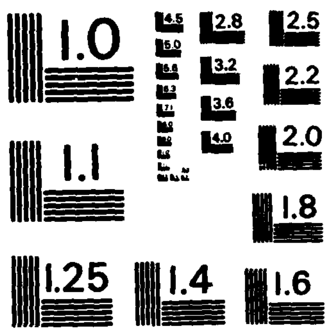
AD-A160 328 DEVELOPMENT OF A SELF-TUNING CONTROLLER FOR HVAC (HEATING VENTILATING AND..(U) NAVAL CIVIL ENGINEERING LAB PORT HUENEME CA R E KIRTS ET AL. AUG 85 1/1

UNCLASSIFIED NCEL-TN-1731 F/G 13/1 NL

END

FILMED

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(12)

TN NO: N-1731

TITLE: DEVELOPMENT OF A SELF-TUNING CONTROLLER FOR HVAC SYSTEMS

AD-A160 328

AUTHOR: R. E. Kirts and I-L Chien

DATE: August 1985

SPONSOR: Naval Facilities Engineering Command

PROGRAM NO: ZO371-01-221B

TECHNICAL NOTE

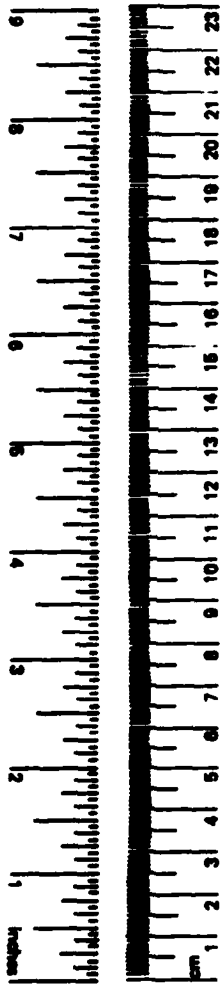
NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

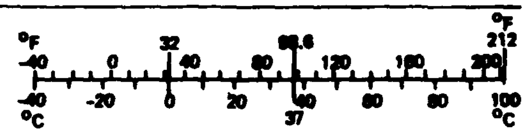
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

AD-A160328

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TN-1731	2. GOVT ACCESSION NO. DN887032	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DEVELOPMENT OF A SELF-TUNING CONTROLLER FOR HVAC SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED Final; Oct 1982 – Nov 1984
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. E. Kirts and I-L Chien		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS NAVAL CIVIL ENGINEERING LABORATORY Port Hueneme, California 93043		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 64710N; ZO371-01-221B
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Facilities Engineering Command Alexandria, Virginia 22332		12. REPORT DATE August 1985
		13. NUMBER OF PAGES 35
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Control systems, self tuning, adaptive control, HVAC

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A self-tuning control algorithm suitable for application to many processes, including those of heating, ventilating, and air conditioning, was developed and tested. Initial experimental evaluation indicates that the controller may be applicable to a variety of common HVAC processes. Self-tuning controls can improve process efficiency and reduce maintenance.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

Library Card

Naval Civil Engineering Laboratory
DEVELOPMENT OF A SELF-TUNING CONTROLLER FOR HVAC SYSTEMS (Final), by R. E. Kirts and I-L Chien
TN-1731 35 pp illus August 1985 Unclassified

1. Control systems 2. Self tuning I. ZO371-01-221B

A self-tuning control algorithm suitable for application to many processes, including those of heating, ventilating, and air conditioning, was developed and tested. Initial experimental evaluation indicates that the controller may be applicable to a variety of common HVAC processes. Self-tuning controls can improve process efficiency and reduce maintenance.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

CONTENTS

INTRODUCTION

This report describes the development of a self-tuning control algorithm suitable for application to many processes, including those in heating, ventilating, and air conditioning (HVAC) systems. The controller was developed to reduce the effort required to set up and maintain controls for HVAC systems and to assure optimum control (and, consequently, maximum operating efficiency) over a wide range of conditions.

BACKGROUND

Small independently operating digital control systems were introduced by the building controls industry a few years ago as an alternative to the traditional pneumatic and analog electronic control systems for control of heating, ventilating, and air conditioning equipment. These new control systems, called direct digital control (DDC) systems, are rapidly gaining acceptance by building designers, owners, and operators because of their accuracy, versatility, reliability, and cost effectiveness. The benefits of DDC may, however, come at the expense of increased complexity in adjusting the control system. For example, most pneumatic controllers provide only proportional control, while a DDC system can readily provide the more accurate proportional-integral-derivative (PID) control. However, to gain the benefits of PID control requires considerably more effort to determine the correct values of control parameters, such as gains, to input into the controller. In addition, the optimum control parameters for one mode of operation, such as heating, may not be the optimum parameters for another mode of operation, such as cooling. If the control parameters for a DDC system are not chosen with care, the resulting control may well be worse than that obtainable with the simplest pneumatic control system. Therefore, it is very desirable to develop a controller methodology, or algorithm, which could automatically determine what the optimum control parameters should be and change the control parameter values as operating conditions require. A few years ago, the computational requirements of such a self-tuning, or adaptive, controller would have required a sizable computer to implement. Today, however, the computational requirements of the algorithm presented below are within the capabilities of many small DDC systems.

DISCUSSION

Approach

The guidelines for developing the controller methodology were: (1) the method must not require the input of a detailed mathematical model of the process being controlled, and (2) the method should not be sensitive to variations in time delays. Although adaptive control algorithms have been developed and applied to the control of HVAC components (e.g., Park and David, 1982), these previous controller designs required input of a model of the process being controlled. The authors felt that this modeling requirement would severely restrict the applications of a self-tuning controller because it would be difficult for control engineers to develop the necessary models for each controller installation. Also, it was desired that the self-tuning algorithm be insensitive to variations in system time delays, such as response lag, as these delays would also be different at each controller installation and change with the process dynamics.

The first step in the development of a self-tuning controller for HVAC applications was to conduct a thorough review of past work on adaptive control and select the most promising approach to further analysis. This work was reported by Seborg et al. (1983).

Based on the guidelines and review of past work, a self-tuning controller was designed by I-Lung Chien (Chien, 1985). This controller is described below in detail. The controller was then evaluated using a computer simulation of a hot water coil. The performance of the self-tuning controller was compared to that of an optimally tuned proportional-integral (PI) controller operating under the same conditions. The optimum controller settings for the PI controller were determined using analytical and experimental methods and were manually input into the controller. On the basis of the encouraging results of the computer simulations, experiments on an actual hot water coil system were conducted.

Controller Design

The self-tuning controller is based on the following design strategy. Parameters in a simple dynamic model of the process are updated on-line. The controller setting calculations are then based on the current parameter estimates. The dynamic model is a simple, empirical model rather than a detailed physical model. Thus the user need only specify the model order and the estimated time delay. Typically, a second-order plus time delay model is adequate. The model parameters are updated at each sampling instant from input-output data using standard least squares techniques. The controller settings are then calculated in a straightforward fashion from the model parameters so as to minimize a quadratic cost function.

The starting point of the analysis is a single-input/single-output (SISO), discrete-time process model (see List of Symbols and Figure 1 for notation).

$$G_p(z^{-1}) = \frac{B(z^{-1})z^{-k}}{A(z^{-1})} \quad (1)$$

where the polynomials A and B are expressed in terms of the backward shift operator, z^{-1} (i.e., $z^{-1}y(t) = y(t-1)$):

$$A(z^{-1}) = 1 + a_1 z^{-1} + \ldots + a_{n_A} z^{-n_A} \quad (2)$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + \ldots + b_{n_A} z^{-n_B} \quad (3)$$

and the time delay represented by k is expressed as a multiple of the sampling period ($k \geq 1$), while t denotes the sampling instant, t = 0, 1, 2, ... It is also assumed that the poles of $A(z^{-1})$ lie inside the unit circle in the complex z-plane, i.e., that the system is open-loop stable.

Consider the Smith predictor approach to time delay compensation (Smith, 1957). Figure 1 shows the block diagram of the discrete-time Smith predictor. Transfer function $G_p'(z^{-1})$ denotes the process model without the time delay, i.e., with k = 1:

$$G_p'(z^{-1}) = \frac{B(z^{-1})\, z^{-1}}{A(z^{-1})} \tag{4}$$

Adapting the Smith predictor to accommodate parameter variations requires estimating the a_i and b_i parameters of the process model as well as the time delay, k. However, as discussed by Kurz and Goedecke (1981) and Vogel (1982), time delays are difficult to estimate on-line directly, and thus this approach should be avoided. In an alternative approach, Vogel and Edgar (1982) assumed that *the minimum and maximum* values of the expected time delay, k_{min} and k_{max}, are available. They then performed the parameter estimation by rewriting Equation 1 with a sufficient number of terms in the numerator of the process transfer function model to include implicitly any extra time delay in excess of k_{min}. Using their approach, the process model becomes

$$G_p(z^{-1}) = \frac{B_E(z^{-1})\, z^{-k_{min}}}{A(z^{-1})} \tag{5}$$

where

$$B_E(z^{-1}) = b_0' + b_1'\, z^{-1} + \ldots + b_r'\, z^{-r} \tag{6}$$

and

$$r = k_{max} - k_{min} + n_B \tag{7}$$

Note that the variation in the process time delay is accounted for implicitly when leading coefficients of B_E are zero, since B_E can be expressed as

$$B_E(z^{-1})\ z^{-k_{min}} = B(z^{-1})\ z^{-k} \qquad (8)$$

Next, the process model without time delay, $G_p'(z^{-1})$, is redefined as

$$G_p'(z^{-1}) = \frac{\left(\Sigma_{B_E}\right) z^{-1}}{A(z^{-1})} \qquad (9)$$

with

$$\Sigma_{B_E} = \sum_{i=0}^{r} b_i' \qquad (10)$$

$G_p'(z^{-1})$ is chosen in this fashion because it eliminates the time delay in the process model without requiring explicit knowledge of k, and yet it contains the same denominator as $G_p(z^{-1})$ and has the same steady-state gain. It is important to note that, with the above choices of $G_p(z^{-1})$ and $G_p'(z^{-1})$, the difficult problem of explicit on-line time delay estimation is completely avoided.

Note also that $G_p'(z^{-1})$ provides only an approximate prediction of the undelayed process output. Vogel (1982) shows that this time delay compensator, even with the inherent approximation, generally has a more beneficial effect on the closed-loop performance and stability than the standard Smith predictor.

In principle, the design of the controller $G_c(z^{-1})$ in Figure 1 can be based on the undelayed process model $G_p'(z^{-1})$ since the time delay is eliminated from the characteristic equation. The SISO self-tuning controller of Clarke and Gawthrop (1975, 1979) for $G_p'(z^{-1})$ can be obtained as:

$$u(t) = \frac{Fy(t) + Rw(y) - Ed}{\Sigma_{B_E} \cdot E + Q} \qquad (11)$$

where y(t) is the measured output, u(t) is the manipulated input, w(t) is the setpoint, and d is a constant, steady-state bias response for a zero input signal. E and F are polynomials in z^{-1} which satisfy the identity,

$$P = EA + z^{-k} F \qquad (12)$$

and

$$E(z^{-1}) = 1 + e_1 z^{-1} + \ldots + e_{k-1} z^{1-k} \qquad (13)$$

$$F(z^{-1}) = f_0 + f_1 z^{-1} + \ldots + f_{n_A-1} z^{1-n_A} \qquad (14)$$

For the undelayed process model, k = 1 and thus E = 1. P, Q, and R are user-specified polynomials to achieve a desired response time and degree of oscillation for the closed-loop system. Guidelines for the choice of these design parameters can be found in Chien (1985).

Figure 2 shows the block diagram when the self-tuning controller is used in conjunction with Smith-predictor-type time delay compensation (STC-TDC). The resulting control law can be expressed as

$$\frac{u}{\varepsilon} = \frac{A}{p \Sigma_{B_E} + Q A - F B_E z^{-k_{min}}} \qquad (15)$$

where

$$\varepsilon = Rw - Fy - d \qquad (16)$$

In summary, at each sampling instant, the following calculations are performed for the new STC-TDC:

1. Read new values for the output y(t) and setpoint w(t).

2. Update model parameters $\hat{A}$, $\hat{B}_E$, and $\hat{d}$ by using a parameter estimation scheme such as the recursive least-squares algorithm.

3. Obtain $\hat{F}$ from Equation 12.

4. Calculate the new control action from Equation 15.

Chien (1985) also describes a load disturbance rejection scheme to improve the load response during upset periods.

Simulation Results

A heating, ventilating, and air conditioning process model developed by Tödtli et al. (1982) has been used to evaluate the performance of this STC-TDC. This process consists of an air heater operating under conditions of varying air inlet temperature, air flow rate, and water inlet temperature. A schematic diagram of the air heater is shown in Figure 3. The variables in Figure 3 are defined as:

u = normalized valve position ($0 < u < 1$)

T_{wi} = water inlet temperature, °C

T'_{wi} = water inlet temperature at the entrance of the air heater, °C

T_{wo} = water outlet temperature, °C

T_{ai} = air inlet temperature, °C

T_{ao} = air outlet temperature, °C

$\dot{m}_w$ = mass flow rate of water after the control valve, kg/sec

$\dot{m}'_w$ = mass flow rate of water at the entrance of the air heater, kg/sec

$\dot{m}_a$ = mass flow rate of air, kg/sec

From a control point of view, the process has four input variables: u, T_{ai}, $\dot{m}_a$, and T_{wi}; u is the single manipulated variable and the other three variables are considered to be disturbances. The output variable that has to be controlled is T_{ao}.

Based on experimental data for a particular commercial air heater, the process model that describes its static and dynamic behavior was developed by Tödtli et al. (1982). A detailed derivation of the process model can be found in Chien (1985).

The nominal operating point is selected to be: $\dot{m}_a$ = 0.388 kg/sec, T_{wi} = 90°C, T_{ai} = 0°C, and u = 0.262. The resulting air outlet temperature at steady state is 20°C. Figure 4 shows the open-loop response for changes in u at this operating point, and Table 1 shows the time constants and gains for these changes in u.

Figure 5 shows the operating window for this HVAC process in the operating regime: $-20°C \leq T_{ai} \leq 20°C$, $0.2 \text{ kg/sec} \leq \dot{m}_a \leq 1.0 \text{ kg/sec}$, and T_{wi} = 90°C.

The HVAC process model described above was simulated to examine the performance of the STC-TDC in comparison with a PI controller. For control purposes, a sampling period of 10 seconds was chosen; process noise was simulated by adding a Gaussian noise signal with a standard deviation of 0.5°C to the air inlet temperature, T_{ai}. Setpoint changes were made at t = 300 seconds and t = 1,300 seconds, while a load change was made at t = 800 seconds.

A linearized model of the above HVAC process valid around the nominal operating point was used to determine Ziegler-Nichols settings for the PI controller. The resulting PI controller settings were calculated to be K_p = 0.0793 1/°C and τ_I = 83.2 seconds. For STC-TDC, the assumed process model used had $n_A = 1$, $r = 3$, $n_C = 0$, and $k_{min} = 1$. Also, the design parameters were chosen to be $P = 1 - 0.7z^{-1}$, $q = 1 - z^{-1}$, and R = 0.3.

Figures 6 and 7 show the performance of the PI and STC-TDC controller when the air inlet temperature increases by 5°C. The PI controller becomes oscillatory after the load disturbance, while the STC-TDC performs very well for both setpoint and load changes. Figures 8 and 9 show the performance of the two controllers when air mass flow rate provides a load disturbance. It is assumed that the process time delay decreases to 10 seconds when air mass flow rate increases 20%. When the time delay decreases, the PI controller yields about the same response as the STC-TDC, as shown in Figures 8 and 9. However, Figures 10 and 11 show that when time delay increases, the PI controller becomes unstable after the load change occurs, while the STC-TDC still gives perfect response.

EXPERIMENTAL RESULTS

Apparatus

The experimental apparatus is diagrammed in Figure 12. A portable computer was purchased to serve as both a programmable controller and as a data logging device (Figure 13). The computer was equipped with a high performance analog and digital input/output (AD/DA) board to enable data to be read into the computer and enable the output of the control program to affect the process. Experimental results were recorded on one of the computer's disk drive units to facilitate later analysis. Results were also printed to provide a hardcopy record of the experiments. A real time graphics program was written to display the results of the experiment while it was in progress.

The temperature sensors were 1,000-ohm platinum resistance temperature devices (RTD) mounted on the ends of duct probes. Current loop transmitters located near the sensors converted the temperature-dependent voltage signals from the RTDs to electrical currents to reduce the problems caused by electrical noise in the input signals. The current loop transmitters were connected to precision load resistors on the AD/DA board by shielded cable.

The output voltage from the AD/DA board was converted into an air pressure signal by means of an electrical-to-pneumatic transducer. The air pressure signal operated the hot water control valve.

Method

A computer program was written to experimentally verify the performance of the self-tuning, time-delay-compensating (STC-TDC) controller algorithm. The computer program actually was capable of performing three types of controller experiments: open-loop tests, closed-loop PID tests, and the self-tuning controller tests. Open-loop tests were conducted on the experimental apparatus to determine the response characteristics of the hot water valve/coil system. These characteristics were used to determine the optimum values of proportional gain and reset rate for the PI controller tests. The hot water coil was controlled by an optimized PI controller and the results were used as a basis for judging the performance of the self-tuning controller. Experiments were then conducted using the self-tuning controller. Experiments were performed for two cases: (1) the load on the coil (as measured by the coil inlet temperature) is constant but the setpoint (as measured by the coil discharge temperature) is changed, and (2) both the load on the coil and the setpoint are changed.

Results

Eleven separate experiments were conducted using an air handler at the HVAC Test Facility (Figure 14) at the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) in Champaign, Illinois. Occasional noise in the input data for the first few experiments had a serious detrimental effect on the performance of the STC-TDC algorithm. After the usual fixes for problems of signal noise (i.e., connecting common circuit grounds, adding by-pass capacitors) failed to eliminate the noise spike problem, the computer program was modified to add a digital filter to the input data. The digital filter cured the noise problem. The second problem with the experimental test activity was that the valve used to control the flow of hot water to the heating coil was greatly oversized. As a consequence, the valve operated at only about 10 to 15% of capacity at the design point, rather than the standard 50% of capacity at the design point. The resultant reduced throttling range made it difficult to control the coil with any precision. For reasonable values of changes in setpoint, the valve was either open or closed, with the result that any control method behaved like on-off control. The problem of the oversized valve was minimized by conducting experiments using only comparatively small changes in setpoint. The comparatively small temperature range over which the coil discharge temperature was controlled emphasized the effect of another variable: hot water supply temperature. Hot water was supplied to the coil by a steam convertor and the temperature of the water was controlled by on-off regulation of the flow of steam to the convertor. The temperature of the supply water fluctuated by about 0.5°C which, unfortunately, was about the magnitude of the changes in setpoint.

Figures 15 and 16 present the results of an experiment to determine the performance of a PI controller under the conditions of setpoint change but no load disturbance. Figure 15 shows controller performance; Figure 16 shows coil inlet temperature. The apparent oscillation in temperature about the setpoint is attributed to the fluctuating temperature of the supply water.

Figures 17 and 18 show the results for a PI controller experiment in which the coil inlet air temperature was suddenly changed.

Figures 19 through 22 present results for the STC-TDC controller comparable to those presented in Figures 15 through 18 for a PI controller. Figure 19 illustrates how the STC-TDC controller "learns" as information about system response to disturbances is received and processed. Notice (in Figure 19) how the response of the STC-TDC controller to the first setpoint change (at time equals 10 minutes) is quite poor, the controller response to the second setpoint change (at time equals 30 minutes) is better, and the controller response to subsequent setpoint changes (at time equals 60 minutes) is comparable to that of an optimally tuned PI controller (see Figure 15).

Figure 21 presents the results of an experiment to evaluate the response of the STC-TDC controller to a disturbance in the coil load. At time equals 60 minutes, the outside air dampers were opened to admit cold air and lower the coil inlet temperature. As Figure 21 shows, the response of the STC-TDC was less than satisfactory. The STC-TDC provided good initial recovery from load upset (using the load rejection scheme described by Chien (1985)). However, the STC-TDC tended to switch back to the standard STC-TDC control law too soon, which introduced an additional upset. It is believed that this problem can be eliminated by a simple change to the computer code. However, additional experimental tests are necessary to confirm this hypothesis (see Chapter 4 of Chien (1985)).

Before the experiment could be repeated with a modified STC-TDC, the hot water convertor at the HVAC Test Facility broke down and the remainder of the experiment had to be postponed until the hot water convertor was repaired.

Funding for the work described in this report expired before additional experimental work could be performed.

It should be noted that the STC-TDC has been successfully applied to a pilot-scale multicomponent distillation column by Chien (1985).

CONCLUSIONS

An algorithm for a self-tuning controller was developed and tested. The control methodology has potential for wide-spread application in industrial processes such as control of the apparatus of heating, ventilating, and air conditioning systems.

The controller was developed to reduce the effort required to set up and maintain the modern, more complex, digital control systems being installed on HVAC equipment. A controller that could adjust itself to maintain optimum HVAC operating conditions would result in improved plant efficiency and, possibly, improved equipment reliability. Maintenance expenditures for controller adjustments would be eliminated.

Although the controller has been demonstrated to work well in some applications, additional experimental work is required to verify its applicability to the variety of controlled devices found in HVAC systems.

RECOMMENDATIONS

It is recommended that additional experimental work be performed to evaluate the performance of the STC-TDC algorithm for control of a hot water coil subject to changes in coil inlet air temperature. The experimental evaluations performed using a hot water coil should be repeated using a chilled water coil. It is also recommended that the STC-TDC controller algorithm be evaluated for control of a two-phase coil, such as a steam coil or a direct expansion coil, and a variable speed fan. If these tests prove successful, the algorithm should be installed on a commercially available model of a digital controller for extended field evaluation.

ACKNOWLEDGMENTS

The authors wish to thank the U.S. Army Construction Engineering Research Laboratory for the use of their HVAC Test Facility. In particular, we wish to thank Dr. David Johnson, Mr. Victor Storm, and Mr. Rick Rundus for their assistance in setting up the experiments.

REFERENCES

Chien, I-L. (1985). Self-tuning control strategies for distillation columns, Ph D dissertation, University of California at Santa Barbara. Santa Barbara, Calif., 1985.

Clarke, D.W., and Gawthrop, P.J. (1975). Self-tuning controller," in Proceedings of the Institution of Electrical Engineers, vol 122, 1975, p. 929.

Clarke, D.W., and Gawthrop, P.J. (1979). "Self-tuning control," in Proceedings of the Institution of Electrical Engineers, vol 126, 1979, p. 633.

Kurz, H., and Goedecke, W. (1981). "Digital parameter-adaptive control of processes with unknown dead time," Automatica, vol 17, 1981, p. 245.

Park, C., and David, A.J. (1982). Adaptive algorithm for the control of a building air handling unit, National Bureau of Standards, NBSIR 82-2591. Washington, D.C., 1982.

Seborg, D.E., Shah, S.L., and Edgar, T.F. (1983). "Adaptive control strategies for process control: A survey," in Proceedings of the American Institute of Chemical Engineers Diamond Jubilee Meeting, Washington, D.C., 1983.

Smith, O.J.M. (1957). "Close control of loops with dead time," Chemical Engineering Progress, vol 53, no. 5, 1957, p. 217.

Tödtli, J., Schaufelberger, W., and Wehrli, P. (1982). "Realization of adaptive control systems: Experiences and open problems," in Proceedings of the International Federation of Automatic Control Symposium on Theory and Application of Digital Control, New Delhi, India, 1982.

Vogel, E.F. (1982). Adaptive control of chemical processes with variable dead time, Ph D dissertation, University of Texas at Austin. Austin, Tex., 1982.

Vogel, E.F., and Edgar, T.F. (1982). "Application of an adaptive pole-zero placement controller to chemical processes with variable dead time," in Proceedings of the American Control Conference, vol 536, Arlington, Va., 1982.

LIST OF SYMBOLS

A,B	Process z-transform polynomials
a_i, b_i, c_i	Coefficients of the process polynomials
B_E	Expanded B polynomial
b_i'	Coefficient of B_E polynomial
d	Bias term in process model
E	Polynomial
e_i	Coefficient of E polynomial
F	Polynomial
f_i	Coefficient of F polynomial
G_c	Controller transfer function
G_p	Process transfer function
G_p'	Undelayed process transfer function
k	Time delay (k>1)
k_{max}	Maximum expected time delay
k_{min}	Minimum expected time delay
n_A	Order of A polynomial
n_B	Order of B polynomial
P	Weighting polynomial for output
Q,Q'	Weighting polynomials for input
R	Weighting rational function for setpoint
r	Order of B_E polynomial
s	Laplace transform
t	Sampling instant
u	Manipulated input
w	Setpoint
y	Measured output
z	Z-transform variable
$\hat{}$	Estimated value of a polynomial or scalar

Greek Letters

ε	Output error
Σ_{BE}	Scalar

Table 1. Time Constant and Gain Variations for the HVAC Process

Change in u (%)	Process Time Constant (sec)	Process Gain (°C)
+100	54.5	24.7
+75	59.5	27.0
+50	65.6	29.8
+25	73.0	33.1
+10	78.3	35.5
-10	86.7	39.4
-25	94.4	42.8
-50	110.5	50.2
-75	133.4	60.5
-100	168.1	76.3

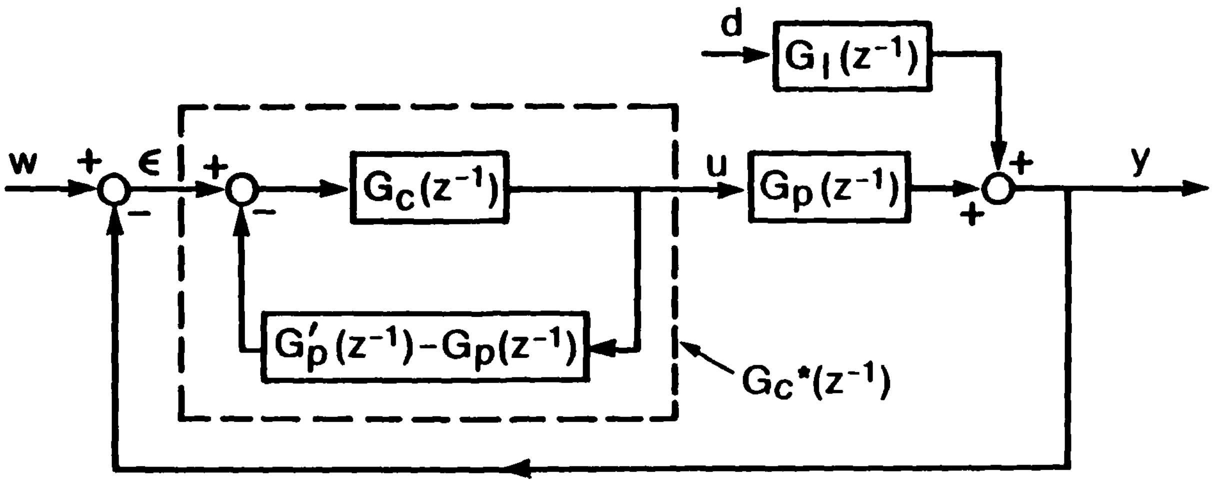


Figure 1. Block diagram of discrete-time Smith predictor.

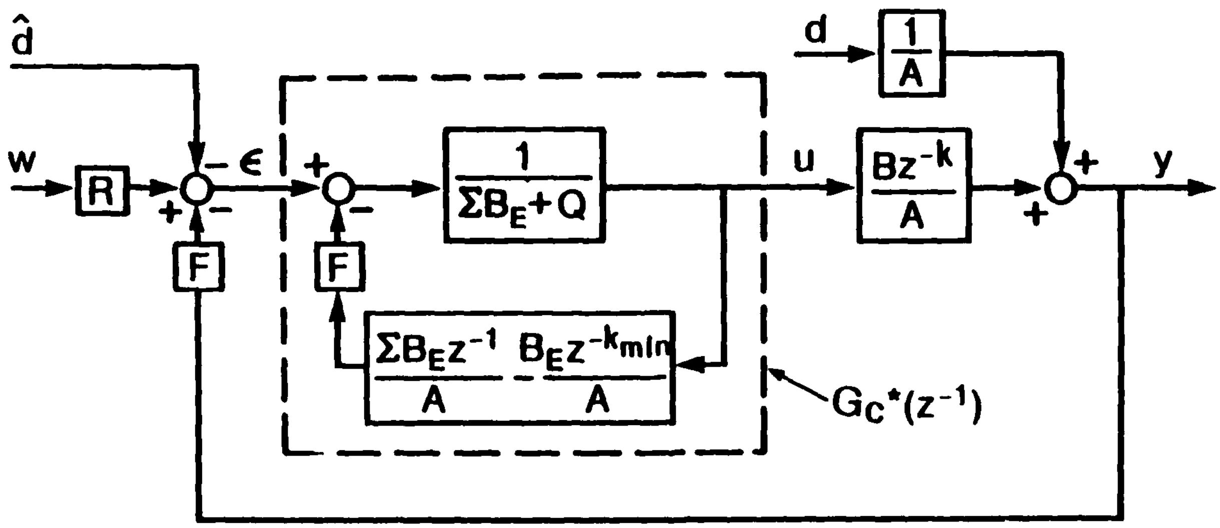


Figure 2. Block diagram of the STC with time delay compensation.

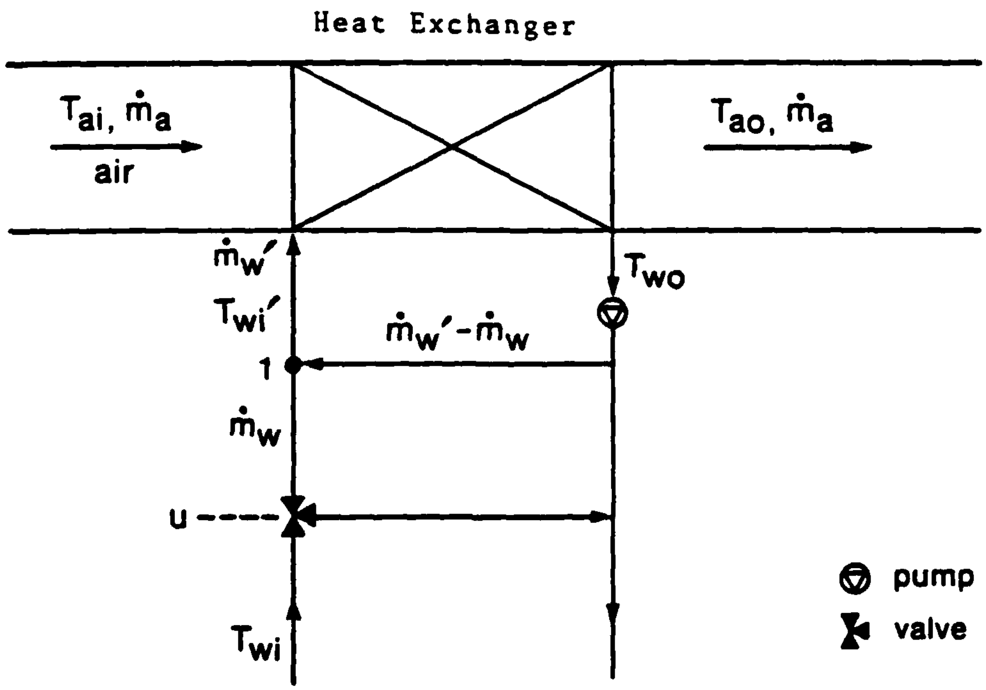


Figure 3. Schematic diagram of air heater.

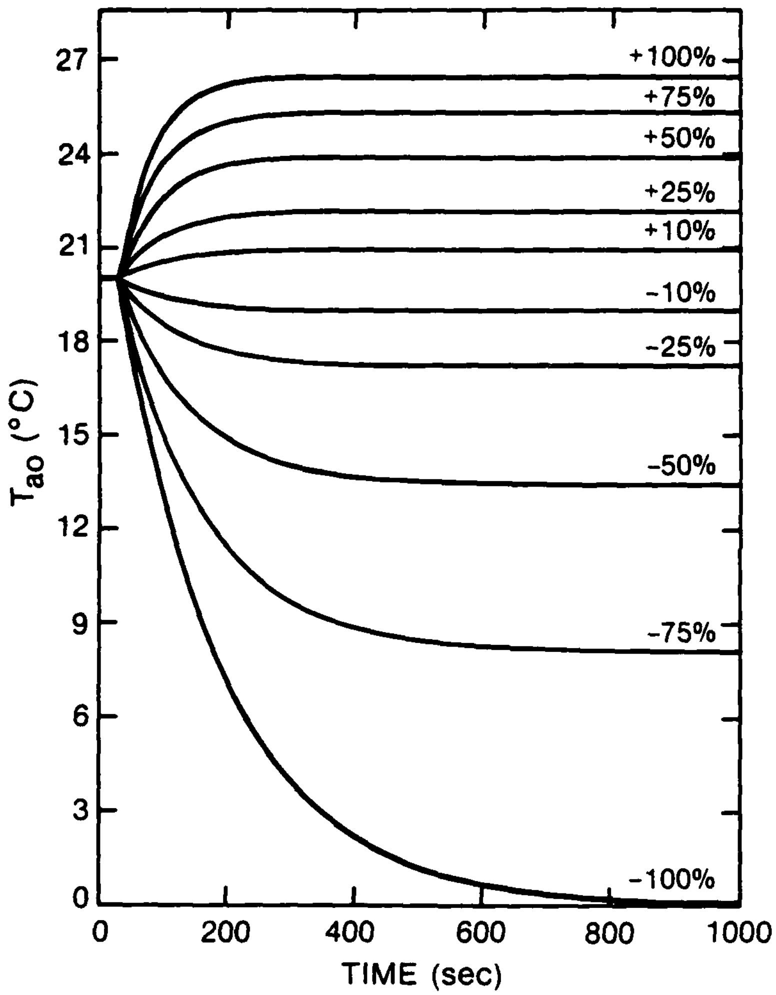


Figure 4. Open-loop response for HVAC process.

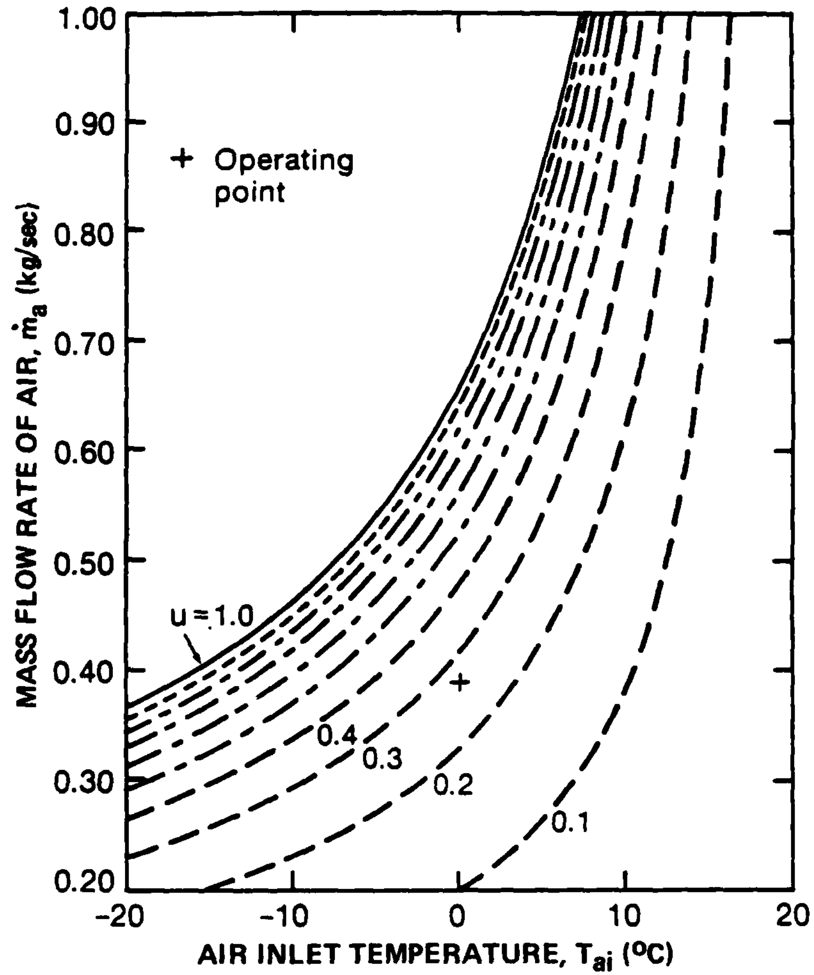


Figure 5. Operating window for the HVAC process.

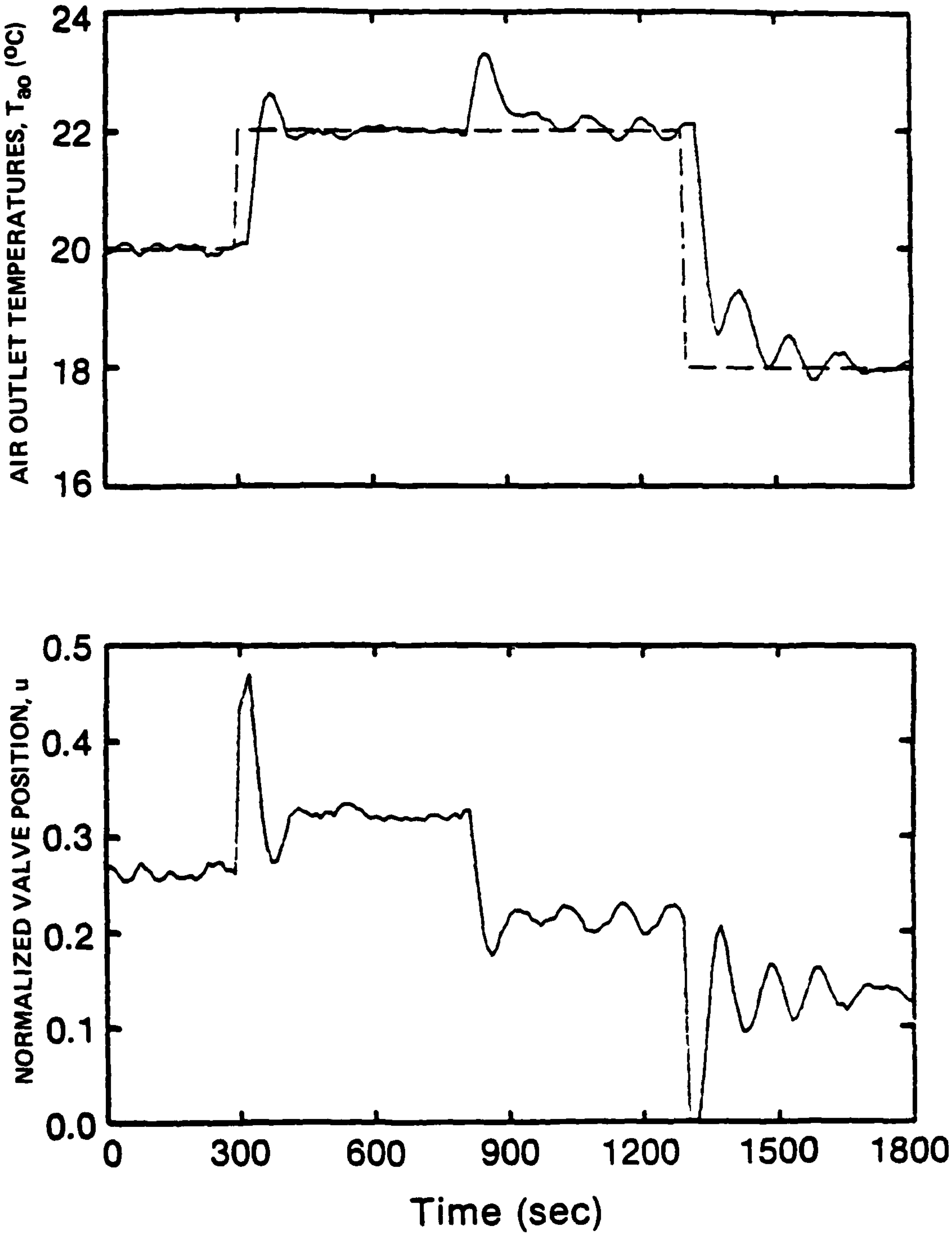


Figure 6. PI controller for setpoint changes with T_{ai} increases by 5°C occuring at t = 800 sec.

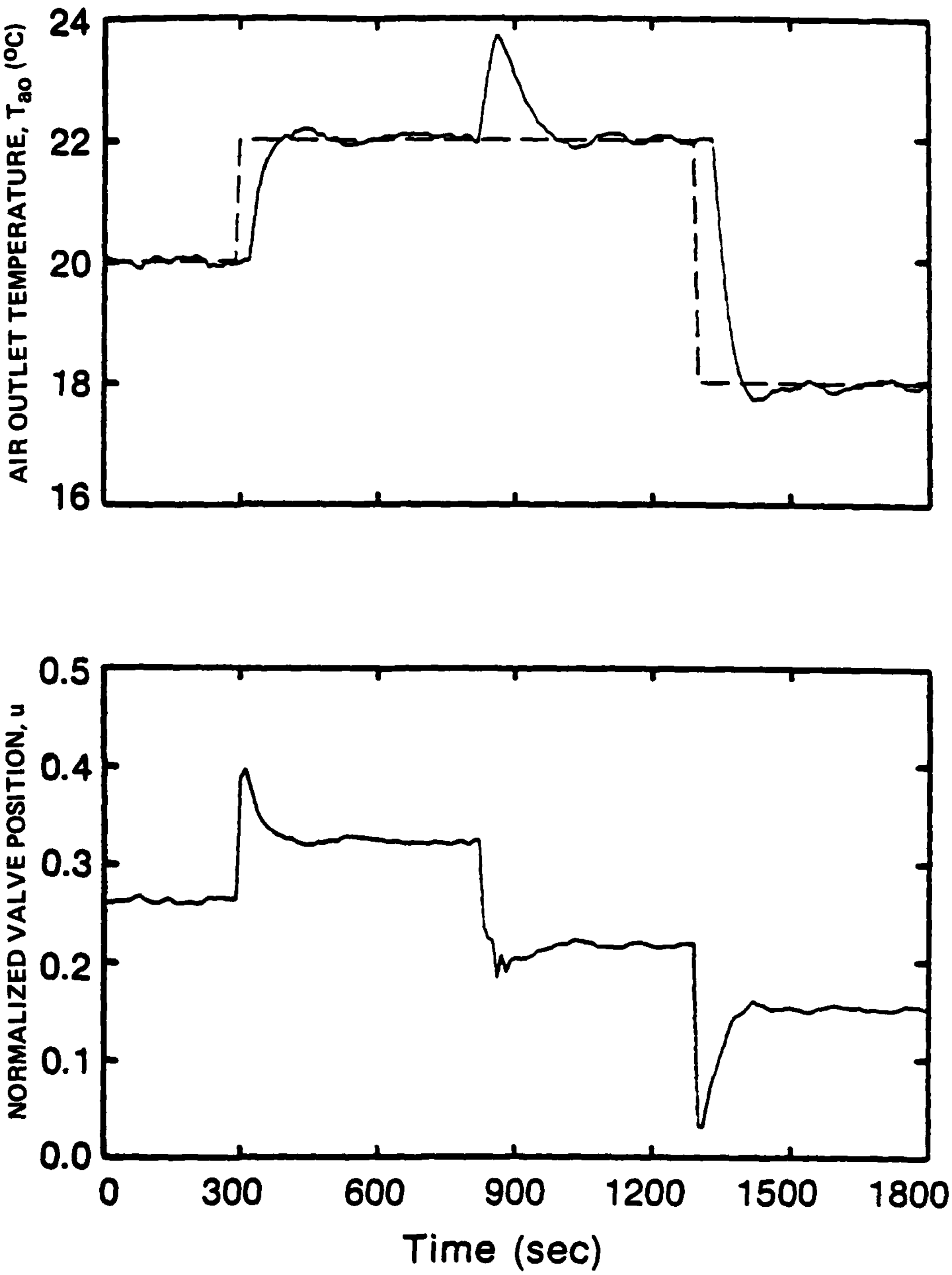


Figure 7. STC-TDC with same test sequence as shown in Figure 6.

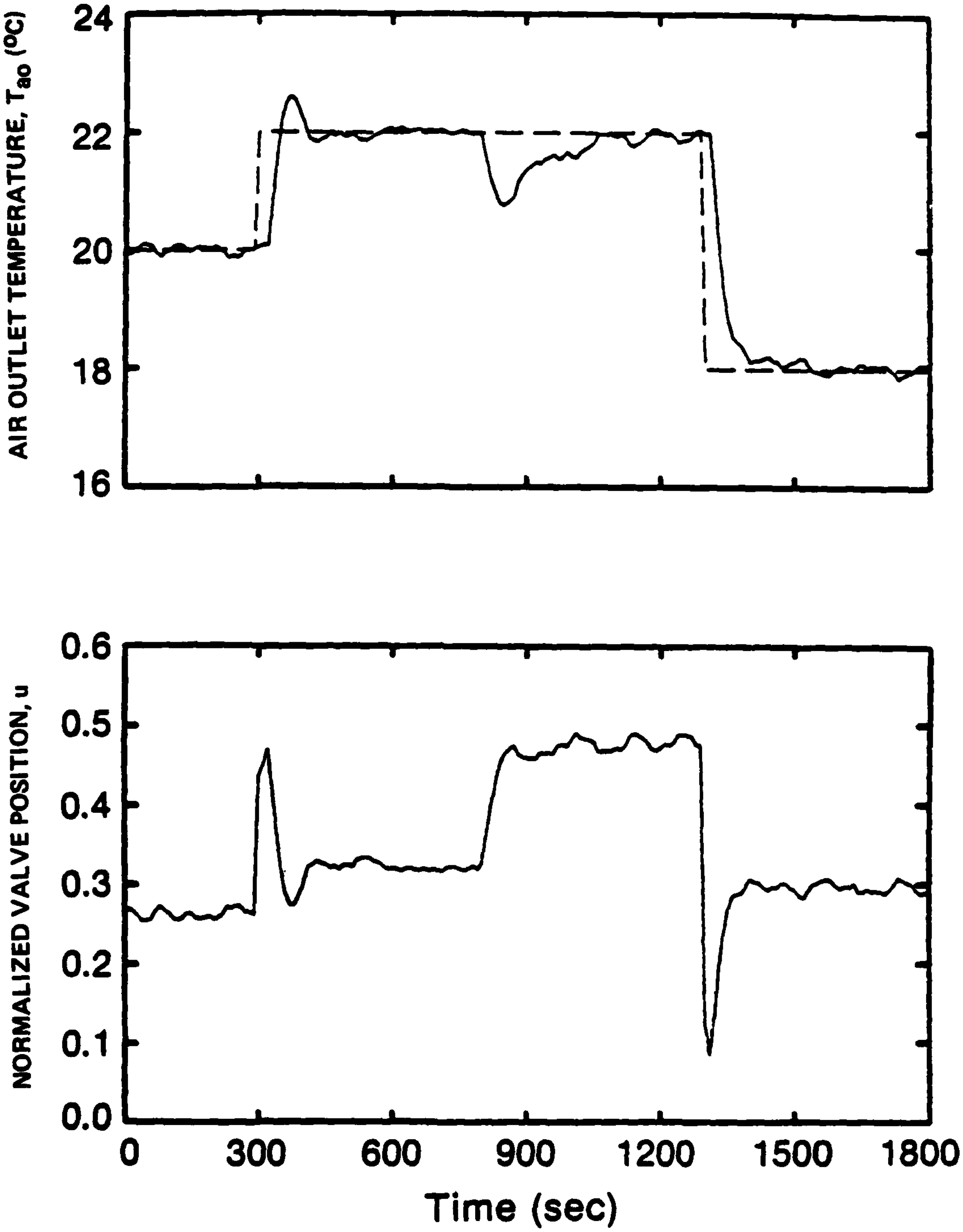


Figure 8. PI controller for setpoint changes when air mass flow rate ($\dot{m}_a$) decreases 20% and time delay increases to 30 sec at t = 800 sec.

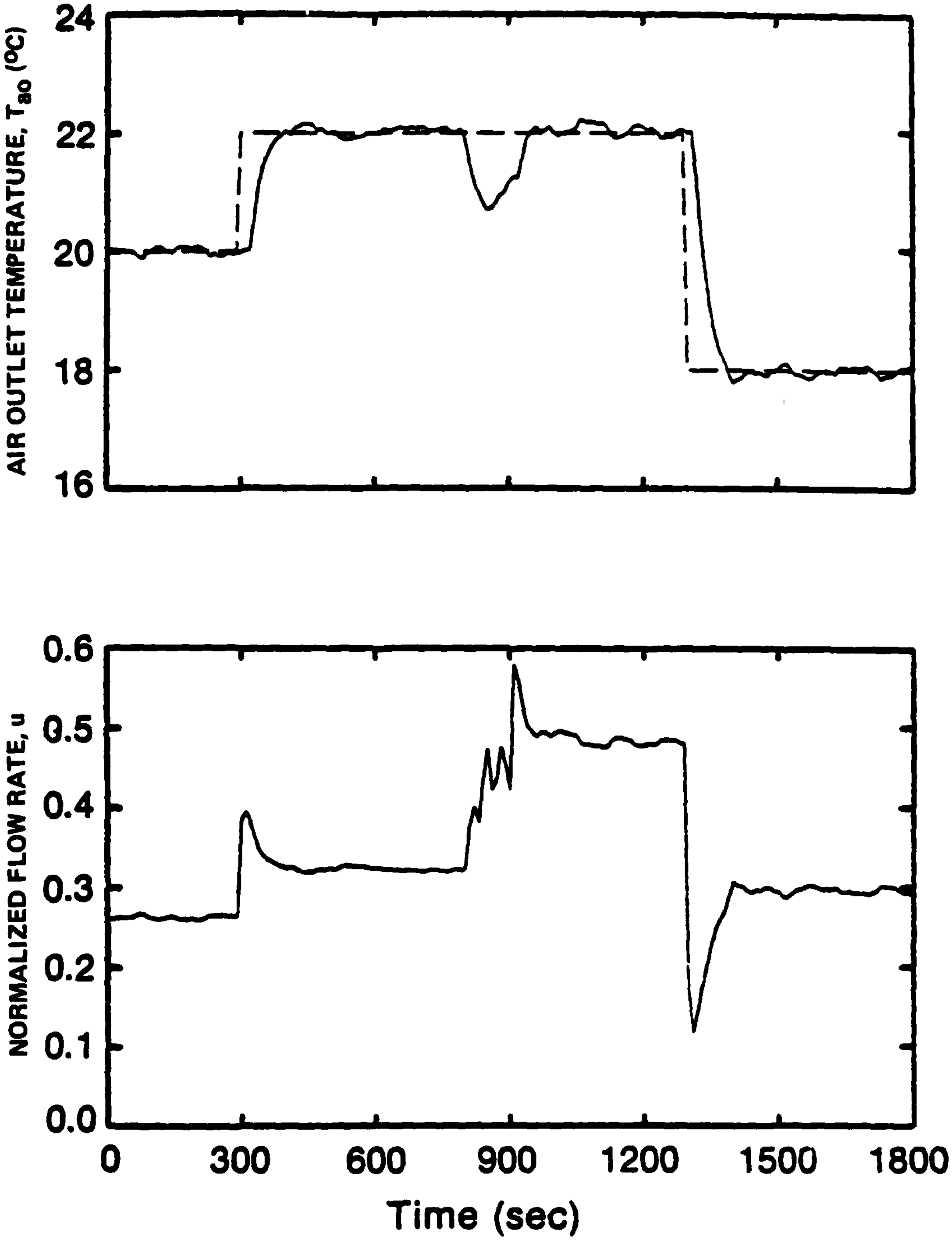


Figure 9. STC-TDC with the same test sequence as shown in Figure 8.

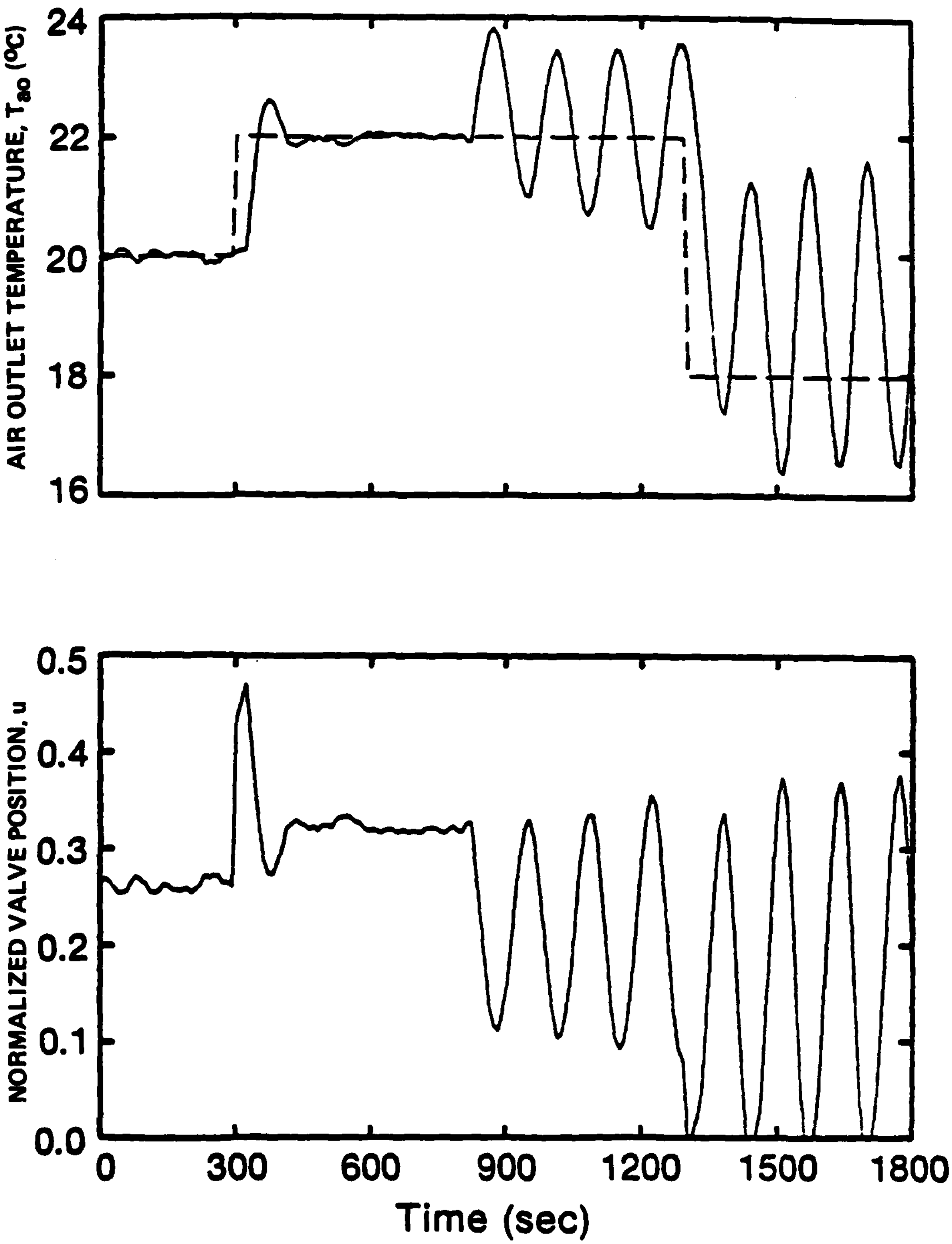


Figure 10. PI controller for setpoint changes when air mass flow rate ($\dot{m}_a$) decreases 20% and time delay increases to 30 sec at t = 800 sec.

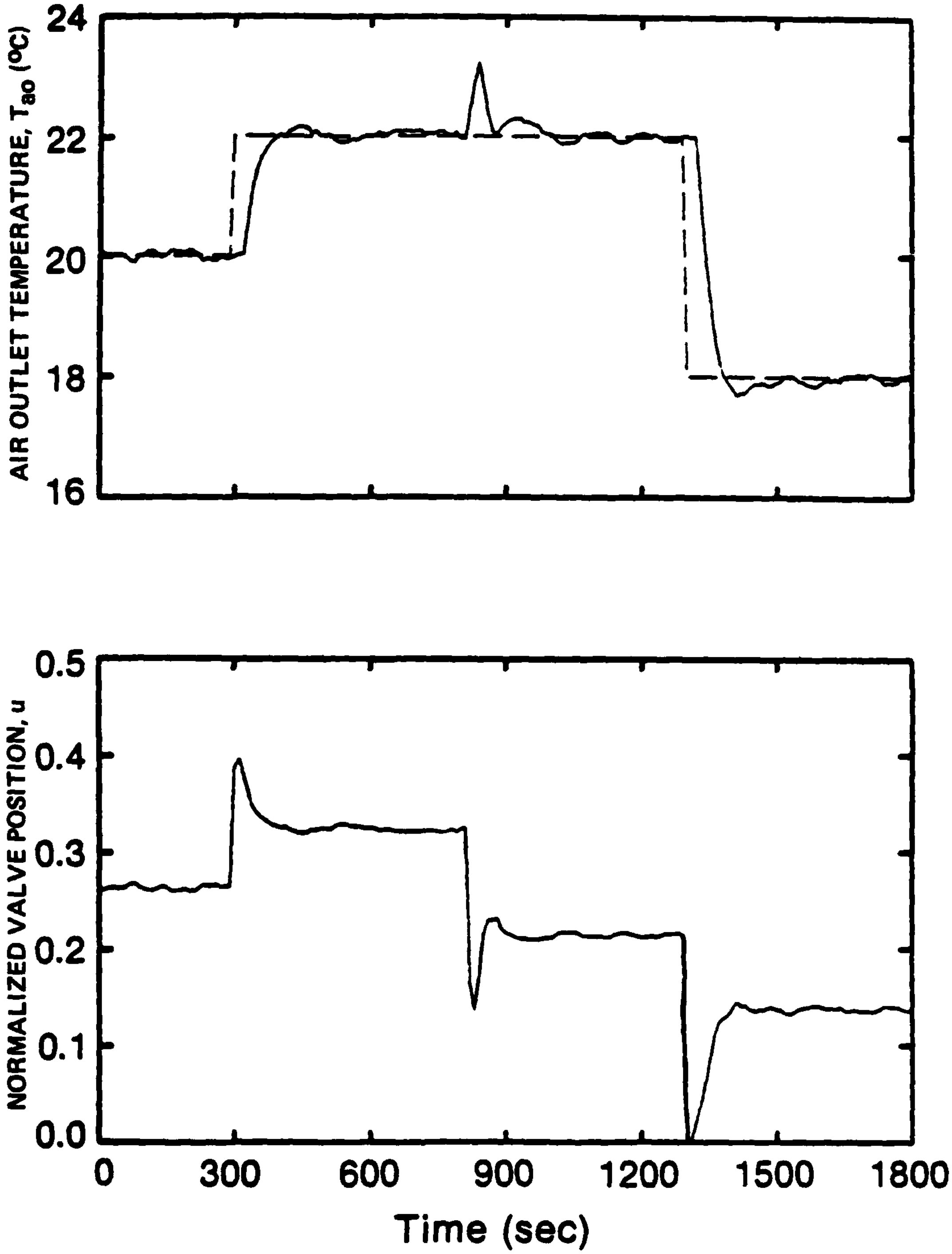


Figure 11. STC-TDC with the same test sequence as shown in Figure 10.

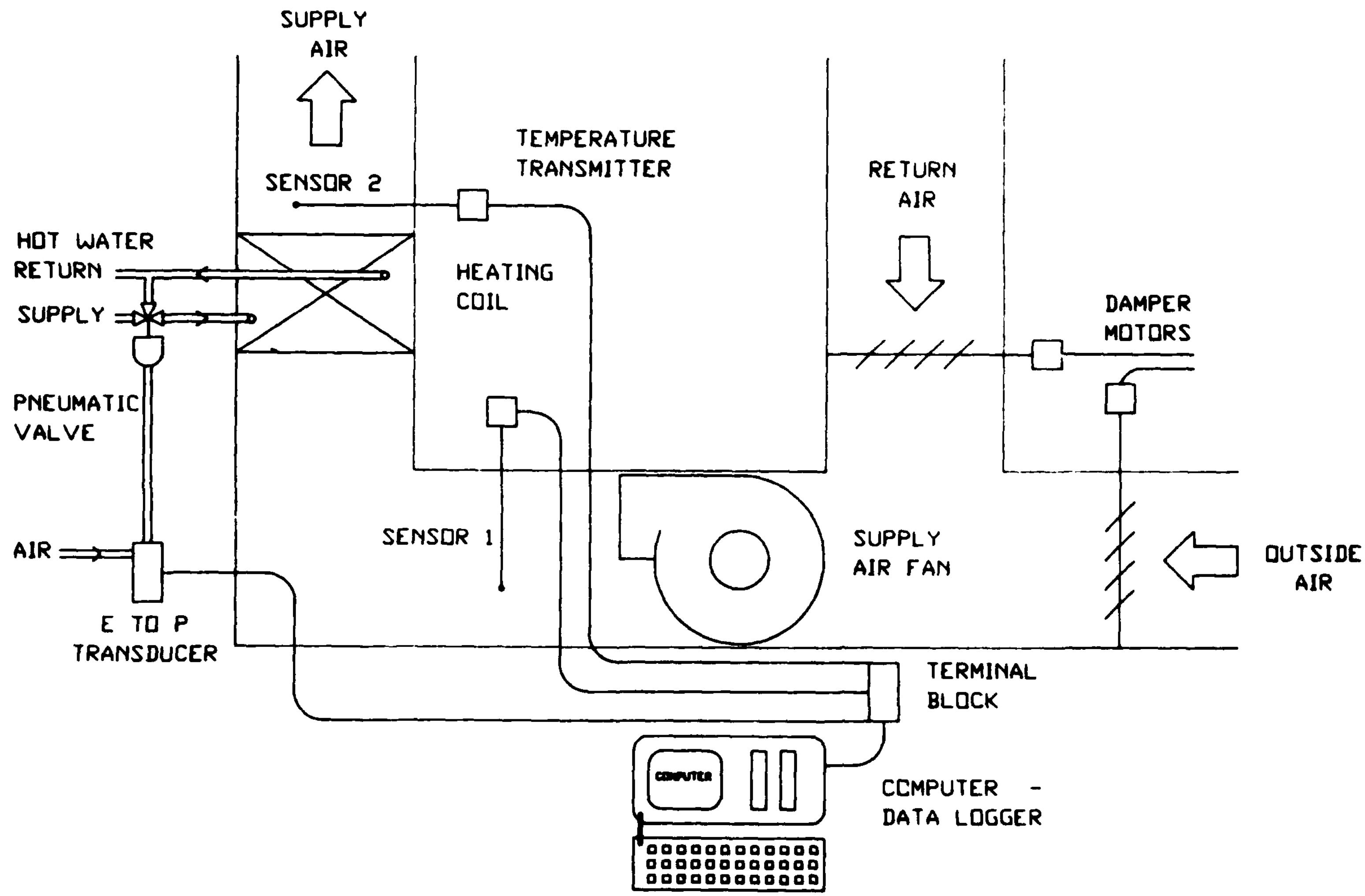


Figure 12. Diagram of experimental apparatus.

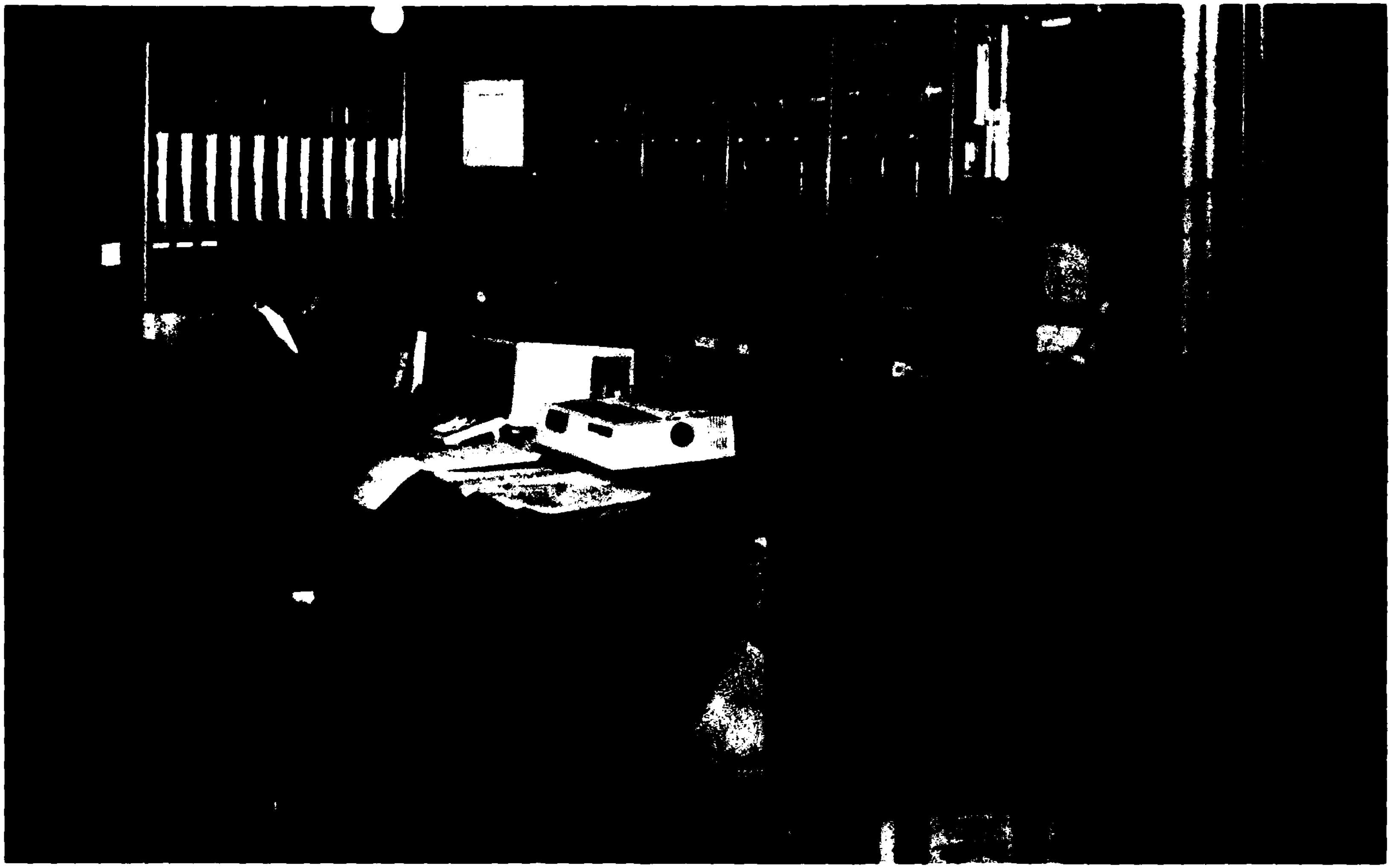


Figure 13. Portable computer used as programmable controller and data logger.

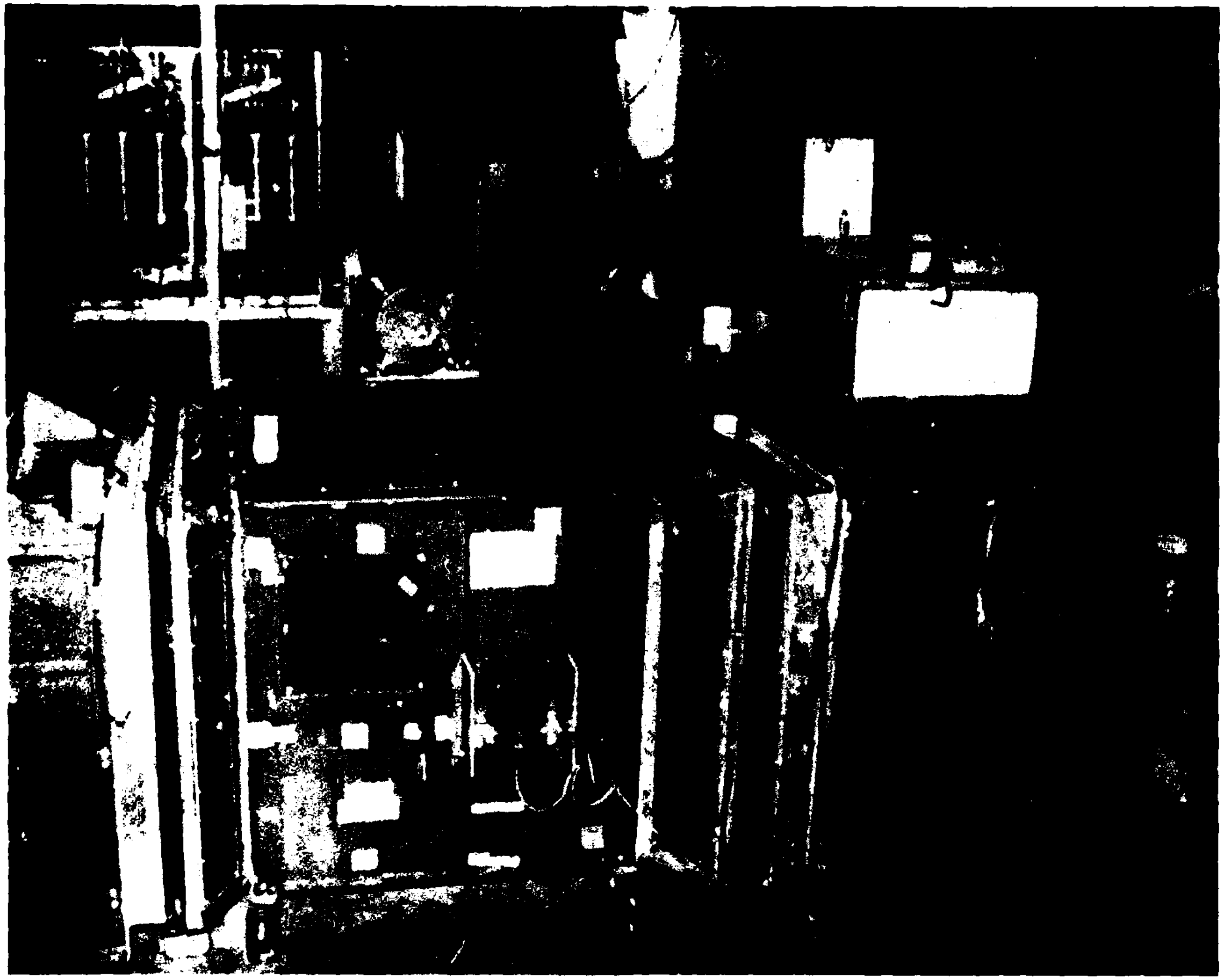


Figure 14. Experimental setup using air handler at CERL HVAC facility.

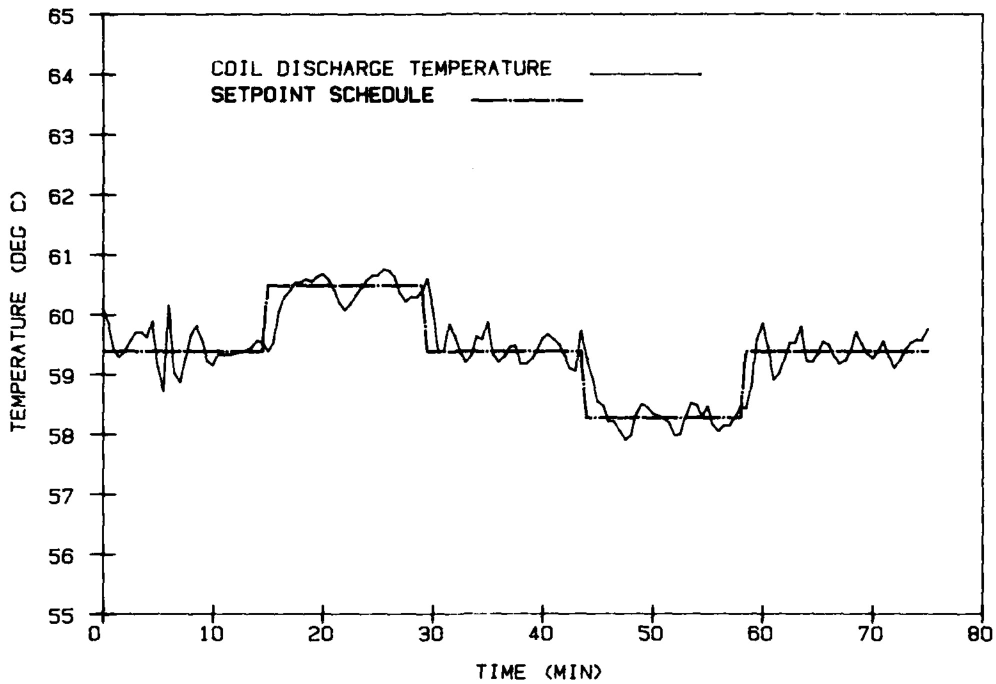


Figure 15. Coil discharge temperature data from experiment PI.1.

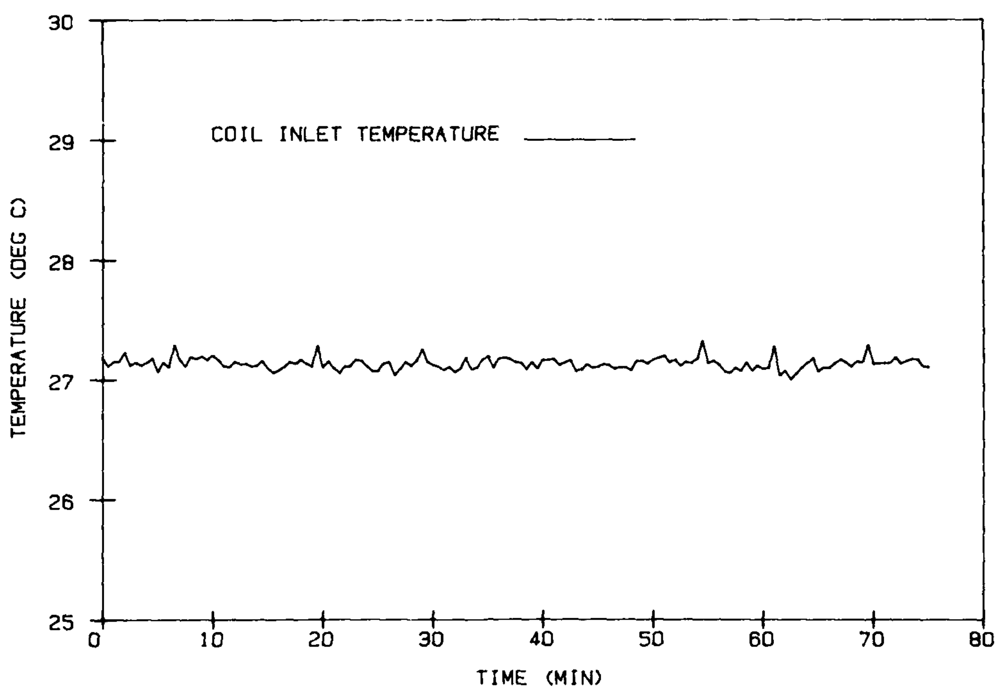


Figure 16. Coil inlet temperature data from experiment PI.1.

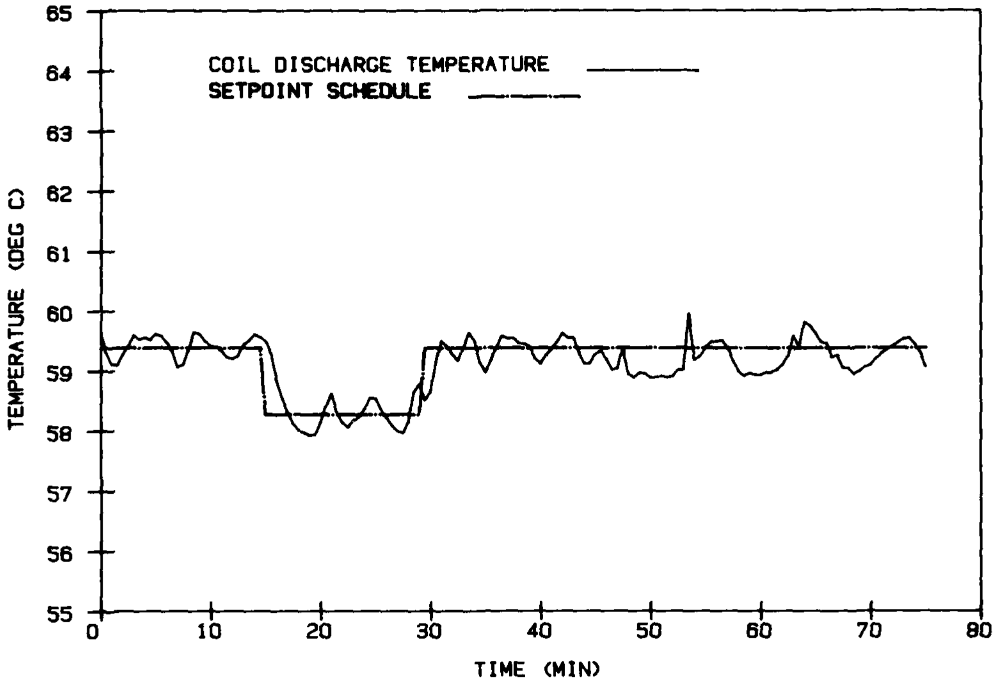


Figure 17. Coil discharge temperature data from experiment PI.2.

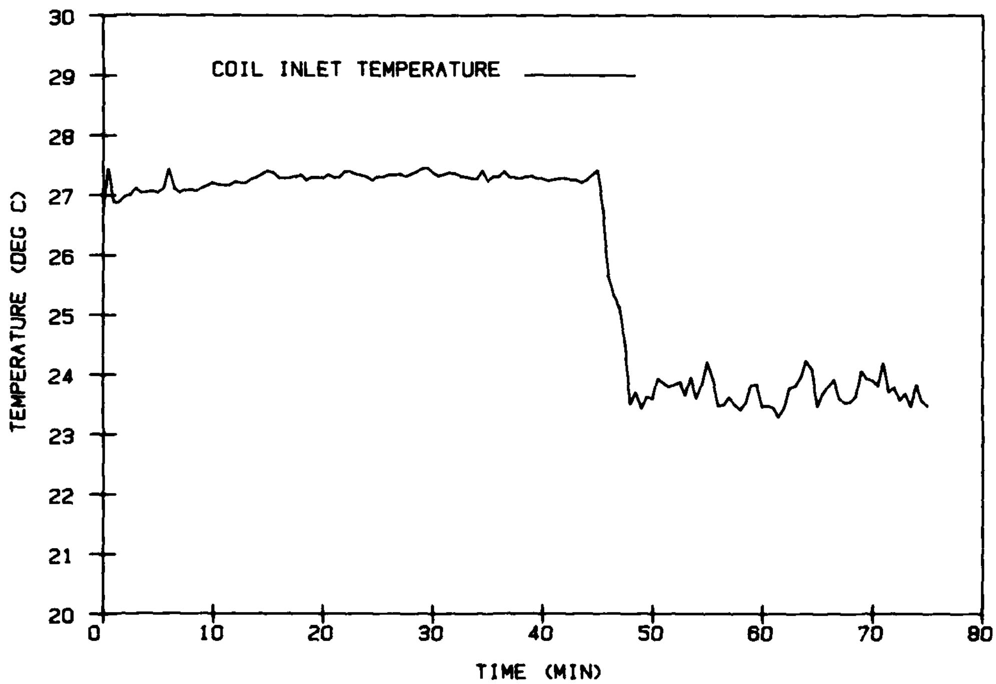


Figure 18. Coil inlet temperature data from experiment PI.2.

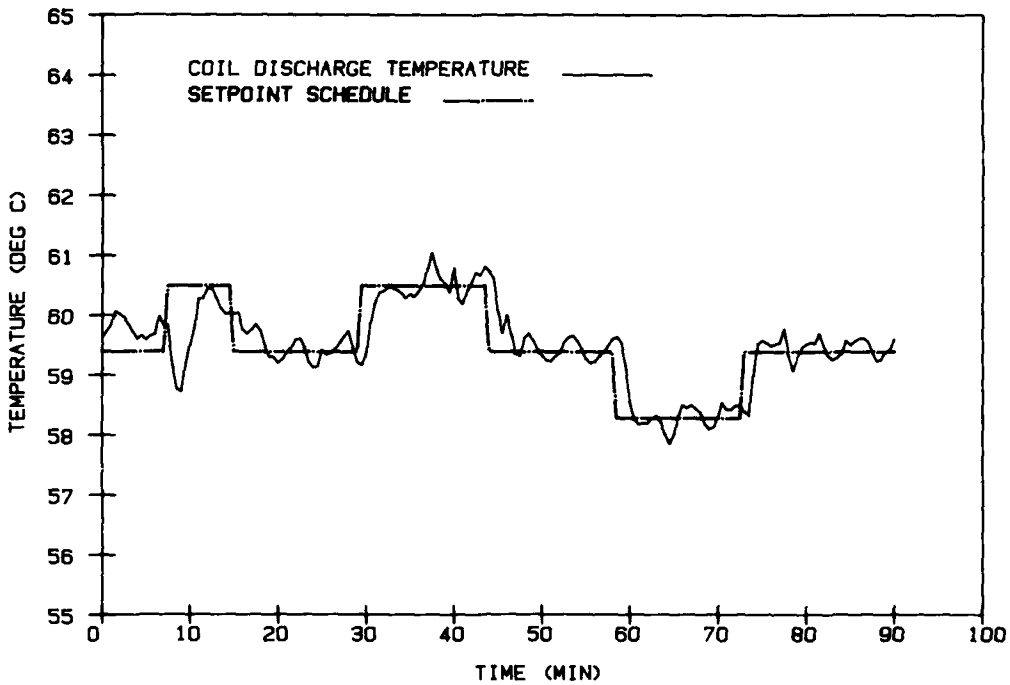


Figure 19. Coil discharge temperature data from experiment STC.13.

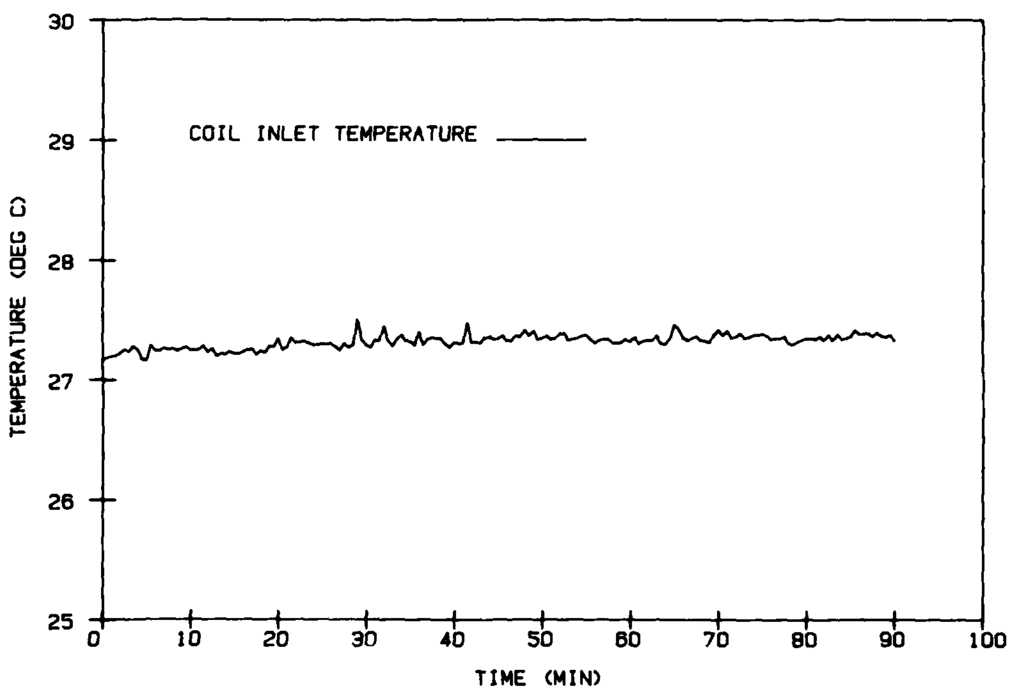


Figure 20. Coil inlet temperature data from experiment STC.13.

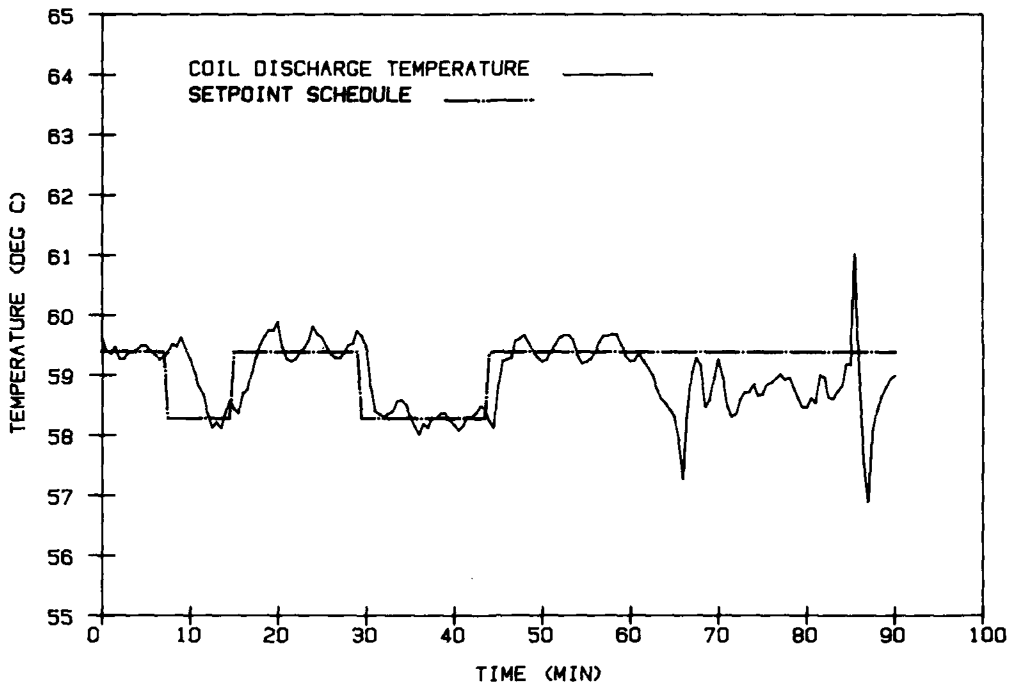


Figure 21. Coil discharge temperature data from experiment STC.16.

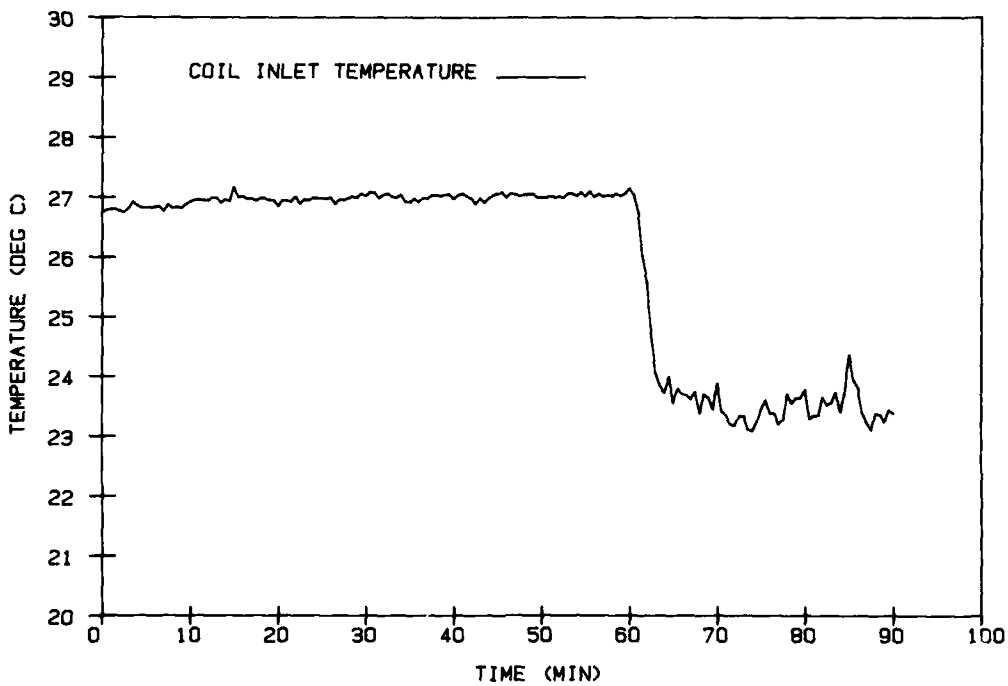


Figure 22. Coil inlet temperature data from experiment STC.16.

DISTRIBUTION LIST

AFB DET Wright-Patterson OH; Scol of Engrng (AFIT/DET)
AFESC AFESC/TST, Tyndall AFB, FL; DEMM (Strother), Tyndall AFB, FL
ARMY ERADCOM Tech Supp Dir. (DELSD-L) Ft. Monmouth, NJ; HQDA (DAEN-FEE-A)
ARMY - CERL Energy Systems, Champaign, IL; Library, Champaign IL
ARMY CRREL G. Phetteplace, Hanover, NH
ARMY MATERIALS & MECHANICS RESEARCH CENTER Dr. Lenoe, Watertown MA
DTIC Alexandria, VA
DTNSRDC Code 522 (Library), Annapolis MD
ENVIRONMENTAL PROTECTION AGENCY Reg. III Library, Philadelphia PA
GSA Assist Comm Des & Cnst (FAIA) D R Dibner Washington, DC ; Off of Des & Const-PCDP (D Eakin) Washington, DC
LIBRARY OF CONGRESS Washington, DC (Sciences & Tech Div)
NAS Moffett Fld, CA
NAVFACENGCOM Code 03 Alexandria, VA; Code 032E, Alexandria, VA; Code 03T (Essoglou) Alexandria, VA; Code 04B3 Alexandria, VA; Code 082, Alexandria, VA; Code 1113, Alexandria, VA; Code 111B (Hanneman), Alexandria, VA; Code 112, Alexandria, VA
NAVFACENGCOM - CHES DIV. Library, Washington, D.C.
NAVFACENGCOM - LANT DIV. Code 111, Norfolk, VA; Code 1112, Norfolk, VA; Code 403, Norfolk, VA; Library, Norfolk, VA
NAVFACENGCOM - NORTH DIV. Code 04 Philadelphia, PA; Code 04AL, Philadelphia PA; Code 111 Philadelphia, PA
NAVFACENGCOM - PAC DIV. Code 402, RDT&E, Pearl Harbor HI; Library, Pearl Harbor, HI
NAVFACENGCOM - SOUTH DIV. Code 1112, Charleston, SC; Code 406 Charleston, SC; Library, Charleston, SC
NAVFACENGCOM - WEST DIV. Code 04B San Bruno, CA; Library, San Bruno, CA; RDT&ELO San Bruno, CA
NAVPGSCOL Code 1424, Library, Monterey, CA
NAVSHIPYD Library, Portsmouth NH
NRL Code 5800 Washington, DC
OFFICE SECRETARY OF DEFENSE OASD (MRA&L) Dir. of Energy, Pentagon, Washington, DC
ONR Code 700F Arlington VA
PWC Code 101 (Library), Oakland, CA; Code 123-C, San Diego, CA; Library, Guam, Mariana Islands; Library, Norfolk, VA; Library, Pearl Harbor, HI; Library, Pensacola, FL; Tech Library, Subic Bay, RP; Library, Yokosuka JA; Tech Lib (Code 154), Great Lakes, IL
USCG Library Hqs Washington, DC
USNA Ch. Mech. Engr. Dept Annapolis MD; Mech. Engr. Dept. (Hasson), Annapolis, MD
CORNELL UNIVERSITY Ithaca NY (Serials Dept, Engr Lib.)
LEHIGH UNIVERSITY Bethlehem PA (Linderman Lib. No.30, Flecksteiner)
MIT Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.)
PURDUE UNIVERSITY Lafayette, IN (CE Engr. Lib)
UNIVERSITY OF HAWAII HONOLULU, HI (SCIENCE AND TECH. DIV.)
UNIVERSITY OF ILLINOIS URBANA, IL (LIBRARY)
SANDIA LABORATORIES Library Div., Livermore CA
UNITED TECHNOLOGIES Windsor Locks CT (Hamilton Std Div., Library)
WESTINGHOUSE ELECTRIC CORP. Library, Pittsburgh PA
WM CLAPP LABS - BATTELLE DUXBURY, MA (LIBRARY)

PLEASE HELP US PUT THE ZIP IN YOUR MAIL! ADD YOUR FOUR NEW ZIP DIGITS TO YOUR LABEL (OR FACSIMILE), STAPLE INSIDE THIS SELF-MAILER, AND RETURN TO US.

(fold here)

DEPARTMENT OF THE NAVY

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043-5003

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300
1 IND-NCEL.2700/4 (REV. 12-73)
0930-LL-L70-0044

POSTAGE AND FEES PAID
DEPARTMENT OF THE NAVY
DOD-316

U.S.MAIL

Commanding Officer
Code L14
Naval Civil Engineering Laboratory
Port Hueneme, California 93043-5003

INSTRUCTIONS

The Naval Civil Engineering Laboratory has revised its primary distribution lists. The bottom of the mailing label has several numbers listed. These numbers correspond to numbers assigned to the list of Subject Categories. Numbers on the label corresponding to those on the list indicate the subject category and type of documents you are presently receiving. If you are satisfied, throw this card away (or file it for later reference).

If you want to change what you are presently receiving:

- Delete – mark off number on bottom of label.
- Add – circle number on list.
- Remove my name from all your lists – check box on list.
- Change my address – line out incorrect line and write in correction (ATTACH MAILING LABEL).
- Number of copies should be entered after the title of the subject categories you select.

Fold on line below and drop in the mail.

Note: Numbers on label but not listed on questionnaire are for NCEL use only, please ignore them.

Fold on line and staple.

DEPARTMENT OF THE NAVY

NAVAL CIVIL ENGINEERING LABORATORY
PORT HUENEME, CALIFORNIA 93043

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300
1 IND-NCEL-2700/4 (REV. 12-73)
0930-LL-L70-0044

POSTAGE AND FEES PAID
DEPARTMENT OF THE NAVY
DOD-316

U.S.MAIL

Commanding Officer
Code L14
Naval Civil Engineering Laboratory
Port Hueneme, California 93043

DISTRIBUTION QUESTIONNAIRE

The Naval Civil Engineering Laboratory is revising its primary distribution lists.

SUBJECT CATEGORIES

1 **SHORE FACILITIES**
2 Construction methods and materials (including corrosion control, coatings)
3 Waterfront structures (maintenance/deterioration control)
4 Utilities (including power conditioning)
5 Explosives safety
6 Construction equipment and machinery
7 Fire prevention and control
8 Antenna technology
9 Structural analysis and design (including numerical and computer techniques)
10 Protective construction (including hardened shelters, shock and vibration studies)
11 Soil/rock mechanics
13 BEQ
14 Airfields and pavements
15 **ADVANCED BASE AND AMPHIBIOUS FACILITIES**
16 Base facilities (including shelters, power generation, water supplies)
17 Expedient roads/airfields/bridges
18 Amphibious operations (including breakwaters, wave forces)
19 Over-the-Beach operations (including containerization, materiel transfer, lighterage and cranes)
20 POL storage, transfer and distribution
24 **POLAR ENGINEERING**
24 Same as Advanced Base and Amphibious Facilities, except limited to cold-region environments
28 **ENERGY/POWER GENERATION**
29 Thermal conservation (thermal engineering of buildings, HVAC systems, energy loss measurement, power generation)
30 Controls and electrical conservation (electrical systems, energy monitoring and control systems)
31 Fuel flexibility (liquid fuels, coal utilization, energy from solid waste)
32 Alternate energy source (geothermal power, photovoltaic power systems, solar systems, wind systems, energy storage systems)
33 Site data and systems integration (energy resource data, energy consumption data, integrating energy systems)
34 **ENVIRONMENTAL PROTECTION**
35 Solid waste management
36 Hazardous/toxic materials management
37 Wastewater management and sanitary engineering
38 Oil pollution removal and recovery
39 Air pollution
40 Noise abatement
44 **OCEAN ENGINEERING**
45 Seafloor soils and foundations
46 Seafloor construction systems and operations (including diver and manipulator tools)
47 Undersea structures and materials
48 Anchors and moorings
49 Undersea power systems, electromechanical cables, and connectors
50 Pressure vessel facilities
51 Physical environment (including site surveying)
52 Ocean-based concrete structures
53 Hyperbaric chambers
54 Undersea cable dynamics

TYPES OF DOCUMENTS

85 Techdata Sheets
86 Technical Reports and Technical Notes
82 NCEL Guide & Updates
☐ None— remove my name
83 Table of Contents & Index to TDS
91 Physical Security

END

FILMED

11-85

DTIC