Signatures of Heating and Cooling Energy Consumption for Typical AHUs

Guanghua Wei
Energy Systems Laboratory
Texas A&M University
College Station, Texas

Mingsheng Liu, Ph.D., P.E.
Energy Systems Laboratory
Texas A&M University
College Station, Texas

David E. Claridge, Ph.D, P.E.
Energy Systems Laboratory
Texas A&M University
College Station, Texas

Astract

An analysis is performed to investigate the signatures of different parameters on the heating and cooling energy consumption of typical air handling units (AHUs). The results are presented in graphic format. HVAC simulation engineers can use these graphs to make quick and rational decisions during the model calibration, identify faulty parameters, and develop optimized operation and control schedules. An application example is given as well in the paper.

Introduction

Calibrated building system models have been used for projecting potential energy savings of retrofits [Katipamula and Claridge, 1993], identifying operating problems [Katipamula and Claridge, 1993; Liu, 1993; Liu and Claridge

performed by modifying simulation inputs until the outputs agree with the measured whole building energy consumption, such as the monthly utility bills.

Very sophisticated software has been developed and used for the model calibration in the last 30 years [APEC, 1967; Kusuda, 1971; Henninger, 1975; Bennett, 1977; Hittle, 1977; LBL, 1980;]. Model calibration remains an existing topic for both researchers and practitioners in the HVAC field [Bronson el at., 1992; Haberl el at., 1993]. One of the major issues for model calibration is the heating and cooling energy consumption. In this paper, the authors produced graphic signatures of heating and cooling energy consumption for typical AHUs. These signatures can help simulation engineers make quick and rational decisions during the model calibration. It can also help commissioning engineers identify faulty parameters, and develop optimized operation and control schedules.

Methodology

Both heating and cooling energy consumption of building AHUs are dependent on system type, weather, occupancy, internal load, and outside air intake, etc. To help HVAC simulation engineers identify the impacts of different parameters on the AHUs heating and cooling energy consumption, graphic energy signatures were generated by simulation. The signature of each parameter was defined to be the ratio of the changes in the AHU heating/cooling energy consumption to the maximum baseline heating/cooling energy consumption when the

This section describes the simulation program and the building used in the study, as well as the assumptions made and the weather data used. Followed by the simulation procedures.

Simulation Program

The simulations were performed by using AirModel, an HVAC simulation program developed at the Energy Systems Laboratory (ESL) at Texas A&M University [Liu, 1997]. This program is capable of simulating a variety of HVAC systems, including constant volume and variable volume systems, single-duct and dual-duct systems, and coordinate control systems, etc.

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

387

Case Study Building Description

To facilitate the demonstration of the concept and to have better control of the parameters used, a pseudo building is constructed to be used in the model simulation and calibration. Figure 1 is the schematic of the building floor plan. Some key building parameters are listed below.
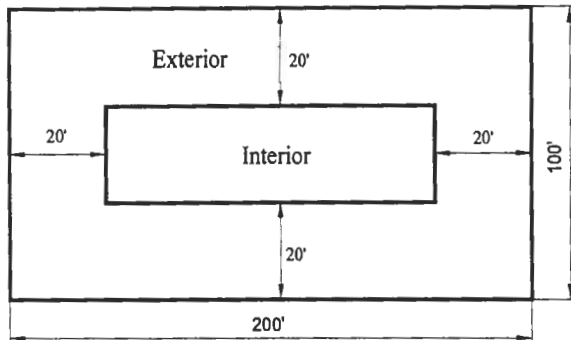

Figure 1. Floor plan of the building

Building length: 200 ft
Building width: 100 ft
Building height: 15 ft
No. of story: 6
Total conditioned area: 120,000 ft^2

Wall area:	East	6,300	ft^2
	South	12,600	ft^2
	West	6,300	ft^2
	North	12,600	ft^2
Roof area:		20,000	ft^2
	Total	37,800	ft^2
Window area:	East	2,700	ft^2
	South	5,400	ft^2
	West	2,700	ft^2
	North	5,400	ft^2
	Total	16,200	ft^2

Wall U-value: 0.1 Btu/h-°F-ft^2
Window U-value: 0.7 Btu/h-°F-ft^2
Roof U-value: 0.09 Btu/h-°F-ft^2
Occupancy: 200 ft^2/person
Lighting: 1.0 W/ft^2
Power equipment
  and appliances: 0.5 W/ft^2
Internal load: 0.8 W/ft^2
Supply air: 1.2 cfm/ft^2
Outside air: 0.1 cfm/ft^2
Total supply air: 120,000 cfm
Interior area ratio: 0.5
Room temperature: 73 °F
Supply air fan: 100 kW

Weather Data

Bin weather data for San Antonio, Texas [Degelman, 1984] is used for the model simulation. The median of each 5-°F bin is used as the average temperature, and the weighted average of the coincident wet bulb temperatures is used as the average wet bulb temperature. Figure 2 shows the annual average dry bulb and wet bulb temperature for San Antonio, Texas.
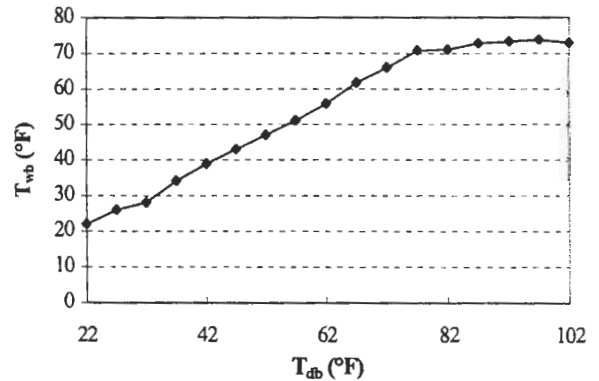

Figure 2. Annual average dry bulb and wet bulb temperatures for San Antonio, Texas

Simulation Procedures

The building is simulated as a two-zone system. Four different types of AHU systems were fully investigated. The general simulation procedure is outlined here.

Inputs

Besides the general inputs discussed in the building description section, there are some specific inputs for each type of AHU. The inputs that are specific to a constant volume dual-duct system are listed below.

Deck schedule: For the dual-duct system, the cold deck temperature is set to 55 °F. The hot deck temperature is reset based on the outside air temperature: it is set to 110 °F when the outside air temperature is below 40 °F and linearly decreases to 80 °F when the outside air temperature is 70 °F.

Preheat coil: The set point is 45 °F when outside air temperature is below 45 °F.

Air leakage: Considering the leakage of the air dampers, minimum air flow through each duct

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

388

is 5%, the excessive air leakage in the terminal box is 0.1 cfm/ft^2.

Energy Consumption Baseline

To obtain the building AHUs baseline energy consumption information, the above input data is entered into AirModel for simulation. It is assumed that the AHUs use chilled water (CHW) for cooling and hot water (HW) for heating purposes. Figure 3 is the scatter plot of the simulated chilled water and hot water energy consumption versus the outside air temperature. This is considered as the baseline energy consumption for the building.
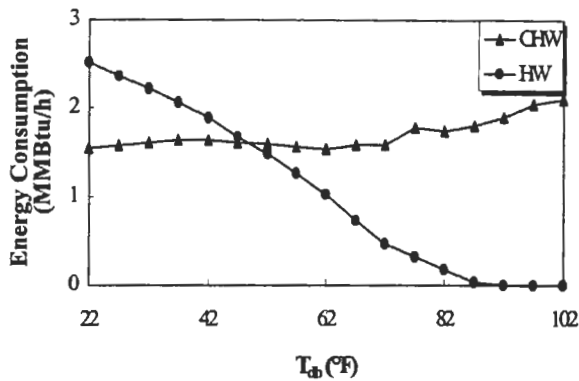

Figure 3. Simulated building energy consumption

Parameter Signature Identification

To identify the unique "signature" of each input parameter, the values of these input parameters are varied one at a time for each run of the simulation to see its impact on the system energy consumption. The magnitude of the parameter changes are selected such that their impacts on the heating and cooling energy consumption are within 10%. The input parameters that have been investigated are described in Table 1.

Results and Discussions

To help visualize the impacts of each parameter, the AHUs chilled water and hot water energy consumption obtained from the above simulations are compared to their respective baseline. The ratio of the differences to the maximum baseline values are plotted in a percentage manner (see Figure a in Appendix). A short discussion of the signature of each parameter for the constant volume dual-duct AHU system follows. Signatures of variable volume dual-duct system, constant volume single-duct system, and variable volume single-duct system are also attached in the Appendix.

Table 1. Descriptions of input variables changes

Input variables	Changes made
Cold deck temperature set point T_c	decreased from 55 °F to 53 °F
Supply air	raised from 1.2 cfm/ft^2 to 1.3 cfm/ft^2
Floor area	raised from 120,000 ft^2 to 130,000 ft^2
Preheat coil temperature set point T_{ph}	raised from 45 °F to 55 °F
Hot deck temperature set point T_h	increased by 2 °F
Internal heat gain	decreased from 0.8 W/ft^2 to 0.4 W/ft^2
Outside air flow	increased from 0.1 cfm/ft^2 to 0.15 cfm/ft^2
Room temperature T_{room}	raised from 73 °F to 74 °F
U-value	decreased from 0.1 to 0.08 Btu/h-°F-ft^2
Economizer cycle	from none to temperature economizer cycle

Cold Deck Temperature Set Point T_c

Lowering the cold deck temperature set point increases both the cooling and heating energy consumption. To maintain room conditions, less air will flow through the cold

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

389

deck and more air will flow through the hot deck. Since the hot deck temperature set point does not change, the result is an increase in heating energy consumption and a corresponding increase in cooling energy consumption. The shapes of these two signatures are not identical, however, due to better humidity control at a lower cold deck temperature set point which consumes more cooling energy.

Supply Air

Increasing the amount of supply air results in an increase in both the heating and cooling energy consumption. Due to the higher hot deck set point at lower outside air dry bulb temperatures, the consumption decreases as outside air dry bulb temperature increases.

Floor Area

The effect of increasing the floor area is the same as that of increasing the amount of supply air.

Preheat Coil Temperature Set Point T_{ph}

Raising the preheat coil temperature set point increases both heating and cooling energy consumption in the temperature range where the preheat coil functions.

Hot Deck Temperature Set Point T_h

An increase in the hot deck temperature set point results in redistribution of the cold air and the hot air. In order to maintain the room conditions, less air flows through the hot deck and more air flows through the cold deck, resulting in an increase in cooling energy consumption. The impact of increased hot deck temperature on heating energy consumption outweights the impact of decreased hot air flow, as a result, the heating energy consumption increases. The dramatic differences in these two signatures are again due to the better humidity control when more moisture is condensed as more air flows through the cold deck.

Internal Heat Gain

A reduction in internal heat gain calls for more heating and less cooling. To maintain the room conditions, less air flows through the cold deck and more air flows through the hot deck, resulting in an increase in heating and a decrease in cooling energy consumption.

Outside Air Flow

Increasing the amount of outside air reduces the demand for cooling and increases the need for heating during the heating season. The situation reverses during the cooling season when more cooling is needed and less heating is required.

Room Temperature T_{room}

When the outside air temperature is low, an increase in room temperature set point results in an increase of air flow through the hot deck and a reduction in air flow through the cold deck. However, due to the higher return air temperature, the heating energy consumption tends to be reduced and the cooling energy consumption to be increased. The net effect in this case is an increase in both heating and cooling energy consumption. However, when the outside air temperature is high, the impacts of less cold air through the cold deck is greater than that of higher mixed air temperature due to higher returned air temperature, which results in an reduction in cooling energy consumption. On the other hand, the impacts of higher mixed air temperature is greater than that of the increased air flow through the hot deck, causing a reduction in heating energy consumption as well.

U-Value

A lower U-value results in less heat loss in the heating season and less heat gain in the cooling season through the building envelop. The result is that less air flows through the hot deck and more air flows through the cold deck during the heating season, thus reduces the heating energy consumption and increases the cooling energy consumption. During the cooling season, less air is required to flow through the cold deck and more air can flow through the hot deck, thus reduces the cooling energy consumption. Notice that there is almost no change in the heating energy consumption since the hot deck temperature set point comes very close to the mixed air temperature.

Economizer cycle

The introduction of the economizer cycle reduces the cooling energy consumption significantly within the temperature range in which it functions. However, since the temperature of outside air entering the hot deck is

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

390

lower than the mixed air temperature when there is no economizer cycle, the economizer results in a heating energy penalty.

Applications

The signatures of heating and cooling energy consumption for AHUs can help HVAC simulation engineers calibrate the model, identify malfunctions of HVAC components, and develop optimized HVAC operation and control schedules.

These signatures have been successfully applied to the calibration of HVAC models developed by the authors. One example is a 12-story building located at Galveston, Texas [Liu and Claridge, 1995]. This is an in-patient hospital facility with a total conditioned floor area of 298,500 ft^2. There are four constant

volume dual-duct AHUs, which supply 302,000 CFM to the building with about 30% outdoor air intake. An Energy Management and Control System (EMCS) controls the pre-cooling deck discharge air temperature at 60 °F and the main cold deck discharge air temperature at 55 °F. Hourly whole-building cooling and heating consumption (chilled water and steam) are being measured by the LoanSTAR program [Turner, 1990].

Figure 4 is a comparison of the measured and initial model predicted heating and cooling energy consumption. It was found that the model predicted heating and cooling energy consumption were 26% and 16% lower than the measured values, respectively.
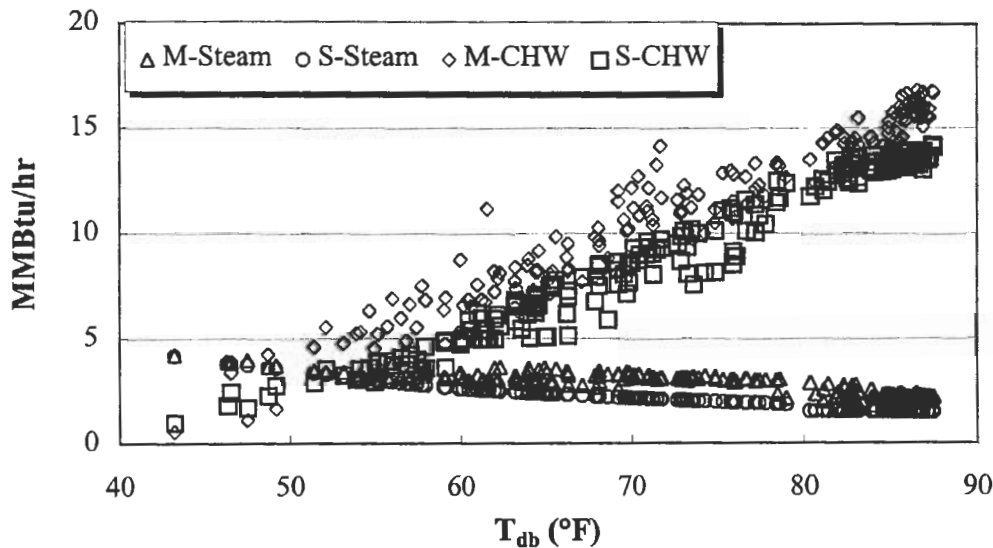

Figure 4. Comparison of measured and initial model predicted heating and cooling energy consumption (M stands for measured values and S stands for simulated values)

To raise the model predicted heating and cooling energy consumption in order to match the measured energy consumption. The simulation engineer has several ways to accomplished this based on the parameter signatures: lower the cold deck temperature set point; increase the amount of total supply air; increase the floor area; or increase the hot deck temperature set point.

Since total supply air and floor area values were believed to be accurate, it was speculated that the actual cold deck discharge air temperature might be lower than the set point due to malfunctioning control components or temperature sensors. Consequently, the simulated pre-cooling deck discharge air temperature, main cold deck discharge air temperature, and hot deck discharge air temperature were adjusted to match simulated

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

391

and measured cooling and heating energy consumption.

It was found that the simulated cooling and heating energy consumption matched measured values within 5% when the pre-cooling deck discharge air temperature was decreased by 8 °F to 52 °F, the main cold deck discharge air temperature was decreased by 3 °F to 52 °F, and the hot deck air temperature was assumed to be 5 °F higher than the set point.

To verify this, site measurements of these parameters were made. The cold and hot deck discharge air temperatures of all four AHUs were simultaneously measured using portable thermometers and the EMCS. It was found that the average main cold deck discharge air temperature was 2.4 °F lower than the EMCS measured value, and the average pre-cooling deck discharge air temperature was 3.2 °F lower

than the EMCS measured value. The higher temperature values measured by the EMCS were due to the short probe sensors used by the EMCS. Normally, an averaging sensor is required to sample the entire cross-sectional area.

The measured pre-cooling and cold deck discharge air temperatures were 7.2 °F and 3.5 °F lower than the set point values, receptively, while the measured hot deck discharge air temperature was 5 °F higher than the set point. This confirmed the speculation.

When the measured results were introduced to the model, the predicted total cooling and heating energy consumption was only 3% and 0.3% lower than the measured values, respectively. Figure 5 shows the scatter plot of consumption versus temperature, Figure 6 presents the time series comparison of measured and predicted energy consumption data.
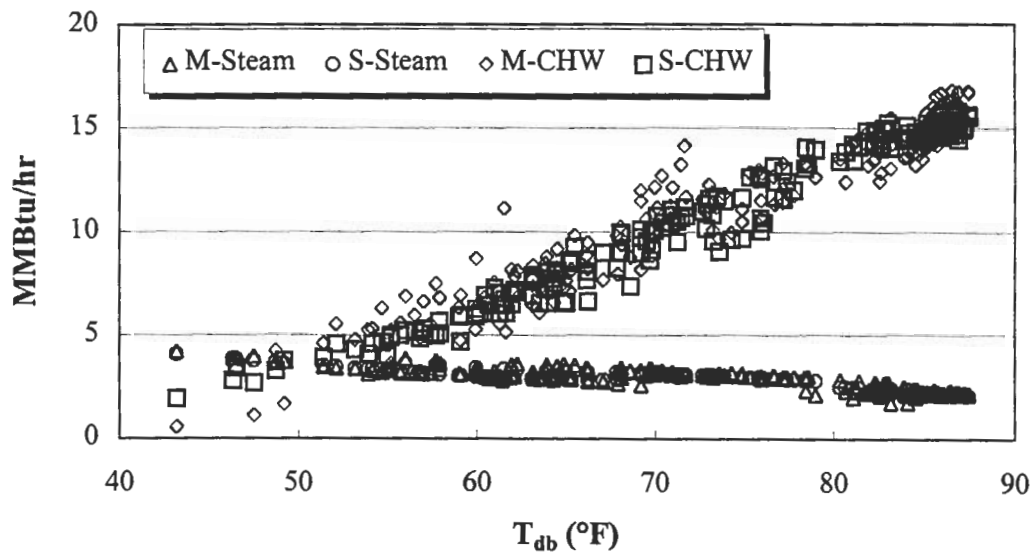

Figure 5. Comparison of measured and calibrated model predicted heating and cooling energy consumption

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998
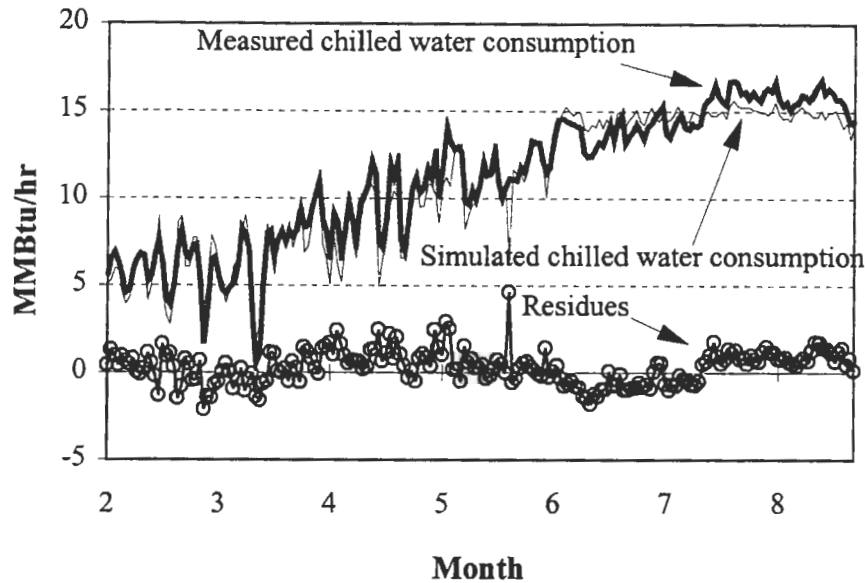
392

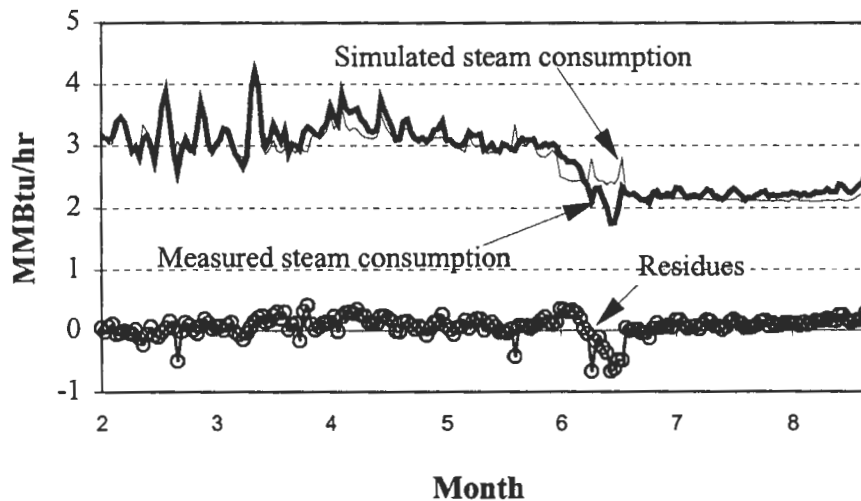Figure 6a. Comparison of daily average model predicted and measured cooling energy consumption

Figure 6b. Comparison of daily average model predicted and measured heating energy consumption

Conclusion

The signatures of heating and cooling energy consumption for AHUs can help simulation engineers make quick and rational decisions during the model calibration. It can also help commissioning engineers identify faulty parameters in order to optimize the operation and control schedules.

Reference

APEC, 1967. "HCC-Heating/Cooling Load Calculation Program", Automated Procedures for Engineering Consultants Inc, Dayton, Ohio.

Bennett, G., et al., 1977. "CAL-ERDA Manual", Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

393

Bronson, D. J., Hinchey, S. B., Haberl, J. S., O'Neal, D. L., 1992. "A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather Dependent Measured Loads", ASHRAE Transactions: Symposia, pp. 636-652.

Degelman, L., 1984. "Bin Weather Data for Simplified Energy Calculations and Variable Base Degree Day Information", Department of Architecture, Texas A&M University, College Station, Texas.

Haberl, J. S., Bronson, J. D., Hinchey, S. B., O'Neal, D. L., 1993. "Graphical Tools to Help Calibrate the DOE-2 Simulation Program, ASHRAE Journal, January, 1993, pp. 27-32.

Henninger, R.,ed, 1975. "NECAP, NASA's Energy-Cost Analysis Program", National Aeronautics and Space Administration, Washington, DC.

Hittle, D., 1977. "The Building Loads Analysis and System Thermodynamics Program, BLAST", US Army Construction Engineering Research Laboratory, Champain, Illinois.

Katipamula, S. and Claridge, D. E., 1992. "Monitored Air Handler Performance and Comparison with a Simplified System Model", ASHRAE Transactions, Vol. 98, Pt. 2, pp. 341-351.

Katipamula, S. and Claridge, D. E., 1993. "Use of Simplified Models to Measure Retrofit Energy Savings", ASME Journal of Solar Energy

Engineering, Vol. 115, pp. 77-84.

Kusuda, T., 1971. "NBSLD, Computer Program for Heating and Cooling Loads in Buildings", National Bureau of Standards, Washington, DC.

LBL, 1980. "DOE-2 User Guide, Version 2.1", LBL Report No. LBL-8689 Rev. 2, Lawrence Berkeley Laboratory, Berkeley, California.

Liu, M. 1997. User's Manual for Air Side Simulation Programs (AirModel). Energy Systems Laboratory, Mechanical Engineering Department, Texas A&M University, College Station, Texas.

Liu, M. And Claridge, D. E., 1995. "Application of Calibrated HVAC System Models to Identify Component Malfunctions and to Optimize the Operation and Control Schedules", ASME Journal of Solar Engineering, Vol. 1, pp. 209-217.

Liu, M., Houcek, J., Claridge, D. E., and Haberl, J., 1993. "Potential Operation and Maintenance Savings at Dunbar Middle and Sims Elementary Schools", Energy Systems Laboratory Report No. 93/04-08, Texas A&M University, College Station, Texas.

Turner, D., 1990. "Overview of the Texas LoanSTAR Monitoring Program", 7th Annual Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, Texas, pp. 28-34.

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

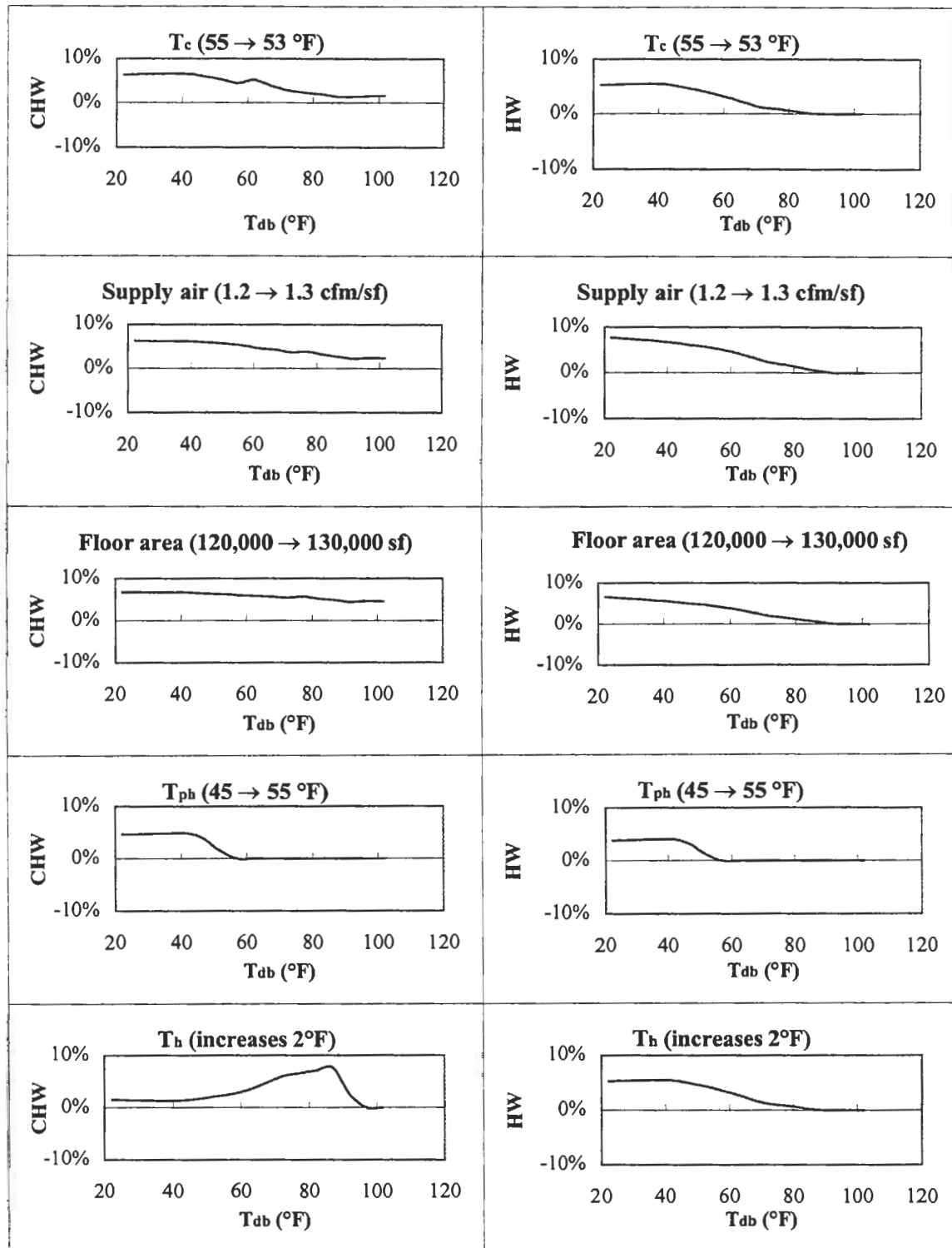394

APPENDIX SIGNATURES OF TYPICAL AHU SYSTEMS

Figure a. Signatures of heating and cooling energy consumption for constant volume dual-duct AHUs

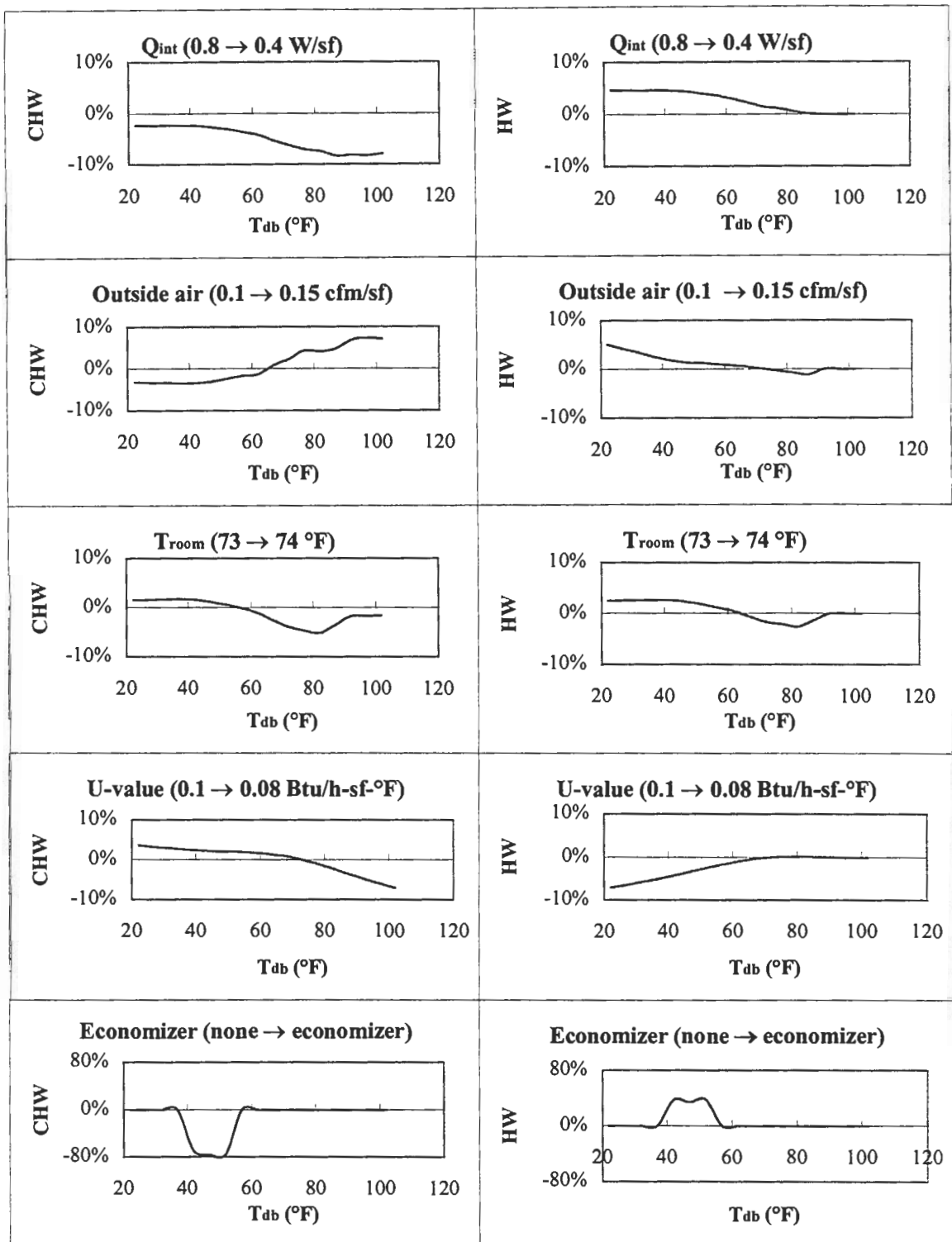Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

395

Figure a. Signatures of heating and cooling energy consumption for constant volume dual-duct AHUs (continued)

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

396

Figure b. Signatures of heating and cooling energy consumption for variable volume dual-duct AHUs

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

397

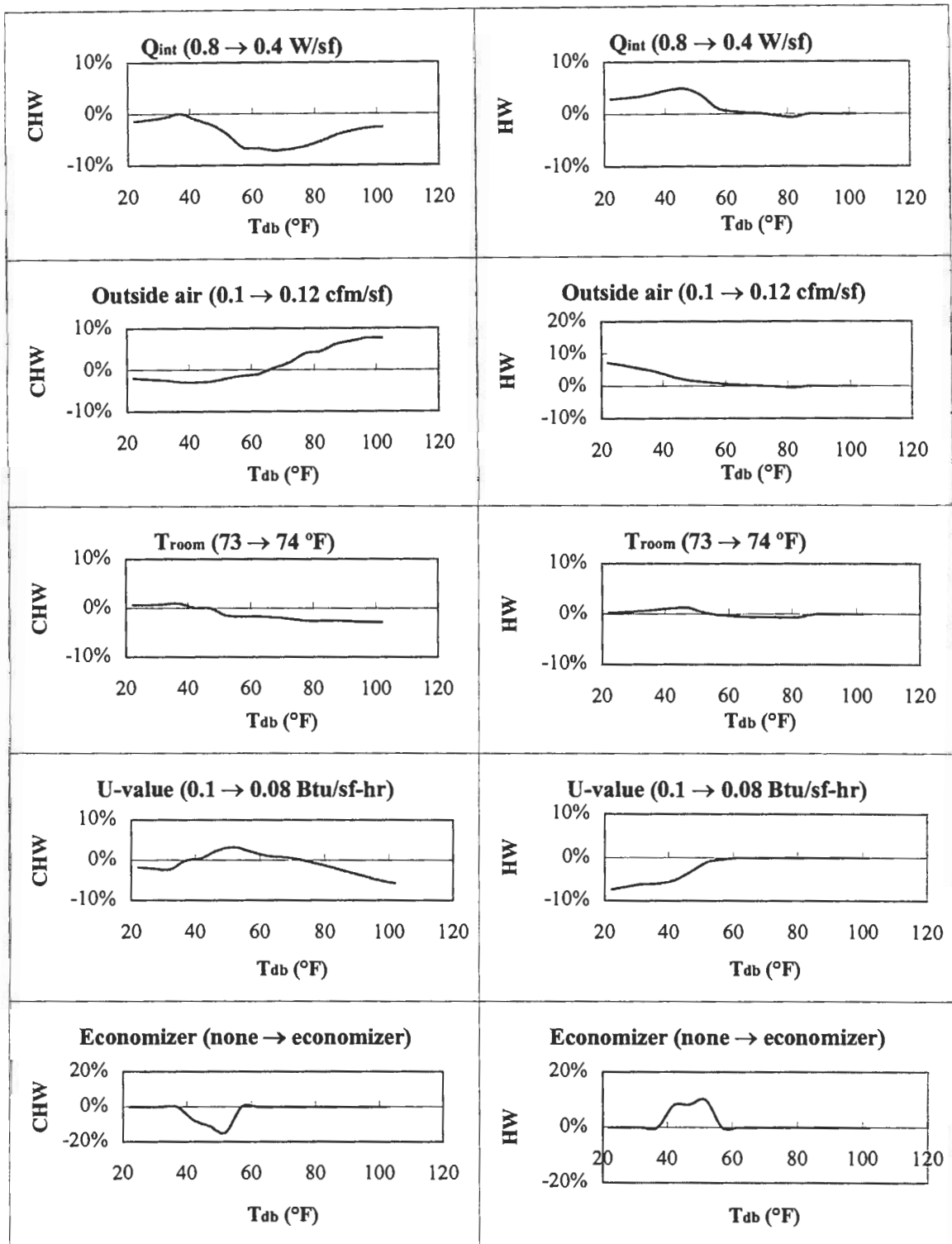Figure b. Signatures of heating and cooling energy consumption for variable volume dual-duct AHUs (continued)

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

398

Figure c. Signatures of heating and cooling energy consumption for constant volume single-duct AHUs

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

399
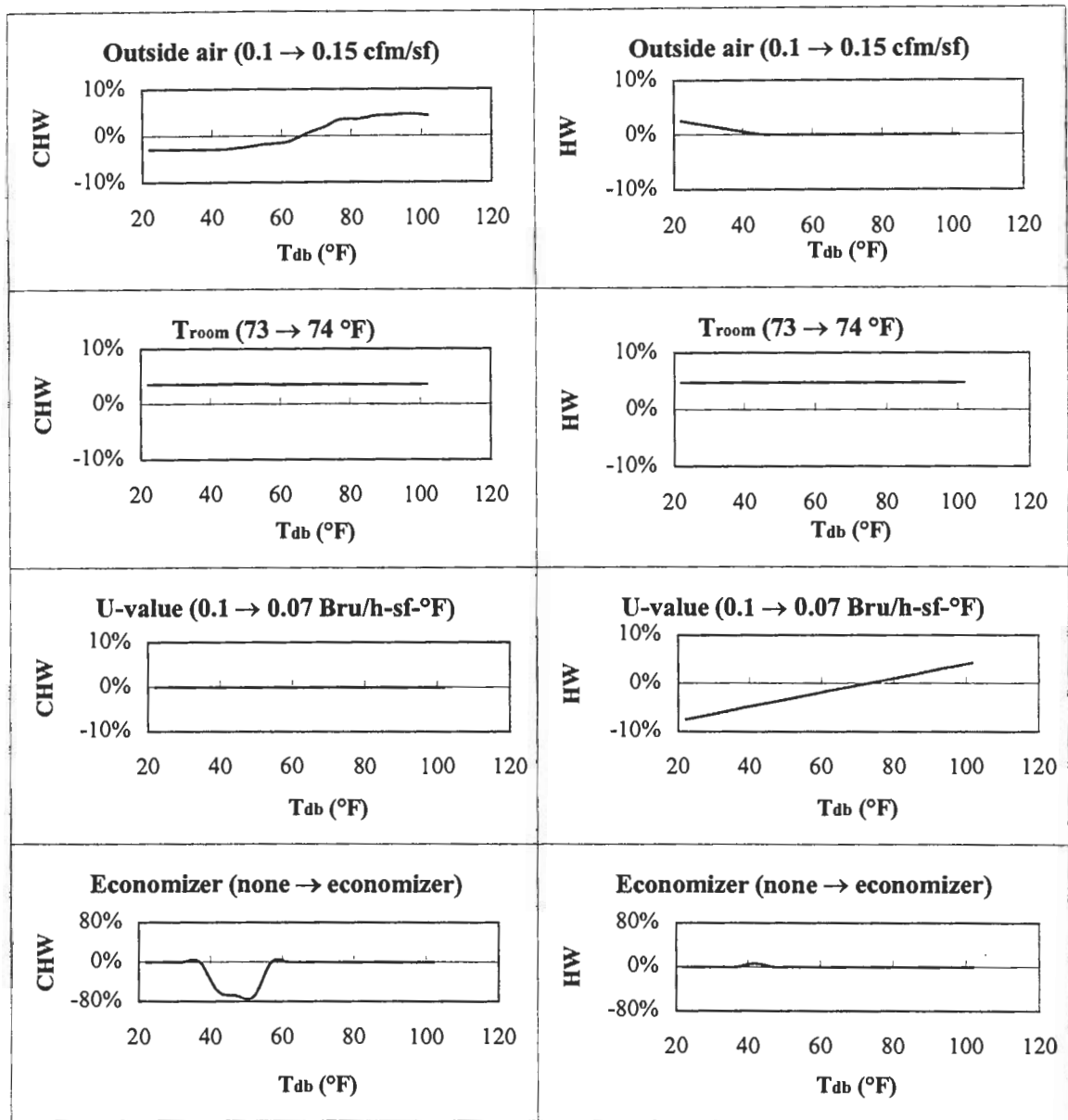
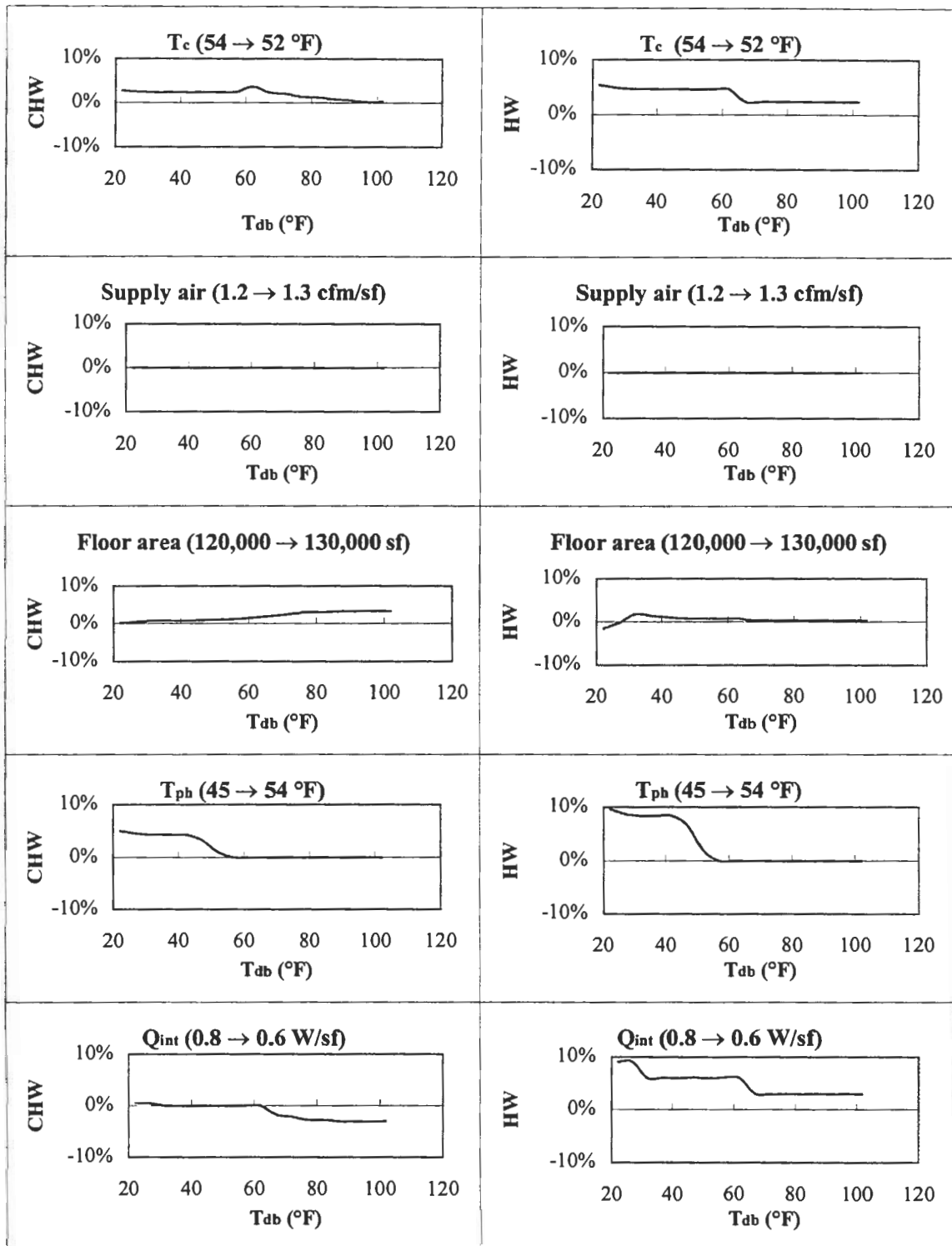Figure c. Signatures of heating and cooling energy consumption for constant volume single-duct AHUs (continued)

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

400

Figure d. Signatures of heating and cooling energy consumption for variable volume single-duct AHUs

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998
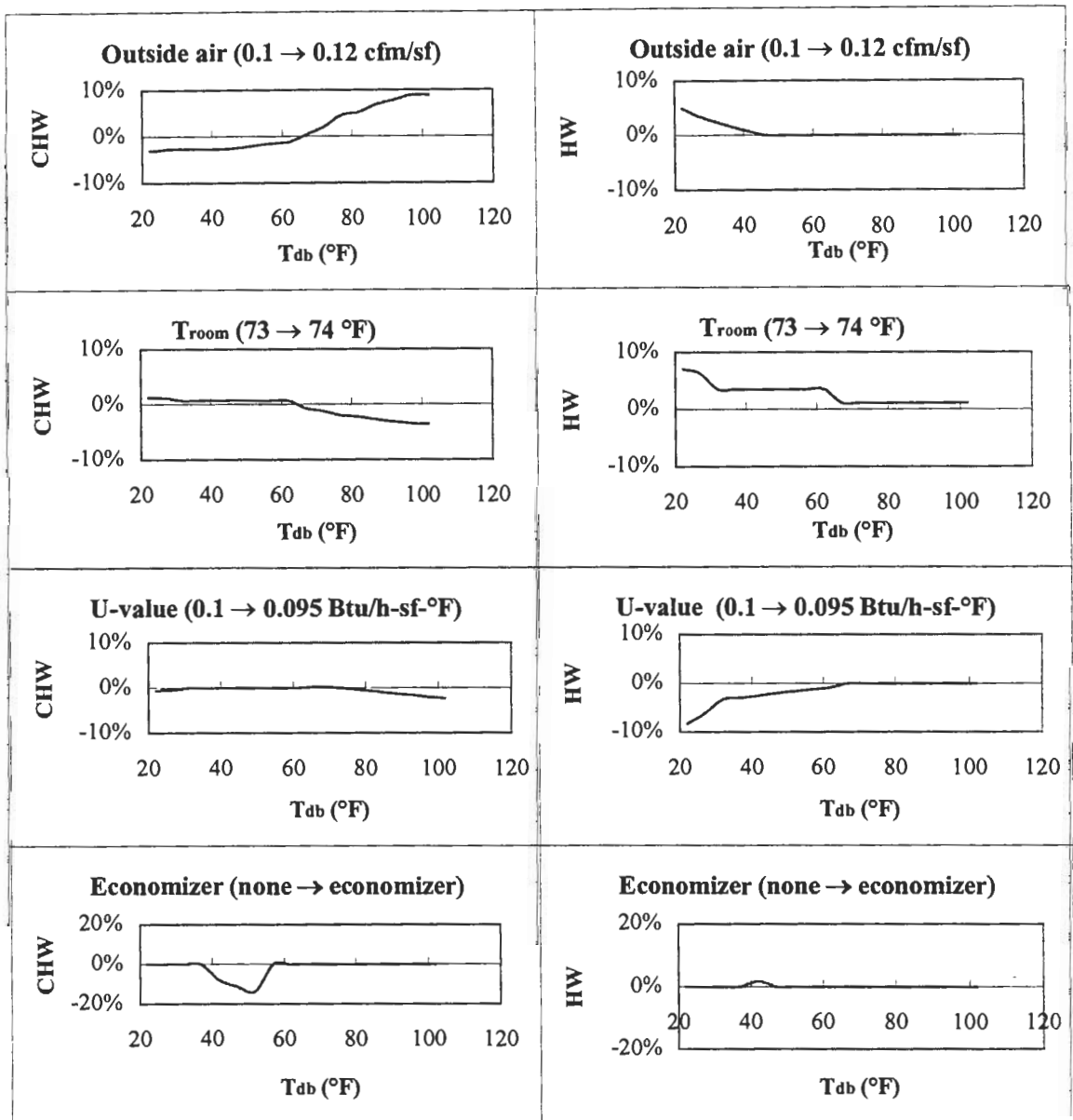
401

Figure d. Signatures of heating and cooling energy consumption for variable single-duct AHUs (continued)

Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX, June 1-2, 1998

402