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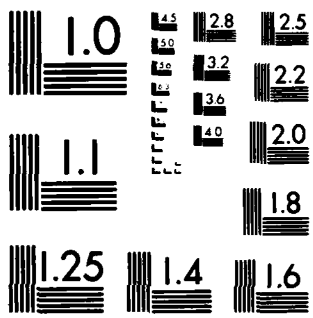

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US Army Corps
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Construction Engineering
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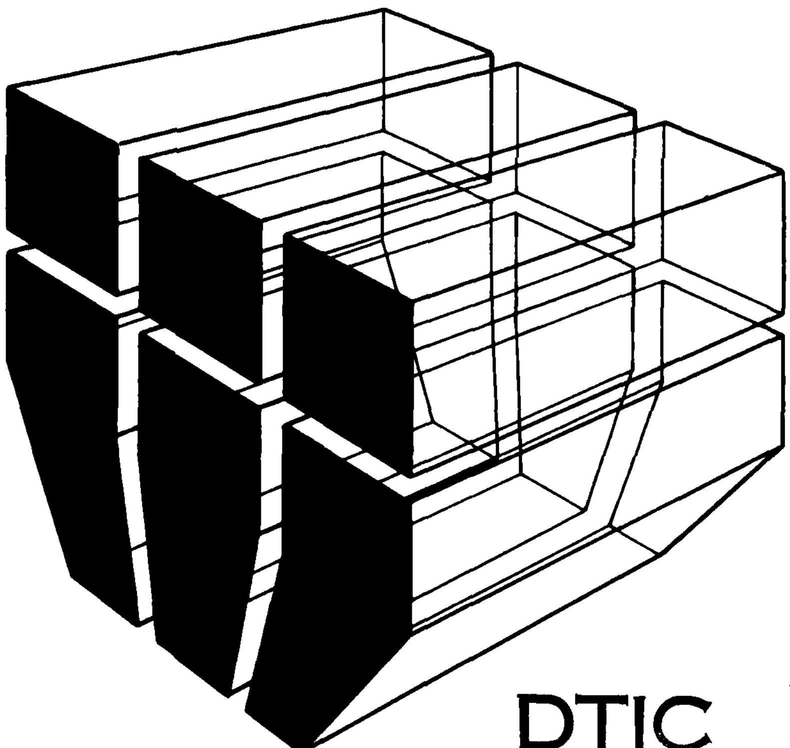
SPECIAL REPORT E-197
July 1984
Retrofit Control Systems for Energy Conservation

AD-A145 530

SUMMARY OF USA-CERL RESEARCH ON CONTROL OF HEATING, VENTILATING, AND AIR-CONDITIONING SYSTEMS



by
Douglas C. Hittle
David L. Johnson

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This report summarizes research conducted to date by the U.S. Army Construction Engineering Research Laboratory (USA-CERL) to devise new technologies for improving heating, ventilating, and air-conditioning (HVAC) controls. As new technologies are developed, they will be disseminated not only through the usual mechanisms (i.e., Army, Corps of Engineers, and USA-CERL publications), but also through users groups, in which potential recipients will have a chance to ensure that the products are responsive to their needs.

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The research will be done in three main areas: (1) component evaluation, (2) control loop implementation, and (3) system application. The objective will be to develop control systems, especially for retrofit applications, that are simple, efficient, reliable, maintainable, and well-documented.

Conclusions of research done so far indicate that:

1. Many HVAC systems are not performing as designed.

2. In some applications, pneumatic temperature control equipment is not accurate enough.

3. Pneumatic actuators should be retained, when possible.

4. Thermistor temperature detectors are not appropriate for HVAC applications.

5. Humidity sensors are prone to drift and hard to calibrate in the field.

6. Proportional plus integral control schemes, coupled with accurate sensing and control, can significantly reduce operating costs.

7. The prototype retrofit control panel developed by USA-CERL should provide both reliability and cost savings.

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) and the Department of Energy (DOE). The Army portion of the funding came from Project 4A762781AT45, "Basic Research in Military Construction"; Task B, "Energy Systems"; Work Unit 002, "Retrofit Control Systems for Energy Conservation." The DOE portion of the funding came under IAO DE-AI02-83CE30802 dated 22 September 1983.

Dr. Douglas C. Hittle and Dr. David L. Johnson of USA-CERL's Energy Systems Division (ES) were the Principal Investigators. Mr. B. Wasserman, DAEN-ZCF-U, was the ACE Technical Monitor. Mr. R. G. Donaghy is the Chief of USA-CERL-ES.

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

CONTENTS

SUMMARY OF USA-CERL RESEARCH ON CONTROL OF HEATING, VENTILATING, AND AIR-CONDITIONING SYSTEMS

1 INTRODUCTION

Background

The large increase in fuel prices and the need to cut costs has motivated the Army to conserve energy at its installations. This has prompted military planners to seek methods that will decrease the Army's energy use as much as possible, while retaining the quality of its programs.

Heating and cooling buildings consume a large percentage of the Army's energy. Therefore, recent goals have been to improve and devise systems that will make both new construction and present buildings as energy-conservative as possible.

Research has shown that one of the areas needing improvement is heating, ventilating, and air-conditioning (HVAC) controls. Widespread failures of these devices to perform properly have caused building energy consumption to be much higher than necessary. Therefore, there was a need to find ways of correcting these failures.

One of the energy research programs conducted by the U.S. Army Construction Engineering Research Laboratory (USA-CERL) has been an investigation into why these HVAC controls have failed and to devise new technology to prevent such failures in the future.

Purpose

The purpose of this report is to summarize USA-CERL's research to date on improving HVAC controls.

2 PROBLEM ANALYSIS

Field and laboratory research activities conducted by USA-CERL have indicated the severity of problems with HVAC controls. One of these activities was evaluating 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 HVAC control components were imprecise and unreliable.[1]

In another project, USA-CERL built a full-scale HVAC system and incorporated precision sensors for performance measurements.[2] Although the purpose of the experiments with the HVAC system 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 manufacturer's 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 several times by USA-CERL and the manufacturer's servicemen, they would continue to drift out of calibration.

The controls in the test facility were specified and installed in much the same way as those used for Army buildings. Also, the brand and model of the components were known to have been widely used across the country. Thus, 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 revealed that controls are a major problem at Army installations. The publication of the experimental results in the *ASHRAE Journal*[3] (see Appendix) attracted nationwide attention; many engineers from both the Army and the private sector contacted USA-CERL to indicate their negative experience with many HVAC control systems.

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[1] D. L. Johnson and D. M. Joncich, *Procedures for Acceptance Testing of Solar Energy Systems*, Technical Report E-192/A141839 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], April 1984).

[2] William Dolan, *Validation Data for Mechanical System Algorithms Used in Building Energy Analysis Programs*, Technical Report E-177/ADA115182 (USA-CERL, February 1982).

[3] D. 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).

Based on field and lab observations and the reaction of field practitioners to the preliminary results, it was determined that problems with control systems in heating and air-conditioning systems were severe and widespread, justifying a major research effort. This research was examined at a meeting held to discuss the responsiveness of upcoming products from USA-CERL's overall energy research program to military needs. Potential users of the research attending the meeting included representatives from the Directorate of Engineering and Housing, the major commands (Training and Doctrine Command [TRADOC], Forces Command [FORSCOM], and Development and Readiness Command [DARCOM]), Office of the Chief of Engineers (OCE), and the Army Energy Office. The discussion of HVAC system controls research prompted a vigorous response from these representatives. Both FORSCOM and TRADOC later indicated that the area of "upgrading existing control systems" was their highest energy research priori Other groups have also recognized the severity of the problems with control systems, including the Air Force, Navy, Department of Energy, and ASHRAE.

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. They 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 these components makes implementation of the designed complex control strategies unsuccessful.

These systems are maintenance-intensive, and FE staff often do not have the skilled manpower needed to make them perform as designed. Since detailed, systems-specific maintenance instructions are rarely provided during design and construction of buildings, maintenance burdens become very 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. On the other hand, malfunctions which lead to occupant discomfort require action from the maintenance staff. The most 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 being used at military facilities are too complex, unreliable, energy-inefficient, difficult to maintain, and poorly documented. This problem is no secret. A recent Air Force survey[4] of maintenance personnel from various Air Force installations summarized the maintenance staff's impression of heating and air-conditioning systems as follows: "The typical HVAC system in the USAF is in a total state of disarray, and our technicians are ill-equipped to remedy the problem."

3 RESEARCH OBJECTIVE AND APPROACH

The objective of USA-CERL's research is to develop control systems, especially for retrofit applications, that are simple, efficient, reliable, maintainable, and well-documented.

This research will be done in three main areas: (1) component evaluation, (2) control loop implementation, and (3) system applications. Figure 1 shows the schedule and Table 1 shows the list of deliverables.

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 more commonly used in process industries will be evaluated to determine its applicability to

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[4] R. L. Schultz and T. M. Kenna, *An Investigation into the Operation and Maintenance of Heating, Ventilating, and Air-Conditioning Systems in the United States Air Force* (School of Civil Engineering, Air Force Institute of Technology, Wright-Patterson AFB, OH, November 1982).

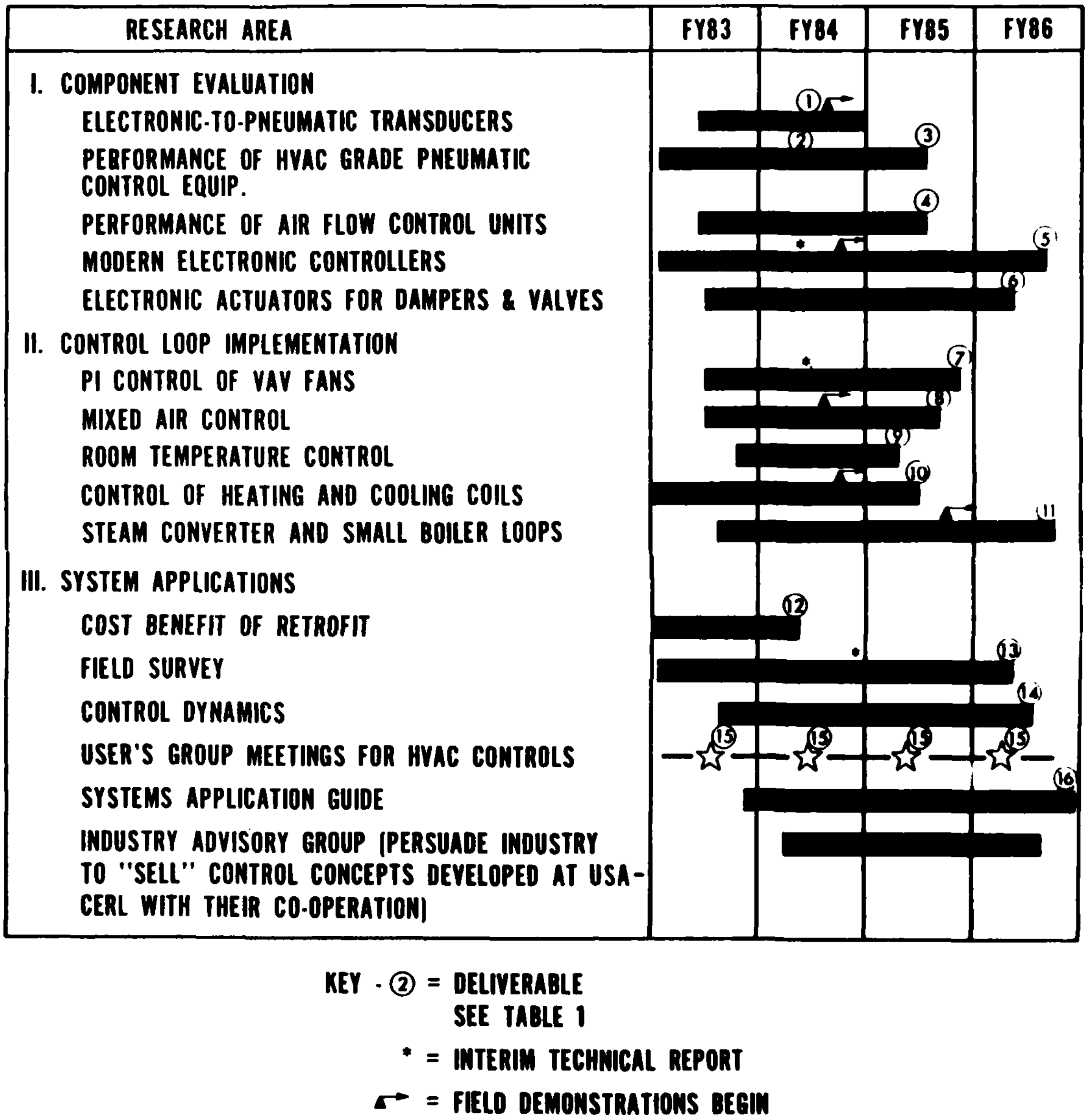

Figure 1. Projected schedule HVAC controls retrofit.

Table 1

List of Deliverables

1. Draft ETN, EIRS Bulletin, "Electronic-to-Pneumatic Transducers"

2. Draft ETN, "Preliminary Performance Assessment of HVAC Grade Pneumatic Control Equipment"

3. Draft ETN, "Performance of HVAC Grade Pneumatic Control Equipment"

4. Draft ETN, EIRS Bulletin, "Air Flow Control Devices"

5. Draft ETN, EIRS Bulletin, "Electronic Controllers"; draft ETL "Electronic Controllers" summarizes 1 through 4 above

6. Draft ETN, EIRS Bulletin, "Application of Electronic Actuators for Dampers and Valves"

7. Draft ETN, EIRS Bulletin, "Proportional Plus Integral Control of VAV Fans"

8. Draft ETN, "Mixed Air Control"

9. Draft ETN, "Room Temperature Control"

10. Draft ETN, "Control of Heating and Cooling Coils"

11. Draft ETN, "Steam Converter and Small Boiler Control"

12. Draft ETN, "Cost Benefit of Retrofit Control Systems" (includes specification and use of modular retrofit control panel developed at USA-CERL)

13. Draft ETN, "Results of Field Surveys on Control Systems"

14. Draft ETN, "Dynamics of HVAC System Control"

15. Users Group Meetings

16. Draft TM, "HVAC Control Systems Application Guide"; dra[illegible]isions to CEGS and draft ETN and ETL

HVAC control problems. Some specific components to be assessed are:

1. Typical HVAC grade pneumatic control equipment. Preliminary experiments on the performance of HVAC grade pneumatic temperature transmitters and receiver controllers have been completed. The results are described in *Retrofit of HVAC Control Systems*.

Performance [illegible] This control equipment [illegible]

[illegible] Systems, Draft Technical Report [illegible] USA-CERL [illegible]

if it is reliable and accurate enough for effective control.

3. Electronic to pneumatic transducers. These components provide a key link between modern electronic (and digital) controllers and existing pneumatic actuators for valves and dampers.

4. Performance of air flow components. The performance of variable air volume boxes and various dampers must be characterized to (a) determine which characteristics lead to reliability and (b) identify how these devices impact system controllability.

5. Electronic actuators for valves and dampers. These components can be directly linked to modern electronic and digital electronic controllers.

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 where accuracy is needed. Some of the subsystem control loops being studied are:

1. Efficient control of variable-volume fans.

2. Mixed air control (i.e., outdoor and return air damper control).

3. Room temperature control.

4. Effective control of heating and cooling coils.

5. Control of steam converter and small boiler systems.

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. USA-CERL's work in this area has already led to construction of a prototype modular control panel which is being tested and evaluated.

4 SUMMARY OF RESEARCH TO BE COMPLETED

The component evaluation research will comprise a number of important experiments. For example, if electronic controls are to be used more often, it is important to characterize the performance of electronic-to-pneumatic transducers and begin to understand how to specify accuracy and reliability. Also, it is necessary to more fully evaluate the performance of pneumatic control equipment for those small systems where complete retrofit may not be cost-effective. Another important area of component evaluation research is assessing the performance of air-flow control components. Variable air volume (VAV) boxes are an important part of the retrofit concept. Also, the characteristics of outdoor- and return-air dampers will be investigated to be certain that mixed-air control loops can be implemented without difficulty and to assess the potential for freeze damage caused by cold air leakage in cold climates.

Modern electronic controllers must also be fully assessed. Additional experiments will be conducted on drift, accuracy, and reliability so that test procedures can be defined and included as part of future guide specifications.

One portion of the research will involve establishing the characteristics of electronic actuators for valves and dampers. This will determine whether these devices can be applied in small-scale systems where pneumatic compressors would be prohibitively expensive.

In the general area of control loop implementation, experimental research will be done to verify control concepts for variable-volume fans. The characteristics of the sensors, the PI loop, and the fan system will be carefully defined to avoid potential instabilities.

The dynamics of room temperature control will also be explored. While room temperature control is fundamental to HVAC system design, very little experimental or theoretical analysis has been done to establish how closely room temperature can be controlled, what the dynamics of room temperature control are, how to design and place thermostats and thermostat enclosures, and how to ensure that rooms are controlled with an acceptable level of comfort.

Research will continue on the control of heating and cooling coils, since even these simple control loops are not fully understood. Both simulation and experimental research will be conducted to give direction on commissioning of control systems (setting the proportional and integral gain constant) so that the systems will operate stably under a wide variety of loads.

Another problem area is the control of steam converters and small boilers. Steam is particularly hard to control because a small amount of steam, when condensed, releases a large amount of heat. Furthermore, resetting water temperatures with outdoor-air temperature may be desirable in many applications to improve the stability of the system and its energy efficiency. Reliable schemes for controlling steam converters and small boilers will be investigated.

In the area of systems applications, research will continue on the interaction of the various loops in the HVAC system. The results will ensure that proposed designs will be stable under wide-ranging field conditions.

Demonstration programs like those currently planned for several Army and Air Force installations will be done to show that new control strategies and control equipment can be implemented easily. Finally, training programs, system application guides, and training aids will be developed for rapid transfer of these technologies to the field.

5 MODE OF TECHNOLOGY TRANSFER

To ensure the earliest possible implementation of research results, USA-CERL hopes to foster a shared technology transfer program involving researchers, field users, manufacturers, trainers, and policy-makers. It will require several years to complete the research needed to solve most of the control problems experienced by the field. However, all the work need not be completed before products are transferred to the field. For example, information on solutions to office system control can be made available, even though hospital control problems are not yet solved. Research products will be introduced to the field in phases. This approach has the dual advantage of providing information to the field at the earliest possible date while allowing field users a way to provide feedback on the solution's effectiveness.

Part of the technology transfer plan is to disseminate information through the usual mechanisms: for example, Engineer Technical Notes, Engineer Technical Letters, revisions to technical manuals and guide specifications, and technical reports. However, these mechanisms can often be time-consuming, delaying the transfer of the information to the field, and they do not provide the beneficial face-to-face contact between researchers and in-field users. Therefore, USA-CERL is forming a users group made up of representatives from installations, major commands, Districts, and OCE. This group will provide guidance to ensure that USA-CERL's research products are responsive to field needs by viewing directly the hardware and control schemes being developed. They will also help ensure that research results and recommendations reach the field practitioners who need them most.

Long-term technology transfer will be assured if new control concepts are adopted as standard engineering practice. To help foster acceptance of the research on HVAC controls, USA-CERL has been actively working with engineers from the private sector, specifically research and sales representatives from most of the major control companies. In addition, USA-CERL has established an informal industry advisory group to foster a continuing liaison with the control industry. The goal is to ensure that the type of retrofit control systems which evolve from research can be procured from control system manufacturers. USA-CERL hopes to persuade the industry to aggressively market more energy-efficient and reliable components and control schemes.

Laboratory personnel are also enhancing technology transfer by actively participating in engineering societies, serving on technical committees dealing with control systems, presenting papers on research results, and helping edit the *ASHRAE Handbook*[6] sections dealing with controls. Researchers are also teaching "continuing education" for courses on controls offered practicing engineers by ASHRAE, the University of Wisconsin, and the University of Illinois. As a result, USA-CERL's research results will impact both private- and public-sector engineering practice immediately.

Another part of the technology transfer process is a demonstration program of control research products which began in FY84 and will continue through FY87. The research products will be demonstrated in phases in cooperation with members of the users group; this will allow the products to be fully evaluated in a field environment, with the results providing the feedback needed to further refine them. The demonstration program will also allow potential users to view the products in field use and thus prepare for their implementation on a large scale at Army installations.

Use of the current research products involves the use of some control components and concepts which may be unfamiliar to potential field users. To help these users, USA-CERL has designed and built several training aids. These aids consist of apparatus with appropriate gauges and instruments that show how the components work. This type of training aid can be used to instruct users in control operations methods (for example, selecting the settings for a controller with proportional plus interval modes of control). The training aids are also valuable for demonstrating the research products to Army leaders and showing them the principles on which they were designed. They can then use this information to successfully implement the products in the field. Four such aids are close to completion: (1) a prototype of a versatile retrofit control panel, (2) a VAV box for controlling air flow to a room, (3) a proportional plus interval (PI) loop controller applicable to modern electronic controllers, and (4) a static pressure control for variable air volume fans. As the research progresses, USA-CERL will explore other possibilities for training aids, collaborating with Huntsville Division, where the units may ultimately be used in training courses.

6 CONCLUSIONS OF RESEARCH TO DATE

Preliminary findings from research to date have led to a number of conclusions which should impact current design and maintenance practice:*

1. Many HVAC systems are probably not performing as designed.

2. Pneumatic temperature control equipment is not very accurate.

3. When possible, pneumatic, rather than electronic, actuators should be used since they are cheaper and require less maintenance.

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[6] *Handbook Series of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers* (ASHRAE).

*The experimental work leading to these conclusions and detailed instructions for implementing prototype retrofit control systems are described in the USA-CERL Draft Technical Report, *Identification of HVAC Control System Problems for the Development of Retrofit Procedures in Military Buildings.*

4. Thermistor temperature detectors are inappropriate for HVAC applications because they must be calibrated so often.

5. Humidity sensors are prone to rapid drift and difficult to calibrate in the field. This makes implementation of enthalpy economy cycles almost impossible.

6. 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.

7. The prototype retrofit control panel developed at USA-CERL emphasizes simplicity, reliability, maintainability, accuracy, appropriate use of PI, higher-quality components, and the use of standard sensors and signals as a means to achieve reliability and cost savings.

8. Significant energy costs savings can be expected by using the prototype control panel scheme on VAV systems and on multizone and reheat systems converted to variable air volume systems; maintenance costs should also be reduced.

APPENDIX:

Theory Meets Practice In A Full-Scale Heating, Ventilating And Air-Conditioning Laboratory

Experiments performed at the Construction Engineering Research Laboratory (CERL) on a full-scale HVAC system produce results having an immediate, practical bearing on the design of new HVAC systems and on retrofit of existing systems.

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This article describes selected results from experiments performed at the Construction Engineering Research Laboratory (CERL) on a full-scale heating, ventilating, and air-conditioning system. More than 100 experiments were performed on variable volume systems, terminal reheat systems, dual-duct variable air volume systems, dual-duct constant volume systems, packaged direct expansion systems, and fan coil units.[1] Results from some of these experiments may have immediate, practical bearing on the design of new HVAC systems and on retrofit of existing systems. These experimental results are discussed, along with problems encountered in the commissioning of the HVAC system laboratory.

In the following presentation, the experiment and its instrumentation are described and the measured performance of the following components and systems are discussed: (1) control of fan inlet guide vanes, (2) variable air volume temperature controller, (3) volume regulators on VAV boxes, (4) pneumatic temperature transmitters, (5) receiver/controllers, (6) enthalpy economy cycle logic, and (7) humidity transmitters. Commissioning problems associated with the main fan, the inlet guide vanes, the duct pressure transmitter, the VAV boxes, the chiller, and the boiler are also described.

UNDER the sponsorship of the U.S. Department of Energy and the Army Corps of Engineers, a full-scale HVAC test facility was constructed inside a high bay at the Construction Engineering Research Laboratory (CERL) in Champaign, Illinois. The system consists of four spaces or rooms and an air-handling system served by a boiler and chiller. Each zone is equipped with two fan coil units and a supply and return air-duct system. The zones are each 4.6 × 3 × 3 meters high. Construction is typical stud wall with interior gypsum board and exterior plywood siding.

Walls are fully insulated; a vapor barrier was attached to the outer surface of the four zones before surface paneling was applied. Access to the zones is through well-sealed panels. By using heavy insulation between zones and by maintaining the zone temperatures at or about the same temperature as the surrounding building which houses the experiment, heat transfer between zones and between the zones and the surrounding environment is negligible.

A built-up air handler provides conditioned air at a regulated temperature to meet the heating and cooling loads required in each zone. Loads can be imposed on the zones by controlling the amount of heating or cooling performed by the two fan coil units placed in each zone. The fan coil units were designed to supply a maximum of about 10.5 kW of heating or cooling.

The main air-handling unit is a conventional two-deck blow-through unit with forward-curved fan blades designed to deliver up to three cm/s of air. Appropriately sized heating and cooling coils are placed downstream of the main fan, and the fan is equipped with variable inlet guide vanes to control capacity. The system is configured so that varying amounts of outdoor air (up to 100 percent) can be introduced. In addition, an outdoor air simulator is provided on a branch of a duct leading from the outdoors; thus, outdoor air can be conditioned to emulate summer during the winter or winter during the summer. The researcher then does not have to depend on the outdoor climate to provide a source of outdoor air at a specified condition.

The duct system delivering air from the air handler to each zone is designed to operate at constant or variable volume in either a dual-duct or single-duct mode. A terminal reheat coil is installed in the duct just before the air is delivered to the zone (Fig. 2).

Hot water is supplied to the main air handler coil, reheat coil, heating coil in the outdoor air simulator, and the fan coil units in each zone, using a boiler and a steam-to-hot-water converter. The overall design capacity of the boiler system is 73 kW.

A nominal 70 kW (20-ton) capacity chiller provides system cooling. The four-cylinder reciprocating compressor on the chiller is fitted with three-stage cylinder unloaders. The chiller rejects heat to a 105 kW capacity cooling tower with capacity control.

Instrumentation

A full complement of instruments was installed throughout the HVAC test facility. Measurements were required for: (1) water temperature, (2) air temperature, (3) water flow, (4) air flow, (5) electric power, (6) differential pressure, and (7) relative humidity. Tem-

D C Hittle, team leader, W H Dolan, principal investigator, D J Leverenz, team leader, and R Rundus, researcher, are all with the Energy Systems Division of the Construction Engineering Research Laboratory (CERL), Champaign, IL

peratures are measured using four-wire, calibrated platinum probes. Temperature measurement accuracy of ±.05°C was obtained by using the four-wire probes, which eliminated the effects of lead wire resistance, and by carrying out exacting calibration experiments.

Both air- and water-flow measurements are made using venturis in the flow streams. Pressure taps at the inlet and at the throats of the venturis are connected to transducers; output is a DC voltage. Tees were also inserted in the lines to connect the venturis to control panel manometers. Each water-flow venturi was bench-tested four times before installation to obtain its average coefficient. The large air-flow venturis were calibrated using hot wire annometer traverses in the throat of each venturi. (Note that the air-flow venturis are so large that their performance is nearly theoretical.)

Electrical power is measured with watt transducers fed by appropriately placed potential and current transformers. Relative humidity is measured using thin-film capacitance humidity probes which produced an output voltage ranging from 0 to 150 mV, proportional to relative humidity. Data is logged with a microcomputer-controlled scanning digital voltmeter.

An important feature of the HVAC test facility is that its instrumentation is sufficient to carry out energy balances on several streams simultaneously. For example, the air stream energy can be calculated by measuring the entering air temperature, air volume flow rate, and return air temperature of the air being supplied to a zone. Similarly, by measuring water flows and temperatures, the amount of energy being added to the zone by the heating or cooling fan coil unit can be determined; the two numbers can then be compared to determine if there are any sensor calibration errors or malfunctions. These types of energy balances can be performed for each zone and for the system as a whole. By calculating these energy balances with the microcomputer, which is simultaneously collecting data from the system, consistency checks can be performed "on the fly," and any defective or out-of-calibration sensor can be repaired before proceeding to collect accurate experimental data. This approach has been particularly valuable for saving time and labor.

Results

One of the subsystems tested was the **static pressure control systems on a fan equipped with inlet guide-vane flow control**. The fan tested was a .4-meter-diameter, forward curve, centrifugal fan, equipped with inlet guide vanes. Initially, the speed was set by means of an adjustable pulley to bring the fan's capacity to three cm/s at 590 kp. Two automatic inlet vane controllers were tested: a conventional pneumatic proportional control and a high-gain, low-pass, electronic control scheme.

The pneumatic proportional control had a differential pressure transmitter, a pneumatic actuator fixed to the inlet vane control shaft, and a receiver controller with adjustable gain and offset. The receiver/controller received inputs from the differential pressure transmitter and from a set point pressure source, and provided an output signal to the pneumatic actuator controlling the inlet guide vanes.

The second type of controller had the same pneumatic transmitter, as

Figure 1 CERL's HVAC experimental facility

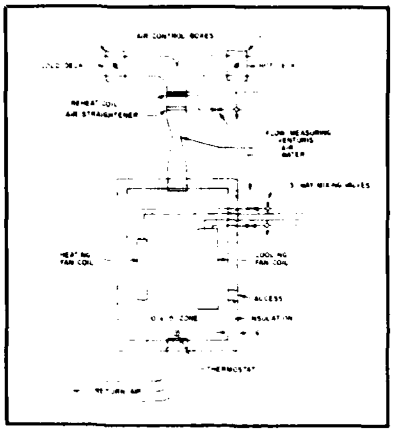

Figure 2 Diagram of typical zone

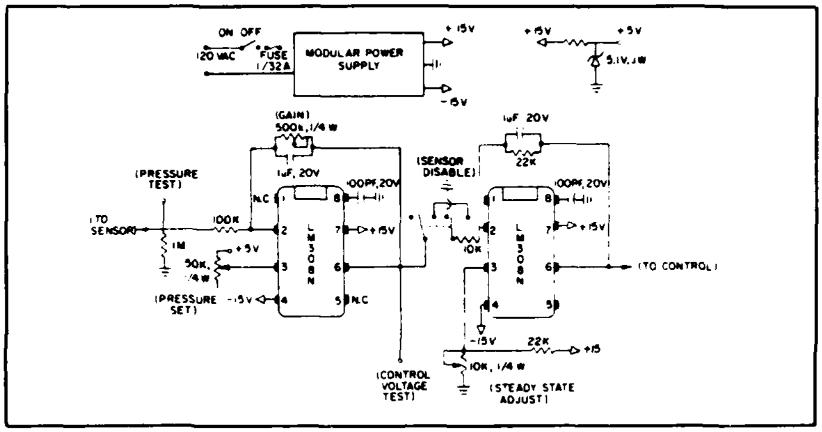

Figure 3 Control schematic — electronic inlet vane controller

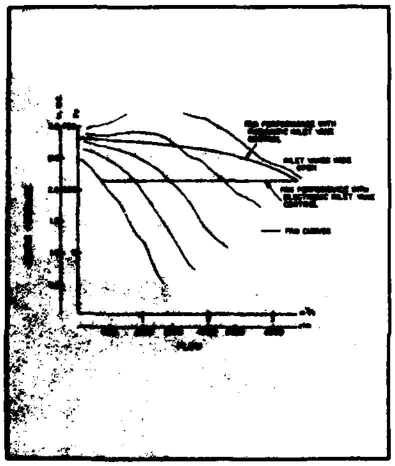

Figure 4 Fan operation under automatic control

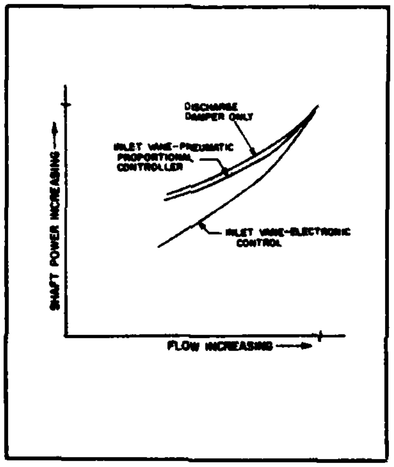

Figure 5 Fan performance with different volume-control schemes

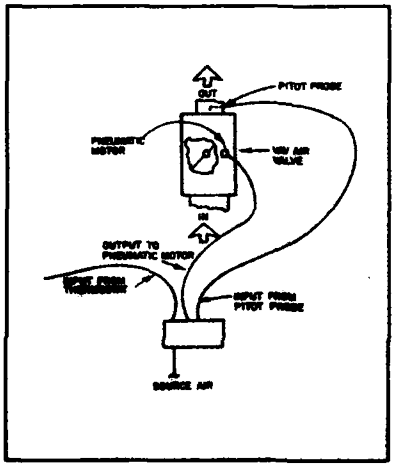

Figure 6 VAV zone temperature controller results

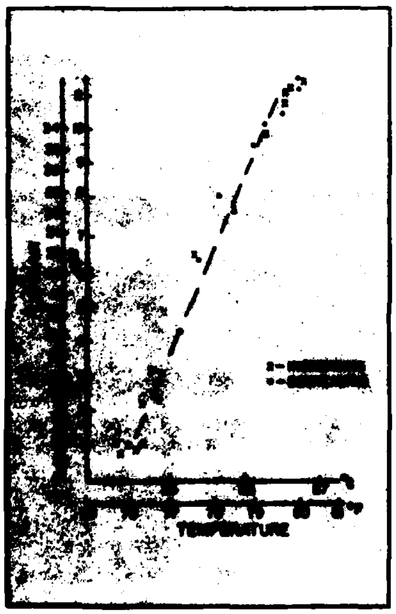

Figure 7 Pneumatic volume regulator (PRV)

Table 1 Record of Receiver/Controller Drift Over 72 Hours

	Input (psi)*	Output as Calibrated (psi)†	Output Observed After 72 Hours†
Circulating hot water	7	10	19
	9	9	18
	11	8	14
Hot deck	4	12	19
	10	8	18
	11	7	14
Cold deck	7	7	14
	10	[illegible]	14
	12	[illegible]	17
OES heating coil	8	[illegible]	18
	9	11	14
	11	7	14
OES cooling coil	8	8	16
	10	11	12
	13	13	15

*Input pressure (signal from temperature transmitter) was controlled from a variable pressure source and measured by a mercury manometer.
†Output pressure (control pressure for mixing valves) was measured on precision gauge internal to the receiver/controller.

Metric conversion: 1 psi = 6.9 kPa.

well as a pneumatic-to-electric transducer that provided an electric signal to an amplifier circuit which had high gain at low frequency and low gain at high frequency. This output from the amplifier was supplied to an electric-to-pneumatic transducer, which provided the control signal to the pneumatic actuator fixed to the inlet vane control shaft.

The distinction between the two control schemes is that the conventional pneumatic device has an essentially constant gain, irrespective of the frequency with which changes in the error signal (difference between sensed duct pressure and set point pressure) being sensed occur. On the other hand, the electronic device has very high gain for slowly changing signals, but very low gain for rapidly oscillating signals. By virtue of the high low-frequency gain and low high-frequency gain, steady-state error can be reduced without causing control instability. Figure 3 shows the circuit for this simple amplifier.

Figures 4 and 5 give the results of tests for these two control schemes. Figure 4 shows how the duct pressure increases substantially under part load when the pneumatic receiver/controller is used, as compared to almost no increase in pressure when the electronic device is used. Figure 5 shows the dramatic improvement in the part load power consumption of the fan with the electronic high-gain, low-pass amplifier. This change is caused by the ability of the control system to maintain the set point pressure by regulating the inlet guide vanes. Notice that the conventional pneumatic controller performs only slightly better than a discharge damper system.

Tests were also performed on the **variable air volume (VAV) zone temperature controller** to determine the relationship between room temperature and the amount of cooling delivered to the room. Results are shown in Figure 6. Figure 7 shows the pneumatic volume regulator control configuration used for the variable volume boxes tested. Note from Figure 6 that there is an approximately straight-line relationship between zone temperature and the amount of cooling delivered to the zone (a straight-line relationship is frequently assumed in simulating the cooling system in a room).

This straight-line relationship, however, arises from the combination of nonlinear effects. First, as zone temperature increases, the rate of cold air increases proportionally to the square root of the increasing temperature. This is caused by the performance of the VAV box which positions the cooling air damper to match the thermostat pressure to the pressure differential of the pitot tube in the VAV box. Second, as the zone air temperature increases, the temperature difference between the supply air and the zone air temperature increases (assuming constant delivery air temperature), thus increasing the cooling effect.

The pressure volume regulators on the VAV boxes were also examined separately. The input range to the pressure volume regulators is nominally 55 to 89 kPa. However, this pressure range was found to be inexact. Several pressure volume regulators did not respond until inputs exceeded 62 kPa, while several others responded to inputs as low as 48 kPa. Since each VAV box has a pressure volume regulator, this lack of precision can cause problems when the thermostat is used to control two pressure volume regulators, as in a dual-duct VAV system, or when a single-duct VAV system is equipped with a reheat coil.

For example, in the dual-duct VAV system, one zone thermostat is used to control two pressure-volume regulators sequentially. In this application, the thermostat signal for the dual-duct box is piped directly to the pressure-volume regulator used for cooling, and the signal is inverted and offset prior to being connected to the pressure-volume regulator used for heating. If one pressure volume regulator operates between 48 and 82 kPa and the other from 62 to 96 kPa, more chilled air will blend with the heated air than is necessary or intended by the system designer. This can substantially waste energy.

In a similar configuration using a single-duct VAV with reheat, imprecise response of the pressure-volume regulators can allow the reheat coil to begin to add heat before the VAV box has been closed to its minimum position. While it was simple enough to make adjustments to preclude inefficiency during these lab experiments, such imprecisions may not be detected in the field, so the controls may operate below optimum efficiency.

Figure 8 shows another important result. Here, the **pneumatic temperature transmitters** were tested as received. Of the five temperature transmitters, two performed roughly as expected. For the other three, the gain and/or the set point had to be adjusted to bring the temperature transmitters within the expected performance range. For example, Figure 8b shows a transmitter in which both the gain and the set point require adjustment. Figure 8e shows a case in which the gain adjustment is nearly correct, but set point adjustment is required. A practical conclusion that can be drawn from this test of pneumatic temperature transmitters is that field adjustment is probably required, even though factory calibration is claimed by the manufacturer.

In other tests, six **fluidic receivers/controllers** were calibrated, and the various gains and set points were documented. One week after the initial calibration, the state of each control device was investigated. Testing was accomplished by disconnecting the receiver/controllers from input signals (i.e., temperature transmitters) and providing a manually adjusted pressure source as input. Mercury manometers were used to measure the pressure of the input and output ports of the receiver, and the output pressure was recorded for various input pressures. These test results are given in Table 1.

Unfortunately, all six receiver/controllers experienced severe problems. Drifting off calibration occurred often in less than 72 hours. In fact, receiver/controllers were calibrated daily so that testing of other components in the system could continue. What is particularly disturbing about the results of this test is that if receiver/controllers like the ones tested had been placed in a field system, the heating and cooling coil valves they controlled probably would have remained open for the life of the system, unless the controllers were calibrated daily.

Another control subsystem that failed was the **enthalpy economy cycle control logic**. This device has four pneumatic inputs: outdoor air temperature, outdoor air relative humidity, return air temperature, and return air relative humidity. It is intended to allow appropriate amounts of outdoor air to be introduced at the mixing box if the outdoor air has a lower enthalpy than the return air. Four cases were tested. The testing was done by controlling the pneumatic inputs to the device and observing the output, thus eliminating errors caused by humidity and temperature transmitters. Table 2 provides the test results. Note that in two of the four cases, the wrong choice was made between outdoor air and return air.

Another serious shortcoming was the accuracy of the humidity transmitters. For example, in an environment measured to be 62 percent relative humidity, the output of three pneumatic humidity transmitters tested was 63 percent, 88 percent, and 96 percent. Hence, even if the enthalpy logic device had performed satisfactorily, input humidity measurements to the device would probably be so unrealistic that improper control would result

In addition to the problems identified in the tests described above, a number of start-up problems were discovered.

The original fan supplied for the air-handling unit was found to be less than 20 percent efficient, even with the guide vanes wide open. The fan was a backward incline-type centrifugal fan—the type least suited for VAV service because it provides poor power savings under dampered air-flow conditions. The principal reasons for the poor performance were: (1) the design of the inlet guide vanes greatly reduced the fan inlet area when they were in the wide open position, and (2) the way one of the two fan bearings

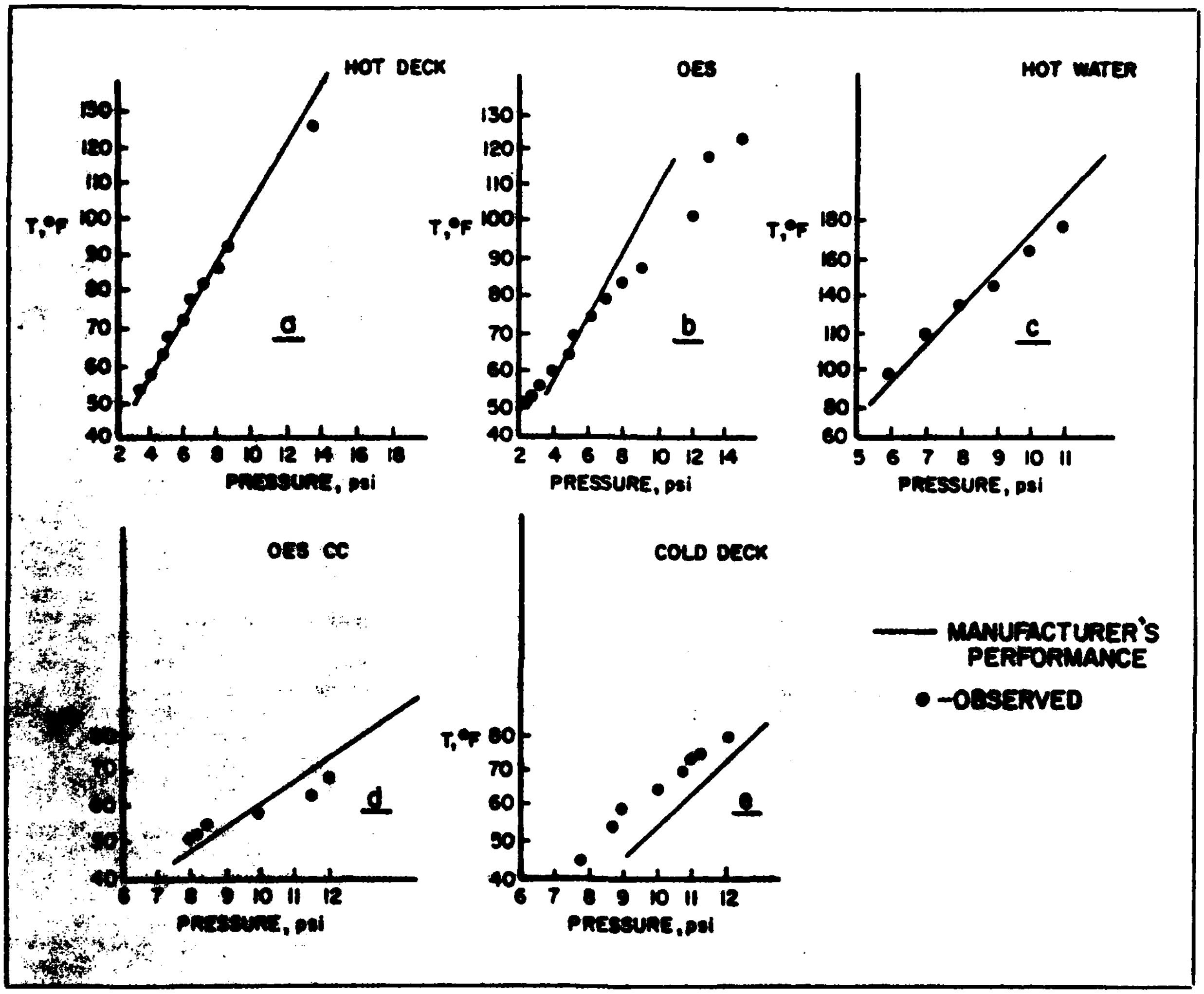

Figure 8 *Pneumatic temperature transmitter tests (Metric conversions 1 psi = 6.9 kPa, (°F − 32)/1.8 = °C)*

Table 2 Enthalpy Logic Device

[illegible]	TODA %psi	HODA %psi	EODA Btu/lbm	TRA °F/psi	HRA %/psi	ERA Btu/lbm	Output pressure/action	Comments
TRA > TODA ERA < EODA	85° 13.2	40% 7.8	32	90°F 13.8	50% 9	38.6	0 psi 100% ODA	Correct Operation
TRA > TODA ERA < EODA	85° 13.2	70% 11.4	40.8	90°F 13.8	50% 9	38.6	0 psi 100% ODA	Incorrect Operation
TRA < TODA ERA ≥ EODA	85° 13.2	40% 7.8	32	80°F 12.6	80% 12.6	38.6	12 psi Minimum ODA	Correct Operation
TRA < TODA ERA < EODA	80° 12.6	60% 10.2	34	75°F 12	50% 9	28.2	0 psi 100% ODA	Incorrect Operation

*T = temperature; H = relative humidity; E = enthalpy; RA = return air; ODA = outdoor air.
Pneumatic input from temperature transmitters, psi = T 0.12 + 3 (1 psi = 6.9 kPa).
Pneumatic input from humidity transmitters, psi = % v.h 0.12 + 3 (1 psi = 6.9 kPa).

was positioned and supported at the fan inlet furthe, reduced the fan inlet area.

Since the original fan did not meet the 50 percent efficiency specified, CERL required that the manufacturer replace the fan. The substitute was a forward-curved blade fan with a significantly improved mechanism for inlet vane control. Under similar testing conditions, the new fan gave 44 percent efficiency at its best operating point. However, a problem was experienced when half of the inlet guide vane linkages became uncoupled from the control shaft, causing the inlet vanes to remain closed on one side of the fan. As expected, the fan capacity dramatically decreased.

Without careful inspection and perhaps some field measurement, the poor performance of the original fan might have been undetected over the service life of the system. Similarly, the failure of half of the inlet guide vanes could also go undetected unless the fan system was inspected frequently.

Pressure transmitters were used to sense duct pressure and control the inlet vanes on the fan, described previously. However, the first two pressure transmitters supplied were inoperative and had to be replaced. The third transmitter, while it did not perform up to catalog specifications, was functional and was used.

The reverse acting accumulators, which were used to control the two VAV boxes in sequence in the dual-duct variable air volume configuration or the single-duct VAV box and reheat coil, drifted significantly. This malfunction would go undetected in almost any field system, resulting in an excessive blending of warm and chilled air or an excessive use of reheat energy.

The **70 kW chiller** used in CERL's HVAC experiment was supplied ready for operation. It required only the connection of electric lines, chilled water piping connections and condenser water piping to the cooling tower. As installed, however, the unit performed at less than 80 percent of the catalog coefficient of performance. This poor performance was traced to the improper setting of the refrigerant expansion valve. The superheat of the unit as supplied was about 14°C, while the manufacturer recommended about 3°C. This discrepancy in the superheat setting was particularly unexpected since the manufacturer advertised that the unit was bench-tested and adjusted at the factory. However, contact with the factory revealed that the bench-testing and factory adjustment were not begun until after the CERL unit was manufactured and shipped.

In addition to the poor superheat setting, one of two solenoids in the compressor head never worked properly. This solenoid was designed to unload one of the four cylinders. Since the chiller was fully instrumented, both problems were identified quickly; however, it is doubtful whether either would have been discovered in a typical field installation. The result would have been poor chiller performance over the life of the system.

The **boiler** used for CERL's HVAC experiment was tested and measured to be 78 percent efficient at full load. This was very close to the nameplate efficiency of 80 percent. However, the maximum output capacity was measured at 73 kW, even though the boiler nameplate claimed that the unit had a capacity of 105 kW.

The VAV boxes were installed complete with pressure-volume regulator devices that modulated the box to match the rate of supply air to the thermostat signal. The pressure-volume regulators were intended to eliminate changes in air flows if the duct pressure fluctuated. Of the eight pressure-volume regulators supplied with the boxes, two were totally inoperative and were replaced under warranty. However, all eight pressure-volume regulators were installed vertically. It was only after it was determined that they would not regulate the flow below 30 percent of maximum rate that the manufacturers were contacted to determine the cause of the malfunction. After contacting the original equipment manufacturer who supplied the pressure-volume regulator to the control company which supplied the unit to the VAV manufacturer, it was found that the device had gravity-actuated components and would function correctly only if mounted horizontally. This horizontal mounting requirement was not specified in any of the installed instructions or in the catalog. Consequently, if the unit had been mounted in the field, the problem might have been undetected for the life of the system.

Conclusions/recommendations

The results of some of the tests performed at the HVAC test facility have important implications to HVAC system designers. These conclusions must be drawn somewhat tentatively, since only one manufacturer's product was tested for each case. However, the products were supplied by manufacturers who have a large share of the HVAC market.

Apparently, relatively complex control systems of the type tested are difficult to maintain. While these systems can theoretically improve system efficiency, poor performance and failure of control system components suggest that the theoretical improvements may be difficult to achieve in the field.

The measured performance of many of the HVAC system components tested did not meet the manufacturer's specifications as delivered. For much of the equipment, efficient performance was achieved only after field adjustment.

Many, if not all, of the problems detected by the heavily instrumented HVAC system experiments would be undetected in a field application where there is little or no instrumentation.

If deficiencies like the ones CERL encountered were undetected for the life of the system, much more energy would be used than was intended.

On the matter of recommendations, complex control systems probably should not be used unless regular, skilled maintenance is available. Function indicators should be part of a central system control panel to facilitate maintenance and to allow control component failures to be identified quickly.

Because as-received HVAC components may not perform as specified without field adjustment, performance-indicating meters (flow meters, thermometers, power meters, etc.) should be used to test and adjust equipment in the field. Provision for temporary or permanent installation of these meters is required, and field performance tests are *essential* if poor system efficiencies are to be avoided.

More research and development is needed to improve the reliability and maintainability of HVAC components and systems.

Future research at test facility

Because of the difficulties encountered in installing and maintaining the pneumatic control system used at the HVAC test facility, future laboratory work at the CERL facility will focus on testing many different types of control systems and components. Work is underway to test additional pneumatic and electronic components to determine the dynamic and steady-state performance of control components and systems. This evaluation will determine which types of control components and systems can be expected to perform in the field with minimal maintenance and high reliability. In addition, field surveys will be performed to determine the reliability and the functionality of control systems on "real world" HVAC systems.

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