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NEW CONTROL DESIGN PRINCIPLES BASED ON MEASURED
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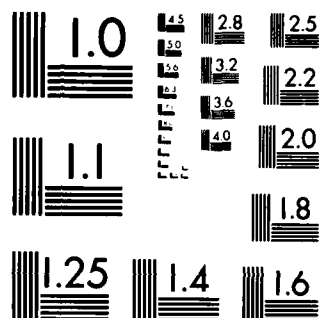
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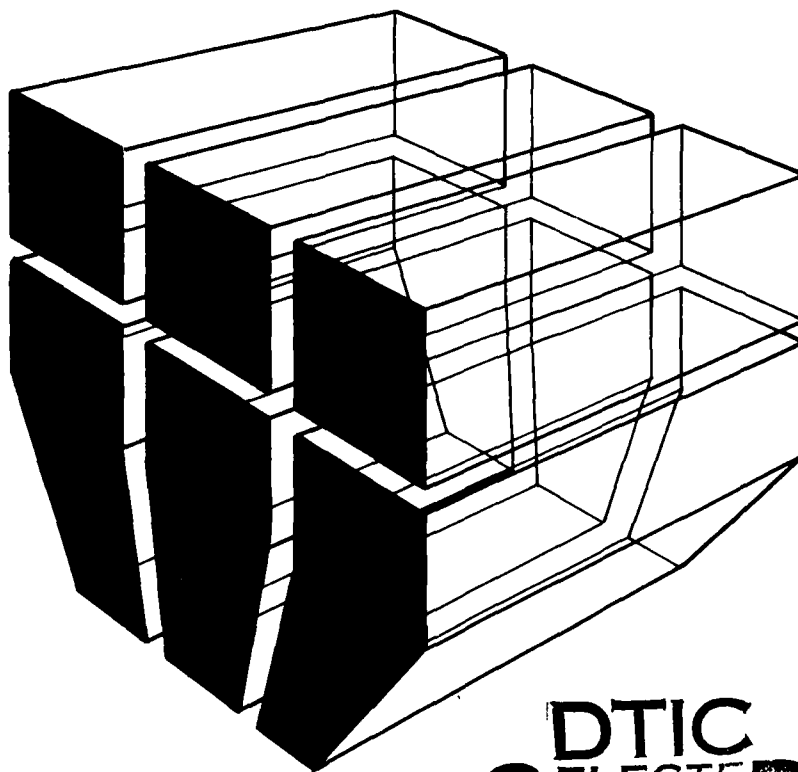
January 1985

Retrofit Control Systems for Energy Conservation

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NEW CONTROL DESIGN PRINCIPLES BASED ON MEASURED
PERFORMANCE AND ENERGY ANALYSIS OF HVAC SYSTEMS

by
Douglas C. Hittle
David L. Johnson



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The evaluation of currently used controls showed that pneumatic temperature control equipment requires a very clean source of supply air and is also not very accurate. Pneumatic, rather than electronic, actuators should be used because they are cheaper and require less maintenance. Thermistor temperature detectors should not be used for HVAC applications because they require frequent calibration. It was found that enthalpy economy cycles cannot be used for control because the humidity sensors required for their use are prone to rapid drift, inaccurate, and hard to calibrate in the field.

Performance of control systems greatly affects HVAC operating costs. Significant savings can be achieved if proportional-plus-integral control schemes are used.

Use of the retrofit prototype control panel developed in this study on variable-air-volume systems should provide significant energy cost savings, improve comfort and reliability, and reduce maintenance costs. It is recommended that this retrofit system be installed in field applications to verify its accuracy and reliability and to determine if design improvements are needed.

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FOREWORD

This research was conducted at the U.S. Army Construction Engineering Research Laboratory (USA-CERL) with funds provided by the Department of the Army (Office of the Assistant Chief of Engineers [ACE]) and the Department of Energy (DOE). The Army portion of the funding came from Project 4A162781AT45, "Basic Research in Military Construction"; Task B, "Energy Systems"; Work Unit 002, "Retrofit Control Systems for Energy Conservation." The DOE funding was obtained under a Letter of Agreement dated September 1983. Dr. Douglas C. Hittle and Dr. David L. Johnson of USA-CERL's Energy Systems (ES) Division were the Principal Investigators. Mr. B. Wasserman, DAEN-ZCF-U, was the ACE Technical Monitor. Mr. R. G. Donaghy is Chief of USA-CERL-ES.

COL Paul J. Theuer is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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NEW CONTROL DESIGN PRINCIPLES BASED ON MEASURED PERFORMANCE AND ENERGY ANALYSIS OF HVAC SYSTEMS

1 INTRODUCTION

Background

Heating and cooling buildings accounts for a large portion of the Army's energy expenditures. Therefore, recent goals have been to improve or devise systems that will make both new construction and present buildings as energy-conservative as possible. Field and laboratory research conducted by the U.S. Army Construction Engineering Research Laboratory (USA-CERL) has indicated that problems with heating, ventilating, and air-conditioning (HVAC) controls are severe and that these problems are causing a great deal of energy to be wasted.

One study evaluated the performance of solar energy systems applied to a variety of Army buildings. While many problems were associated with this new technology, one of the most pervasive was control system failure, especially when control systems were complex. As a result, the solar energy systems failed to save energy because conventional heating, ventilating, and air-conditioning (HVAC) control components were imprecise and unreliable.

In another project, USA-CERL built a full-scale HVAC system and incorporated precision sensors for performance measurements. Although the purpose of the HVAC system test was to measure the energy performance of the system and its components, the measurements revealed that some control components performed poorly. Despite visits from the manufacturers' engineers, the control components continued to perform far below the expected level. In fact, the test revealed that the set points maintained by the controls would gradually change from the original value and eventually move the controlled device (modulating values of air dampers) to a maximum or minimum position. As a result, the system was operating "out of control" and consuming more energy than needed to heat or cool the building. Although the controls were recalibrated by USA-CERL and the manufacturers' servicemen, they continued to drift out of calibration.

Since the controls in the test facility were specified and installed similarly to those in Army buildings, and since the brand and model of the components were known to have been widely used across the country, the laboratory results indicated that many HVAC systems in Army buildings may be consuming excessive amounts of energy.

Information obtained from engineers in the field has also indicated that controls are a major problem at Army installations. The publication of the experimental results in the ASHRAE Journal¹ attracted nationwide attention;

¹D. C. Hittle, et al., "Theory Meets Practice in a Full-Scale Heating, Ventilating, and Air-Conditioning Laboratory," ASHRAE Journal (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, November 1982).

many engineers from both the Army and the private sector contacted USA-CERL to indicate their negative experiences with many HVAC control systems.

USA-CERL next focused on identifying the causes of the HVAC control problems, beginning with an analysis of current design practice. Designers frequently specify control components, but give only general descriptions of the functions they will provide. The specifications do not give quantitative performance requirements for control components or systems. Designers have also devised complex control strategies for heating and cooling systems with the intent of minimizing energy consumption. Sales engineers from control companies often provide details of the control system design. Their goal is to provide a system at the lowest first cost in order to be competitive. Often, however, the limited performance of those components makes implementation of the designed complex control strategies unsuccessful.

These systems are maintenance-intensive, and groups responsible for building operations often do not have the skilled manpower needed to make them perform as designed. Since detailed, system-specific maintenance instructions are rarely required or provided during design and construction of buildings, maintenance burdens become particularly onerous. Also, the diagnostic equipment (i.e., gauges, meters, etc.) needed by maintenance staff to identify equipment and system failures is often either not provided or is malfunctioning.

Control system malfunctions which lead to energy inefficiency usually go undetected. Conversely, malfunctions which lead to occupant discomfort require action from the maintenance staff. A common response is to disconnect much of the equipment designed to improve system efficiency and to simplify the system by reconfiguring it to perform basic heating and cooling functions more reliably. For example, field personnel often disconnect enthalpy-based economy-cycle controls within 6 months of start-up, either because they have failed completely or because they require frequent and difficult calibration.

Many HVAC control systems are too complex, unreliable, energy-inefficient, difficult to maintain, and poorly documented. What is needed are simple, reliable, maintainable, energy-efficient control systems which can be easily and economically retrofitted to existing HVAC systems.

Objective of Overall Study

The objective of the overall research is to develop HVAC control systems, especially systems for retrofit applications, that are simple, efficient, reliable, maintainable, and well-documented.

The research will be done in three main areas: (1) component evaluation, (2) control loop implementation, and (3) system applications.

Laboratory and field studies to evaluate HVAC control components will focus on identifying a level of performance that can be expected from "typical" HVAC control equipment in use today. Control equipment most commonly used in process industries will be evaluated to determine its applicability to HVAC control problems.

Control components are combined to provide individual HVAC system control loops (for example, the control of the discharge temperature from a cooling or heating coil). Several subsystem control loops are being studied to determine the best way to achieve accurate control for applications where accuracy is needed. HVAC control systems consist of individual components connected in semi-independent individual control loops to provide the overall system control. The system applications research emphasizes an investigation of the overall performance of heating and air-conditioning systems. Specifically USA-CERL is studying the cost/benefit of various HVAC control retrofit schemes and the dynamics of combining various individual control loops.

To provide reliable, effective control systems, the results of component evaluation and control implementation studies must be combined to develop system application guidance.

Objective of This Phase of Work

The objective of the phase of work reported here was to identify the major problems associated with current HVAC control systems and to develop a retrofit control system applicable to military buildings that will allow easy identification of component failures, facilitate repair, and minimize system failures. A secondary objective was to summarize how this research should influence the design and installation of HVAC control systems.

Approach

Systems currently used as HVAC controls were evaluated in terms of their advantages and disadvantages (Chapters 2, 3, and 4). The effects of the various control systems were then analyzed in terms of their operating costs (Chapter 5). Using the information obtained from these studies, a prototype retrofit control panel and system was developed that would provide the benefits associated with an ideal control system, especially accuracy and reliability (Chapter 6). Applications for this system were determined and the benefits which it could provide outlined (Chapter 7).

Mode of Technology Transfer

The information in this report will be disseminated to DEH organizations through an Engineer Technical Letter to be prepared separately. Dissemination to Divisions and Districts will be through an EIRS Bulletin. The information provided in the overall study will be incorporated into a Technical Manual and Guide Specifications to be prepared on HVAC controls.

2 PNEUMATIC CONTROLS

Pneumatic controls have been used in most military building HVAC applications. Besides being inherently modulating, pneumatic valve and damper actuators are inexpensive and reliable compared to the electric motors and gears required to produce the same control force. Also, designers and maintenance personnel are familiar with pneumatic controls and therefore tend to keep using them.

However, pneumatics have some disadvantages. First, most pneumatic control manufacturers insist on a very clean source of supply air, which must usually be dry and free of oil. While it is not difficult to install a system with "clean air," one mistake, such as overfilling the compressor with oil or failure of a compressor piston ring, can permanently foul the entire system. Another potential disadvantage of pneumatic controls is that they are not particularly precise, as shown by tests for temperature transmitters and receiver/controllers.

Temperature Transmitters

Temperature transmitters are used as sensors in many control loop applications, especially for control of heating and cooling coils and mixed-air dampers on fan systems. Several temperature transmitters were tested to determine the degree to which the measured output pressure conformed to the manufacturer's stated pressure/temperature curve. The tests were carried out over the operating range of the transmitters. The testing apparatus consisted of a thermo-electrically cooled and heated box (a camping cooler designed to keep food hot or cold when powered from an automobile cigarette lighter); a controlled current supply to allow the temperature in the box to be lowered or raised; a small muffin fan to circulate air inside the box; a compressed air supply which was connected to the pneumatic temperature transmitters through a restrictor; a mercury manometer to measure transmitter output pressure; and a standard platinum temperature sensor connected to a precision digital multimeter for measuring the temperature inside the box.

The temperature inside the box was gradually raised and lowered over the operating range of the transmitters; this allowed equilibrium to be reached at many different temperatures. Once equilibrium was reached, the temperature inside the box and the output pressure of each transmitter was measured and recorded. Up to three temperature transmitters could be tested at one time.

Figure 1 shows the results for five of the six temperature transmitters of the various brands tested; the sixth transmitter had a 2-psig output, regardless of temperature. The solid line in Figure 1 is the manufacturer's specified pressure/temperature relationship. The plotted points are the measured results, and the two parallel dashed lines on either side of the line encompass all the data points. The results indicate that the error in output pressure from the temperature transmitters tested is equivalent to roughly $\pm 4^{\circ}\text{F}$ ($\pm 2^{\circ}\text{C}$).

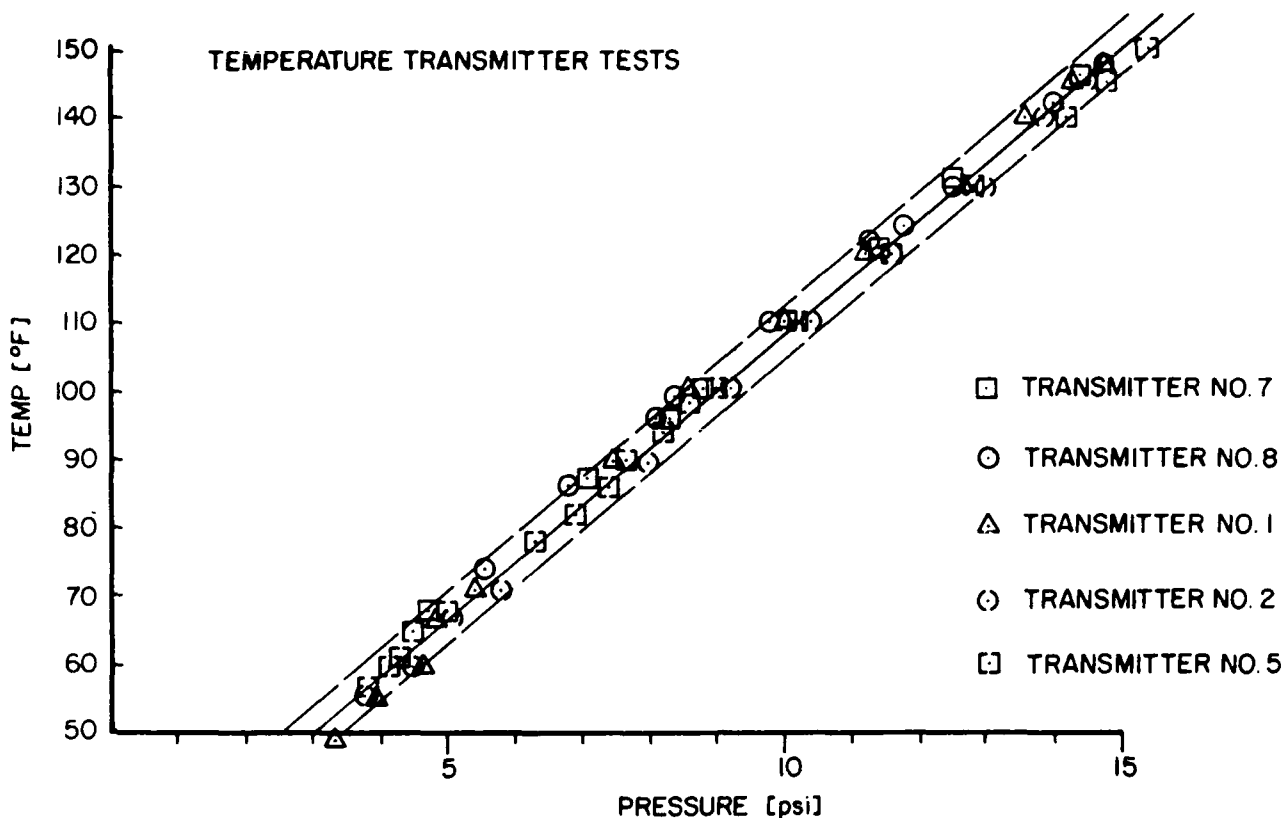


Figure 1. Pneumatic temperature transmitter test results.

While even a single-point field calibration adjustment or corresponding set-point adjustment would improve accuracy, field calibration is difficult and requires accurate instruments like those used in the test. Accurate field calibration is probably infrequent.

Receiver/Controllers

Many pneumatic control loops also contain so-called receiver/controllers. These devices accept an input signal from a temperature transmitter or other device, compare it to a local or remotely adjustable set point, and provide an output pressure to the control device. The output pressure is proportional to the difference between the set-point signal and the sensed value (the error). For example, a temperature transmitter would be connected to a receiver/controller with an adjustable set point; the output from the receiver/controller would control a chilled water valve in a cold-deck control application. Since these components must also perform accurately if control is to be accurate, tests were made to determine if these components were likely to introduce more errors into the control systems.

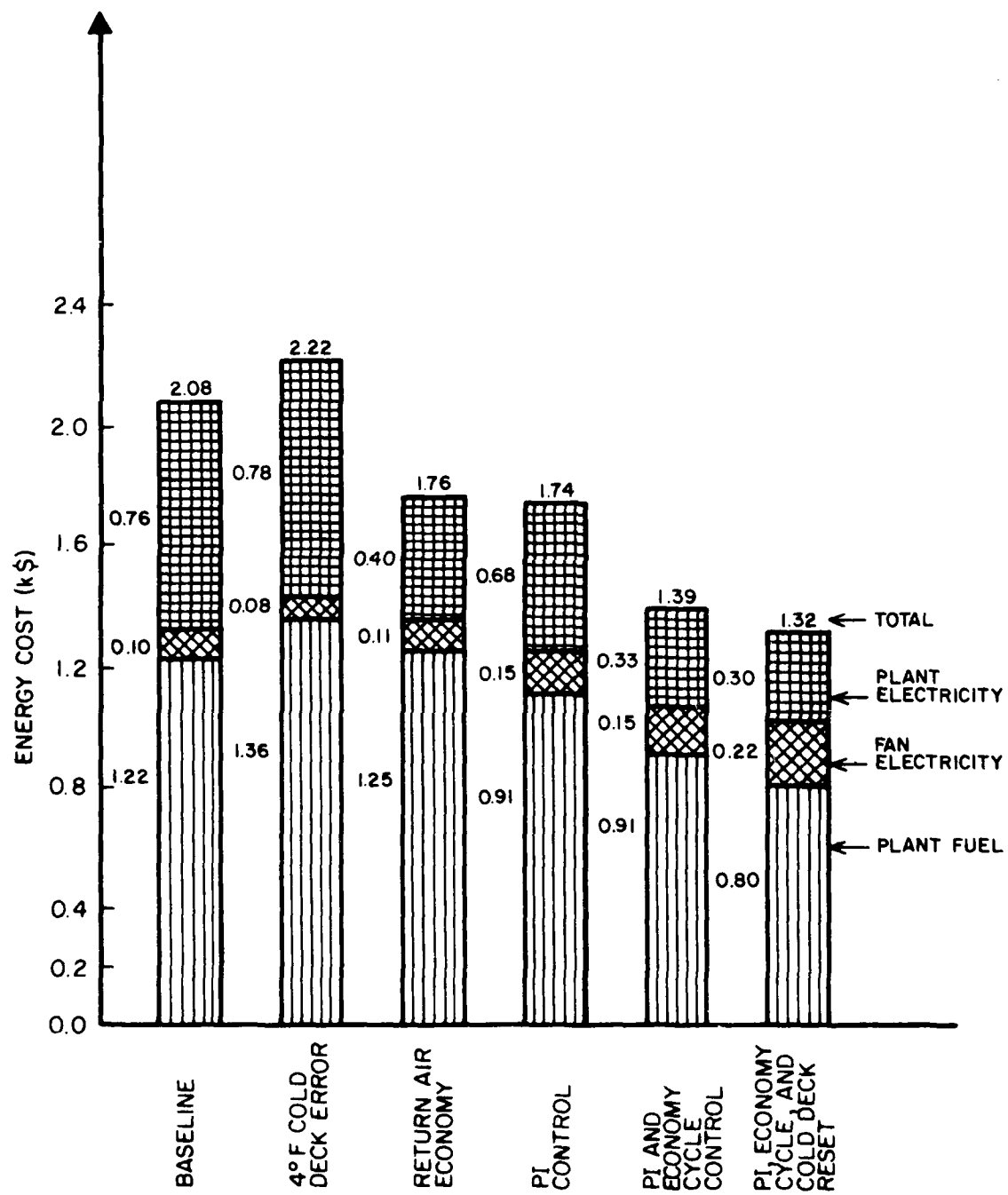


Figure 6. VAV system energy cost for various control options.

as small as the dental clinic studied may be about 5 years. Moreover, there are other advantages, such as reduced maintenance and easier trouble-shooting, which can result from using carefully designed retrofit control panels (Chapter 6).

fraction is of the same order of magnitude as the savings achievable by adding an economy cycle. The use of PI control instead of proportional-only control provides savings over the baseline case of about 20 percent. This is more than the savings achievable with an economy cycle that does not use PI control. Using PI control for both the cooling coil and the economy cycle produces more than a 20 percent savings over the same system with proportional-only control. The system using PI control for both the coil and dampers cold-deck reset is the most efficient. However, it also greatly increases the complexity of the control systems, since room temperature measurements must be made for each zone, with the highest signal selected and sent to the controllers.

A review of what might go wrong with a cold deck reset scheme indicates the reliability may also be low:

1. If a room thermostat fails, it may cause the cold deck set point to be always low, greatly increasing energy use.
2. If an occupant adjusts a thermostat to a low setting, this thermostat will cause an unnecessarily low cold-deck set point.
3. If extra electrical equipment or other heat-producing devices are placed in a space, the higher heat load will cause the cold-deck set point to be too cold; air system rebalancing is needed in this case but probably will not occur because the cold, energy-inefficient cold-deck temperature will keep the space comfortable.
4. If the high signal selector fails, a high or low cold-deck set point could result.

In buildings with more than a few thermostats, one or more of the above failure modes is very likely to occur often enough to make the reset system a maintenance problem or cause the operator to disable it. Worse, because some inefficient failure modes do not cause discomfort, they may go undetected for indefinite periods, resulting in considerable extra energy cost.

Furthermore, the use of PI control instead of proportional-only control has much the same beneficial impact on system energy consumption as using cold-deck reset. The droop toward lower discharge air temperatures which would occur with proportional-only control as cooling loads diminish is eliminated with PI control. PI control keeps the discharge temperature up at its set point. Cold-deck reset schemes also keep the discharge temperature up by resetting the cooling coil and damper controllers, but these schemes are more complicated and less reliable than simple PI control.

The additional control complexity of cold-deck reset is probably not warranted by the relatively small savings it provides in this case.

Accurate PI control for this small building can save several hundred dollars a year (see Figure 6). However, the building's fan system is also small. A larger fan system in a larger building could be controlled accurately with no greater control system cost, but would achieve proportionally greater savings. For large fan systems, the payback period for retrofit of accurate PI control may be 1 year or less. The payback period for buildings

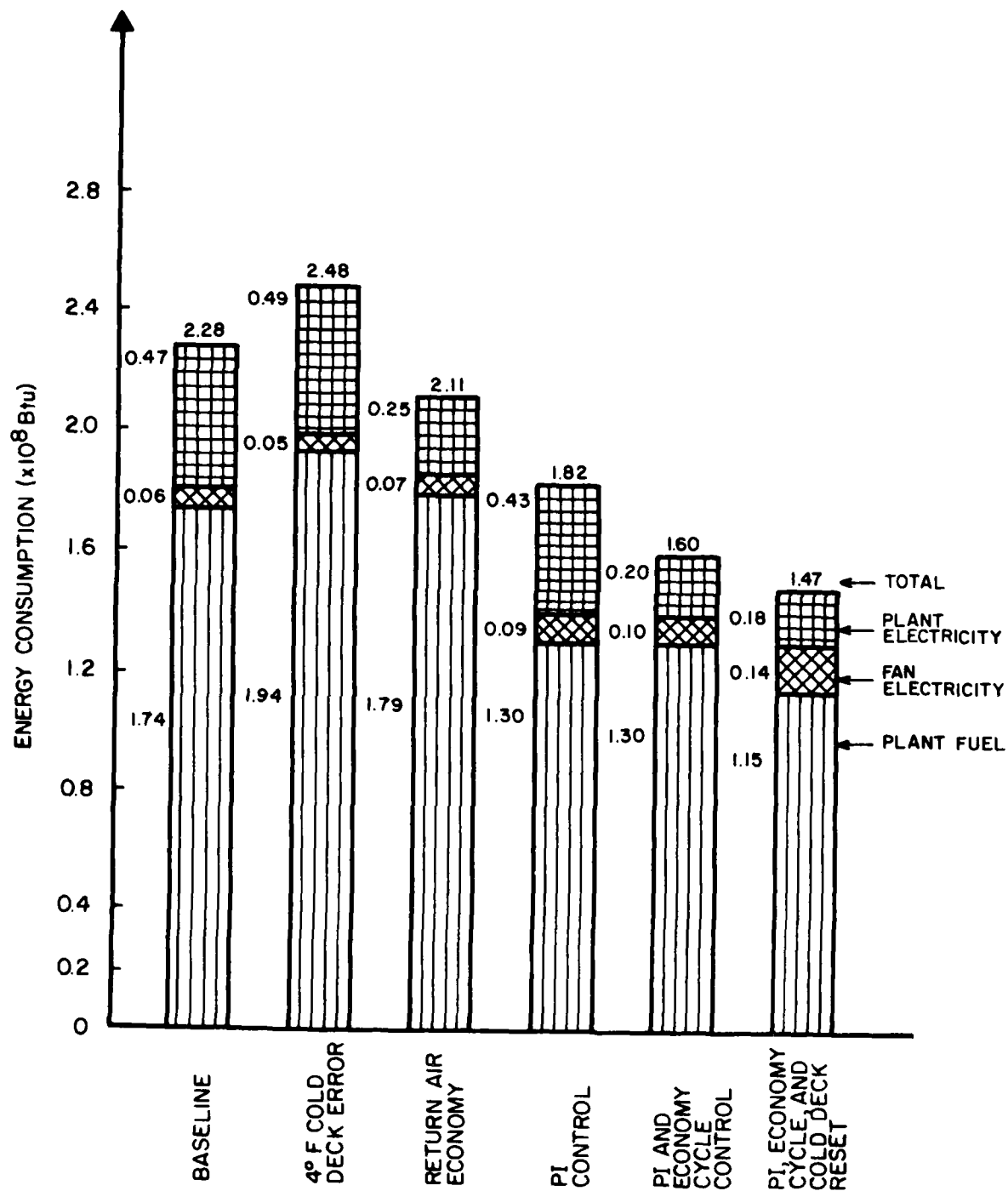


Figure 5. VAV system energy consumption for various control options.

5 EFFECT OF CONTROL SYSTEM PERFORMANCE ON OPERATING COST

To examine the effects of control system performance and the effects of various control strategies on energy consumption, the energy demands of a small dental clinic were simulated using the Building Loads Analysis and System Thermodynamics (BLAST)⁴ energy analysis computer program. The building is a single-story, 10,000-sq ft (100-m²) structure of typical brick and block construction with a flat roof; about 15 percent of its exterior wall area is single-pane glass. It was assumed that the building would be in use from 7 a.m. to 5 p.m. on weekdays and that the air-conditioning system would be off except during these hours.

One of the systems simulated was a variable air volume (VAV) with reheat system serving both exterior and interior zones. Several control-related alternatives were considered. Figure 5 identifies each case and shows its estimated HVAC energy consumption. In the baseline case, conventional proportional cold-deck control was assumed with a proportional band or throttling range of 10°F (5.5°C). With a design cold-deck temperature of 60°F (15.5°C), the actual delivery-air temperature would vary from 60°F (15.5°C) at full load to 50°F (10°C) at no load. In the baseline case, a constant 15 percent outdoor air was assumed to be introduced any time the system was running.

In the "4°F Cold Deck Error" case, the expected energy use of the same system is shown as the baseline; however, it is assumed that control error caused by the temperature transmitter and receiver/controller results in a cold-deck delivery air temperature which is 4°F (2.2°C) colder than the baseline case. That is, the delivery air temperature ranges from 56°F (13.3°C) at full load down to 46°F (7.8°C) at no load, instead of from 60°F (15.5°C) down to 50°F (10°C).

The "Return Air Economy" case is like the baseline case (i.e., with no cold-deck temperature sensor receiver/controller); however, the cold deck is assumed to be controlled with a proportional plus integral controller. In this case, the cold-deck temperature is controlled without "droop" or steady-state error at exactly 60°F (15.5°C).

The "PI and Economy Cycle" case is like the "Return Air Economy" case, except that both the cooling coil and the outdoor- and return-air dampers are assumed to be controlled by a PI control loop.

The "PI Economy Cycle and Cold Deck Reset" case includes the addition of a control point reset of both the cooling coil and the mixed-air controllers based on the zone requiring the most cooling.

Figure 5 illustrates the order-of-magnitude difference caused in system energy consumption by both poor control component performance and the choice of control strategies. For example, a 4°F (2.2°C) error in sensed cold-deck temperature can increase system energy consumption by about 10 percent. This

⁴D. C. Hittle, The Building Loads Analysis and System Thermodynamics (BLAST) Program, Technical Report E-119/ADA048734 (U.S. Army Construction Engineering Research Laboratory, 1977).

Enthalpy economy-cycle control is only marginally more effective than using simple temperature measurements in the outdoor- and return-air stream. In most locations, temperature is a reasonably good indicator of the total heat content of the return and outdoor-air streams. Any small improvement which is theoretically possible with enthalpy economy cycles is rarely achieved in practice, and the additional maintenance burden and tendency to fail make enthalpy economy-cycle control undesirable. For most locations, the added first cost, maintenance cost, and potential consequences of failure are not justified by a maximum savings of only a few percent. Until more reliable humidity sensors and enthalpy control logic devices can be developed, enthalpy economy cycles should not be used.

4 ECONOMY-CYCLE CONTROL

This chapter discusses the effects of component performance on the economy-cycle control--a commonly used HVAC control subsystem. The performance of humidity sensors, either electronic or pneumatic, is important in choosing the type of economy-cycle control subsystem to be used.

Economy cycles are designed to allow the use of outdoor air to offset all or part of a system's cooling requirement. There are at least three ways to implement economy cycles. The simplest involves a single outdoor-air thermostat set at a specified value to energize or de-energize the economy cycle. Whenever the outdoor-air temperature is below a specified set point, a mixed-air temperature sensor and controller modulate the outdoor and return-air dampers to maintain the mixed-air temperature as close to the set point as possible. When the outdoor temperature is above the set point, a minimum amount of outdoor air is introduced.

In some systems, the temperature of the return air varies (for example, in systems where the return air is directed over lighting fixtures, and variations in the lighting load lead to variations in return air temperatures). In these cases, the economy cycle can be improved by having sensors in both the outdoor and return ducts. Any time the outdoor air is cooler than the return air, a mixed-air control loop modulates the outdoor- and return-air dampers; this minimizes the amount of artificial cooling required. Any time the outdoor temperature is above the return-air temperature, a minimum amount of outdoor air is introduced.

Enthalpy economy cycles represent a further refinement. Here, the outdoor temperature and outdoor humidity are measured, as well as the return-air temperature and humidity. Using these measurements, the enthalpy of these air streams can be deduced. Thus, if the outdoor-air enthalpy is less than the return-air enthalpy, outdoor air is used as much as possible to minimize cooling requirements. Unfortunately, test results and field experience suggest that enthalpy economy-cycle controls are prone to failure. The most serious shortcoming with these systems is the lack of accurate humidity sensors. For example, testing showed that in a measured 62 percent relative humidity environment, the output of three pneumatic humidity transmitters was found to be 63 percent, 88 percent, and 96 percent. Hence, even if the enthalpy logic device performed satisfactorily (tests showed that the performance of these devices is also somewhat erratic), the input humidity measurement would be so unrealistic that there would be improper control. Practitioners, researchers, and control manufacturers all recognize this problem.

Most manufacturers recommend frequent recalibration of humidity sensors used in HVAC applications (a minimum of every 6 months). Unfortunately, calibration of humidity-measuring equipment is very difficult and is not accurate. The typical method involving a psychrometer (a dry-bulb and a wet-bulb mercury thermometer) provides only a rough indication. Calibration is time-consuming and only partly effective. Given the limited resources at Army installations, it is unlikely that this frequent calibration requirement can be achieved.

temperature control is needed (for example, in the control of discharge air temperature or mixed-air temperature in air-handling systems).

A potential disadvantage of using electronic controls is that electronic actuators are more expensive, usually somewhat slower, and may require more maintenance than pneumatic actuators. To avoid this problem, pneumatic actuators for valves and dampers can be used by interfacing them to electronic controllers through electric-to-pneumatic transducers.

Several kinds of resistance temperature detectors (RTDs) have been used with electronic controls in the HVAC industry. One type is the thermistor, which has the advantages of relatively large resistance and large change in resistance with temperature. This means that the resistance of the leads connecting the thermistor to the controller will be very small compared to the resistance of the thermistor itself and compared to the change in resistance with temperature. Hence, no compensation is needed for lead resistance in circuits involving thermistors. However, thermistors have the undesirable property that their resistance temperature curves change over time, i.e., they age. This means that thermistors must be calibrated frequently (some manufacturers recommend a 6-month calibration interval); this makes them unsuitable for HVAC applications.

Other RTDs are wire-wound resistors that use wire made of nickel, platinum, or Balco (a metal alloy). Platinum RTDs are used almost exclusively in the process industry. Most platinum sensors conform to DIN 43760,³ a German standard; their resistance varies with temperature according to the following formula:

$$R=R_0 (1+aT+bT^2) \quad [Eq 1]$$

where:

T = temperature in °C

$a = 3.9088 \times 10^{-3}$

$b = -5.874 \times 10^{-7}$

R_0 = the probe resistance at 0°C (most often 100 ohms).

Because the probe's resistance is low (usually near 110 ohms at room temperature), three wire probes should be used. This will compensate for lead resistance by putting the two leads going to the same end of the probe in opposite legs of the measuring bridge circuit used in the electronic controller.

Nickel and Balco resistance temperature detectors can be used and do not have the disadvantageous drift associated with thermistors. However, they are not used as frequently as platinum; as a result, they cannot be routinely interfaced to a wide range of electronic control equipment.

Electronic controllers with standard voltage ranges and standard platinum bridges will be both interchangeable and reliable if used in conjunction with DIN 43760 standard platinum temperature detectors. Platinum RTDs manufactured to .5°F (.27°C) tolerances are relatively inexpensive, never require field calibration, and are drift-free. If high-quality electronic components are used, electronic controls should remain calibrated for years. Platinum temperature detectors and electronic controls should be used where accurate

³DIN 43760 (Deutsches Institut für Normung, Burggrafenstrasse 4-10, D-1000 Berlin 30).

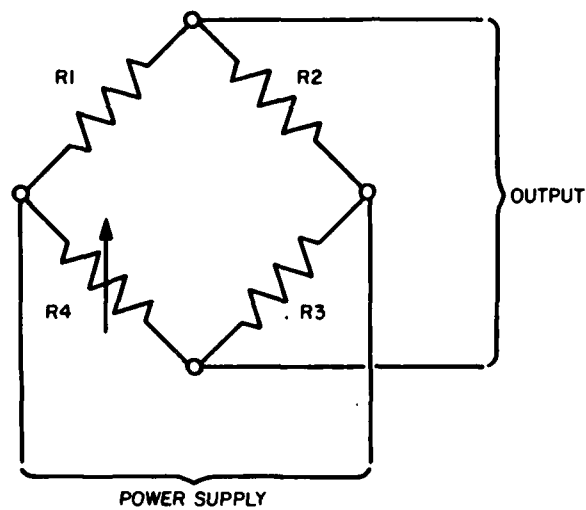


Figure 3. Wheatstone bridge.

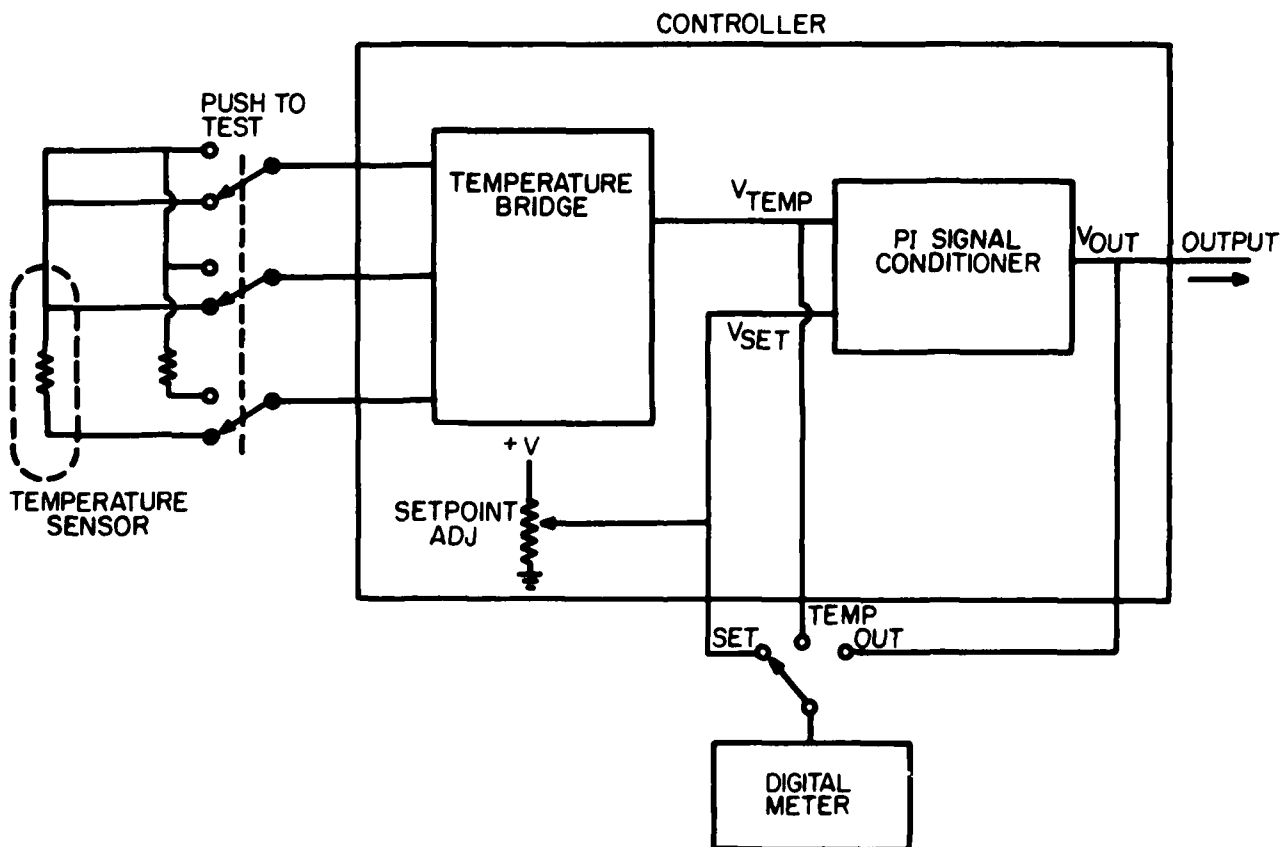


Figure 4. Electronic controller.

3 ELECTRONIC CONTROLS

Most electronic control equipment is based on temperature measurements using resistors whose resistance changes with temperature. In the simplest cases, Wheatstone bridges (Figure 3) are used to measure temperature. The bridge consists of four resistors arranged in a diamond; a constant power supply voltage is applied at two corners of the diamond, and the output is taken from the other two corners. When all the resistances are equal, the output value will be zero. However, if one or more of the resistances changes (especially for the temperature probe, whose resistance changes with temperature), the output will change proportionally. Practical analog electronic control equipment uses the Wheatstone bridge principle with other electronic signal conditioning to provide an output signal in a standard range of 0 to 10 V or 4 to 20 mA. The 4- to 20-mA signal corresponds to a standard adopted by the Instrument Society of America.

Figure 4 shows a typical electronic controller. The portion labeled "temperature bridge" converts the temperature probe resistance into a voltage signal, V_{temp} , which is compared to a set-point signal, V_{set} . The bridge works much like a Wheatstone bridge, but also includes active electronic components which help compensate for any nonlinearity in the sensor. Good controllers allow both V_{set} and V_{temp} to be measured with a built-in or portable voltmeter. V_{set} and V_{temp} are compared to produce an error signal, which is the voltage difference between V_{set} and V_{temp} . The controller output voltage, V_{out} , is produced by applying gain to the error (amplifying it) and by integrating the error signal if proportional-plus-integral (PI) control is used.

There are some very convenient control designs which, when used with 100-ohm platinum resistance temperature detectors, produce a bridge voltage which ranges from 0 to 10 V as the sensed temperature ranges from 0 to 100°C. The output voltage should also range from 0 to 10 V, or possibly 4 to 20 mA, to interface with other equipment such as electronic actuators or electric-to-pneumatic transducers. It is becoming common for devices, particularly electric-to-pneumatic transducers, which are to be driven by the output of the electronic controller, to have a 500-ohm resistance, and to have their action proportional to current. Since voltage in a DC circuit is proportional to the product of current and resistance ($V = IR$), these devices can be driven by a controller whose output is 4 to 20 mA (the voltage drop across the device is 2 to 10 V), or by a controller with a 2- to 10-V output (this voltage produces a 4- to 20-mA current through the 500-ohm resistance).

Electronic controllers are also used with input signals from devices such as pressure sensors, where the input may be 0 to 10 V. These inputs simply bypass the temperature bridge shown in Figure 4 and are compared directly to the set point. Desirable characteristics of electronic controllers include high accuracy, a low temperature coefficient (changes in output caused by temperature change in the room housing the controller), a standard voltage range (0 to 10 VDC), good noise filtering, and easy access to V_{set} and V_{temp} . The appendix gives a sample performance specification. This sample is a rough outline of a portion of the type of specification that will eventually be written in more detail for Corps use.

Air Supply

Another often overlooked problem with pneumatic controllers is that many require supply air pressure to be maintained even when the controlled HVAC system is turned off. Regarding supply air interruptions, one manufacturer recommends that the supplier always remain on. If not, errors from 2° to 5°F may occur at the control point within 24 hours after the supply air pressure resumes. Unfortunately, some pneumatic systems are provided with an electric-to-pneumatic relay, which closes the air supply and bleeds the entire system down when the fan system is shut off. For these systems, the effects on control by time switches for night and weekend shutdown are unknown. Attempts to calibrate pneumatic systems which are not continuously supplied with air may also be futile.

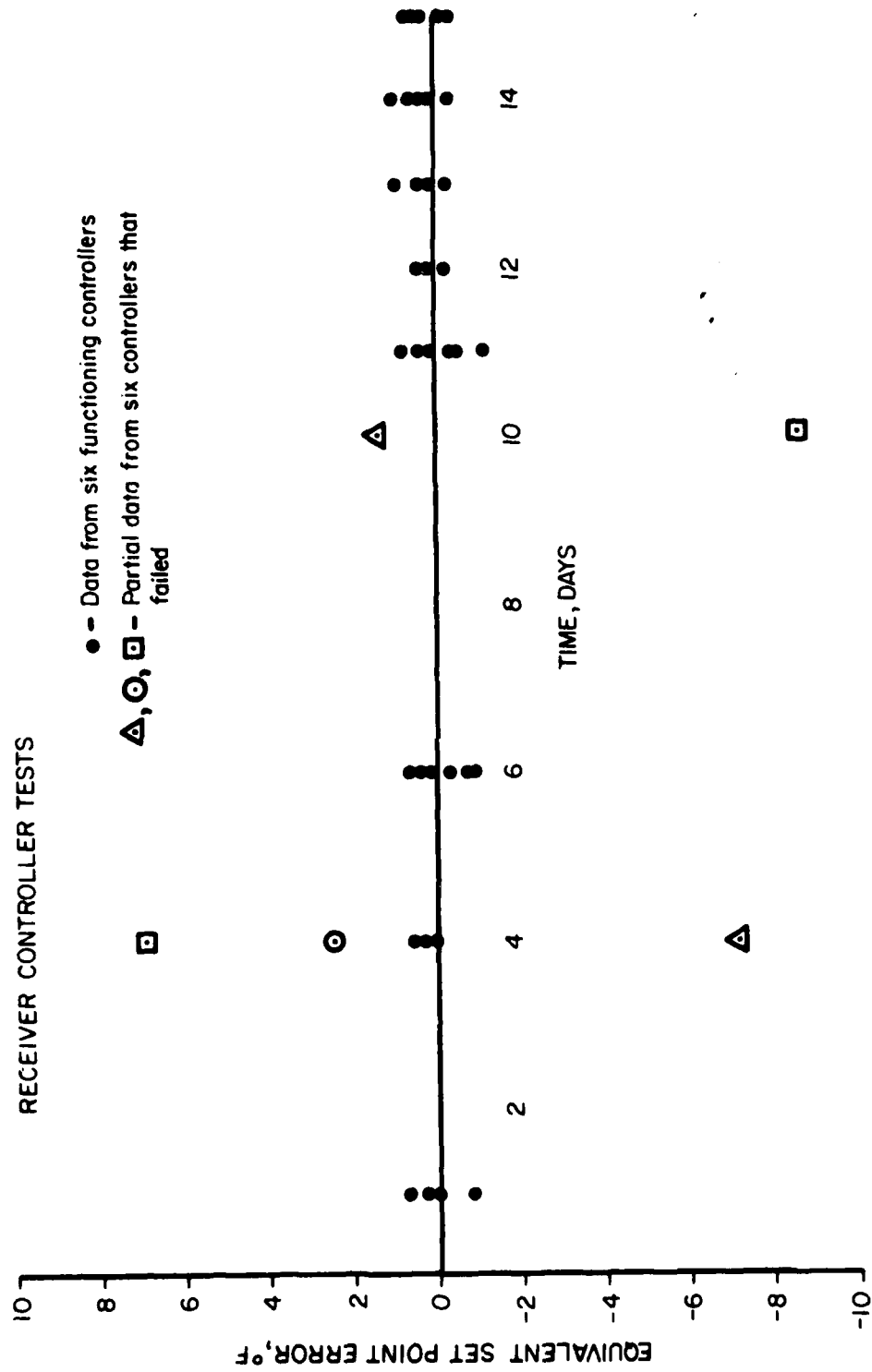


Figure 2. Pneumatic receiver/controller test results.

Figure 2 shows the results of several tests. Equivalent set-point error (y-axis in Figure 2) is simply the drift from 9 psi (62 kPa) of the output pressure multiplied by 8.33°F per psi (.67°C/kPa)--the approximate slope of the temperature pressure curve for the 50° to 150°F (10° to 65°C) temperature transmitters previously tested. These figures represent the change in measured temperature away from the set-point value that would be needed to make the output pressure of the receiver/controller 9 psi (62 kPa). In defining an equivalent set-point error, it was assumed that a "perfect" temperature transmitter was used that followed the manufacturer's curve exactly. Thus, the equivalent set-point error would be the error in the controlled temperature caused exclusively by the error in the receiver/controller.

Figure 2 shows two sets of data: one for a set of receiver/controllers that would not remain in reasonable calibration for more than 1 or 2 weeks (some of these would not remain calibrated for 1 day), and one for a set of controllers with reasonably good performance over the test period. While the receiver/controllers which performed poorly were of the fluidic type and from one manufacturer, the widespread use of this receiver/controller around the country suggests that many systems may not be working properly.

Examining the data from the units that "worked" (some were the same type as those that failed but had received special attention from the manufacturer's factory), the drift over time is shown to be on the order of $\pm 2^\circ$ (about $\pm 1^\circ\text{C}$).

Combination in a Control Loop

Since a typical control loop contains both a temperature transmitter and a receiver-controller, the performance of the combination was considered by using the data from both Figures 1 and 2. The effects of separate transmitter and receiver/controller errors are not directly additive, and neither has a high probability of being in error by as much as the worst units tested. Still, errors on the order of $\pm 4^\circ\text{F}$ ($\pm 2^\circ\text{C}$) seem plausible based on the test data shown in Figures 1 and 2. This is not particularly surprising, given the fairly wide temperature range for most pneumatic sensors used in HVAC applications and given the type of technology used to construct temperature transmitters and receiver/controllers. However, these test results are in contrast to optimistic statements offered in the ASHRAE Handbook,² which suggest control accuracies of $\pm 0.5^\circ\text{F}$ for pneumatic equipment. Errors of about $\pm 4^\circ\text{F}$ ($\pm 2^\circ\text{C}$) can affect system energy consumption.

Since the equipment tested was essentially brand new, long-term drift remains to be established; however, accuracy after extended operation will certainly be no better than provided by tests of new equipment in the laboratory.

²Handbook of Systems (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1980), p 34.4.

6 A PROTOTYPE STANDARD RETROFIT CONTROL PANEL AND SYSTEM

Prototype System Development

The use of proportional plus integral control coupled with accurate sensors can improve the expected energy consumption of HVAC systems. This allows goals of accuracy and maintainability to be set for retrofit control systems. An additional goal should be simplicity. With these goals in mind, a retrofit control system and an easily installed modular retrofit control panel were developed.

Figure 7 shows a control system which maximizes efficiency while minimizing complexity. This hybrid system uses pneumatic control components for damper and valve actuators and for less critical room temperature control subsystems, and electronic components to measure and control more critical mixed-air and coil-discharge temperatures. A prototype of this system (described below) has been implemented as a retrofit on a system at USA-CERL.

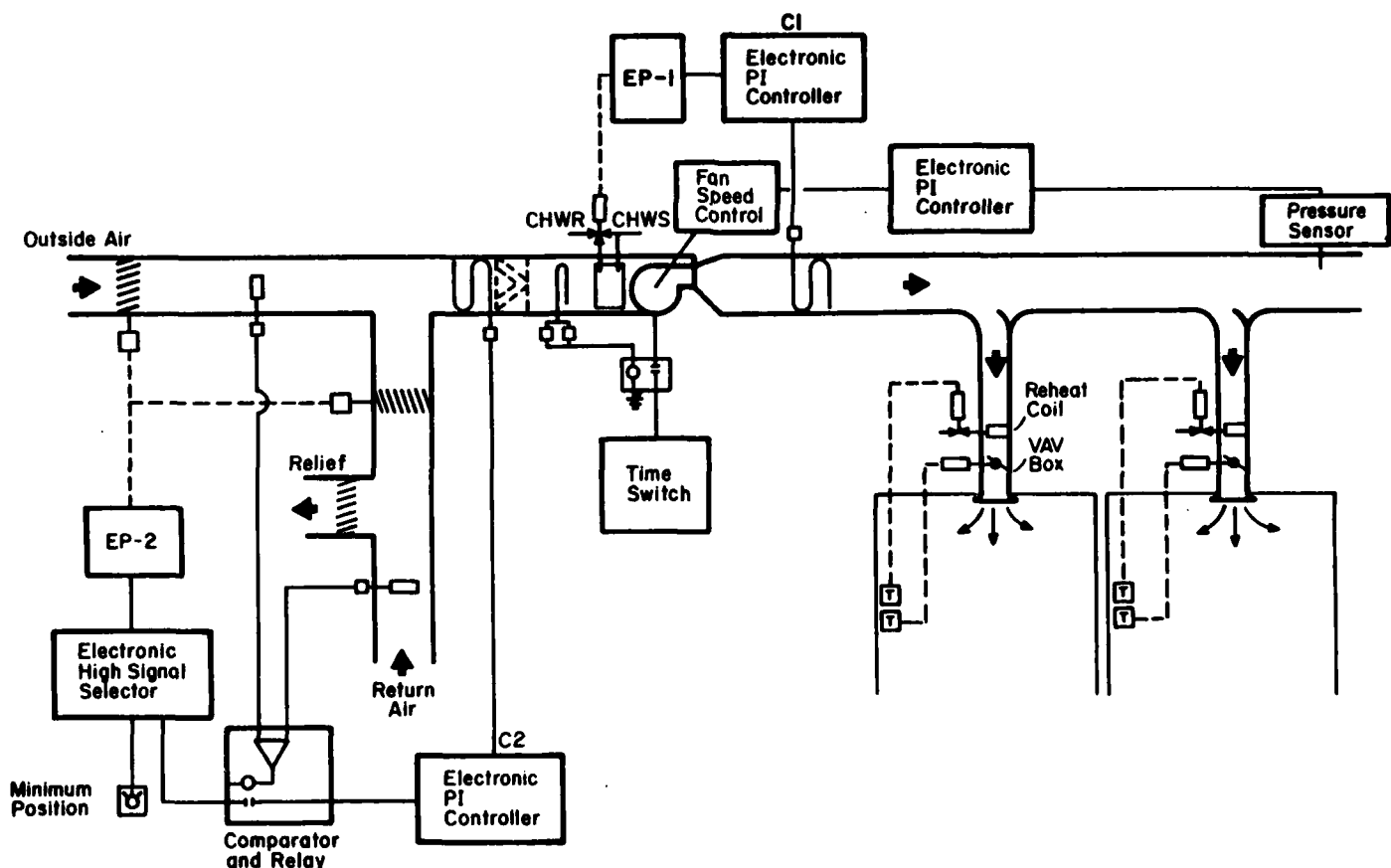


Figure 7. Prototype VAV control system.

Prototype System Description

For room temperature control, the zero energy band (two separate thermostats in one case with a dead band separating the heating and cooling modes) is used to control the VAV boxes and reheat coils or baseboard heaters in sequence in each room. In rooms where heating is never needed, the reheat coil or baseboard heaters can be omitted and a single thermostat used to modulate the VAV box. A fairly low minimum flow setting for the VAV box should be used when no heat source is provided. In spaces needing heat, baseboard heaters are the preferred approach since their use permits lower minimum air flow settings on the VAV boxes and since any required morning warm-up can be achieved without running the fan.

The cooling coil is controlled to produce a fixed-discharge air temperature using a platinum averaging sensor (accurate and reliable), an electronic proportional-plus-integral controller (an accurate, drift-free unit with standard 0- to 10-V signal was selected), and an electronic-to-pneumatic (EP) transducer which provides the pressure signal to the pneumatic valve actuator.

The outdoor- and return-air dampers are controlled using essentially the same hardware. The electronic PI controller acts to maintain the sensed temperature (averaging platinum probe) in the mixed-air stream at the set point whenever possible. However, two platinum point probes in the outdoor- and return-air streams measure the temperature for the comparator relay. If the outdoor temperature is hotter than the return-air temperature, the relay opens and no signal is passed. Under these conditions, the voltage signal from the minimum position device is the highest signal to the electronic high signal selector; it controls the EP transducer and thereby the outdoor- and return-air dampers. If the outdoor air is cooler than the return air, the comparator relay is closed and the PI controller output drives the EP transducer; this drives the dampers unless the controller output voltage is less than that produced by the minimum position device. (The minimum position device determines the lowest voltage that will be sent to the EP transducer.) The time switch of Figure 7 represents some appropriate setback or shutoff scheme. For an office building, for example, the entire fan/heating system would be shut off at night and on weekends unless the temperature in one or more key locations in the building gets too low. Thermostats in these key locations set at about 50°F would be wired to energize the heating if the temperature dropped below their set point. If the time switch is off, but one of these low-limit thermostats calls for heating, only the portion of the system required for heating would be energized. For example, if the building is served by baseboard heaters, only the pumps, boilers, and pneumatic room temperature controls need be energized. If reheat coils are used, however, the fan and static pressure control system must also be turned on. In any case, the VAV temperature control panel should not be energized.

A timed warmup cycle can also be used, again energizing only those parts of the HVAC system needed for heating during the warmup period.

To control the pressure in the ductwork, an electronic pressure sensor is used with an electronic PI controller to modulate a variable-speed drive, inlet guide vanes, or variable pitch system on the fan (discharge dampers could also be used for pressure control but they provide much less fan power savings than other schemes).

Figure 8 shows the control panel for the temperature control system. In this system, the digital voltmeter displays various voltages, depending on the position of the meter select switch. It can display the voltage corresponding to the sense temperature downstream from the cooling coil, the corresponding set-point voltage for the cooling-coil controller (C1 in Figure 8), and the output voltage from the controller to the electronic-to-pneumatic transducer. The sensor bridge voltage and the set-point voltage can easily be scaled to display digits which correspond to temperature. Note that since PI control is used, the sensor bridge voltage and the set-point voltage will usually be the same when this control loop is working, except for a few minutes following a system disturbance. By examining the input, set point, and output of the cooling-coil controller, the building operator can determine the cold-deck temperature, find the cold-deck set point and adjust it precisely, and ascertain the output of the controller to be sure that it is functioning properly.

The same values can be displayed for the mixed-air controller (C2 in Figure 8), and a similar assessment of the performance of the controller can be made. (There will be cases when the outside air is too warm or too cold and the mixed-air controller will not be able to control the mixed-air temperature. In these cases, the output voltage will be at its high or low extreme.)

The meter select switch also allows display of the voltage (proportional to temperature) from the outdoor- and return-air sensor bridges. This lets the operator determine if the economy cycle is working properly. The economy-cycle light on the panel should be on if the outdoor air is colder than the return air.

By using the meter select switch to alternately display outdoor, return, and mixed-air temperature, it is also possible to accurately determine and adjust the minimum outdoor-air fraction. This is best done during very cold or very hot weather and requires that the mixed-air controller be disconnected or have a lower output than the minimum position switch. Without this type of accurate measurement, outdoor-air settings will probably be fairly crude.

The meter panel also contains four test buttons which each disconnect one of the four temperature sensors in the control system and connect a precision resistor in its place. By pushing one of these test buttons while reading the corresponding sensor bridge voltage, the operator can determine the integrity of the sensor bridge electronics.

Above each controller are manual adjustment sections. By setting a timer and pressing one of the test buttons, the output from the cooling-coil and mixed-air controllers is disconnected from its respective electronic-to-pneumatic transducer; knobs can then be turned to supply a varying voltage to these transducers. Pressure gages on the panel display the output pressure from each transducer. By turning the knobs and watching the pressure gages, any fault in the EP transducer can be identified quickly. The timer is used so that the system will revert to automatic control after the timer has elapsed; this prevents the operator from inadvertently leaving the valve or dampers under manual control. Finally, the pneumatic actuator position is displayed to allow stuck dampers or valves to be detected.

VAV Temperature Control Panel

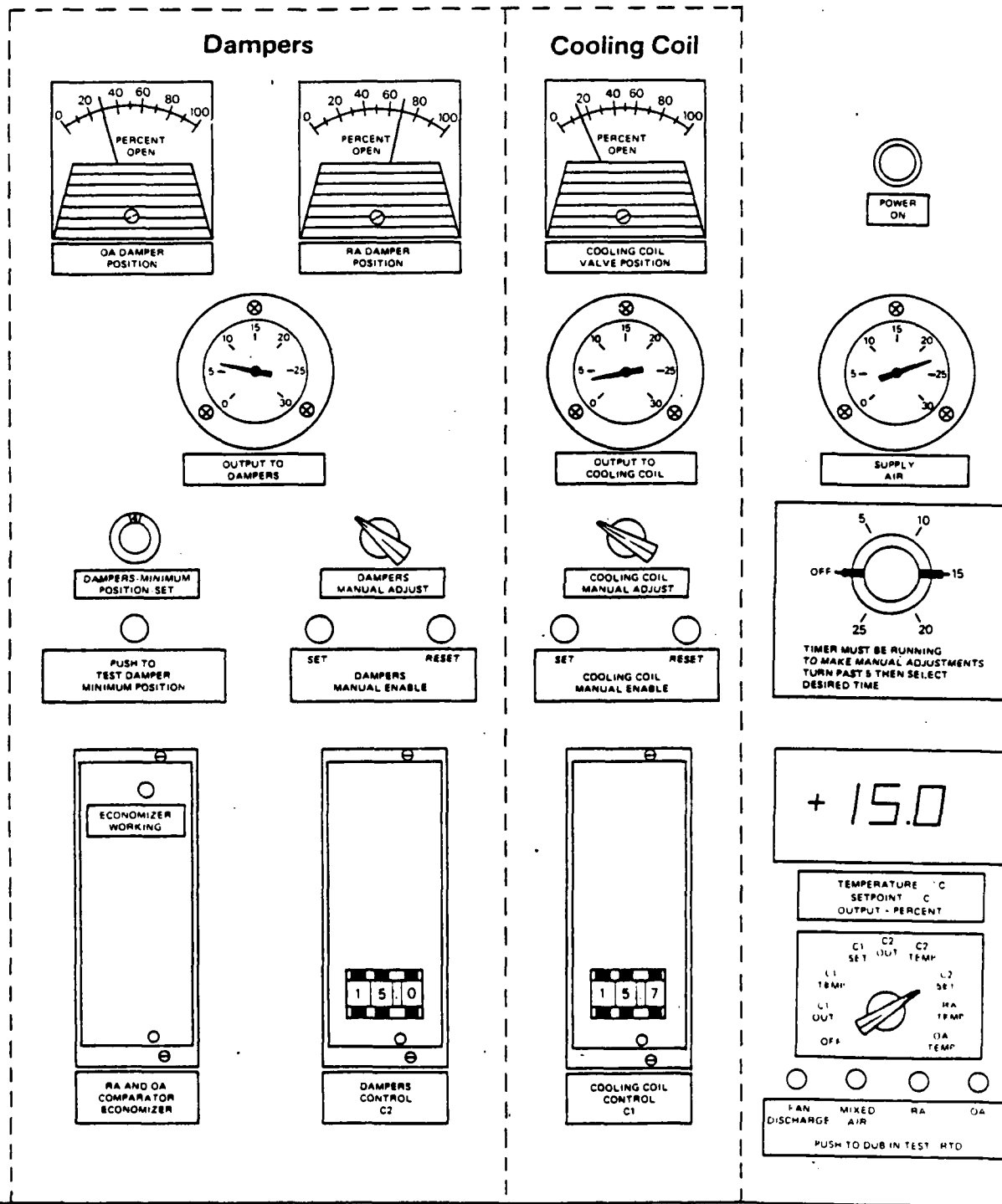


Figure 8. Prototype control panel.

The control panel diagnostics allow the building operator to identify faulty components quickly. While electronic components are expected to be reliable, failures that do occur can be diagnosed quickly and defective parts replaced. If a malfunction occurs, the defective module should be replaced. This approach reduces downtime and time required for repair. A large inventory of replacement control equipment should not be required since standard voltage ranges and temperature sensors are used.

Figure 9 shows the fan pressure control panel. The control system consists of an electronic pressure sensor, a PI controller, and an electronic-to-pneumatic transducer, if required. Diagnostics follow the same philosophy as for the temperature control panel.

All panels are heavy steel or aluminum. The equipment shown in Figures 8 and 9 is mounted on an inner hinged panel. An outer locking door hides all equipment when it is closed.

Design Features

The control system and panels emphasize several important design considerations: (1) simplicity, (2) reliability, (3) maintainability, (4) accuracy, (5) appropriate use of PI control, (6) use of high-quality components, and (7) use of standard sensors and signals to provide simplicity and interchangeability. Another important feature of the panel concept is that changeover to new control systems can be made with almost no downtime. Replacing the main fan-control systems requires only installing the sensors in the duct, running the wire back to the panel, connecting the new sensors, running pneumatic tubing from the electronic-to-pneumatic transducers close to the existing valve and damper actuators, and finally disconnecting the existing actuator lines, connecting the new lines, and starting the new control system.

If the control system is accompanied by very specific and clear operating and maintenance instructions, it should provide efficient, accurate, and reliable service for many years without calibration of the temperature sensors or any of the electronic controllers.

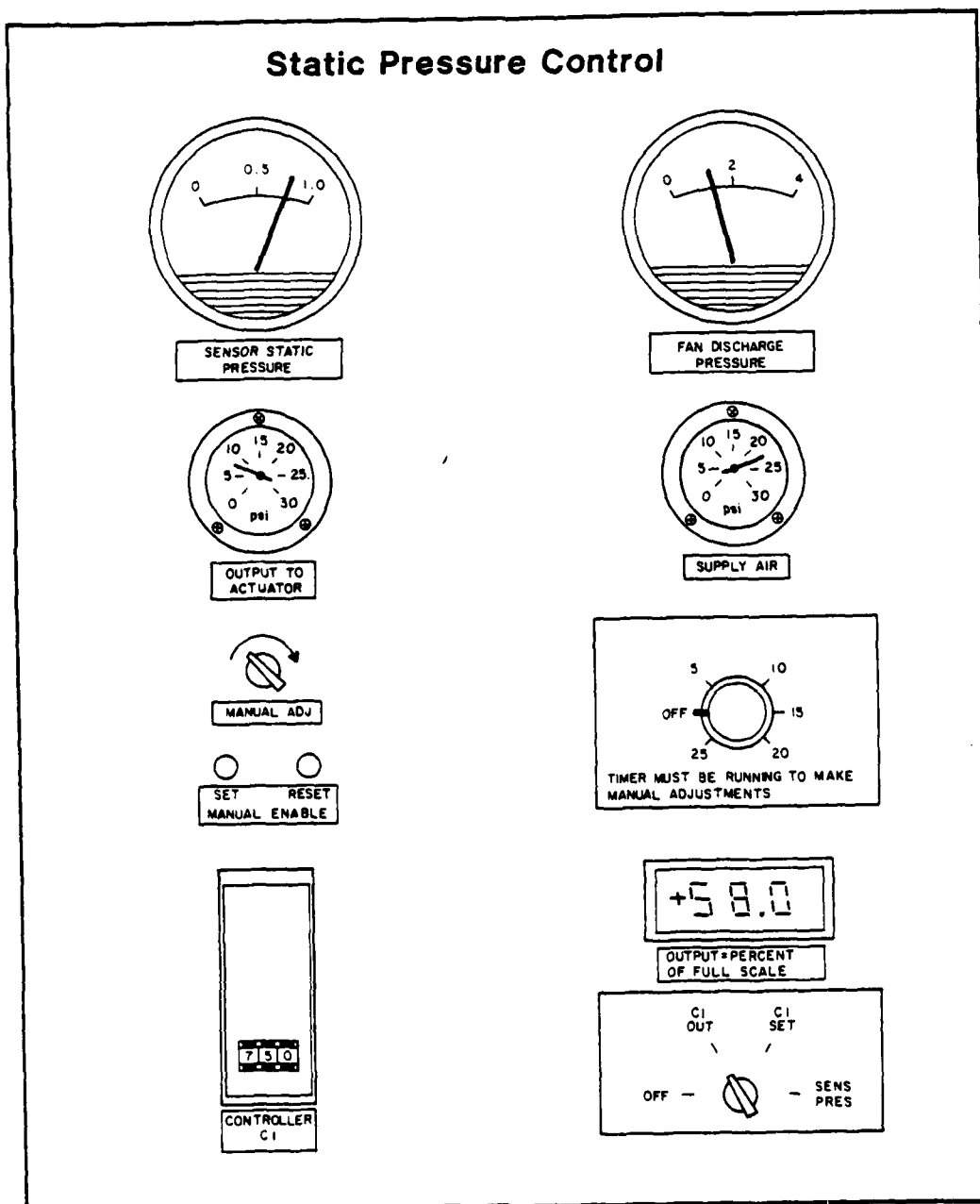


Figure 9. Fan pressure control panel.

7 APPLICATIONS AND BENEFITS OF THE RETROFIT CONTROL PANEL AND SYSTEM

The retrofit control panel has obvious applications to all VAV systems. In some cases, with smaller VAV systems and with fans of appropriate characteristics, the duct pressure control subsystem can be omitted, and the fan allowed to "ride the fan curve."

The retrofit control panel can provide energy savings of about 20 percent as compared to a perfectly functioning conventional control system. Savings will vary by location and building. However, based on lab experiments and field experience, it is unlikely that any existing VAV systems are controlled perfectly. Thus, the retrofit control panel may provide savings even greater than those estimated, will reduce maintenance costs considerably, and may make the building more comfortable.

Reheat systems have potential for even greater energy savings if the prototype panel is used and the system is converted to variable air volume. Figure 10 is a simulation of the dental clinic described in Chapter 5 in which a constant volume reheat system is used as the baseline. As in the previous dental clinic example, the energy impact of an error in the cold-deck sensor is shown. The use of a PI controller to control the cold deck produces obvious energy savings. The figures show that adjusting the cold-deck temperature based on the zone requiring the most cooling is an important conservation alternative if the reheat system is not to be fully converted to variable air volume. This control option allows the set-point temperature of the cold deck to drift upward as the building's cooling load diminishes. This reduces both the cooling and reheat requirements. Figure 10 also shows the energy savings that can be achieved with an economy cycle. Most of the savings are in electrical power consumed for chilling.

The savings achieved by fully converting to VAV, in comparison to the reheat system with the best controls, is about \$2300/year (see Figure 11). Even for this fairly small building, this retrofit would probably pay for itself in 3 to 5 years. Clearly, for a larger fan system with larger zones, the payback period would be proportionally shorter.

Another possible use for the retrofit control panel is to gain better control of multizone systems. Again, the multizone system can be completely converted to a variable-air-volume system by simply blocking off the hot coil, removing the modulating zone dampers, placing variable air volume boxes near the air handler in the ducts running to each zone, and installing reheat coils in these ducts near the air handler as required. Fan pressure control is only required if the fan can produce unacceptably high pressures.

This complete conversion has two major advantages: it has the efficiency of a variable-air-volume system, and as part of the VAV system, economy-cycle cooling can be implemented. It is not usually effective to implement economy cycles with multizone systems, particularly in applications where heating is required. This is because multizone economy-cycle cooling reduces the mixed-air temperature to near that of the desired cold-deck temperature. While cooling is reduced, this air is colder than would ordinarily be the case using minimum outside air. Heating consumption is increased, since this air goes over the heating coil to supply hot air to the hot deck.

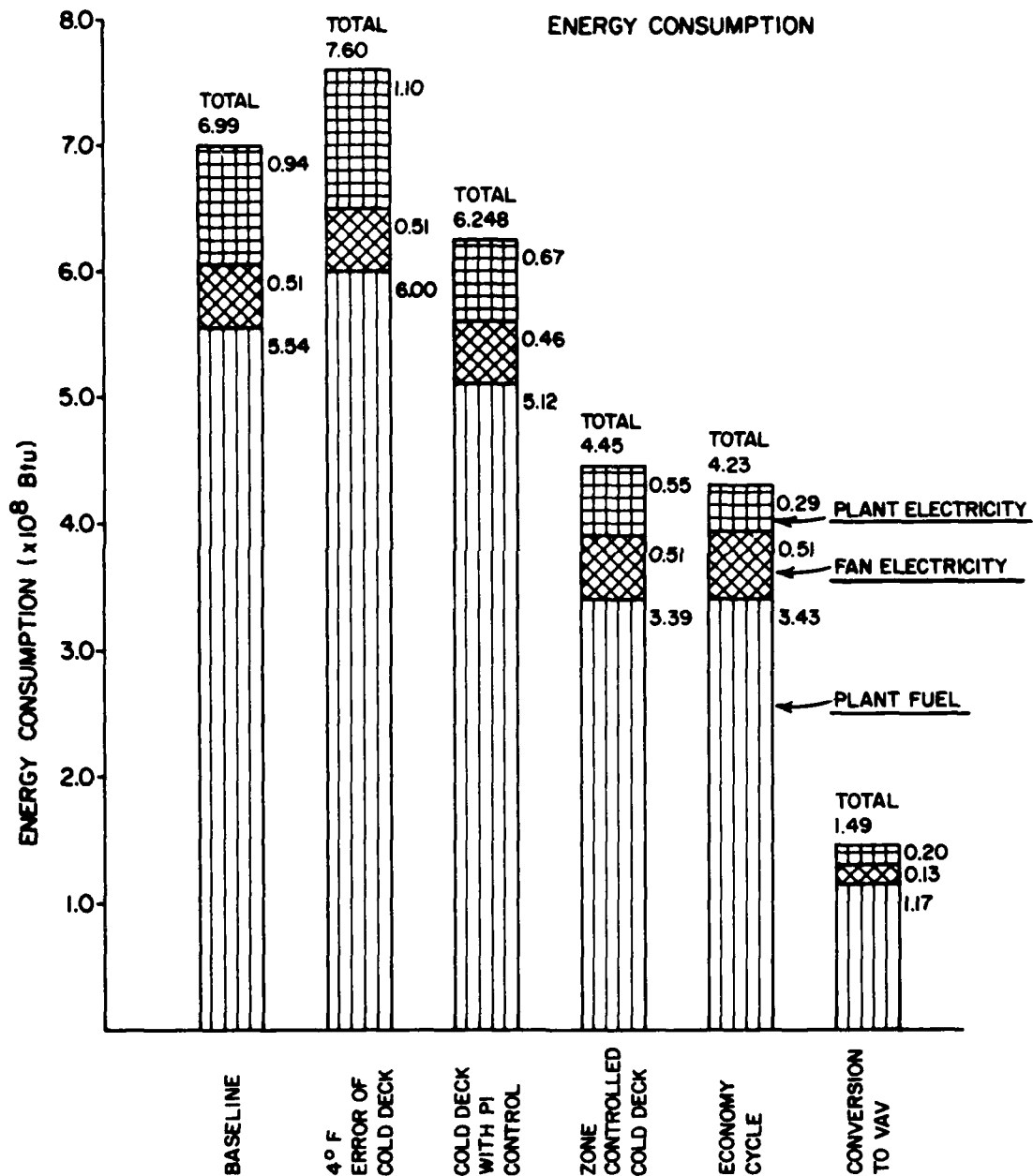


Figure 10. Reheat system energy cost for various control options.

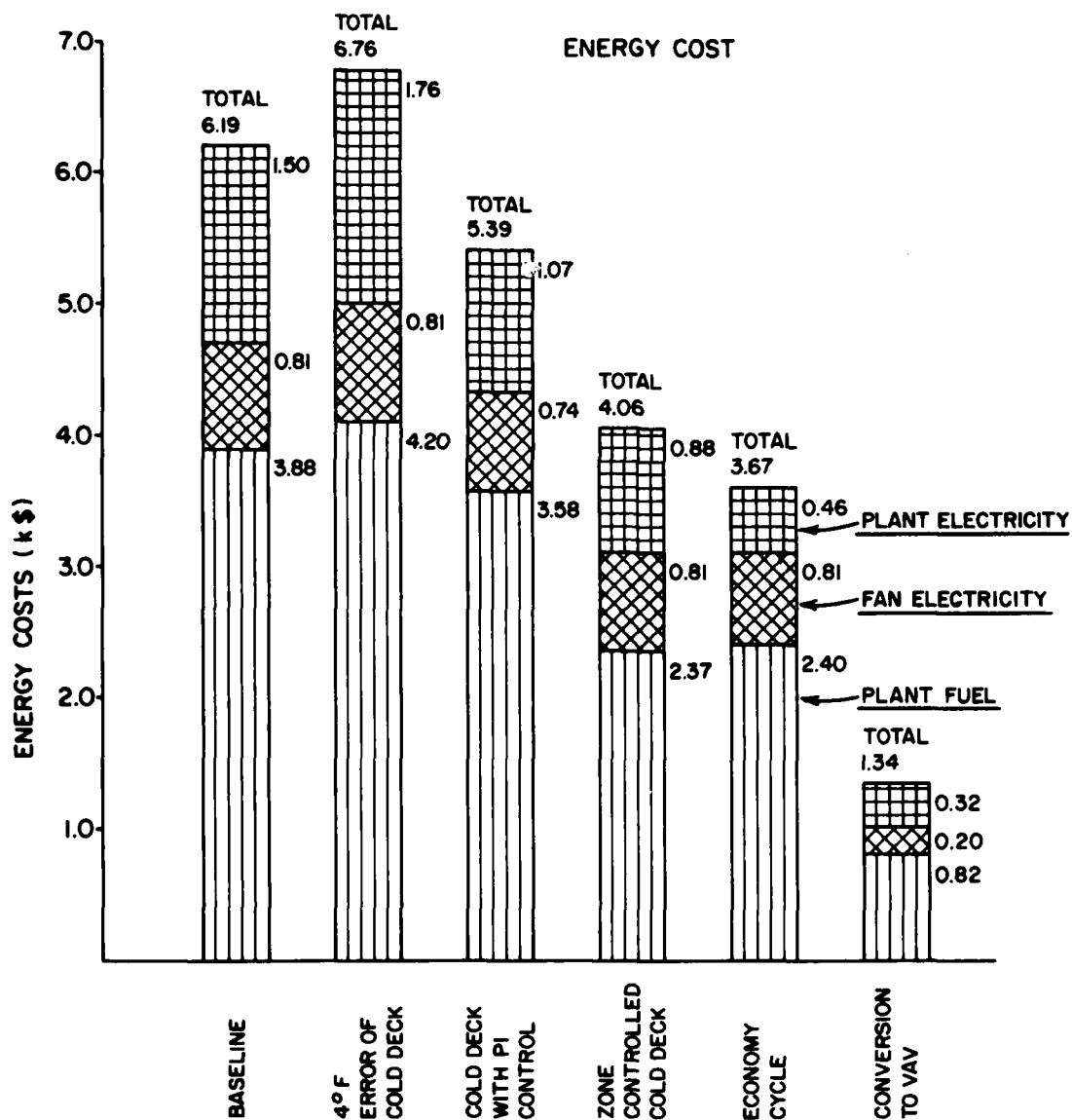


Figure 11. Reheat system energy cost for various control options.

An alternative to converting the multizone system to a variable-air-volume system is using the prototype control panel to control the main fan system (the pressure control system is not needed), and adding one additional control loop to control the hot deck. This control loop would consist of a platinum sensor, a PI electronic controller, and an electronic-to-pneumatic transducer to provide pressure to the existing hot-coil control valve.

In this case, manual changeover of the system is recommended to keep the economy cycle from operating during very cold weather. In fact, it is probably desirable to omit most of the economy-cycle control section, since economy cooling should only be used when the weather is comparatively warm and only cooling is required. During these periods, the heating coil can be de-energized and the comparator relay used to modulate the outdoor air dampers into one of two positions: when the outdoor air is warmer than the return air, dampers should be at their minimum position; when the outdoor air is cooler than the return air, the outdoor air dampers can be fully opened. This scheme provides some benefit when outdoor conditions are moderate. (However, the economy cycle cannot be used when it is particularly cool outside, because this will either increase the demand on the heating coil or overcool the space if the heating coil is off.) This eliminates the need for mixed-air control, since the economy-cycle operation should occur when the outdoor temperature is above the set point of the cold-deck controller but colder than the return air.

8 CONCLUSIONS AND RECOMMENDATIONS

This research has led to the following conclusions:

1. Pneumatic temperature control equipment requires a very clean source of supply air and is not very accurate.
2. When possible, pneumatic, rather than electronic, actuators should be used, since they are cheaper and require less maintenance.
3. Thermistor temperature detectors are inappropriate for HVAC applications, because they must be calibrated so often.
4. Humidity sensors are prone to rapid drift, are of only modest accuracy, and are difficult to calibrate in the field. This makes the implementation of enthalpy economy cycles almost impossible.
5. The performance of control systems has an important impact on HVAC operating costs. The use of proportional-plus-integral control schemes can provide significant operating cost savings over conventional control schemes.
6. The diagnostic features incorporated in the retrofit control panel will make identification of component failures easy and allow diagnosis and repair without special tools or equipment. Failures of the proposed high-quality sensors, controllers, and transducers should occur much less frequently than is common with "HVAC grade" equipment; if failures do occur, they can be repaired with minimum effort and downtime.
7. The prototype control panel scheme on VAV systems and on multizone and reheat systems converted to variable-air-volume systems should produce significant energy cost savings, improve comfort and reliability, and reduce maintenance costs.

The following recommendations are based on the research to date:

1. High-quality electronic controls should be used on most HVAC fan systems to achieve energy efficiency, reliability, and maintainability.
2. Standard platinum temperature detectors should be used exclusively in HVAC temperature measuring and controlling applications. Thermistors should never be used.
3. Existing pneumatic control systems should only be retained after analyzing the requirements for maintenance and periodic recalibration of the equipment; this cost should then be compared to that of replacement with high-quality electronic equipment.
4. Enthalpy economy cycles should not be specified for new systems. For existing systems, enthalpy economy cycles should be replaced with economy cycles based on the measurement of outdoor- and return-air temperature only.

5. The prototype retrofit control panels should be installed in field applications to determine if design improvements are needed and to verify that they are accurate and reliable.

APPENDIX:

SAMPLE ELECTRONIC PERFORMANCE SPECIFICATION

This sample performance specification is a rough outline of a portion of the type of specification that will eventually be written in more detail for Corps use. The numbering for this sample follows the format used by the Construction Specifications Institute. Headings beginning with "2" provide information on controls.

2.2 Electronic Control Panel for Air Handlers

2.2.1 General

(A)

Provide an electronic control panel for each air handler where indicated in the Equipment Schedule of the Drawings. The control panel shall provide pneumatic control signals for cooling coil and mixed-air actuators. The panel shall include electronic controllers, economy cycle for outside air control, electronic temperature sensors, electronic-to-pneumatic transducers, and diagnostic features.

2.2.2 Electronic Controller

(B)

All electronic controllers shall be plug-in modules which provide proportional-plus-integral control action with output control signals of 0 to 10 (2 to 10) volts DC or 4 to 20 milliamps DC. All controllers shall provide DC voltage outputs for the set point and the measured value of the control sensor to permit suitable display for diagnostics. Each controller shall be directly connected to electronic temperature sensors described below and provide an accuracy of 0.5 degrees C (0.9 degrees F) or better for all steady-state load conditions. The change in the controller output shall be less than .01% of full scale for each degree C change in ambient temperature from 10 to 40 degrees C (50 to 104 degrees F). Every controller shall have a filter on each input which attenuates signals with frequencies above 5 Hertz at the rate of at least 40 decibels per decade.

2.2.3 Economy Cycle Control for Mixed Air

(C)

An electronic differential control unit shall automatically switch mixed-air control from the modulating electronic controller described above to a minimum outside air control device which can be manually adjusted. The differential control unit shall be a plug-in module and permit direct connection to electronic sensors described below and provide automatic switching action based on a comparison of outside air (OA) temperature with return air (RA) temperature as follows:

- (1) As OA temperature decreases and falls below RA temperature by 1 degree C (1.8 degrees F), the mixed air control is switched to permit control by the modulating electronic controller.
- (2) As OA temperature rises and goes above RA temperature by 1 degree C (1.8 degrees F), control of mixed air is switched to the minimum outside air control unit.

The minimum outside air control device shall be manually adjustable to permit outside air fraction to be adjusted from 0% to 20% of full flow. The differential control module shall provide voltage outputs for the measured values of both control sensors for diagnostic display. The differential control module will provide a voltage output to display the status of the output on an indicator lamp.

2.2.4 Electronic Temperature Sensors

(D)

All temperature sensors shall be resistance temperature detectors with platinum sensing elements having a resistance of 100 ohms at 0 degrees C (32 degrees F), an accuracy of 0.3 degrees C (0.5 degrees F) or better throughout the temperature range of 0 to 100 degrees C (32 to 212 degrees F), and shall have a temperature characteristic in conformance with the international standard DIN 43760. Averaging temperature sensors shall be used to measure the temperature of mixed-air streams in ductwork in the locations noted on the Drawings. The averaging sensors shall include a continuous sensing element of sufficient length to permit mounting in accordance with the Drawings.

2.2.5 Electronic-to-Pneumatic Transducers

The voltage output of each controller shall be converted to a proportional pneumatic signal with an electronic-to-pneumatic transducer. The voltage input range of the electronic-to-pneumatic transducer shall match the output voltage range of the controller, and the output pneumatic signal of the transducer shall match the range of the pneumatic actuators on the valves and dampers. All transducers shall meet the following performance criteria:

Accuracy of conversion: 5% of full scale or better

Linearity: within 2% of full range or better

Hysteresis: within 1% or less of full scale.

Variations of air supply pressure: less than 5% for changes from 18 psi to 30 psig.

Effect of ambient temperature: less than 5% of full scale for changes in ambient air temperature from 10 to 40 degrees C (50 to 104 degrees F).

2.2.6 Provisions for Diagnostics

Each control panel shall include a 3-1/2 digit digital voltmeter with an accuracy of 0.1% of full scale. The voltmeter shall be connected to the controller outputs by means of a switch to display all temperatures measured by control sensors, all set points in the controllers, and all outputs of the controllers in each panel. A push-button, momentary contact switch shall be wired to enable a precision resistor to be connected in place of the control sensor and provide a calibration check. A status light on the control panel shall indicate the status of the economy-cycle unit for outside air control.

2.3 Electronic Control Panel for Fan Speed Control

2.3.1 General

Provide an electronic control panel for fan speed control for each fan where indicated in the Equipment Schedule of the Drawings. The control panel shall provide a DC voltage output to the variable-speed motor drive for the fan, and maintain the static pressure at the control point in the ductwork at the setpoint of the controller. Every panel shall include an electronic controller, electronic pressure transducer, and diagnostic features.

2.3.2 Electronic Controller

All electronic controllers shall be plug-in modules which provide proportional-plus-integral control action with output control signals of 0 to 10 (2 to 10) volts DC or 4 to 20 milliamps DC. The set point of the controller shall be displayed digitally by one of the following methods:

- (1) Numbers are printed on a thumbwheel switch which indicate the value of the set point, or
- (2) The set point voltage is adjusted with a potentiometer and displayed on a digital voltmeter with at least 2-1/2 digits and an accuracy of 1% or better.

Every controller shall provide an accuracy of 0.5% of full scale for all steady-state load conditions. The change in the controller output shall be less than .01% of full scale for each degree Celsius change in ambient temperature from 10 to 40 degrees C (50 to 104 degrees F). Every controller shall have a filter on each input which attenuates signals with frequencies above 5 Hertz at the rate of at least 40 decibels per decade.

2.3.3 Electronic Pressure Transducer(E)

All electronic pressure transducers shall provide an output signal of 0 to 10 (2 to 10) volts DC or 4 to 20 milliamps DC for the static pressure range (of inches of water) (indicated on the

Drawings). All transducers shall meet the following performance criteria:

Accuracy: 2% of full scale or better

Repeatability: 0.5% of full scale or better

Effect of ambient temperature: less than 2% of full scale for ambient temperature changes from 10 to 40 degrees C (50 to 104 degrees F).

Effect of variations in line voltage: less than 1% for 10% changes in the nominal value of the line voltage.

2.3.4 Provisions for Diagnostics

Each control panel shall include a digital voltmeter with at least 2-1/2 digits and an accuracy of at least 1%. The digital voltmeter shall permit the measured value of the control sensor to be displayed. A direct-reading mechanical gauge for measuring static pressure shall be provided which is separate and independent of the electronic pressure transducer. The gauge shall be a dial type with a dial diameter of 4 inches or larger and an accuracy of at least 3% of full scale. The range of the mechanical gauge shall be equal to that of the electronic pressure transducer.

Technical Notes

A. This guide specification is for electronic control panels and was written to provide an example of how to incorporate electronic controls in a particular VAV system design. Brackets around phrases, such as 0 to 10 (2 to 10), are used to indicate options to be selected by the specification writer. Where blank spaces are provided, such as inches of water, the specification writer is to fill in the data required for the specific application. The letters on the right margin refer to these Technical Notes and must be deleted during preparation of project specifications.

B. Throughout this guide specification, numerical values of temperatures are given in units of degrees C where C is the abbreviation for "Celsius" and followed by the corresponding value in degrees Fahrenheit in parentheses. To prevent confusion, specification writers should alter these as needed to provide a uniform style throughout the project specifications.

C. Paragraph 2.2.3: The differential control module with an output to switch states is sometimes referred to as a differential thermostat. A specific method of implementing the logic for selecting the appropriate control output was illustrated in Figure 7 of the main text of this report and used a differential control module, a relay, and a High-Signal Selector. A similar block diagram should be included in the drawings.

D. Paragraph 2.2.4: In the citation for the temperature characteristic of platinum thermometers (DIN 43760), DIN is the abbreviation for the standards organization in Germany -- Deutsches Institut fur Normung, Burggrafenstrasse 4-10, Postfach 1107, D-1000 Berlin 30. Other citations for this platinum characteristic include "Type-385 platinum" or platinum with a temperature coefficient (alpha-value) equal to 0.385% per degree C.

E. Paragraph 2.3.3: The pressure range may be listed on the drawings, since this allows different pressure ranges for different fan systems. Typical ranges are 1/2 inch, 1 inch, 2 inches, and 4 inches of water.

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