the mix duct by the compartment gain factor, (refer to para. 5.5) which is typically 0.1 to 0.5. This factor is cascaded with Ke to obtain the total gain from valve to sensor.

The primary emphasis of the foregoing paragraphs has been how to obtain the steady state gain from the valve through to the sensor. This has included two significant cases: First, where Ke is augmented by a factor; second, where Ke is cascaded with an attenuation.

Additionally, there are dynamics that have to be considered. These result from:

1. The time it takes the air to traverse the compartment.

2. The thermal inertia of the compartment.

3. Leakage through the walls of the compartment.

The method used to evaluate the dynamics of a compartment is detailed in Paragraph 5.5.

Since there frequently is a marked discrepancy between the predicted and measured values of compartment gains and dynamics, the systems designer is well advised to establish empirical means of adjusting design calculations. Such means are best established by keeping thorough records of design calculations and continually updating the adjusting procedure.

The evaluation of the lag associated with the response of a temperature sensor can be conveniently done by reference to curves. These curves show the variation of sensor time constant as a function of weight flow per unit area. The data from such curves can be related to the design by simply establishing the weight flow per unit area at the sensor location.

5.3 Equipment Gain: Ke, the equipment gain, should be evaluated, whether or not the temperature control system is to be analyzed by means of an analog simulation. The equipment gain is a numeric that defines the ratio of the change in duct-mix-temperature to the change in valve angle. In the mathematical model (as in the actual system), Ke effectively closes the loop from the output of the valve actuator to the actual air temperature that results from valve movement. From the above considerations it can be seen that Ke is in reality, $\frac{dT}{dB}$. This derivative can be expressed as follows in terms of derivatives, that are shown below, to be available from consideration of equipment parameters.

$$Ke = \frac{dT}{dB} = \frac{dA}{dB} \frac{dW}{dA} \frac{dT}{dW} \qquad (1)$$

where

$\frac{dA}{dB}$ is the rate of change of effective valve area as a function of valve shaft angle.

$\frac{dW}{dA}$ is the rate of change of weight flow through the valve as a function of effective valve area.

$\frac{dT}{dW}$ is the rate of change of mixed air flow temperature as a function of the change in flow of the hot or cold air.

For a more detailed discussion of equipment gain, refer to paragraph 3K 6.3 of the SAE Aerospace Applied Thermodynamics Manual, Second Edition.

5.4 Effect of Heat Loads on Equipment Gain: When the temperature control problem can be reduced in simplicity so that changes in inlet duct temperature versus valve angle need only be considered, then Ke as previously defined may be used as an indication of changes in duct temperature per unit of valve displacement. This situation often arises where air flow is regulated, such as in personnel compartments.

Frequently, however, although Ke can be used to represent conditions at the inlet duct, an additional term must be added to obtain an indication of exhaust duct temperature per unit of valve displacement.

The equation for this term is

$$\frac{dT\ out}{dB} = \frac{\partial Tout}{\partial W} \frac{dA}{dB} \frac{dW}{dA} + Ke \qquad (2)$$

Derivation of this equation is found in Paragraph 3K 6.4 of the SAE Aerospace Applied Thermodynamics Manual, Second Edition.

5.5 Compartment Gain: For the purposes of system analysis, the most convenient way to describe a compartment or cabin is by means of a transfer function. A transfer function is the mathematical expression relating the response of a particular parameter (e.g. temperature) to a disturbance in one of the other parameters (e.g. weight flow of air). Such a means of quantitatively describing system response is required if a meaningful evaluation of the performance of a temperature control system is to be made.

In developing a transfer function to describe a compartment, the mathematical model that is formulated for the compartment is purposely simplified. Cabin configurations vary widely and for this reason the considerations discussed below should only be taken as a guide to the line of reasoning to be used.

A typical cabin can be represented thermodynamically by the heat transfer equations which define the heat flow inputs being equal to the heat storage rate plus the heat flow output. The total heat flow inputs are the sum of (1) the total heat content of the air ducted into the compartment, (2) the sensible heat flow of the compartment occupants, and (3) the heat generated by the electrical and electronic equipment within the compartment. An energy balance is obtained by equating the heat flow inputs to the heat flow outputs which are typically (1) heat storage rate of the compartment air, (2) heat storage rate of the compartment mass, (3) heat flow through the compartment walls, and (4) heat flow of the air leaving the compartment. The heat transfer equation is then:

$$Q_{in} + Q_p + Q_e = Q_a + Q_m + Q_w + Q_o \tag{3}$$

Each of these terms represent a more detailed thermodynamic expression which based on several simplifying assumptions can be defined as follows:

(a) Heat flow into the compartment through the incoming air:

$$Q_{in} = W\,C_p\,T_{in} \tag{4}$$

(b) Sensible heat flow of personnel within the compartment:

$$Q_p = N\,H_s \tag{5}$$

(c) Heat flow generated by electrical and electronic equipment within the compartment:

$$Q_e = 56.89\,P_e \tag{6}$$

(d) Heat storage rate of the compartment air:

$$Q_a = M_a C_p \frac{d\,T_a}{d\,t} = M_a C_p P\,T_a \tag{7}$$

(e) Heat storage rate of the compartment mass:

$$Q_m = h_m A_m (T_a - T_m) = M_m C_m P\,T_m \tag{8}$$

(f) Heat flow stored in walls and lost to outside air:

$$Q_w = Q_{w1} + Q_{w2} + Q_{w3} \tag{9}$$

$$Q_{w1} = h_{11} A_{w1} (T_a - T_{11}) = \frac{2k_{w1} A_{w1}}{L_{w1}} (T_{11} - T_{w1}) \tag{10}$$

$$\frac{2k_{w1} A_{w1}}{L_{w1}} (T_{11} - T_{w1}) = M_{w1} C_{w1} P T_{w1} + \frac{2k_{w1} A_w}{L_{w1}} (T_{w1} - T_{12}) \tag{11}$$

$$\frac{2k_{w1} A_{w1}}{L_{w1}} (T_{w1} - T_{12}) = h_{12} A_{w1} (T_{12} - T_{amb}) \tag{12}$$

Q_{w2} and Q_{w3} have comparable equations with appropriate reidentification of the constants and variables.

(g) Heat flow of air leaving the compartment:

$$Q_o = W\,C_p\,T_a \tag{13}$$

This thermal representation of the compartment is shown in the block diagram of Fig. 1.

To formulate the electrical analog of these equations, it is only necessary to use voltage as the analog of temperature, current as the analog of heat, electrical resistance as the analog to thermal resistance and capacitance as the analog of thermal mass. The representation of an analog for the typical compartment that is defined thermodynamically above using the standard electrical symbology is illustrated in Fig. 2.

5.6 Typical Personnel Compartment Analysis and Design: Figure 3 illustrates in block diagram form a typical cabin temperature control system. Briefly, the system represented consists of a valve to control the proportion of hot to cold air admitted to a cabin in order to control the temperature of the cabin, duct and cabin temperature sensors, compensation networks, and a controller to position the valve so as to produce the desired or set point temperature.

In operation, an analog signal of the desired cabin temperature is generated and differentially summed with the signal output of the cabin temperature sensor. The output signal from the duct sensor, after passing through a derivative network, is subtracted from the error signal generated by the first differential summation. The resultant error signal is again summed with the negative feedback signal from the motor rate network, which is a negative signal proportional to actuator velocity. The final error signal thus generated is amplified and causes the valve to move to the position resulting in the least error, or in other words, causes the cabin temperature to come into closest correspondence with the desired temperature.

The analysis of a system, such as the one described above, is carried out through the use of linearization techniques. This involves writing partial differential equations describing the system and assuming that the values of the partials hold for small perturbations about the conditions that the equations were written to describe. This means that different values of equipment gains (defined as the incremental change in duct temperature per incremental change in valve angle) must be obtained for each system condition to be investigated. The cabin transfer function is derived from considerations of the mass flow of air into the cabin and the heat transfer rates from the air into the cabin furnishings and through the cabin walls as discussed in Paragraph 5.5.

The stability analysis of the system is nominally performed through the use of algebraic manipulation of the transfer functions and Bode diagrams, backed up by an analog computer simulation.

Referring again to Fig. 3, the system block diagram, it can be seen that there are three feedback paths illustrated. The bottommost feedback path includes the cabin lag and a lag circuit between the compartment temperature, T_a, and the voltage developed that corresponds to the compartment temperature. The sensor lag network illustrated represents the time lag between which a change in temperature takes place and when the output of the temperature sensor indicates the new value.

The middle feedback path includes a lag and a rate lag representative of the duct sensor lag and the duct derivative network. The top feedback path includes the valve rate network. This network has the characteristic of a rate circuit and an associated short lag.

One of the significant characteristics of a control loop employing negative feedback is that the forward gain of the closed loop is equal to the reciprocal of the feedback gain, if the forward gain is high enough. This can be easily seen by reflecting for a moment upon a simple loop with a forward gain represented by G and negative feedback gain represented by H. The transfer function of such a loop can be seen to be:

$$\frac{\text{Output}}{\text{Input}} = \frac{G}{1 + GH} \text{ or } \frac{1}{1/G + H} \approx \frac{1}{H}$$

The above result appears in numerous servo texts. It is reproduced here to illustrate why, if G (the forward gain) is high, the loop gain is equal to the reciprocal of the feedback gain.

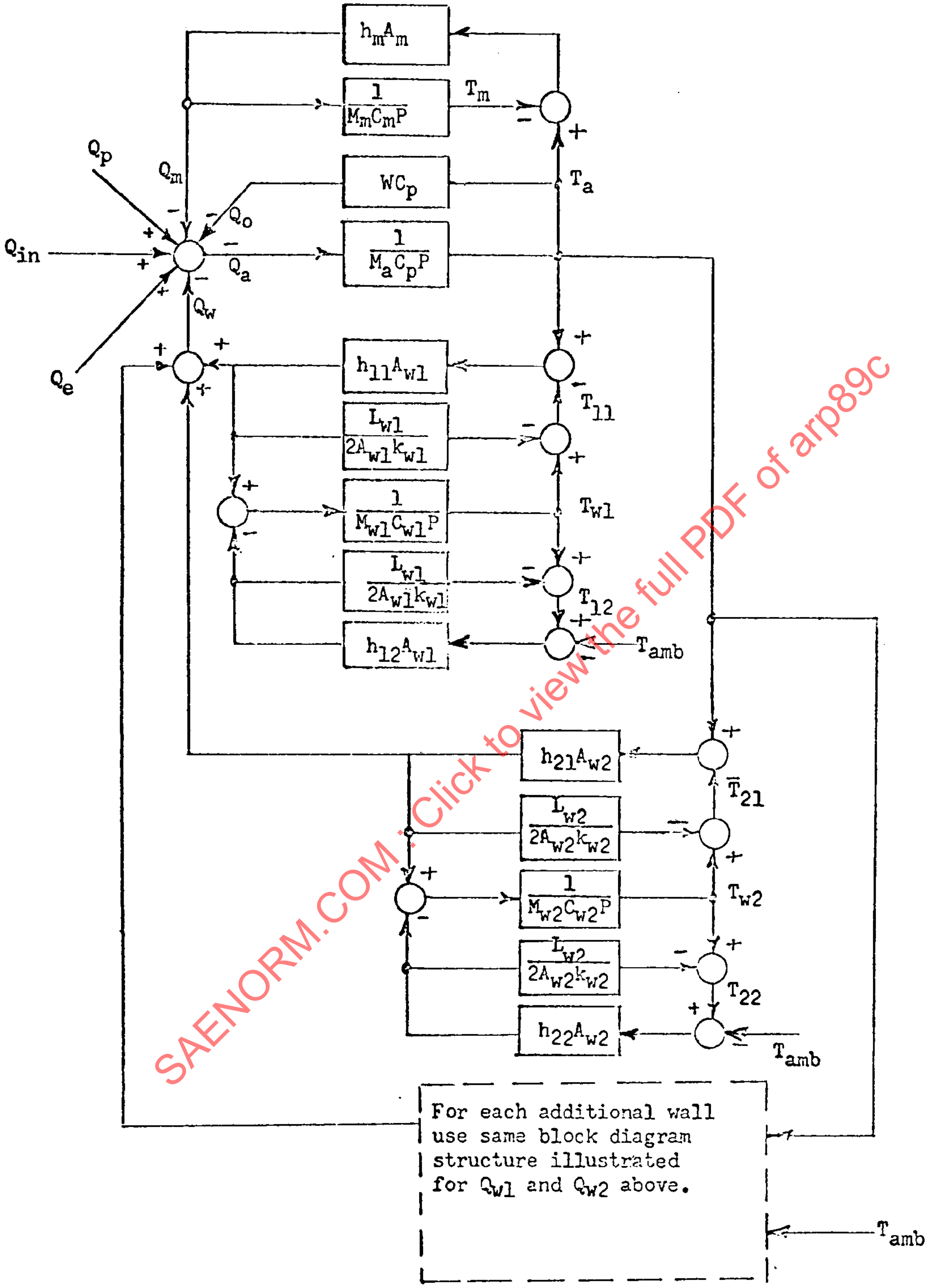
Thus, the middle feedback path is utilized to correct for the cabin and cabin sensor lags. As can be noted from the block diagram, the middle feedback path includes the duct sensor lag as well as the derivative and lag that make up the duct derivative network. As noted before, however, if the forward path (amplifier, actuator, and equipment gain, Ke) gain is high enough, the overall transfer function will have the characteristic of the reciprocal of the middle feedback path. Thus, the two lags in the feedback path will appear as leads in the forward path and the one lead will appear as a lag if Ke is high enough. Ideally then, the two feedback lags should cancel the effects of the cabin lag and cabin sensor lag. The duct derivative network lag can usually be selected to cancel the effect of the cabin lag. However, difficulty is frequently experienced in attempting to cancel the cabin sensor lag with that of the duct sensor. This is due to the fact that the weight flow per unit cross-sectional area is so much greater past the duct sensor than it is past the cabin sensor because of their relative locations.

Since the time constant of the sensors is dependent upon the weight flow per unit area past them, the net result is a large disparity between the time constants of the cabin and duct sensors. Even so, some benefit is derived from the resultant lead, produced by the duct sensor lag, in the feedback path. If the benefits derived are not adequate, however, improvements might be realized through slowing down the duct sensor until its time constant is more nearly commensurate with that of the cabin sensor.

The value of Ke (equipment gain) varies throughout the range of operating conditions encountered. When Ke falls below a minimum value, the forward gain of the cabin temperature control loop no longer approximates the reciprocal of the duct derivative feedback path and the cabin and cabin sensor lags are no longer cancelled. Past experience has shown that where the maximum value of Ke is 10 the cabin and sensor lags are no longer cancelled by the duct derivative feedback when Ke has dropped to a value of 0.5.

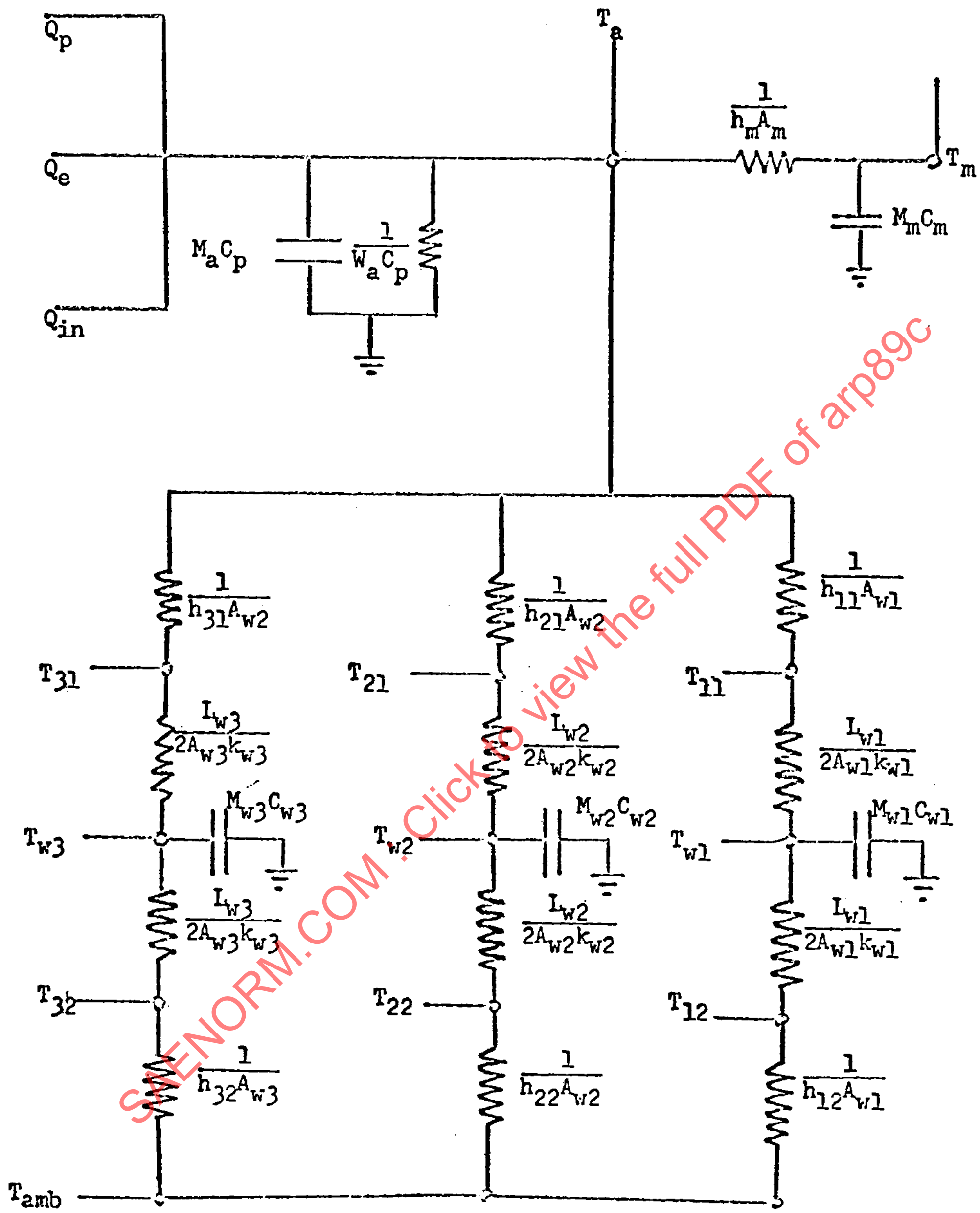
To compensate for the effects produced by variations in Ke as well as to stabilize the duct derivative loop, the rate feedback is employed around the actuator. This is illustrated on the block diagram by the top feedback path. This feedback does not produce any noticeable effect on the major loop, for high values of Ke since for such values of Ke the valve rate feedback effect upon the major loop is effectively masked by the duct derivative feedback. At lower values of Ke, however, the duct derivative feedback is no longer effective and the valve rate feedback tends to cancel out the cabin time constant. Thus, the value selected for the valve rate feedback time constant must be a compromise between what is needed to stabilize the duct derivative loop at high values of Ke and what is needed to stabilize the main temperature (or major) loop, by cancelling out the cabin time constant at low values of Ke.

An additional benefit is derived from the rate feedback around the actuator. This is the high value of breakaway power that is made available to initiate movement of the actuator. The high value of starting power results from the fact that since the feedback path is a rate lag, its output is zero until the actuator starts to move. Thus, the amplifier drives the actuator at maximum gain until the initiation of movement effectively completes the feedback path. Once completed, the feedback path reduces the gain to a value more in keeping with stability requirements. This feature helps to keep the effects of actuator static friction to a minimum. The importance of doing so becomes apparent when it is considered that, as shown on the block diagram, the system has the overall characteristics of an integrator. As such it has no temperature droop (i.e. deviation from the set point as a function of load) and neglecting inherent drift, its steady state accuracy depends only upon the actuator dead zone.



BLOCK DIAGRAM OF AN AIRCRAFT COMPARTMENT TRANSFER FUNCTION

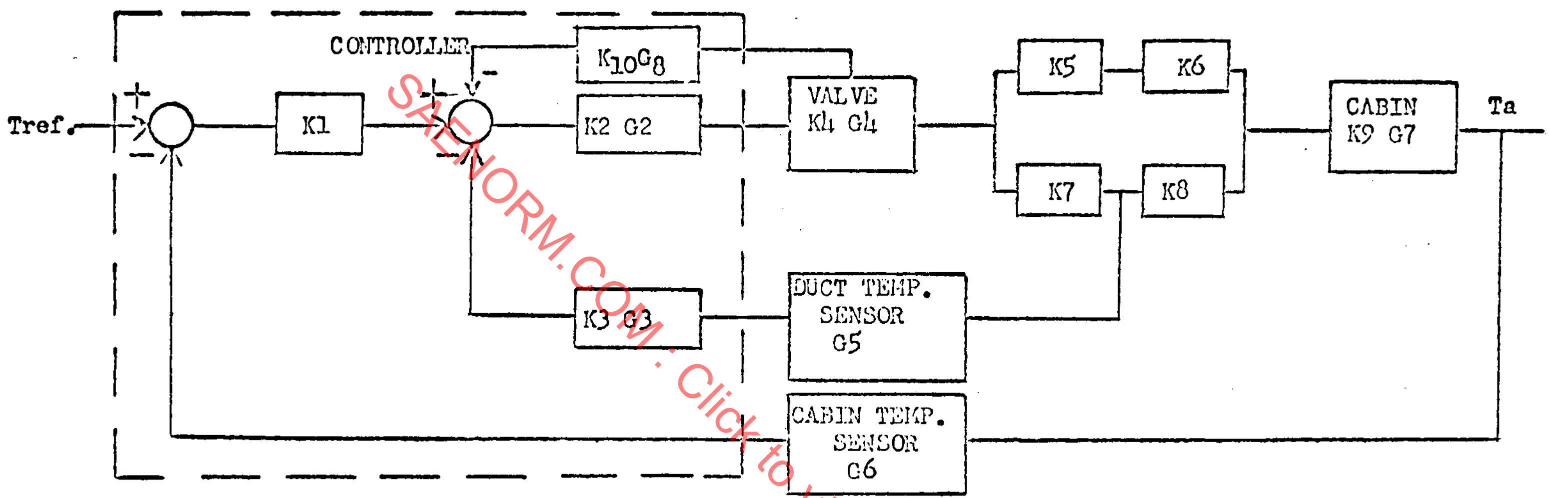
FIGURE 1



ELECTRICAL ANALOG OF COMPARTMENT TRANSFER FUNCTION

FIGURE 2

BLOCK DIAGRAM OF TYPICAL CABIN TEMPERATURE CONTROL SYSTEM



K1 - CABIN TEMPERATURE BRIDGE NETWORK SENSITIVITY (VOLTS/°F)
K2G2 - AMPLIFIER AND COMPENSATING NETWORK (VOLTS/VOLT)
K3G3 - DUCT TEMPERATURE BRIDGE NETWORK SENSITIVITY AND COMPENSATING NETWORK (VOLTS/°F)
K4G4 - VALVE TRANSFER FUNCTION (% OPENING/VOLT)
K5 - $\left(\frac{\text{CHANGE IN WEIGHT FLOW}}{\text{CHANGE IN \% VALVE OPENING}}\right)\left(\frac{\partial W}{\partial P}\right)\left(\frac{\text{LBS./MIN.}}{\text{\% OPENING}}\right)$
K6 - $\left(\frac{\partial Q}{\partial W}\right)\left(\frac{\text{BTU/MIN.}}{\text{\#/MIN.}}\right)$
K7 - $\left(\frac{\partial T(\text{DUCT})}{\partial P}\right)\left(\frac{°F}{\text{\% OPENING}}\right)$
K8 - $\left(\frac{\partial Q}{\partial T\ (\text{DUCT})}\right)\left(\frac{\text{BTU/MIN.}}{°F}\right)$
K9G7 - CABIN TRANSFER FUNCTION $\left(\frac{°F}{\text{BTU/MIN.}}\right)$

K10G8 - VALVE RATE FEEDBACK (VOLTS/$\frac{dB}{dt}$)

G5 - TRANSFER FUNCTION OF DUCT TEMPERATURE SENSOR (°F/°F)
G6 - TRANSFER FUNCTION OF CABIN TEMPERATURE SENSOR (°F/°F)

FIGURE 3

NOMENCLATURE

Symbol	Description	Units
A	Area	ft^2
B	Valve angle	deg
C	Specific heat	
C_p	Specific heat of air at constant pressure	BTU/lb - R
G	Forward gain of servo loop	Various
H_s	Sensible heat of people in compartment	BTU/min
H	Feedback gain of servo loop	Various
h	Heat transfer coefficient	$BTU/R\text{-}ft^2\text{-}min$
k	Thermal conductivity	BTU/min-ft-R
Ke	Equipment gain	R/deg
L	Thickness	ft
M	Weight	lb
N	Number of people in compartment	people
P	Derivative operator, $\frac{d}{dt}$	-/min
P_e	Electrical power output of equipment in compartment	kw
Q_{in}	Heat flow into compartment through incoming air	BTU/min
Q_a	Heat stored in compartment air	BTU/min
Q_p	Heat generated by personnel in compartment	BTU/min
Q_m	Heat stored in compartment thermal mass	BTU/min
Q_e	Heat generated by equipment in compartment	BTU/min
Q_w	Heat lost through compartment walls	BTU/min
Q_o	Heat flow out of compartment in exit air	BTU/min
T	Temperature	R
W	Air flow	lb/min

SUBSCRIPTS

11	Inside wall number one
12	Outside wall number one
21	Inside wall number two
22	Outside wall number two
a	Compartment air
amb	Ambient air
w1	Wall number one
w2	Wall number two
w3	Wall number three

6. ACCURACY OF CONTROL

6.1 General:

The specification of control system accuracy must necessarily be a compromise between cost, complexity, the degree of accuracy possible and the degree of accuracy that is practical and usable. It is generally considered that systems which maintain the temperature within ± 1.5 F of the set point at the location of the sensor are as accurate as is practical for comfort in occupied compartments. In equipment compartments it is usually sufficient to maintain ±5 F and many times ±10 F will suffice.

Systems which include a set point selector should be primarily considered from the aspect of how well the temperature is maintained around the set point. The accuracy of setting the set point is of secondary importance.

6.1.1 Determining Factors: Control system accuracy is determined by:

1. Initial manufacturing tolerances
2. Drift with time
3. System sensitivity
4. Type of control action
5. The adequacy of air distribution
6. Transient response

The six factors listed above are the basic contributors to system error.

6.1.2 Specifying the System: The system specification must include these basic items:

1. Steady state accuracy
2. Damping (overshoot and time to return to within some limit for specific transient disturbances)
3. The location of the controlled variable. (Duct temp., comp. temp. or exhaust temperature.)
4. System input conditions and transfer function.

The designer must decide at which location the temperature most accurately represents the effect on personnel or equipment. It has been found that for small occupied compartments with high heat loads and where personnel are quite exposed to the inlet air, the delivered air temperature is often the best parameter to control. Conversely large compartments with good distribution are best controlled by sensing exhaust air temperature. The temperature is controlled at some point in the compartment on many aircraft if there is no point at which outflow air temperature can be measured or if, because of poor distribution, exhaust air temperature does not adequately represent the temperature at the point of greatest effect on personnel.

6.2 Static Accuracy:

Static accuracy can be defined as the degree to which the controlled temperature coincides with the specified or selected temperature after all transients have decayed. Static accuracy is usually specified as a deviation from nominal (e.g., 70 F ±2 F for a 4 F tolerance band).

6.2.1 Allocation of Static Error: The control system designer usually allocates the allowable tolerance to cover such things as:

1. Dead band
2. Drift (sensor and controller)

3. Set point calibration error

4. Uncompensated system droop

It is sometimes desirable to specify the accuracy in terms of absolute accuracy and repeatability. This is particularly true when the system includes a temperature selector. The selector dial is often not precisely graduated and in fact sometimes is simply labeled "HOT" at one extreme and "COLD" at the other. In that case absolute accuracy is of relatively little consequence but repeatability is still very important.

6.2.2 Floating and Proportional Controls: Most compartment temperature controls fall into one or the other of these categories. The only difference from the aspect of accuracy is that proportional controls introduce droop into the system. Special compensating techniques can reduce the droop to negligible values. Proportional controls can often be made to operate with less dynamic error than the floating system.

6.3 Dynamic Accuracy: Dynamic error is that part of the total error which is due to a transient condition. The dynamic error adds algebraically to the static error. In most practical control systems the dynamic error will, under some transient conditions, exceed the static error. Dynamic error is minimized as the response time of the controlled system is reduced.

6.3.1 Specification of Dynamic Accuracy: The specification statement of dynamic accuracy should include one or both of the following:

1. For a change in selected temperature

   A. A limitation of overshoot for a specified selector change.

   B. The maximum time to return to some specified deviation from the selected temperature, for a specified selector change (e. g., Must settle to within ± 5 F of the new selected temperature within 60 sec after a 10 F selector change).

2. For a change in supply air temperature and/or pressure

   A. A limitation of error during a specified transient condition. (e.g., the temperature shall remain within ± 8 F of the selected temperature, when the bleed air temperature changes linearly from 400 F to 600 F in 2 seconds.)

   B. A time limitation for the system to return to a specified error, usually larger than the static error allowed. (e.g., The system must control the temperature to within ± 4 deg of the selected temperature within one min. after the transient described in (A) above has been completed.)

6.3.2 Factors contributing to Dynamic Error: These factors are the largest contributor to dynamic error, though they do not all contribute to errors due to all types of transients. (e.g., The compartment response time adds to the dynamic error due to a selector change but reduces the dynamic error due to a supply temperature change.)

1. Ratio of air flow to compartment volume

2. Duct and cooling package time lags

3. Sensing time lags

4. Motor operated valve stroke time

Item (1) effects the compartment time constant. As such it contributes to dynamic error for selector changes but reduces the error due to supply or load changes. Item (2) contributes to the error except for changes in supply air condition. Item (3) contributes to the dynamic error in all transient conditions. Item (4) always adds dynamic error but must be limited for stability in many cases.

7. SYSTEM DESIGN REQUIREMENTS

7.1 General: Design requirements should be in accordance with the detail specification for the system and applicable Industry and Government specifications. Compliance with the design requirements should be demonstrated by conducting appropriate qualification tests as outlined in Par. 11.

7.1.1 Materials and Workmanship: Materials should be of a quality which experience and/or tests have demonstrated to be suitable and dependable for use in aircraft. Workmanship should be consistent with high grade aircraft manufacturing practice.

7.1.2 Identification: Applicable portions of the following information should be legibly and permanently marked on the equipment or attached thereto:

a. Nomenclature

b. Specification number

c. Manufacturer's part number

d. Manufacturer's serial number or date of manufacture

e. Manufacturer's name or trademark

f. Ratings

7.1.3 Environment: The components of the system should be designed for exposure to a range of environmental conditions including temperature, humidity, altitude, salt spray, vibration, fungus, sand and dust, ozone, explosive atmosphere, attitude, acceleration and shock, and contamination with tobacco tar as specified in the detail specification or applicable portions of MIL-STD-810. Consideration should be given to condensation and freezing of water in ducts and servo air lines.

The environment of individual components of the system depends on their location in the aircraft. Externally mounted components are exposed to both the natural environment at ground level and the environment produced by the aircraft flight speed and altitude characteristics. Internally mounted components are exposed to the compartment environment which may, or may not, be controlled while in flight. An appropriate range of environmental conditions for each component should be specified by the aircraft manufacturer or the equipment procuring agency.

7.1.4 System Complexity: The complexity should be the minimum required to meet the specified level of control performance. A high degree of control system precision tends to increase complexity and cost.

7.2 Sensing System Requirements:

7.2.1 Temperature Sensing:

7.2.1.1 Controlled Space Temperature: The temperature is sensed in controlled spaces which include passenger compartments and electronic equipment bays.

7.2.1.2 Duct Temperature: The temperature sensors may be mounted in ducts such as the inlet and outlet ducts to compartments and mixing ducts downstream of cooling turbines.

7.2.2 Rate of Change of Temperature: In order to improve system performance or stability, it is sometimes necessary to apply corrective action in the control loop as a function of the rate of change of the fluid temperature in a duct control, or the rate of change of the inlet air in a compartment control.

The sensor signal is supplied to a differentiating circuit in the controller to provide a rate of change signal. Two sensors with different time constants can be used to generate lag-lead signals which permit a narrower control band.

7.2.3 Measurements Other Than Temperature: It is sometimes desirable to reset the control temperature as a function of some parameter such as altitude, pressure, etc. These parameters can be sensed by transducers compatible with the control system.

7.2.4 Types of Sensors:

7.2.4.1 Electric:

7.2.4.1.1 Resistance Wire: The electrical resistance of the wire (usually pure nickel or platinum) increases quite linearly with temperature increase and can be used in one leg of a Wheatstone bridge to detect temperature changes. Resistance change with temperature amounts to approximately 0.3% per deg F for nickel and .21% per deg F for platinum.

7.2.4.1.2 Thermistor: The electrical resistance of a thermistor changes non-linearly with temperature and is used in a bridge circuit in the same manner as a resistance wire sensor. The resistance change with temperature is 1 to 5% per deg F, which is substantially higher than resistance wire.

7.2.4.1.3 Thermocouple: Thermocouples produce a voltage proportional to the temperature difference between the sensing junction and a reference junction. Voltage change with temperature is typically .02 millivolts per deg F depending on materials.

7.2.4.1.4 Temperature Switches: Temperature switches usually consist of a single-pole double-throw switch actuated by a bi-metal or a liquid or vapor-filled bellows. The minimum temperature change necessary to actuate the switch is called the differential and is about 1.5 F for a filled bellows and about 5 F for a bi-metal.

7.2.4.1.5 Mercury Tube: A special class of temperature switches consists of a mercury-in-glass thermometer with platinum wires sealed into the column at various heights to act as electrical contacts. The current carrying capacity is low (100 ma). The temperature differential is about 0.2 F.

The use of a mercury alloy rather than pure mercury permits exposure to -65 F without freezing.

7.2.4.1.6 Solid State Temperature Resistors: These devices are made of pure silicon and their resistance increases in an essentially linear fashion with an increase in temperature. Resistance change with temperature is 0.4% per deg F.

7.2.4.2 Pneumatic:

7.2.4.2.1 Bi-Metal: Pneumatic thermostats produce pressure changes in response to temperature changes at the bi-metal. The bi-metal can be in the form of a rod and tube where the tube is in direct contact with the medium whose temperature is to be sensed. Expansion of the tube relative to the rod (usually Invar) actuates a small valve which in turn varies the pressure output. The pressure output can actuate a valve directly without an intermediate amplifier. The bi-metal may also be in the form of laminated strips or discs.

Pressure changes are in the order of 1.5 psi per deg F.

7.2.4.2.2 Liquid and Vapor Filled: These devices are similar to the bi-metal except that they are actuated by liquid or vapor filled bellows. The liquid filled are not affected by ambient pressure, but are slower in response time.

7.2.5 Sensor Location:

7.2.5.1 Representative Sampling:

7.2.5.1.1 Adequate Velocity: In order to minimize the time constant, adequate velocity should be maintained across the sensor. In a compartment where velocities are low, a small fan should be considered and it would usually be located downstream of the sensor.

7.2.5.1.2 Local Heating or Cooling Influences: The sensor should not be located where it would be subjected to local heating or cooling. Thermal barriers are used between the sensor and its mounting surface to prevent conducted heat from causing an apparent change in the set-point.

7.2.5.1.3 Thermal Radiation: In certain applications, it may be necessary to shield the sensor against sources of thermal radiation.

7.2.5.1.4 Effect of Compartment Pressure: The sensor, if affected by changes in compartment pressure, (as in some pneumatic sensors) should be protected from or compensated for such changes.

7.2.5.2 Accessibility: Sensors should be positioned and located where they may be easily removed for testing or replacement.

7.2.6 Sensor Design:

7.2.6.1 Time Constant: The time constant is a critical parameter in sensor design and affects system performance and stability. Generally, if the time constant of the sensor can be made small compared to the time constant of the remainders of the control loop, the stability of the system will be improved.

7.2.6.2 Protection from Environment: Sensors must be designed to withstand high humidity, sand and dust, altitude, condensate or other environmental conditions. Duct sensors must also withstand impingement of foreign objects such as ice and sand.

7.2.6.3 Calibration and Stability: Sensor should be designed to maintain calibration and stability during its operating life. Calibration shifts should not occur when sensor is subjected to stresses applied as a result of mounting or installation. Consideration should be given to prevention of calibration shifts due to stresses outside of normal operating range.

7.2.6.4 Self-Heating: When resistance type sensors (resistance wire or thermistor) are used as one leg of a Wheatstone bridge, power is dissipated which causes a temperature rise or self-heating. Sensors with excessive self-heating become sensitive to fluid velocity which introduces an error in their sensed temperatures.

7.2.6.5 Thermal Lead or Lag Devices: Normally a sensor has thermal capacity and its output signal will lag the input. The introduction of this lag in addition to other lags in the control loop can cause system instability.

Anticipators or rate control devices can be added to the control loop to compensate for these lags and produce system stability. Care must be taken so that the time constant of these devices is not affected by such contaminants as dirt and tobacco tars.

7.2.6.6 Mounting Provisions: Sensors should be designed for installation with standard tools. Mounting should not be susceptible to resonant vibrations.

7.2.7 Cooling Effect Detectors:

7.2.7.1 Applications: In unoccupied compartments containing heat-generating equipment, consideration should be given to cooling effect detectors which are mounted usually in the inlet duct but sometimes in the outlet duct to the compartment and monitor the cooling air and measure its cooling capability. A cooling effect detector (CED) responds to the weight flow of the cooling air as well as its temperature. The CED will close a set of alarm contacts if the combination of flow and temperature is insufficient to cool the equipment properly (inadequate cooling). When the combination of flow and temperature is such as to provide adequate cooling, the alarm contacts open. CED's can be used with a valve and controller to decrease the air flow when the temperature is low and increase the flow when the temperature is high. Such systems can be used where the quantity of cooling air must be held to a minimum.

Design of a CED must consider prolonged operation at zero air flow, and in the case of detectors utilizing integral heating elements provision must be made to prevent damage from overheating.

7.2.7.2 Advantages: A thermal switch is sometimes mounted at a strategic point in the compartment to detect inadequate cooling. However, if, as is usual, the compartment contains several pieces of equipment, there is some question as to the proper location (or locations) for the thermal switch. Also, consideration must be given to the possibility that the specific piece of equipment monitored may not be "on" and thus the thermal switch would indicate adequate cooling even if this were not the case.

A thermal switch mounted in the outlet air duct could be set to alarm if the outlet air temperature exceeded a safe value. However, in case of a failure of the air supply, the thermal switch at the outlet would show a safe temperature even though the equipment in the compartment were overheating.

A CED overcomes these disadvantages by actually measuring the cooling capacity of the cooling air and can be used to close an alarm circuit if the cooling capability falls below the required value (inadequate cooling).

7.2.7.3 Theory of Operation: If the compartment is insulated, a heat balance equation can be written: $Q = C_p\, W\, (T2 - T_1)$

Q = Heat to be removed	$\frac{BTU}{min.}$
C_p = Specific heat of coolant	$\frac{BTU}{lb.\ deg\ F}$
W = Weight rate of flow of coolant	$\frac{lb.}{min.}$
T_1 = Coolant inlet temperature	deg F
T_2 = Coolant outlet temperature	deg F

With air as the coolant (C_p = .24), the heat balance equation can be rearranged:

$$\frac{W}{Q} = \frac{1}{.24\,(T_2 - T_1)}$$

This equation is plotted in Fig. 4. In a given application, Q is known. (A useful relationship here is that 1.0 watt is equal to 0.0569 BTU/min.) Also a value is assigned to T_2 which is the maximum safe temperature of the outlet air. With known values for Q and T_2, Fig. 4 establishes the required weight flow for a wide range of inlet temperatures. For proper cooling of electronic equipment, $T2$ is usually selected between 140 F - 160 F. T_1 will, with most aircraft cooling systems, vary between -65 F and 80 F and up to 120 F for ground operation.

A CED in the cooling air duct will distinguish between combinations of weight flow and inlet temperature which are above the curve or below the curve.

7.3 Actuating System : The actuating system converts the control signal into a force or motion. The actuating system's performance depends upon the inertia, friction, compliance, dead band, and saturation level of the actuator and its load. It also depends upon the characteristics of the power source available for driving the actuator. These factors must be specified to insure proper dynamic and steady-state performance and adequate stability margins.

7.3.1 Applications: The actuating system controls valves which, in turn, control air temperature and/or flow into or from an aircraft compartment. Auxiliary functions include actuating switches, sensors, and transducers used for monitoring, feedback and limiting.

7.3.2 Available Power: The actuating system's power source can be electric, fluid (pneumatic or hydraulic), mechanical, or hybrid combinations of these. Whatever the type, the power source characteristics must be specified. In addition to the nominal characteristics, the power specification must include high and low limits, capacity, regulation, transients and the permissable loading by the actuating system.

7.3.3 Motor: The actuating system's motor converts available power into force or motion as directed by the control signal. The motors may be electric, fluid (pneumatic or hydraulic), mechanical or a hybrid combination.

7.4 Control Amplifier Requirements: The control amplifier is the most important element in the temperature controller. It amplifies the normally low power output of the sensing device to a power level capable of driving the actuating system or heater. The amplifier output is nominally proportional to system error over the normal control range but is usually modified by anticipation and/or feedback.