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Aircraft Compartment Automatic Temperature Control Systems

RATIONALE

ARP89D has been reaffirmed to comply with the SAE five-year review policy.

TABLE OF CONTENTS

1. SCOPE 4

1.1 Purpose 4

2. REFERENCES 4

2.1 SAE Publications 4
2.2 ANSI Publications 4
2.3 Military Publications 5
2.4 FAA Publications 5
2.5 Other Publications 5
2.6 Terminology 5
2.7 Definitions 6

3. CONTROL SCHEMES 8

3.1 On/Off Control 8
3.2 Floating Control 9
3.2.1 Single Speed Floating Control 9
3.2.2 Proportional Speed Floating Control 9
3.2.3 Pulse Width Modulation Control 9
3.3 Proportional Control 10
3.4 Reset Control 10
3.5 Rate Control 10
3.6 Feedforward Control 11
3.7 Cascade Control 11
3.8 Adaptive Control 11
3.9 Decoupling Control 11
3.10 Optimal Control 11

TABLE OF CONTENTS (Continued)

4. DYNAMIC ANALYSIS 12

4.1 Graphical Methods 12
4.2 Computer Simulation 12
4.2.1 Digital Computer Simulation 13
4.2.2 Hybrid Computer Simulation 14

5. ACCURACY OF CONTROL 15

5.1 Static Accuracy 15
5.2 Dynamic Accuracy 16

6. SYSTEM DESIGN REQUIREMENTS 16

6.1 Environment 16
6.2 Function 17
6.3 Performance 20
6.4 System Complexity 20
6.5 Specification of Temperature Control Requirements 20
6.5.1 Temperature Selection 20
6.5.2 Stability 20
6.5.3 Transient Response 20
6.5.4 System Isolation 21
6.5.5 Overheat Protection 21
6.5.6 Manual Temperature Control 21
6.6 Temperature Sensing Requirements 21
6.6.1 Rate of Change of Temperature 21
6.6.2 Measurements Other Than Temperature 21
6.6.3 Types of Sensors 21
6.6.4 Sensor Location 22
6.6.5 Sensor Design 22
6.6.6 Mounting Provisions 23
6.7 Actuating System 23
6.7.1 Pneumatic Actuators 23
6.7.2 Electropneumatic Actuator 25
6.7.3 Electromechanical Actuators 25
6.8 Controllers 29
6.9 Special Requirements 31
6.9.1 High and Low Temperature Limits 31
6.9.2 Monitoring Instrumentation 32
6.9.3 Readability and Scale Markings 32
6.10 Regulations 32
6.10.1 Civil Regulations 32
6.10.2 Military Regulations 33

TABLE OF CONTENTS (Continued)

7. RELIABILITY AND MAINTAINABILITY 33

7.1 Reliability 34
7.1.1 Fail-Safe Provisions 34
7.1.2 Override Provisions 34
7.1.3 Warmup and Power Interruption 34
7.1.4 System Failure Analysis 34
7.2 Maintainability 35
7.2.1 Maintainability Review 35
7.2.2 Malfunction Detection 35
7.2.3 Troubleshooting Devices 35
7.2.4 Repairability and Overhaul 36

8. COMPATIBILITY WITH OTHER AIRCRAFT SYSTEMS 36

8.1 Compatibility With Compressors, Ice Prevention, and Pressure Controls 36
8.1.1 Air Compression 37
8.1.2 Pressure Controls 37
8.2 Electromagnetic Interference 37
8.3 Acceleration, Shock, Vibration, and Acoustical Noise 38
8.4 Overall Temperature Control System Size and Weight 38
8.5 Air Shutoff 38
8.6 Aircraft Performance and the Temperature Control System 38
8.6.1 Normal Operation 39
8.6.2 Abnormal Operation 39

9. TEST PROCEDURES 39

9.1 Component Tests 39
9.1.1 Breadboard/Brassboard Tests 39
9.1.2 Qualification Tests 39
9.2 System Tests 40
9.3 Flight Tests 40

FIGURE 1 Cabin Temperature Control System 18
FIGURE 2 Cabin Zone Temperature Control 19
FIGURE 3 Pneumatic Temperature Control System 24
FIGURE 4 Electropneumatic Temperature Control System 26
FIGURE 5 Electropneumatic Temperature Control System With Position Feedback 27

1. SCOPE:

The recommendations of this SAE Aerospace Recommended Practice (ARP) for aircraft compartment automatic temperature control systems are primarily intended to be applicable to occupied or unoccupied compartments of civil and military aircraft.

1.1 Purpose:

The purpose of this ARP is to outline the design considerations and criteria for automatic temperature control systems, for use as a guide in the aircraft industry. In most environmental control systems (ECS), temperature control is accomplished by an ECS controller; several of the control schemes discussed are based on these controllers. 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. REFERENCES:

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

2.1.1 ARP85 Air Conditioning Systems for Subsonic Airplanes

2.1.2 ARP147 Aircraft Air Conditioning Equipment Nomenclature

2.1.3 ARP292 Environmental Control Systems for Helicopters

2.1.4 ARP986 Guide for Qualification Testing of Aircraft Air Valves

2.1.5 AIR1168/6 Characteristics of Equipment Components, Equipment Cooling System Design, and Temperature Control System Design

2.1.6 AIR1823 ECS Transient Analysis Computer Program (EASY)

2.1.7 SAE Paper 820867 A Hybrid Facility for Simulation, Development of ECS Microprocessor Based Controls

2.2 ANSI Publications:

Available from American National Standards Institute, 11 West 42nd Street, New York, NY 10036-8002.

2.2.1 ANSI MC85.1M-1981 Terminology for Automatic Control, American National Standard, American Society of Mechanical Engineers

2.3 Military Publications:

Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

2.3.1 MIL-E-18927 Environmental Control Systems, Aircraft, General Requirements

2.3.2 MIL-E-87145 Environmental Control, Airborne, General Design Specification

2.3.3 MIL-STD-810 Environmental Test Methods and Engineering Guidelines

2.4 FAA Publications:

Available from Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC 20591.

2.4.1 Federal Aviation Regulations, Airworthiness Standards (Parts 23, 25, 27, and 29)

2.4.2 Federal Aviation Regulations, Part 121 Certification and Operations: Domestic, Flag and Supplemental Air Carriers and Commercial Operators of Large Aircraft

2.5 Other Publications:

2.5.1 Joint Airworthiness Requirements (Parts 23, 25, 27, and 29)

2.5.2 Air Transport Association of America, Airline Industry Standard: World Airlines Technical Operations Glossary (WATOG) - 8th Edition

2.5.3 Air Transport Association of America, Maintenance Steering Group (MSG-3)

2.5.4 ARINC 604, Guidance for Design and Use of Built In Test Equipment

2.5.5 RTCA/DO-160 Environmental Conditions and Test Procedures for Airborne Equipment

2.5.6 Federal Information Processing Standards (FIPS) PUB 101, Guideline for Life Cycle Validation, Verification and Testing of Computer Software, National Institute of Standards and Technology (NIST)

2.5.7 PB82-209172, A Survey of Software Validation, Verification and Testing Standards and Practices at Selected Sites, National Institute of Standards and Technology (NIST)

2.5.8 NATO Standardization Agreements (STANAG)

2.6 Terminology:

The terminology of ARP147 should be used where applicable. Further terminology may be found in ANSI MC85.1M-1981.

2.7 Definitions:

The following definitions apply to the special items related to automatic temperature controls as used in this document. In addition, the various control schemes are defined in Section 4.

ACCURACY: The degree to which the controlled temperature approaches the steady-state set point value. It is usually expressed as +/- a given amount.

ANALOG SYSTEM: A continuous time system. A system where all signals can change continuously with time.

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.

CLOSED LOOP CONTROL: A system where the control action is dependent on the output. The controller acts on a process in such a way to correct an error detected by direct measurement.

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

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.

CONTROL POINT: The actual value of the controlled temperature at which the system is controlling.

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.

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.

CORRECTIVE ACTION: Controller output which results in a change in controlled temperature in the direction of the control point.

CRITICAL DAMPING: Exponential convergence to stable, steady-state operation. When two roots of the system characteristic equation are real and identical, it is considered to have critical damping.

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

2.7 (Continued):

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 dead band, 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.

DIGITAL SYSTEM: A system where inputs and outputs of the system are discrete data time sequences.

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

ERROR: The difference between the reference or selected value and the actual or sensed value.

FEEDBACK: The property of a closed loop system which allows comparison of the output of a system to the input (reference) to allow for a control action to take place.

HYBRID: A combination of two or more integrated circuits (ICs) in one package. A combination of an analog and digital computer.

NEUTRAL ZONE: Same as dead band.

NULL: An error whose value is zero; in this situation, there is no input to the controller.

OPEN LOOP CONTROL: A system where the control action is independent of the output. A feedback control system which has been broken at some point in the signal path.

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.

PULSE BAND: That range of controlled variable over which the final control device is pulsed to take corrective action.

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.

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

RESPONSE: A quantitative expression of the output as a function of the input under conditions explicitly stated.

2.7 (Continued):

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; this is the typical definition of the time constant.

SAMPLED DATA SYSTEMS: A system that does not continuously update information, normally a digital/discrete system. In general, a sampled data system includes a data hold device, inserted directly following the system, to preclude high-frequency components inherent in the sampled signal from disrupting the controlled parameter or controller operation.

SENSING ELEMENT: A transducer which measures the value of a variable by providing an output that can be utilized by the controller.

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

SET POINT: That value of the controlled parameter to which the selecting device is adjusted, representing the desired value of controlled variable.

THRESHOLD: In a system or component, the smallest signal input capable of causing an output signal having desired characteristics.

TRANSFER FUNCTION: The mathematical expression relating the output to the input of a control system or component thereof.

3. CONTROL SCHEMES:

Various schemes are available for automatic control of temperature. Each scheme 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.

3.1 On/Off Control:

As its name implies, the final controlled device can assume only two output states as dictated by the controller output being either on or off; also known as a "bang-bang" control. Typically this is an analog controller.

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 (0.8 °C) to move the contacts from open to closed or vice-versa.

3.1 (Continued):

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. Control elements such as variable rate integrators and lead-lag networks can be used to minimize these overshoots.

3.2 Floating Control:

A control scheme in which the rate of change of signal to the actuator depends on the error.

3.2.1 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. The motor remains stationary when the sensed temperature is in the dead band of the controller. This will occur with 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 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.

3.2.2 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.

3.2.3 Pulse Width Modulation Control: A control scheme wherein the controller output is a series of pulses of variable duration. 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.

3.3 Proportional Control:

A control scheme in which the signal to the actuator is directly proportional to the difference between the measured variable and its setpoint. 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); i.e., the controlled temperature must depart from the set point in order to move the controlled device. Droop is a normal characteristic 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).

3.4 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.

3.5 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. Rate control is also known as derivative control.

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

3.6 Feedforward Control:

A control technique in which an anticipating correction signal is applied to input changes before the output is affected.

3.7 Cascade Control:

An automatic control system in which various control units are connected sequentially such that each control unit regulates operation of the next control unit in line.

3.8 Adaptive Control:

A control method in which one or more system parameters are identified on-line and used to vary the feedback control signals in order to satisfy the control performance criteria or to improve dynamic response of the closed-loop system.

3.9 Decoupling Control:

A control method which minimizes the control interactions among the control loops in a multi-input and multi-output system. As a result, the compensated multi-input and multi-output system behaves as if it is a family of independent, single-input and single-output control loops, each of which can be tuned by conventional feedback control techniques.

3.10 Optimal Control:

Optimal control denotes the class of control laws which will minimize the selected performance index. The index, which describes the system objectives to be achieved and the physical constraints of the process, is a function of the ECS process control and input variables. A common system objective is to minimize the ECS operating energy consumption, and is equivalent to minimizing bleed air and ram air usage as well as ECS component horsepower and electrical power input. Other possible objectives include the disturbance rejection ability of the controlled ECS against both bleed air pressure variations and rapid changes in the ECS operating environment. ECS transient response characteristics can also be used as an objective. Process variables may include temperature, pressure and flow.

Physical constraints may include process input supply and control temperature, flow, and pressure limits as well as individual component performance limitations, such as saturation. Examples of performance indices include:

a. Integral of the square of the error (ISE)
b. Integral of the absolute magnitude of the error (IAE)
c. Integral of the time multiplied by absolute error (ITAE)
d. Integral of the time multiplied by the squared error (ITSE)
e. Settling time
f. Overshoot magnitude

3.10 (Continued):

Many complex mathematical techniques are available to compute the optimal control laws. These include linear and nonlinear programming, stochastic programming based on the theory of probability, gradient optimization and optimal control theory. Extensive numerical computation is required to generate the solution for a specific problem. The most commonly known solution is the optimal regulator. It is derived using a branch of optimal control theory in which the ECS to be controlled is described by linear differential equations and the performance index to be minimized is the integral of a quadratic function of the ECS variables and control inputs (a generalized ISE for the multi-input and multi-output system). It is also known as the linear quadratic regulator (LQR).

4. DYNAMIC ANALYSIS:

Aircraft compartment temperature control system designs should be subjected to a thorough dynamic analysis to evaluate system stability and transient response characteristics. This is accomplished by using a mathematical model that defines the gains and dynamics of each significant element of the system. A detailed discussion of equipment gain, compartment gain, and a typical compartment transfer function is included in the temperature control system design section of AIR1168/6.

Dynamic analysis is usually accomplished using both graphical methods and computer simulations.

4.1 Graphical Methods:

Since temperature control systems, for the most part, involve the cascading of simple leads and lags, the direct graphical method of accomplishing gain multiplication is possible through the use of classical control theory such as Bode diagrams. 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. Graphical methods such as Bode diagrams, root locus, Nichols, and Nyquist plots can be found in texts on classical control theory.

4.2 Computer Simulation:

Analog computer simulation has been replaced by pure digital simulation and hybrid analog/digital simulation due to advancements in high speed digital computers. Also the increased use of microprocessor-based temperature control systems has favored digital simulation. Pure digital computer simulation provides a practical design and analysis tool using a high speed digital computer. Specialty hybrid computers allow real-time simulation capability as well as provisions for software verification. For complex temperature control systems, it is recommended that digital computer simulation be utilized during the initial design phase, followed by real-time simulation using a hybrid computer.

4.2.1 Digital Computer Simulation: Computation of gain and phase lag characteristics for a typical linear representation of a system can usually be accomplished using a generalized digital computer program for expedited analysis of the general dynamic behavior of the system. A detailed nonlinear digital simulation of the control and process is usually created for system performance evaluation, in addition to the linear analysis. The simulation covers most of the nonlinearities that are pertinent to the system stability and dynamic response. Nonlinearities such as friction in the valve/actuator, hysteresis or dead band between the valve position and the control signal, and nonlinear sensor responses are often represented in detail for a valid dynamic performance evaluation.

The advantage over analog or hybrid analog/digital simulation is that specialized computing equipment is not required. The program user can define a system by specifying the topology of a network of predefined component models. New concepts can be tried, control schemes investigated, and both transient and steady-state performance can be demonstrated faster and easier than by analog simulation or with breadboard or prototype hardware.

The dynamic simulation and analysis can be accomplished using tools such as the Environmental Control Analysis System (EASY) computer program described in AIR1823. The EASY program allows simulation and dynamic analysis of a temperature control system by use of standard, preprogrammed component subroutines within a program library. Standard components within the EASY library which could be used to simulate the cabin temperature control system include:

a. Transfer functions and generalized controls

   (1) First order lag
   (2) Lead-lag
   (3) Second order transfer function
   (4) Proportional plus integral (PI) controller with or without derivative feedback
   (5) Integrator with saturation

b. System controls

   (1) Cabin temperature control
   (2) Cabin thermal model
   (3) Temperature sensor

c. Ducting components

   (1) Duct
   (2) Inlet
   (3) Exit
   (4) Merge
   (5) Valve

4.2.1 (Continued):

d. Miscellaneous

(1) Switches
(2) Analytical function
(3) Function generator
(4) Arithmetic functions
(5) Saturation

The transfer function and generalized controllers are useful building blocks which can be used to model a control system. Generalized controllers such as PI and integral control with a feedback limiter are preprogrammed for easy usage. To give an accurate dynamic representation, a detailed model of a given controller should be constructed, but the more significant dynamic effects can be reproduced with the standard controllers. The standard cabin temperature control receives cabin and supply air temperatures as inputs, and outputs the mixing valve angle which controls the temperature of the supply air. Control features include integral control to achieve zero steady-state error and temperature anticipation to improve control dynamics. The cabin thermal model determines the overall energy balance for a cabin, including the effects of enthalpy inflow and outflow of air, heat generated by equipment and personnel, heat transfer through the cabin walls, and heat storage in the cabin air, equipment and walls. Temperature is detected by a thermostat, and its current is an input to the controller, the output of which positions the butterfly valve. The ducting components are used to model the inlet, supply, trim air, exit and valves in the system. The miscellaneous functions allow switching, generation of analytical functions with time, and modeling saturation to limit output from a controller to within prescribed values. For a more detailed discussion of the general features of the EASY program, the program capabilities, organization, limitations, sample problem, and access to the program, consult AIR1823.

4.2.2 Hybrid Computer Simulation: Simulation hardware, consisting of hybrid analog/digital computers have been developed to provide real-time simulation capability for microprocessor-based temperature control systems. In general, a mix of digital and analog elements are contained within a typical controller implementation or dynamic system simulator. Partitioning between digital and analog sections is mainly dependent upon the frequency spectrum of the event to be simulated. Rapid events, containing high frequencies, are implemented on wide bandwidth analog computers. Slower phenomena can easily be represented with a discrete simulation on a digital mini-computer. An important advantage of using a hybrid simulation is that after the system is simulated on the computer, the controller hardware can be connected to the computer simulation for software verification. The development of real-time simulation capability offers the following benefits:

a. The capability of systematic controller development
b. The capability of interfacing with hardware such as a microprocessor controller and actuator
c. Facilitates parametric studies for controller and system optimization

Additional information on hybrid computer simulation, the methodology for creating a dynamic simulation library, and an example of controller development and software validation is available in SAE Paper 820867.

5. ACCURACY OF CONTROL:

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 ±1.0 °F (±0.5 °C) 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 (±3 °C) and many times ±10 °F (±5.5 °C) 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.

Control system accuracy is determined by the following basic contributors to system error:

a. Initial manufacturing tolerances
b. Drift with time
c. System sensitivity
d. Type of control action
e. The adequacy of air distribution
f. Transient response

The system specification must include these basic terms:

a. Steady state accuracy
b. Damping (overshoot and time to return to within some limit for specific transient disturbances)
c. The location of the controlled variable (duct temperature, compartment temperature or exhaust temperature)
d. System input conditions and transfer function

The designer must decide at which location the temperature most accurately represents the effect on occupants 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 occupants.

5.1 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 ± 1 °F (21 °C ± 0.5 °C) for a 2 °F (1 °C) tolerance band).

5.1 (Continued):

The control system designer usually allocates the allowable tolerance to cover such things as:

a. Dead band
b. Drift (sensor and controller)
c. Set point calibration error
d. 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.

5.2 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 the same transient conditions, exceed the static error.

The following 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 to a supply temperature change).

a. Ratio of airflow to compartment volume
b. Duct and cooling pack time lags
c. Sensing time lags

The ratio of airflow to compartment volume 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. Duct and cooling package time lags contribute to the error except for changes in supply air condition. Sensing lags contribute to the dynamic error in all transient conditions. Valve stroke time always adds dynamic error, but must be limited for stability in many cases.

6. SYSTEM DESIGN REQUIREMENTS:

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 tests as outlined in Section 9.

6.1 Environment:

The components of the system should be designed for exposure to a range of environmental conditions including temperature, humidity, altitude, salt spray, fungus, sand and dust, ozone, explosive atmosphere, attitude, acceleration, vibration and shock as specified in the detail specification.

6.1 (Continued):

Consideration should be given to condensation and freezing of water in ducts and servo air lines, and contamination of components with tobacco tar.

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.

6.2 Function:

Systems of any degree of complexity can best be broken down into more manageable blocks by individual function. The specification using this approach to the system design results in a simpler design process, and is more in tune with digital control systems, where software configuration becomes a key factor. Functionally, a temperature control system may be composed of a combination of the following individual control loops:

a. Air Systems:

(1) Precooling of bleed air
(2) Flow control of ram air
(3) Turbine flow control
(4) Turbine anti-ice control
(5) Source selection/mixing control
(6) Recirculation mixing control
(7) Trim controls
(8) Individual zone temperature controls

b. Vapor Cycle Systems:

(1) Compressor inlet superheat control
(2) Compressor speed control
(3) Compressor surge control
(4) Evaporator flow/coolant temperature control
(5) Evaporator flow/air discharge temperature control
(6) Condenser sink temperature control
(7) Hot gas bypass control

Hybrid systems will include control loops from both of the above groups.

An example of a temperature control system is the individual zone control of a transport aircraft. This example is illustrated in Figure 1 (system arrangement) and Figure 2 (control block diagram). General temperature control requirements and recommendations for passenger compartments can be found in ARP85 for transport category airplanes and in ARP292 for commercial helicopters.

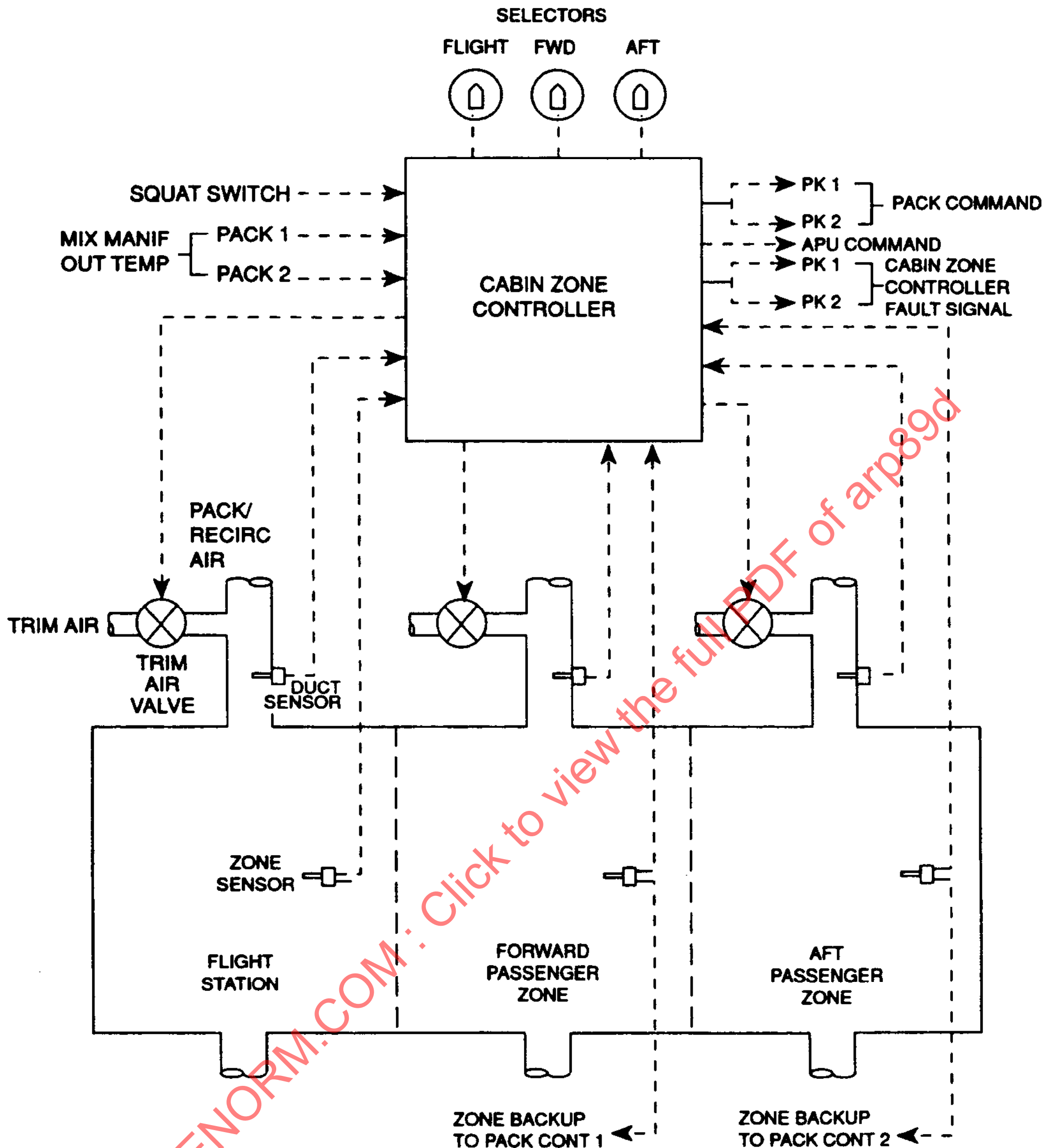

FIGURE 1 - Cabin Temperature Control System

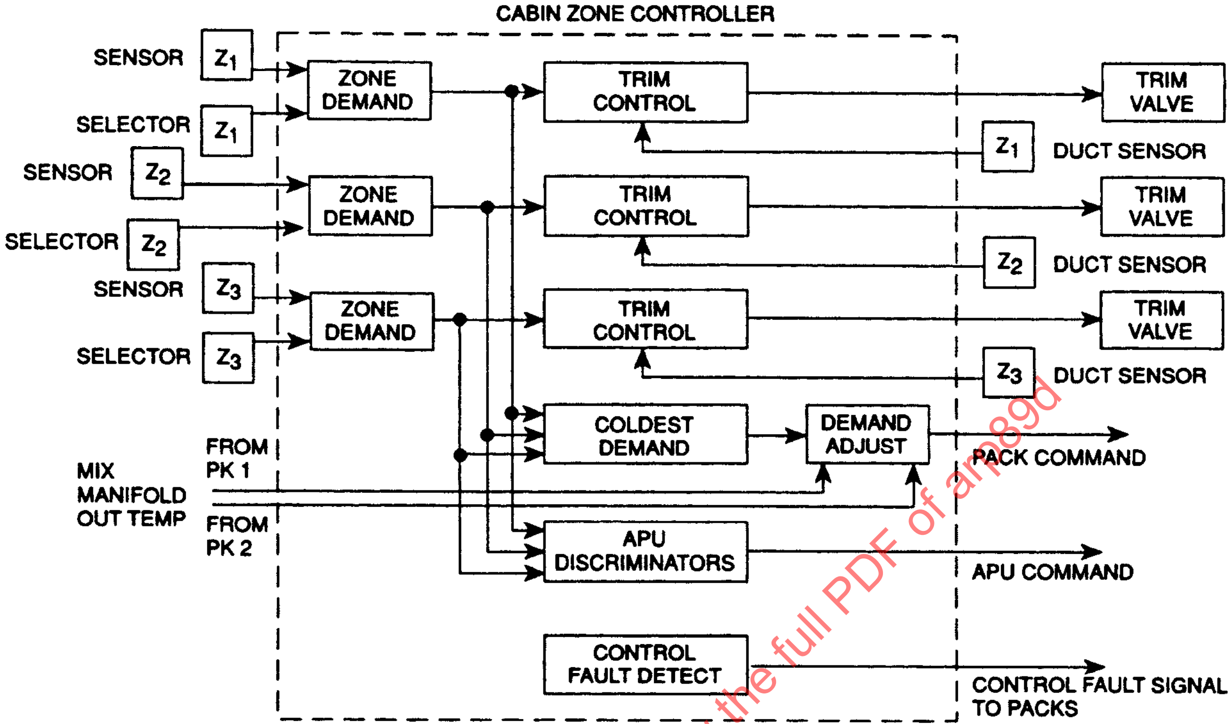

FIGURE 2 - Cabin Zone Temperature Control

6.3 Performance:

The design requirements should specify static operational performance (see 5.1) and dynamic behavior (see 5.2).

6.4 System Complexity:

The complexity should be the minimum required to meet the specified levels of control performance and complete functionality. A high degree of control system precision tends to increase complexity and cost.

6.5 Specification of Temperature Control Requirements:

The specification of temperature control requirements should include requirements for temperature selection, stability, transient response, system isolation, and overheat protection. The following requirements are applicable to cabin temperature control:

6.5.1 Temperature Selection: The system shall be capable of automatically controlling conditioned air temperature to the cabin zones during in-flight and ground operation in response to the temperature setting selected for each individual zone. Each electronic controller shall receive all zone duct temperature signals and automatically use the coldest of the zones for controlling air conditioning pack discharge temperature. Depending on how pack flows are mixed for distribution to cabin and flight station zones, the coldest zone may control one, two or all air conditioning pack discharge temperatures. This permits a dedicated pack to be used primarily for flight station supply.

6.5.2 Stability: Operation of all automatic controls will result in stable operation of the system, with no limit cycling allowed in any component system parameter.

6.5.3 Transient Response: With conditions changing at any possible rate over the full range of operating conditions, all elements of the system shall exhibit smooth response with minimal overshoots and low settling time.

Specifically, the following transient limits are typical recommendations during any normal operation.

Transient air temperature in any of any distribution ducts shall not exceed 180 °F (82 °C), and shall not exceed 165 °F (74 °C) for more than 10 s during one change in operating conditions.

When the cabin temperature selector is rotated to a new desired temperature setting (automatic mode), the cabin temperature control system shall operate to bring the temperature at the corresponding zone sensor to within 1 °F (0.5 °C) of the new setting within 5 min, unless limited by the capability of the air conditioning equipment. Overshooting shall be limited to a maximum of 1 °F (0.5 °C) or 10% of the change in cabin temperature required to reach the setting, whichever is greater.

6.5.4 System Isolation: The power supply for control of the automatic mode shall be independent and isolated when multiple air conditioning packs are used. A single failure in the cabin temperature control system shall not cause the loss of automatic temperature control in all zones for a cabin with multiple zones.

6.5.5 Overheat Protection: Overheat protection shall be provided which will result in automatically limiting the supply air temperature to 160 °F (71 °C). Closure of the hot air supply shall occur at 190 °F (88 °C) inlet temperature.

6.5.6 Manual Temperature Control: A manual temperature control override shall be provided to permit modulation of the hot air inlet into the cabin.

6.6 Temperature Sensing Requirements:

Temperature control systems require that compartment and/or duct temperatures be accurately measured to effect accurate compartment or duct temperature control, since sensor error is generally the major contributor to overall system inaccuracy. Compartment sensors may be located in flight decks, passenger compartments, cargo compartments, and electronic equipment bays. Duct temperature sensors may be mounted in ducts such as inlet and outlet ducts to compartments, downstream of heat exchangers, and in mixing ducts downstream of cooling turbines.

6.6.1 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.

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

6.6.3 Types of Sensors: The most commonly used temperature sensors for electronic (analog or digital) temperature control systems are the thermistor type for temperatures up to 250 °F (121 °C) and platinum wire coil type (RTDs) for temperatures above 250 °F (121 °C). Both of these sensor types provide a resistance change with temperature, and allow tailoring of the sensor time constant to fit the application. The thermistor is a high resistance negative coefficient sensor, while the RTD is a low resistance positive coefficient device. The resistance signals are used in a controller bridge circuit to obtain the temperature measurement. For accuracy, the RTDs use a 4-wire connection because of the low sensor resistance values to allow compensation for wiring resistance error; thermistors use a 2-wire connection since wire resistance is small compared to the resistance values of this type of sensor.

6.6.3 (Continued):

Pneumatic temperature sensors are used for pneumatic temperature control systems. One commonly used type is a bi-metal type in the form of a rod and tube, where the tube is in direct contact with the airflow. Expansion of the tube relative to the rod (usually Invar) varies the servo pressure proportional to the duct temperature. Silicon fluid filled sensors are also widely used in pneumatic temperature sensor applications. A capillary tube is filled with a silicon fluid. The expansion of the fluid displaces a bellows which varies sensor pressure. The capillary type tube maximizes sensed surface area with respect to fluid volume which minimizes response time; response times less than 5 s are achievable.

6.6.4 Sensor Location:

6.6.4.1 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.

6.6.4.2 Stratification: The temperature sensor should not be located too close to the outlet of a heat exchanger where the airflow is not properly mixed.

6.6.4.3 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.

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

6.6.4.5 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.

6.6.4.6 Accessibility: Sensors should be positioned and located where they may be easily removed for testing, replacement or cleaning; this is especially true for compartment sensors.

6.6.5 Sensor Design:

6.6.5.1 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 remainder of the control loop, the stability of the system will be improved.

6.6.5.2 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 or sand, and must withstand buffeting and vibration from airflow. Compartment sensors should be protected against airborne contamination by a cleanable grille.

6.6.5.3 Calibration and Stability: Sensors should be designed to maintain calibration and stability during their operating life. Calibration shifts should not occur when the 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.

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

6.6.5.5 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 contaminations as dirt and tobacco tars.

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

6.7 Actuating System:

The actuating system converts the control signal into a force or motion to position a valve. 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 available for driving the actuator.

The three types of valve actuators most commonly used for temperature control systems are pneumatic, electropneumatic and electric motor drives.

6.7.1 Pneumatic Actuators: A simplified schematic of a typical pneumatic actuation system in a temperature control system is shown in Figure 3. A regulated supply pressure is applied to an orifice restriction A_1. The variable A_2 restrictor represents a pneumatic temperature sensor. As the controlled temperature varies, the A_2 restrictor area increases or decreases as desired. The recovered pressure between the restrictions varies proportional to measured temperature. This pressure applied to the pneumatic actuator generates a force which opposes the actuator spring force. Motion of the actuator occurs until the pneumatic forces are in equilibrium with the spring force and the force reflected by the load. Pneumatic actuators are either diaphragm or piston type. Diaphragms offer the advantage of zero leakage and low friction for ambient temperatures below 300 °F (149 °C). Nomex fabric backed diaphragms with high temperature elastomers are frequently used. Diaphragm pistons may be free floated permitting self centering of the diaphragm or they may be mechanically guided. Conventional piston actuators are also used with various seal configurations. Teflon bridge seals are frequently employed with either metallic or elastomer energizers.

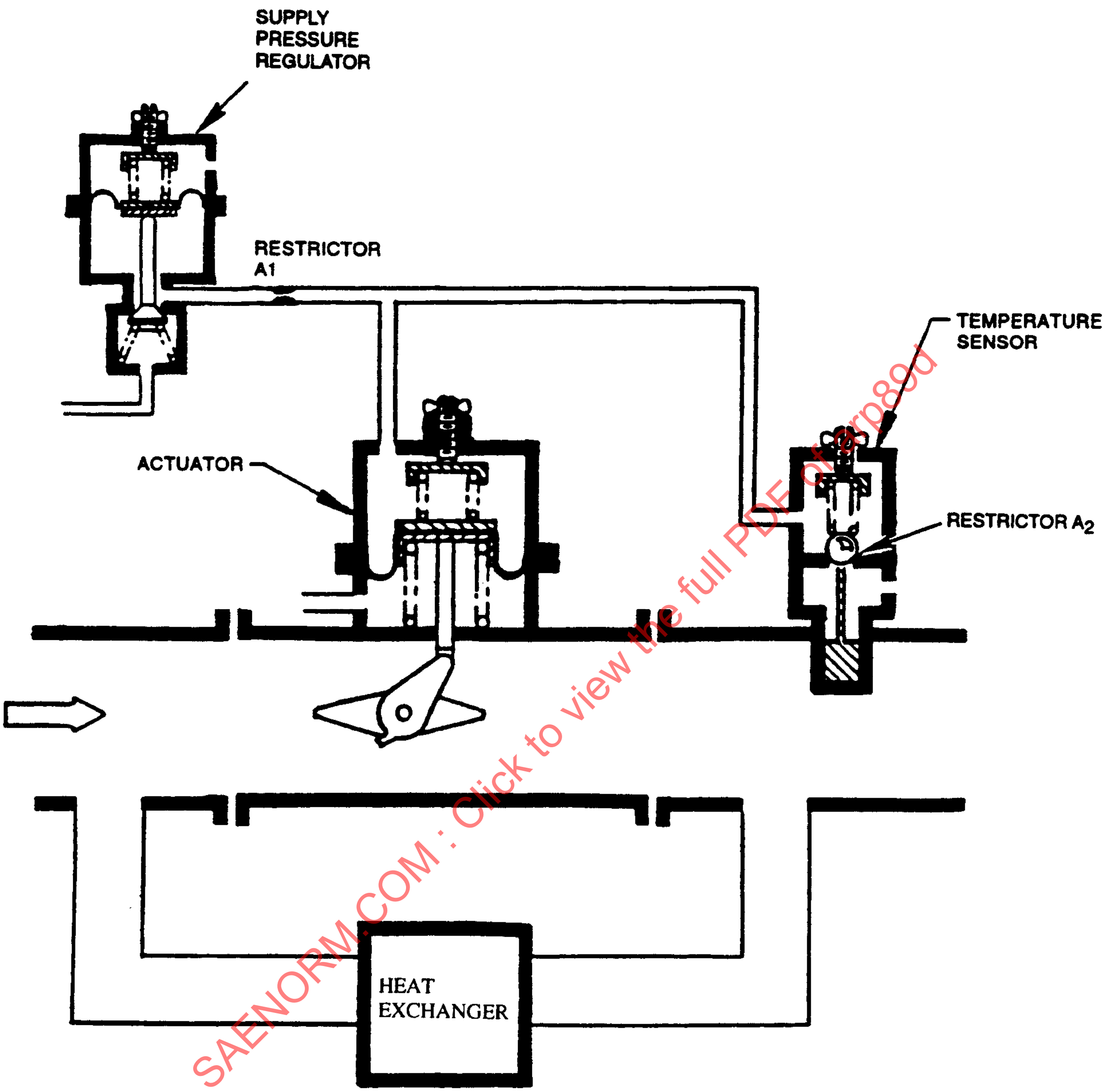

FIGURE 3 - Pneumatic Temperature Control System

6.7.2 Electropneumatic Actuator: Figure 4 shows a conventional torque motor actuated valve operating within an electropneumatic temperature control system. Temperature is sensed by a resistance type sensor. This signal is detected by an electronic controller and summed with a reference temperature. The resulting error signal appears at the output. The output signal is processed by a current amplifier to assure constant torque motor current independent of coil resistance. System dynamic compensation is accomplished within the controller.

As torque motor current increases, the torque motor flapper moves away from the regulated supply pressure nozzle toward the vent nozzle. The recovered pressure is supplied to the valve actuator. In general, torque motors of this type recover approximately 80% of the regulated supply pressure when the flapper is against the vent nozzle. Thus, a proportional relationship of actuator pressure versus torque motor current is established. Actuator pressure acting upon the actuator diaphragm produces a force which is reacted by the spring forces and valve aerodynamic forces moving the valve until the forces are in balance.

Valve friction or hysteresis can result in excessive temperature control system dead band or hysteresis. In a high gain system, valve friction can produce instability in a temperature control system. To prevent instability, valve position feedback is sometimes introduced. The schematic of Figure 5 is the same concept depicted in Figure 4 except that a direct mechanical method of valve position feedback has been added.

As the butterfly rotates clockwise, the position feedback spring force decreases. With a given torque motor current level, this decreased spring force causes the flapper beam to rotate away from the nozzle. This action causes the actuator pressure to decrease. Small butterfly position errors can produce substantial changes in actuator pressure through the position feedback loop. This high gain feedback path significantly reduces valve hysteresis.

Valve position feedback can also be implemented in the electronic controller by using a potentiometer or rotary variable transducer (RVT) on the actuator shaft to provide an electrical signal of valve position.

6.7.3 Electromechanical Actuators: The vast majority of electric actuators utilized to drive temperature control valves are of the rotary type. These actuators are configured with an electric motor, a speed reduction gear train, and usually other elements such as feedback devices and stroke limiting provisions. Other elements may include mechanical or electrical torque limiting and manual override capability. Feedback for control purposes and position indication utilize devices such as tachometers, RVTs, and potentiometers. Stroke limiting is usually accomplished by limit switches (mechanical or electronic), electronic control from feedback devices or mechanical stops.

The prime power conversion device in the actuator is the motor. The following types of electric motors or variations of them are commonly used to drive temperature control valves.

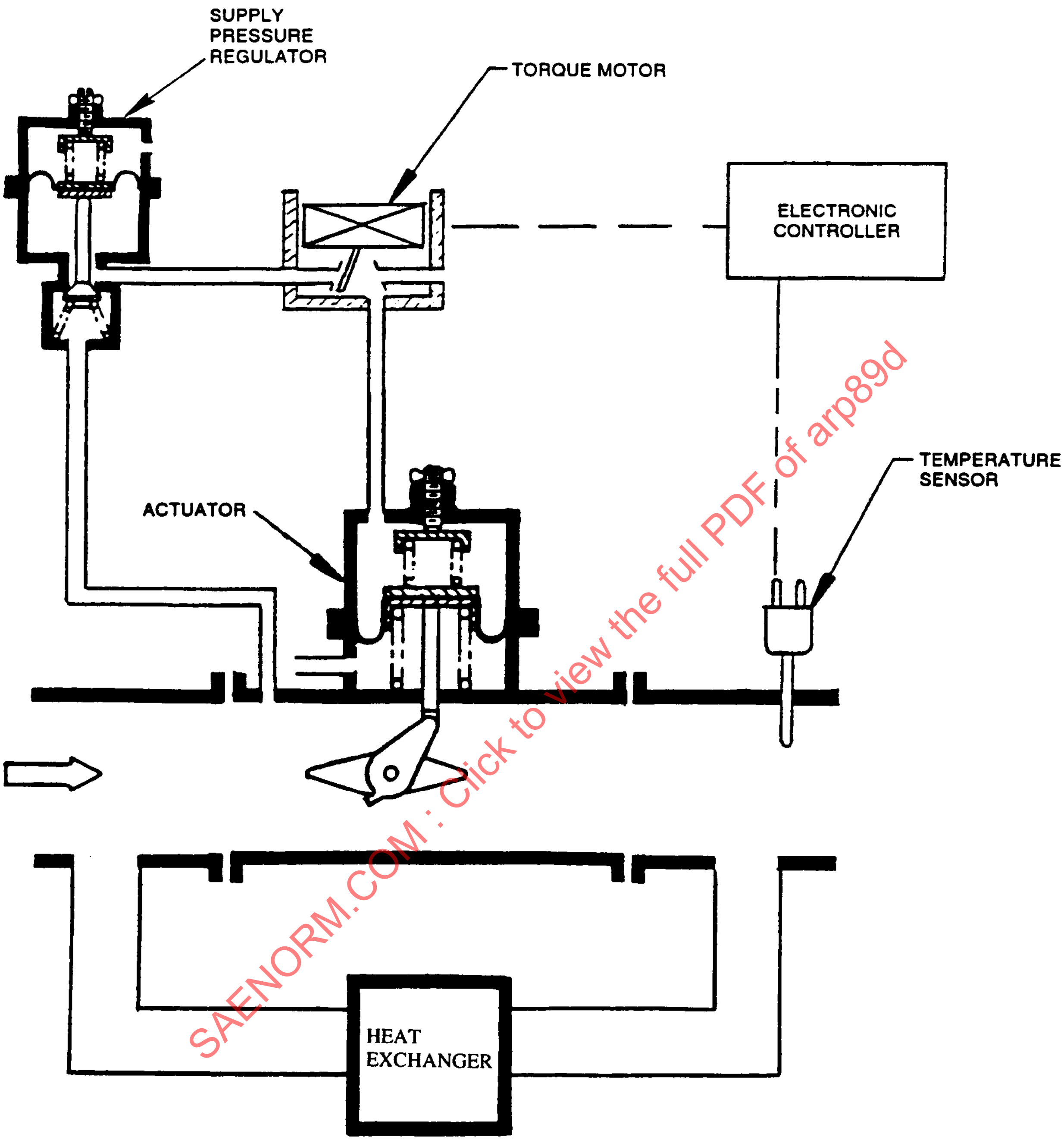

FIGURE 4 - Electropneumatic Temperature Control System

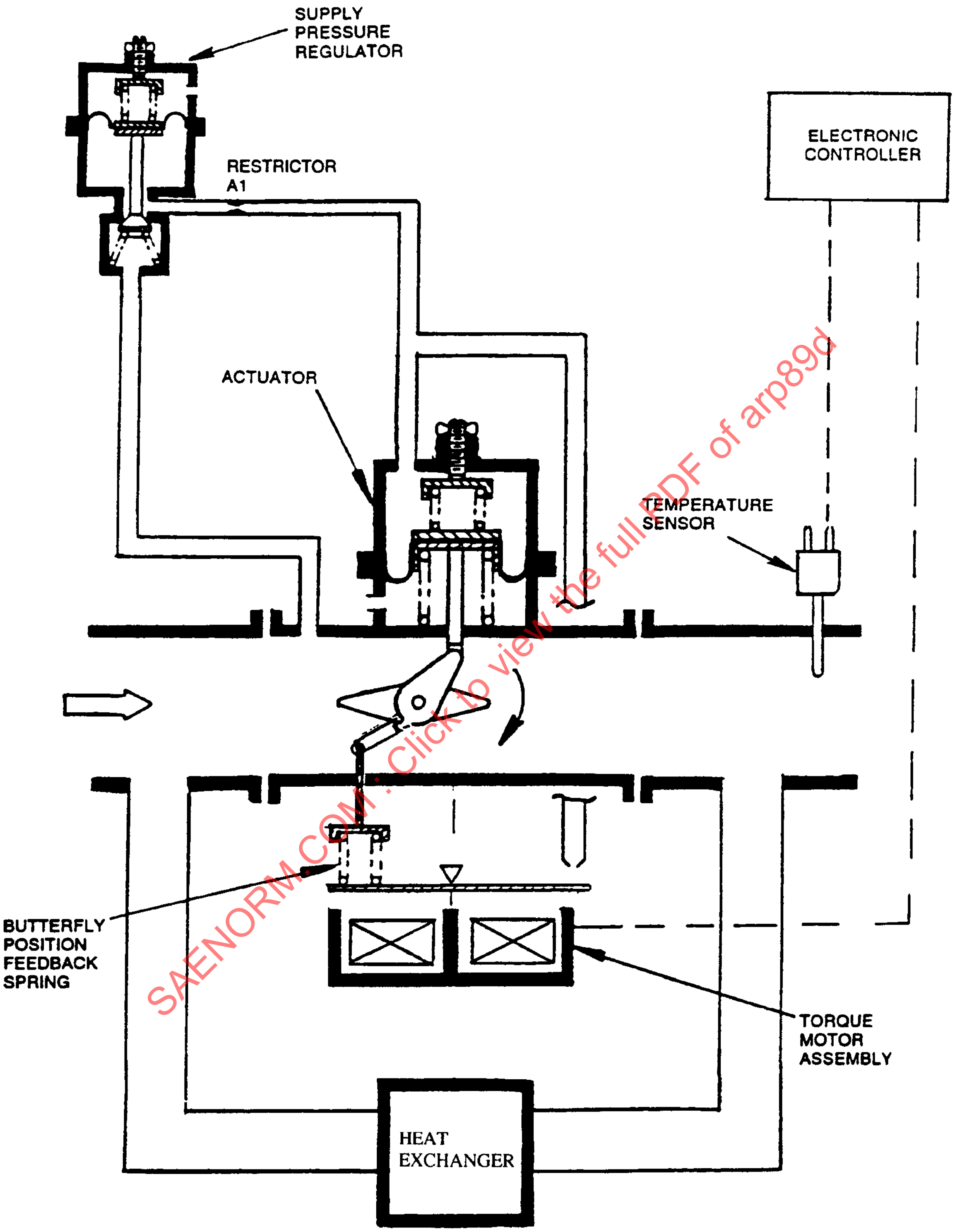

FIGURE 5 - Electropneumatic Temperature Control System with Position Feedback

6.7.3 (Continued):

a. AC servomotor
b. Brush type DC servomotor
c. Brushless DC servomotor
d. DC stepper motor

AC servomotors used for temperature control valves are basically induction motors modified to provide the necessary speed torque characteristic by careful design of rotor resistance. These motors are sometimes specified because of the availability of the aircraft's single phase 400 Hz AC power supply. The standard AC servomotor is a two-phase reversible induction motor incorporating two stator windings and a squirrel cage rotor. A capacitor connected between the windings converts the single phase power to two phase power in order to drive the AC induction motor. The motor direction of rotation is controlled by energizing either windings with the capacitor providing the required phase shift to the other windings.

Brush type DC servomotors utilized for valve actuators are separated into two families; wound field or permanent magnet. The wound field DC motors can be shunt, series, or compound wound. These motors have wound armatures as well as wound stator fields. The series wound motor has the armature and field connected in series. For bi-directional motion, split-series motors incorporating two field coils, oppositely connected are used. The series motor has high starting torque and a very nonlinear speed-torque relationship that complicates control regulation. The shunt wound motor has the field and armature connected to the power supply in parallel. As in the split series motor, the shunt motor can be configured in a split shunt mode for ease of bi-directional motion. The speed-torque curve characteristics offer better speed regulation than the series motor except at higher current levels where the torque drops dramatically. The compound motor has both series and shunt field windings. This motor has a powerful starting torque. The compound winding provides a relatively flat speed-torque curve providing fair regulation at the load point. Because of the complicated configuration of the windings rather complex circuits are required for bi-direction operation. In all of the wound field motors, non-linear characteristics are exhibited which require more complex feedback circuit elements to effectively provide good control. Heat dissipation is also a concern due to inefficiency coupled with low conduction and radiation characteristics.

The DC brush permanent magnet (PM) motor has a stator consisting of permanent magnets that require no electrical power be supplied to provide field energization. These motors exhibit a very linear speed-torque relationship over the entire range allowing for simple control circuits. The PM motor has high starting torque especially with the advent of the earth magnets now available. Demagnetization of the PM field is now almost non-existent due to the rare-earth fields. Simple circuitry can be utilized to provide control. Braking is easily accomplished by shorting the rotating armature after power has been removed. Also, static braking can be obtained through "slot lock" of the permanent magnet motor. The PM brush motor offers low cost, simple regulation, compact size and low total system weight for the servo application. Brush type DC motors require periodic maintenance or replacement because of wear of the brush and commutator; internal heat generation can also be a problem due to the poor conduction characteristics of the wound rotor.

6.7.3 (Continued):

Brushless DC (BLDC) motors offers the servo designer a motor with PM brush characteristics without the brush/commutator wear problems and permit better heat dissipation. These motors have permanent magnet rotors with wound fields. The brushes are replaced with electronic commutation by sensing rotor position through Hall effect devices, absolute encoders, resolvers, syncros and back EMF effects. The units produce greater torque to inertia ratio, less EMI, longer life, greater reliability and better thermal characteristics. The disadvantages include complexity, cost and a higher torque ripple, especially at low speeds, that is not prevalent in the brush PM motor.

Stepper motors are another brushless design utilized in temperature control valve actuators because of their simple construction and their compatibility with digitally controlled drivers. A stepper motor consists of a laminated steel stator with a series of field coils wound on the stator poles. The rotor is typically a permanent magnet with toothed iron end caps. Stepper motor actuators can be used in open loop mode or combined with position transducers in a conventional closed loop mode. Stepper motors require special driver circuits to translate a microprocessor output signal into high power signal coded appropriately for the motor. These driver circuits frequently contain acceleration and deceleration ramp compensation. In open loop, controllers initialize valve position at power-up, and counting circuits track valve position by counting steps. The technique is reliable as long as stepping rate is carefully controlled. Stepper motors running in the open-loop mode must be sufficiently derated for operation in high performance systems with variable loading conditions. Steppers have the added characteristic of failing in the last position unless the valve load is sufficient to overcome the magnet detent torque of the actuator. Stepping motor actuators are either variable reluctance, permanent magnet or hybrid type. The hybrid type is the most costly actuator but generally provides higher torque capacity, better step accuracy and excellent speed capability.

Overall, there are many choices available to the designer for motors to power the temperature control valve. Each type has certain advantages depending on the application considerations such as speed-torque requirements, load predictability, duty cycle, control needs, environmental conditions, cost, reliability, system compatibility and service life.

6.8 Controllers:

Pneumatic controls and analog or digital electronic controllers are used in temperature control systems to provide the control functions and regulate the pneumatic or electrical power required to modulate the temperature control valve in response to the temperature sensor signal.

Pneumatic controls are generally part of the actuator and temperature sensor assemblies, and function by modulating orifices in a pneumatic circuit to control servo pressure to the actuator. The characteristics vary over a wide range depending on the detailed input configuration and output power requirements. The pneumatic controls/valve actuator can be configured to provide either proportional or integral control. Fluidic devices form a special class of pneumatic controls, performing an amplifying function by using dynamic effects of moving fluid.

6.8 (Continued):

Electronic controllers are used for electropneumatic and electric motor actuators. In electropneumatic systems, the electronic controller provides the control logic and drives the torque motor, which in turn regulates the servopressure used to power the pneumatic actuator. In electric motor systems, the electronic controller provides the control logic and regulates the electrical power required to drive the electric motor actuator.

Analog electronic controllers are based on operational amplifiers. The operational amplifier is a solid-state integrated circuit having good stability and high immunity to oscillation, generally achieved by using a large amount of negative feedback. These operational amplifiers are used to perform analog control functions such as summing, integration and dynamic compensation, and to amplify low level transducer signals for either monitoring or control functions.

Digital electronic controllers are usually based on a microprocessor. The microprocessor is a solid-state, large scale integrated circuit which contains the arithmetic and logic functions of a digital computer. The sequence of operations can be programmed to perform calculations or logic functions required for complex control functions, schedule, dynamic compensation and built-in-test. It is the central control element within a digital controller and usually requires peripheral integrated circuits, such as memory and input/output interface devices to perform the temperature control function.

Several types of compensating techniques are used to alter the output of the pneumatic or electronic controller to achieve specific control characteristics. Feedback signals can be processed to obtain proportional, integral and derivative (PID) functions. Anticipator sensors can be used to vary the actuating system response as a result of the magnitude of a transient in the supply duct or ambient temperature, and feedback devices can be used to change the controller output as a result of rate of change of some controlled variable such as actuator system speed. In microprocessor based controls, dynamic compensation is implemented as part of the software program. Feedback and anticipation may have either a positive or negative effect on system response, depending on which is needed to meet system requirements. A system dynamic analysis, as discussed in Section 4, should be used to determine the correct combination of anticipation and feedback necessary for stable system operation.

While pneumatic controllers and analog electronic controllers are still in wide use for temperature control applications, the digital electronic controller has become the preferred means of temperature control because of its ability to perform complex algorithms, built-in-test capability, and ability to communicate with other aircraft systems via a data bus. Many current pneumatic systems utilize a digital computer to provide the same monitoring and built-in-test functions available with the electronic controller. The typical functions of a digital temperature controller consist of:

a. Control

(1) Data acquisition (digital data bus and analog inputs)
(2) Control laws
(3) Reconfiguration (alternate source, alternate control, synthesis, fail safe and transfer)

6.8 (Continued):

b. Built-In-Test

(1) Self-test (microprocessor, memory, inputs and outputs)
(2) Subsystem test (system LRUs such as valves, actuators, sensors, and digital buses)
(3) System monitoring (performance, signal correlation, rate of use, rate of change)

c. Maintenance Support

(1) Fault isolation (LRU)
(2) Installation checks (initiation checks, actuator commands, wire continuity, built-in-test)
(3) Fault history (occurrences, details, available on request)

The following design considerations may be applied to digital electronic controllers.

The analog sensor signals after amplification may either be passed straight to an analog-to-digital convertor or first multiplexed with other signals. The multiplexing rate is determined by control loop bandwidth requirements and is usually between 5 and 10 times the band cutoff frequency of the closed control loop.

Digital conversion time is not a driving influence in slowly responding thermal systems and, hence, the less costly, slower conversion techniques can be used in most cases.

The functional breakdown of the system (6.2) is a good basis for driving the control block diagrams, and these, in turn, can be used to generate modular control, protection and built-in-test software. Software in this form presents fewer configuration problems and is of a higher quality.

The choice of software language is dependent on its operational requirement, the host microprocessor selected, and the availability of development and production tools such as compilers.

Microprocessor selection is driven by the speed and complexity required and could range from a highly numerical microprocessor to a microcontroller with integral converters, memory and other functional features.

6.9 Special Requirements:

6.9.1 High and Low Temperature Limits: The particular system application and design will define the temperature limitations. General consideration should be given to the following.

6.9.1 (Continued):

Passenger aircraft cabins should be controllable at any point within the range of 65 to 85 °F (18 to 29 °C). Special purpose aircraft, i.e., cargo convertible, etc. may require temperature controllability below 65 °F (18 °C).

The inlet air temperature to the cabin should be in the range of 35 to 160 °F (1.5 to 71 °C). Some military cargo aircraft may require higher compartment inlet air temperatures.

Maximum duct temperature downstream of contamination producing components should be kept below the level at which these contaminants vaporize (oil fumes, smoke).

The minimum duct temperature should be controlled to prevent formation of ice.

6.9.2 Monitoring Instrumentation: Consideration should be given to instrumentation that will allow monitoring of system operation to permit:

a. Troubleshooting both in flight and on the ground
b. Observation of critical parameters to allow operation in manual override mode
c. Observation of programmers, valves, and similar units with external position indicators
d. Monitoring instrumentation should be isolated from the temperature control system so as to prevent secondary failure resulting from instrumentation malfunction.

6.9.3 Readability and Scale Markings: Readability and scale markings must be consistent with the design requirements of the particular instrument or indicator. Cabin temperature indicators should be calibrated in one degree increments and should be easily read at normal instrument panel distances for the particular aircraft.

6.10 Regulations:

The design of the temperature control equipment shall comply with airworthiness requirements, the scope of which would be defined in the airplane specification. Design will also be regulated by the airplane specification. In the event of conflict, airworthiness requirements will prevail.

6.10.1 Civil Regulations: Regulatory bodies include the (FAA) and the European Joint Aviation Authority (JAA). The FAA regulates the design of transport category airplanes in FAR Part 25. The JAA regulates design in JAR Part 25, which represents the combined requirements of the airworthiness authorities of the participating European nations. The FAR Part 25 and JAR Part 25 applicable requirements include the following paragraphs:

a. 25.561 General
b. 25.831 Ventilation
c. 25.833 Heating Systems