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UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

AUTOMATIC VARIABLE VENTILATION CONTROL SYSTEM

FINAL REPORT

February 1981

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AUTOMATIC VARIABLE VENTILATION CONTROL SYSTEM

Honeywell, Inc.
Technology Strategy Center
Roseville, Minnesota

February 1981

Prepared under UCLBL PO No. 4500610 for: The Energy Efficient Buildings Program, Energy and Environment Division, Lawrence Berkeley Laboratory. Principal Investigators: Craig Hollowell and Arthur Rosenfeld.

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Contract No. 4500610

February 1981

Prepared for:

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Submitted by:

Honeywell Inc.
Technology Strategy Center
1700 West Highway 36
Roseville, Minnesota 55113

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SECTION 1.0
EXECUTIVE SUMMARY

Heating and cooling of ventilation air used in commercial buildings to satisfy building codes is recognized as a major part of total energy consumption in such buildings. Past design practices used outdoor air freely for control of odors, moisture, temperature and occupant needs, with little concern for attendant energy consequences. Rising energy costs and a national concern for conservation of scarce resources make such wasteful practices undesirable. Many building managers have restricted the use of outdoor ventilation air without knowledge of the consequences and often in violation of building codes. A potential solution to this problem is a ventilation control concept that would measure demand and provide only the amount of outdoor air necessary to meet occupant needs. Such a concept also would derive energy savings benefits by implicitly including infiltration as a part of the ventilation air; past design practices ignored infiltration.

This program was undertaken to study such a control system concept with the objective of determining whether an Automatic Variable Ventilation Control System based on actual demand would provide energy savings while maintaining conditions acceptable to the occupants.

A recently constructed 10,000-square-foot music wing at Fridley Junior High School, Fridley, Minnesota, was selected for the test and demonstration site. This wing of the building essentially was a separate building with its own heating and cooling system--an ideal arrangement for the test purposes of the program. Carbon dioxide was selected as the load-sensitive parameter to be measured and used for ventilation control. The CO_2 concentration gives a direct indication of the number of occupants as well as reflecting activity level of the occupants.

A CO_2-based control system was designed and installed in the school. The basic concept was that the outdoor air intake and exhaust damper were normally closed, while the recirculation damper was normally open. Outdoor air was introduced only to satisfy a demand for reducing CO_2 or to satisfy the demand for reduced temperature when the outdoor air temperature was low enough. The CO_2-controlled ventilation system differs from the conventional ventilation control system in that the outdoor air dampers normally are closed, in contrast to a nominal design minimum position, which in the Fridley case was 16 percent of total air-handling capacity.

The ventilation system installed for the Fridley tests included modifications to allow the original HVAC system (a terminal reheat system) to be run. Also, because the original terminal reheat system was known to be wasteful of energy, it was modified to give optimized terminal reheat. This revised version of the original HVAC system represented a common state-of-the-art improvement and was used as the base of reference for subsequent energy savings comparisons with the CO_2 system.

To further meet the objective of maintaining comfort within the school while controlling ventilation, subjective responses were obtained from the students, with parental permission, to ascertain their perceptions of various comfort parameters under the different test conditions. Iowa State University designed, conducted and analyzed the subjective testing program.

All of the above elements of the program were exercised throughout an intensive test period during February 1980. The CO_2 control system and the optimized terminal reheat system were activated on specific days during the test. Certain classes throughout the day were selected to fill out questionnaires related to perceived comfort. An extensive data acquisition system recorded CO_2, temperatures, airflows and other physical parameters for subsequent analysis of energy use and comfort. Lawrence Berkeley Laboratory's mobile laboratory was present and measured a variety of significant indoor air pollutants. (Their report is issued separately.)

During this intensive test period, the CO_2 set point or reference value for air quality ventilation control was set at a high value of 3000 parts per million (ppm). This high setting maximized energy savings and allowed the subjective response statistical correlation analysis to be made over a wide range of CO_2 values. The relatively low occupancy level, however, did not provide enough load to reach the 3000 ppm set point, and the outdoor air dampers remained closed during the intensive test period. The set point was subsequently lowered to demonstrate control action.

Analysis of test data produced the following primary results or conclusions:

- The CO_2 system conserved energy. During the test, an average of 24 percent of energy was conserved compared to the optimized terminal reheat system. These savings were on cold days (-3° to 23°F), where savings are expected to be maximized. Extrapolation by computer simulation forecast predicts seasonal heating savings on the order of 20 percent for Fridley Junior High School. National implementation of a ventilation or demand concept, using a conservative value of savings of 10 percent, could conserve on the order of 58×10^6 barrels-of-oil-equivalent annually.

- Comfort was maintained, although the students could perceive several differences between CO_2 control and the revised original system. With CO_2 control, they felt the air was more stale and warmer, with less movement. They also felt warmer. Statistical correlation is shown between comfort, as expressed by the SET* parameter, and CO_2 levels--an unexpected result. There is an unexplored implication that a CO_2 system might tolerate lower heating thermostat set points with some further attendant energy savings.

- Poor location of return grills with respect to supply outlets in the rooms led to incomplete mixing of the ventilation and room air. This was shown to introduce a ventilation efficiency loss that can be avoided by proper design of the return air system.

- The ability of a CO_2 ventilation system to control CO_2 to specified levels of concentration was demonstrated. Separate tests at lower set points controlled to CO_2 concentrations of 800 to 1200 ppm.

- A CO_2 ventilating system is compatible, as an add-on feature, with existing ventilation systems. Cost analyses, including evaluation of currently available CO_2 sensor types, low-leak dampers and other installation features, show present-day practicality of CO_2 ventilation control implementation. Ongoing development of low-cost, solid-state CO_2 detectors offers future improvement of the economic issues.

It is concluded, therefore, that the prime objectives of this program were met, i.e., energy can be conserved while maintaining comfort within the space by controlling outdoor air on the basis of occupant demand and comfort. Further, the cost of installation is justified by the dollar savings associated with the energy conservation.

SECTION 2.0
INTRODUCTION

It is generally accepted that past practices resulted in overventilated buildings. When fuel was cheap, concern was for providing enough fresh (outdoor) air to assure control of moisture, odors and other contaminants. The ASHRAE ventilation standard, 62-73, specified a minimum of 5 CFM per person in essentially clean environments. The recommended rate was 10 CFM per person. No credit was given for infiltration, intermittent occupancy, or the fact that occupancy load might be less than design load.

This generous use of outdoor air represented a substantial waste of energy. Excess ventilation air was brought into a building from outdoors, either heated or cooled, distributed to rooms, and exhausted at temperatures equal to room temperature. Building operators were quick to recognize this loss of energy when fuel prices began to escalate. Many either closed the outdoor air intake or greatly restricted it, without regard to the effect on occupants. These measures generally violated building codes and could not be recommended actively.

The obvious solution to the problem of supplying only that ventilation air actually required is to install a control system that will open the intake damper only when outside air actually is needed. Such a control system requires some kind of sensor to measure the ventilation demand. The most direct indicator of ventilation demand is some change that people produce in the atmosphere surrounding them. Decrease in the oxygen level, increases in the carbon dioxide, moisture, odor or other contaminant levels are possible parameters that could be used to indicate ventilation demand. Carbon dioxide was selected because it is probably the most sensitive indicator.

The basic premise seemed quite straightforward: equip the ventilation system with a carbon dioxide sensor to control the outside air damper as a function of the CO_2 level in the occupied space and measure the energy savings. It was recognized, however, that some unexpected effects might be encountered. Reduction of ventilation air could be expected to make the system less forgiving of problems associated with ventilation. Also, since human subjects were involved, it was necessary to take every precaution to protect the health and welfare of the subjects. It was also very desirable to measure all performance factors of the physical system so that the effects of the modified control system could be appreciated fully.

Honeywell and Iowa State University (ISU) personnel then collaborated to demonstrate that a ventilation system controlled on the basis of room CO_2 level could reduce energy consumption. The objectives were to determine the potential energy savings, measure subjective response of the occupants and identify potential problems in such a control system.

The principle of an Automatic Variable Ventilation Control System (AVVCS) is to supply only enough outside air to satisfy the actual needs of the building occupants unless indoor and outdoor temperature conditions are such that additional outside air will reduce energy demand (i.e., economizer operation). A control sensor was required that sensed some contaminant, CO_2 in this case, and throttled the ventilation air so that the contaminant level was held at some acceptable level. Questions to be answered were:

- What contaminant level represents an acceptable control point?
- Does this introduce other problems relating to occupant acceptance?
- Is the energy savings significant?

An experimental site was needed that could be modified to accept the ventilation control system and give an unambigous correspondence between energy consumption and ventilation airflow. This was found at Fridley, Minnesota, Junior High School, where a 794-square-meter (8,550-square-foot) music department had been added to the school. The area essentially was self-contained, with heating and cooling systems separate from the rest of the building. It had a pneumatic control system that could be modified easily, and the building was located only 10 miles from Honeywell's Technology Strategy Center.

The project responsibilities were divided between Honeywell and ISU on the basis of capability and cost. Honeywell accepted responsibility for program management, system modification, data collection and some data analysis. ISU accepted responsibility for measurement of subjective response, system modeling and energy calculations.

The Lawrence Berkeley Laboratory also participated to the extent of measuring a variety of indoor contaminants during the intensive test period. The LBL-instrumented trailer recorded the level of a variety of contaminants during the period January 28, 1980, to February 29, 1980. Their findings are contained in a separate report. The subjective responses of the students to both normal and reduced ventilation rates were measured during the period January 28 to February 13, 1980.

This report contains a detailed discussion of the objectives and strategy for the experiment, a description of the system tested, a discussion of the proceedures, the results of the measurements, and conclusions and recommendations.

SECTION 3.0
OBJECTIVES AND ISSUES

The objective of this program was to determine whether an Automatic Variable Ventilation Control System based on air quality would provide energy savings while maintaining conditions acceptable to the occupants.

To meet this objective a program was defined with several discrete goals:

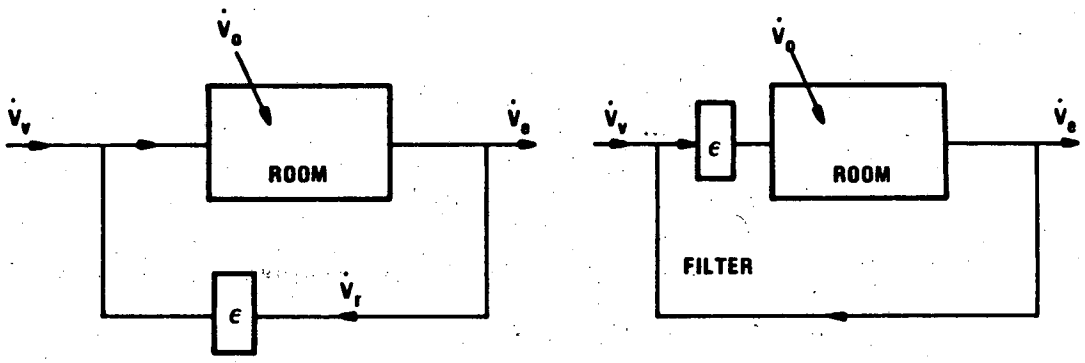
- Demonstrate the suitability of CO_2 as a viable air quality control parameter.
- Determine energy savings using CO_2 control.
- Determine subjective response to CO_2 controlled ventilation.
- Identify and define implementation problems.
- Define commercialization issues.

These issues were addressed specifically in this study. They are expanded on in the following paragraphs and serve as background for the detailed results of subsequent report sections.

3.1 RATIONALE FOR SELECTING CO_2 CONTROL

The minimum ventilation in a building must satisfy the physiological needs of the occupants. The distinction between respiratory and room ventilation rates was established to show that occupant-generated CO_2 concentration was probably an adequate measure of ventilation demand.

The engineer and the physiologist have defined ventilation differently. To the physiologist, ventilation is understood to mean "the inspiration of fresh air followed by the expiration of some alveolar gas" [1].* The engineer considers ventilation to mean "that portion of supply air which comes from outside (outdoors) plus any recirculated air that has been treated to maintain the desired quality of air within the designated space" [2]. If a person were outside, the two definitions would result in the same ventilation quality. However, within confined spaces, the resultant values are not synonymous. To relate these values, two systems were modeled, as shown in Figure 3-1.



a. Filter in Return Air System b. Filter in Mixed Air System

Figure 3-1. Schematic Representation of Ventilation System Models

The steady-state mass balance equation for the system in Figure 3-1a, with the filter in the return air duct, is:

$$\dot{V}_e C_o + \dot{V}_r C_s (1 - \varepsilon) + \dot{N} = (\dot{V}_e + \dot{V}_r) C_s \qquad (3\text{-}1)$$

where

C_o = Outdoor air concentration

*Numbers in brackets are referenced at end of report.

C_s = Steady-state concentration in the space.

$\dot{N}$ = Generation rate in the space.

$\dot{V}_e$ = Ventilation airflow rate.

$\dot{V}_r$ = Recirculated airflow rate.

ε = Filter efficiency (by mass).

The solution for the ventilation rate is:

$$V_e = \frac{\dot{N}}{\left[C_s - C_o\right] + \left(\frac{\dot{V}_r}{\dot{V}_e}\right) \varepsilon\, C_s} \tag{3-2}$$

The mass balance equation for the system in Figure 3-1b, with the filter in the mixed air duct, is:

$$\dot{V}_e C_o\ (1 - \varepsilon) + \dot{V}_r\ C_s\ (1 - \varepsilon) + \dot{N} = (\dot{V}_e + \dot{V}_r)\ C_s \tag{3-3}$$

and

$$\dot{V}_e = \frac{\dot{N}}{\left[C_s - (1 - \varepsilon)C_o\right] + \left(\frac{\dot{V}_r}{\dot{V}_e}\right) \varepsilon C_s} \tag{3-4}$$

For this model, it is assumed that the air in the space is mixed fully and has a uniform composition. It also is assumed that no infiltration occurs at the boundary of the space.

For a 100 percent unfiltered outdoor air system, as shown in Figure 3-2, Eq. (3-4) can be simpliefied ($\varepsilon = 0$) to:

$$V_e = \frac{\dot{N}}{C_s - C_o} \tag{3-5}$$

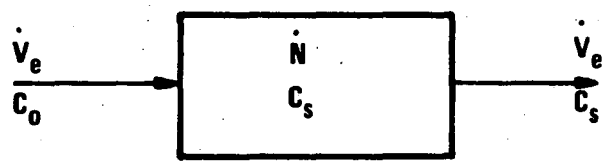


Figure 3-2. 100 Percent Outdoor Air System

Examples 1 and 2 are presented to show how respiratory and room ventilation rates can differ.

Example 1--Oxygen.

The amount of O_2 consumed by a normal adult at sedentary activity is about 250 ml/min [1,3], or 0.00883 CFM. Normal atmospheric air has an O_2 concentration of 20.84 percent. The minimum allowable indoor concentration can be assumed to be 14.47 percent, which corresponds to a partial pressure of 110 mm Hg (i.e., P_{O_2} at 10,000 feet altitude). This partial pressure still provides a minimum ΔP between the alveolar air and venous blood for oxygenation to occur [1,3].

If the O_2 production rate in the room is -0.00883 CFM per person, the steady-state requirement for minimum room ventilation is:

$$\dot{V}_e = \frac{\dot{N}}{C_s - C_o} \tag{3-6}$$

$$= \frac{-0.00883\ CFM_{O_2}/person}{(0.1447 - 0.2084)\ \frac{CFM_{O_2}}{CFM_{air}}}$$

$$\dot{V}_e = 0.139\ CFM_{air}/person$$

Conversely, if the individual were outdoors, Eq. (3-6) would not apply as no measurable change in the O_2 concentration would occur. Therefore, the required ventilation rate outdoors would be 0.00883/0.2084 or 0.0423 CFM. Thus, the required room ventilation rate indoors is more than three times that estimated if the individual were outdoors. Moreover, the steady-state quality of the indoor air would be reduced to 14.47 percent O_2.

Example 2--Carbon Dioxide

At sedentary activity, the amount of CO_2 expired will vary with diet. The ratio of CO_2 expired to O_2 inspired is known as the respiratory quotient (RQ) and varies from 0.7 to 1.0 with a normal value of about 0.83 [1,3]. Normal atmospheric air has a CO_2 concentration of about 0.04 percent. The maximum allowable CO_2 concentration is not well-defined, but values of 1 to 2 percent have been detected in nuclear submarines [4]. Some long-term effects may occur at these concentrations [4], and values of 0.5 percent are generally accepted as safe. Again, from Eq. (3-6), the required ready-state room ventilation rate is estimated at:

$$\dot{V}_e = \frac{\dot{N}}{C_s - C_o} \qquad (3\text{-}7)$$

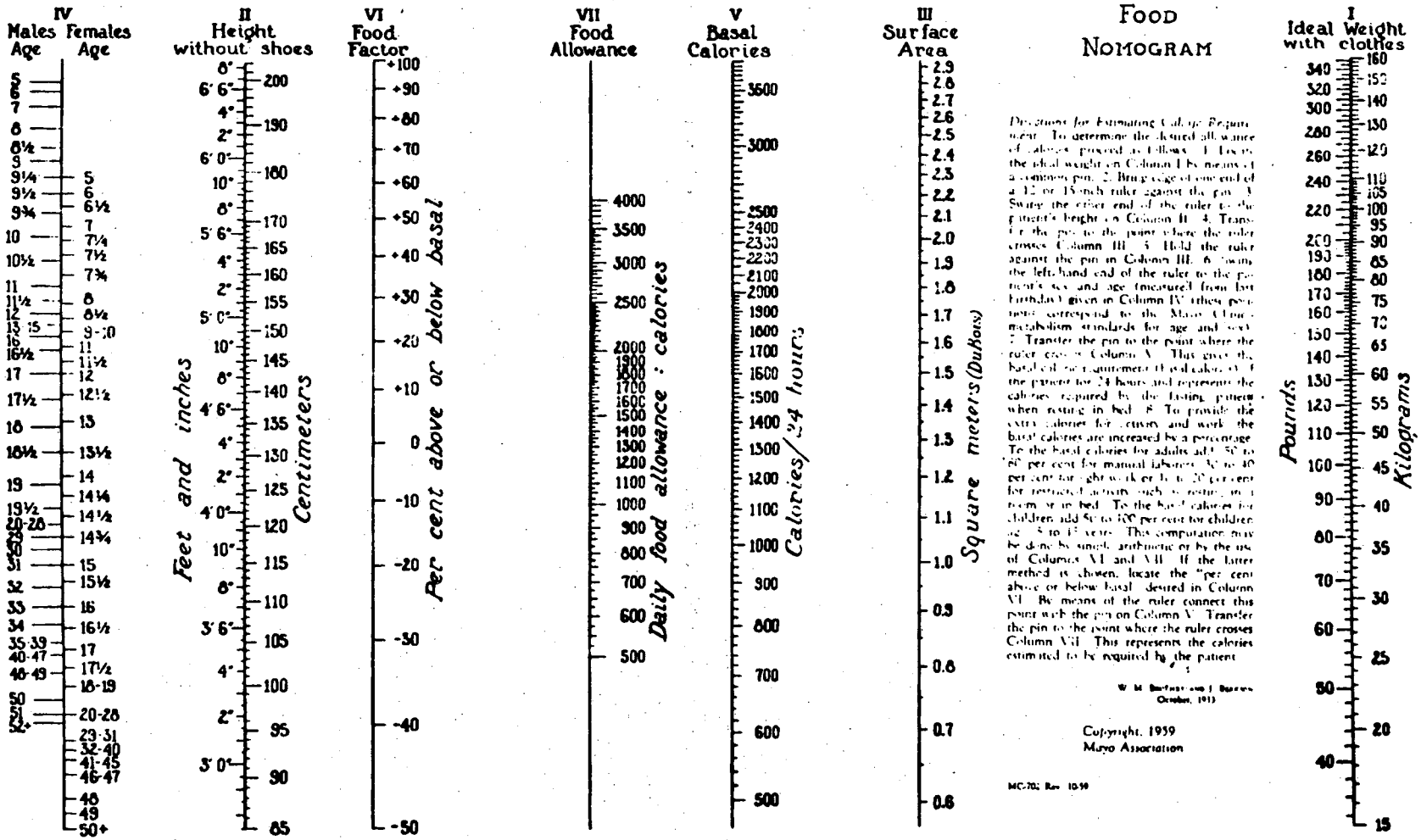
$$\dot{V}_e = \frac{(RQ)(0.00883)}{(0.005 - 0.0004)} = 1.92\ (RQ)$$

Therefore, as RQ varies from 0.7 to 1.0, $\dot{V}_e$ varies from 1.34 to 1.92 CFM per person.

Outdoors, the amount of CO_2 expired would have no measurable effect on the ambient concentration of CO_2, and the respiratory ventilation rate would be 0.0423 CFM as determined for O_2 requirements. Thus, to maintain 0.5 percent CO_2 in the occupied space, the required room ventilation rate would be more than 30 times greater than the respiratory ventilation rate.

As the metabolic rate increases, the O_2 inspired and CO_2 expired will increase [3]. Metabolic rates for normal adults during various activities are available in the literature [5,6]. However, on metabolic rates for adolescent children, as required for the studies at Fridley Junior High School, very little information was found. The best estimate of the children's metabolic activity found was the "Food Nomogram," Figure 3-3, developed by Mayo Clinic, Rochester, Minnesota. This nomogram was made available to us by Dr. Ralph Nelson.* Although the numbers yielded by this method should be interpreted as averages, measurements show that the actual values are indeed very close to the expected values [7]. Thus, given the relatively large number of children in the classrooms, this method should yield acceptable accuracy. A sample comparison of the production rate of CO_2 from children and adults for various activity levels is shown in Table 3-1. The values of CO_2 produced at basal metabolic rate, shown in Table 3-1 add credibility to the value of 0.00733, which was previously used in calculating required room ventilation rates. However, the values shown

*Dr. Ralph Nelson is presently at the Clinical Education Center, Carle Clinic, Urbana, Illinois.



Source: Dr. Ralph Nelson, Mayo Clinic, Rochester, Minnesota.

Figure 3-3. Food Nomogram

in Table 3-1 for adults and children at light work, which might be experienced at Fridley Junior High School, indicate that values 30 to 80 percent higher might be required. Thus, required ventilation rates at light work may range from 2.02 to 2.97 CFM per person when the RQ is 0.83. Therefore, since $\dot{V}_e$ is linearly related to $\dot{N}$, $\dot{V}_e$ must be increased by comparable factors.

Table 3-1. Sample CO_2 Production for Children and Adults

AGE	WEIGHT (kg)	HEIGHT (m)	SEX	METABOLIC RATE[a] (Kcal/DAY)		CO_2 PRODUCTION[b] (CFM)	
				BASAL	LIGHT WORK	BASAL	LIGHT WORK
25	75	1.80	M	1900	2850	0.0080	0.0120
25	75	1.80	F	1700	2550	0.0072	0.0108
35	75	1.80	M	1770	2655	0.0075	0.0112
35	75	1.80	F	1650	2475	0.0070	0.0104
45	75	1.80	M	1750	2625	0.0074	0.0111
45	75	1.80	F	1650	2475	0.0070	0.0104
15	55	1.40	M	1560	3120	0.0066	0.0132
15	55	1.40	F	1350	2700	0.0057	0.0114
12	40	1.10	M	1150	2300	0.0049	0.0097
12	40	1.10	F	1110	2220	0.0047	0.0094

[a] FROM FIGURE 3-3.
[b] USING RQ = 0.83 AND 4.825 Kcal/LITER O_2 (SEE REFERENCES 1 AND 3).

These two examples indicate that the room concentrations of O_2 and CO_2 will vary as functions of occupancy density and activity and that they can be used to control air quality in confined spaces. It is also clear that the CO_2 concentration is a more sensitive parameter than the O_2 concentration. Thus, CO_2 concentration was chosen as the control variable for the system.

However, the selection of CO_2 as a primary control variable for ventilation is not without problems, especially in spaces where large quantities of other contaminants are generated. In these cases, the use of the ventilation rates to maintain CO_2 below 0.5 percent possibly could result in concentrations of the other contaminants that may exceed those allowable by safety and health standards. Typical examples are the carbon monoxide and total suspended particulate (TSP) concentrations in places where smoking is permitted, as shown in Examples 3 and 4 below.

Example 3--Carbon Monoxide

A cigarette releases approximately 50,000 μg of CO into the room by means of mainstream and sidestream discharge [8]. If the allowable short-term (8 hours) concentration is 10,000 $\mu g/m^3$ [10] and the allowable long-term outdoor concentration is 5,000 $\mu g/m^3$*, the required room ventilation rate is estimated at:

$$\dot{V}_e = \frac{\dot{N}}{C_s - C_o}$$

$$= \frac{50{,}000\ \mu g_{CO/cig}}{10{,}000 - 5{,}000\ \mu g_{CO}/m^3} \qquad (3\text{-}8)$$

$$\dot{V}_e = 10.0\ m^3/cig$$

If one cigarette per hour is smoked in the room, the required steady-state room ventilation is $(10\ m^3/hr)/(cig/hr)$, i.e., 6 CFM/(cig/hr). Therefore, if 10 cigarettes were smoked in the room during one hour, the required steady-state room ventilation rate would be 60 CFM.

*Long-term values estimated from short-term exposure. If this value is high, the required ventilation would decrease.

Example 4--Total Suspended Particulates (TSP)

A cigarette releases approximately 30,000 to 40,000 μg TSP by means of mainstream and sidestream discharge [8,9,11]. If the allowable short-term (24 hours) indoor air concentration is 260 $\mu g/m^3$* and the allowable long-term (year) outdoor concentration is 75 $\mu g/m^3$ [10], the required steady-state room ventilation rate, without filtration, is:

$$\dot{V}_e = \frac{\dot{N}}{C_s - C_o}$$

$$= \frac{30{,}000\ \mu g\ TSP/cig}{(260 - 75)\ \mu g\ TSP/m^3} \qquad (3\text{-}9)$$

$$\dot{V}_e = 162\ m^3/cig = 95\ CFM/(cig/hr)$$

If a filter, rated at 90 percent efficiency (atmospheric dust) according to ASHRAE Standard 52-76 [14], were installed in the return air system, as shown in Figure 3-1a, and the recirculation rate were a constant 80 percent, the required steady-state room ventilation rate would be:

$$\dot{V}_e = \frac{\dot{N}}{(1 + \varepsilon\dot{V}_r/\dot{V}_e)C_s - C_o}$$

$$= \frac{30{,}000\ \mu g\ TSP/cig}{(1 + 0.9\ \frac{0.8}{0.2})\ 260 - 75\ \mu g\ TSP/m^3} \qquad (3\text{-}10)$$

$$\dot{V}_e = 27\ m^3/cig = 16\ CFM/(cig/hr)$$

*This number may be too high, according to information contained in the draft of the Nordic Ventilation Code [12] and in ASHRAE Standard 62-73R [13].

If the filter were installed in the mixed air system, as shown in Figure 3-1b, and other factors were as described in the preceding sentence, the required steady-state room ventilation rate would be:

$$\dot{V}_e = \frac{\dot{N}}{(1 + \varepsilon\dot{V}_r/\dot{V}_e)C_s - (1 - \varepsilon)C_o}$$

$$= \frac{30{,}000\ \mu g/cig}{(1 + 0.9\,\frac{0.8}{0.2})\ 260 - (0.1)(75)\ \mu g\ TSP/m^3} \qquad (3\text{-}11)$$

$$\dot{V}_e = 25\ m^3/cig = 15\ CFM/(cig/hr)$$

Thus, with reasonably good filtration, a substantial reduction in required ventilation can be achieved. However in both cases, the sum of outdoor and treated recirculated airflow rates is about 5 x 16 = 80 CFM/(cig/hr). Moreover, even with the 90 percent filter, the required steady-state room ventilation rate of outdoor air is approximately 10 times greater than that required for CO_2 in a nonsmoking area.

Where smoking is not allowed, as in schools, CO_2 does appear to be an adequate control variable and thus was used in this program. However for spaces where smoking is allowed, and where other contaminants are produced in large amounts, other control variables may be needed.

3.2 CO_2 CONTROL ENERGY SAVINGS

The strategy was to characterize the energy savings possible with a CO_2 controlled ventilation system so that the results could be extrapolated to other buildings in other parts of the United States. The energy savings, translated into dollars, also were needed to assess the commercial viability of this idea.

Two methods were employed to measure the energy consumption. A Btu meter was installed on the water heater that supplied all of the heat in the music department. Instrumentation also was installed to measure the heat balance in the airstreams. Thus one system provided backup for the other.

An important consideration was the reference on which energy comparisons were based. One possibility was the constant velocity, terminal reheat system that existed prior to this project. This system had a fixed supply air temperature of 13°C (55°F), with a minimum outdoor airflow of 16 percent. Return air was cooled to 13°C with outdoor air. The mixed air was then reheated to a temperature high enough to carry the thermal load on the system. The outdoor air temperature had to be -31°C (-24°F) before the minimum flow setting on the outdoor air damper was reached. The minimum outdoor airflow of 16 percent of supply provided 10 CFM per person for a design occupancy of 200 students. This was a very energy-wasteful system and is a poor basis for comparison since state-of-the-art techniques such as "reheat optimization" are commonly implemented today.

Thus, the first obvious energy conservation measure was to raise the mixed air temperature from 13°C (55°F). This was done by removing control of the mixed air temperature. The control system then was modified so that the outside air damper remained at the 16 percent minimum flow position until one of the room thermostats reached its upper limit and began to call for cooling. This was called the revised control system. The energy savings for the CO_2-controlled system then were compared to this revised system.

The relative effects of these control system changes on the theoretical ventilation airflow is illustrated schematically in Figure 3-4. The airflow rates must be multiplied by the difference between the return air temperature (room temperature) and the outdoor air temperature and by the amount of time the system operates at any given outdoor temperature. In a cold climate such as Minnesota, much of the operating time and temperature are in the area of reduced ventilation airflow. The objective was to characterize the savings in terms of

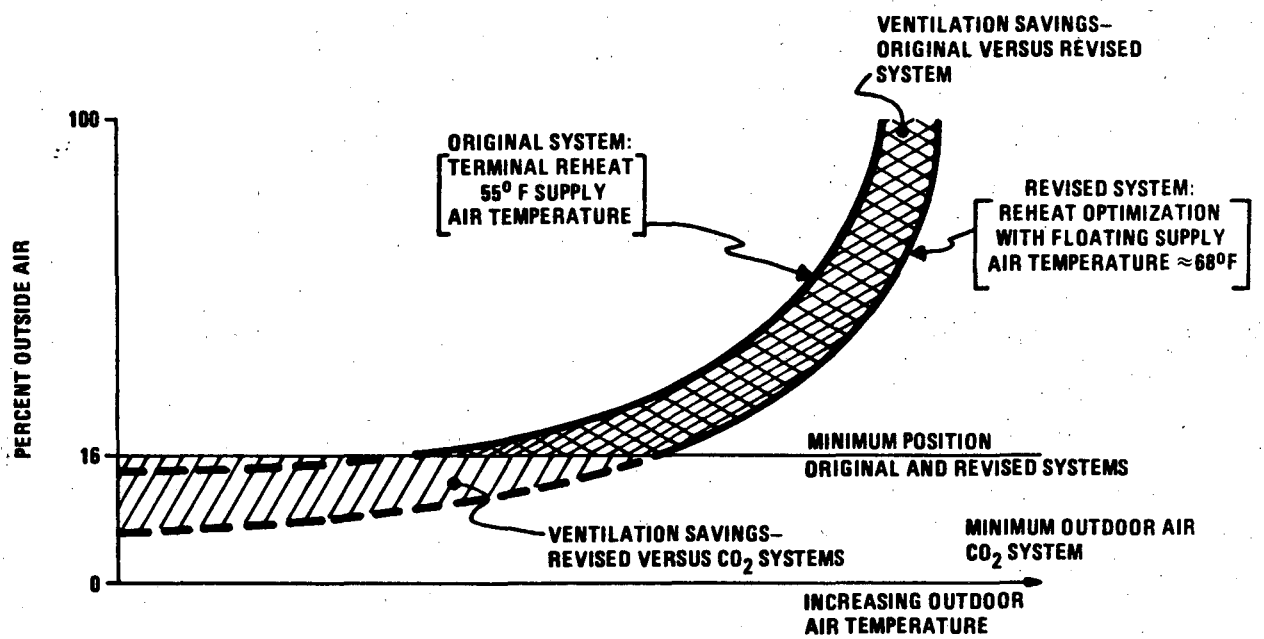


Figure 3-4. Schematic Representation of Outdoor Air Quantity as a Function of Various Control Concepts (Typical) (No Internal Loads)

ventilation airflow so that the results could be extrapolated to other locations on the basis of weather data. A further objective was to determine potential air conditioning energy savings achievable through reduced ventilation. It should also be noted that Figure 3-4 does not account for infiltration. In the Fridley tests, the temperature damper often remained closed throughout the day--thereby indicating even greater reduction in ventilation air and increased

3.3 SUBJECTIVE RESPONSES

The purpose of measuring subjective responses of occupants in the spaces was to determine whether human beings could detect differences between the conventional temperature-driven control system and the experimental CO_2-driven control system. This information was essential because, no matter what the physical measurements showed, the experimental system could not be considered successful if occupants of the space perceived major unfavorable differences in their well-being with the experimental system as compared to the conventional system.

Human beings may discern differences, such as faint odors, in the indoor environment that physical instruments do not detect. Perceived phenomena may result from interaction among two or more physical variables that would not be predicted from the individual physical measurements. Also, the sense of well-being of human subjects may be influenced strongly by small differences in one or more physical variables, whereas large differences in other variables may have little or no effect on their perception of well-being.

This research presented several problems that did not seem to be addressed in the literature. First, it was important to develop a psychometric instrument to gather reliable data from junior high students. The instrument had to be sensitive enough to reveal subtle differences in room conditions. The response format had to provide data of suitable quality for complex statistical analysis--not merely computation of means and standard deviations. Large quantities of information had to be collected from the same subjects on several different days so that there would be repeated observations from each system, with a minimum of missing or defective responses. Data from each subject responding on different days had to be matched without violating confidentiality. Finally, federal regulations applying to university research required that parental permission be obtained for minor subjects to take part in the research.

3.4 DEFINE PROBLEMS

Several potential problems with variable ventilation control were addressed. Reduced ventilation increased the concentration of pollutants emitted by people as well as those generated in the space arising from the outgassing of materials. The LBL Energy Efficient Buildings Mobile Air Quality Laboratory was used to measure the indoor pollution level coincident with the Honeywell/ISU intensive test period in February 1980. The objective was to determine if there were any objectionable pollutant levels or other constituents more easily detected than CO_2 on which ventilation control could be based. The LBL laboratory

monitored the levels of CO, CO_2, SO_2, NO, NO_X, NO_2, O_3, aldehydes and radon gas. Their findings are published separately.

HVAC system variations pose potential problems for variable ventilation control. Figure 3-5 shows the relative number of different kinds of HVAC systems in office buildings, schools and apartment buildings [15]. Multizone systems are most common in schools and office buildings. Appropriately the HVAC system serving the music wing at Fridley Junior High is a multizone system. It is a common-type system with one outdoor air inlet and a common return air system. The mixed air is then distributed to the various zones for further heating or cooling.

If a ventilation control sensor is located in each zone of such a system, outdoor air use will be at a minimum when the population is distributed uniformly among the zones. However, if the population is concentrated in any one zone, raising the ventilation demand in that zone, more outdoor air will be required to meet this demand. This, in turn, tends to overventilate the other zones unless the distribution of air to the high-load zone can be increased relative to the other zones. Recirculation tends to accomplish this.

Another complication can occur in large systems due to duct stratification. Figure 3-6 shows a typical arrangement for the return and outside air systems. Three dampers are linked together so that a decrease in outdoor air induction is achieved by closing the outside air and exhaust dampers and opening the recirculation air damper. When the outside airflow is small but the recirculated airflow is large, there is a tendency for the outdoor airflow to be stratified along one side of the duct. Downstream branches in the duct then may get a disproportionate distribution of the outside and return air. Thus, the characteristics of the air distribution system can have considerable effect on the operation of the ventilation system.

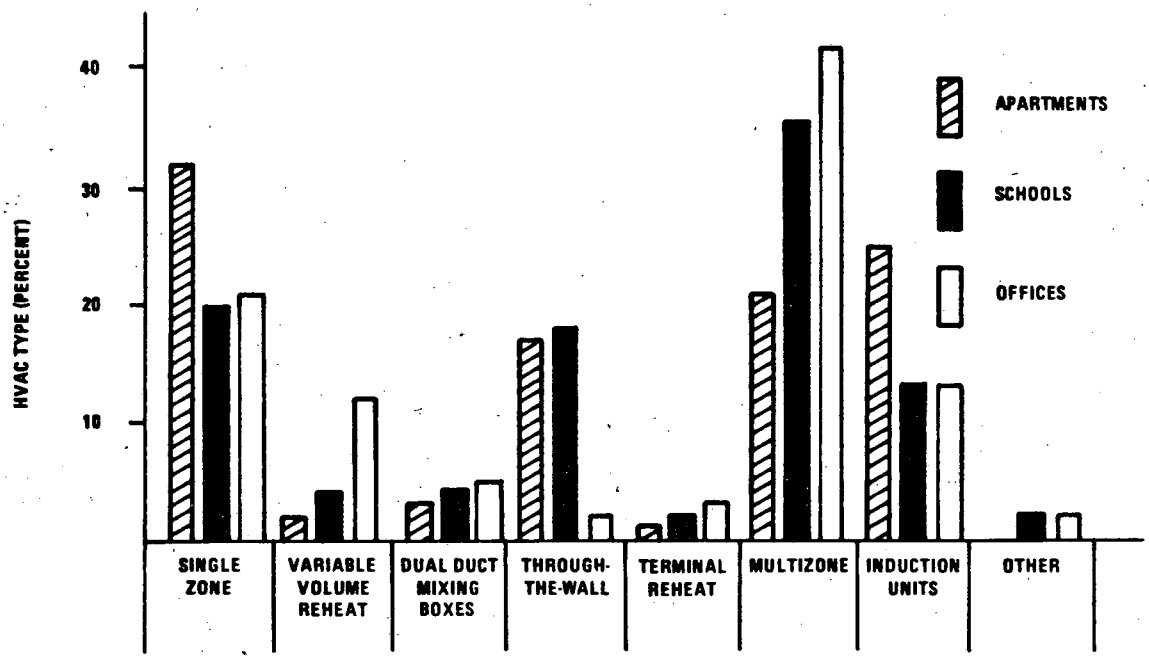


Figure 3-5. Frequency of Occurrence of HVAC Type by Building Sector

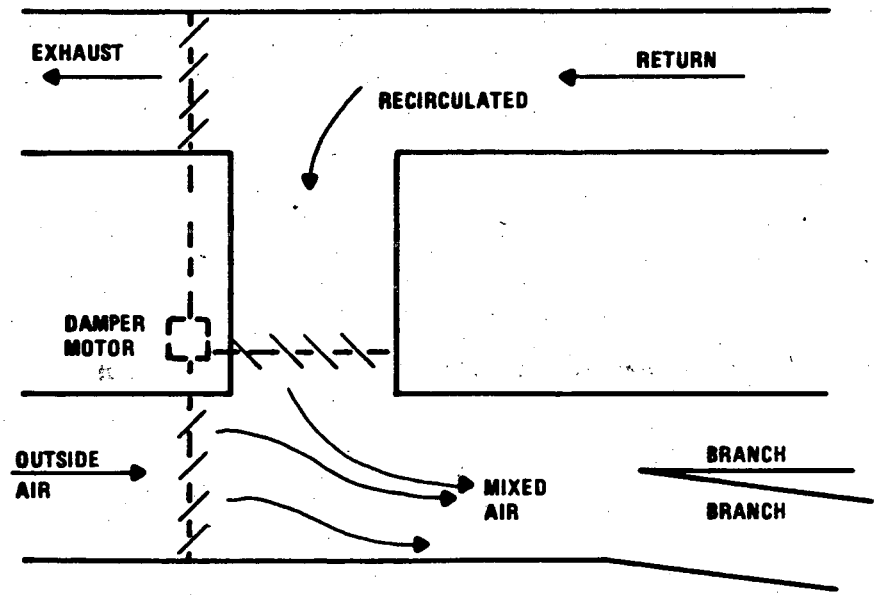


Figure 3-6. Duct Stratification

To characterize the distribution system effects, methane tracer gas measurements were made. The tracer gas was fed at a measured flow rate into the outdoor airstream. The concentration of tracer gas in the downstream branches then revealed the flow from each source. Methane concentrations were kept below 500 ppm (safety factor of 100). An NDIR instrument was used to measure the methane concentration. These measurements have defined the mixing and ventilation efficiency. Poorly located supply and return outlets and inlets can allow part of the supply air to return without mixing with the air at occupant level. Then only a part of the outdoor air induced to meet the occupant's ventilation requirements is effective for that purpose. Energy used to heat that portion of outdoor air that bypasses the occupied level is exhausted and wasted.

Minimum ventilation requirements are specified by standards and codes for the buildings of interest. Present codes, however, do not address the variable ventilation type of control system. Application of variable ventilation systems will require changes in the appropriate standards to permit reduced ventilation under controlled conditions.

3.5 COMMERCIALIZATION ISSUES

Even though a concept is established as valid from the viewpoint of saving energy, it is of little use if barriers to its eventual commercial implementation exist. Such barriers can exist in several forms:

- Institutional - Current codes require that a minimum amount of outdoor air be provided to commercial or public buildings at a level based on design load and other criteria.

- Cost - Real-life constraints exist in the form of payback or return on investment criteria. Savings must be sufficient to justify the cost of installation, operation and maintenance, if such installations are not merely mandated.

- Technical - This issue has been alluded to earlier and refers to such elements as subjective responses, mixing characteristics of the air distribution system, amenability to retrofit with different HVAC systems, etc.

SECTION 4.0
TEST SYSTEM DESCRIPTION

The music department wing of Fridley Junior High School (Figure 4-1) essentially is a separate building, measuring 103 by 83 feet, with an independent, constant-volume, terminal reheat heating and cooling system. A single heat exchanger provides hot water for the reheat coils. The building is divided into four zones--a band room, two chorus rooms and a group of small practice rooms that includes an office. The only windows in the wing are the two located in the office. There is one outside door into the band room.

The existing control system was modified to provide a control system that could operate the HVAC system: (1) in the conventional manner, as designed; (2) in a revised mode to optimize reheat; or (3) control the induction of outdoor air on the basis of measured CO_2 level. Economizer operation also was included with the CO_2-based control systems so that outdoor air could be used for cooling when a room thermostat called for cooling and outdoor air temperature was low enough. The CO_2 control was used for both heating and air conditioning.

A laboratory-type (ANARAD Model AR-101) nondispersive infrared instrument was used to measure CO_2 concentration and to supply a signal to an electric-to-pneumatic transducer in the control system. A sampling system with a six-channel multiplexer was built that would permit the one CO_2 instrument to be used with all zones. The room temperature control was modified so that a high temperature in any room would operate the system on an economizer cycle. The outdoor air intake was modified so that part of the intake could be used for control of CO_2 level in the space and part could be used for economizer operation. A data logger was provided for recording on magnetic tape all data that would indicate system status and energy consumption.

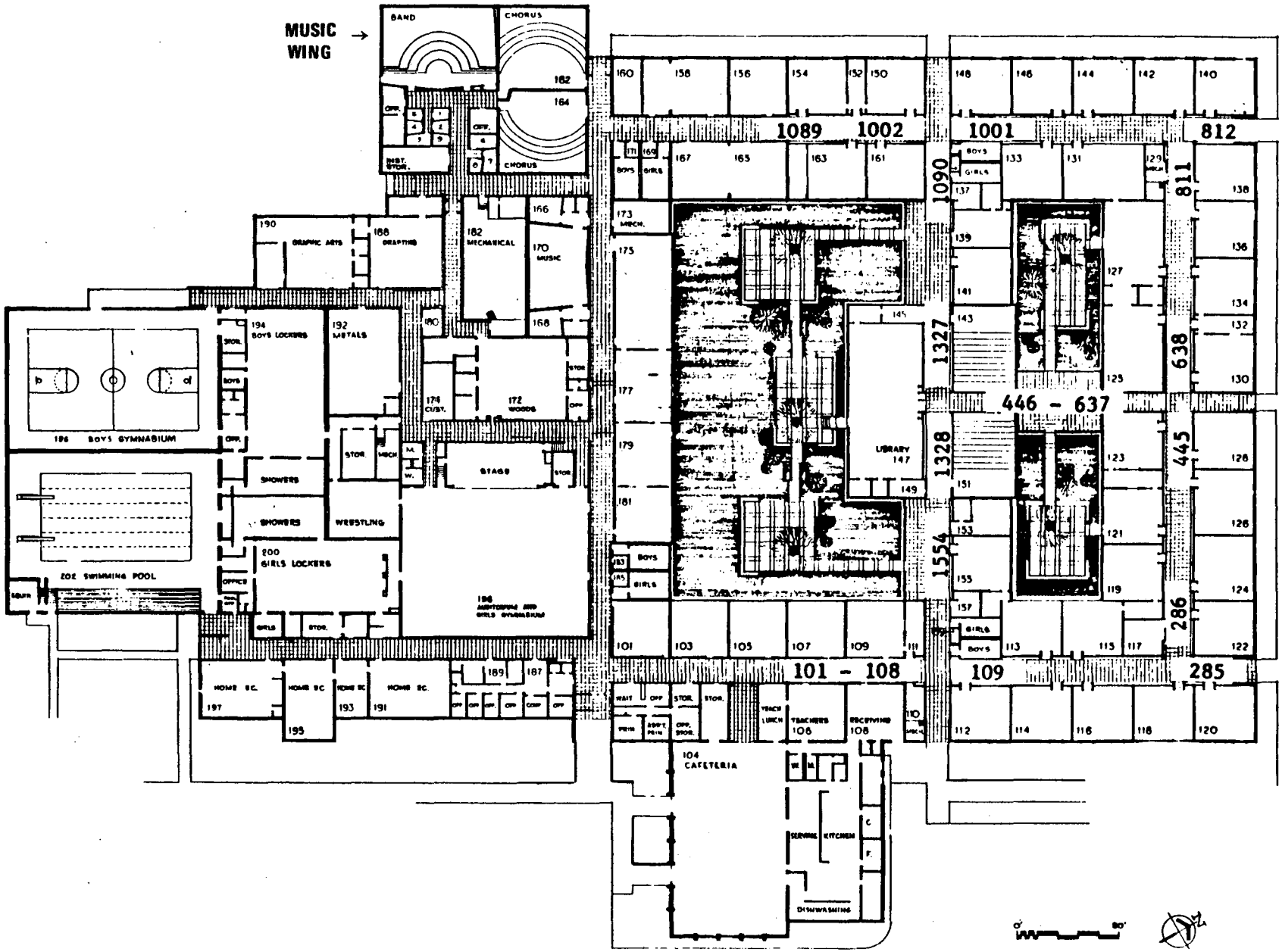


Figure 4-1. Fridley Junior High School Music Wing

4.1 VENTILATION SYSTEM

4.1.1 Original System

The ventilation system as originally installed is illustrated in Figure 4-2. It consisted of a single constant-volume supply fan of 12,560 CFM design capacity and a 9600 CFM return/exhaust fan. The balance of supply air was removed from the space by two additional exhaust fans vented directly to the roof. The outdoor air intake and exhaust hood for the music wing ventilation unit also were located on the roof of the school.

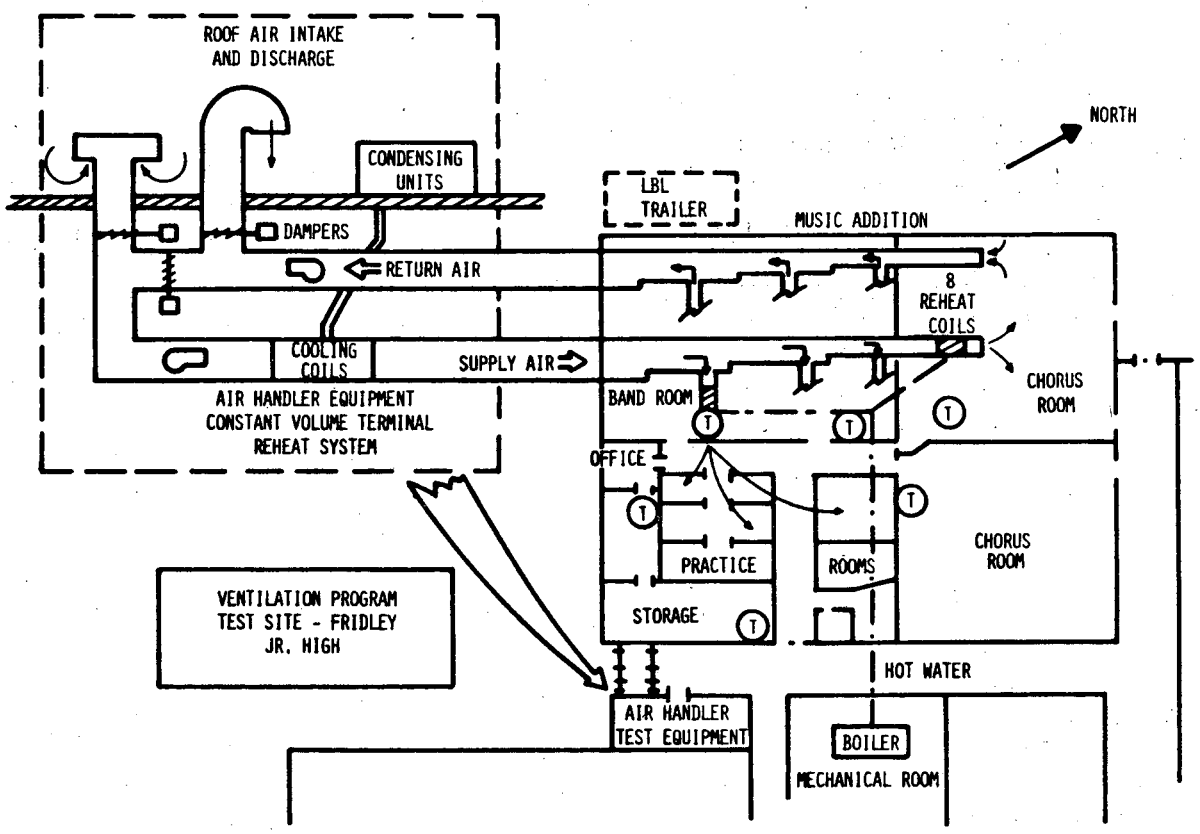


Figure 4-2. Ventilation System Layout

There are eight reheat coils served by the supply unit, five of which serve the four main zones of the music wing (the band room, two chorus rooms and the band director's office) and are controlled by the four zone thermostats. The band room had two reheat coils. The other three reheat coils served small interior practice and storage areas: one coil was controlled by a thermostat (storage area) and the other two (practice areas) were controlled by discharge air temperature controllers located in the discharge airstream. One converter (steam-heated heat exchanger) supplied hot water for all eight reheat coils. This converter also supplied hot water to a hallway radiator in the music wing and a small cabinet unit heater located in the southwest entryway near the music wing. Aside from the small hallway radiator, the only heat supplied to the music wing was provided by the eight reheat coils.

For summer operation, a 30-ton Carrier direct expansion cooling unit with evaporator coils was located on the roof just upstream of the supply fan and the condensing unit. Outdoor air intake was controlled by a set of intake, return and exhaust air dampers connected for simultaneous operation. The temperature control system was an entirely pneumatic system operated by 13 psig supply air during the day and 18 psig control air at night under clock control.

4.1.2 Modified Ventilation System

For test purposes, it was necessary to modify the existing system to permit accurate ventilation control and airflow measurement based on the CO_2 level in the space. The changes and their rationale are as follows:

- Separate control of the outside air based on both room CO_2 level and temperature (for economizer operation) suggested a split inlet air system with two dampers and two airflow meters. This allowed more accurate airflow measurements as well as separation, for test purposes, of CO_2 and temperature ventilation needs.

- The inlet and exhaust air dampers were supplemented with low-leak dampers to achieve maximum control of the airflow and enhance energy savings. With the CO_2 system, the original and low-leak damper operated independently.

- The doors and windows were weatherstripped or sealed to minimize infiltration. This helped maximize the sensitivity of the measurements.

- The two roof-mounted exhaust fans were disabled and their vents sealed off.

The modified duct system is shown in Figure 4-3. The original dampers were not disturbed. The new inlet air dampers were installed upstream of the original inlet dampers, and the Air Sentinel flowmeters were located just upstream of the new dampers. The low-leak exhaust damper was installed downstream of the original damper. These changes were all above the roof of the building. Installation and restoration costs after completion of the project thus were minimized.

Two separate intake dampers were used so that the CO_2 control function and economizer (temperature) control functions could be separated. The original air inlet duct had a cross-sectional area of 0.93 square meter (10 square feet). The modified duct had 0.14-square-meter (1.5-square-foot) inlet for CO_2 control and 0.33-square-meter (3.5-square-foot) inlet for temperature control. The duct area was reduced to increase velocity and improve flow measurement sensitivity. The restriction did, however, modify somewhat the constant-volume characteristic of the system. This is discussed further in the results section.

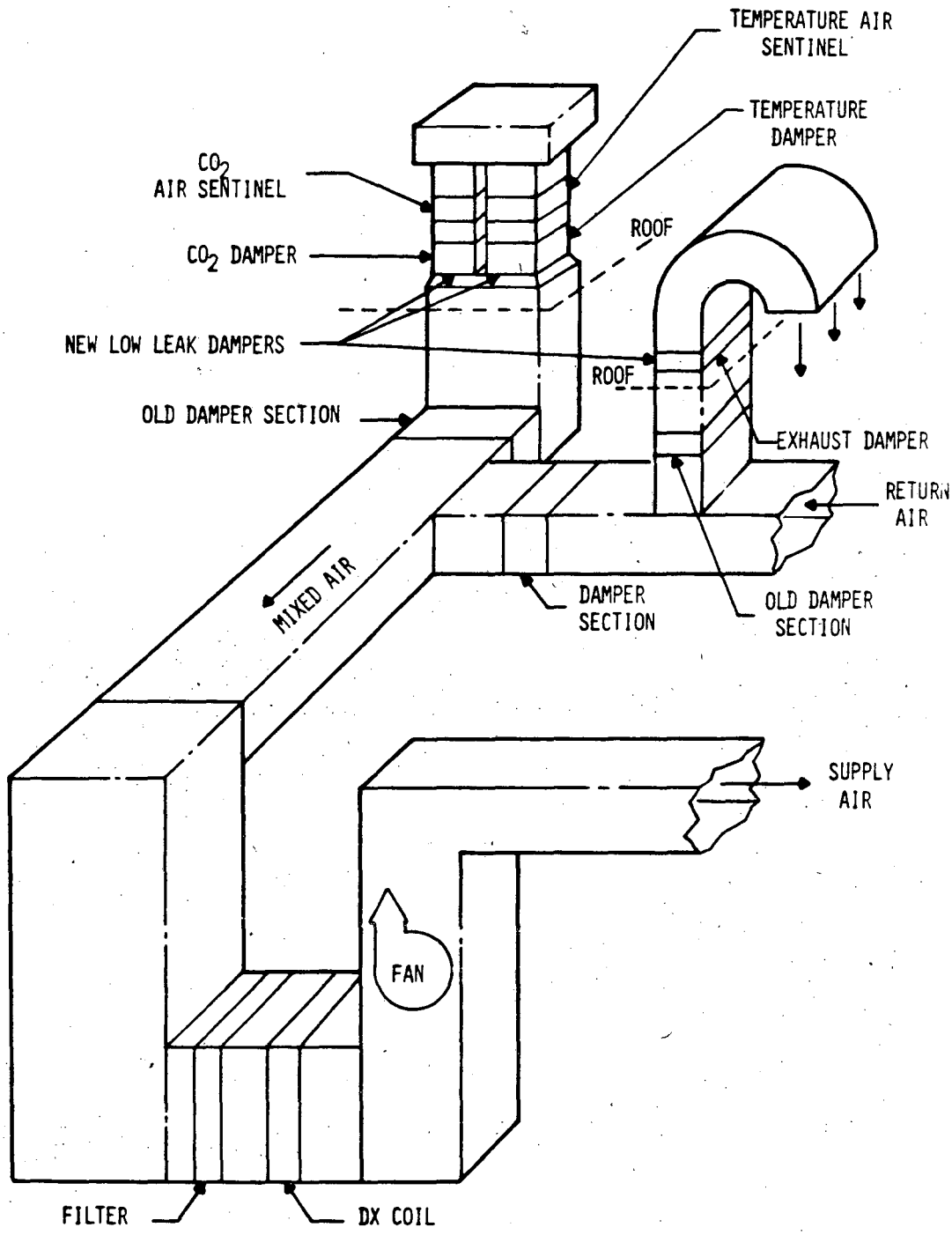


Figure 4-3. Location of Low-Leak Dampers

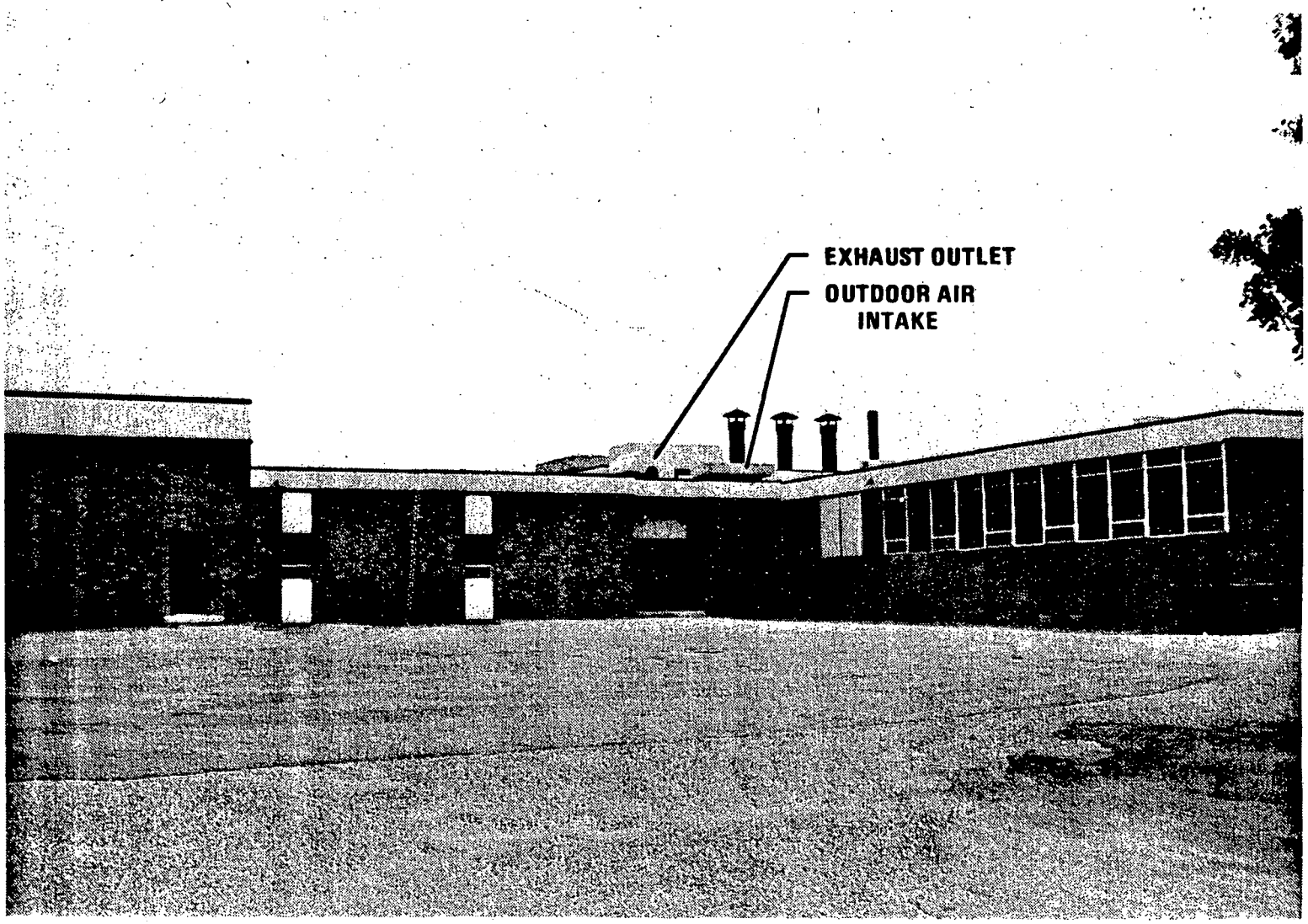


Figure 4-4. Original Air Intake and Exhaust Rooftop Installation

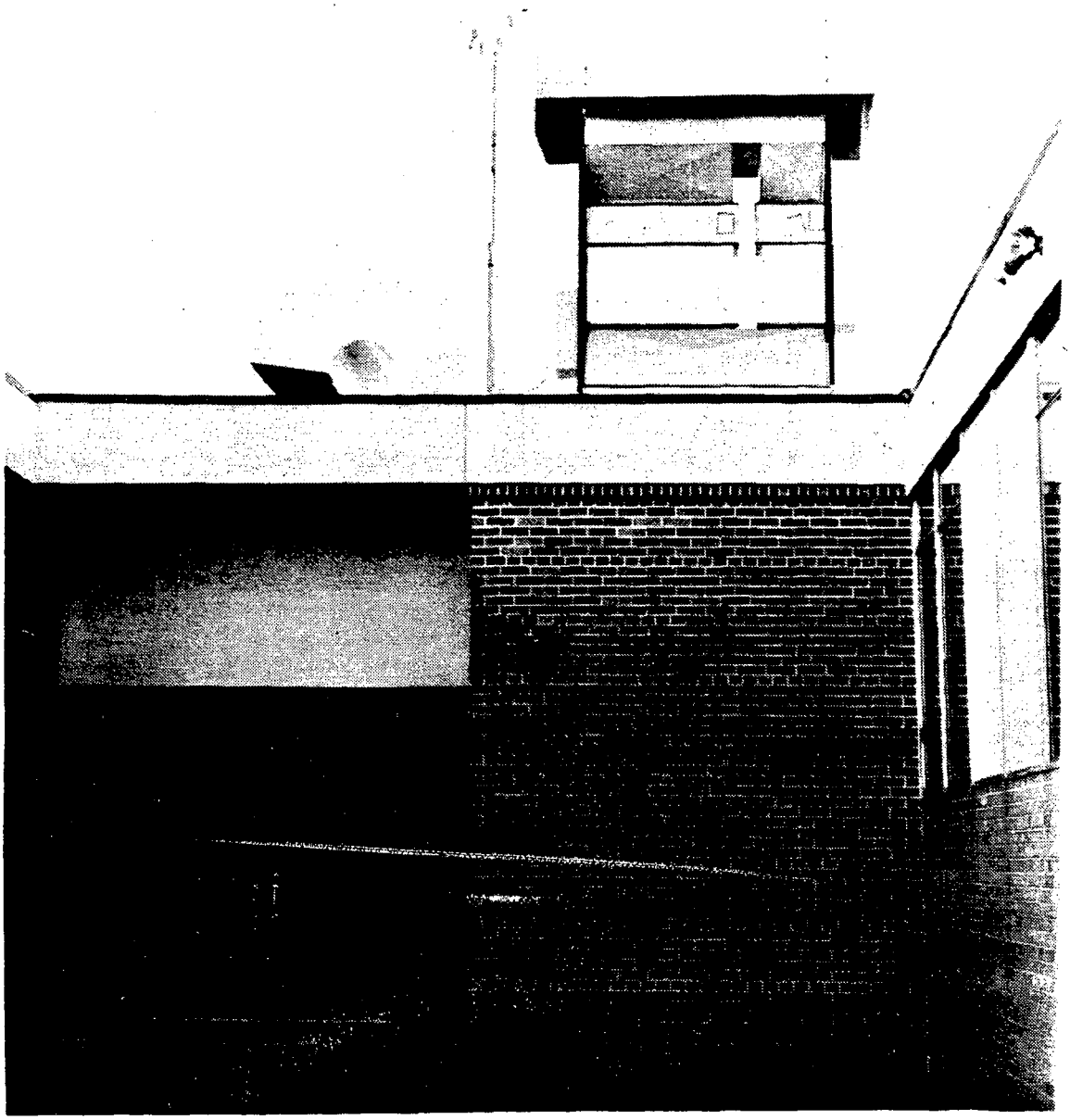


Figure 4-5. Modified Rooftop Intake and Exhaust Systems

4.2 CONTROL SYSTEM

Pneumatic controls were used on the original system. Night and weekend setback was performed manually. This system was modified to permit operation by the three control modes under study.

4.2.1 Original System Controls

The original ventilation control system, as installed before any modifications were made for the variable ventilation project, is shown schematically in Figure 4-6. This system could operate in a summer or winter mode and a day/night mode, as manually selected. The original system had no provision for economizer cycle operation. Figure 4-7 is a photograph of the fan unit before the AVVCS project.

With the summer/winter switch in the winter position, the DX cooling unit was disabled. During daytime operation the supply, return and exhaust fans were enabled and the outdoor air damper was at minimum position, as set by a minimum position switch. Winter design minimum position was set at 16 percent outdoor air. The intake, return and exhaust air dampers modulated above the minimum outdoor air intake to maintain 55°F primary discharge air on command from the primary discharge air controller. If the primary discharge air was, for any reason, below 40°F, an aquastat located in the fan discharge turned the fan off to prevent reheat coil freeze-up. Space temperature was maintained by modulating reheat coil inlet valves according to commands from the thermostats in each of the four main zones, the single thermostat in the instrument storage area, and two discharge air temperature controllers.

The changeover switch in the summer day position enabled the supply, return and exhaust fans and the DX unit and moved the outdoor air intake to a minimum position determined by a summer minimum position. The primary discharge air

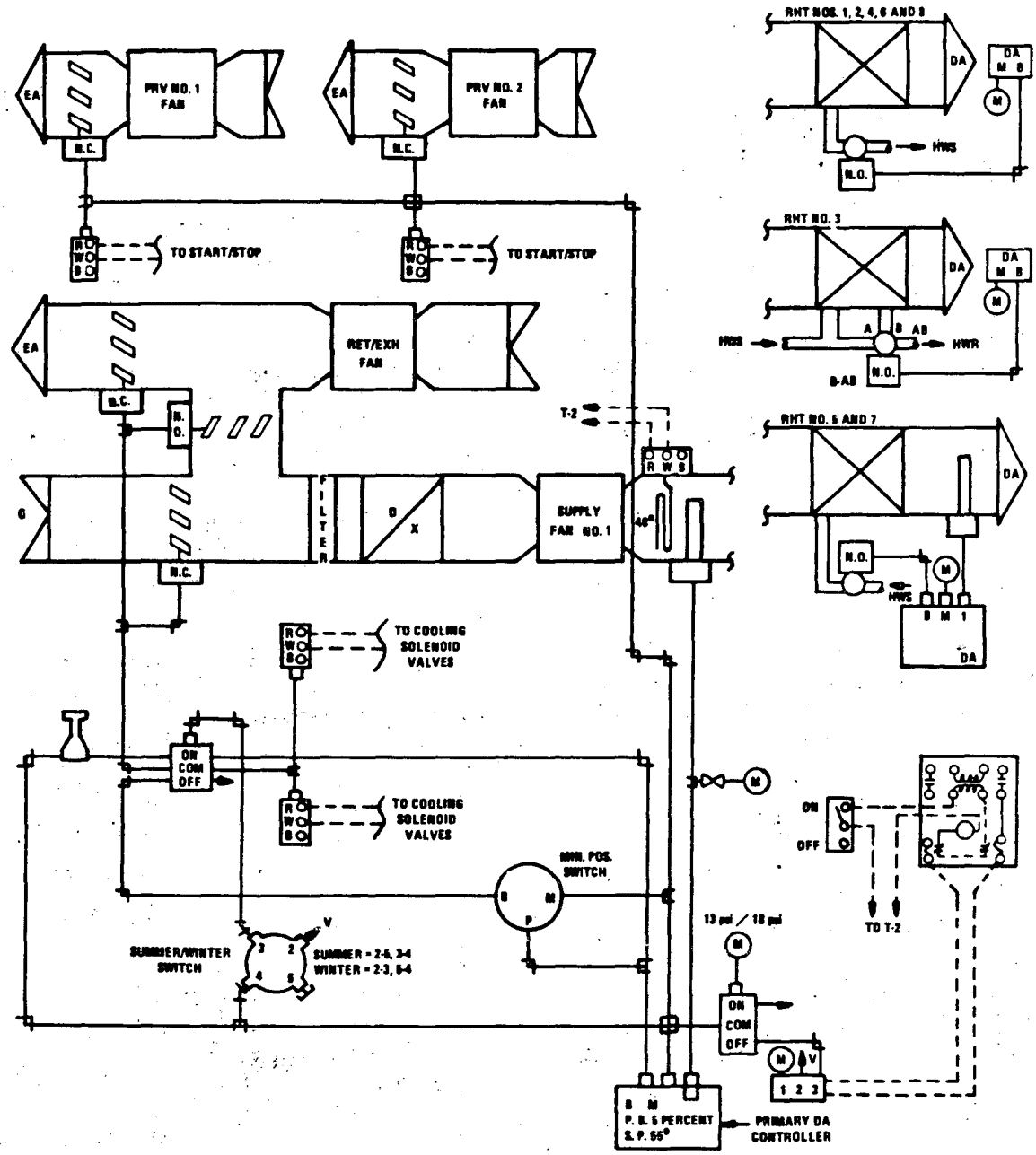


Figure 4-6. Original Control System Schematic

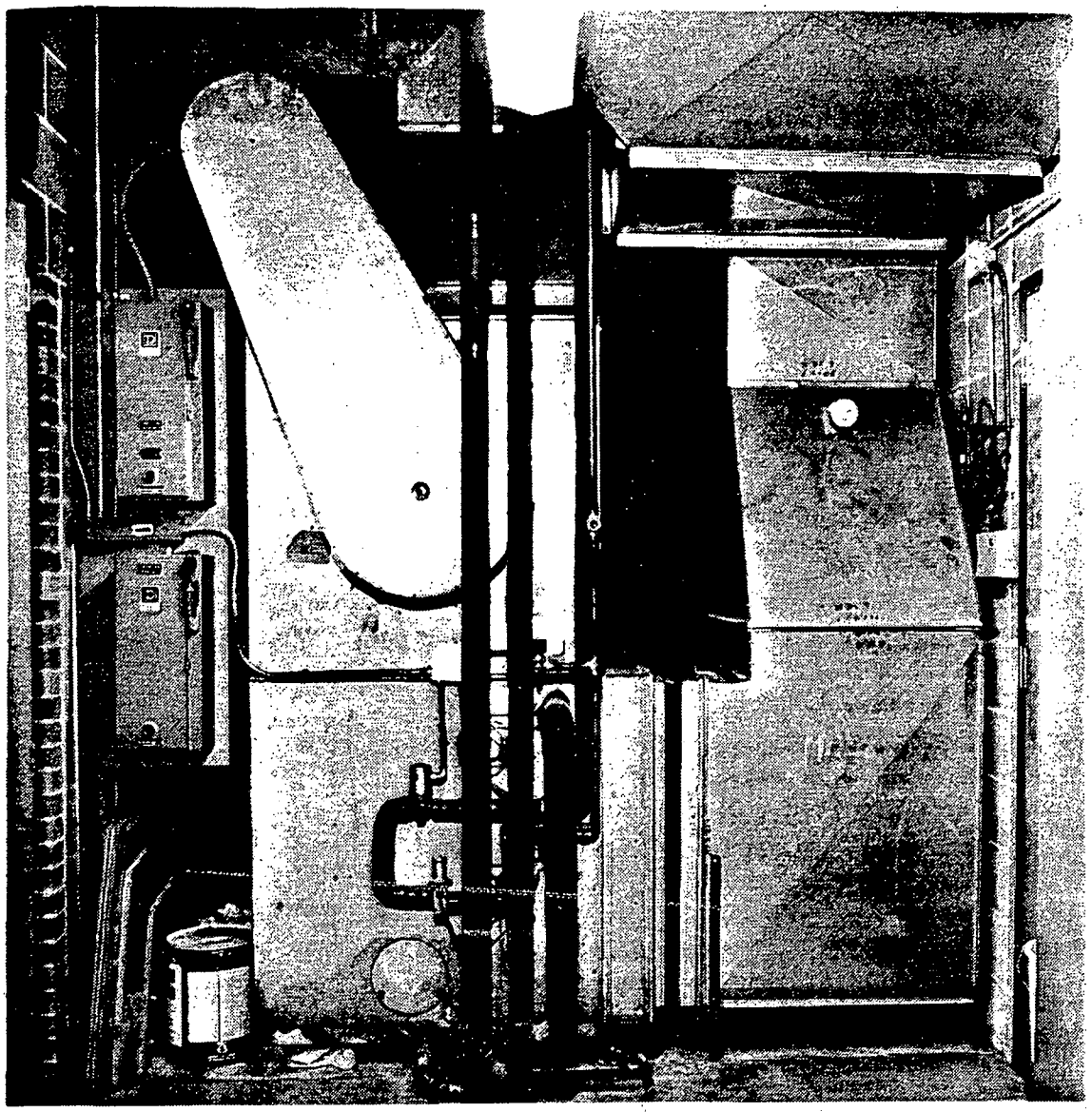


Figure 4-7. Fan Unit Before AVVCS Project

controller maintained the primary discharge air at 55°F by cycling the condensing unit and cooling coil valves. Space temperature was maintained by thermostatic control of reheat coil valves in each of the main zones.

On summer night operation the supply and return fans remained on (unless manually stopped) but the exhaust fans and condensing units were disabled and the intake damper was fully closed. Space temperature was allowed to float unless the temperature went below the night time set point at which time reheat valves would be open until the night temperature set point was achieved.

4.2.2 Modified Control System

The modified control system shown in Figure 4-7 had the capability of providing comfort control in three separate ways--according to original design specifications, according to carbon dioxide level in the space, and floating supply temperature with economizer operation. They are referred to as the "original," "carbon dioxide" and "revised" control modes, respectively.

Original Control--Original control operation was the same as the preventilation project control presented earlier, with several exceptions. A 7-day time clock was installed for automatic night and weekend setback as part of the modified system. Night setback was performed manually prior to the test modifications. Also during the night cycle the supply and return fans were off instead of running continuously, as in the original system. They cycled on at night only with a call for heat (summer and winter) from any one of the four zone thermostats. Primary discharge air control and damper operation remained the same. The new intake and exhaust dampers were positioned fully open, allowing outdoor air control by the original dampers when operating in the original mode.

Carbon-Dioxide-Based Ventilation Control--The CO_2-based control system was the most important of the three control systems used for the test. An important part of this mode of control was the outdoor air intake damper that opened and closed according to the CO_2 concentration measured in the test area. This damper was controlled by the CO_2 sensing system.

An ANARAD model AR-101 infrared gas analyzer was used for measuring CO_2 concentration. A gas-sampling multiplexer, Figure 4-8, was built to enable one analyzer to sample six channels. Gas samples were drawn continuously through a common manifold from six different sampling points by an air pump, making all six gas samples available at any time at the location of the gas analyzer. The six areas sampled were the band room, the two chorus rooms, the main supply air, the main return air and the outdoor air. A six-channel multiplexer control with variable scan rate and scan duration controlled three-way valves on each of the six sample lines. These valves were connected to a sample manifold through which the gas sample was drawn to the gas analyzer. The valves were normally open to the main manifold and normally closed to the gas analyzer. Also connected to the sample manifold was a manually operated calibration valve to supply the gas analyzer with gases of known CO_2 concentration.

At the beginning of a CO_2 scan, the multiplexer started at Channel 1 and energized each valve solenoid, one at a time, in sequence. Each valve was opened to the sample manifold for one-sixth of the total scan duration selected on the multiplexer, nominally 2 minutes. The energized valve diverted the gas sample to the sample manifold, where another sample pump moved the sample into the gas analyzer. The gas analyzer gave a 0- to 1-volt DC signal directly proportional to CO_2 concentrations from zero to 1.0 percent CO_2.

The multiplexer CO_2 scan and data sampling scans are illustrated in Figure 4-9 and explained as follows:

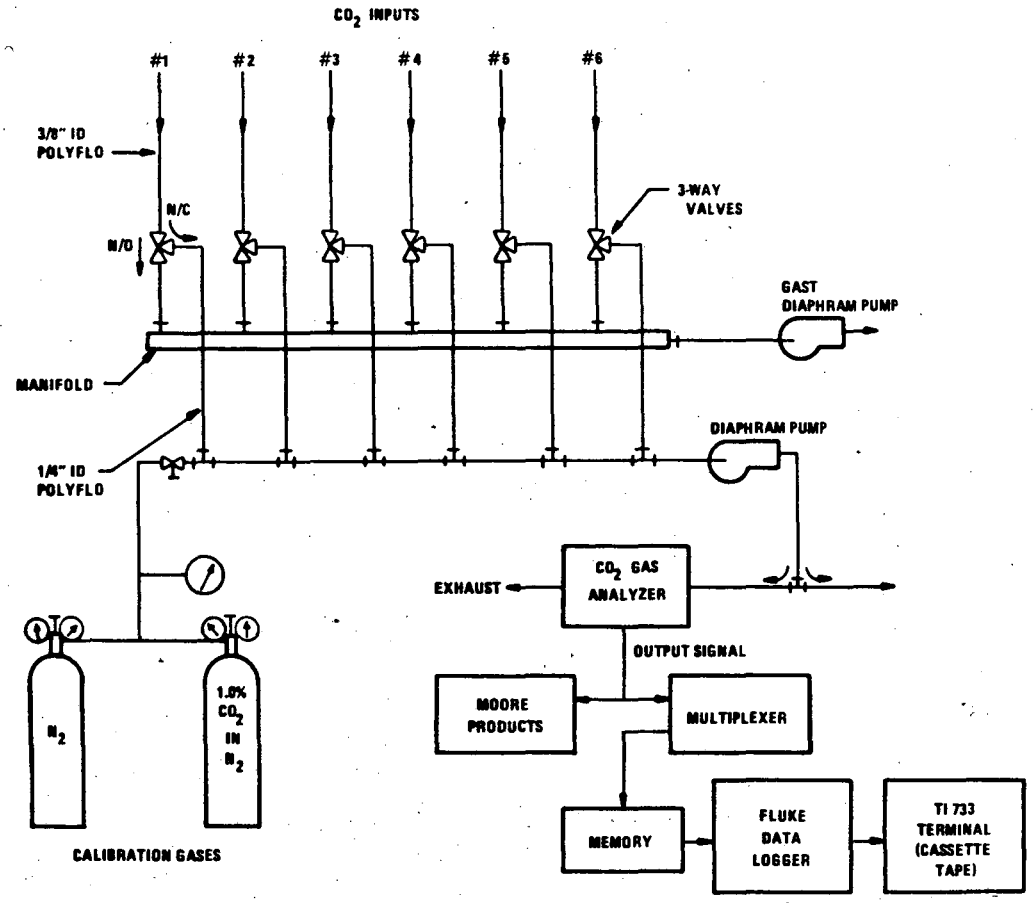


Figure 4-8. Gas-Sampling Multiplexer

At 7-minute intervals, the multiplexer sequenced each of the three-way valves for 20 seconds, diverting each CO_2 measurement to the ANARAD for measurement. At the end of each 20-second period, the resultant channel reading was stored in a data memory. The multiplexer itself compared each reading to it's stored maximum and retained the larger. After scanning all six channels, the multiplexer opened the three-way valve to the zone that had the highest reading during the 2-minute scan period. The output of the ANARAD was used continually as a control signal, even during the multiplexer scan period. Thus for 2 out of 7 minutes, the control signal followed <u>each</u> channel (including the outdoor CO_2 signal) for 20 seconds. Since the multiplexer stored the signal at the

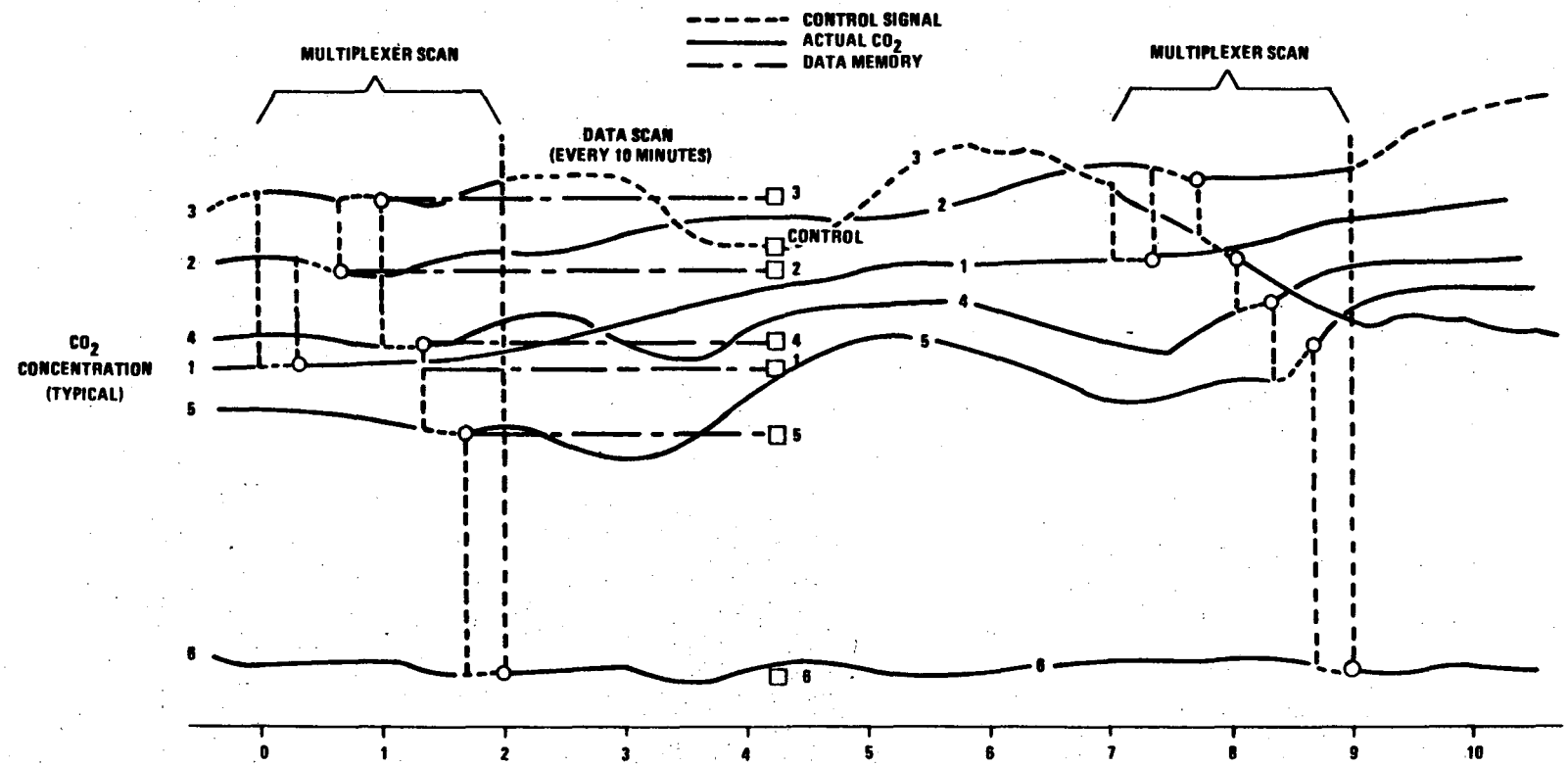


Figure 4-9. Multiplexer and Data Scan Samples

end of the 20-second scan period and there was some noise in the signals, it was possible to store a high or low value that was not truly representative of the CO_2 level in that channel. Normally this was corrected during the next scan, but it did introduce noise in the data.

The CO_2 values stored by the data logger were read every 10 minutes. The two scans, multiplexer and data memory, were not synchronized. In addition to the six CO_2 channels in memory, the data logger also read the ANARAD for the "control CO_2."

When the data scan occurred during the multiplexer scan period, the recorded CO_2 control signal was not necessarily the maximum. Further, since the control signal was updated only once every 7 minutes, there could be periods when the CO_2 control signal was not the maximum signal. Over a long period of time, control shifted from zone to zone as dynamic variations of zone CO_2 concentration occurred. This was an important factor in evaluating CO_2 control, as will be discussed in the test results sections.

The ANARAD output voltage was input, through a step-down potentiometer, as a 0- to 10-mV DC signal into a Moore Products model 7712C electric-to-pneumatic transducer. This transducer gave a 3 to 13 psig pneumatic signal with variable gain and zero offset from an input of 0 to 10 mV DC. The pneumatic signal in turn operated the CO_2 damper via a Honeywell Modutrol pneumatic damper motor capable of fully closed to fully open movement on a selectable signal range of 3, 5 or 10 psig with a variable start point.

The flexibility available with the CO_2 damper control process allowed many damper operations for any given set of control parameters. A possible control setup is illustrated in Figure 4-10, showing how the overall CO_2 control process was implemented.

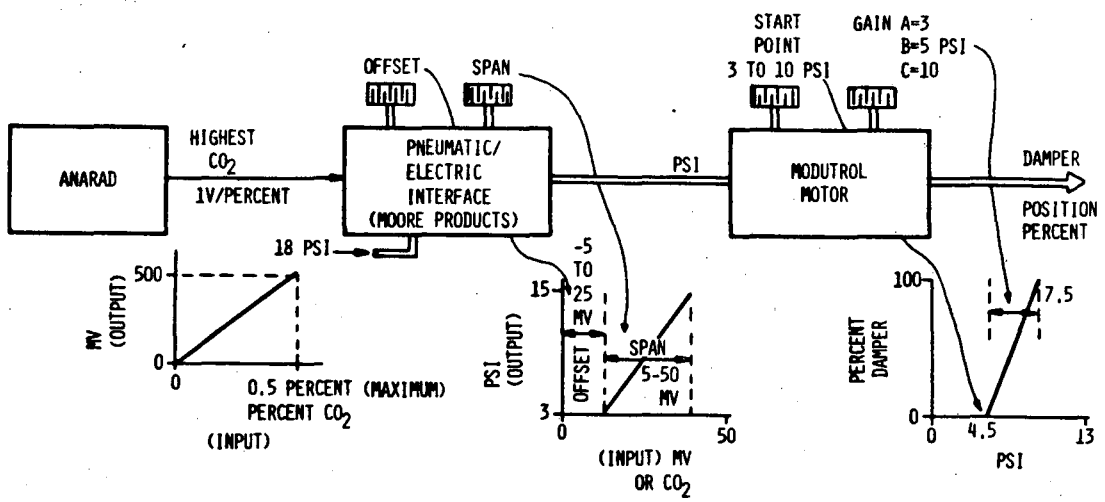


Figure 4-10. CO_2-Based Damper Control

The CO_2 damper movement was only part of the overall CO_2-based control mode. The CO_2-based ventilation system could operate in winter and summer modes on both day and night cycles. Switchover from the original control mode to CO_2 control was performed by moving switches 4 and 5 on the schematic of Figure 4-11 from position 1 to position 2. This disabled the two rooftop exhaust fans and positioned the original intake and exhaust dampers fully open. The low-leak intake and exhaust dampers were then in control of the flow.

Winter Operation--The winter position of the summer/winter changeover switch disabled the cooling unit and moved the temperature damper to the minimum position set on the minimum position switch. (The minimum position for CO_2-based control was 0 percent outdoor air, i.e., temperature and CO_2 dampers fully closed.) The primary discharge air controller then acted as a

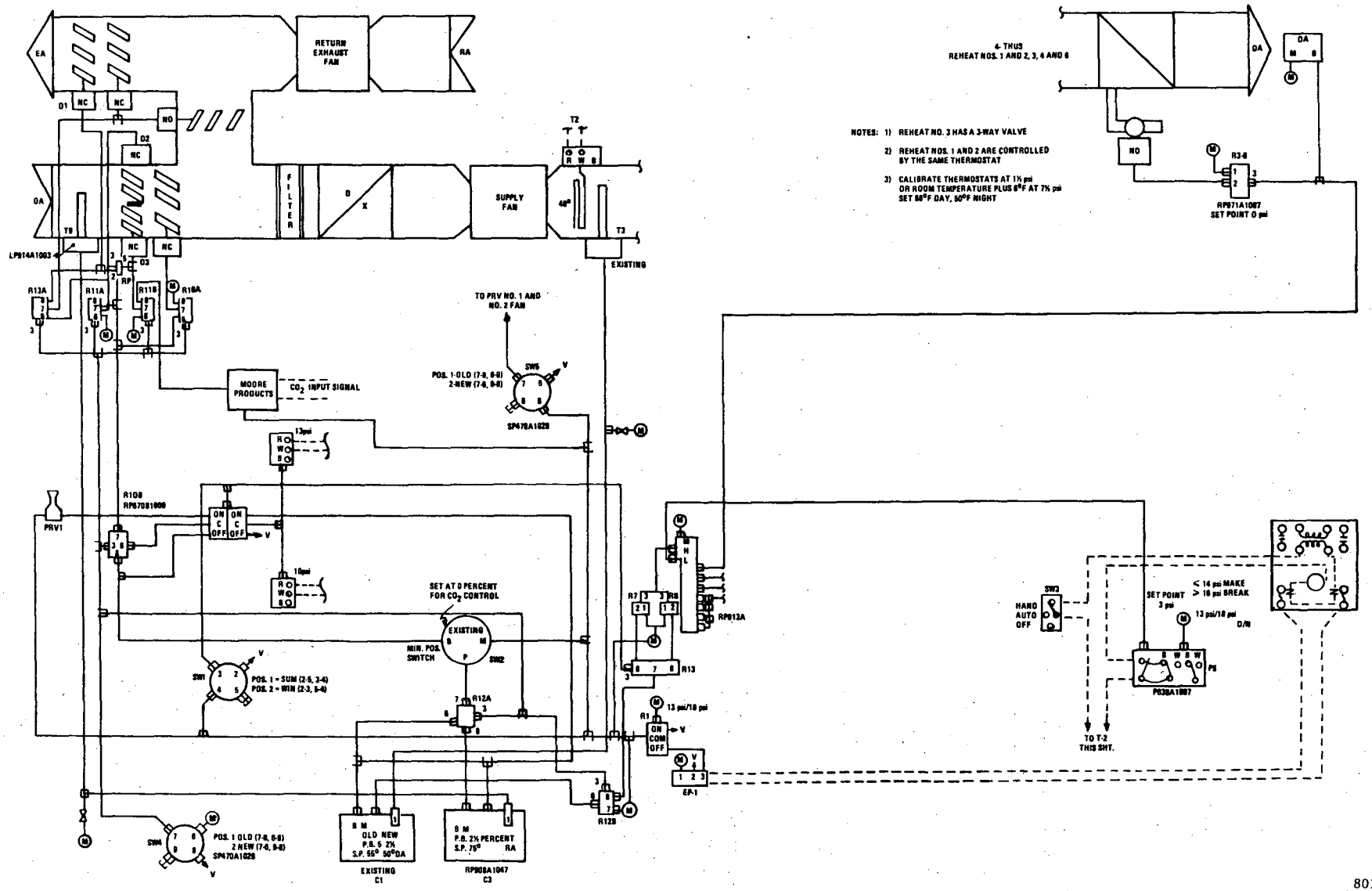


Figure 4-11. Modified Control System Schematic

low-limit controller; it could not control the primary discharge air temperature except by preventing the discharge air from going below 55°F during winter operation. (Original control always maintained 55°F discharge air temperature.)

Summer Operation--In summer operation the cooling unit was enabled. The CO_2 damper operated on a signal from the Moore Products E/P transducer as before. The zone thermostat with the greatest cooling load controlled the primary discharge air temperature. Below 75°F outdoor air temperature, the temperature damper opened to provide outdoor air cooling according to the zone thermostat with the largest cooling load. If the controlling zone was not satisfied, additional cooling was required from the direct expansion cooling unit. Above outdoor air temperatures of 75°F, the temperature damper was maintained at minimum position (0 percent outdoor air for CO_2 control), and all cooling was provided by the cooling coil to meet the needs of the largest cooling load. In all other zones the supply air was reheated to provide comfort if the reheat pump was running.

Summer night operation was the same as winter night operation; the cooling unit was disabled, the fans were off, intake dampers were fully closed and fans cycled on and off if any heating was required.

Revised Control Mode--The "revised" control mode was a variation of the CO_2 control mode. The only differences were that the CO_2 damper was disabled in a closed position (i.e., no control according to air quality) and the temperature damper was set to 16 percent outdoor air. (This is the original design outside air volume.) The temperature damper operated exactly as in the CO_2 mode, both summer and winter, to satisfy the needs of the zone with the largest cooling load, but went to minimum position instead of fully closed when cooling loads for all zones were met. The primary discharge air temperature again was determined by the zone with the highest cooling load, summer and winter, as in the CO_2 mode, instead of being maintained at 55°F, as in the original control mode.

4.3 DATA ACQUISITION

The data acquisition system consisted of a Fluke Model 2240B data logger and a Texas Instruments Model 733 teletype/cassette recorder. Forty channels of information were recorded. Table 4-1 and Figure 4-12 list all 40 channels, their information description and the location of each data point on the system. The data logger scanned each point at 10-minute scan intervals and transmitted the data to the recorder, where the information was stored on cassette tape. The cassette was a permanent copy of the data taken and was read into a computer file from the tape. Figures 4-13 and 4-14 show the data acquisition instrumentation, the multiplexer and the control panel, respectively.

Channel 0 was a spare channel. Channels 1 through 16 were temperatures at various points within the ventilation ductwork. Each point was an average of a matrix of type T thermocouples (nine thermocouples per matrix in supply ducts, four thermocouples per matrix in return ducts) to reduce errors caused by temperature gradients in the duct. Locations of these temperature measurement points are shown in Figure 4-12. The outdoor ambient air temperature was measured by a single thermocouple located under the hood of the outdoor intake 6 feet above the surface of the roof.

Channels 17 through 19 were the operative temperatures of the band room and the two chorus rooms. These were measured with thermocouples inside 6-inch-diameter black spheres suspended from the ceilings. The band room black sphere was located 6 feet below the ceiling at room center. The chorus room spheres were located 2 feet below the ceiling at room center.

Channels 21 through 24 were Honeywell Series Q457A relative humidity sensors in the return air ducts. The output of these sensors was recorded as a 0.5- to 9.5-mV DC signal that was directly proportional to 5 to 95 relative humidity.

Table 4-1. Data Logger Connections[a]

CHANNEL NO.	POINT DESCRIPTION	POINT CODE
1	REHEAT COIL NO. 1 DISCHARGE AIR TEMPERATURE	TS1
2	REHEAT COIL NO. 2 DISCHARGE AIR TEMPERATURE	TS2
3	REHEAT COIL NO. 3 DISCHARGE AIR TEMPERATURE	TS3
4	REHEAT COIL NO. 4 DISCHARGE AIR TEMPERATURE	TS4
5	REHEAT COIL NO. 5 DISCHARGE AIR TEMPERATURE	TS5
6	REHEAT COIL NO. 6 DISCHARGE AIR TEMPERATURE	TS6
7	REHEAT COIL NO. 7 DISCHARGE AIR TEMPERATURE	TS7
8	REHEAT COIL NO. 8 DISCHARGE AIR TEMPERATURE	TS8
9	MAIN SUPPLY TEMPERATURE	TS
10	RETURN TEMPERATURE, ROOM 115	TR115
11	RETURN TEMPERATURE, ROOM 117	TR117
12	RETURN TEMPERATURE, ROOM 119	TR119
13	MAIN RETURN	TR
14	DX COIL UPSTREAM TEMPERATURE	TDX1
15	DX COIL DOWNSTREAM TEMPERATURE	TDX2
16	OUTDOOR AIR INTAKE TEMPERATURE	TOA
17	OUTDOOR AIR TEMPERATURE	TAMB
18	OPERATIVE TEMPERATURE, ROOM 115	MRT115
19	OPERATIVE TEMPERATURE, ROOM 117	MRT117
20	OPERATIVE TEMPERATURE, ROOM 119	MRT119
21	RELATIVE HUMIDITY, ROOM 115	RH115
22	RELATIVE HUMIDITY, ROOM 117	RH117
23	RELATIVE HUMIDITY, ROOM 119	RH119
24	RELATIVE HUMIDITY, MAIN RETURN	RHR
25	SUPPLY AIR DEW POINT	DPS
26	OUTDOOR AIR INTAKE DEW POINT	DPOA
27	RELATIVE HUMIDITY DX COIL UPSTREAM	RHDX1
28	RELATIVE HUMIDITY DX COIL DOWNSTREAM	RDHX2
29	CO_2 CONTROL SIGNAL	CO_2
30	CO_2 CONCENTRATION, ROOM 119	CO2119
31	CO_2 CONCENTRATION, ROOM 117	CO2117
32	CO_2 CONCENTRATION, ROOM 115	CO2115
33	CO_2 CONCENTRATION, MAIN RETURN AIR	CO2R
34	CO_2 CONCENTRATION, MAIN SUPPLY AIR	CO2S
35	CO_2 CONCENTRATION, OUTDOOR AIR	CO2OA
36	Btu METER	Btu
37	TEMPERATURE AIR SENTINEL	TEMPDAMPER
38	CO_2 AIR SENTINEL	CO2 DAMPER
39	PYRANOMETER	SOLAR

[a] ROOM NUMBERS 115 (BAND ROOM), 117 (EXTERIOR CHORUS ROOM) AND 119 (INTERIOR CHORUS ROOM) ARE FROM THE MECHANICAL DRAWINGS OF THE MUSIC WING. THE DATA ACQUISITION POINTS ARE LABELLED WITH THESE NUMBERS. THE ACTUAL ROOM NUMBERS ARE 300 (BAND ROOM), 162 (EXTERIOR CHORUS ROOM) AND 164 (INTERIOR CHORUS ROOM). THE ACTUAL ROOM NUMBERS WILL BE USED ELSEWHERE IN THIS REPORT.

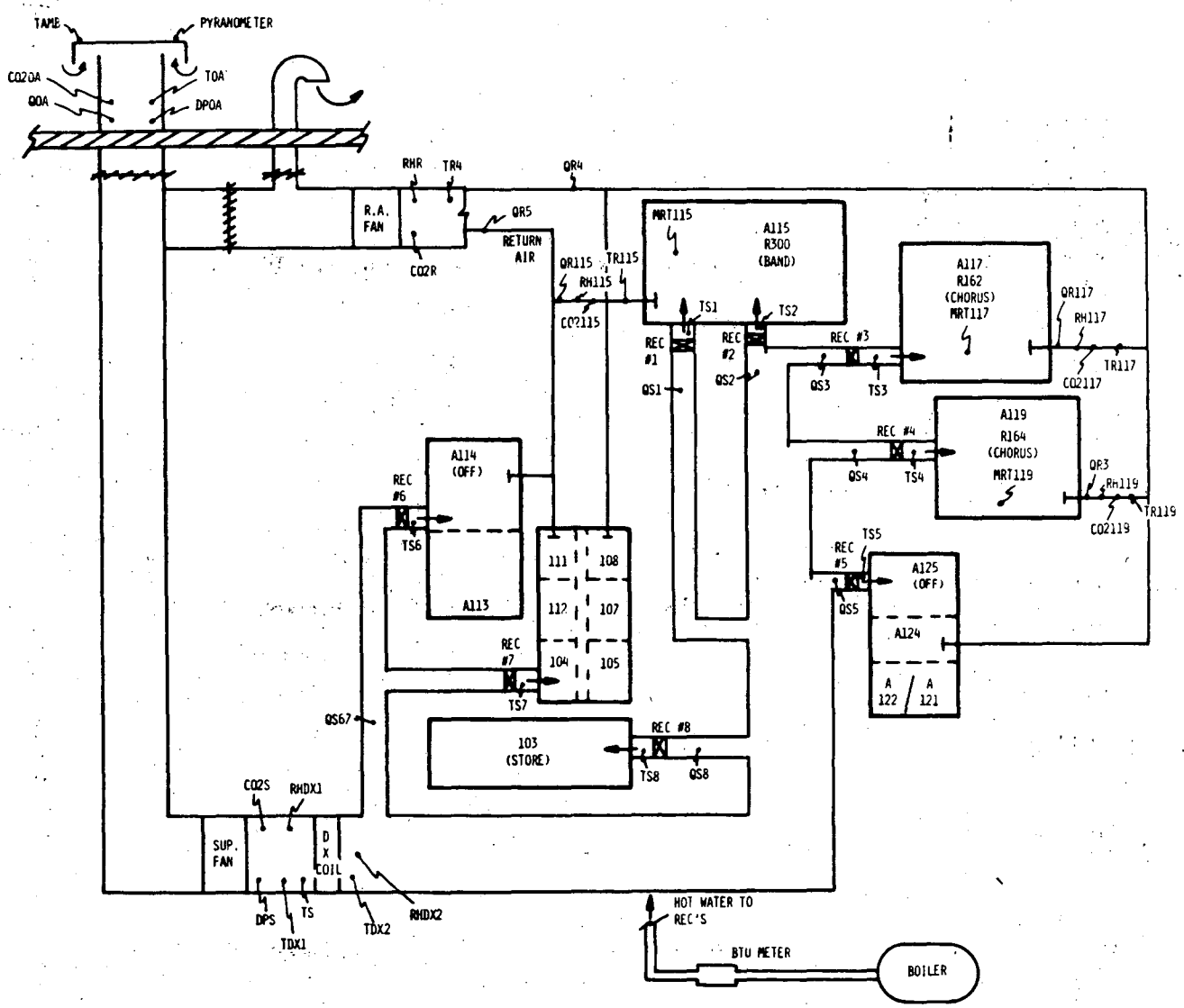


Figure 4-12. Data Acquisition Point Locations

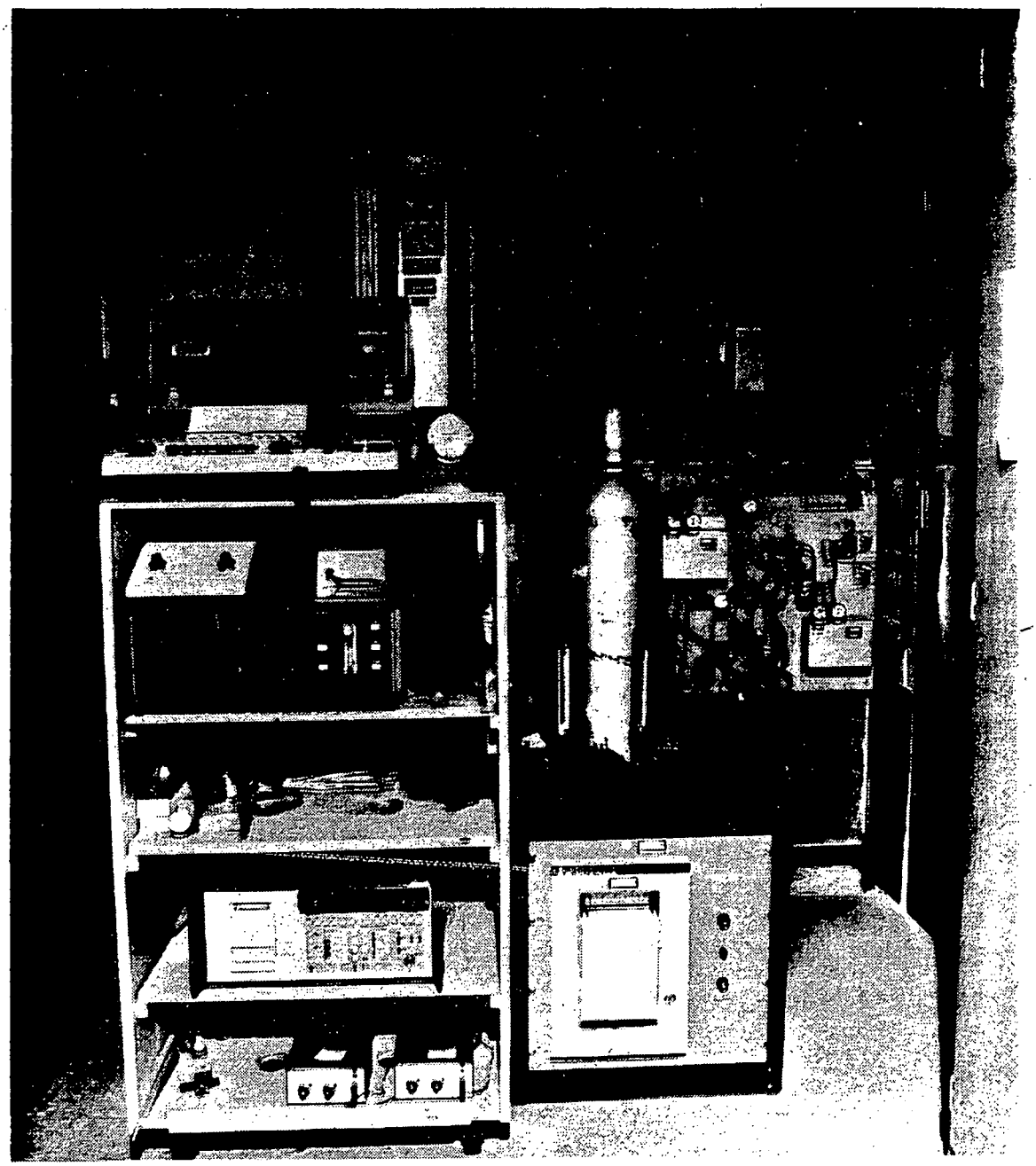


Figure 4-13. Data Acquisition Instrumentation

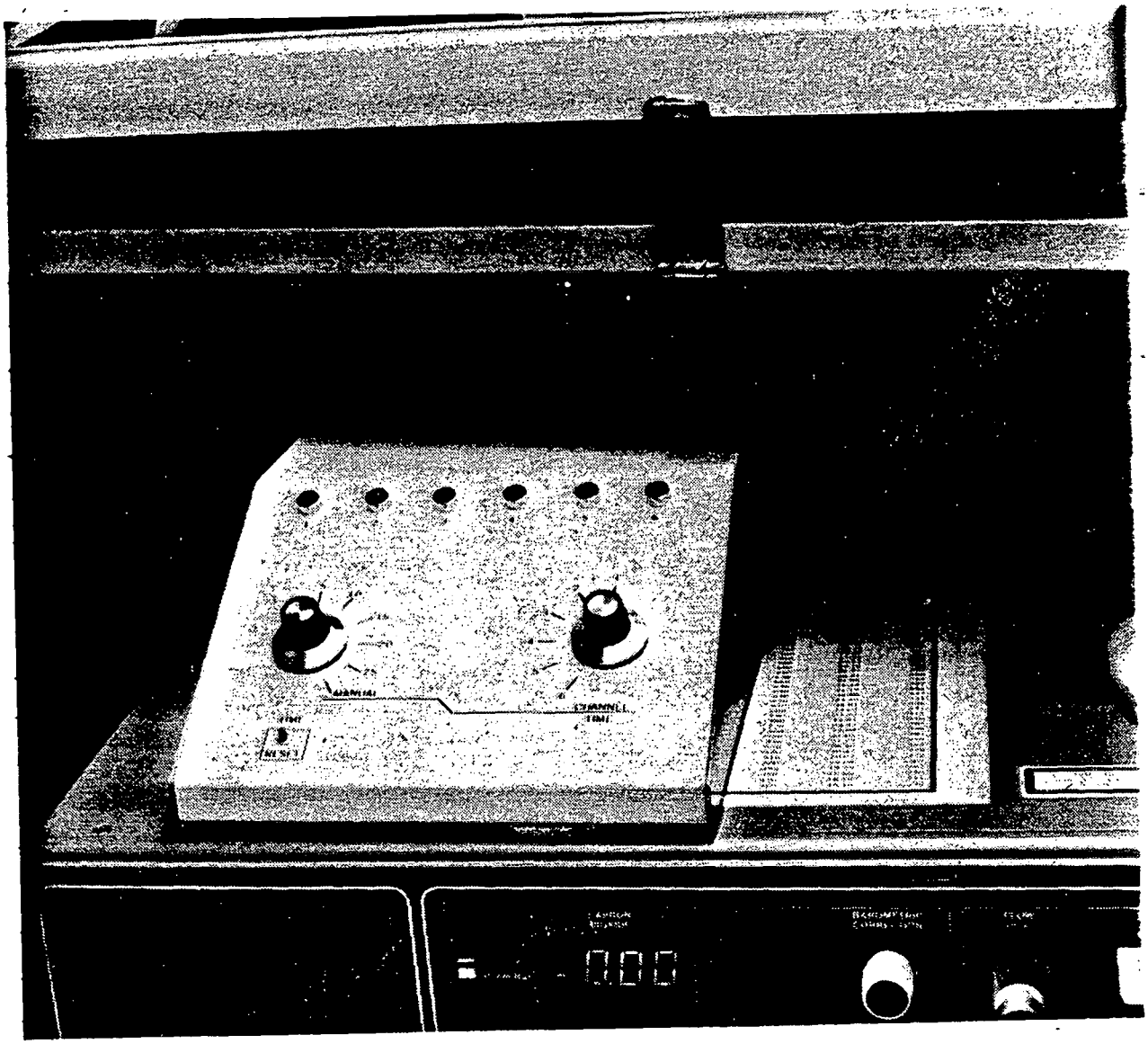


Figure 4-14. Close-up of Multiplexer

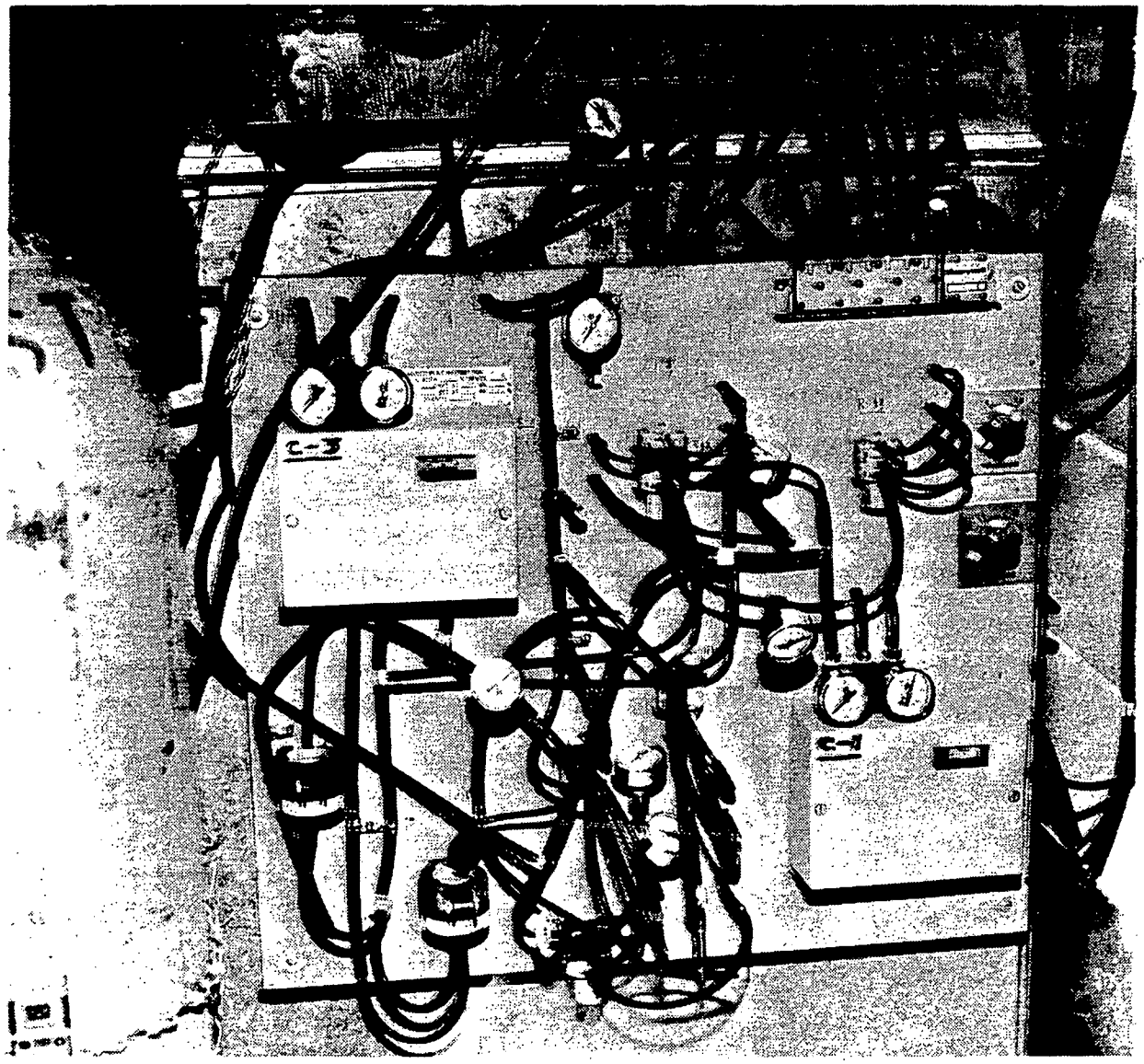


Figure 4-15. Ventilation Unit Control Panel

Channels 25 and 26 were the dew probe cavity temperatures of Honeywell Series SSP129 dew probes. A calibration curve provided with each unit converted the cavity temperature to the dew point temperature of the air around the probe.

Channels 27 and 28 were relative humidity measurements upstream and downstream of the cooling coil. Sensors similar to those used to measure the return air relative humidity were used.

Channel 29 was the instantaneous ANARAD output signal recorded in millivolts directly proportional to the CO_2 concentration measured. Referring to the previous multiplexer discussion, the ANARAD output signal at the time of the data recording was either the instantaneous CO_2 channel being scanned or the channel that the multiplexer had selected as the highest CO_2 concentration during the multiplexer scan preceding the data scan.

Channels 30 through 35 were DC voltages directly proportional to the values of CO_2 concentration measured at each multiplexer channel. These values were stored in a data memory attached to the multiplexer during the most recent multiplexer scan. This allowed a recorded history of not only the controlling CO_2 level, but the CO_2 level at all other sampling points as well. They were updated every 7 minutes.

Channel 36 was a 0- to 10-volt DC output corresponding to 2000 Btu/min/volt measured by a Wilgood Corporation Model HM-1RC Btu meter located in the reheat converter hot water line. The Btu meter had a flow sensor, supply and return water temperature sensors and a separate electronic computer connected to the data logger providing the 0- to 10-volt DC analog output.

Channels 37 and 39 recorded the Air Sentinel velocity measurement devices for the air velocity through the temperature and CO_2 dampers. The Air Sentinels are averaging pitot probe devices. Each consists of a honeycomb flow straightener and a matrix of pitot probes in the flow stream to produce an average pressure difference between the stagnation and static pressures of the flow stream. The average ΔP is measured by a small transducer that converts the ΔP to a proportional voltage that is logged by the data logger. Figures 4-16 and 4-17 are the flow versus pressure drop (or voltage) at STP (standard temperature and pressure) for airflow through the Air Sentinels. These are the flowmeter calibration curves. The fan system pressure capacity limited the flow through the CO_2 damper to about 2400 SCFM. Maximum flow through the temperature damper was about 4,400 SCFM.

Channel 39 was the millivolt output of an Eppley Model P5P pyranometer. The output of this unit was 10.27×10^{-6} volts/WM^{-2}.

Other system information was collected at Fridley Junior High but not recorded on the data logger. Weather data (wind speed and direction) were recorded on a strip chart recorder from a Texas Electronics wind vane and anemometer located 10 feet above the roof of the school. Pitot tubes were located at 12 locations in the supply and return ductwork at the center of the duct cross section. Figure 4-12 shows the location of the pitot tubes. The flow measurement points were designated QS or QR for supply and return. The velocity at the cross section center of each branch was calculated from the ΔP read from a manometer attached to each calibrated pitot probe.

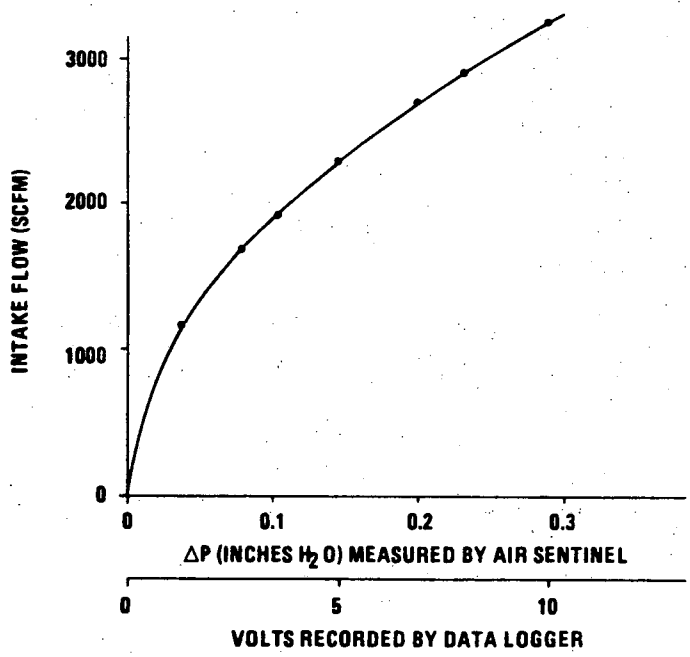


Figure 4-16. CO_2 Damper Airflow

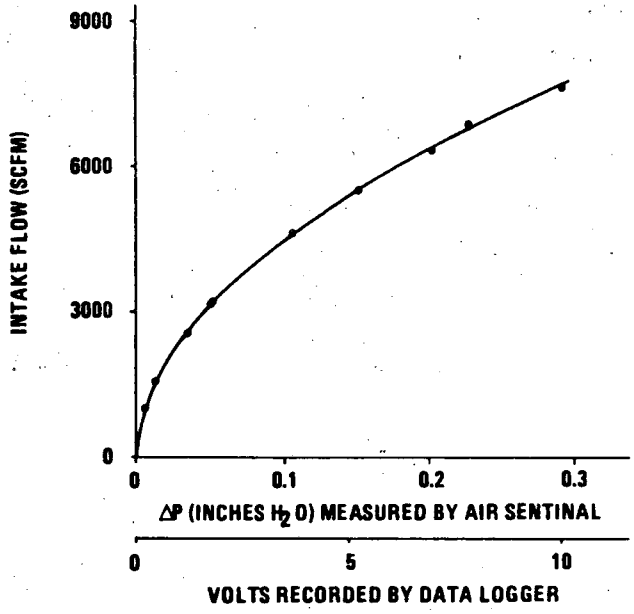


Figure 4-17. Temperature Damper Airflow

SECTION 5.0
TEST PROCEDURE AND ANALYSIS

The physical characteristics of the HVAC system were measured before and after an intensive test period in February 1980. The subjective response of the students was obtained and energy measurements were made during this intensive test period. The Lawrence Berkley Laboratory Mobile Air Quality Laboratory also was present during the intensive test period and measured the basic indoor air contaminents: CO_2, CO, NO, NO_x, SO_2, aldehydes, particulates and radon. Their results are presented in a separate report. The specific test procedures used for measuring energy consumption and evaluating subjective responses are described in the following paragraphs.

5.1 AIR DISTRIBUTION

Calculation of ventilation rates and energy consumption in each test space required knowledge of the airflow to each room. The airflows through branches of the supply and return ducts were determined by making a velocity traverse across the flow streams. A TSI hot wire anemometer was used for each velocity measurement. The velocity values taken at each traverse grid section were integrated across the face of the duct and then divided by the area of the cross section to produce an average duct velocity. The average duct velocity and the average duct volume flow were calculated for standard air given the centerline static temperature and pressure of the flow stream. These were compared to measurements to obtain a calibration factor. Pitot tubes then were installed at each traverse measurement location at the center of the area cross section. The calibrated pitot probes provided a quick check of the airflow throughout the distribution system given the measured flow profiles taken at the pitot tube locations. Figure 5-1 shows the location of each pitot probe and the volume flow rates calculated from the hot-wire traverse measurements at these locations.

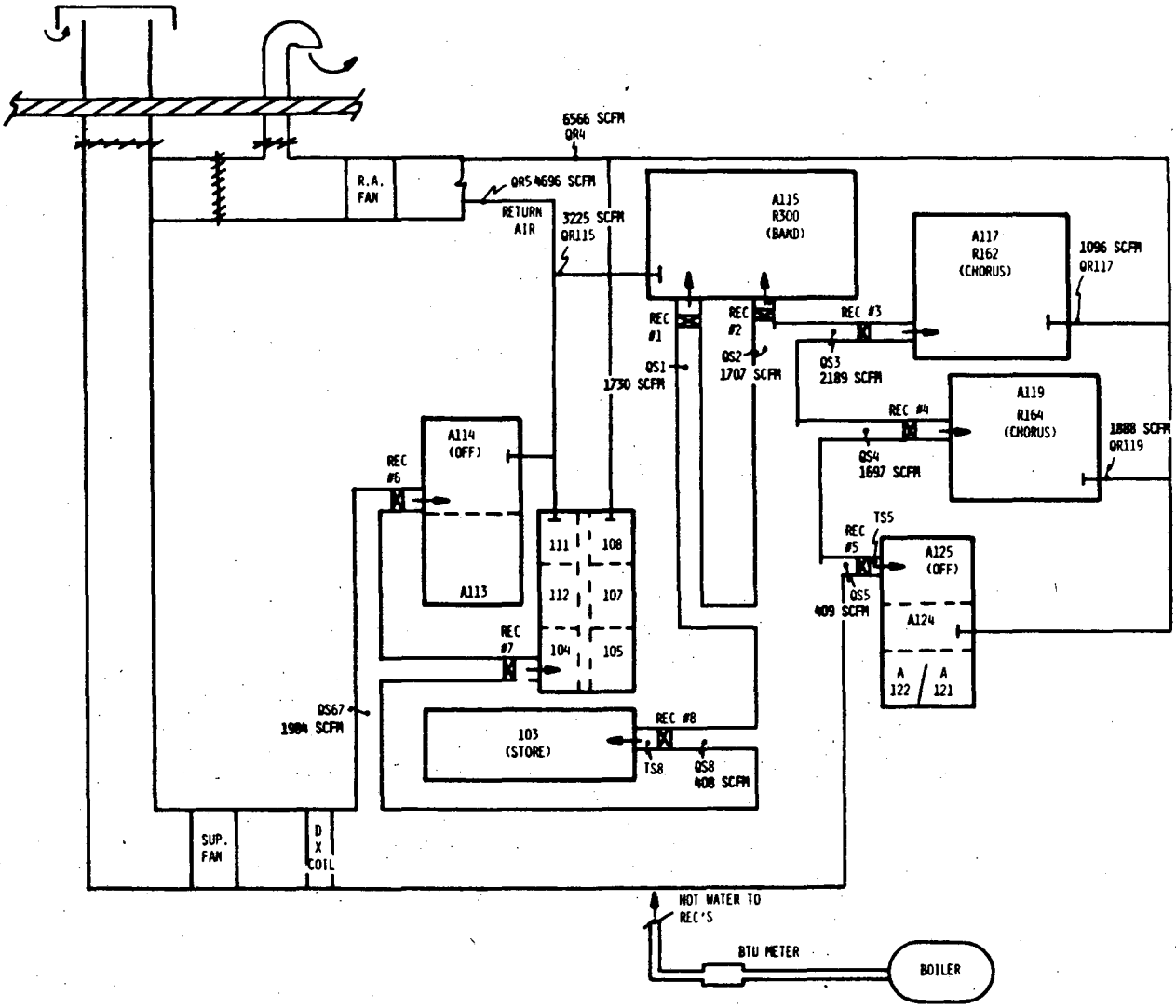


Figure 5-1. Flow Rate Distribution Through Ventilation System (Dampers Open)

Methane tracer gas measurements were made to characterize the outdoor air distribution to the rooms. The tracer gas was fed at a measured flow rate into the outdoor air stream. The concentration of tracer gas in the downstream branches then revealed the distribution of outdoor air to each room. Methane concentrations were kept below 500 ppm (safety factor of 100). An NDIR instrument was used to measure the methane concentration.

5.2 INFILTRATION

Infiltration was measured by the tracer decay method [16]. The music department was charged with a dilute concentration (about 200 ppm) of chemically pure methane. The rate of decay of the methane concentration then was measured with a nondispersive infrared instrument. Full-scale sensitivity was 1000 ppm, which was never exceeded. This gave a minimum safety factor of 50 under the lower flammability limit of 50,000 ppm of methane in air. Since chemically pure gas was used, there were no problems of odor or toxicity. All infiltration tests were performed when the music department was unoccupied.

The procedure was to feed methane at a measured flow rate into the main supply duct for a measured length of time, usually about 40 minutes. The injection flow rate was adjusted to keep the concentration in the ducts at least a factor of 10 below the lower flammability limit, and the process was monitored continuously. The tracer concentration was measured at six sampling points, using the gas sampling multiplexer. The leakproof outdoor air dampers were held fully closed.

Assuming the methane tracer was uniformly mixed with the air in the music wing and that the infiltration rate was constant, the concentration, C, at a time, t, after the start of the decay period was:

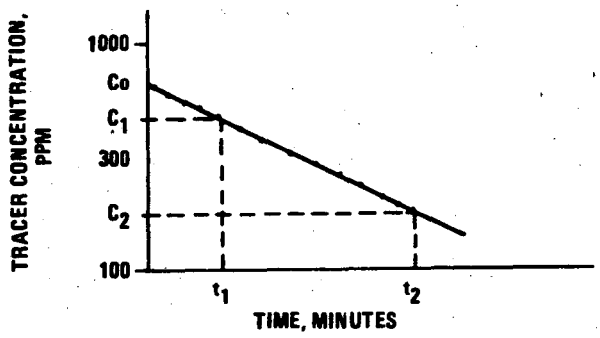
$$C = C_o e^{-t/\tau_i} \tag{5-1}$$

The infiltration rate in air changes per hour was:

$$I = 1/\tau_i \tag{5-2}$$

if τ_i is measured in hours.

The data were reduced by plotting the concentration decay on a semi-log plot.



The best straight line was drawn through the points, and the infiltration rate then was:

$$I = \frac{\ln (C_1/C_2)}{(t_2 - t_1)} \tag{5-3}$$

The infiltration flow rate is given by

$$\dot{V}_i = I\ V_s \tag{5-4}$$

where

V_s = volume of the test space.

The infiltration test apparatus used at Fridley Junior High is shown in Figures 5-2 and 5-3. Methane was injected into the supply duct just upstream of the supply fan. The injection flow rate was regulated by a methane flowmeter in the methane supply line. The CO_2 sampling system was used to draw air samples to the methane analyzer. This sampling system (see Section 4.0) draws gas samples from six different locations to a common manifold. A multiplexer in the sample system diverts sample flow to a sample manifold and then into the methane analyzer for all six sample locations, one at a time. The sampling points are the same points used for CO_2 sampling with one exception; the outdoor air sample point was replaced with a sampling point at the occupant level in the band room. An ANARAD model AR401 infrared gas analyzer was used to measure the tracer concentrations. The output signal from the analyzer was recorded on a strip chart recorder. Results of infiltration tests are presented for measurements taken under heating, cooling and no-load conditions.

5.3 AIR MIXING

The air distribution system in the Fridley Junior High School music wing employed ceiling diffusers and ceiling or high sidewall returns. Thus, under heating operation there was stratification. This was revealed quantatively by the infiltration measurements.

Infiltration was measured by introducing methane as a tracer gas into the supply duct at the supply fan. The tracer concentration was measured in each room at the return air grill. The system was charged with a few hundred parts per million of tracer gas and the concentration decay rate was measured. Figure 5-4 shows the decay in one chorus room. The infiltration rate is proportional to the slope of the line on a semi-log plot.

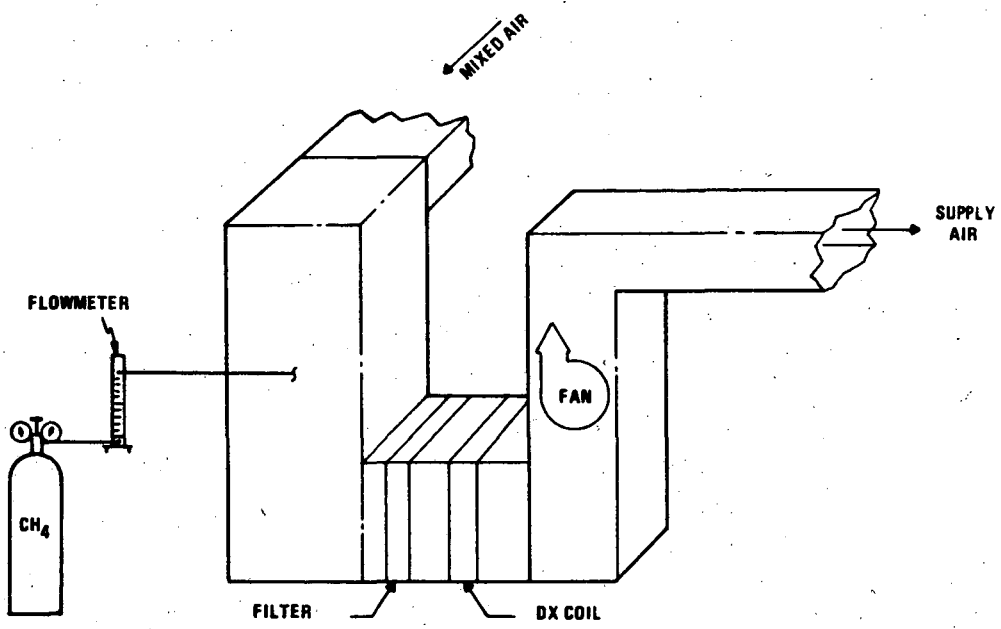


Figure 5-2. Infiltration Measurement Apparatus Setup

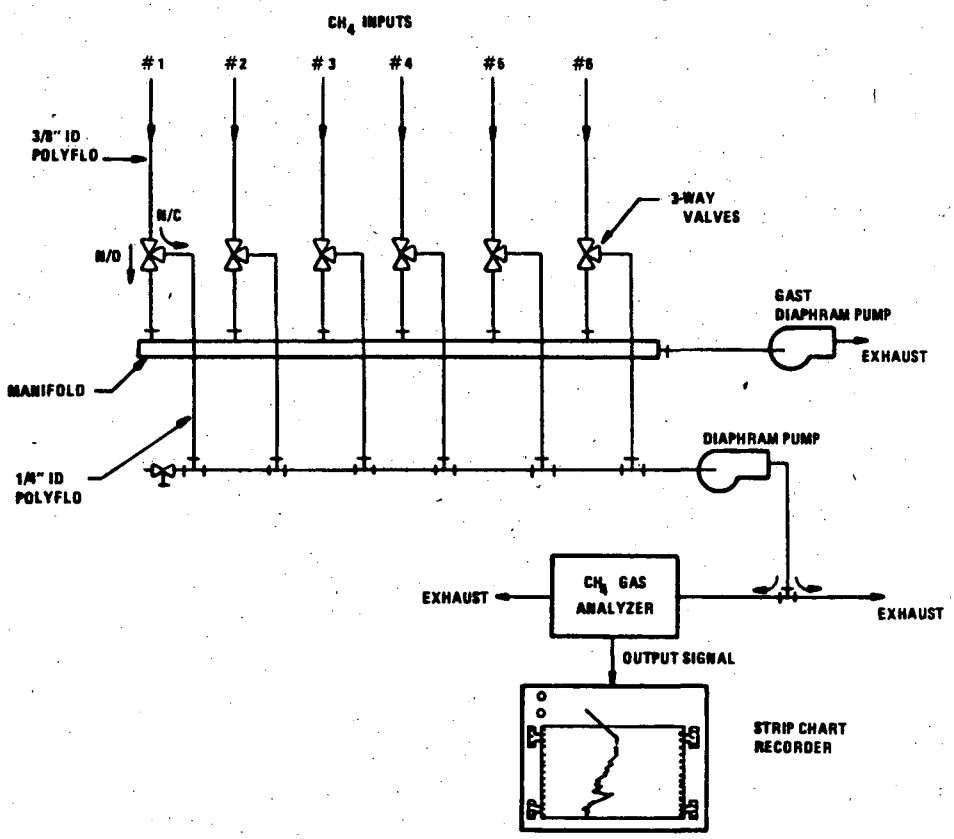


Figure 5-3. Infiltration Measurement Setup

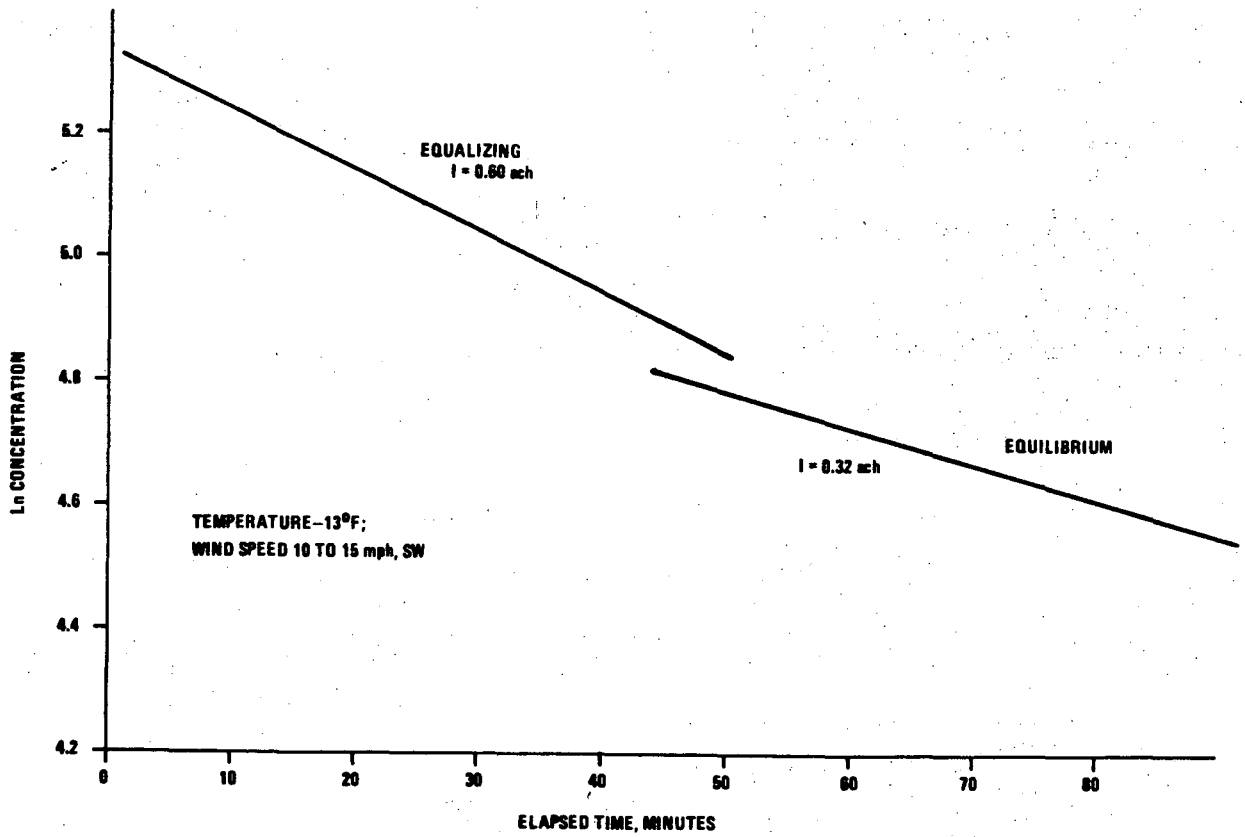


Figure 5-4. Infiltration Measurement in External Chorus Room No. 2

It was very evident that two separate decay rates were present. The initial tracer concentration was almost twice the final rate. The final decay rate of 0.31 to 0.35 air change per hour (ach) for the various rooms was assumed to be the steady-state infiltration rate for the wind and temperature conditions at that time. The higher initial tracer decay rate was interpreted to be due to stratification or mixing in the room.

The tracer gas was introduced into the supply duct. If a substantial amount of tracer failed to mix with the room air due to stratified flow across the ceiling, the tracer concentration circulating in the supply and return ducts would be higher than in the room. The rooms would, however, act as another sink for this gas as it circulated and gradually mixed with the room air. Kusuda [17] defined a mixing factor, K, as the ratio of the apparent infiltration rate to the steady-state infiltration rate:

$$K = \frac{I_o}{I_\infty} \tag{5-5}$$

$$I_o = \frac{\ln(C_o/C_1)}{(t_1 - t_o)} \tag{5-6}$$

where

C_o = initial tracer concentration at time t_o ;

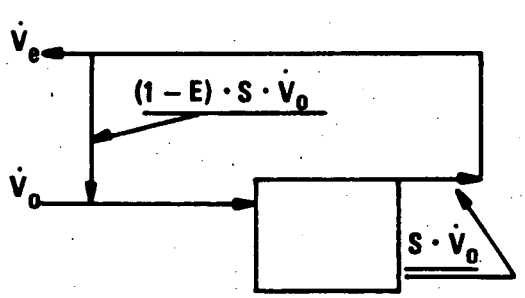
C_1 = tracer concentration at time t during the equalizing part of the decay period;

$$I_\infty = \frac{\ln\ (C_2/C_3)}{(t_3 - t_2)} \qquad 5\text{-}7)$$

C_2, C_3 = tracer concentration at times t_2, t_3 during the equilibrium period of the decay.

If mixing is perfect, K = 1. If there is no mixing at all, K = ∞.

Instead we have defined a stratification factor that is related to the mixing factor in the following way. Consider a typical room with a ceiling diffuser, ceiling level return and a normal exhaust/recirculation arrangement:



where

$\dot{V}_o$ = flow rate of outside air into the system;

$\dot{V}_e$ = flow of outside air that is exhausted;

S = fraction of stratified flow that essentially bypasses the occupied space;

E = fraction of return flow that is exhausted;

(1-E) = fraction of return flow that is recirculated.

The infiltration flow rate is equal to the infiltration rate multiplied by the volume in which the tracer gas is dispersed:

$$\dot{V}_o = I_o V \tag{5-8}$$

$$\dot{V}_\infty = I_\infty V \tag{5-9}$$

The fraction of the flow that is stratified and bypasses the occupied zone is:

$$S = \frac{\dot{V}_o - \dot{V}_\infty}{\dot{V}_o} = 1 - \frac{\dot{V}_\infty}{\dot{V}_o} \tag{5-10}$$

$$= 1 - \frac{I_\infty}{I_o} \tag{5-11}$$

Substituting equation (5-5) into (5-11) results in:

$$S = 1 - \frac{1}{K} \tag{5-12}$$

The use of the stratification factor, S, enables one to calculate the total amount of outside air that is exhausted without mixing in the occupied space:

$$\dot{V}_e = ES\dot{V}_o + (1 - E)\ S\dot{V}_o SE + (1 - E)^2 S^2 \dot{V}_o\ SE + \cdots \tag{5-13}$$

$$= ES\dot{V}_o \left[1 + (1 - E)\ S + (1 - E)^2 S^2 + \cdots\right] \tag{5-14}$$

$$\frac{\dot{V}_e}{\dot{V}_o} = \frac{ES}{1 - S\ (1 - E)} \tag{5-15}$$

The amount of ventilation flow to the occupied space then is:

$$\dot{V}_v = \dot{V}_o - \dot{V}_e \tag{5-16}$$

and the fraction of the outside air effective in ventilating the space is:

$$\eta_v = \frac{\dot{V}_v}{\dot{V}_o} = 1 - \frac{\dot{V}_e}{\dot{V}_o} \tag{5-17}$$

$$\eta_v = 1 - \frac{SE}{1 - S(1 - E)}$$

$$= \frac{1 - S + SE - SE}{1 - S + SE}$$

$$= \frac{1 - S}{1 - S(1 - E)} \tag{5-18}$$

Equation (5-18) is plotted in Figure 5-5.

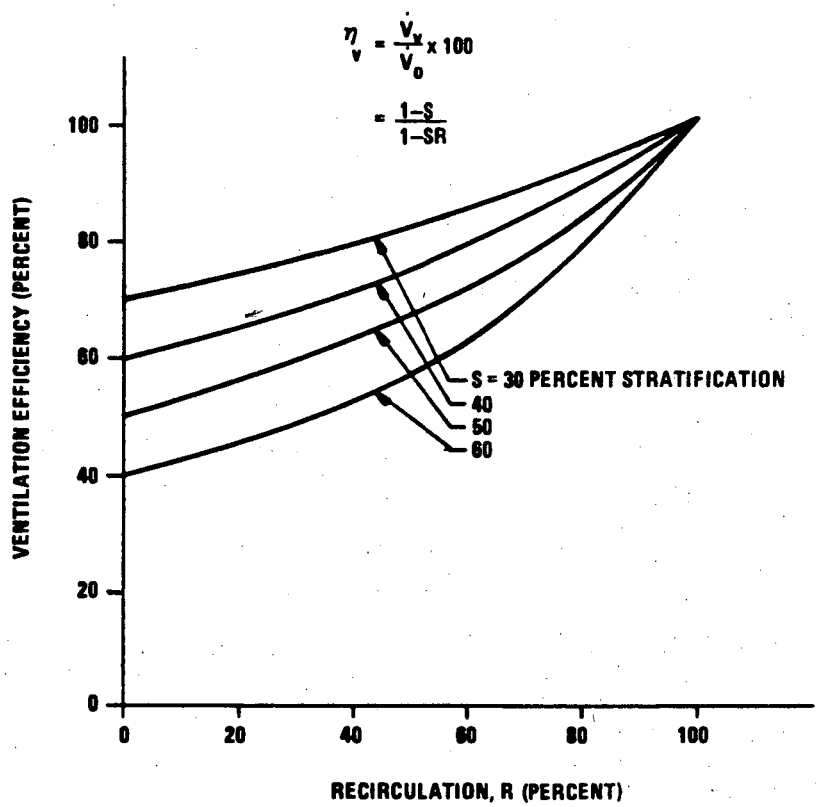


Figure 5-5. Effect of Stratified Flow in a Room on Ventilation Efficiency

Equation (5-12) can be combined with (5-18) to give the ventilation efficiency in terms of Kusuda's [17] mixing factor, K:

$$\eta_v = \frac{1/K}{1 - (1 - 1/K)\ (1 - E)} \tag{5-19}$$

$$\eta_v = \frac{1}{K - (K - 1)\ (1 - E)}$$

$$= \frac{1}{1 + E\ (K - 1)} \tag{5-20}$$

Stratification factors of 40 to 60 percent have been measured in the Fridley Junior High School. When combined with a recirculation rate of 50 percent, the ventilation efficiency is only 60 to 70 percent. In other words, 30 to 40 percent of the ventilation air brought in to dilute contaminants goes through the rooms without mixing or aiding in dilution of the contaminants. This air is, however, heated and exhausted. Thus it is a direct degradation of heating efficiency also.

5.4 THEORECTICAL VENTILATION REQUIREMENTS

The amount of oxygen consumed and carbon dioxide produced by human subjects depends on physical activity (metabolic rate) and diet. L.A. McHattie [18] has shown that for normal diets and sedentary activity, the CO_2 production rate is 0.0105 CFM (5 ml/s). The ASHRAE Ventilation Standard defines 0.25 percent CO_2 as the maximum acceptable concentration. Outdoor air has a CO_2 concentration of about 0.03 percent. Thus, the quantity of outdoor air needed to maintain 0.25 percent CO_2 indoors in steady state is:

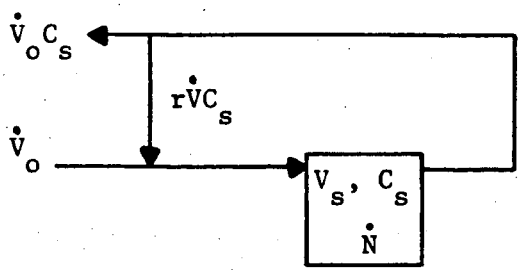
$$\dot{V}_o = \frac{\dot{N}}{C_s - C_o} \tag{5-21}$$

$\dot{N}$ = CO_2 production rate per person.
C_s = indoor concentration in the room space.
C_o = outdoor concentration.

$$\dot{V}_o = \frac{0.0105}{0.0025 - 0.0003} = 4.77 \text{ CFM}$$

The ventilation standard rounds this off to 5 CFM per person to maintain 0.25 percent CO_2.

The loads in the school were quite transient, changing each hour. A dynamic model was derived for this case. Consider a space in which outdoor air is supplied along with recirculated air.



The dynamic material balance is given by:

$$V_s dC_s = \left(\left(\dot{V}_o C_o - \dot{V}_o C_s\right) + \dot{N}\right) dt \qquad (5\text{-}22)$$

V_s = Volume of space.
C_s = Concentration in space.
$\dot{V}_o$ = Outdoor airflow rate.
$\dot{N}$ = CO_2 production rate in the space.
t = time.

The variable in equation (5-22) can be separated.

$$\frac{dC_s}{\left[\dot{V}_o\ (C_o - C_s) + \dot{N}\right]} = \frac{dt}{V_s} \qquad (5\text{-}23)$$

This equation then can be integrated to show that:

$$C_s = \left[\frac{\dot{N}}{\dot{V}_o} + C_o\right]\left(1 - e^{-t/\tau}\right) + C_1 e^{-t/\tau} \qquad (5\text{-}24)$$

$\tau = V_s/\dot{V}_o$

C_1 = CO_2 concentration when $t = 0$

It will be noted that equation (5-24) appears to blow up if the outdoor air, $\dot{V}_o$, goes to zero, whereas equation (5-22) reduces, as would be expected, to a linear increase with time.

$$C_s = \frac{\dot{N}t}{V_s} + C_1 \qquad (5\text{-}25)$$

Equation (5-24) actually reduces to this case when $e^{-t/\tau}$ is expanded in an infinite series. Equations (5-24) and (5-25) provide models for estimating the CO_2 concentration in the space for a given occupance and ventilation rate. Conversely, the ventilation rate needed to maintain a given CO_2 concentration with a given occupancy also can be computed. The generation rate, $\dot{N}$, was assumed to be 0.0105 times the number of students for 14-year-old students at light work (see Table 3-1).

Perfect mixing of the outdoor air with room air was assured. The infiltration measurements showed that mixing was not perfect. As $\dot{V}_o$ increases, its effectiveness in diluting the CO_2 concentration decreases. It is necessary, therefore, to multiply $\dot{V}_o$ by the ventilation efficiency to calculate the actual room concentration.

5.5 ENERGY ANALYSIS

The overall objective of this energy analysis was to estimate the potential energy savings that could result from the use of a CO_2-controlled air handling system for any outdoor climate situation. Thus it was necessary to develop a model capable of simulating the performance of the entire air handling system at the music wing of Fridley Junior High School, including its interactions with the building, the occupants and the control system.

Development of this model resulted in the discovery of unexpected peculiarities in the air handling system. Description of the energy model required consideration of those peculiarities and, in certain cases, assumptions to make the model more general.

were adjusted until a reasonable agreement was obtained between the compared quantities over a sufficiently long period of time. The model then was assumed to be finalized.

For each zone, balances of energy, water vapor and CO_2 were performed for each time step. However, due to the location of the sensors within the music wing, different zones required different treatments.

Zone 1, Band Room--This room exhibited an airflow pattern such that a significant fraction (S) of the hot supply air bypassed the occupied space. Thus the air exhausted from this room was warmer than the average conditions that existed within the occupied space. The different balances then were expressed as follows (see Figure 5-7).

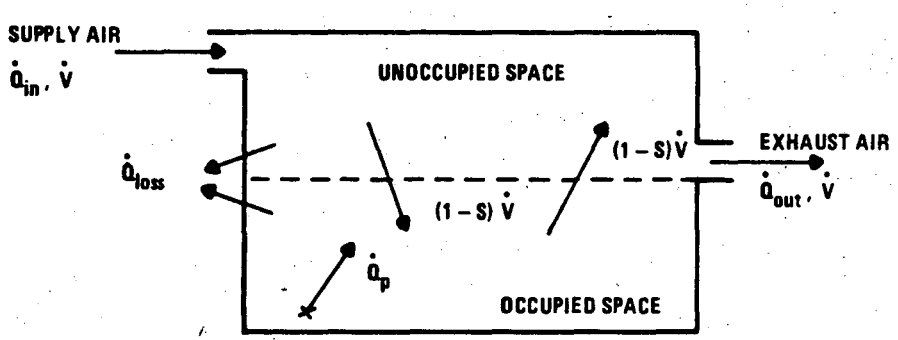


Figure 5-7. Schematic of Zone 1

Energy Balance--

$$\begin{bmatrix}\text{Increase in stored energy} \\ (\Delta Q_s)\end{bmatrix} = \begin{bmatrix}\text{Energy into space} \\ (\dot{Q}_{in})(\Delta t)\end{bmatrix} - \begin{bmatrix}\text{Energy leaving the space} \\ (\dot{Q}_{out}+\dot{Q}_{loss})(\Delta t)\end{bmatrix} + \begin{matrix}\text{Energy produced in the space*} \\ (\dot{Q}_p)(\Delta t)\end{matrix}$$

* $\dot{Q}_p$ resulted from people, lights and appliances.

Once these three terms were calculated, the term $(\dot{Q}_{loss} - \dot{Q}_p)$ was calculated. This term, which represented the net energy loss through the boundary of the space during each time-step (i.e., the loss through the boundary minus the energy produced in the space), was used to characterize heat loss through the boundary and occupancy patterns in further studies.

Water vapor and CO_2 balances--The amounts of water vapor and CO_2 produced inside the zone (by people and infiltration through walls, windows and doors) were calculated for each time-step. In a mass balance similar to the form of equation (5-20), balances were expressed as:

$$V\ (\Delta W) = \dot{V}\ \Delta t\ (W_{in} - W_{out}) + W_p \qquad (5\text{-}27)$$

and

$$V(\Delta C_{CO_2}) = \dot{V}\ \Delta t\ (C_{CO_{2(in)}} - C_{CO_{2(out)}}) + CO_{2p} \qquad (5\text{-}28)$$

The supply and exhaust concentrations were measured directly during each time step, but the change in stored amounts required the calculation of their concentrations within the occupied space. It was assumed that the exhausted air was a mixture of (S) $(\dot{V})$ from supply air and (1 - S) $(\dot{V})$ from occupied space air. Thus:

$$\dot{V}\ (W_{out}) = (S\ \dot{V}(W_{in}) + (1 - S)\dot{V}\ (W_{room}) \qquad (5\text{-}29)$$

and

$$\dot{V}\ (C_{CO_{2(out)}}) = (S\ \dot{V}\ (C_{CO_{2(in)}}) + (1 - S)\ \dot{V}\ (C_{CO_{2(room)}}) \qquad (5\text{-}30)$$

The production terms W_p and CO_{2p} were used in further analysis to characterize the occupancy of the zones.

The development of the energy model consisted of two separate phases:

- Development of a model that simulated the music wing of Fridley Junior High School with all its peculiarities. After calibration of the model of the control systems, this model was used to calculate the energy consumption that actually occurred in the intensive test period in the music wing.
- Extension of the model to simulate the same music wing after some of the pecularities were assumed to have been corrected. This more general model was used to estimate the energy consumption that would occur in a similar building with a similar occupancy pattern, under different outdoor weather conditions.

In the following sections, both models will be described in detail.

5.5.1 Model Simulating the Music Wing of Fridley Junior High School in Detail

The air handling system at the music wing is represented schematically in Figure 5-6. The total space of the music wing was divided arbitrarily into four zones according to the major room divisions.

To simulate the thermal performance of the music wing, a time-marching finite-difference approach was selected. Under this approach, all conditions in the wing were assumed constant during a period equal to the time-step of the time-marching procedure. Then, based on these "quasi-steady-state" conditions, the new equilibrium points of several variables were estimated for the next time-step. These estimated variables then were compared to their corresponding measured values for validation of the model. In general, the model assumed that the properties of the air within each zone were known and thus estimated the performance of the air handling system based on the control characteristics of the operating control system. The calculated quantities (i.e., humidity ratio, dry-bulb temperature, and CO_2 concentration of the supply air to each zone and the supply rate of outdoor air flowing through the outdoor air dampers) then were compared to the corresponding measured values. Control set points

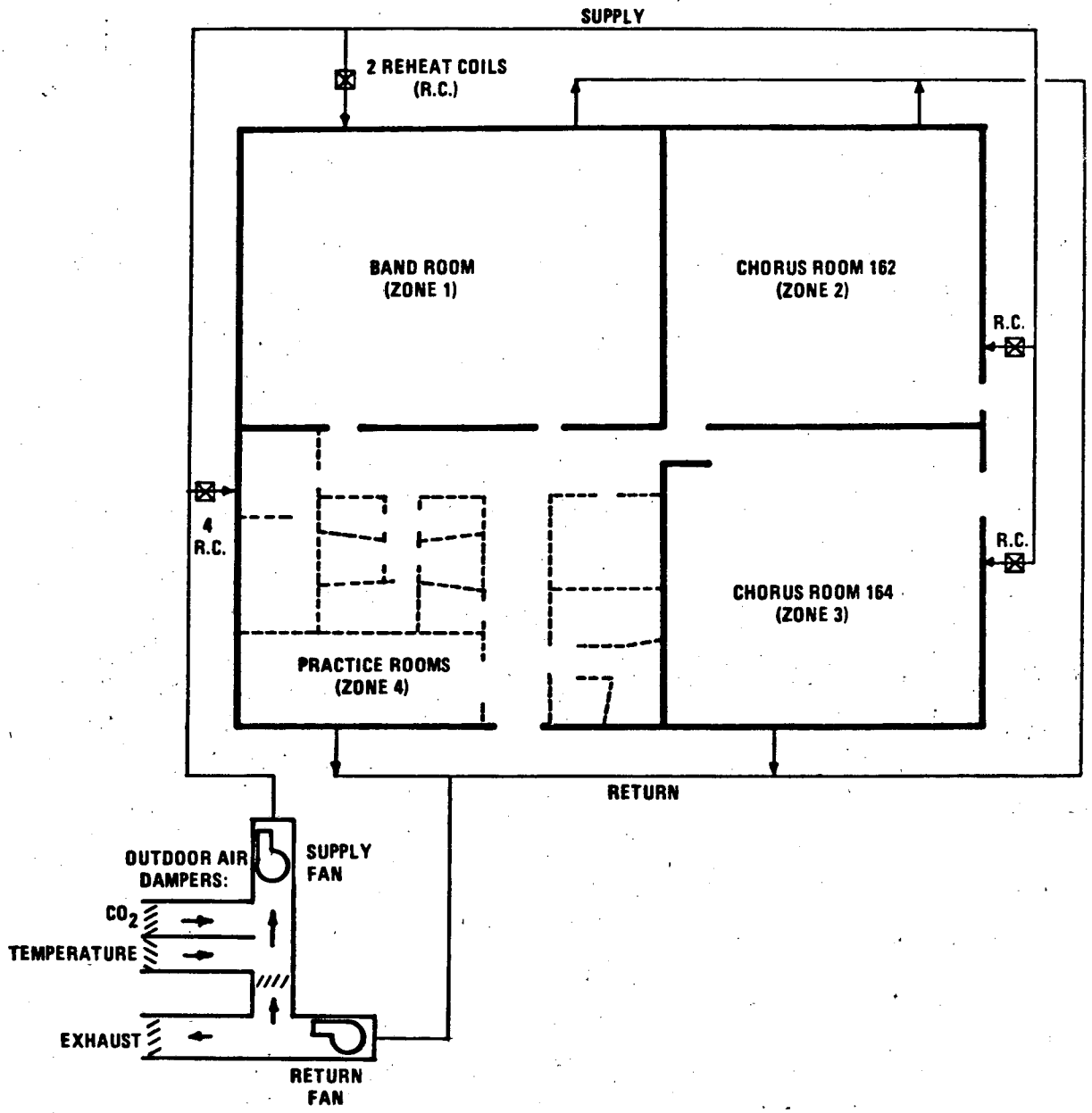


Figure 5-6. Schematic Diagram of Music Wing of Fridley Junior High School With Air Handling System

or

$$\Delta Q_s = (\dot{Q}_{in} + \dot{Q}_p - \dot{Q}_{out} - \dot{Q}_{loss})(\Delta t) \qquad (5\text{-}26)$$

where Δt is the time-step of the time-marching procedure. The heat flux ($\dot{Q}$) and energy content (Q) of a mass of moist air were calculated as a function of the volume of the air, its dry-bulb temperature and its humidity ratio using the procedure outlined in Appendix A. In equation (5-26), all terms except $\dot{Q}_p$ and $\dot{Q}_{loss}$ could be calculated from measured values as follows:

- $\dot{Q}_{in}$ -- was calculated from the airflow rate, measured to be 3440 CFM when the fans were on and the outdoor dampers were fully closed, decreasing linearly to 85 percent of that value when the outdoor dampers were fully open; the supply dry-bulb temperature and the relative humidity were measured during every time-step.

- $\dot{Q}_{out}$ -- was calculated from the exhausted airflow rate, assumed to be equal to the supply airflow rate; the dry-bulb temperature and the relative humidity of this airstream were also measured during every time-step.

- ΔQ_s -- the increase in stored energy was calculated as the difference in enthalpy of the air in the space at the beginning and end of each time-step:

$$\Delta Q_s = Q_f - Q_i \qquad (5\text{-}26)$$

where Q_f and Q_i were calculated based on the room's volume (43,320 cubic feet), and the measured relative humidity within the space. The room dry-bulb temperature was not measured and had to be estimated using the method outlined in Appendix B.

Zones 2 and 3, Chorus Rooms--Contrary to the band room, most of the hot air supplied to these two zones reached the occupied space. Thus the air exhausted from each zone was assumed to have properties (i.e., dry-bulb temperature, CO_2 concentration and humidity ratio) that were equal to the average properties of the air within the zone.

Energy Balance--Equation (5-26) still applies, and all the terms were calculated as for Zone 1 except that the airflow rate into Zone 2 was 2070 CFM and the flow rate into Zone 3 was 1700 CFM (both flow rates decreased by 15 percent when the outdoor air dampers were open as for Zone 1). Zones 2 and 3 had a volume of 16,340 cubic feet each.

Water vapor and CO_2 balances--Equations (5-27) through 5-30) are still valid. As there was no airflow bypass, S was set to zero for these two zones.

Zone 4, Practice Rooms--The energy and water vapor balances in this zone were treated in exactly the same way as Zones 2 and 3, but Zone 4 required special treatment because the return air properties were not measured directly. The dry-bulb temperature, humidity ratio and CO_2 concentration of the air in Zone 4 were calculated from the measured corresponding quantities in the return airstreams from Zones 1 through 3 and from those of the main return. The balances were expressed as (see Figure 5-8):

Energy $$\dot{Q}_A + \dot{Q}_B + \dot{Q}_D = \dot{Q}_C \qquad (5\text{-}31)$$

Water vapor $$\dot{V}_A W_A + \dot{V}_B W_B = \dot{V}_C W_C \ * \qquad (5\text{-}32)$$

CO_2 $$\dot{V}_A C_{CO_{2(A)}} + \dot{V}_B C_{CO_{2(B)}} = \dot{V}_C C_{CO_{2(C)}} \qquad (5\text{-}33)$$

Equations (5-32) and (5-33) were solved directly. Equation (5-31) was solved iteratively and the $\dot{Q}$ terms were calculated using the procedure in Appendix A.

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* The ducts were assumed to have no infiltration.

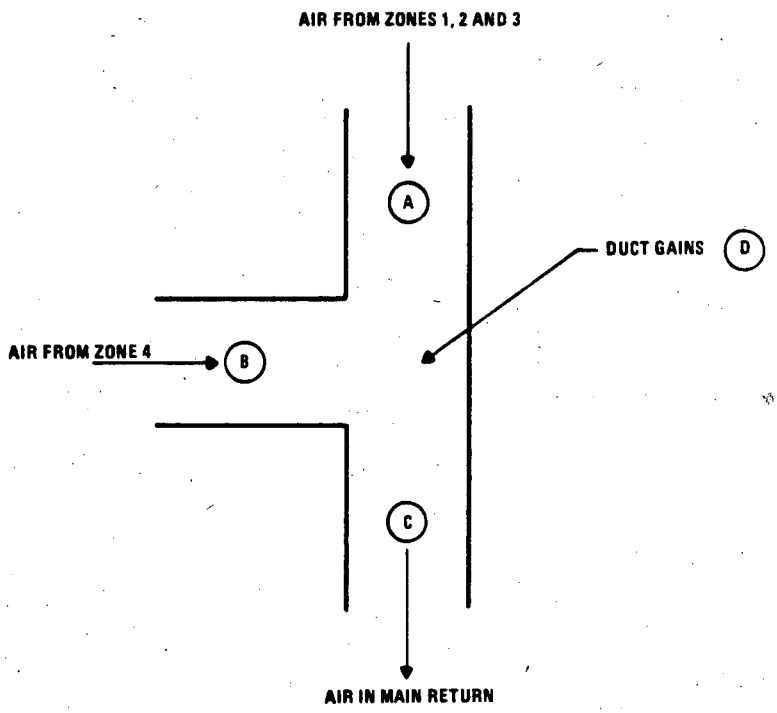


Figure 5-8. Balances to Determine the Properties of the Air in Zone 4

Air Handling System--For each time-step, the properties of the air supplied to each zone were calculated and compared to the corresponding properties measured during the period under simulation.

The properties of the air in the main return underwent successive modifications in the following order:

- The value of the return air dry-bulb temperature was altered to account for the temperature rise across the return air fan.

- The return and outside airstreams were mixed based on the value of "percent-open" of the outside air damper. The humidity ratio, dry-bulb temperature and concentration of CO_2 for the mixed airstream were determined.

The amount of outdoor air supplied by the system (i.e., the position of the outdoor air dampers) depended on which control system was operating. Under temperature control, the dampers were controlled by the maximum "zone temperature," which opened the outdoor air dampers over some minimum position (about 1500 CFM) based on the zone set point temperature. Under CO_2 control, the dampers were always fully closed unless the maximum "zone CO_2 concentration" exceeded the CO_2 set point. In addition, the CO_2 control could be overridden by the temperature control if the "zone temperatures" so required.

- The dry-bulb temperature was readjusted to include the effect of temperature rise across the supply fan.

- Individual duct gains for the eight main supply branches (dry-bulb temperature rise) were included. Negligible changes in humidity ratio and CO_2 concentration were assumed because the supply duct was under positive pressure relative to its environment (the duct gains were interpreted to include unaccounted heat gains from reheat coils also).

- Finally, the increase in dry-bulb temperature of the supply air as it was transported through the reheat coil was included. This increase was based on the zone set point temperature and control range and the maximum possible temperature rise across the reheat coil.

The energy consumed by the heating system then was evaluated as the difference in energy content of the air supplied to the four zones and the supply air just after the supply air fan.

A Fortran computer program that represents the model just described is listed in Appendix C.

5.5.2 Model That Simulates a "Corrected" Wing for Fridley Junior High School

The stratification that occurred in Zone 1 and the method used for calculation of the dry-bulb temperature in its occupied space yielded a reasonable agreement in simulating supply air properties to all four zones, as shown in Figures 5-9 through 5-11. The main conclusions derived from the simulations indicated that:

- Zones 3 (Chorus Room 164) and 4 (practice rooms) had a consistent behavior that could be predicted quite adequately with the exception of rapid transients during system start-up (see Figures 5-11 and 5-12).

- Zone 2 (Chorus Room 162) consistently showed an unstable behavior, and the magnitude of the oscillations could not be simulated accurately; however, the model did simulate the occurrence of the unstable pattern, as shown in Figure 5-10.

- The Zone 1 (band room) model proved to be too insensitive to predict zone temperature due to the assumed constant stratification factor (S). In addition, a sharp change in the system control point occurred every day around 1 P.M. (with the exception of 01/28/80, the first day of the intensive test period), as shown in Figures 5-13 through 5-16. The reason for this change remains unknown, but may have been due to a manual readjustment of the thermostat set point that was not reported or by some change in air pattern distribution within the space.

- As shown in Figures 5-9 through 5-12, most of the energy supplied to the music wing was introduced into the supply air for the band room. Thus, the band room was actually driving the indoor air quality of the whole music wing.

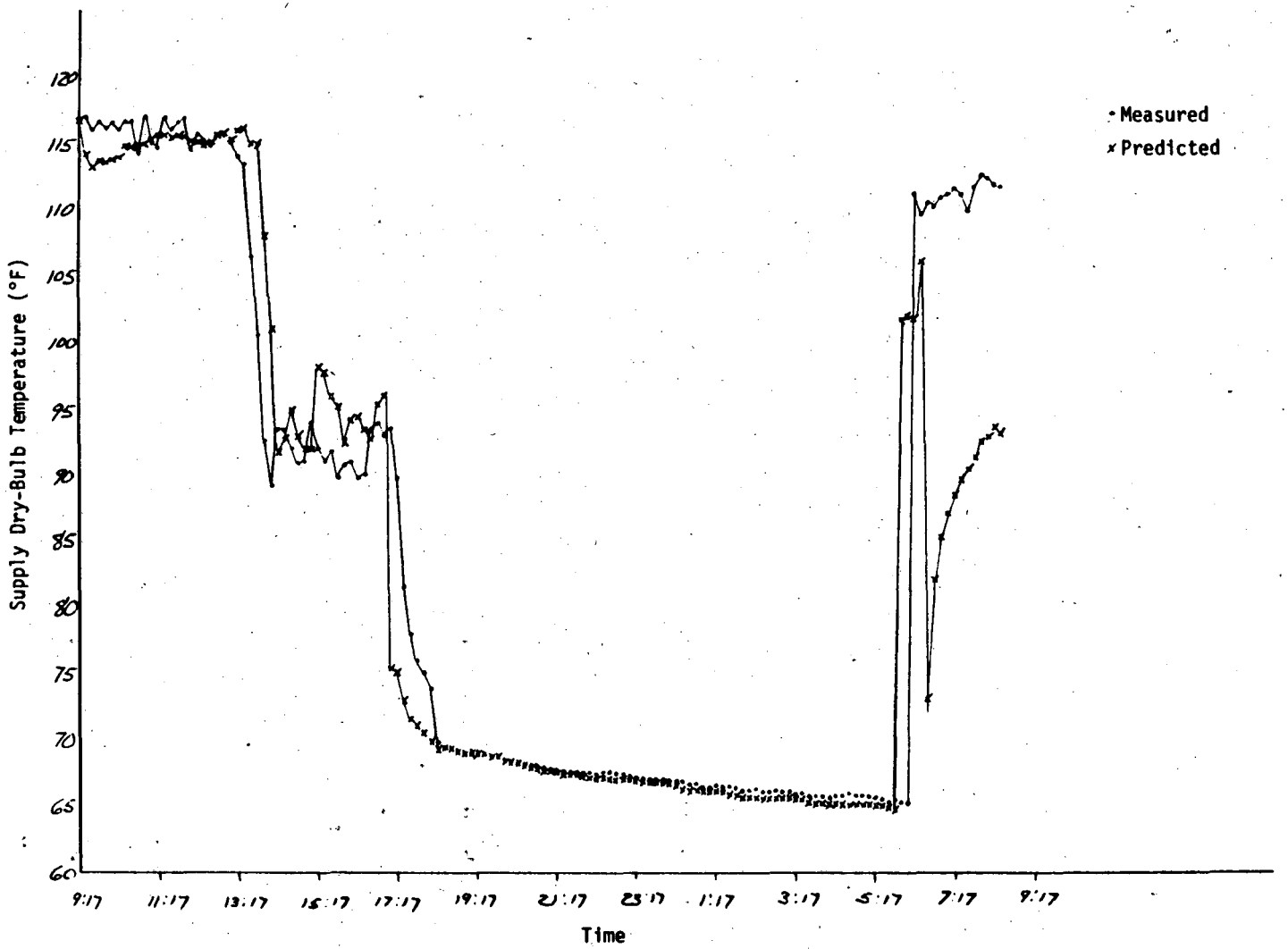


Figure 5-9. Supply Dry-Bulb Temperature for Period 9:17 A.M. (01/29/80) to 9:17 A.M. (01/30/80) (Zone 1)

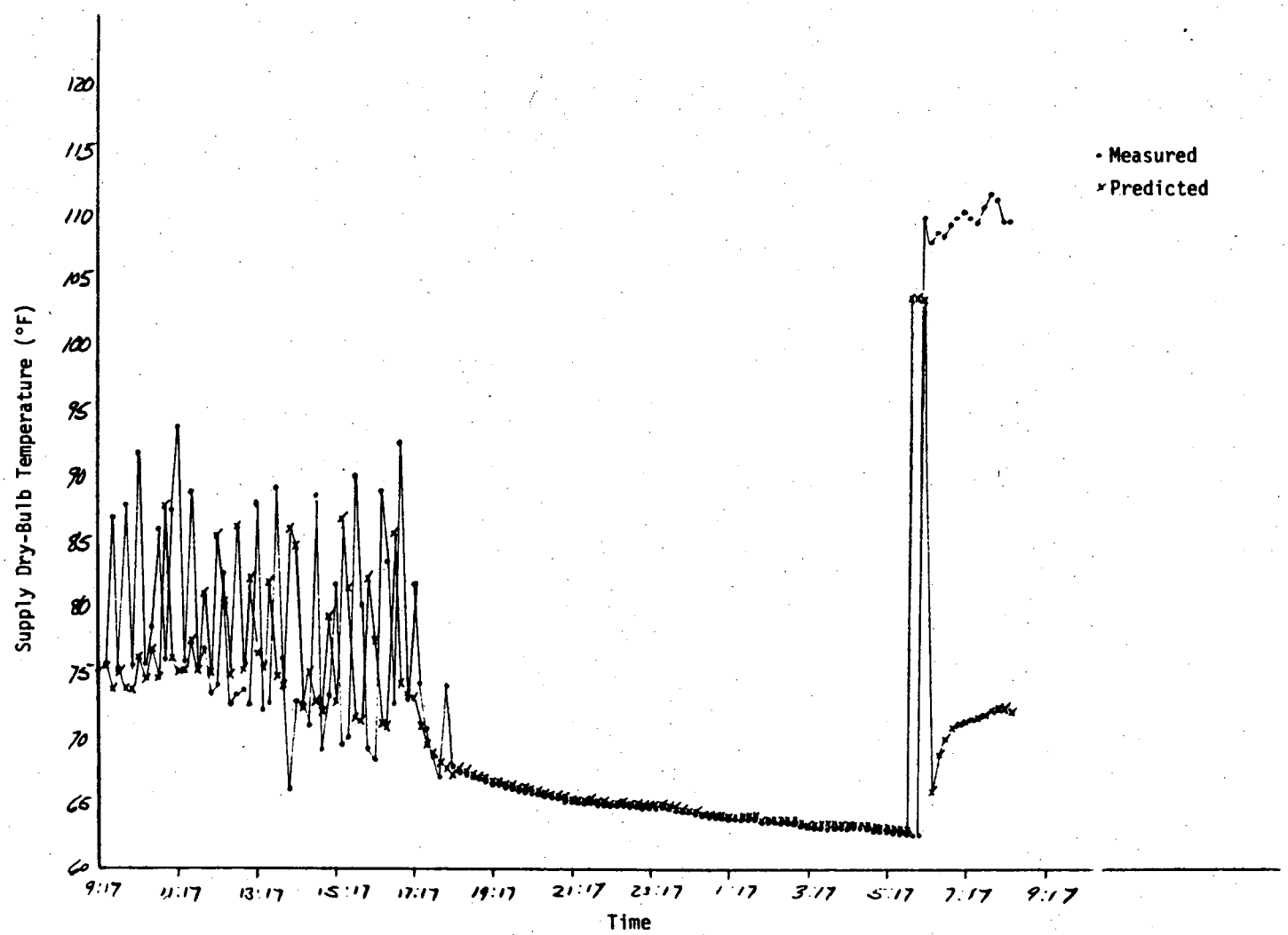


Figure 5-10. Supply Dry-Bulb Temperature for Period 9:17 A.M. (01/29/80) to 9:17 A.M. (01/30/80) (Zone 2)

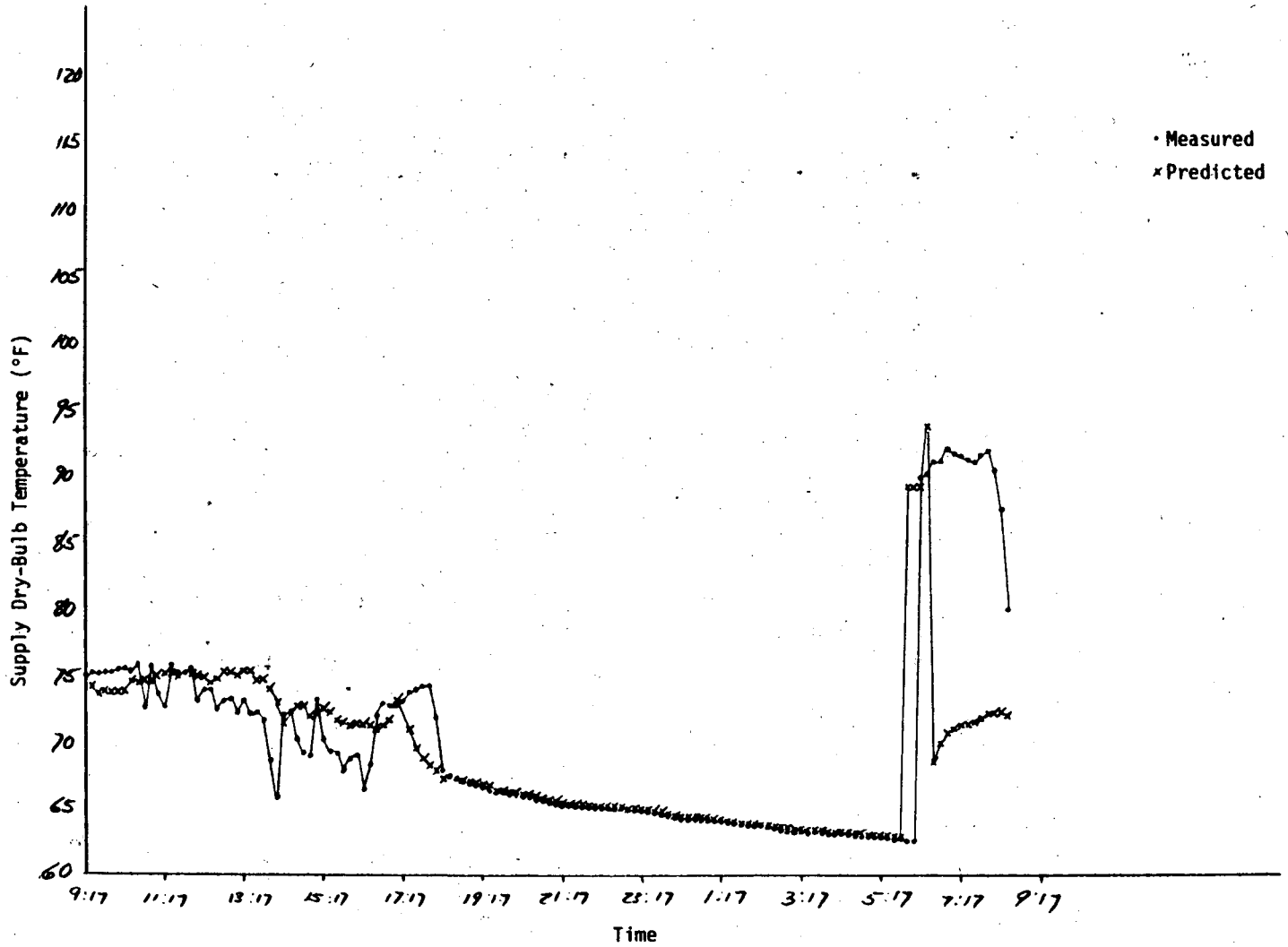


Figure 5-11. Supply Dry-Bulb Temperature for Period 9:17 A.M. (01/29/80) to 9:17 A.M. (01/30/80) (Zone 3)

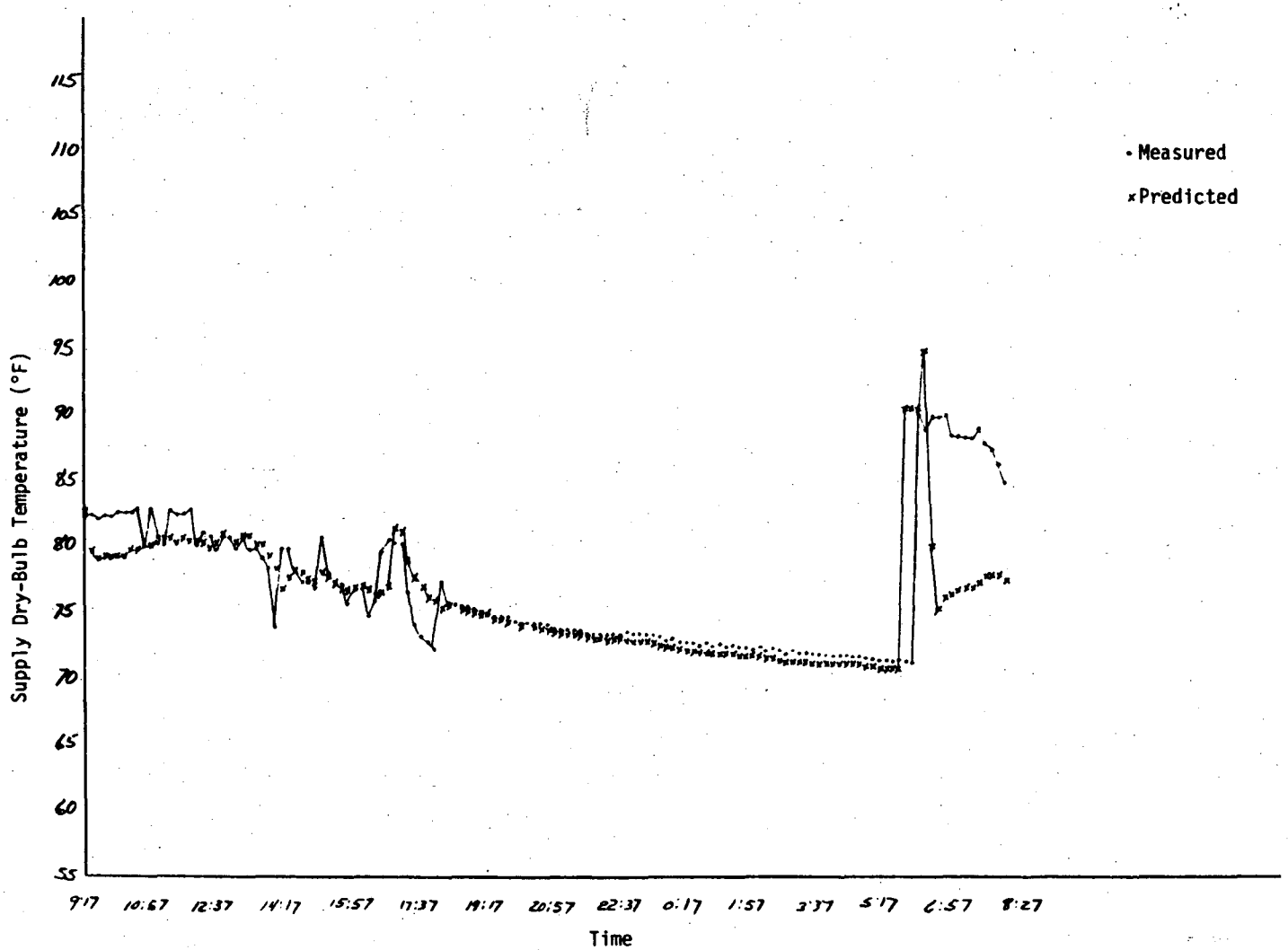


Figure 5-12. Supply Dry-Bulb Temperature for Period 9:17 A.M. (01/29/80) to 9:17 A.M. (01/30/80) (Zone 4)

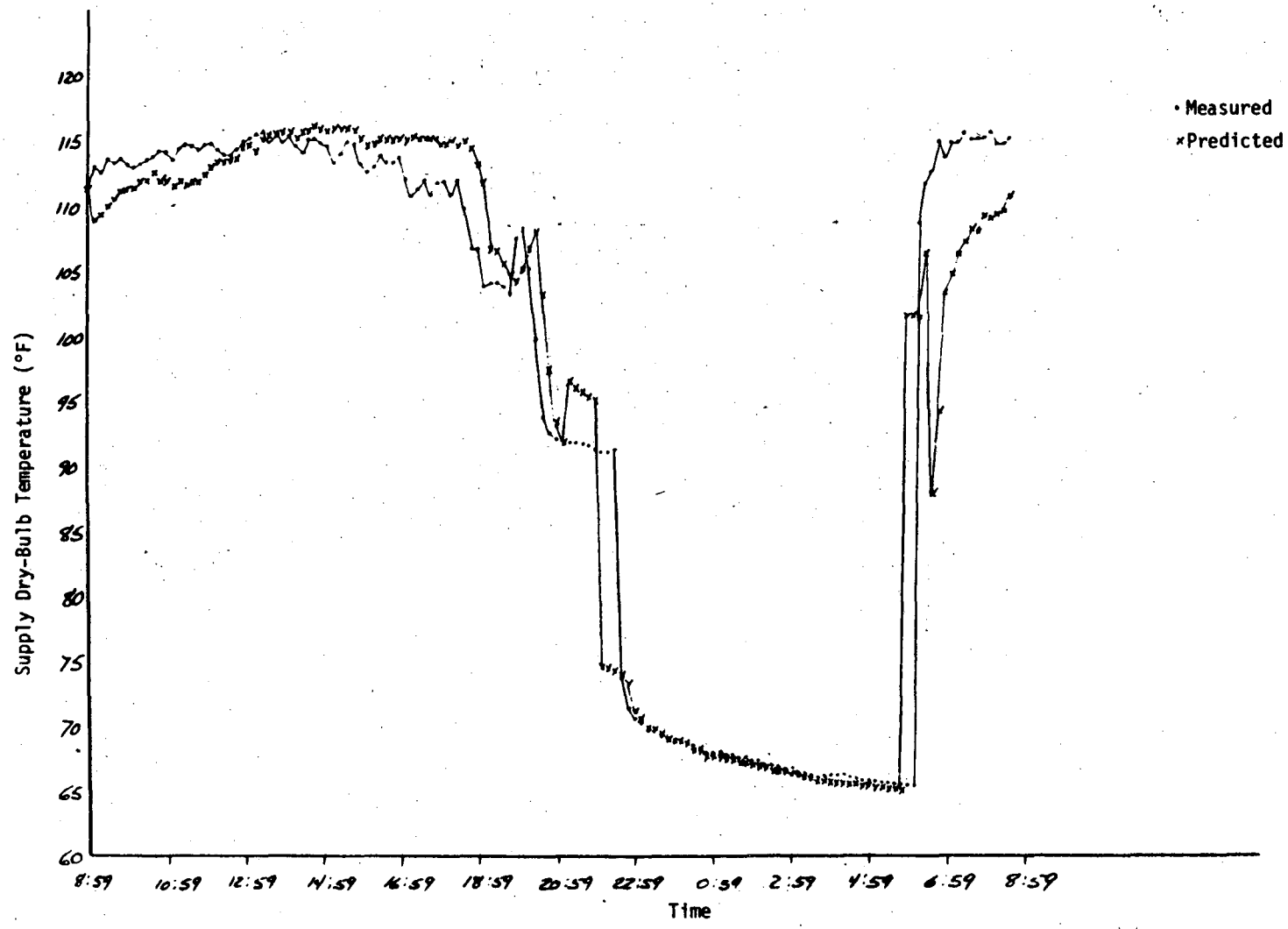


Figure 5-13. Supply Dry-Buld Temperature for Period 8:59 A.M. (01/28/80) to 8:59 A.M. (01/29/80) (Zone 1)

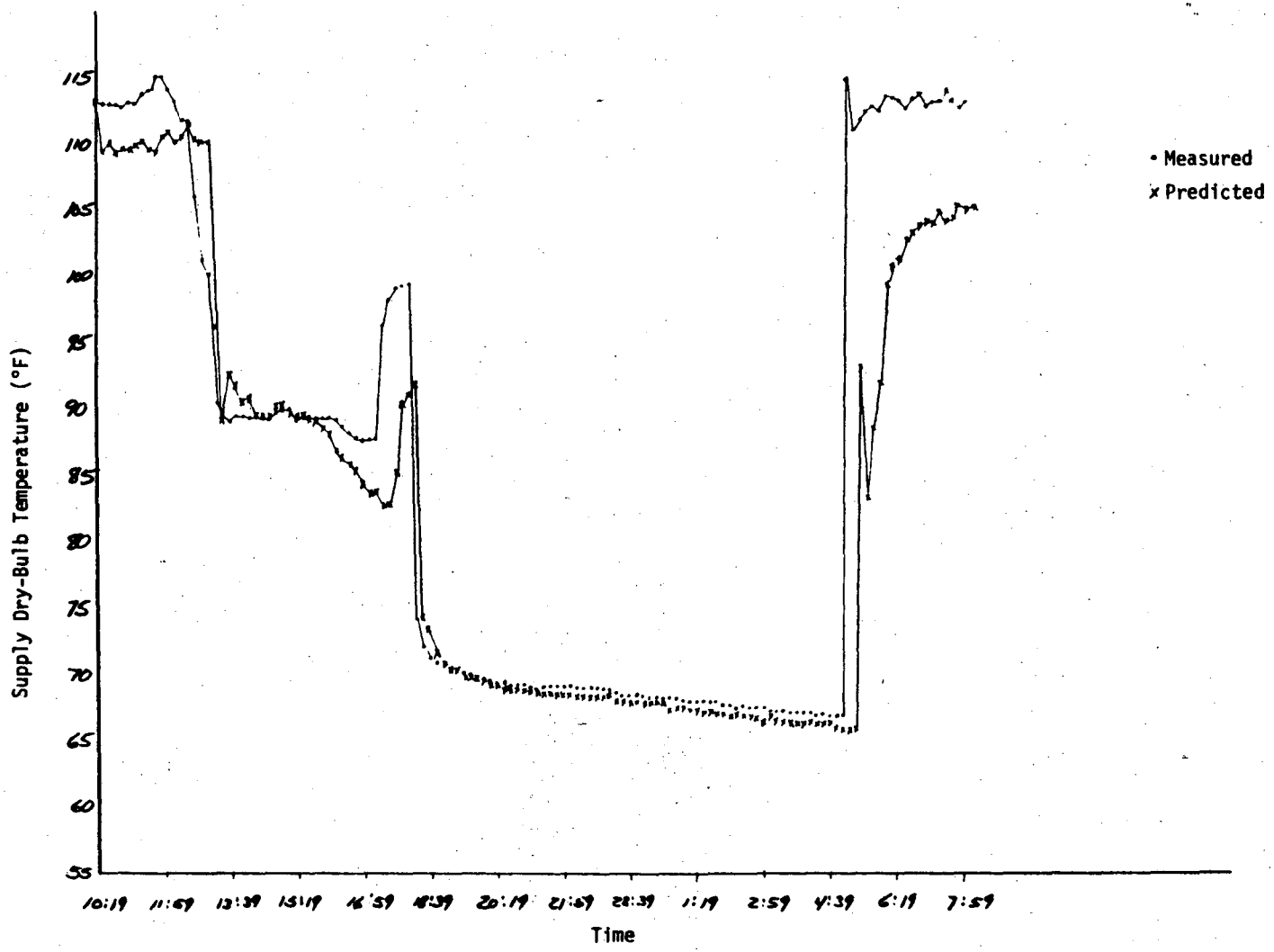


Figure 5-14. Supply Dry-Bulb Temperature for Period 10:19 A.M. (01/31/80) to 8:19 A.M. (02/01/80) (Zone 1)

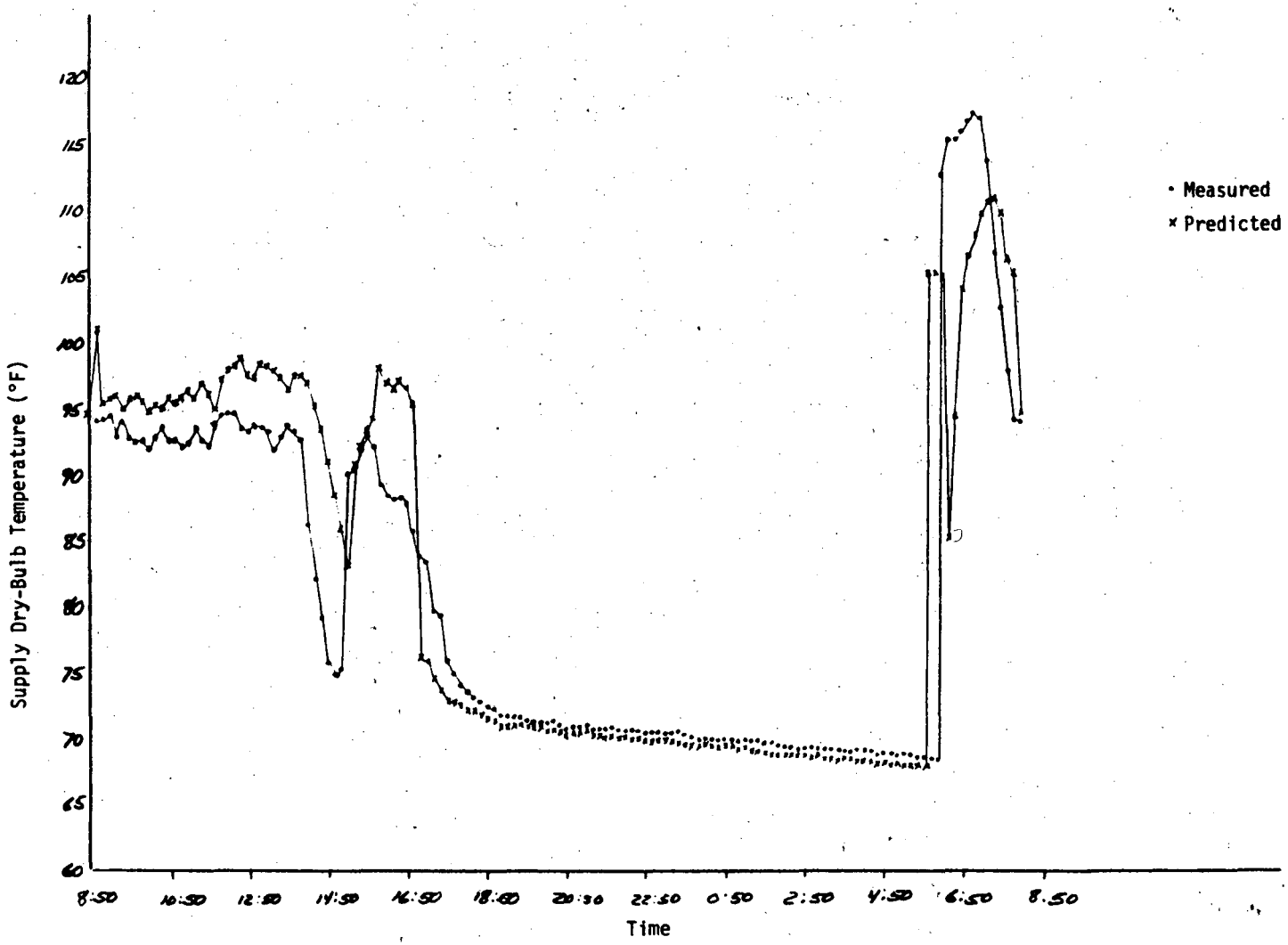


Figure 5-15. Supply Dry-Bulb Temperature for Period 8:50 A.M. (02/05/80) to 8:50 A.M. (02/06/80) (Zone 1)

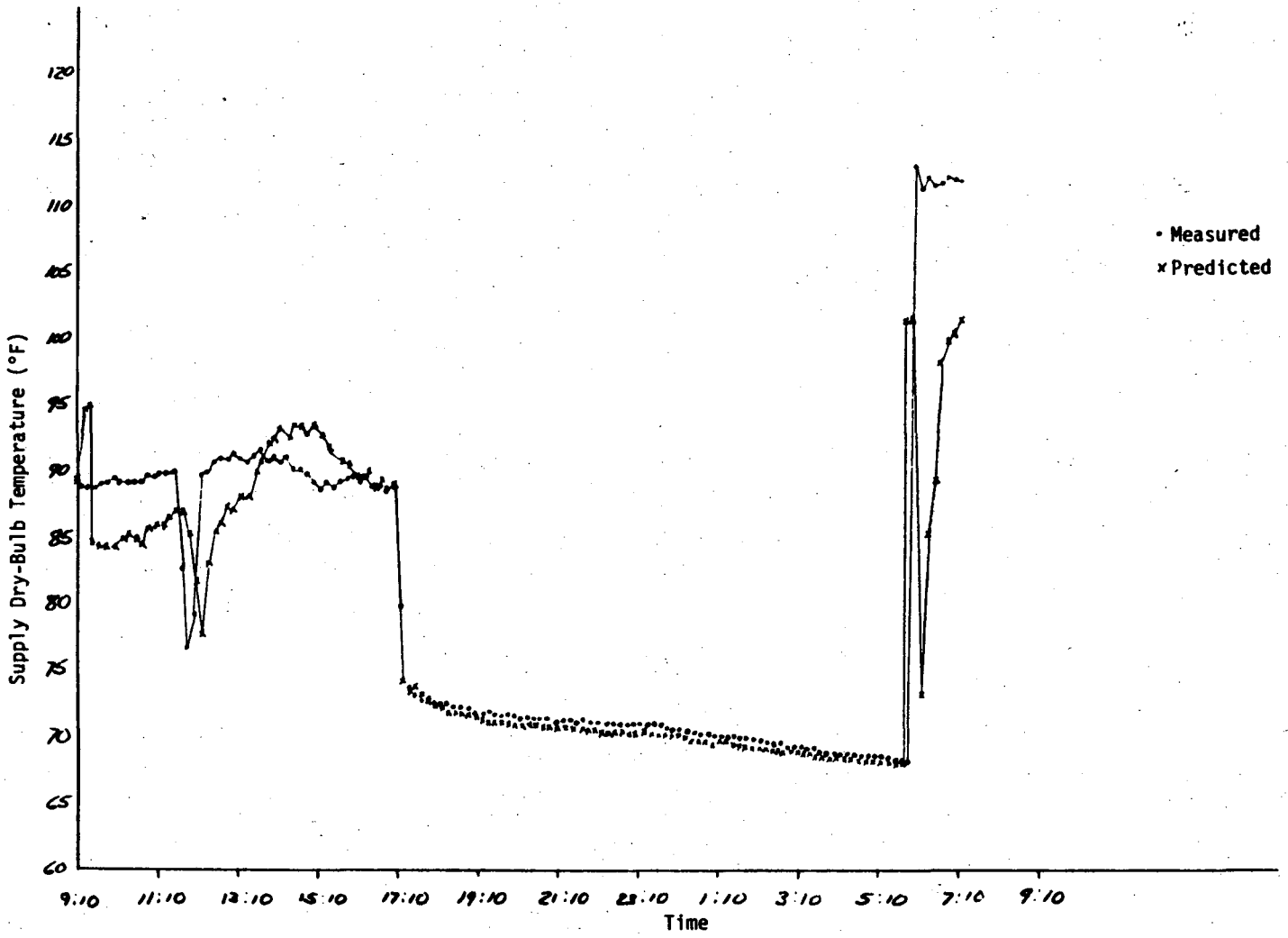


Figure 5-16. Supply Dry-Bulb Temperature for Period 9:10 A.M. (02/06/80) to 9:10 A.M. (02/07/80) (Zone 1)

The anomalies just described introduced so much error into the energy calculations that no significant conclusions could be obtained regarding the potential savings from the CO_2 control system (see Table 5-1).

Thus, to obtain a prediction of the potential energy savings which would result from a CO_2-driven control system, two assumptions had to be made:

- The control system in the music wing was assumed to operate ideally (i.e., no change in set points during the day).

- The air exhausted from the band room was assumed to have the same properties as air in the occupied space (i.e., rather than the mixture that actually occurred).

The model in the previous section (A) was adopted to fit these two assumptions. In addition, the structure of the model was changed:

1) the simulation started, for each day, with the same initial conditions as for the same period with model A;

2) knowing the terms $\dot{Q}_{in}$, $\dot{Q}_{out}$, and $(\dot{Q}_{loss} - \dot{Q}_p)$ for the initial period, ΔQ_s was calculated [see Equation (5-1)]. From ΔQ_s and the initial conditions, the zone dry-bulb temperature at the end of the time-step was calculated.

3) the time-marching procedure progressed to a new time-step, repeating steps 1 and 2 until the end of the simulated period.

This procedure was repeated, for each period, for both control strategies. The Fortran program which represented this model is listed in Appendix B.

NOMENCLATURE

C_{CO_2} -- CO_2 concentration (ppm).

CO_{2p} -- Amount of CO_2 produced within a zone per time step (ppm • ft^3).

Q -- Energy content associated with a mass of air (Btu).

$\dot{Q}$ -- Energy flux associated with a mass flow of air (Btu/hr).

$\dot{Q}_{in}$ -- Energy flux associated with the air supplied to a zone (Btu/hr).

$\dot{Q}_{loss}$ -- Energy loss through the boundary of a zone (Btu/hr).

$\dot{Q}_{out}$ -- Energy flux associated with the air exhausted from a zone (Btu/hr).

$\dot{Q}_p$ -- Energy released per unit time by people, lights and appliances in a zone (Btu/hr).

S -- Stratification efficiency.

V -- Volume (ft^3).

$\dot{V}$ -- Volume flow rate (ft^3/hr).

W -- Humidity ratio (lb of water vapor/lb of dry air).

W_{in} -- Humidity ratio of supply air (lb of water/lb of dry air).

W_{out} -- Humity ratio of exhausted air (lb of water/lb of dry air).

W_p -- Amount of water vapor produced in a zone per time step (ft^3 • lb of water vapor/lb of dry air).

W_{room} -- Humidity ratio in the occupied space of a zone (lb of water vapor/lb of dry air).

ΔC_{CO_2} -- Variation of CO_2 concentration (ppm).

ΔQ_s -- Variation in energy content of the mass of air within a zone (Btu).

ΔW -- Variation in humidity ratio (lb of water vapor/lb of dry air).

Δt -- Time step (hour).

Table 5-1. Sample Energy Consumption in the Music Wing

DATE[a]	CONTROL TYPE	MEAN OUTDOOR TEMPERATURE (°F)	ENERGY CONSUMED (10^6 Btu)[b]
01/28/80	TEMPERATURE (0% OPEN)[c]	0	2.19
01/29/80	CO_2 (0% OPEN)	−3	1.28
01/31/80	TEMPERATURE (16% OPEN)	8	1.14
02/05/80	CO_2 (0% OPEN)	21	1.23
02/06/80	TEMPERATURE (16% OPEN)	23	0.743
02/11/80	CO_2 (0% OPEN)	16	1.32
02/13/80	TEMPERATURE (16% OPEN)	18	0.788
02/14/80	CO_2 (0% OPEN)	13	0.927
02/30/80[d]	CO_2 (0% OPEN)	4	0.947
03/03/80	CO_2 (0% OPEN)	27	1.63
03/04/80	CO_2 (0% OPEN)	7	1.07
03/05/80	CO_2 (0% OPEN)	7	0.939
03/06/80	CO_2 (0% OPEN)	10	1.30

[a] ANALYSES AFTER 02/29/80 WERE MADE FROM DATA WHICH INCLUDED VALUES FROM A DEFECTIVE HUMIDTY SENSOR IN THE BAND ROOM. HOWEVER, IT IS ESTIMATED THAT ITS EFFECT UPON ENERGY CONSUMPTION WAS MINIMAL.

[b] FROM MEASURED QUANTITIES.

[c] MINIMUM SETTING OF OUTDOOR AIR DAMPERS.

[d] A MISWIRED VALVE WAS CORRECTED ON 02/07/80.

5.6 SUBJECTIVE RESPONSE

A question to be answered was, "Can the occupants of a space in which the CO_2 level is controlled detect the difference from an uncontrolled CO_2 level, and if so, what is their reaction?" A test instrument (questionnaire) was developed to answer this question. Statistical methods then were used to analyze the data and make unambiguous comparisons between cause and effect.

5.6.1 Test Instrument Design

The instrument used to gather data from junior high school students (Figures 5-17 through 5-19) in this research was a modified semantic differential questionnaire [19] consisting of 22 polar adjective (or polar phrase) scales plus a few additional items. Subjects responded using an 11-point certainty scale. Responses were transformed to normalized ranks for analysis of data [20]. Wolins (Statistics and Psychology consultant) believed, based on experience with child development research, that subjects of junior high school age could respond successfully to this type of instrument. However, he cautioned that students younger than this probably could not provide meaningful data for this type of research because they would be very active and would not be conscious of subtle environmental differences.

The polar scales covered four different stimuli:

- The subject's perception of room conditions;
- The subject's personal feelings of body temperature, moistness, and other variables that might be related to comfort, as well as feelings of comfort as such;

9-79

Environmental Questionnaire

All of us need to help conserve energy. Your school has been chosen to take part in a study about energy conservation. We want to learn how much heat and air movement are needed to keep rooms comfortable for people at different times of the year, so we can find new ways to save gas, oil, and electricity in schools and other buildings. By filling out this form, you can tell us how you feel about indoor conditions in this room right now. You do not have to answer every item, but it will be a great help if you fill out this form as carefully as you can.

DIRECTIONS

This form gives a pair of words or phrases on each line.

In each pair, circle the word that you think describes what you see or feel.

Then, on the same line, circle a number to show how sure you are that this is the right word. The number you circle should be on the same side as the word.

Here is an example:

		sure				unsure					sure		
This type is:	black	5	4	3	2	1	0	1	2	3	4	5	white.

(This person circled the word black because the type is black and the 5, closest to the word black, because the person is very sure the type is black.)

Another example:

		sure				unsure					sure		
This type is:	large	5	4	3	2	1	0	1	2	3	4	5	small.

(This person circled the word small because he or she thinks the type is small, but also the number 2, on the same side of the middle as small, because he or she isn't very sure that the type is small--small compared to what??)

If you can't decide which word is best or if you feel halfway between the two words, circle BOTH words and the center number (0).

Conditions in this room are:

		sure				unsure					sure		
1.	bright	5	4	3	2	1	0	1	2	3	4	5	dim
2.	stale	5	4	3	2	1	0	1	2	3	4	5	fresh
3.	silent	5	4	3	2	1	0	1	2	3	4	5	noisy
4.	bad-smelling	5	4	3	2	1	0	1	2	3	4	5	good-smelling
5.	dry	5	4	3	2	1	0	1	2	3	4	5	damp
6.	moving air	5	4	3	2	1	0	1	2	3	4	5	still air
7.	clear	5	4	3	2	1	0	1	2	3	4	5	hazy
8.	warm	5	4	3	2	1	0	1	2	3	4	5	cool
9.	pleasant	5	4	3	2	1	0	1	2	3	4	5	unpleasant
10.	dirty air	5	4	3	2	1	0	1	2	3	4	5	clean air

I feel:

11.	comfortable	5	4	3	2	1	0	1	2	3	4	5	uncomfortable
12.	damp	5	4	3	2	1	0	1	2	3	4	5	dry
13.	cool	5	4	3	2	1	0	1	2	3	4	5	warm
14.	free	5	4	3	2	1	0	1	2	3	4	5	crowded
15.	Compared to my body, my hands feel: warmer	5	4	3	2	1	0	1	2	3	4	5	cooler
16.	Compared to my body, my feet feel: warmer	5	4	3	2	1	0	1	2	3	4	5	cooler

Physically at this time I am:

17.	sick	5	4	3	2	1	0	1	2	3	4	5	well

Mentally at this time I am:

18.	jittery	5	4	3	2	1	0	1	2	3	4	5	calm
19.	down	5	4	3	2	1	0	1	2	3	4	5	up
20.	alert	5	4	3	2	1	0	1	2	3	4	5	sluggish

The clothing I am wearing indoors today is:

21. light 5 4 3 2 1 0 1 2 3 4 5 heavy

22. bulky 5 4 3 2 1 0 1 2 3 4 5 not bulky

23. Right now I am wearing a total of (circle one number) layers of clothing over the upper part of my body (chest and back). Count as one layer each undershirt, bra, shirt, blouse, sweater, vest, jacket, parka, coat, etc. Do not count scarves, belts, neckties, etc.

1 2 3 4 5 6 7 or more

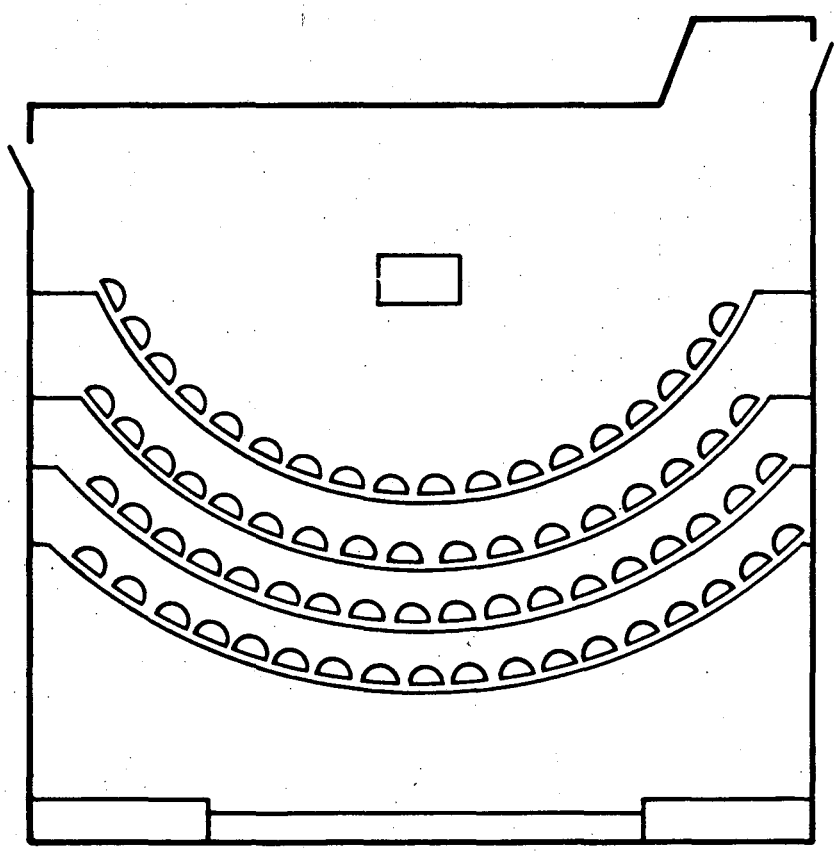
24. My sex is (circle one) M F

25. I was born_____month_____year.

Please write your initials in the space provided_____.
We are asking for your initials only to match up forms that you fill out on different days; your initials will not be used in any other way.

Date_____ Approximate time_____

On the room diagram below, please draw a small circle to show your location in the room as you filled out this questionnaire. Draw a nose on the circle to show the direction you are facing.



CHORUS ROOM 162

Figure 5-17. Chorus Room 162 Questionnaire

9-79

Environmental Questionnaire

All of us need to help conserve energy. Your school has been chosen to take part in a study about energy conservation. We want to learn how much heat and air movement are needed to keep rooms comfortable for people at different times of the year, so we can find new ways to save gas, oil, and electricity in schools and other buildings. By filling out this form, you can tell us how you feel about indoor conditions in this room right now. You do not have to answer every item, but it will be a great help if you fill out this form as carefully as you can.

DIRECTIONS

This form gives a pair of words or phrases on each line.

In each pair, circle the word that you think describes what you see or feel.

Then, on the same line, circle a number to show how sure you are that this is the right word. The number you circle should be on the same side as the word.

Here is an example:

		sure				unsure						sure	
This type is:	black	5	4	3	2	1	0	1	2	3	4	5	white.

(This person circled the word black because the type is black and the 5, closest to the word black, because the person is very sure the type is black.)

Another example:

		sure				unsure						sure	
This type is:	large	5	4	3	2	1	0	1	2	3	4	5	small

(This person circled the word small because he or she thinks the type is small, but also the number 2, on the same side of the middle as small, because he or she isn't very sure that the type is small--small compared to what??)

If you can't decide which word is best or if you feel halfway between the two words, circle BOTH words and the center number (0).

Conditions in this room are:

		sure				unsure						sure	
1.	bright	5	4	3	2	1	0	1	2	3	4	5	dim
2.	stale	5	4	3	2	1	0	1	2	3	4	5	fresh
3.	silent	5	4	3	2	1	0	1	2	3	4	5	noisy
4.	bad-smelling	5	4	3	2	1	0	1	2	3	4	5	good-smelling
5.	dry	5	4	3	2	1	0	1	2	3	4	5	damp
6.	moving air	5	4	3	2	1	0	1	2	3	4	5	still air
7.	clear	5	4	3	2	1	0	1	2	3	4	5	hazy
8.	warm	5	4	3	2	1	0	1	2	3	4	5	cool
9.	pleasant	5	4	3	2	1	0	1	2	3	4	5	unpleasant
10.	dirty air	5	4	3	2	1	0	1	2	3	4	5	clean air

I feel:

11.	comfortable	5	4	3	2	1	0	1	2	3	4	5	uncomfortable
12.	damp	5	4	3	2	1	0	1	2	3	4	5	dry
13.	cool	5	4	3	2	1	0	1	2	3	4	5	warm
14.	free	5	4	3	2	1	0	1	2	3	4	5	crowded
15.	Compared to my body, my hands feel: warmer	5	4	3	2	1	0	1	2	3	4	5	cooler
16.	Compared to my body, my feet feel: warmer	5	4	3	2	1	0	1	2	3	4	5	cooler

Physically at this time I am:

17.	sick	5	4	3	2	1	0	1	2	3	4	5	well

Mentally at this time I am:

18.	jittery	5	4	3	2	1	0	1	2	3	4	5	calm
19.	down	5	4	3	2	1	0	1	2	3	4	5	up
20.	alert	5	4	3	2	1	0	1	2	3	4	5	sluggish

The clothing I am wearing indoors today is:

21. light 5 4 3 2 1 0 1 2 3 4 5 heavy

22. bulky 5 4 3 2 1 0 1 2 3 4 5 not bulky

23. Right now I am wearing a total of (circle one number) layers of clothing over the upper part of my body (chest and back). Count as one layer each undershirt, bra, shirt, blouse, sweater, vest, jacket, parka, coat, etc. Do not count scarves, belts, neckties, etc.

1 2 3 4 5 6 7 or more

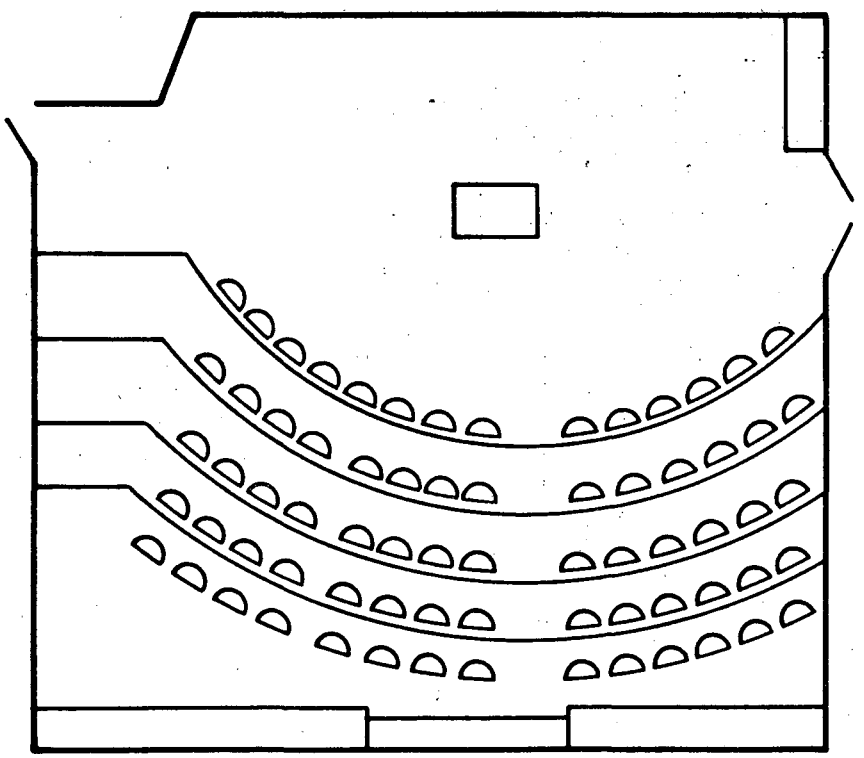
24. My sex is (circle one) M F

25. I was born_____month_____year.

Please write your initials in the space provided_____.
We are asking for your initials only to match up forms that you fill out on different days; your initials will not be used in any other way.

Date_____ Approximate time_____

On the room diagram below, please draw a small circle to show your location in the room as you filled out this questionnaire. Draw a nose on the circle to show the direction you are facing.



CHORUS ROOM 164

Figure 5-18. Chorus Room 164 Questionnaire

9-79

Environmental Questionnaire

All of us need to help conserve energy. Your school has been chosen to take part in a study about energy conservation. We want to learn how much heat and air movement are needed to keep rooms comfortable for people at different times of the year, so we can find new ways to save gas, oil, and electricity in schools and other buildings. By filling out this form, you can tell us how you feel about indoor conditions in this room right now. You do not have to answer every item, but it will be a great help if you fill out this form as carefully as you can.

DIRECTIONS

This form gives a pair of words or phrases on each line.

In each pair, circle the word that you think describes what you see or feel.

Then, on the same line, circle a number to show how sure you are that this is the right word. The number you circle should be on the same side as the word.

Here is an example:

		sure					unsure					sure	
This type is:	black	5	4	3	2	1	0	1	2	3	4	5	white.

(This person circled the word black because the type is black and the 5, closest to the word black, because the person is very sure the type is black.)

Another example:

		sure					unsure					sure	
This type is:	large	5	4	3	2	1	0	1	2	3	4	5	small.

(This person circled the word small because he or she thinks the type is small, but also the number 2, on the same side of the middle as small, because he or she isn't very sure that the type is small--small compared to what??)

If you can't decide which word is best or if you feel halfway between the two words, circle BOTH words and the center number (0).

Conditions in this room are:

		sure					unsure					sure	
1.	bright	5	4	3	2	1	0	1	2	3	4	5	dim
2.	stale	5	4	3	2	1	0	1	2	3	4	5	fresh
3.	silent	5	4	3	2	1	0	1	2	3	4	5	noisy
4.	bad-smelling	5	4	3	2	1	0	1	2	3	4	5	good-smelling
5.	dry	5	4	3	2	1	0	1	2	3	4	5	damp
6.	moving air	5	4	3	2	1	0	1	2	3	4	5	still air
7.	clear	5	4	3	2	1	0	1	2	3	4	5	hazy
8.	warm	5	4	3	2	1	0	1	2	3	4	5	cool
9.	pleasant	5	4	3	2	1	0	1	2	3	4	5	unpleasant
10.	dirty air	5	4	3	2	1	0	1	2	3	4	5	clean air

I feel:

11.	comfortable	5	4	3	2	1	0	1	2	3	4	5	uncomfortable
12.	damp	5	4	3	2	1	0	1	2	3	4	5	dry
13.	cool	5	4	3	2	1	0	1	2	3	4	5	warm
14.	free	5	4	3	2	1	0	1	2	3	4	5	crowded
15.	Compared to my body, my hands feel: warmer	5	4	3	2	1	0	1	2	3	4	5	cooler
16.	Compared to my body, my feet feel: warmer	5	4	3	2	1	0	1	2	3	4	5	cooler

Physically at this time I am:

17.	sick	5	4	3	2	1	0	1	2	3	4	5	well

Mentally at this time I am:

18.	jittery	5	4	3	2	1	0	1	2	3	4	5	calm
19.	down	5	4	3	2	1	0	1	2	3	4	5	up
20.	alert	5	4	3	2	1	0	1	2	3	4	5	sluggish

The clothing I am wearing indoors today is:

21. light 5 4 3 2 1 0 1 2 3 4 5 heavy

22. bulky 5 4 3 2 1 0 1 2 3 4 5 not bulky

23. Right now I am wearing a total of (circle one number) layers of clothing over the upper part of my body (chest and back). Count as one layer each undershirt, bra, shirt, blouse, sweater, vest, jacket, parka, coat, etc. Do not count scarves, belts, neckties, etc.

1 2 3 4 5 6 7 or more

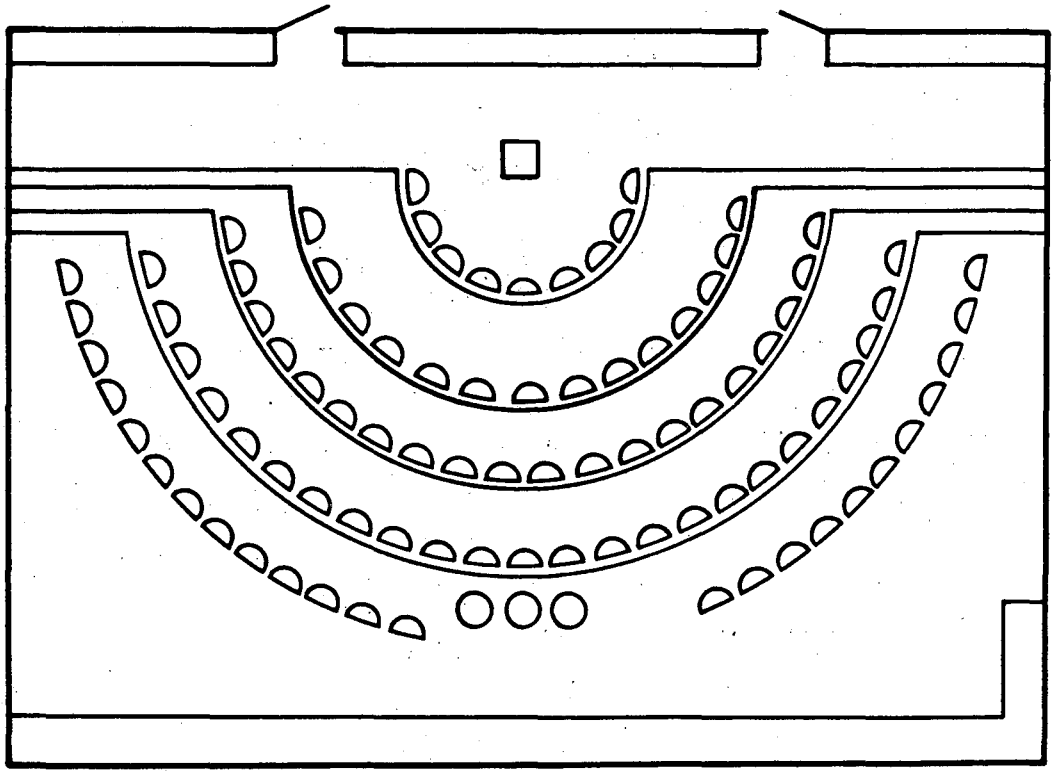
24. My sex is (circle one) M F

25. I was born_____month_____year.

Please write your initials in the space provided_____.
We are asking for your initials only to match up forms that you fill out on different days; your initials will not be used in any other way.

Date_____ Approximate time_____

On the room diagram below, please draw a small circle to show your location in the room as you filled out this questionnaire. Draw a nose on the circle to show the direction you are facing.



BAND ROOM 300

Figure 5-19. Band Room Questionnaire

- The subject's health, physical and mental activity levels;
- The subject's clothing.

The certainty scale requires the subject to make two judgments about the stimuli: first, the subject must decide which of the two words or phrases better describes the situation or condition, and second, the subject must decide how certain he or she is that this word or phrase describes the situation. The scale must consist of an odd number of points so that the middle response is available to describe uncertainty or a situation that is halfway between the two polar adjectives; the midpoint also can be used to indicate that neither adjective applies. The scale must consist of at least nine points to permit transformation to normalized ranks [21], but the more points in the scale, the more information it will provide. In this research, the 11-point scale was selected as a compromise to provide as much information as possible, while remaining understandable to young subjects and minimizing error due to fatigue [20].

The purpose of transforming the responses to normalized ranks is to increase validity and reliability of measurement [22]. Psychological researchers have observed that people respond to numerical scales, not as if the intervals between the numbers were equal, but in terms of the area under the normal curve. Therefore, the differences between a person's responses near the extremes of the numerical scale are greater than the differences between his or her responses near the middle of the scale. The transformation makes the data more nearly linear by pushing together responses near the middle of the scale and spreading out responses near the tails. The transformed data more nearly meet the assumption that data are linear, which is necessary for regression, analysis of variance, and other statistical techniques.

The word pairs, questionnaire format, and instructions for the instrument were adapted directly from the December 1978 version of a longer instrument designed by Winakor in conjunction with Woods. The longer instrument consisted of 40 polar scales and was intended for use with adults. It had been tested in Iowa State University classrooms and revised several times since its original development in February 1978.

It was necessary to modify the adult version of the instrument for use with junior high school students. First, instructions were simplified. Also, polar adjectives had to be simplified and some of the more difficult words changed or eliminated. All nonessential or inapplicable items were removed to shorten the instrument as much as possible and minimize subject fatigue and nonresponses. However, some items that had to be omitted from student questionnaires were included on observation sheets to be filled out by teachers.

The following response format, with instructions to circle the appropriate number, could be keypunched directly from the completed instruments:

1 2 3 4 5 6 7 8 9 10 11

A score of 6 represented uncertainty.

The first version of the junior high school form was tested in the summer of 1979 on about 10 subjects of junior high school age in Ames, Iowa. The same problems occurred consistently with nearly all subjects. The directions were either too long or too complicated; subjects did not read them carefully or did not understand them. They were confused by the 1 to 11 scale and also thought that each pair of adjectives was two separate items. They understood most of the adjectives, but some such as "harsh-subdued", did not function, partly because some subjects did not understand "subdued" and partly because most subjects were more literal-minded toward this item than were university

students; they wanted to know what was supposed to be "harsh" or "subdued." We conferred with Dr. Damaris Pease, Professor in the Department of Child Development at Iowa State University, and she offered several suggestions.

A new introductory paragraph was written to be more conversational and to better catch the attention and interest of this age group. Directions were simplified and modified further, and two examples were included to show the subjects how to use the response format. This revised form was tested on additional subjects in early fall, 1979. The introduction was rewritten again to make it more specific. This was extremely important because, as Dr. Pease, had suggested, junior high school students have to be well-motivated to answer the questionnaire accurately and completely. Sample items in the instructions worked well, except that both circled responses were on the left; consequently one of the examples was reversed in polarity. The two-step directions (circle the word and then circle the number) suggested by [20] eliminated the problem of the subjects' thinking that each pair of adjectives was really two questions. However, they were still confused by the 1 to 11 response scale. Consequently this was changed to:

5 4 3 2 1 $\underline{\bar{0}}$ 1 2 3 4 5

with zero representing uncertainty. Although this response scale would make keypunching slightly more difficult, it was concluded that it was better to use a form that subjects would understand than one more adaptable to direct keypunching.

The word pair "Harsh-subdued" was dropped from the final form because it continued to cause problems. Students asked questions about certain items, but these were not changed because students were responding to them appropriately. The question about number of layers was rewritten to state that it applied to the upper body because at least two subjects thought that they should include pants and other garments worn in the seat area.

To shorten the instructions and to place information where it would be most effective, the statement about anonymity of response was moved to the area where the student's identification number was requested.

Preliminary versions of forms were submitted to the Iowa State University Committee on Use of Human Subjects in Research, along with a draft of a letter to obtain parental permission for children to take part in the research. Child development specialists had provided model letters and suggestions for obtaining parental permission. The Committee approved the research project and requested minor changes in the introductory paragraph of the questionnaire. After these changes were made, letters requesting permission of parents were distributed to all students taking classes in the music wing of the Fridley Junior High School, and preparations were made for testing of the instrument and procedure.

In November 1979, the research team went to Fridley, Minnesota, for intensive trial of both the instrument and procedure. About 26 percent of the parental consent letters that had been distributed were returned, and nearly all of these granted permission for students to take part. However, many students were enrolled in more than one class in the music wing and received duplicate letters. Because no copy of the class rolls was available to the researchers, it was impossible to compute the actual percentage of students whose parents granted permission. In any case, only those students whose parents had signed letters of consent were asked to complete the questionnaire.

As a result of conferences between Iowa State and Honeywell researchers, one question about clothing ("too much - not enough") was deleted from the instrument and the response "0" was omitted from the question on number of layers of clothing. The instructions were changed so that they would apply to different colors of paper because the instrument was printed on different colors for each of the three classrooms. A floor plan of each room was included on the

version to be used in that room so that students could show their location in the room. The instrument was reduced in size and printed on both sides of a single sheet of 8½ x 11-inch paper. Samples of the instrument are shown in Figures 5-17 through 5-19.

The Iowa State researchers observed the physical setup of the music wing and individual classrooms and discussed matters related to administration of the questionnaires with several of the teachers whose classes would be responding to the subjective questionnaire.

The instrument was administered to students in several classes, with the researchers giving a brief introduction. Potential problems in administration during the actual research period were noted and discussed with Honeywell researchers and Fridley Junior High School teachers.

After the trial period, the instruments completed by the students were analyzed. Because the instrument appeared to be functioning satisfactorily, no items were changed. However, the assignment of student identification numbers was judged to be impractical and instead it was decided to request the students' month and year of birth and initials. This information was then used to match up questionnaires filled out by the same students on different days.

Because actual data collection was to take place in the second semester, additional parental consent forms were sent for those students who were not enrolled in classes in the music wing during the first semester. Teachers were provided with a list of students whose parents had returned consent forms so that a second consent form would not be sent to the parents.

Teacher observation sheets and detailed instruction sheets for teachers were prepared for the actual data collection period. Details of preparing and bundling questionnaires before and after administration were determined.

5.6.2 Test Instrument Application

The mechanics of conducting the intensive tests where students were asked to fill out the questionnaires deserve some comment. The respective class teachers administered the test at the end of the class hour, reserving 5 to 10 minutes of time. This represented a significant intrusion on classroom activities. We had excellent cooperation from students, school officials and teachers.

The installation of equipment and the arrival of the LBL trailer focused attention on the project. Teachers were invited by LBL personnel to tour the trailer and were given information on the testing in progress. Honeywell engineers gave presentations to the science class students. Local TV and newspapers featured the project. These events served to maintain interest and motivation for the students and teachers to cooperate fully. However, it was obvious that interest was falling off as the testing continued. The intensive test period was terminated when the number of questionnaires returned satisfied statistical criteria.

The intensive test period also coincided with the only extended cold period of an unusually mild Minneapolis winter. Thus we were able to obtain the data in a temperature regime where savings are maximized.

5.6.3 Analysis of Subjective Data

Completed questionnaires collected during the intensive test period were assembled by class along with the teachers' observation sheet for each class. The questionnaires first were edited for keypunching.

A questionnaire was rejected if:

- The student skipped ten or more items.
- Two or more numbers were circled for each question. (If this happened for only one or two items, the questionnaire was retained and edited.)
- Sex of the respondent was not identified.

Very few questionnaires were rejected for these reasons; out of the 1510 collected, 1504 usable questionnaires were retained after checking.

Retained questionnaires were edited as follows:

- Omitted questions were left blank and treated as missing data in the statistical analysis. Among the questionnaires that were retained, virtually none had more than four missing answers.
- If the student circled a word but no number, the number 5 closest to the circled word was edited in.
- If two numbers were circled, the middle value between them was chosen; if the numbers were adjacent, one was chosen randomly.
- If one word was circled and a number on the opposite side of the scale was also circled, the question was treated as missing.

For this type of analysis, one class had to be dropped from the analysis so that the matrix could be inverted. In this case, Class 9 (1 7th period band class on the Day 2 schedule) was chosen. As a result, the main effects for each class should be interpreted as relative differences in response of that class compared to the response of Class 9.

The analysis of variance was iterated for all 225 students for each of the 23 items. The results showed:

(a) Whether the mean difference between the two systems was statistically significant for each question, aside from individual class effects;

(b) Whether any of the remaining nine classes differed significantly from the reference class, for that question, in terms of difference in response to the two ventilation systems.

If (b) was significant, this meant that there was an interaction involving type of class (including activity level), room, or time of day. These interactions then were examined separately.

If interactions were found, analysis of variance was done for some cases, on the original response data (as transformed) rather than the difference between the systems.

Teacher observation forms were summarized and compared with student responses. Class means and other data were examined individually and plotted against selected physical measurements.

Data for items 1 through 22 were transformed to normalized ranks as follows:

-5 -4 -3 -2 -1 0 +1 +2 +3 +4 +5 (keypunching responses)

-8 -5 -3 -2 -1 0 +1 +2 +3 +5 +8 (transformed responses)

A Fortran program was used to select data for the major analysis of variance to test the hypothesis that the responses of the students did not differ between the two ventilation systems. For items 1 through 23, one item at a time, data were selected ONLY FOR THOSE STUDENTS WHO RESPONDED TO THAT ITEM AT LEAST TWICE UNDER EACH SYSTEM. The mean of the student's response to each

system was computed and the mean for the experimental CO_2-driven control system subtracted from the mean of the conventional temperature-driven control system. The input data into the analysis of variance were thus the individual's difference in responses to the two systems.

The analysis of variance was then computed to assess the student's response difference as a function of which of the ten classes he or she was in when responding. The statistical model was expressed as:

$$\delta = \bar{\delta} + a_0x_0 + a_1x_1 + \cdots a_9x_9 + \varepsilon$$

where

δ = Individual difference in response to the two control systems;

$\bar{\delta}$ = Average difference in response to the two control systems (for all students);

x_n = Category variable for class n (x_n = 1 for class n; x_n = 0 otherwise);

a_n = Coefficient associated with x_n;

ε = Random error.

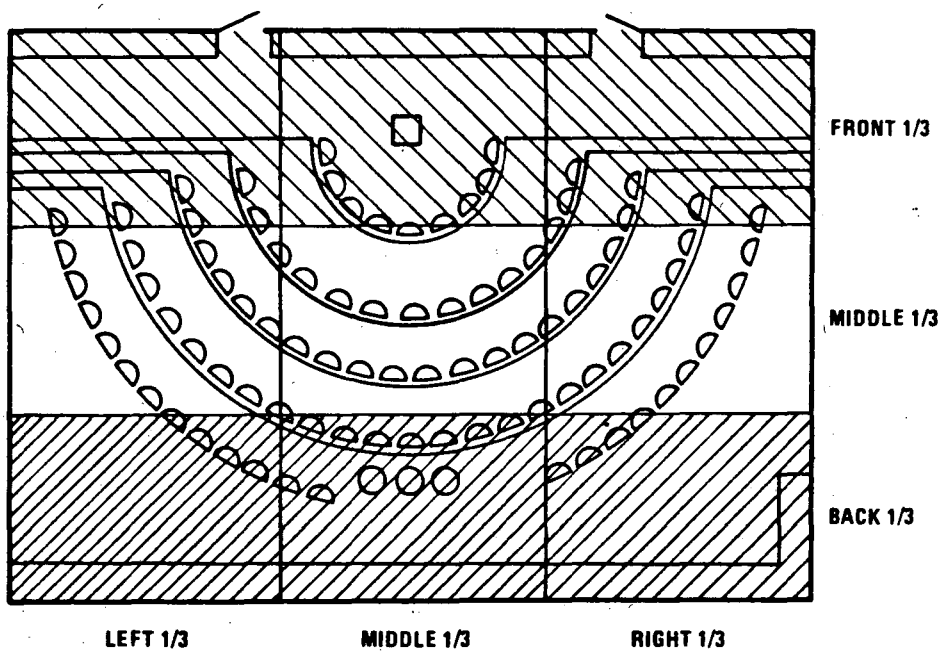
Questionnaires from the same students on different days were matched by using the initials and birth year and month. In the ten classes providing data, each of a total of 225 students provided usable questionnaires at least twice under the temperature-driven control system and at least twice under the experimental CO_2-driven control system. This was considered sufficient for data analysis.

Data were coded for keypunching as follows: Sex was coded -1 for male, +1 for female. Items 1 through 22 were coded by punching numbers on the left as negative and numbers on the right as positive. Item 23 (layers) was coded as the student responded to it. Room number, class, day, period and system were coded as category variables. Location in the room was coded as a category variable according to the student's perspective. Two different location studies were performed:

- First, a grid of nine equal blocks was superimposed over the plan of all three classrooms. The position of each student was identified as right one-third, middle one-third or left one-third, and as front one-third, middle one-third and back one-third of the room.

- Second, a grid, which was used only for the band room, accounted for the floor level of the different rows within the room; the position of each student was identified as right one-third, middle one-third or left one-third, and as front two rows, third row or back two rows.

A diagram of these two grids is shown in Figure 5-20. If the student failed to record his or her location, the student's usual location was found by examining other questionnaires filled out by the same student; if the student did not sit in the same place every day, the location on the missing day was coded 0000 (for the middle section of the room on the first grid and for the middle section of the lower two rows for the second grid, which would have the least impact on the findings.



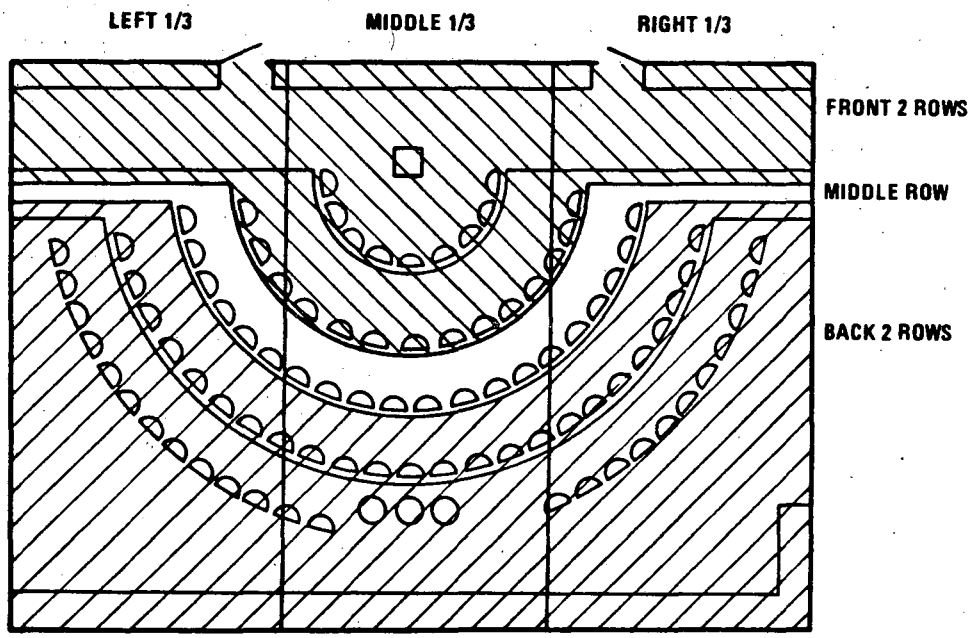


Figure 5-20. Grids Used for Definition of the Location of the Students

5.6.4 Intensive Test Period

Subjective data were collected from January 28, 1980, through February 13, 1980. Because the spaces were to serve as their own controls for statistical analysis of the data, selection of classes for data collection was critical. Classes followed two sequences designated Day 1 and Day 2. Factors considered were time of day, sequence (Day 1, 2), type of activity, room, subject matter and class size and control sequence (see Table 5-2). Because it was expected that levels of carbon dioxide and possibly other contaminants might increase during the school day, classes were chosen primarily from the first two periods of the day (1,2) and from the last two periods (6,7). Classes were selected from band, chorus, general music and health, but not from music lessons because enrollment in these classes was very small. Classes were selected from all three major rooms in the music wing. Insofar as possible, classes were replicated in the two sequences (Days 1, 2) so that if a second period health class was chosen on the Day 1 sequence, there would be a second period health class of about the same size and in the same room on the Day 2 sequence, and so forth. With minor exceptions, this goal was met. Altogether, ten classes were chosen, and the numbers of usable questionnaires collected during the intensive test period are summarized in Table 5-3. It was not possible to estimate response rates precisely because on some days classes were combined or teachers did not report the number of students present; however, from attendance estimated from teachers' counts, it appeared that somewhat more than 61 percent and possibly as many as 65 percent of the students present completed questionnaires. A total of 1,510 completed questionnaires were collected.

Two control modes were exercised--the reference control (revised control) and the experimental control (CO_2-based control). Each control was run for two consecutive 24-hour periods (see Table 5-2) to assure that both types of control were operated during both Day 1 and Day 2 class schedules. The original

control was not operated during the intensive test. The effectiveness of the CO_2 control system should be measured against state-of-the-art optimized reheat control (revised control).

Each day of the test, objective data were recorded on system's status. Each morning the gas analyzer was calibrated and an unrecorded side of a cassette tape was loaded into the TI733 terminal. All 40 channels of data (Subsection 4.3) were recorded at 10-minute scan intervals. On one side of a cassette tape 24 hours of data were recorded. One recorded cassette held 2 days of data. Completely recorded cassettes were brought back to Honeywell TSC offices and loaded into permanent computer files. At the end of the test period, all computer data files were downloaded onto a master magnetic tape. All site weather data were documented and collected daily. All test activities were logged.

Table 5-2. Sequence of Control System Operation

	M	T	W	T	F
WEEK 1	C[a]	E	E	C	C
WEEK 2	E[b]	E	C	C	E
WEEK 3	E	C	C	–	–

[a] C – CONVENTIONAL CONTROL (TEMPERATURE-DRIVEN)

[b] E – EXPERIMENTAL CONTROL (CO_2-DRIVEN)

Table 5-3. Number of Students Responding to the Questionnaire Out of the Total Number Present in Class

ROOM NO.	DAY	PERIOD	CLASS	C1[a]	E1	E1	C1	C2	E2	E2	C2	C3	E3	E3	C3	C4
				JANUARY[b]				FEBRUARY[b]								
				28	29	30	31	1	4	5	6	7	8	11	12	13
162	1	1 H	0[c]	–		14/50[d]		17/27		17/28		14/58[d]		16/22		12/45[d]
162	1	7 CH	1	–		64/65		60/65[e]		48/60		51/65		48/60		52/59
164	1	2 GM	2	06/22		08/21		09/22		08/20		08/20		04/16		08/17
164	1	6 CH	3	23/45		26/49		26/49		17/45		–		15/36		–
300	1	7 BAND	4	51/71		58/75		54/75		56/75		46/75		–		47/70
162	2	2 H	5		23/27		23/25[e]		20/25		18/24		16/23		16/57[d]	
162	2	7 CH	6		28/37		30/40[e]		28/40[e]		31/40		22/40		19/34	
164	2	3 GM	7		12/29		10/22		09/22		10/22		08/23		07/18	
164	2	6 GM	8		15/17[f]		16/18		15/17		15/17		14/16		10/11	
300	2	7 BAND	9		46/57		47/52		–		43/51		35/46		41/50	
TOTAL[f]				80 138	124 166	170 260	126 157	166 238	72 104	146 245	117 154	119 218	95 148	83 134	93 170	119 191

[a] C – REVISED CONTROL (TEMPERATURE DRIVEN); E – CO_2-DRIVEN CONTROL.

[b] DATE.

[c] CLASS NUMBER (CODE).

[d] THESE CLASSES ARE TEAM TAUGHT SOME DAYS AND TWO CLASSES ARE PRESENT.

[e] ESTIMATED ATTENDANCE. TEACHER DID NOT REPORT THE NUMBER OF STUDENTS PRESENT.

[f] FRACTION OF STUDENTS ANSWERING QUESTIONNAIRES WAS 1510/2323 = 0.65.

SECTION 6.0
RESULTS

The results of the experiment fell into four main areas: System performance, energy consumption, subjective response and national implications. The system performance measurements were used to validate the energy consumption model, which was then used to extrapolate the measured results.

6.1 SYSTEM PERFORMANCE

6.1.1 Ventilation System Flow Characteristics

Damper Performance--One of the objectives of this study was to demonstrate a CO_2-controlled ventilation system. The concept seemed quite straightforward--connect a CO_2 sensor to the outside air damper so that it would open only when the CO_2 level in the rooms rose to the control set point. The dampers then would open and hold the CO_2 level within the throttling range of the control. The results, however, have revealed several system complications that confuse such a simple cause-effect relationship.

The student load was found to be quite transient. This was expected, but occupancy during the morning hours was even less than originally expected due to lower enrollment than in the fall of 1979. Only during the last 2 hours of the day was occupancy great enough to raise the CO_2 level to the control range.

The air inlet system was modified to permit separate control of temperature and CO_2 level. This was done by dividing the inlet air duct into two parts. Separate dampers and air-sentinel flowmeters were installed in each part. The

CO_2 control duct and damper had a flow area of 1.5 square feet, and the temperature control system had a flow area of 3.5 square feet. The sum (5 square feet) was about half of the original outdoor air damper area. It was expected that the smaller control dampers and flowmeters would increase sensitivity in the measurements.

The inlet/exhaust system was typical of the system in many buildings and is shown in Figure 6-1.

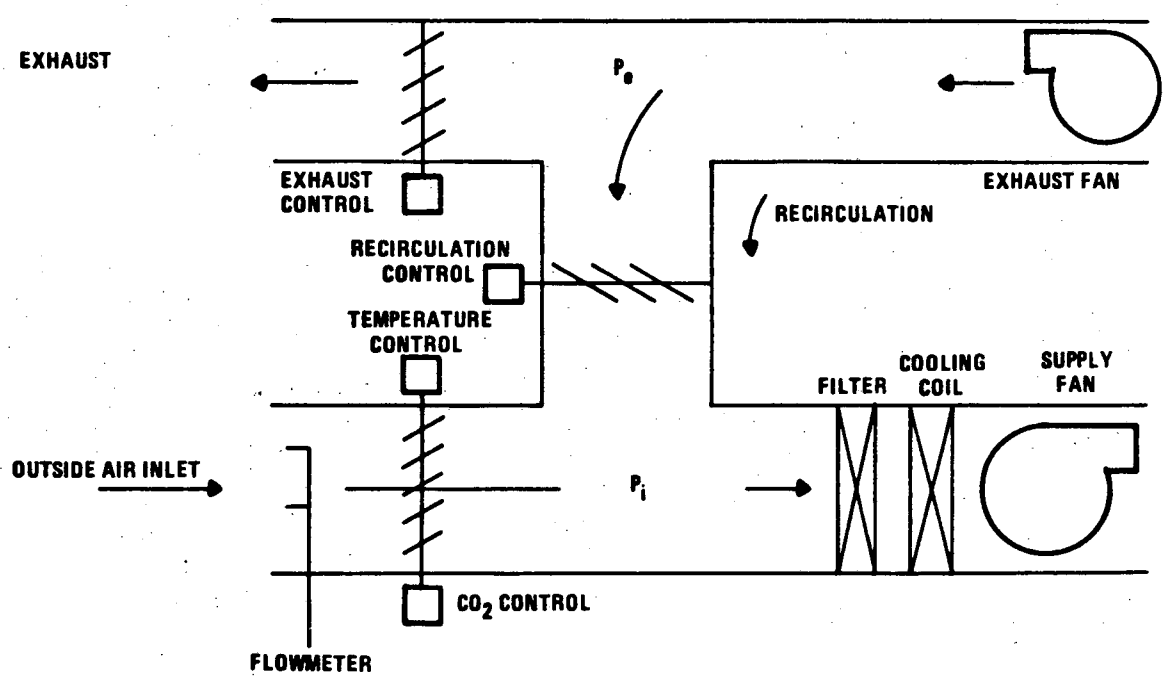
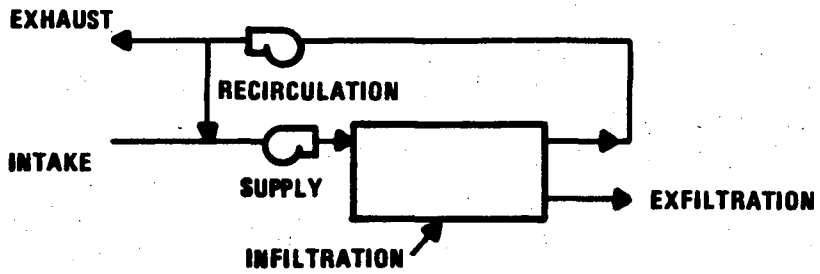


Figure 6-1. Air Inlet/Exhaust System

The supply fan was slightly larger than the exhaust fan. Two additional small exhaust fans, for the band and chorus rooms, made up the difference. For this test these two fans were disabled because of their complicating effect on room air distribution.

It was first assumed that the imbalance between the supply and exhaust fans might permit enough outdoor air to be drawn in merely by opening only the OA damper.

It was clear, however, that the volume of outdoor air inducted in this way would be limited by the exfiltration rate of the building. This is illustrated in the simplified drawing below.



If the exhaust and inlet dampers are closed and the recirculation damper is open, there will be a certain circulation rate. There also will be an infiltration rate equal to the exfiltration rate. If only the inlet damper is opened, the inlet flow can replace the infiltration flow; exfiltration must increase to increase the inlet flow. The fans would have to increase the pressure in the building to increase tne exfiltration rate.

The measured airflow under CO_2 control damper action only was about 500 CFM. The infiltration rate was measured to be about 0.3 air change per hour, which is:

$$0.3 \text{ ach} \times \frac{1 \text{ hr.}}{60 \text{ min.}} \times 90{,}000 \text{ ft}^3 \text{ building space} = 450 \text{ CFM}$$

Thus the flow induced by opening only the CO_2 intake damper was limited by the space infiltration rate. The only effective way to increase the inlet flow was to open the exhaust damper and throttle the recirculation flow.

The controls for the inlet damper, recirculation damper and exhaust damper were thus synchronized so that when the CO_2 sensor began to call for outdoor air, the CO_2 control damper and exhaust damper opened while the recirculation damper closed. The same action occurred when a zone thermostat reached its high limit and called for cooling, except that the temperature control damper opened. Synchronization of all three dampers (intake, recirculation and exhaust) in this manner is the most commonly used damper system and is consistent with standard practice as specified for outdoor air damper control in the Automatic Control section (Chapter 34) of the 1976 ASHRAE Systems Handbook, Systems Volume.

This damper system assured a supply of outdoor air whenever the CO_2 control system or temperature control system called for outdoor air when in the CO_2 control mode.

The system as originally designed had a constant volume of supply air. As the exhaust and outdoor air dampers opened, the recirculation damper closed to maintain a constant supply-air volume. The smaller inlet duct area of the modified system created a restriction at the inlet. When the outdoor air dampers were closed, flow volume through the recirculation duct was at a maximum. However, when the outdoor air dampers were open and the recirculation damper was closed, the restricted inlet reduced the system flow rate about 15 percent.

Figure 6-2 shows the flow versus damper control system pressure for the temperature control damper. This damper motor, the exhaust damper motor and the recirculation damper motor operate over a range of 3 to 13 psi. Damper rotation is approximately linear with control line pressure. The smaller inlet duct area, however, restricted the flow so that it did not begin to increase until

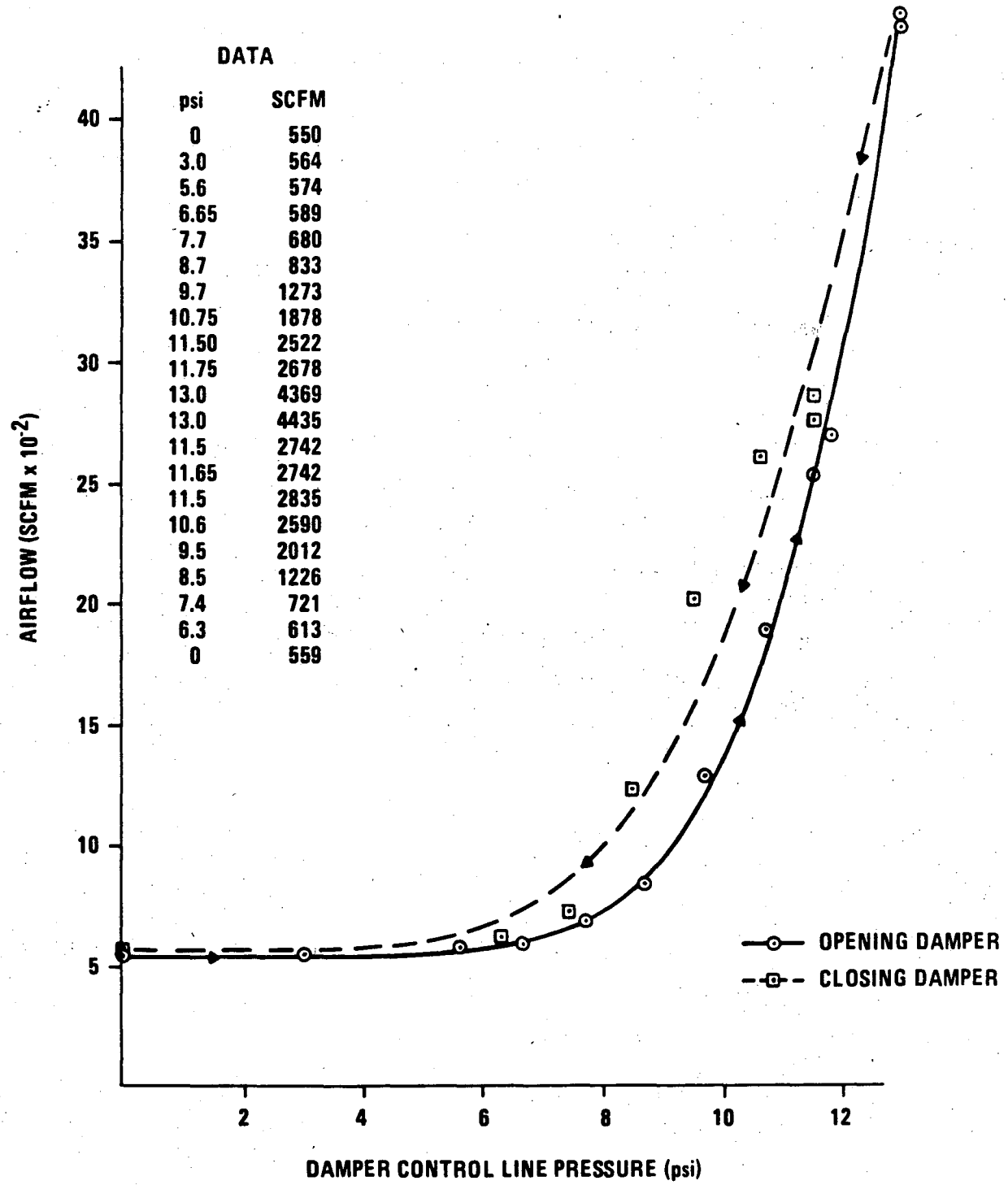


Figure 6-2. Airflow versus Control Line Pressure for Temperature-Controlled Damper

the control line pressure got to about 6 psi. The nonlinear character of the damper restriction added to the flow nonlinearity. This can be explained from the damper geometry.

The location of the dampers was shown in Figure 6-1. Figure 6-3 shows schematically how they operate. They are connected together so that the angle θ is the same for each of the dampers.

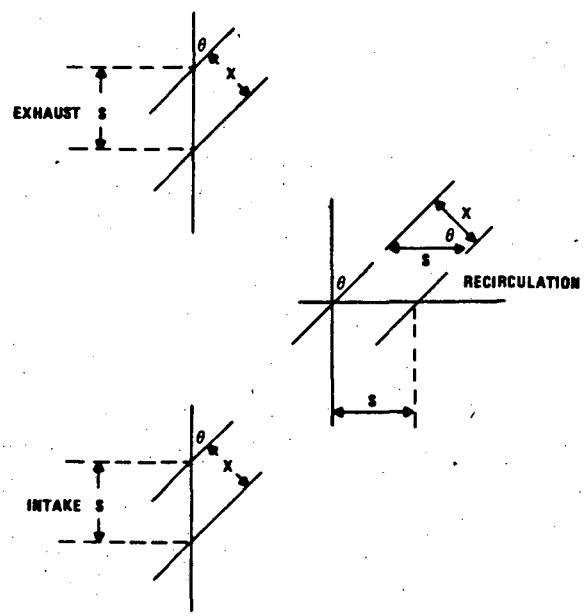


Figure 6-3. Damper Geometry

The open area of the dampers is proportional to the dimension χ and the duct area is proportional to the blade spacing S. The flow area then is given by:

- Exhaust and Intake $\chi_{i,e} = S \sin \theta$ (6-1)
- Recirculation $\chi_r = S \cos \theta$ (6-2)

The flow through the dampers, assuming constant pressures, is proportional to the open area of the dampers, as shown in Figure 6-4.

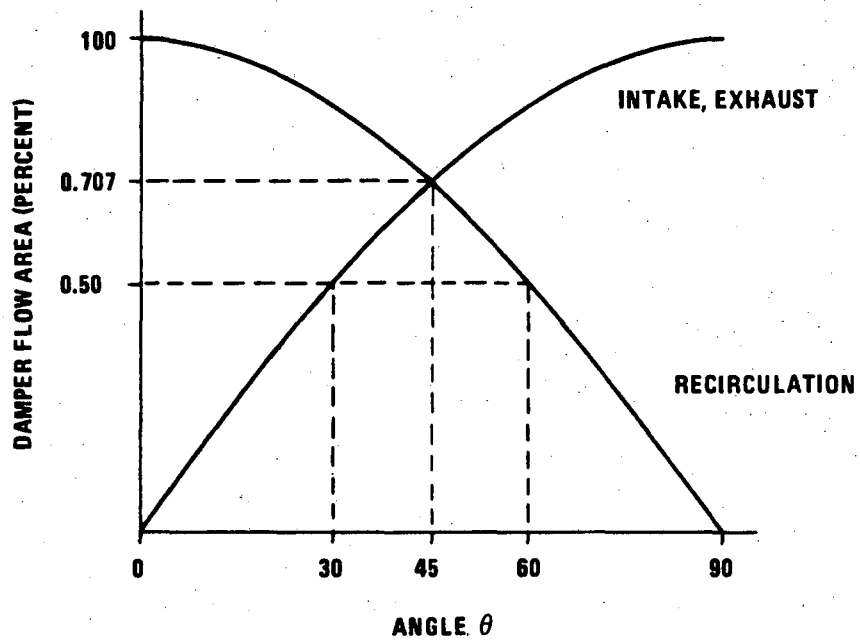


Figure 6-4. Damper Flow Characteristics

When the intake and exhaust dampers are closed, the recirculation damper is fully open and essentially there is no pressure loss through this damper, i.e., $P_e = P_i$. Although the exhaust fan is slightly smaller than the supply fan, the flow and pressures adjust so that each fan produces the same flow. Since the supply fan is somewhat larger, it produces a greater pressure for a given flow than the exhaust fan. Some of this pressure is dissipated in the filter and coils in the supply duct.

The recirculation damper closes as the exhaust and intake dampers open. Figure 6-4 shows that the flow area (exhaust plus recirculation) on the discharge of the exhaust fan increases as the exhaust damper opens. The recirculation damper area decreases more slowly than the exhaust damper area increases. Thus the increased flow from the exhaust fan due to the larger flow area (and lower associated pressure loss) tends to go through the recirculation damper.

An increasing flow area through the inlet damper and recirculation damper is also associated with the supply fan. Restriction of the reduced inlet duct area tends to reduce the inlet pressure, P_i. This also tends to increase recirculation flow. The result is that the first 50 percent of the control system pressure change produces almost no change in outdoor airflow. The nonlinear flow through the dampers during the last 50 percent of the control system differential makes the system operation approach a two-position characteristic rather than a proportional flow characteristic.

An effort was made to overcome this problem with the CO_2 control damper. A damper motor with an adjustable throttling range was used. The range was set for 6 to 11 psi. Thus the damper begins to open at 6 psi and is fully open at 11 psi. Initially the CO_2 signal transducer was set to give a 6 psi control line pressure at 3000 ppm CO_2, and 11 psi at 5000 ppm. This range was reduced to 825 to 1375 ppm when it became obvious that the occupancy load was too low to activate the control damper at the higher level. The flow of outdoor air versus control signal for this control mode is shown in Figure 6-5.

The much smaller duct area for the CO_2 control system as compared to the original air inlet system (1.5 square feet versus 10 square feet) changed the constant-volume system to a modified variable-volume system. The total supply air flow rate was determined by measuring the flow to each reheat coil with the pilot tubes installed and calibrated earlier. The flow to each main branch and the total supply flow as a function of return air CO_2 concentration is shown in Figure 6-6. The difference between the total supply flow in Figure 6-6 and the total CO_2 intake flow in Figure 6-5 for any CO_2 concentration is the amount of air passing through the recirculation damper. It can be seen that the restriction created by the small CO_2 damper inlet area increased the pressure drop across the recirculation damper to the extent that approximately 6000 CFM was passed, even when the recirculation damper control pressure was 13 psi and the damper should have been fully closed.

mV	SCFM	AVERAGE SCFM (PLOTTED)
4.2	0	0
5.0	0	0
6.0	0	0
7.0	186 TO 493	340
7.5	559 TO 776	668
8.0	813 TO 1010	912
8.5	1129 TO 1227	1178
9.0	1428 TO 1578	1503
9.5	1833 TO 1956	1894
10.0	2383 TO 2525	2454
9.0	2193 TO 2309	2251
8.0	1129 TO 1227	1178
7.0	457 TO 549	503
6.0	0	0
5.0	0	0
4.2	0	0

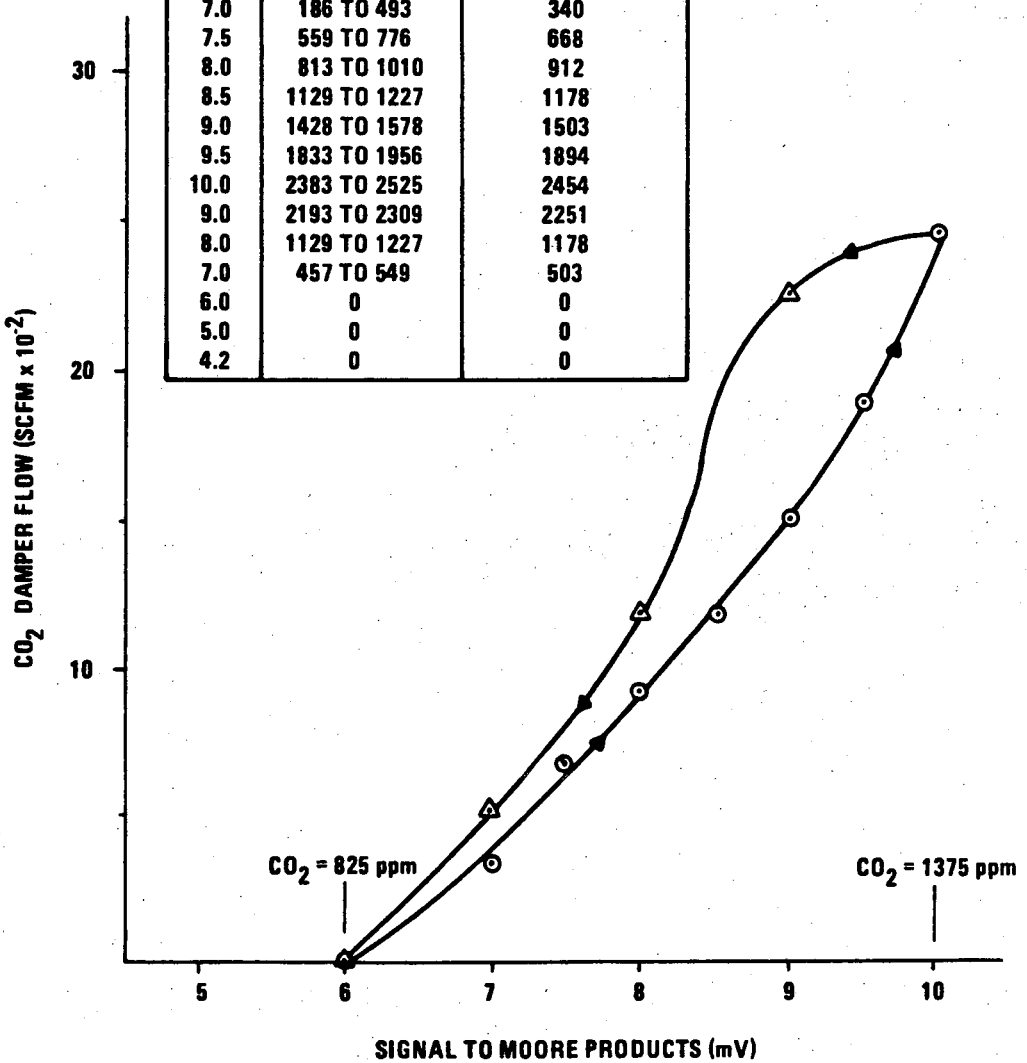


Figure 6-5. Airflow Through CO_2 Damper as a Function of Input Signal

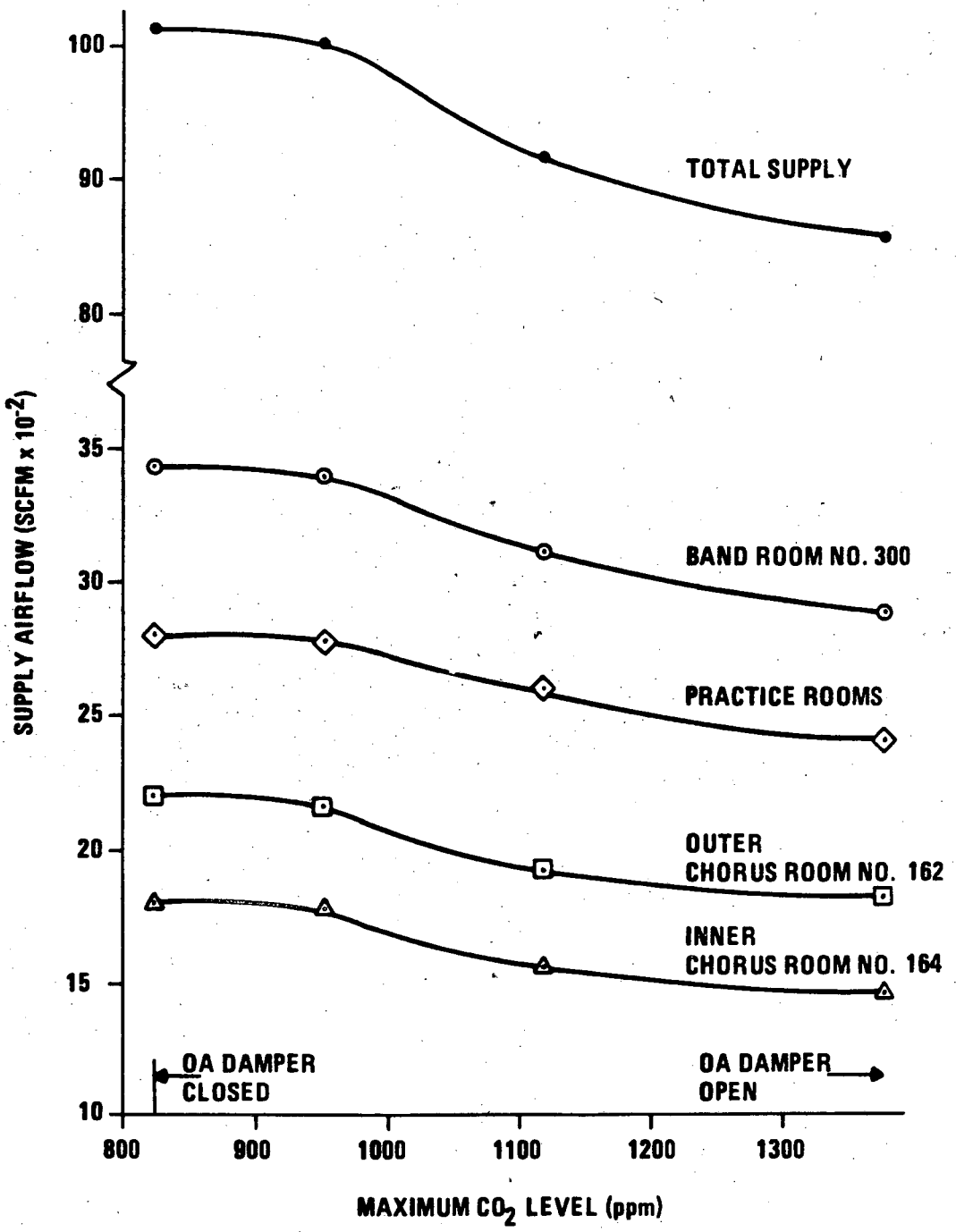


Figure 6-6. Supply Airflow Under CO_2 Control
(Temperature Control Damper Closed)

6.1.2 Infiltration

Methane tracer infiltration measurements were made under three different conditions--winter heating, no load and cooling. Tracer decay curves under winter heating conditions with both CO_2 and temperature control dampers closed are shown in Figures 6-7 to 6-10. The initial high infiltration rate was due to the mixing delay in the rooms. This is discussed further in Section 6.1.3, Ventilation Efficiency.

Additional infiltration measurements were made under no-load and cooling conditions. These methane tracer measurements all were made by introducing the tracer gas into the supply duct and observing the room concentrations at the grill to the return duct. The multiplexer for CO_2 control was used to observe all rooms simultaneously.

A summary of the steady-state infiltration rates is given in Table 6-1. There appears to be some correlation with wind and temperature. Higher outdoor temperatures and lower wind velocities led to lower infiltration, as would be expected. Wind appeared to have a greater effect than indoor-outdoor temperature differences.

The infiltration rate also was measured with CO_2 introduced directly into the rooms. In this case the rates were about the same as the rates measured in March under heating conditions.

The infiltration measurements provided data for calculating the stratification or mixing in the rooms. Ceiling level supply diffusers were used in each room. The return grills were at high sidewall or ceiling level also. Thus there was a strong tendency, especially under heating conditions, for a substantial part of the supply air to cross the room above the occupied level without completely mixing with room air.

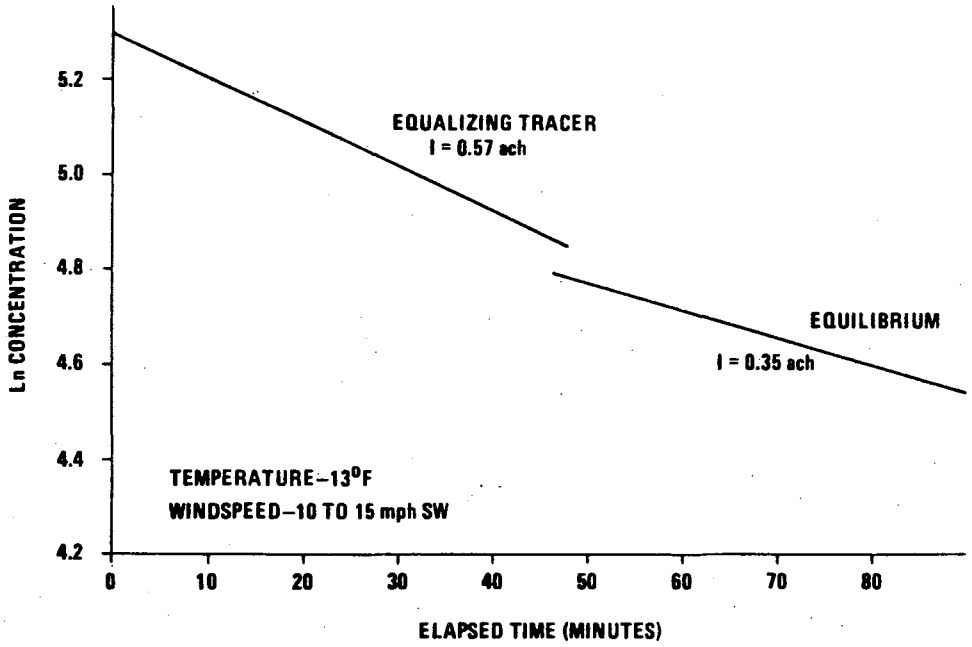


Figure 6-7. Infiltration Measured in Main Return (3-5-80)

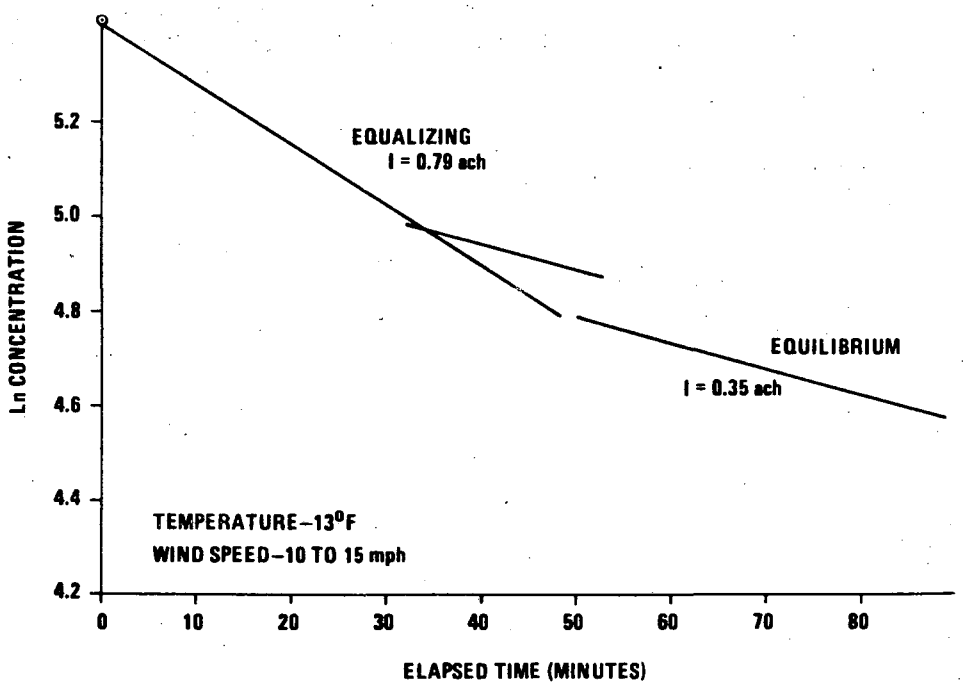


Figure 6-8. Infiltration Measured in Band Room, No. 300 (3-5-80)

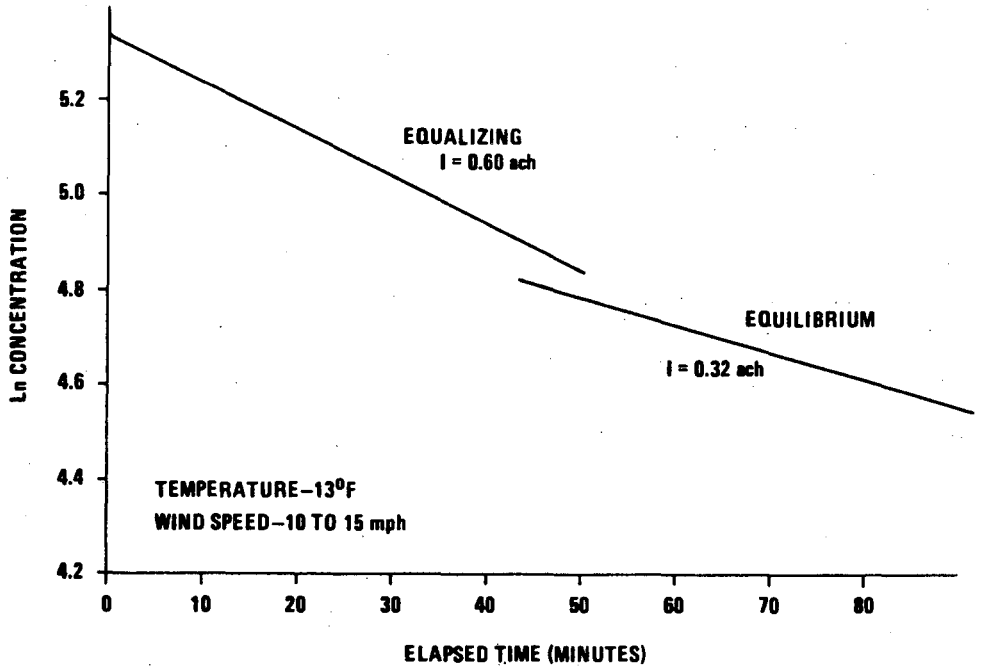


Figure 6-9. Infiltration Measured in Exterior Chorus Room, No. 162

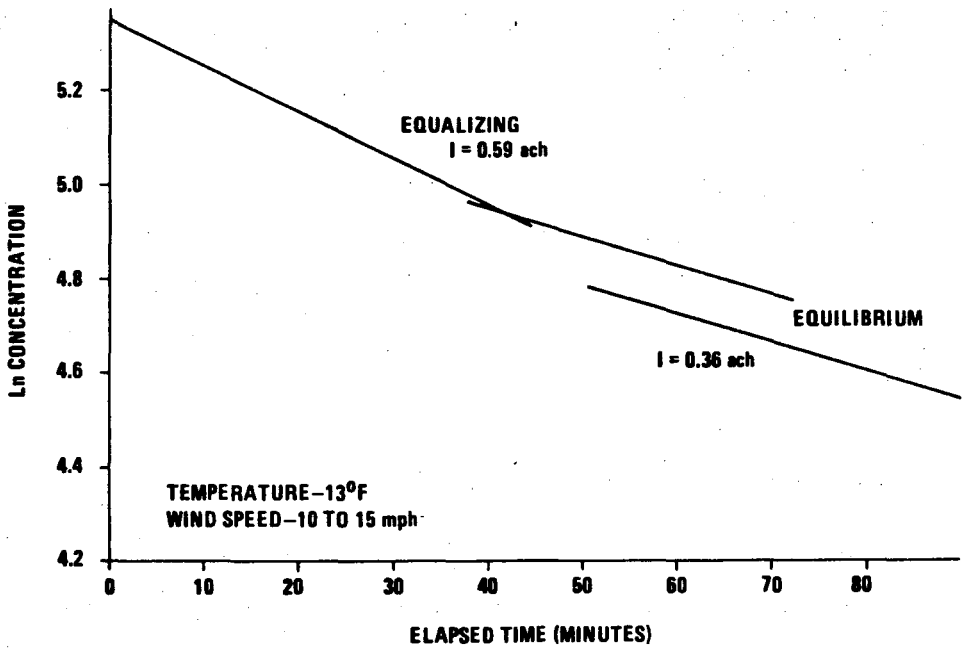


Figure 6-10. Infiltration Measured in Interior Chorus Room, No. 164

Table 6-1. Measured Infiltration (ach)

DATE	LOAD	OUTDOOR TEMPERATURE (°F)	WIND		LOCATION			
			VELOCITY (mph)	DIRECTION	MAIN RETURN	BANDROOM NO. 300	EXTERIOR CHORUS ROOM NO. 162	INTERIOR CHORUS ROOM NO. 164
3-05-80	HEATING	13	10 TO 15	SW	0.35	0.35	0.32	0.36
7-22-80	NO LOAD	76	3 TO 5	S–SW	0.31	0.32	0.24	0.25
7-29-80	COOLING	88	STILL		0.24	0.24	0.24	0.25
7-30-80	CO_2	81	8 TO 10	N	0.34	0.38	0.32	0.31

The effect of this was observed in the infiltration measurements. Figures 6-7 through 6-10 all show an initial high infiltration rate that has been labeled "equalizing." It was clear that after tracer gas had been added in the supply duct it took 40 to 50 minutes for the return duct and room concentration to reach equilibrium. The difference in the initial apparent infiltration rate and the final infiltration rate was interpreted as a lack of mixing. A derivation of this stratification factor was presented in Section 5.3.

It was expected that stratification would disappear under no-load or cooling conditions, but this did not happen. Thus the effect was not due entirely to thermal stratification but was a channeling effect caused by a single return grill that caused a part of the supply air to flow directly to the return without mixing with room air. The results of these mixing measurements and their effect on ventilation efficiency are discussed in Section 6.1.3.

6.1.3 Ventilation Efficiency

Equations for computing the ventilation efficiency were derived in Section 5.3. This efficiency is defined as the fraction of outdoor air brought in that effectively is used to dilute room contaminants. The channeling or stratification factor was obtained from the infiltration measurements.

Table 6-2 shows the channeling factors measured for heating, no-load and cooling conditions. The channeling or stratification factor for the band room decreased as the supply air temperature decreased; this is the expected effect. The band room had a 17-foot ceiling with a return grill in one corner about 8 feet above the floor, as shown in Figure 6-11.

Table 6-2. Channeling Factor

LOAD	BAND ROOM 300	CHORUS ROOM 162	CHORUS ROOM 164	MAIN RETURN
HEATING	0.57	0.47	0.39	0.38
NO LOAD	0.43	0.58	0.56	0.44
COOLING	0.37	0.33	0.46	0.38

High supply air temperatures under heating conditions produced substantial stratification and a high channeling factor. A supply air temperature lower than room temperature under cooling conditions caused the supply air to drop lower into the space and mix better.

The higher channeling factor under no-load conditions in the two chorus rooms is unexplainable at this time. The flow in Chorus Room 117 was from a series of supply registers along one wall at ceiling level, across the ceiling to a

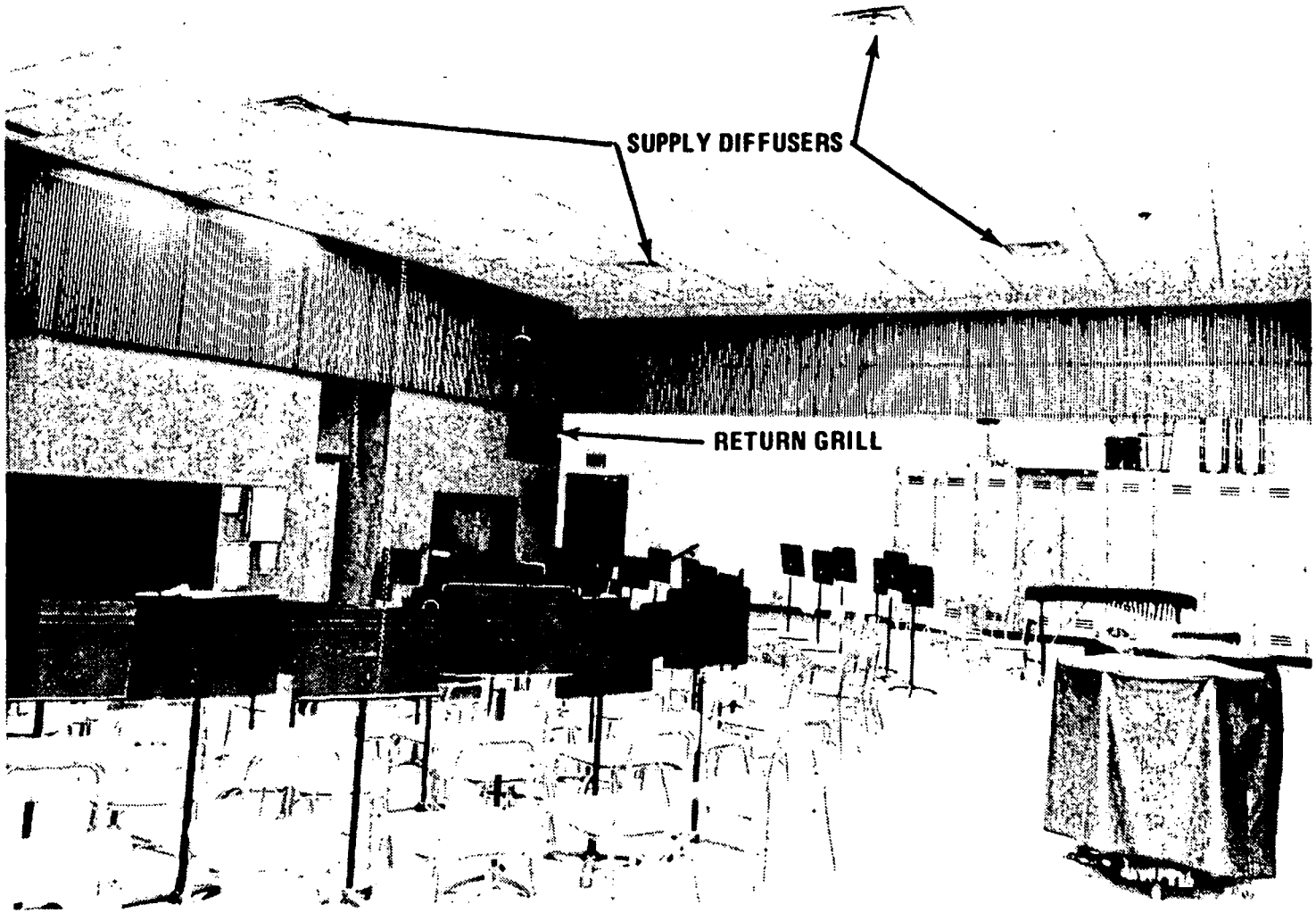


Figure 6-11. Band Room

single return grill at ceiling level in a corner on the wall opposite the supply outlets (Figures 6-12 and 6-13). Under cooling conditions the air did appear to drop down and mix better.

Chorus Room 164 had a flow pattern that was difficult to analyze. The supply registers were along one wall at ceiling level, as in Room 162. The return grill in Room 164, however, was on the same wall as the supply registers and in one corner. Supply and return locations are shown in Figure 6-14. Thus, the flow pattern was out along the ceiling, down into the room and then back to the return. The side of the room opposite the supply registers obviously received a poor distribution of supply air.

The main return integrates the effect of these flow anomalies, reflecting the high channeling factor in the two chorus rooms. The channeling factor for the main return is the one that should be used to calculate the system ventilation efficiency. This channeling factor is relatively constant at about 0.40 and was used to compute the ventilation efficiency, as shown in Figure 6-15.

The maximum flow through the CO_2 control damper was 2400 CFM. The CO_2 control damper, the exhaust damper and the recirculation damper all were interconnected in the normal manner. The exhaust damper opened and the recirculation damper closed when the CO_2 damper opened. The area of the inlet and exhaust dampers in a normal HVAC system would be about the same so that the supply would be 100 percent outdoor air with no recirculation when the outdoor air and exhaust dampers are open. The greatly reduced area of the CO_2 control damper (1.5 square feet versus 10 square feet for the exhaust damper) restricted the outdoor airflow through the CO_2 control damper to 2400 CFM. This increased the pressure drop across the recirculation damper and produced a recirculation flow of 6200 CFM, giving a supply airflow of 8600 CFM (Figure 6-6). The occupancy in the four zones was not uniform. The practice rooms and offices had a low occupant density and acted as a reservoir of uncontaminated air for dilution of the CO_2 in the band and chorus rooms. Determination of the ventilation

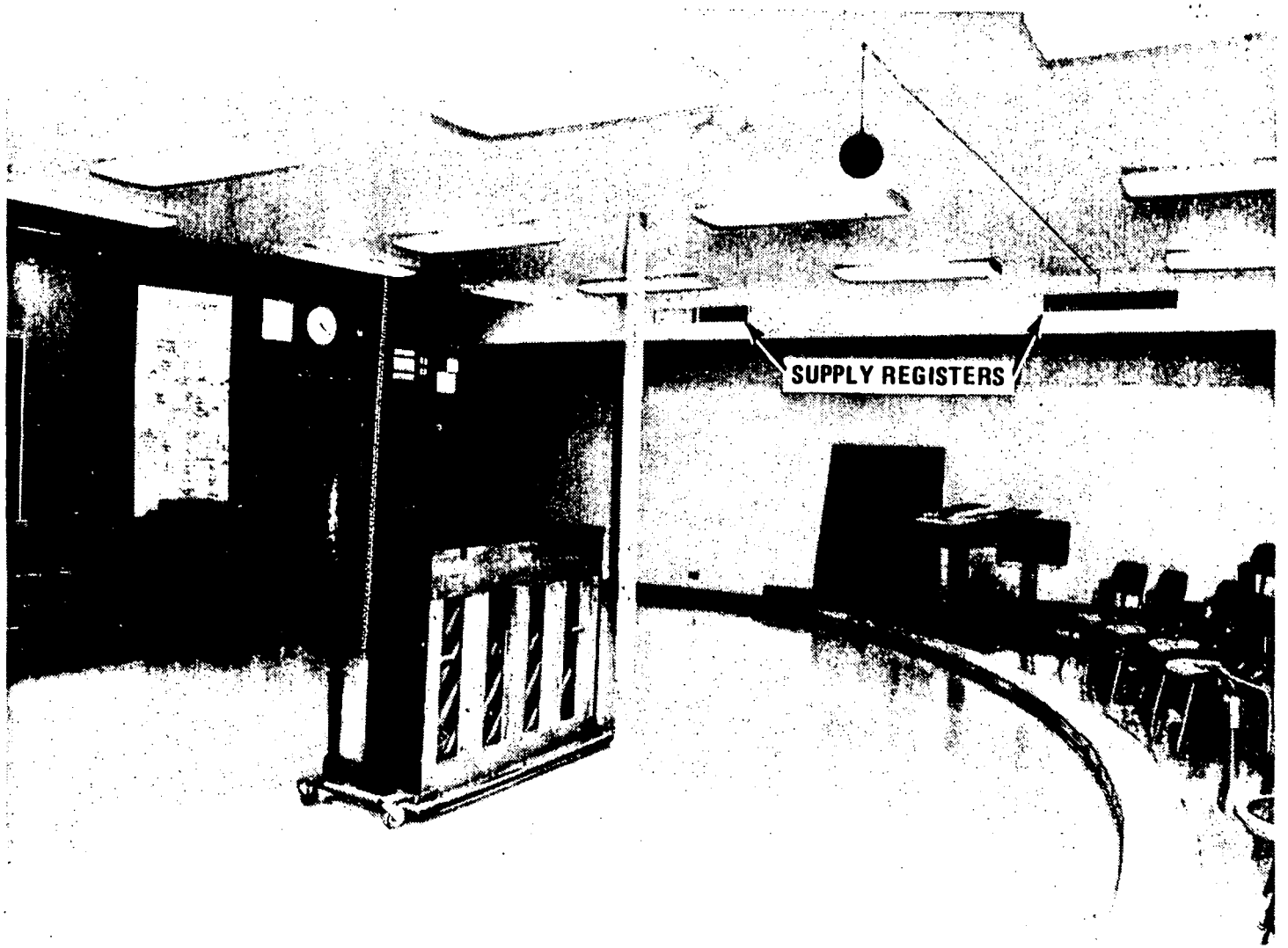


Figure 6-12. Chorus Room 162 Supply Registers

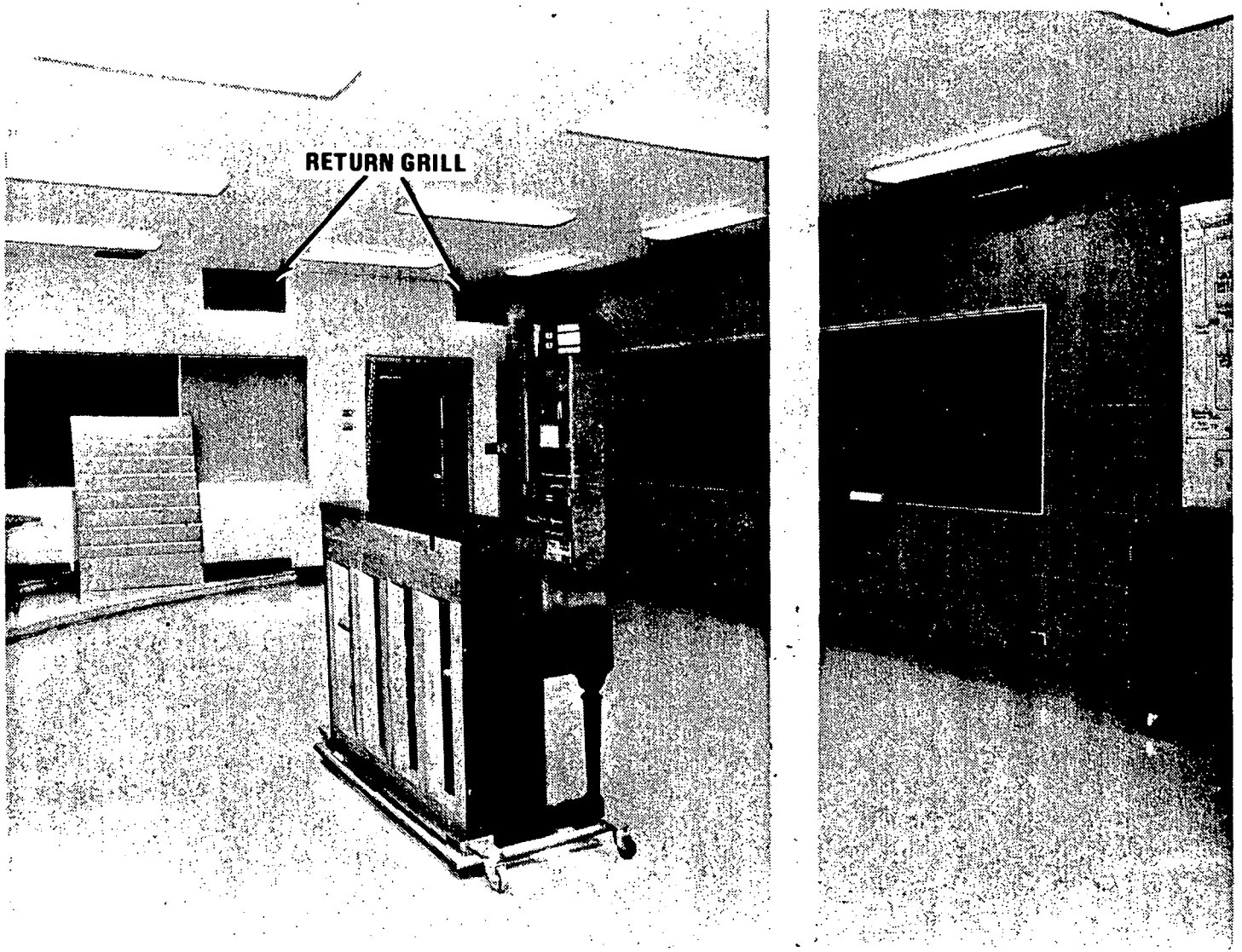


Figure 6-13. Chorus Room 162 Return Grill

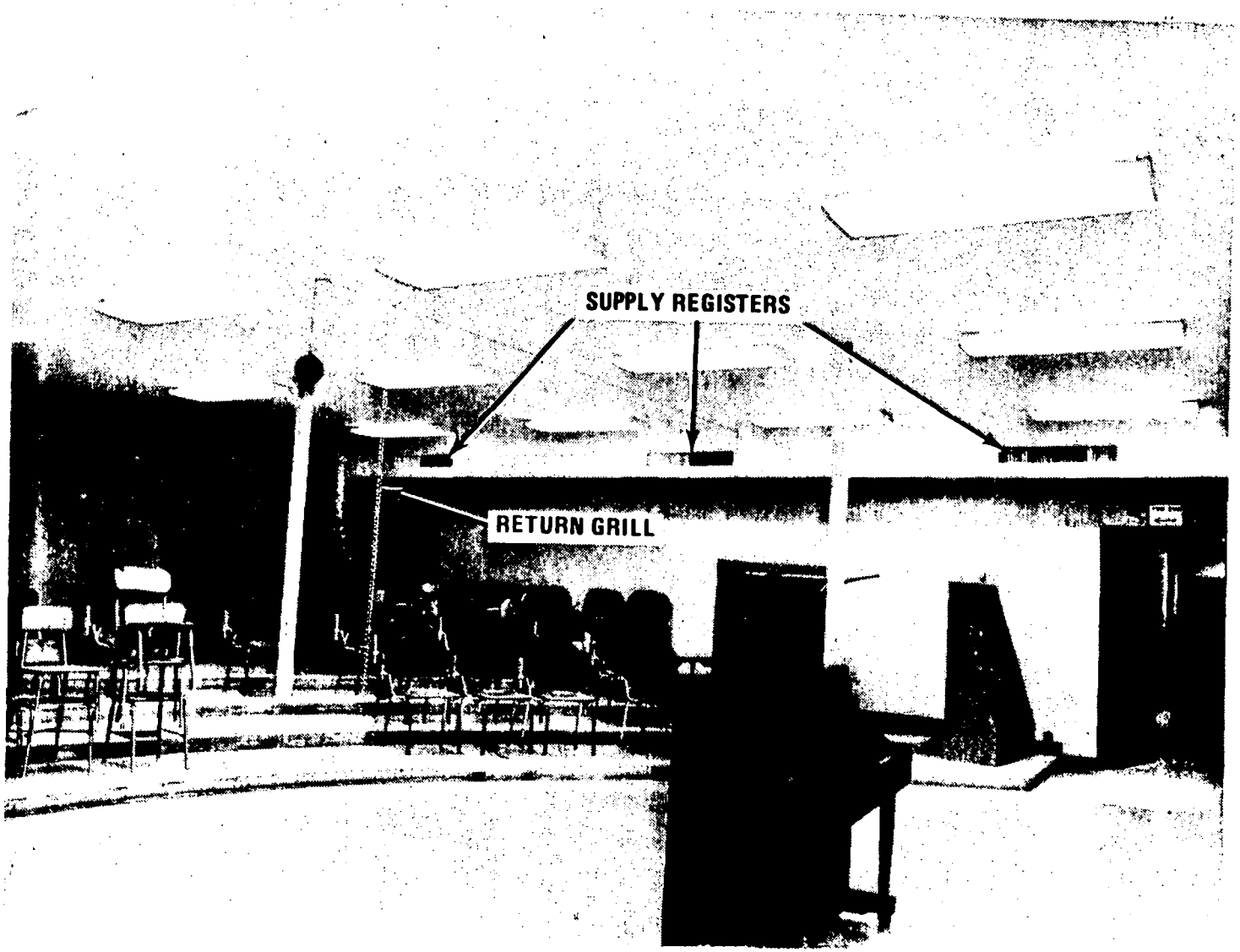


Figure 6-14. Chorus Room 164

efficiency was boxed, therefore, on the channeling factor measured in the return air. This averaged about 0.4, as shown in Table 6-2. Using this average value for channeling and the flow rates shown in Figure 6-6, equation (5-18) was used to calculate the ventilation efficiency, as shown in Figure 6-15. The effect of this efficiency reduction lowered the capacity of the CO_2 control flow from 2400 CFM to (0.79) (2400) = 1900 CFM. This did not jeopardize the safety of the environment for the number of students present.

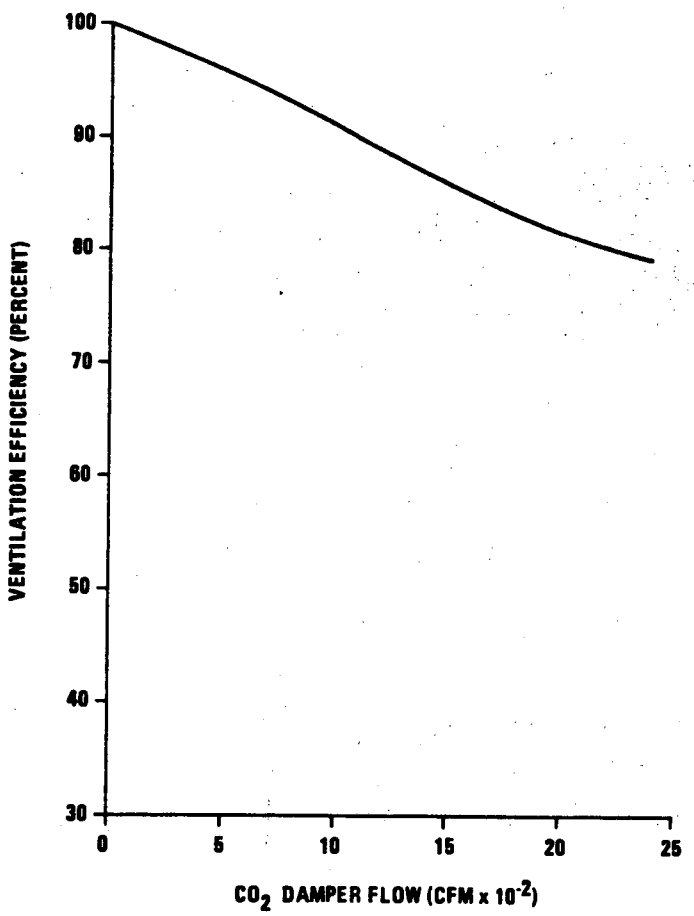


Figure 6-15. Ventilation Efficiency

Locating supply and return registers in such a way that channeling and incomplete mixing occurs probably is common to most HVAC system. A 20 percent loss in ventilation efficiency under maximum load conditions probably is common.

6.1.4 Evidence of CO_2 Control

One objective of this project was to demonstrate control of the CO_2 concentration in the Fridley Junior High music wing. By controlling the CO_2 concentration, ventilation is controlled in direct response to the number of students present at any time. The control concept involved opening nominally closed dampers in response to rising CO_2 concentration, the result of increasing student occupancy.

The expected result of the CO_2 control system was that the CO_2 level would rise to the throttling range of the control and then remain essentially constant as the control opened the CO_2 damper to admit outside air.

During the intensive test period the CO_2 throttling range was set at 3000 to 5000 ppm. This level was selected to maximize energy conservation and any subjective effects. During the Fall semester of 1979, prior to the test period, CO_2 levels greater than 2500 ppm were observed. However, the student load was lower during the intensive test period and the CO_2 level never reached the 3000 to 5000 ppm throttling range of the control. Thus the CO_2 control damper remained closed during these tests.

Table 6-3 shows the minimum and maximum CO_2 level observed each day. The minimum CO_2 level at the beginning of classes was between 320 and 500 ppm, equal to the outdoor background level. Student occupancy was light during the morning and reached a maximum only during the last two periods of the afternoon. Thus the room CO_2 reached its maximum at about 1500 hours. Under CO_2 control mode the peak ranged from 1350 to 1760 ppm, with an average of 1540 ppm. The minimum outside airflow of 16 percent reduced the revised control mode peak values to 850 to 1500 ppm, with an average of 1180 ppm.

Table 6-3. Room CO_2 Range

CO_2 CONTROL MODE							
DATE	MINIMUM CO_2		MAXIMUM CO_2		ROOM TEMPERATURE 0° F		
	TIME	ppm	TIME	ppm	NO. 300	NO. 162	NO. 164
1-29-80	0915	500	1500	1350	80	67.5	70
1-30-80	1115	500	1445	1700	83	68	70.5
2-04-80	0900	400	1430	1400	79	68	71
2-05-80	0900	400	1645	1760	74	68	70.5
2-08-80	0820	350	1515	1580	69	68	71
2-11-80	0900	350	1430	1480	70-75	68	70.5
2-14-80	0900	450	1500	1500	68	68	71
AVERAGE PEAK 1540							
REVISED CONTROL MODE							
1-28-80	0900	400	1500	1500	91	68	70
1-31-80	1145	380	1510	1300	76.7	68	68
2-01-80	0915	450	1500	1250	76	67	67
2-06-80	0900	430	1500	1125	76.5	68.5	70
2-07-80	0900	400	1500	1140	67	67	67
2-12-80	0945	320	1500	850	68	68	67
2-13-80	0900	300	1500	1100	68	68	68
AVERAGE PEAK 1180							

Once the intensive test period was begun it was undesirable to change the set point of the CO_2 control as this would have confused the data. The control throttling range was, however, reduced to 825 to 1375 ppm on February 27, 1979. The data for February 29 are shown in Figures 6-16 and 6-17.

Three parameters have been plotted on the graph in Figure 6-16. The CO_2 levels for each of the five channels are shown at 10-minute intervals in the upper part of the figure. The channels are for the band room (300), the outer and inner chorus rooms (162 and 164) and the main supply and return ducts. The sixth channel was for outdoor air, which is not shown.

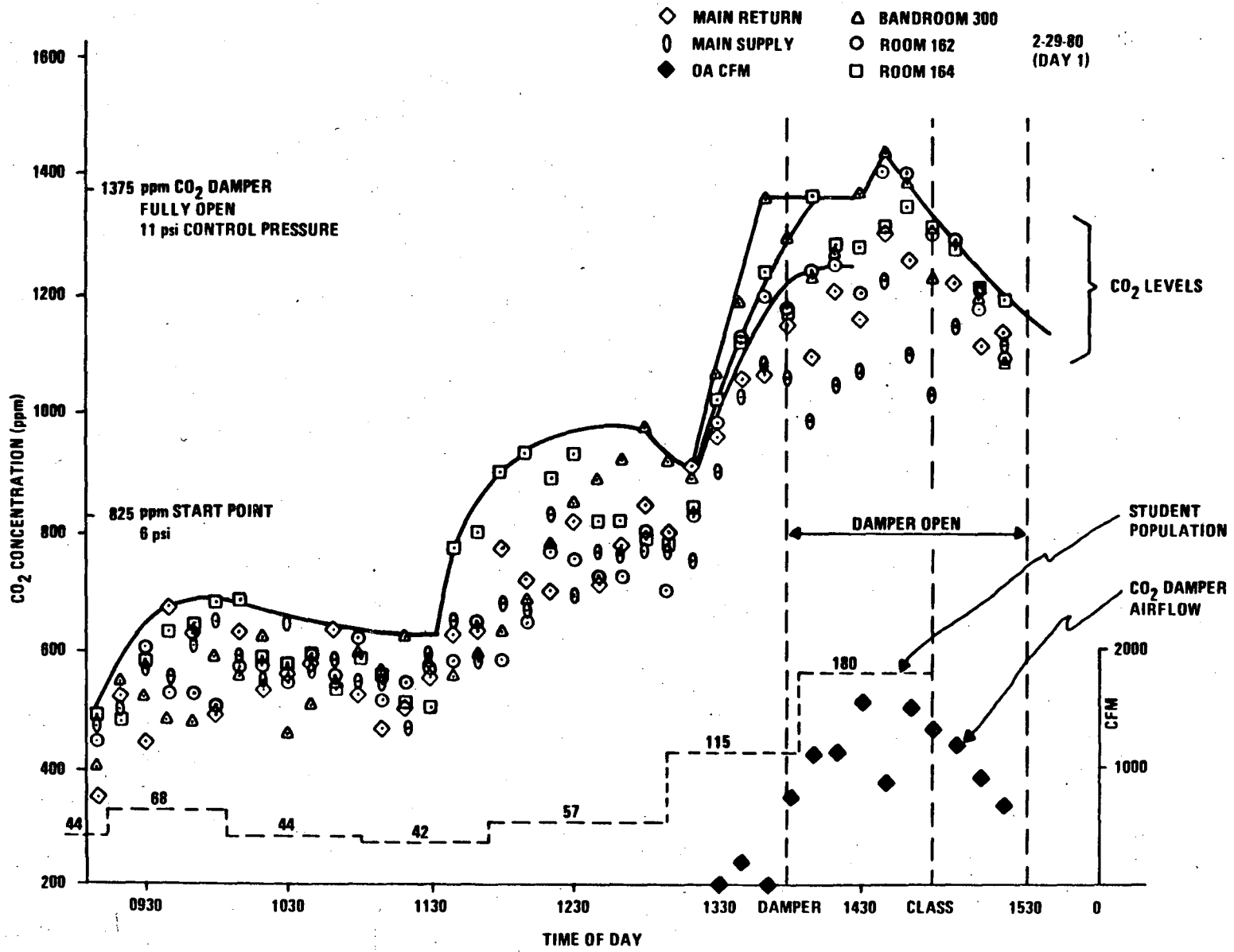


Figure 6-16. CO_2 Levels Under CO_2 Control

The student occupancy level is shown in the bar graph in the lower part of the figure. The outdoor airflow rate is shown in the lower right hand part of the figure.

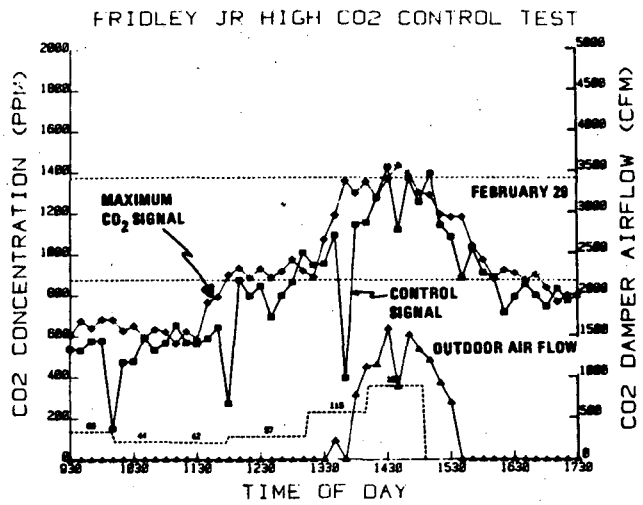


Figure 6-17. Maximum CO_2 Signal and CO_2 Control Signal for February (825 to 1375 ppm Throttling Range)

Figure 6-17 is a computer generated plot of the same data shown in Figure 6-16. It shows the envelope defined by the maximum CO_2 concentration of six channels and the CO_2 damper control signal. The damper control signal is designed to follow the maximum concentration curve when the CO_2 sampling is multiplexed, as it was on February 29. Student population and CO_2 damper airflow are shown, as in Figure 6-16.

Referring to Figures 6-16 and 6-17, the CO_2 concentration changed directly in response to the changes in student population. The CO_2 level rose from a background level to about 700 ppm at 1000 hours, while the occupancy level ranged from 44 to 58 students. During the period from 1000 to 1200 hours, occupancy dropped back to 44 and then 42 students. This was accompanied by a decrease from 700 to 600 ppm of CO_2. The outdoor air dampers were closed

during this time, but leakage through the temperature control duct and dampers was around 300 CFM. The infiltration rate, which included this damper leakage, was around one-third air change, and the volume of the music wing was about 90,000 cubic feet. Thus the infiltration flow rate was approximately:

$$\dot{V}_I = (0.33)\ (90{,}000)\ (1/60) = 500 \text{ CFM}$$

Table 3-1 shows that junior high students produce about 0.0105 CFM of CO_2. If the outdoor airflow rate was 500 CFM and the occupancy level was 68 people, the steady-state concentration would be 1428 ppm. Forty-four students would produce a steady-state concentration of 924 ppm. The steady-state rates were not approached because of the large residual capacity of the air in the building.

At 1200 hours occupancy rose to 57 students, and this was accompanied by an increase in CO_2 to 1000 ppm. Note in Figure 6-17 that the maximum level and control changed from room 164 to the band room during this period. There was a small drop in CO_2 level at 1300 hours when classes changed. This was caused by opening of doors and movement of people.

Occupancy rose to 115 students at about 1300 hours, and the CO_2 control damper began to open. There was about 250 CFM of outdoor airflow through the damper at 1340 hours.

At 1350 hours the control signal followed the outdoor air concentration and closed the damper momentarily. The data scan occurred during a portion of the multiplexer scan that was looking at the outdoor air concentration. The control signal also was recorded on the outdoor air channel at 1010, 1200 and 1350 hours. The time differences between the data logger clock and the multiplexer clock created a beat frequency effect between the data scans and the outdoor air sampling. This recorded beat frequency was 110 minutes and has been observed in all recordings of the multiplexed control signal. The multiplexer had nominal 7-minute scan periods and the data logger scanned precisely at 10-minute intervals.

The beat frequency between the data logger and multiplexer would have a period of 70 minutes if the two clocks were independent and accurate. It was observed, however, that the multiplexer clock ran slightly fast. A beat frequency period of 110 minutes would comtain 11 data logger cycles. This period would have to contain an integral number of multiplexer periods slightly less than 7 minutes. Sixteen 6.875-minute periods would equal 110 minutes total. Thus a multiplexer scan period of 6.875 minutes would produce a 110-minute beat with the 10-minute data logger period.

Referring again to Figures 6-17 and 6-18, after 1350 hours the control system continued to increase the outdoor airflow in response to increasing CO_2 concentrations. At 1440 hours the multiplexer picked a low CO_2 concentration and reduced the outdoor airflow.

The controller occasionally can select a channel that does not have the highest average CO_2 concentration. The multiplexer will select the zone for control for which it obtained the highest CO_2 recording during a scan. The problem of selecting an inappropriate channel occurs when two or more channels have average CO_2 concentrations fairly close together and noise causes the lower channel to exceed the higher channel momentarily.

It also should be noted that the control signal and maximum CO_2 concentration did not agree precisely in most cases. The reasons for this apparent anomaly also are due to the time differences between the CO_2 multiplexer and the data logger and to noise in the CO_2 signals.

The Anarad signal was quite noisy due in part to incomplete mixing in the rooms. The samples were not homogeneous. The fluctuation in concentration was as high as 400 ppm. The multiplexer compared each reading to the previous value in memory and retained the highest reading. CO_2 damper control also shifted from channel to channel during multiplexer sampling. The 20-second sampling time was relatively short compared to the time needed to open or

close a damper, so normally this did not produce large pertubations in the airflow At the end of the six 20-second sampling periods, the multiplexer returned to the channel with the highest value in memory, and that channel retained control for the next 5 minutes. Thus the total multiplexer period was nominally 7 minutes.

The data logger clock was very accurate and initiated a scan at precisely 10-minute intervals; each scan required about 1 minute. The data logger interrogated the multiplexer and recorded the values in the multiplexer memory for each channel. When the data logger and the multiplexer scans coincided for the outdoor air channel, a CO_2 control signal equivalent to outdoor air was recorded. This perturbation lasted a maximum of 20 seconds, but if the outdoor air damper was open, it would begin to close and would perturb the outdoor airflow. The reason for this action was that there was no simple way to retain control on one channel while sampling and recording the other channels.

While this kind of performance in the control system produced noisy and sometimes confusing data, the effect on outdoor airflow was much smaller. The relatively slow response of the pneumatic damper motors tended to integrate this noise. The data presented for February 29 was taken at 10-minute intervals.

Data presented later in this report were taken at 2-minute intervals and averaged over 10-minute intervals to reduce the noise and show control action more clearly.

At 1500 hours on February 29, the students left the space and the control system followed the decay as shown by the decrease in airflow.

Figure 6-18 shows the data of February 29 compared with the average values during the intensive test period. The lower curve is the average of 6 days under revised system control. The outside air damper was set for 16 percent outside air and remained at this setting all day. The dashed line with circled

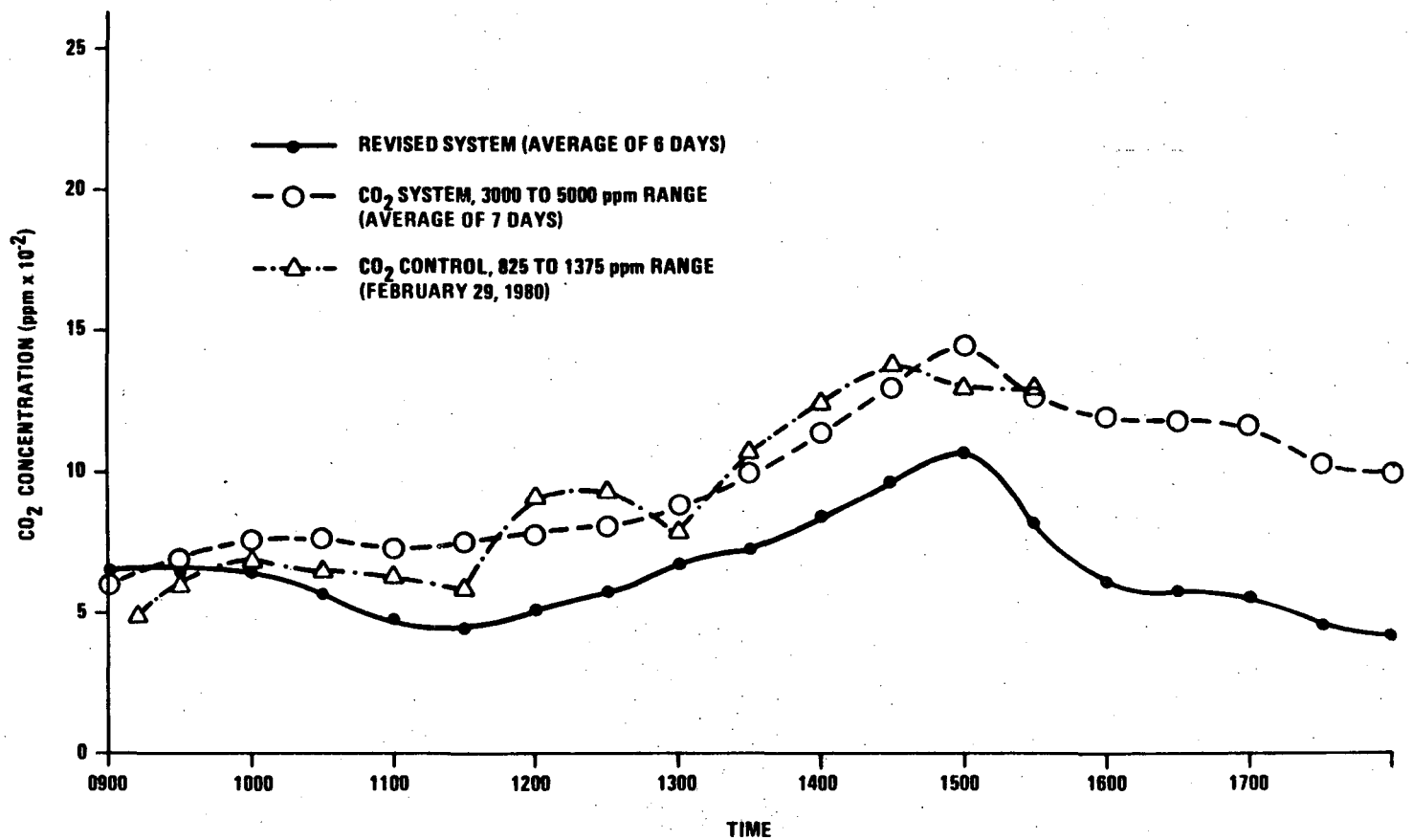


Figure 6-18. Average Daily CO_2 Level During Testing

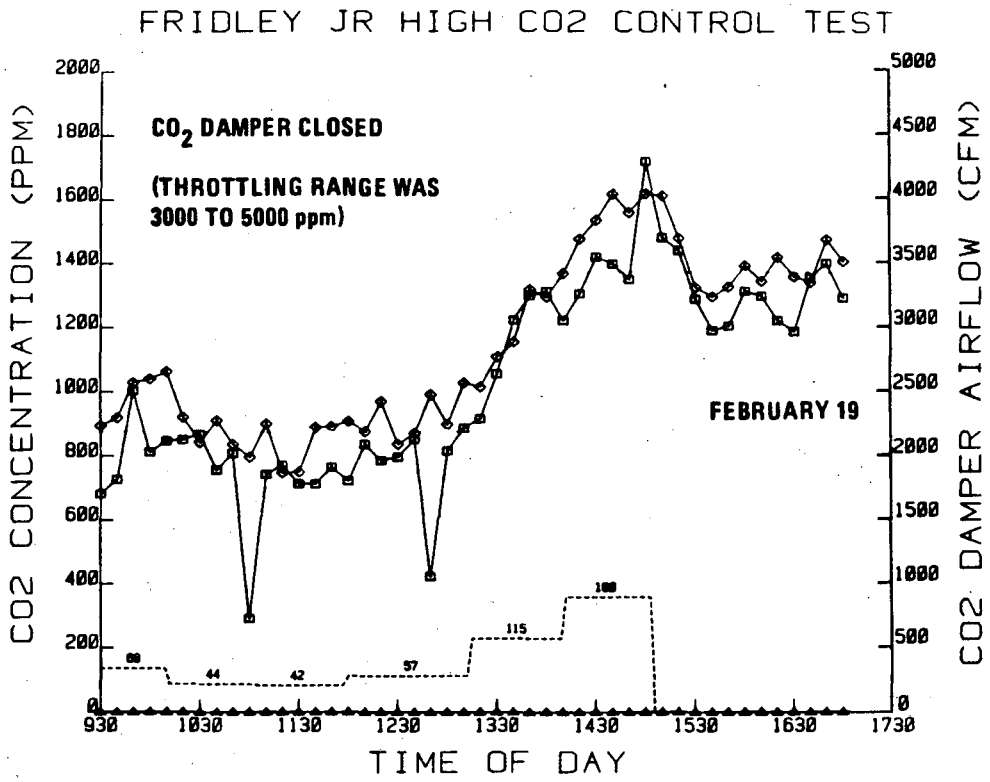
points is the average of 7 days under CO_2 control with a throttling range of 3000 to 5000 ppm. Both the CO_2 control damper and the temperature control dampers remained closed. Damper leakage, duct leakage and infiltration provided about 500 CFM of outdoor air. The peak value of 1450 ppm at 1500 hours differs from Table 6-3 because it is the average of the maximum values at a specific time, i.e., 1500 hours. Table 6-3 shows the peak values independent of time.

The dashed line with triangular points in Figure 6-18 shows the data of February 29 when the throttling range was reduced to 825 to 1375 ppm. The CO_2 levels are nearly the same as for the higher throttling range except that the peak is cut off.

Figure 6-19 shows February 29 data compared to data from February 19 when the CO_2 control range was 3000 to 5000 ppm. Again evidence of control is shown by the clipped peak of the CO_2 concentration on February 29. Otherwise CO_2 profiles for the two days are very similar.

This seemingly small degree of control can be explained with the aid of Figure 6-20, which shows schematically how the CO_2 concentration would rise if a given number of people entered a space that was ventilated at two different rates. The upper curve represents some minimum ventilation rate and the lower curve a higher "standard" outdoor air ventilation rate. If a control system were installed that could switch the outdoor airflow from the minimum rate to the standard rate at some set point such as point A, the CO_2 concentration rate would switch from the higher to the lower curve function. The rate then would follow the dashed line designated two-position control.

A modulating control such as the one used in this experiment would have a throttling range as shown. The outdoor airflow would begin to incrase from the minimum rate at point A to the standard rate at point B. Point B would have to be lower than the minimum ventilation curve because the outdoor airflow would be greater. However, point B would have to be higher than the two-



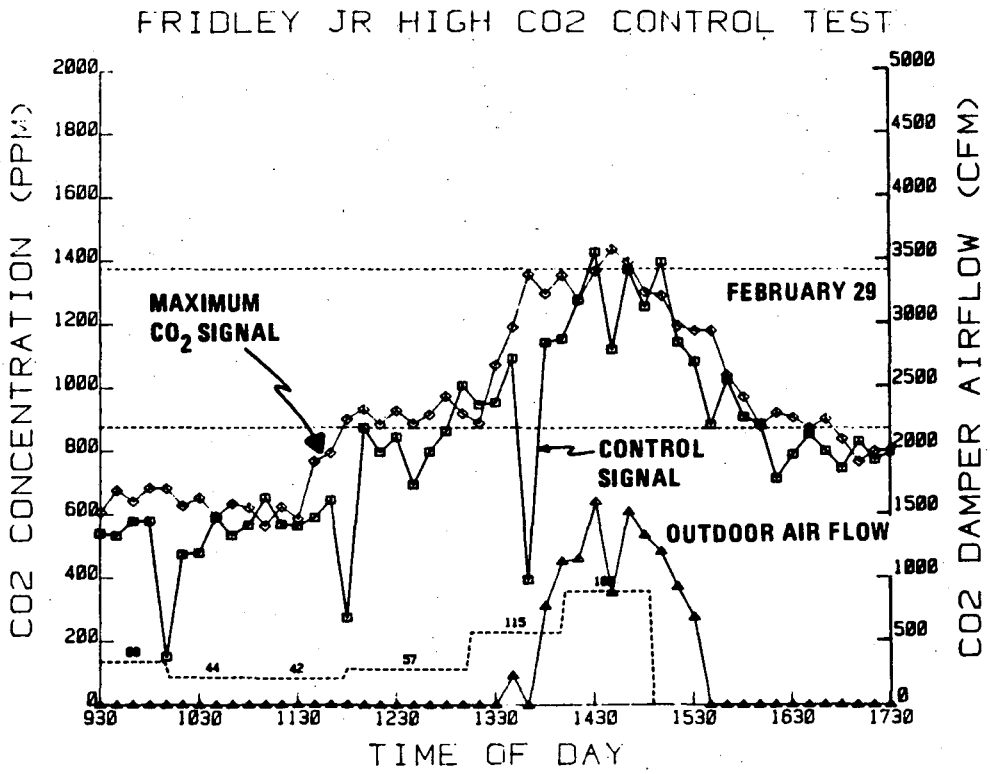


Figure 6-19. Comparison of Data from February 19 and 29

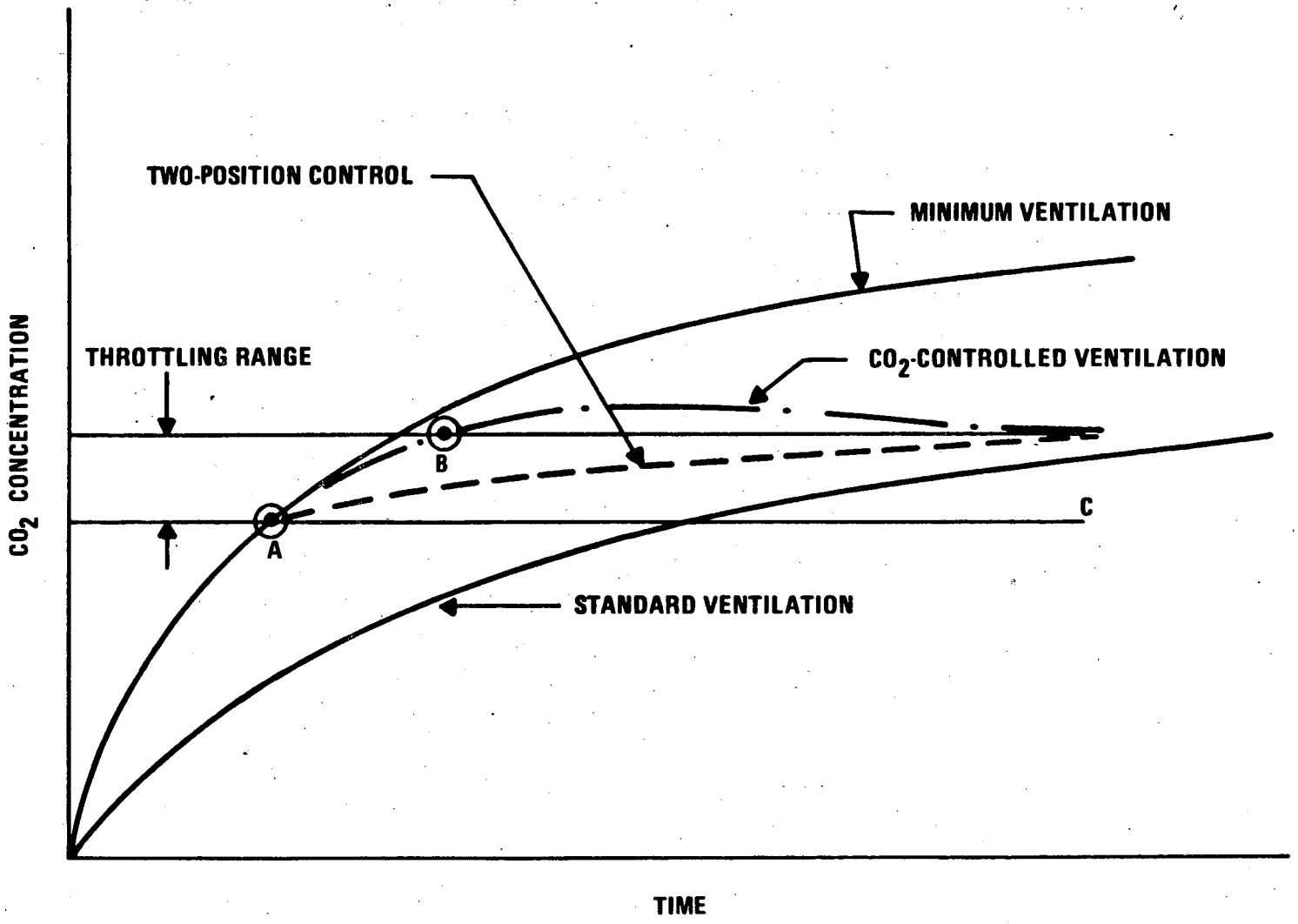


Figure 6-20. Schematic Explanation of Control Overshoot

position control line because the outdoor airflow within the throttling range would be less than the two-position case. The function passing through point B is continuous, and the rate of rise would be given by the standard ventilation curve function. Thus the CO_2 level would overshoot its equilibrium value. The steady-state equilibrium would have to approach the same level as the steady-state value for the standard ventialtion curve. The two-position control curve would asymptotically approach the same value at point C.

Control point overshoot is inherent in any undamped proportional control. Additional features including differential and integral action would be required to prevent overshoot. These refinements probably are unnecessary since the CO_2 sensor is essentially a limit control. Its function is to limit outdoor airflow so that some maximum CO_2 level is not exceeded.

Ventilation capacity also has considerable effect on the control system. If the maximum ventilation rate is large compared with the load, the system will respond quickly and may oscillate or hunt. The system would follow a fluctuating load but would tend to be energy wasteful. A system designed for minimum outside airflow at maximum load with the throttling range set so that the overshoot was within acceptable limits would be most energy efficient. The design load conditions would have to include not only maximum occupancy but also activities such as smoking, exercise and outgassing of building materials. It would be desirable to design a CO_2-controlled system for an outdoor air rate somewhat greater than the expected maximum demand to give good control response, but the optimum value will require further study.

The test data shown for February 29 are typical of data taken on February 29 and during the first week in March 1980. Another experiment was performed in October 1980 to further demonstrate CO_2 control at Friday Junior High School.

These data are shown in Figures 6-21 through 6-24. Figure 6-21 is the reference case with the outdoor air dampers closed. The scan rate was increased to 2-minute intervals to obtain better resolution and permit noise reduction through averaging. All measurements shown were made in the main return duct to prevent confusion from channel switching and permit the higher scan rate. The CO_2 concentrations on the figures are the damper control signals.

Figure 6-21b is the data at 10-minute intervals extracted from the higher frequency data of Figure 6-21a. The 2-minute data were then averaged over 10-minute intervals and plotted in Figure 6-21c. The filtering effect of this averaging is evident from comparing Figures 6-21c and 6-21b. The Relatively slow response of the pneumatic damper motors tends to integrate the noise of the control signal. The control signal the dampers will respond to effectively is the averaged recording that we have shown.

CO_2 control with a throttling range of 700 to 800 ppm was used for the data in Figure 6-21, which presents instantaneous values on a 10-minute scan. When compared with Figure 6-21b, it shows that the CO_2 peak was clipped. The outdoor airflow during the control period in Figure 6-21d reached about 2300 CFM with the control damper wide open. This flow was not quite enough to hold the 800 ppm limit on the throttling range. Thus the system was capacity limited for the student load with this low throttling range.

Figure 6-22 shows similar damper closed reference data for the day 1 schedule when the student load was somewhat greater.

Figure 6-23 shows the CO_2 control data for comparison with Figure 6-22. Figure 6-23a is the raw data at 2-minute intervals. The outdoor air flow also is shown. Figure 6-23b shows the 10-minute interval data and Figure 6-23c shows the 2-minute data averaged over 10-minute intervals. Although the 10-minute instantaneous data of Figure 6-23b shows spikes above the 700 ppm throttling range prior to 1230 when the damper opened, it is clear from the time averaged

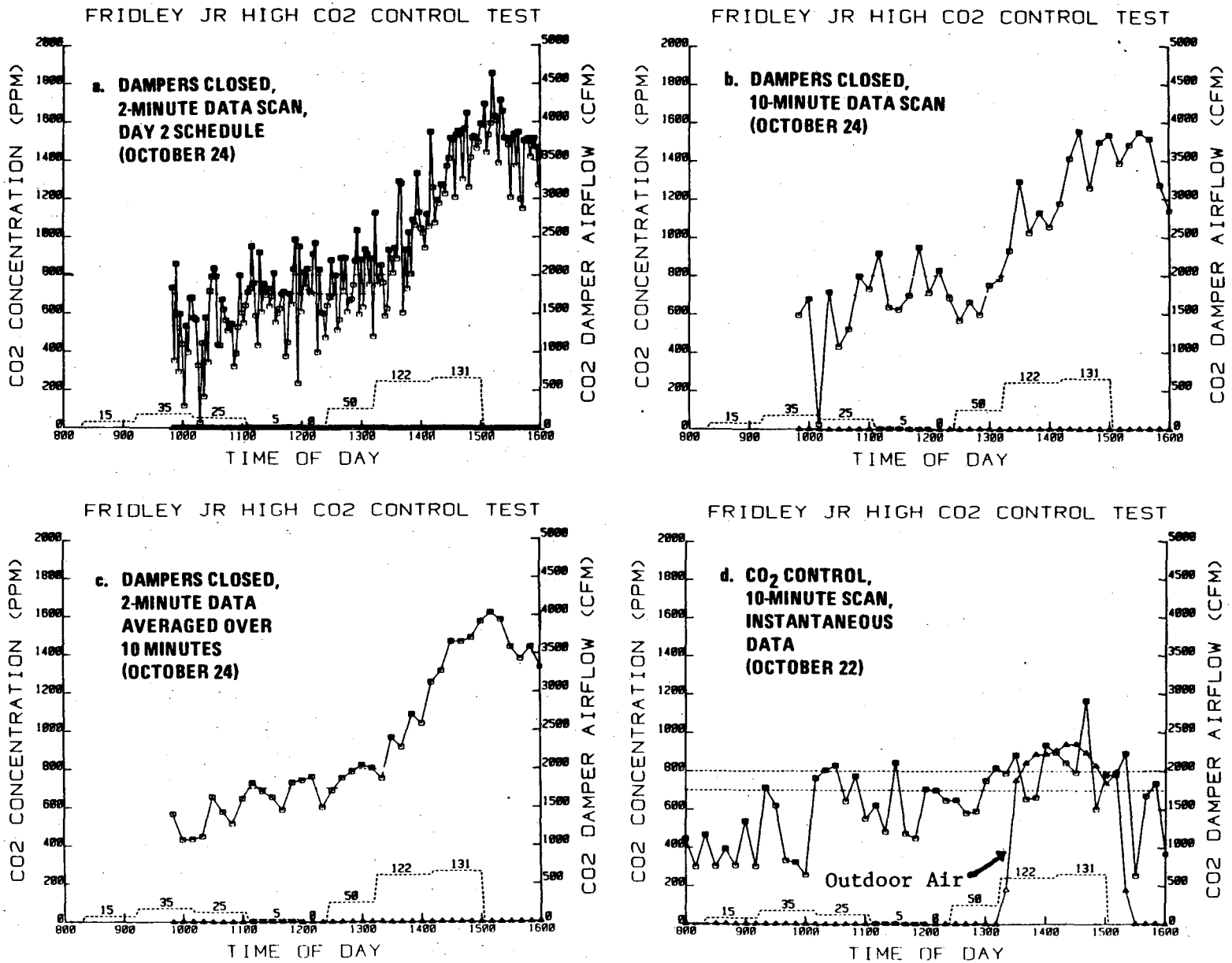


Figure 6-21. Reference Case with Outside Air Dampers Closed

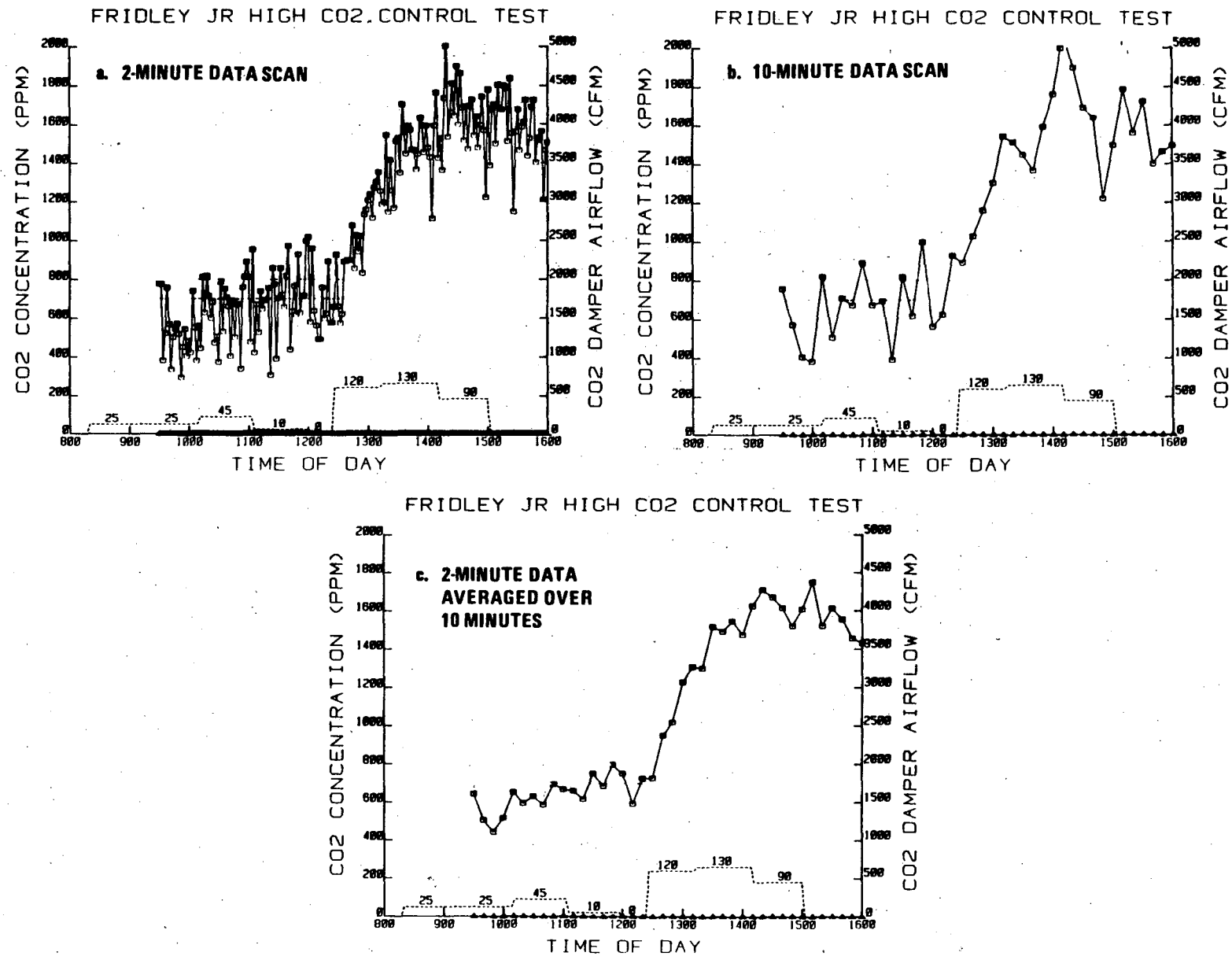


Figure 6-22. Reference Data with Outside Air Dampers Closed for Day 1 Schedule

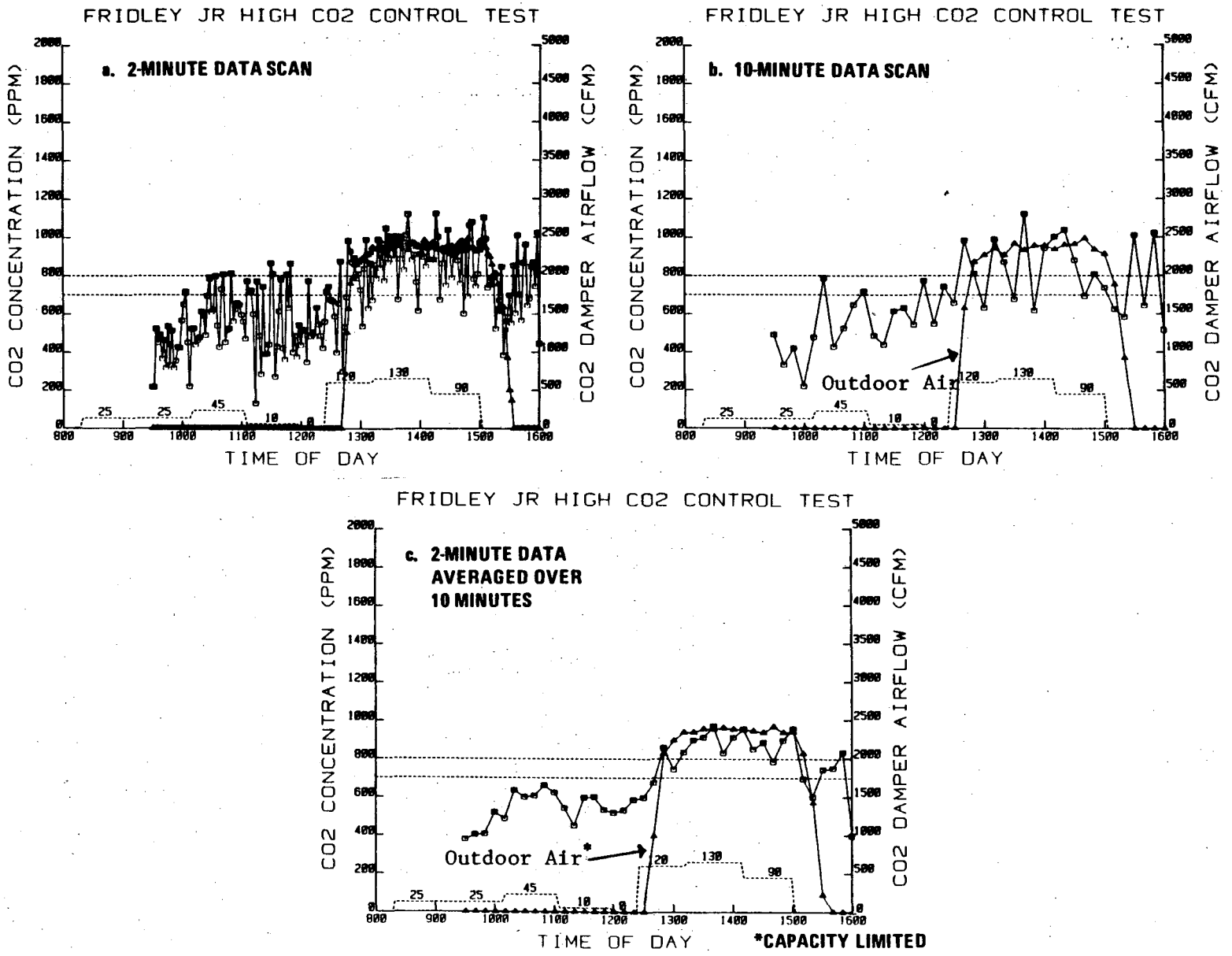


Figure 6-23. CO_2 Control Data for Comparison

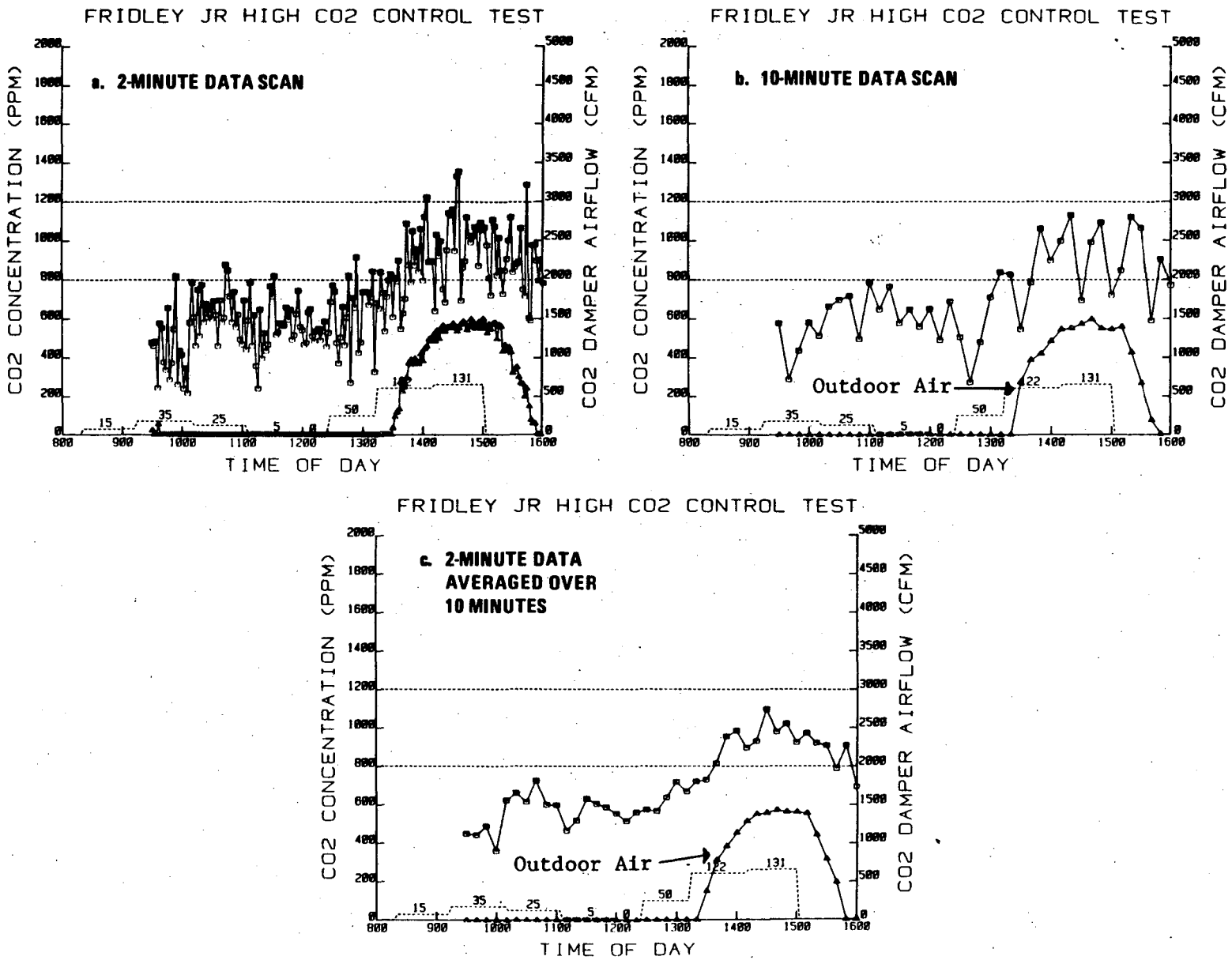


Figure 6-24. Comparison Data with Throttling Range Raised

data of Figure 6-23c that these spikes were of too short duration to open the damper. Shortly after the students entered the classroom at 1225 hours the return air concentration reached the control set point and started to open the outside air damper. There was insufficient capacity to hold the 800 ppm level at this student load, but the return air CO_2 concentration did level off at about 900 ppm with an outdoor airflow rate of about 2400 CFM. The CO_2 level in Figure 6-23c can be compared with that in Figure 6-22c to show CO_2 control.

The throttling range was then raised to 800 to 1200 ppm to match the system capacity with the occupancy load. These data are shown in Figure 6-24. Figure 6-24a is the raw data at 2-minute intervals, and Figure 6-24b is 10-minute interval data showing the substantial noise. Figure 6-24c is the 2-minute data averaged over 10-minute intervals. The noise is much reduced from that of Figure 6-24b. The CO_2 level remained within the throttling range and followed the load variation. The outdoor airflow rate reached only 1400 CFM, as compared with 2400 CFM in Figure 6-23c. The maximum CO_2 level was about 1000 ppm compared with 1700 ppm in Figure 6-22c.

This series of graphs shows a positive correlation between CO_2 level and outdoor airflow under the action of the CO_2 controller. The effect of CO_2 control is evident from the reduction of maximum CO_2 concentration for various control ranges tested with the system in the CO_2 control mode. The objective was to demonstrate this control action.

6.2 ENERGY SAVINGS

The model described in Subsection 5.4.1 (i.e., Model A) was used to simulate the performance of the air handling system in the music wing of Firdley Junior High School during the intensive test period. The energy that was transferred to the supply air for the days that were analyzed is listed in Table 5-1 of Subsection 5.4. Analysis of these data yields no significant conclusion. Factors such as occupancy patterns and outdoor weather (in addition to dry-bulb temperature listed in Table 5-1) probably influenced the variations in the data more than the outdoor dry-bulb temperatures and type of control.

To compensate for the unexplained variations, it was necessary to exercise Model A for both types of control systems, while all other factors were identical. However, lack of information regarding the stratification factor S, and variations in control points (see Subsection 5.4) caused instabilities to occur in the simulations. Therefore, another model (Model B, described in Subsection 5.4.2) was developed.

Table 6-4 compares the energy consumption at Fridley as measured during the intensive test period and the energy consumption predicted by this Model B for the same day and with the same type of control system in operation. From Table 6-4, it can be seen that on some days significant savings can result from correction of the stratification problem. Although on most days the total energy consumed under both stratification efficiencies was of similar magnitude, the behavior of the system was improved if stratification was minimized. With a large stratification, most of the heat supplied to the wing came from the reheat coils of the band room. However, as very little air was exchanged with the outdoors, the excess energy supplied to the band room eventually found its way into the occupied space of the entire music wing. When stratification was not as significant, the reheat coils for the band room did not supply as much

Table 6-4. Energy Savings Associated with Increasing "Stratification Efficiency"

CONTROL TYPE	DAY[a]	MEAN OUTDOOR DRY-BULB (°F)	MEASURED[b] ENERGY CONSUMPTION (10^6 Btu)	PREDICTED[c] ENERGY CONSUMPTION (10^6 Btu)	PERCENT[d] SAVINGS
REVISED CONTROL	01/31/80	8	1.14	0.982	14
	02/06/80	23	0.743	0.734	1
	02/13/80	18	0.788	0.544	31
CO_2 CONTROL	01/28/80[e]	0	2.19	1.97	10
	01/29/80	−3	1.28	1.15	10
	02/05/80	21	1.23	1.13	8
	02/11/80	16	1.32	1.30	2
	02/14/80	13	0.927	0.968	−4
	02/29/80[f]	4	0.947	0.879	7
	03/03/80	27	1.63	1.53	6
	03/04/80	7	1.07	1.06	1
	03/05/80	7	0.939	0.860	8
	03/06/80	10	1.30	1.25	4

[a] A MISWIRED VALVE WAS CORRECTED ON 02/07/80.

[b] AS REALLY HAPPENED IN FRIDLEY (56 PERCENT "STRATIFICATION EFFICIENCY").

[c] SIMULATED WITH THE CORRECTIVE ASSUMPTIONS (100 PERCENT "STRATIFICATION EFFICIENCY").

[d] (MEASURED – PREDICTED)/(MEASURED)

[e] ACTUALLY, DURING 01/28/80, THE SYSTEM WAS CONTROLLED BY THE "REVISED CONTROL SYSTEM," BUT WITH 0 PERCENT MINIMUM POSITION FOR THE OUTDOOR DAMPER, WHICH MAKES ITS BEHAVIOR SIMILAR TO THAT OF THE CO_2 CONTROL BECAUSE THE CO_2 CONCENTRATION NEVER REACHED THE SETPOINT OF 3000 ppm, AND THE WING TEMPERATURE NEVER REACHED 78°F (THE MINIMUM NECESSARY FOR THE OUTDOOR AIR DAMPERS TO OPEN).

[f] ANALYSES AFTER 02/29/80 WERE MADE FROM DATA THAT INCLUDED VALUES FROM A DEFECTIVE HUMIDITY SENSOR IN THE BAND ROOM.

energy to the supply air, forcing the other reheat coils to supply the difference. Thus, the total energy used under both situations was quite similar, although a tendency for savings was clearly present.

Table 6-5 lists the results of the simulation (with Model B) of the energy consumption at the music wing of Fridley Junior High School for both control systems during several days of the intensive test period. Although the influences of weather and occupancy patterns are still present, a consistent energy savings is associated with the CO_2 control system over the revised conventional temperature-driven control system. Thus, it appears that the use of the CO_2-driven control system in the music wing of Fridley Junior High School would produce significant energy savings during the heating season.

6.3 ENERGY SAVINGS--GEOGRAPHIC

The potential energy savings that could result from use of a CO_2-driven control system were calculated for nine cities in the continental United States.* The cities were selected to cover a wide range of climates from Yuma, Arizona, with 1005 heating degree-days, to Glasgow, Montana, with 9251 heating degree-days.

The climate of each city was characterized by the frequency distribution of the 8-hour BINS obtained from Air Force Manual AFM88-29 [22]. The energy savings were predicted by the model described in Subsection 5.4.2 for each BIN.** This model was run for both control strategies under outdoor weather

*The nine cities were Glasgow (MT), Minneapolis (MN), Albany, (NY), Toledo (OH), Tacoma (WA), Albuquerque (NM), Atlanta (GA), Dallas (TX) and Yuma (AZ).

**A slightly changed version of the Fortran Program was developed for this analysis. A listing is shown in Appendix B.

Table 6-5. Comparison of the Energy Consumed by the Corrected[a] Air Handling System Under Revised Control and CO_2 Control

DAY[b]	MEAN OUTDOOR DRY-BULB (°F)	ENERGY CONSUMPTION		PERCENT[c] SAVINGS
		CO_2 CONTROL (10^6 Btu)	REVISED CONTROL (10^6 Btu)	
01/28/80	0	1.98	2.53	22
01/29/80	−3	1.15	1.51	24
01/31/80	8	0.649	0.982	34
02/05/80	21	1.13	1.30	13
02/06/80	23	0.574	0.734	22
02/11/80	16	1.30	1.64	21
02/13/80	18	0.354	0.544	35
02/14/80	13	0.968	1.22	21
02/29/80[d]	4	0.879	0.955	8
03/03/80	27	1.53	1.66	8
03/04/80	7	1.06	1.12	5
03/05/80	7	0.860	0.901	5
03/06/80	10	1.25	1.30	4

[a] CORRECTED WITH THE TWO ASSUMPTIONS MENTIONED IN THE TEXT (i.e., CONSTANT SET POINT AND 100 PERCENT STRATIFICATION EFFICIENCY).

[b] A MISWIRED VALVE WAS CORRECTED ON 02/07/80.

[c] (REVISED − CO_2)/(REVISED)

[d] ANALYSES AFTER 02/29/80 WERE MADE FROM DATA THAT INCLUDED VALUES FROM A DEFECTIVE HUMIDITY SENSOR IN THE BAND ROOM AND FOR A LOWER SET POINT OF THE CO_2 CONTROLLER (825 ppm RATHER THAN 3000 ppm).

conditions that were set equal to the midpoints of the BIN temperature (both dry-bulb and wet-bulb). The building (and its air handling system) simulated was the music wing of Fridley Junior High School, which was assumed to be transposed (i.e., with no modifications) to all nine cities. The occupancy pattern also was assumed to equal that of the music wing as measured during the intensive test period. Due to different hours of operation during the week, the air handling system was assumed to operate daily from 6 A.M. to 5 P.M. Thus, BIN No. 1 included the savings from 6 A.M. to 8 A.M., and BIN No. 2 included the energy savings from 8 A.M. to 5 P.M During BIN No. 3, from 5 P.M. to 12 P.M., the air handling system was assumed to be nonoperational, thus resulting in no energy expenditure (or savings).

Energy savings for both BIN No. 1 and No. 2 for each combination of average dry-bulb and wet-bulb temperatures necessary to characterize the climate of all nine cities were computed. These energy savings are plotted in Figure 6-25 against the enthalpy content of the outdoor air for each combination. The figure shows that the relative humidity of the outdoor air has only a limited effect upon energy savings during most of the heating season. It also was observed in these simulations that the outdoor air dampers should start to open at outdoor dry-bulb temperatures of 52°F under CO_2 control and at 62°F under revised temperature control. For an outdoor dry-bulb temperature above 62°F, no energy savings should occur because both systems would operate in similar modes as both would have outside air dampers fully opened.

The energy savings during the heating season were estimated as the sum of the frequency weighted values obtained in the BINS for each of the nine cities studied. This procedure, shown in Appendix A for all nine cities, is summarized in Table 6-6. As the BINS account for all 7 days of the week and the school only operates during 5 days, the values listed in Table 6-6 are five-sevenths of the totals calculated in Appendix A No energy savings were estimated for the other 2 days, as the systems were assumed to be nonoperational during these times.

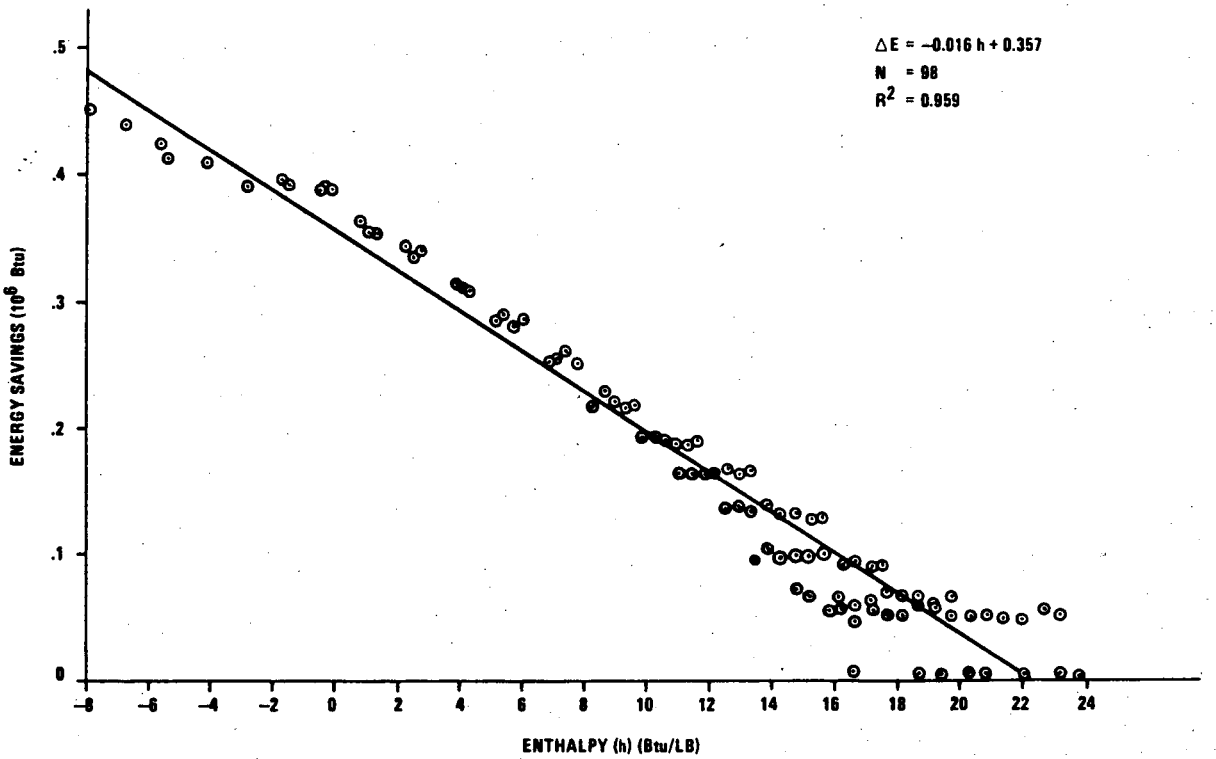


Figure 6-25. Energy Savings Associated with CO_2 Control

From Table 6-5 it can be concluded that, except for very mild climates (i.e., Yuma, Arizona), the savings that result from the use of a CO_2-driven control system should be approximately 20 percent, with greater savings possible in cities with higher numbers of heating degree-days.

It should, however, be kept in mind that the energy savings refer to a building exactly the same size as the music wing of Fridley Junior High School with similar occupancy patterns. Thus, these energy savings should be interpreted with this limiting factor in mind.

Table 6-6. Summary of Energy Consumption for Nine Cities

CITY	HEATING DEGREE DAYS (°F)	TOTAL ENERGY REQUIRED FOR THE HEATING SEASON (10^6 Btu)		SAVINGS	
		CO_2 CONTROL	TEMPERATURE CONTROL	ENERGY (10^6 Btu)	PERCENT
GLASGOW, MONTANA	9251	1040	1310	270	21
MINNEAPOLIS, MINNESOTA	8310	857	1093	236	22
ALBANY, NEW YORK	6888	680	859	179	21
TOLEDO, OHIO	6381	673	849	176	21
TACOMA, WASHINGTON	5287	496	609	113	19
ALBUQUERQUE, NEW MEXICO	4337	453	563	90	16
ATLANTA, GEORGIA	3095	366	444	78	18
DALLAS, TEXAS	2301	314	381	67	18
YUMA, ARIZONA	1005	159	179	20	11

6.4 SUBJECTIVE RESPONSE TO CO_2 CONTROL

6.4.1 Analysis of Differences Between the Two Systems for All Classes

Data for the ten classes studied during the intensive measurement period (see Subsection 5.5.3) were reduced to one set of observations--the mean differences in responses to the two systems--for each student. The difference represented the mean transformed subjective response to the conventional temperature-driven control system minus the mean transformed response to the experimental CO_2-driven control system. Data for items 1 through 23 of the questionnaire were analyzed separately by analysis of variance, using the SAS GLM* procedure [23]. The model expressed the student's response difference as a function of which of the ten classes he or she was in at the time, each class being expressed as a category variable (see Subsection 5.5.3). In fact, each class effect was the difference between the effect for a particular class and class 9, the reference class.

The total enrollment in each of the ten classes participating in the research was not known. However, on the observation sheets, the teachers reported the number of students present in most classes. The number of students providing enough data to qualify for this analysis (at least two observations under each system) totaled 225. The number of missing answers to specific polar adjective items 1 through 22 ranged from a low of 1 to a high of 14. Thus, fewer than 1 percent of responses were missing for some items and no more than 6 percent for the most extreme cases. However, for item 23 (number of layers of clothing) only 161 of a possible 225 students provided usable answers.

Table 6-7 summarizes the results of the 23 analyses of variance. Note that in the first column (mean) the differences in responses to the two systems are almost zero for "conditions in this room are pleasant-unpleasant," and "I feel

*Statistical Analysis System -- General Linear Models.

Table 6-7. Summary of Data (Control versus Experimental Ventilation System), Results of Analysis of Variance on Mean Differences (by Student)

	OVERALL, 10 CLASSES		ANALYSIS OF VARIANCE (PERCENT)		IS MEAN DIFFERENCE SIGNIFICANT AFTER CLASSROOM EFFECTS ARE REMOVED?
	MEAN	STANDARD DEVIATION	R^2	F	
CONDITIONS IN THIS ROOM ARE:					
1. BRIGHT-DIM	-0.16	2.76	14	3.98 (a)	--
2. STALE-FRESH	0.47	3.02	10	2.57 (a)	POSITIVE
3. SILENT-NOISY	0.25	3.29	19	5.45 (a)	--
4. BAD-SMELLING - GOOD-SMELLING	0.24	2.99	8	2.01 (b)	--
5. DRY-DAMP	0.35	2.97	5	1.38	--
6. MOVING AIR - STILL AIR	-0.85	3.18	11	2.97 (a)	NEGATIVE
7. CLEAR-HAZY	-0.16	2.81	5	1.23	--
8. WARM-COOL	0.51	3.49	13	3.63 (a)	POSITIVE
9. PLEASANT-UNPLEASANT	-0.01	3.46	7	1.83	--
10. DIRTY AIR-CLEAN AIR	0.17	2.71	6	1.41	--
I FEEL:					
11. COMFORTABLE-UNCOMFORTABLE	-0.20	3.36	7	1.67	--
12. DAMP-DRY	0.07	3.10	2	0.44	--
13. COOL-WARM	-0.82	3.65	9	2.45 (b)	NEGATIVE
14. FREE-CROWDED	-0.15	3.52	8	1.98 (b)	--
COMPARED TO MY BODY,					
15. MY HANDS FEEL WARMER-COOLER	0.66	4.12	17	4.76 (a)	POSITIVE
16. MY FEET FEEL WARMER-COOLER	0.21	3.52	4	0.89	--
PHYSICALLY AT THIS TIME I AM:					
17. SICK-WELL	-0.06	3.42	6	1.44	--

Table 6-7. Summary of Data (Control versus Experimental Ventilation System), Results of Analysis of Variance on Mean Differences (by Student) (concluded)

	OVERALL, 10 CLASSES		ANALYSIS OF VARIANCE (PERCENT)		IS MEAN DIFFERENCE SIGNIFICANT AFTER CLASSROOM EFFECTS ARE REMOVED?
	MEAN	STANDARD DEVIATION	R^2	F	
MENTALLY AT THIS TIME I AM:					
18. JITTERY-CALM	-0.31	3.49	8	2.12 (b)	-
19. DOWN-UP	-0.13	3.31	7	1.67	-
20. ALERT-SLUGGISH	0.16	3.55	9	2.30 (b)	-
THE CLOTHING I AM WEARING INDOORS TODAY IS:					
21. LIGHT-HEAVY	-0.05	3.46	5	1.14	-
22. BULKY-NOT BULKY	-0.06	3.41	4	0.99	-
23. NUMBER OF LAYERS	-0.06	0.51	7	1.27	-

(a) F-VALUE SIGNIFICANT AT OR BEYOND THE 1 PERCENT LEVEL.

(b) F-VALUE SIGNIFICANT AT OR BEYOND THE 5 PERCENT LEVEL.

EXPLANATION:

1) SIGNIFICANT F-VALUE MEANS THAT THERE ARE DIFFERENCES AMONG THE 10 CLASSES THAT ACCOUNT FOR A PROPORTION OF THE TOTAL VARIATION IN RESPONSES. THESE CAN BE IDENTIFIED FOR THE 10 CLASSES IN TABLE 3.

2) IF THE MEAN DIFFERENCE IS SIGNIFICANT WITH CLASSROOM EFFECTS REMOVED (LAST COLUMN), AN OVERALL DIFFERENCE WAS OBSERVED BY THE STUDENTS BETWEEN THE TWO VENTILATION SYSTEMS OVER AND ABOVE DIFFERENCES RELATED TO ROOM, TIME OF DAY, AND TYPE OF CLASS.

- POSITIVE DIFFERENCE MEANS THAT THE LEFT-HAND POLAR ADJECTIVE WAS ASSOCIATED WITH THE EXPERIMENTAL CO_2 CONTROL SYSTEM.
- NEGATIVE DIFFERENCE MEANS THAT THE RIGHT-HAND POLAR ADJECTIVE WAS ASSOCIATED WITH THE EXPERIMENTAL CO_2 CONTROL SYSTEM.

damp-dry." Also, there is virtually no difference for "Physically at this time I am sick-well" and for the questions about the amount of clothing the students are wearing. This is good because it indicates that how the students felt and what they were wearing did not influence their answers to other questions.

The F-values for the analyses of variance show that the class the student was in at the time accounted for a significant proportion of total variation in response for 11 of the 23 questions. These classroom effects are summarized in Table 6-8. However, in most cases, the classroom effect was not large. The largest proportion of variance accounted for by the model was 19 percent (R^2 column) for "silent-noisy" followed by 17 percent for "compared to my body, my hands feel warmer-cooler." This means that there were not very many or very large differences between the two systems by time of day, type of activity or room. "Silent-noisy" could be related partly to type of class activity. Whenever the F-value is significant, it is necessary to look at individual classes to determine the reason for the difference.

The last column in Table 6-7 is the most important for this project. This column shows that for 5 of the 23 questions, the students observed differences between the revised control (i.e., temperature-driven) and the experimental CO_2 control system after class effects were considered.

These differences formed a pattern indicating that the students observed some real effect. They reported that while the revised control system was operating, the room was <u>fresher</u>, the room was <u>cooler</u> and the air was <u>moving</u> more than when the experimental CO_2 control system was operating. Also, they felt <u>cooler</u> and their <u>hands were cooler than their bodies</u> while the revised control system was operating as compared to the CO_2 control system. No differences were found in answers to questions that were not related in some way to the ventilation systems.

Table 6-8 summarizes the information from this same analysis of variance by showing which classes differed significantly for each item as compared to the reference class. The responses of the reference class are near the overall mean in most cases. Therefore, a class that is quite different from this class on a specific question is identified by Note b in Table 6-8.

Class 4, the 7th period band class on the Day 1 sequence, differed from the reference class on more items than any other class, including all items that were different for the two systems across all students. In general, Class 4 differed in the same direction as the group as a whole, but was more extreme. For example, all students found the room to be cooler while the conventional control system was operating, but students in Class 4 found the difference to be even more pronounced. They also reported a number of other differences.

Class 8 responded differently from the reference class on questions about mental state and their clothing. Examination of teacher observation forms revealed no reason for this. Class 8 was a general music class, as shown at the bottom of Table 6-8. Other differences in responses from various classes did not form a pattern and may have been random results.

Teachers' checklists indicated that the band room was perceived as hotter than the other rooms. Several comments were made about lack of humidity. Comments about stuffiness and poor air quality seemed to occur in classes late in the day (periods 6 and 7) rather than early in the day, although such comments were not made about Class 4, the 7th period band class in the Day 1 sequence.

6.4.2 Detailed Analysis of Data From 7th Period Band Class, Day 1

Because the foregoing analysis revealed a distinct pattern of differences for Class 4, the 7th period band class on the Day 1 sequence, as compared to the reference class, data from this class were analyzed in detail to see why this class was significantly different on several questions. This class also was

Table 6-8. Ten Classes in Which Data Were Collected

CODE FOR CLASS ⓐ:	0	1	2	3	4	5	6	7	8	9
NUMBER OF USABLE ANSWERS:	12	54	8	15	48	16	24	7	13	28
CONDITIONS IN THESE ROOMS ARE:										
1. BRIGHT-DIM							ⓑ		ⓒ	ⓓ
2. STALE-FRESH					ⓒ					ⓓ
3. SILENT-NOISY						ⓒ		ⓒ		ⓓ
4. BAD-SMELLING - GOOD-SMELLING							ⓒ			ⓓ
5. DRY-DAMP										ⓓ
6. MOVING AIR-STILL AIR					ⓒ					ⓓ
7. CLEAR-HAZY					ⓒ					ⓓ
8. WARM-COOL			ⓒ		ⓒ					ⓓ
9. PLEASANT-UNPLEASANT			ⓑ							ⓓ
10. DIRTY AIR-CLEAN AIR					ⓑ					ⓓ
I FEEL:										
11. COMFORTABLE-UNCOMFORTABLE					ⓑ				ⓑ	ⓓ
12. DAMP-DRY										ⓓ
13. COOL-WARM			ⓒ		ⓒ					ⓓ
14. FREE-CROWDED										ⓓ
COMPARED TO MY BODY,										
15. MY HANDS FEEL WARMER-COOLER	ⓒ			ⓒ	ⓒ	ⓑ				ⓓ
16. MY FEET FEEL WARMER-COOLER					ⓑ					ⓓ
PHYSICALLY AT THIS TIME I AM:										
17. SICK-WELL				ⓒ	ⓒ					ⓓ
MENTALLY AT THIS TIME I AM:										
18. JITTERY-CALM									ⓒ	ⓓ
19. DOWN-UP									ⓑ	ⓓ
20. ALERT-SLUGGISH									ⓒ	ⓓ
THE CLOTHING I AM WEARING TODAY IS:										
21. LIGHT-HEAVY									ⓑ	ⓓ
22. BULKY-NOT BULKY										
23. NUMBER OF LAYERS									ⓒ	ⓓ

Table 6-8. Ten Classes in Which Data Were Collected, (concluded)

NOTES:

ⓐ CODE FOR CLASSES:

DESCRIPTION OF CLASSES:	0	1	2	3	4	5	6	7	8	9
NUMBER OF BOYS' ANSWERS	4	0	4	0	19	12	0	5	5	10
NUMBER OF GIRLS' ANSWERS	8	54	4	15	29	4	24	2	8	18
ROOM NUMBER	162	162	164	164	300	162	162	164	164	300
DAY	1	1	1	1	1	2	2	2	2	2
PERIOD	1	7	2	6	7	2	7	3	6	7
CLASS	H	CH	GM	CH	BAND	H	CH	GM	GM	BAND

H = HEALTH

CH = CHORUS

GM = GENERAL MUSIC

ⓑ THE MEAN DIFFERENCE BETWEEN THE REVISED CONTROL AND THE EXPERIMENTAL CO_2 CONTROL SYSTEM DIFFERS SIGNIFICANTLY AT THE 5 PERCENT LEVEL FOR THIS QUESTION FOR THIS CLASS.

ⓒ THE MEAN DIFFERENCE BETWEEN THE REVISED CONTROL AND THE EXPERIMENTAL CO_2 CONTROL SYSTEM DIFFERS SIGNIFICANTLY AT THE 1 PERCENT LEVEL FOR THIS QUESTION FOR THIS CLASS.

ⓓ THIS CLASS IS OMITTED FROM THE ANALYSIS SO THE MATRIX COULD BE INVERTED; THEREFORE ALL OTHER CLASSES ARE COMPARED TO THIS ONE.

used for analysis because it was large, relatively well-balanced by sex and because air stratification occurred in the band room.

The data used were the individual students' transformed responses for each day, rather than the differences between the means as were used in the overall analysis. There were a maximum of 306 usable responses to the nine items examined, and a minimum of 303. In this particular class, students responded four times under the conventional control system and two times under the CO_2 control system.

The model expresses the individual student responses as a function of:

- Which of the two systems was operating;
- Whether it was the first, second, or third day of operation of the temperature control system (as contrasted with the fourth day, which served as the reference day);
- Whether it was the first day of operation of the CO_2 control system (as contrasted with the second day, which served as the reference day);
- The location of the student: the front 1/3 or the back 1/3 (as contrasted with the middle 1/3, which served as the reference location);
- The location of the student: the left 1/3 or the right 1/3 (as contrasted with the middle 1/3, which served as the reference location).

In mathematical form, the model can be expressed as:

$$R = a + b_1x_1 + b_2x_2 + \ldots + b_9x_9 + \varepsilon \qquad (6\text{-}3)$$

where:

R = student's transformed responses;

a = intercept;

x_n = category variables; $x_n = 0$, except:

$x_1 = 1$ if system = CO_2 control,

$x_2 = 1$ if day = first day of temperature control,

$x_3 = 1$ if day = second day of temperature control,

$x_4 = 1$ if day = third day of temperature control,

$x_5 = 1$ if day = first day of CO_2 control,

$x_6 = 1$ if location = left 1/3,

$x_7 = 1$ if location = right 1/3,

$x_8 = 1$ if location = front 1/3,

$x_9 = 1$ if location = back 1/3;

b_n = b-value associated with category variable x_n;

ε = error.

Results are summarized in Tables 6-9 and 6-10. The items analyzed were the first nine that are indicated by Note b for Class 4 in Table 6-8 (i.e., item 17 in Table 6-8 was not analyzed).

Table 6-9. Detailed Analysis of the Data from the 7th Period Band Class[a] in the Day Sequence, Results of Analysis of Variance on Transformed Responses

ITEM	MEAN	STANDARD DEVIATION	NUMBER OF RESPONSES	F	R^2
CONDITIONS IN THIS ROOM ARE:					
2. STALE-FRESH	1.82	4.17	306	6.85[b]	0.17
6. MOVING AIR-STILL AIR	0.27	4.89	304	17.37[b]	0.35
7. CLEAR-HAZY	-2.27	4.61	303	2.77[b]	0.08
8. WARM-COOL	-1.92	4.75	305	14.47[b]	0.31
9. DIRTY AIR-CLEAN AIR	2.37	3.89	304	2.63[b]	0.07
I FEEL:					
11. COMFORTABLE-UNCOMFORTABLE	-1.70	4.94	306	1.02	0.03
13. COOL-WARM	1.60	4.87	304	13.21[b]	0.29
COMPARED TO MY BODY:					
15. MY HANDS FEEL WARMER-COOLER	-0.41	5.27	305	3.90[b]	0.11
16. MY FEET FEEL WARMER-COOLER	-0.18	5.63	305	1.14	0.03

[a] 19 BOYS, 29 GIRLS.
[b] SIGNIFICANCE BEYOND THE 1 PERCENT LEVEL, THIS MEANS THE MODEL (i.e., THE VARIABLES) ACCOUNTS FOR A SIGNIFICANT PORTION OF THE VARIATION IN THE RESPONSES.

NOTE: – CORRESPONDS TO LEFT ADJECTIVE
+ CORRESPONDS TO RIGHT ADJECTIVE

Generally, the means show that students described conditions in the room as "fresh," "clear," "warm," and the air as "clean." They reported that they were personally "comfortable" and "warm." Responses to other items were near the midpoint between the polar adjectives. Standard deviations were fairly large.

The variables in the model accounted for a significant portion of the variation in student responses (as shown by F) for all items analyzed except "comfortable-uncomfortable" and "my feet feel warner-cooler than my body." The variables in the model accounted for up to 35 percent of the total variation in students'

Table 6-10. Detailed Analysis of the Data from the 7th Period Band Class in the Day 1 Sequence, List of the b-Values[a] Obtained in the Analysis of Variance

ITEM	INTERCEPT (a)	SYSTEM (b_1)	TEMPERATURE CONTROL			CO_2 CONTROL	LOCATION IN ROOM[b]			
			DAY 1 - DAY 4 (b_2)	DAY 2 - DAY 4 (b_3)	DAY 3 - DAY 4 (b_4)	DAY 1 - DAY 2 (b_5)	LEFT (b_6)	RIGHT (b_7)	FRONT (b_8)	BACK (b_9)
CONDITIONS IN THIS ROOM ARE:										
2. STALE - FRESH	-0.29	-2.21 [c]	-1.77 [c]	-1.15 [c]	0.55	-0.62 [d]	0.51	-0.15	0.74	-0.37
6. MOVING AIR - STILL AIR	1.57	3.81 [c]	2.43 [c]	2.07 [c]	-1.42 [c]	0.65 [d]	-0.39	-0.26	-0.85	0.38
7. CLEAR - HAZY	-4.06	-0.09	-0.87 [e]	-0.08	-1.70 [c]	-0.33	-0.47	0.26	-1.06	0.23
8. WARM - COOL	-5.62	-2.96 [c]	-2.86 [c]	-1.97 [c]	0.25	-1.57 [c]	0.99 [d]	1.80 [c]	-0.06	-0.25
9. DIRTY AIR - CLEAN AIR	1.93	-1.20	-0.80 [e]	-0.34	0.48	-0.15	0.16	1.11 [e]	0.60	-0.57
I FEEL:										
11. COMFORTABLE - UNCOMFORTABLE	-1.66	0.92	0.42	0.37	-0.40	0.27	-0.20	0.90	-0.52	-0.15
13. COOL - WARM	4.91	3.48 [c]	2.97 [c]	2.31 [c]	-0.32	1.13 [c]	-0.78	-1.15 [e]	-0.29	0.18
COMPARED TO MY BODY,										
15. MY HANDS FEEL WARMER - COOLER	0.90	-1.66 [d]	-0.19	-0.53	0.29	-0.77	-0.67	1.50 [e]	-1.99 [c]	-1.47 [e]
16. MY FEET FEEL WARMER - COOLER	0.40	-0.66	0.06	-0.50	0.26	0.29	0.51	0.37	-0.23	-1.68 [e]

[a] SEE EQUATION (6-3)

[b] LOCATION FROM THE STUDENT'S VIEWPOINT.

[c] SIGNIFICANCE BEYOND THE 1 PERCENT LEVEL.

[d] SIGNIFICANCE BETWEEN 5 AND 10 PERCENT LEVEL.

[e] SIGNIFICANCE BEYOND THE 5 PERCENT LEVEL, BUT NOT AS GREAT AS 1 PERCENT.

NOTE: – = LEFT-HAND POLAR ADJECTIVE.

- = LEFT-HAND POLAR ADJECTIVE.

responses (as shown by R^2). The largest R^2 was for "still air-moving air," and "warm-cool," both for the room and for the individual, were next with 31 percent and 29 percent, respectively. The fact that "comfortable-uncomfortable" and "my feet feel warmer-cooler" were not significant here, whereas they were in the overall analysis (Table 6-8), may be due to this class being different from the other band class on these items (the reference class in the overall model) rather than that anything unusual occurred in this class.

The students observed significant differences ($p \leq 0.05$) between the temperature--driven control system and the CO_2-driven control system for four items. They reported the room to be less fresh, the air to have less movement, the room warmer and themselves warmer while the CO_2-driven system was operating than while the temperature-driven control system was operating. The result for "my hands feel warmer than my body" was not significant at $p = 0.05$, but the probability of this F-value approached significance. Therefore, these results were comparable to the results for all rooms combined.

In addition, students reported considerable day-to-day variation on each of the two systems after the overall variation in the two systems was taken into account. They reported that the air in the room was less fresh on Days 1 and 2 of operation of the conventional system than on Day 4, and also a tendency (approaching significance) for the air on Day 1 of the CO_2-driven system to be less fresh than on the second day of the experimental system. They reported that the air had less movement on Days 1 and 2, but more movement on Day 3 of the conventional system, as compared to Day 4. Likewise, there was a tendency for the air to have less movement on the first day of the CO_2-driven system as compared to the second. The air tended to be clearer on Day 1 and was definitely clearer on Day 3 of the conventional system, as compared to Day 4. Days 1, 3 and 3 of the conventional system and Day 1 of the experimental system were judged to have dirtier air than Day 4. The teacher's observations indicated that conventional control Day 1 was "too warm" and conventional control Day 2 was "a little too warm," whereas both experimental days were "too hot." The

teacher reported nothing unusual about temperature on conventional control Days 3 and 4, nor anything about air quality or velocity on any day. Some of these differences may be random results, but others may be related to a problem with a valve that was incorrectly installed and was corrected on February 7, 1980.*

The students reported no difference in how comfortable they felt on different days. They did, however, report that they felt warmer on the first three days of the conventional system and on the first day of the experimental system. They did not report any differences in how warm their hands and feet were, except that on Day 1 of the conventional system the responses to "my hands feel warmer-cooler" approached significance.

Student location in the room rarely affected the responses to the nine items examined. Students sitting on the sides of the room tended to report that they were cooler and that the room was colder than did students sitting in the middle of the room. This effect was significant for those on the right side of the room, but did not reach significance for those on the left side. Students on the right side also reported that the air was cleaner and that their hands were cooler, as compared to students in the middle of the room.

The students' responses showed no significant effects of stratification. Those in both the front and back of the room reported that their hands were warmer than did students in the middle, and those in the back reported that their feet were warmer. A complicating element in this analysis was that, in the

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*Dates of measurement:

Conventional System	Experimental System
Day 1 -- 01/28	Day 1 -- 01/30
Day 2 -- 02/01	Day 2 -- 02/05
Day 3 -- 02/07	
Day 4 -- 02/13	

band class, students tended to sit in the same places every day.* Therefore, personal variation in responses was confounded with location in the room. However, although the effects of location were not statistically significant, the b-values for location shown in Table 6-10 form a pattern. The b-values for front and back locations showed that the students in the back of the room perceived the air as less fresh, hazier, warmer, dirtier and having less movement, that they were less comfortable and felt warmer, and that they had warmer feet, as compared to the students in the front of the room. But for some reason, those in the back had cooler hands than those in the front.

Part of the reason stratification did not show more clearly in the student responses may have been due to the simicircular design of the seating levels, which does not correspond to the nine-section division of the room into rectangles for identifying student position. To further investigate this point, a second grid based on the row distributions also was used (see Subsection 5.5.3). An analysis similar to that just presented was performed. The model, Equation (6-1), was the same but x_8 was set equal to 1 if the student was located in the third row of the band room and x_9 was set equal to 1 if the student was located in the back two rows of the band room.

Results of this analysis are summarized in Tables 6-11 and 6-12. Here the regressions were computed as in Table 6-10 except for the substitution of level for front-back position. As should happen, the b-values and significance levels of variables for System and Day remained almost unchanged. These were independent of where the students were sitting. There were some small changes in F and R^2. Intercepts changed, but these are unimportant.

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*Ideally, to measure the effects of location in the room, subjects should have been seated in different locations each day according to a planned experimental design. This was not possible in band classes and, even in other types of classes, it would probably involve undue interference in class activities and might affect the quality of the data.

Table 6-11. Detailed Analysis of the Data from the 7th Period Band Class[a] in the Day 1 Sequence with Location Defined by Level, Results of Analysis of Variance on Transformed Responses

ITEM	MEAN	STANDARD DEVIATION	NUMBER OF RESPONSES	F	R^2
CONDITIONS IN THIS ROOM ARE:					
2. STALE-FRESH	1.02	4.17	306	6.81[b]	0.17
6. MOVING AIR-STILL AIR	0.27	4.89	304	17.56[b]	0.35
7. CLEAR-HAZY	−2.27	4.61	303	2.58[b]	0.07
8. WARM-COOL	−1.92	4.75	305	14.98[b]	0.31
10. DIRTY AIR-CLEAN AIR	2.37	3.89	304	2.88[b]	0.08
I FEEL					
11. COMFORTABLE-UNCOMFORTABLE	−1.70	4.94	306	1.17	0.03
13. COOL-WARM	1.60	4.87	304	13.85[b]	0.30
COMPARED TO MY BODY,					
15. MY HANDS FEEL WARMER-COOLER	−0.41	5.27	305	5.06[b]	0.13
16. MY FEET FEEL WARMER-COOLER	−0.18	5.03	304	0.70	0.02

[a] 19 BOYS, 29 GIRLS

[b] SIGNIFICANCE BEYOND THE 1 PERCENT LEVEL. THIS MEANS THE MODEL (i.e., THE VARIABLES) ACCOUNTS FOR A SIGNIFICANT PORTION OF THE VARIATION IN THE RESPONSES.

NOTE: − CORRESPONDS TO LEFT ADJECTIVE
+ CORRESPONDS TO RIGHT ADJECTIVE

Table 6-12. Detailed Analysis of the Data From the 7th Period Band Class in the Day 1 Sequence with Location Defined by Level, List of the b-Values[a] Obtained in the Analysis of Variance

ITEM	INTERCEPT (a)	SYSTEM (b_1)	TEMPERATURE CONTROL			CO_2 CONTROL	LOCATION IN ROOM[b]			
			DAY 1–DAY 4 (b_2)	DAY 2–DAY 4 (b_3)	DAY 3–DAY 4 (b_4)	DAY 1–DAY 2 (b_5)	LEFT (b_6)	RIGHT (b_7)	MIDDLE–LOW (b_8)	HIGH–LOW (b_9)
CONDITIONS IN THIS ROOM ARE:										
2. STALE–FRESH	0.12	−2.17[c]	−1.77[c]	−1.19[c]	0.57	−0.64[d]	0.76	0.12	−0.42	−0.92
6. MOVING AIR–STILL AIR	0.96	3.76[c]	2.42[c]	2.09[c]	1.43[c]	0.68[d]	−0.76	−0.68	0.78	1.27[e]
7. CLEAR–HAZY	−4.62	−0.11	−0.86[d]	−0.07	−1.69[c]	−0.32	−0.68	0.00	0.80	0.82
8. WARM–COOL	−5.36	−2.88	−2.85[c]	−1.94[c]	0.28	−1.60[c]	1.33[e]	2.14[c]	−0.26	−1.00[d]
10. DIRTY AIR–CLEAN AIR	2.19	−1.14	−0.77[e]	−0.33	0.49	−0.18	0.45	1.34[e]	0.15	−0.99[d]
I FEEL										
11. COMFORTABLE–UNCOMFORTABLE	−2.22	0.89	0.43	0.37	−0.40	0.28	−0.40	0.58	1.06	0.72
13. COOL–WARM	4.45	3.40[c]	2.96[c]	2.28[c]	−0.36	1.16[c]	−1.16[d]	−1.57[e]	0.43	1.25[e]
COMPARED TO MY BODY,										
15. MY HANDS FEEL WARMER–COOLER	−1.67	−1.64[d]	−0.12	−0.48	0.37	−0.80[d]	−0.72	0.96	3.31[c]	0.79
16. MY FEET FEEL WARMER–COOLER	0.32	−0.57	0.09	−0.48	−0.26	0.25	1.06	0.77	−1.02	−1.05

[a] SEE EQUATION (6-3)
[b] LOCATION FROM THE STUDENT'S VIEWPOINT.
[c] SIGNIFICANCE BEYOND THE 1 PERCENT LEVEL.
[d] SIGNIFICANCE BEYOND THE 5 PERCENT LEVEL, BUT NOT AS GREAT AS 1 PERCENT.
[e] SIGNIFICANCE BETWEEN 5 AND 10 PERCENT LEVEL.

NOTE: – CORRESPONDS TO LEFT ADJECTIVE
+ CORRESPONDS TO RIGHT ADJECTIVE

Coefficients for left-right position in the room were different when level was included in the equation instead of front-back. The problem was that right-left position was not independent of level. Neither analysis (Table 6-10 or Table 6-12) sorted out these interrelationships of position in the room and level. Table 6-12 presents some evidence of stratification, particularly for warmth, but it is not much stronger than in Table 6-10. As in Table 6-10, most nonsignificant results were roughly in the direction that would have been expected. The reason that hands were significantly cooler in the middle row of seats was not clear.

Finally, a similar analysis was performed on the data obtained in Class 9, and the results are listed in Tables 6-13 and 6-14.

Class 9 was smaller than Class 4, but had about the same proportion of males and females. Class 9 was the reference class in the analysis of differences between the two systems (Tables 6-7 and 6-8). The models in Tables 6-13 and 6-14 were identical to those in Tables 6-11 and 6-12. Comparability of results for the two classes helped to validate the conclusions reached from analysis up to this point.

All means were in the same direction and most were roughly similar in size. Class 9 standard deviations usually were slightly larger than those for Class 4. The $\underline{F}$-values usually were smaller, but the same $\underline{F}$-values were significant for the two classes. Sometimes the R^2 was larger for Class 9, sometimes smaller than for Class 4. In general, Class 9 had a little more unexplained variation than Class 4.

Of importance is that most of the results for system and day of operation were comparable for the two classes (it should be remembered that days were not the same for both classes; they were on different schedules). The greatest differences for system were for "stale-fresh" and "I feel cool-warm," but the differences were toward the same pole for both variables. Class 9 showed the same

Table 6-13. Detailed Analysis of the Data from the 7th Period Band Class[a] in the Day 2 Sequence with Location Designed by Level, Results of Analysis of Variance on Transformed Responses

ITEM	MEAN	STANDARD DEVIATION	NUMBER OF RESPONSES	F	R^2
CONDITIONS IN THIS ROOM ARE:					
2. STALE-FRESH	1.50	4.67	199	2.23[b]	0.09
6. MOVING AIR-STILL AIR	0.11	5.26	198	3.18[c]	0.12
7. CLEAR-HAZY	–3.01	4.61	199	4.18[c]	0.15
8. WARM-COOL	–0.92	5.51	200	6.96[c]	0.23
10. CLEAN AIR-DIRTY AIR	3.17	4.00	199	2.77[c]	0.10
I FEEL					
11. COMFORTABLE-UNCOMFORTABLE	–1.88	5.22	200	1.17	0.05
13. COOL-WARM	1.23	5.82	198	4.75[c]	0.17
COMPARED TO MY BODY,					
15. MY HANDS FEEL WARMER-COOLER	–0.29	5.93	199	2.97[c]	0.11
16. MY FEET FEEL WARMER-COOLER	–1.54	5.33	199	1.74[d]	0.07

[a] 10 BOYS, 18 GIRLS

[b] SIGNIFICANCE BEYOND THE 5 PERCENT LEVEL, BUT NOT AS GREAT AS 1 PERCENT.

[c] SIGNIFICANCE BEYOND THE 1 PERCENT LEVEL. THIS MEANS THE MODEL (i.e., THE VARIABLES) ACCOUNTS FOR A SIGNIFICANT PORTION OF THE VARIATION IN THE RESPONSES.

[d] SIGNIFICANCE BETWEEN 5 PERCENT AND 10 PERCENT LEVEL.

NOTE: – CORRESPONDS TO LEFT ADJECTIVE
+ CORRESPONDS TO RIGHT ADJECTIVE

Table 6-14. Detailed Analysis of the Data From the 7th Period Band Class[a] in the Day 2 Sequence with Location Defined by Level, Results of Analysis of Variance on Transformed Responses

ITEM	INTERCEPT (a)	SYSTEM (b_1)	TEMPERATURE CONTROL		CO_2 CONTROL	LOCATION IN ROOM[b]			
			DAY 1–DAY 3 (b_2)	DAY 2–DAY 3 (b_3)	DAY 1–DAY 2 (b_4)	LEFT (b_5)	RIGHT (b_6)	MIDDLE–LOW (b_7)	HIGH–LOW (b_8)
CONDITIONS IN THIS ROOM ARE:									
2. STALE–FRESH	−1.28	−0.62	−1.40[c]	−0.47	−1.07[d]	0.50	1.07	1.50[c]	0.93
6. MOVING AIR–STILL AIR	1.51	3.63[c]	1.98[c]	2.37[c]	−0.11	0.32	1.20	−1.80[c]	−0.69
7. CLEAR–HAZY	−0.57	0.79	1.07[d]	0.65	−0.01	0.70	−2.61[c]	−1.51[c]	−1.44[c]
8. WARM–COOL	−3.91	−2.54[c]	−2.99[c]	−3.01[c]	−0.94	−1.06	−1.94[d]	2.56[c]	0.38
10. DIRTY AIR–CLEAN AIR	0.81	−0.09	−0.89[d]	−0.17	−0.35	0.14	2.00[c]	1.27[c]	1.14
I FEEL									
11. COMFORTABLE–UNCOMFORTABLE	0.91	0.28	0.79	−0.35	0.65	−1.78[c]	−1.00	0.45	0.58
13. COOL–WARM	3.52	2.20[c]	2.66[c]	2.52[c]	1.23[d]	0.95	2.65[c]	−1.44	0.46
COMPARED TO MY BODY,									
15. MY HANDS FEEL WARMER–COOLER	2.26	−0.40	−1.98[c]	−1.90[c]	−0.75	−0.40	−2.29[d]	1.08	0.16
16. MY FEET FEEL WARMER–COOLER	−0.92	−0.67	−1.08[c]	−0.87	0.24	−0.74	−2.40[c]	−0.24	−0.54

[a] SEE EQUATION (6-3)

[b] LOCATION FROM THE STUDENT'S VIEWPOINT.

[c] SIGNIFICANCE BEYOND THE 1 PERCENT LEVEL.

[d] SIGNIFICANCE BETWEEN 5 AND 10 PERCENT LEVEL.

[e] SIGNIFICANCE BEYOUND THE 5 PERCENT LEVEL, BUT NOT AS GREAT AS 1 PERCENT.

NOTE: – CORRESPONDS TO LEFT ADJECTIVE
+ CORRESPONDS TO RIGHT ADJECTIVE

results as Class 4 for day of operation; the two systems seemed to be warmer and stuffier on the earlier days of operation than on the last days.

On location in the room, the results for Class 9 were quite different from those for Class 4; in fact, some results suggest the opposite of what would be expected if the room environment was stratified. Also, right-left differences were sometimes in the opposite direction for the two classes, but this simply may have reflected the lack of independence between level and right-left location. It is interesting that the "my hands feel cooler" syndrome in the middle row also showed up, but not significantly, in Class 9.

The main conclusion to be drawn from the comparison of the two classes was that caution must be used in interpreting results from just one class. The results were encouraging in terms of the similarity of results for system and day, but the subtle differences in environment resulting from stratification were not seen clearly in these data.

6.4.3 Relationship Between Subjective Responses and Physical Data

The students' subjective responses showed that they perceived differences between the environments that resulted from the temperature-driven and the CO_2-driven control systems. The major differences expected in the environment were the CO_2 concentration levels, the concentrations of other contaminants (odors, for example), and the variables that affect thermal comfort (dry-bulb temperature, wet-bulb temperature, mean-radiant temperature and air velocity). Thus, an analysis was done to look for a correlation between the subjective responses and the measured environmental variables.[†] To simplify the analysis, all thermal variables were combined into a comfort parameter (SET*).

[†]No contaminant levels were measured in Fridley on a regular basis; thus, their effects were not included in the analysis.

The mathematical model used in the statistical analysis was as shown in Equation (6-4).

$$R = a + b_1(SET^*) + b_2(C_{CO_2}) + b_3(SET^* \times C_{CO_2}) + \varepsilon \qquad (6\text{-}4)$$

where:

R = transformed subjective response,

a = intercept,

SET* = average value of SET*[†] for the class in which the response was obtained.

C_{CO_2} = average value of the CO_2 concentration during the class in which the response was obtained,

b_n = b-values for each variable,

ε = error.

The analysis was carried out for the five items previously found to be significantly different for the two systems (see Table 6-7). Data for the analysis were:

- The average response (R) to each question analyzed for each class meeting;
- The value of SET* calculated with the average measured dry-bulb temperature and relative humidity for each class meeting;

[†]SET* values were calculated using the program listed in Appendix A. The environmental variables were as measured and recorded by the datalogger. Metabolic rate was obtained from the teachers' observation sheets: classes reporting "not active" were set at 1 met and classes reporting "moderately active" were set at 1.5 met. Clothing insulation was derived from the number of layers of clothing reported by the student (0.50 Clo per layer).

- The value of the average CO_2 concentration (C_{CO_2}) measured for each class meeting.

The results of the analysis of variance are summarized in Table 6-15. These results form a consistent pattern for all five questions and show a strong interaction between comfort (SET*) and CO_2 levels (i.e., an increase in the CO_2 concentration would bring conditions closer to thermal neutrality). This effect is stronger for lower values of SET* (i.e., tends to decrease as SET* increases). A typical example is shown in Figure 6-26, which shows a plot of the obtained correlation between the transformed subjective responses for item 8, "Conditions in the room are warm-cool," and SET*, with CO_2 concentration as a parameter. Three ranges of CO_2 concentration (400 to 600 ppm, 900 to 1100 ppm and 1400 to 1600 ppm) are shown (cross-hatched zones). Also shown are the data points that correspond to class meetings that had CO_2 concentrations within the limits of the three zones identified above.

6.5 COMMERCIALIZATION

The basic concept of variable ventilation control based on CO_2 measurement, in addition to establishing its technical validity through testing, also must undergo the scrutiny of commercialization issues. These issues are:

- How is the concept implemented in new and retrofit applications?

- What are the economics of installation from the viewpoint of payback or return on investment?

These issues are explored and answered below, drawing as appropriate on the findings of the present investigation.

Table 6-15. Relation Between Subjective Responses and Physical Data

ITEM	a ⓐ	b_1 ⓐ	b_2 ⓐ	b_3 ⓐ	F	R^2
CONDITIONS IN THIS ROOM ARE:						
2. STALE - FRESH	17.3	- 0.59	- 0.024	9.8×10^{-4}	98.3	0.17
6. MOVING AIR - STILL AIR	- 17.8	0.67	0.023	$- 9.1 \times 10^{-4}$	49.7	0.09
8. WARM - COOL	26.1	- 0.87	- 0.033	1.2×10^{-3}	148.0	0.24
I FEEL:						
13. COOL - WARM	- 29.5	1.01	0.036	$- 1.3 \times 10^{-3}$	144.0	0.23
COMPARED TO MY BODY,						
16. MY HANDS FEEL WARMER - COOLER	14.0	- 0.44	- 0.014	5.0×10^{-4}	46.0	0.09

ⓐ SEE EQUATION (6-3)

EXPLANATION: ALL F- AND b- VALUES ARE SIGNIFICANT TO THE 1 PERCENT LEVEL; THEREFORE, THE VARIABLES ACCOUNT FOR A SIGNIFICANT VARIATION IN THE RESPONSES.

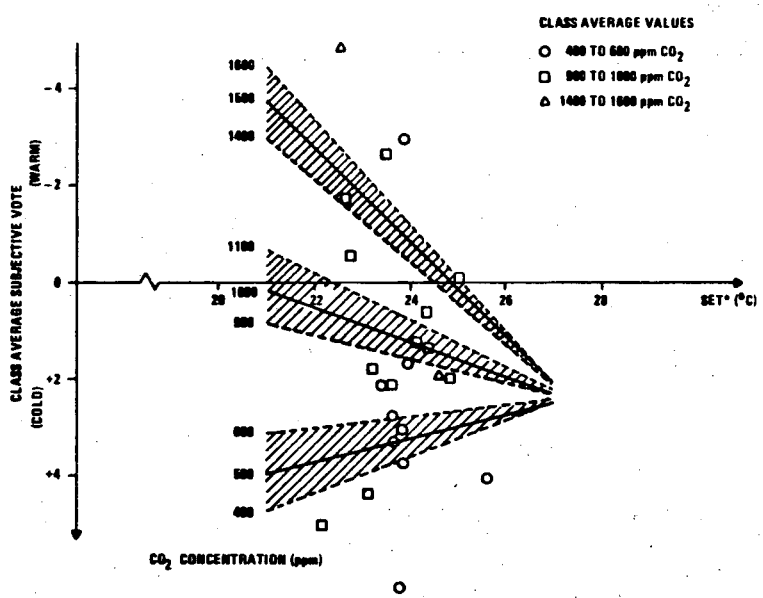

Figure 6-26. Correlation Between Students' Subjective Responses and SET* , with CO_2 Concentration as a Parameter (Item 8: "Conditions in the Room are Warm-Cool.")

6.5.1 Concept Implementation

At the outset of this study, a basic implementation concept was assumed; i.e., the variable CO_2-based ventilation control is added to an existing air economizer system. That is, the demands for air quality and comfort (temperature) control to be provided through the outdoor air dampers are superimposed, with the greater demand governing. This is consistent with the objective of the study to demonstrate that energy could be conserved with the variable ventilation control while maintaining comfort conditions in the controlled space.

In its simplest version, the adaptation of CO_2-controlled ventilation to an existing ventilation system is shown in Figure 6-27. The CO_2 signal replaces the previous minimum position in function. In operation, the outdoor air dampers are nominally in a closed position, opening only on demand for air quality or comfort control, as determined by the appropriate sensors and control logic.

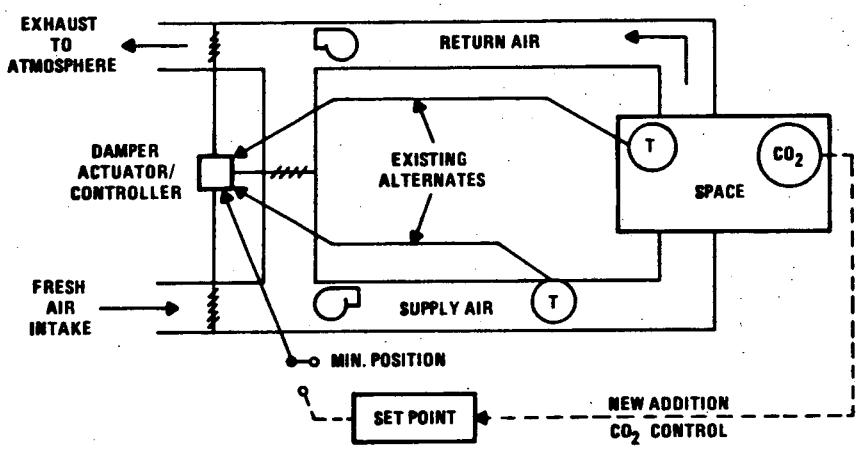

Figure 6-27. Schematic Representation of CO_2 Controlled Ventilation System

Figure 6-28 shows a typical existing mixed-air control system with minimum position switch. This pneumatic system is illustrated with representative Honeywell part numbers for discussion purposes. A single signal synchronously controls all three dampers: intake, exhaust and recirculation.

Figure 6-29 shows the same system with the CO_2 control added. The CO_2 sensor electrical signal is shaped for set-point control, or throttling range, converted to a pneumatic equivalent and "summed" with the pneumatic temperature signal in the pneumatic relay switch. The switch passes the greater of the two signals to the damper actuators which respond proportionately.

This implementation represents the least impact on retrofit costs and preserves comfort operation of the original system.

A variation of this implementation was investigated during the study and involves controlling only the outdoor intake damper with the CO_2 signal. This is a separate issue, related to the ventilation efficiency of the existing duct arrangement and is discussed in detail in a later section.

For the purposes of the present analysis, the implementation system of Figure 6-29 is assumed; that is, all three dampers are controlled synchronously by CO_2 and temperature. (Temperature could be replaced by enthalpy, which has little effect on the present analysis.)

The elements of the installation consist of the duct work--including air inlets and outlets in the controlled space--the CO_2 sensors, dampers and control logic. Each of these elements has an effect on CO_2-based ventilation installation costs, and payback considerations. They are discussed separately.

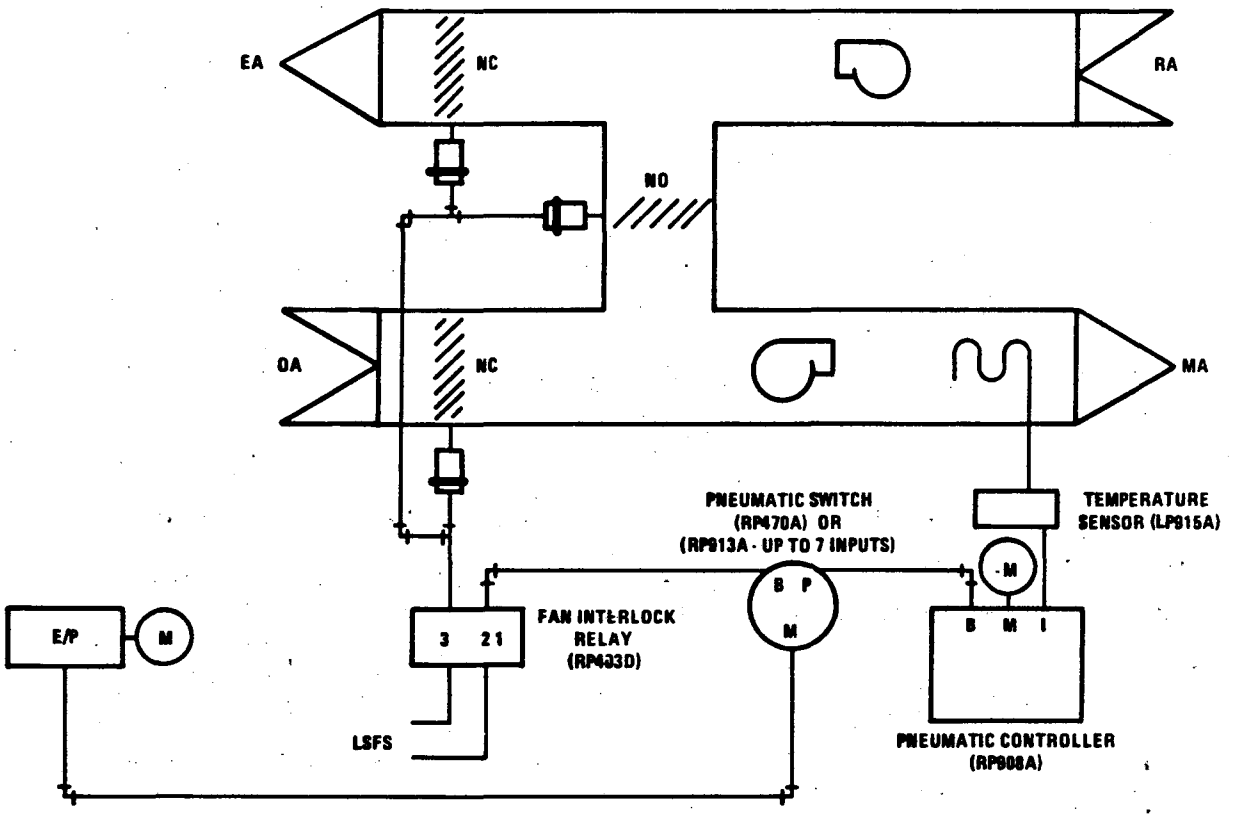

Figure 6-28. Typical Mixed-Air Control with CO_2 Minimum Air Control

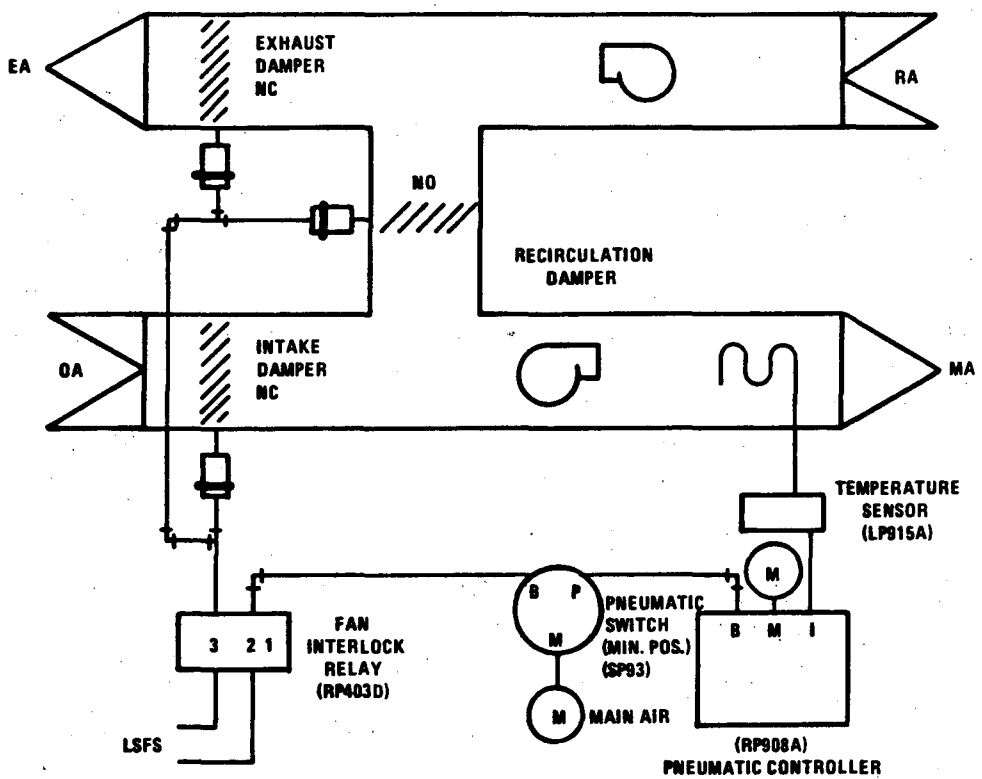

Figure 6-29. Typical Mixed-Air Control with Minimum Position Switch

6.5.11 Dampers--In general, existing damper systems are known to be notoriously imprecise in providing the design ventilation air for a building. Lack of maintenance, varying building loads, changes in air intake criteria, and the ignoring of building infiltration combine to produce situations in which intake air has little relation to actual building needs. These are issues separate from CO_2 control considerations and should be addressed before such additional control is implemented.

Design loads may require that 10 to 20 percent of circulated air be supplied by fresh outdoor air. Typical dampers, when closed, may pass 3 to 10 percent fresh air. Thus, in some buildings it well may be possible to "close" the outdoor air dampers and still meet code requirements for outdoor air. If infiltration is also considered, this further reduces the need for outdoor air. The implication of the above is twofold:

- Significant energy savings may be possible by rebalancing and retuning an existing system to existing standards. This is primarily a labor task, but could involve the addition of "leak-proof" dampers. Such tune-ups could also include "reheat optimization" as was done in the Fridley Junior High School tests.

- The retuned system represents a new standard to which CO_2-based ventilation must be referenced for economic and energy saving impacts. It is intuitive that for such a retuned system, damper leakage could represent a significant part of potential energy savings.

Each building, of course, is unique. We must assume, however, that to realize the maximum benefits of CO_2 control, damper leakage must be minimized. Thus, for the subsequent analysis, the addition of CO_2-based ventilation to an existing system must include "leak-proof" outside air dampers.

The Fridley Junior High School results include some of the above considerations. Leak-proof dampers were installed, and the existing system was improved by the reheat optimization modification. Thus, we feel that test results address at least part of the above constraints.

It should be recognized that a CO_2 implementation could "take credit" for the tune-up aspects of an installation. The following analysis is conservative in that it ignores any tune-up benefits.

Damper replacement costs will vary as to size and accessibility. Drawing upon the Fridley test, it is assumed that exchanging the existing dampers with low-leak dampers will cost the following:

Low-Leak Dampers	$620
72 x 24 inches @ $207 each	
Installation	$320
8 hours @ $40/hour	
Total	$940

6.5.1.2 CO_2 Sensor--The issues related to the CO_2 sensor are cost per unit and number of sensors required per system.

6.5.1.2.1 Number of Sensors and Placement--In the multizone system in the Fridley Junior High School we used a single laboratory-type CO_2 sensor (Anarad AR-101) which periodically sampled air, by a multiplexer arrangement, from three major rooms, outside, and common return and supply locations. The sampled data was stored for data retrieval to allow tracking of CO_2 concentration in all zones. The CO_2 control was mechanized such that in principle, the zone with the highest concentration was used as the control signal to the dampers. It was envisioned that if zone concentrations varied widely, this method would assure that any existing maximum could be controlled.

Data were reviewed to determine the need for multizone sampling. A single CO_2 measurement would minimize implementation costs and would be the ideal situation. CO_2 signals exhibited very dynamic behavior. In the total envelope of the CO_2 concentration from the five primary measurements (excluding outdoor air), any given zone would vary, in time, from maximum to minimum within the envelope. This variation arises from sensor noise itself, plus the mixing that occurred as loads varied in the different zones. The main return CO_2 concentration is seen as a reasonable average within the total envelope and typically did not differ from the maximum envelope values by more than 10 to 20 percent (Figure 6-16). On the basis of the Fridley data it is assumed that a practical mechanization could be based on a single CO_2 measurement in a common return location in the system ductwork.

The idea of multizone sampling, either through the multiplexing arrangement used in Fridley or perhaps with multiple CO_2 sensors, is not rejected as a possibility. Specific applications could dictate the need for multiple sampling. For further discussion, it is assumed that the typical, or general, installation of the CO_2 ventilation concept is based on a single, common location.

6.5.1.2.2 State-of-the-Art Sensors--Reference has been made to the Anarad CO_2 sensor used in the Fridley experiment. This device, while admirably serving the needs of the experiment, is not a likely candidate for general implementation. High initial cost ($2400), over-design for this special purpose application, and the need for frequent calibrations are the primary drawbacks. Alternate, "commercial grade" CO_2 measuring instruments are available. Anarad, for example, has such an instrument that is in the $1000 price range, is dedicated to CO_2 measurement only and requires infrequent calibration. Other brand names are also available. For purposes of cost estimation, it is assumed that current state-of-the-art sensors are suitable for CO_2-based ventilation control and have a price of $1000.

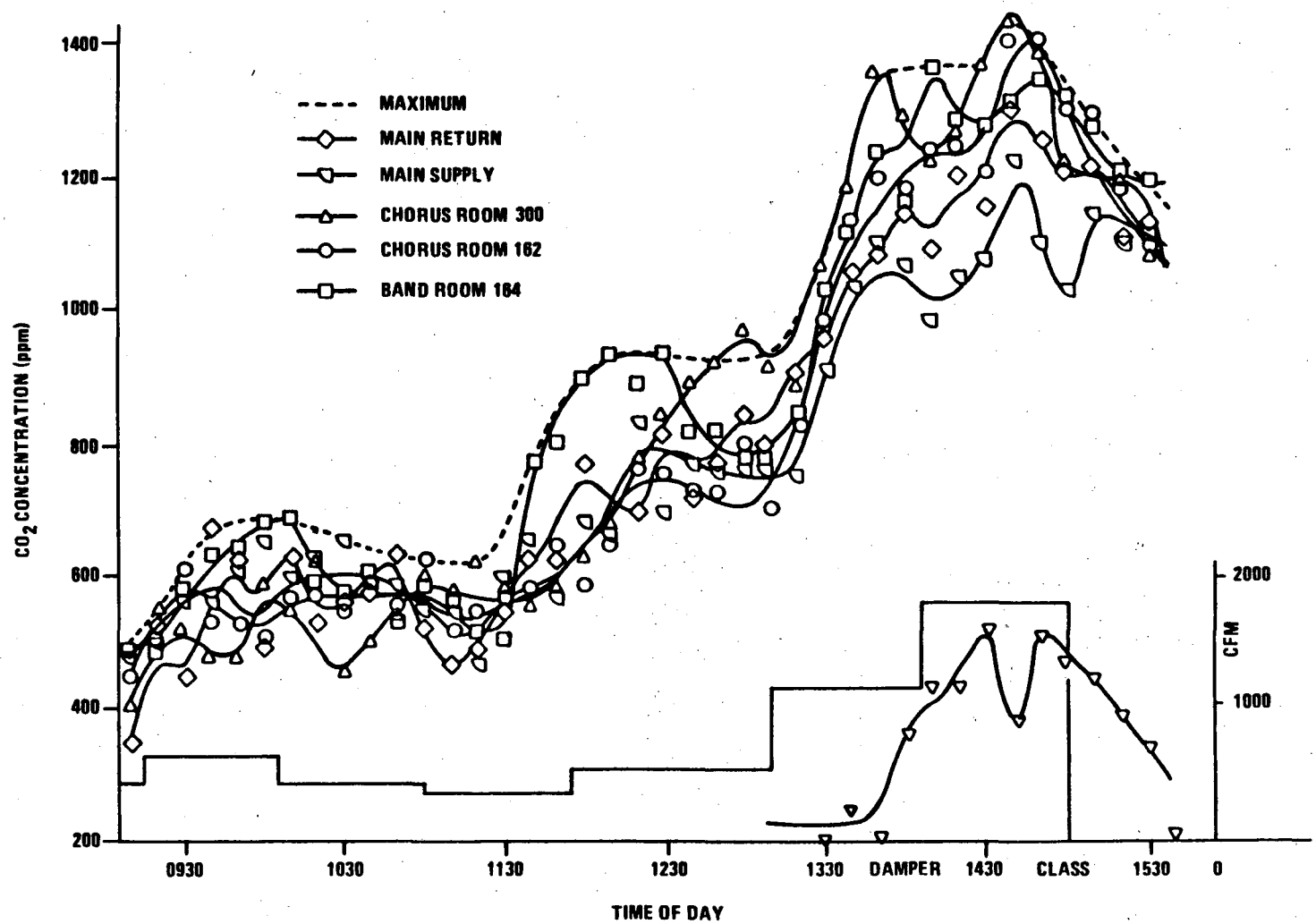

Figure 6-30. Typical Variation of CO_2 Concentration in Fridley Zones

6.5.1.2.3 Advanced Sensor Developments--It is known that several lines of research and development are in progress on alternate means of CO_2 detection and measurement.

One line of present research involves the use of solid-state emitter/detector elements. Sufficient independent research has been accomplished to demonstrate the feasibility of such devices as CO_2 (and other gas) detectors. Infrared light emitting diodes (IRLED's) operating at room temperatures have been made using a number of techniques. The wavelengths of interest in this research are:

H_2O	2.8 μm
CH_4	3.4 μm*
CO_2	4.3 μm
CO	4.7 μm
NO	5.3 μm
NO_2	6.2 μm**
SO_2	8.7 μm**

A brief history of this reseach indicated the current level of development of IRLED sensors. Beginning in about 1974, A.J. Gerritsen at Brown University made a number of IRLED's that were designed to provide outputs peaked at about 3.3 μm to match the absorption of methane. These devices were made of $In_{0.97}Ga_{0.03}As$, epitaxially grown on InAs substrates. Reasonably good results were obtained, even though the growth techniques were fairly crude and there was no attempt at lattice matching. Peak emissions varied from about 3.2 to 3.4 μm with half-height bandwidths of approximately 0.2 μm and average power outputs of 2.4×10^{-5} watts. This work was sponsored by the U.S. Bureau of Mines.

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*3.4 μm is the fundamental C-H stretching band, so that most hydrocarbons will absorb near this wavelength.

**These wavelengths are probably unattainable with IRLED's operating at room temperature.

Some follow-on work was sponsored at Brown University by Honeywell. The plan was to extend the range of emission to the 4.6-to-4.7-μm range to detect carbon monoxide. Since the $In_xGa_{1-x}As$ system will produce emitters to about 3.8 μm, $InAs_{1-y}Sb_y$ was used. As in the previous work, growth techniques were not refined, but devices were made with peak emissions ranging to about 4.3 μm. In several cases multiple peaks were observed, with the shorter wavelength peaks being ascribed to the InAs substrate material. The power output appears to be on the order of a few microwatts, and the room temperature half-height bandwidths are between 0.5 and 1.0 μm. It seems reasonable to assume that more careful work with this system could produce diodes emitting at 4.7 μm at room temperature.

During 1979, Honeywell's Corporate Technology Center proved that diffused junctions in $Hg_{1-x}Cd_xTe$ will emit light at wavelengths determined by the composition of the crystal. Using structures that were designed as photovoltaic detectors, emission was obtained with peak wavelengths ranging from about 3.5 μm to 4.5 μm. Half-height bandwidths ranged from about 0.5 to 1.0 μm, and power outputs were in the nanowatt range (10^{-9} watts). It should be emphasized that these were very small devices that were intended for use as detectors.

Listed in the advance program for CLEOS (Conference on Laser and Electro-Optical Systems) is the following abstract: "Room Temperature 4.6 μm Light-Emitting Diodes, by Wayne Lo and Don E. Swets, General Motors Research Laboratories. Infrared emission (4.6 μm) has been obtained from lead-salt p-n junctions at room temperature for the first time. These devices may have potential as sources for gas sensing and optical communications.

It is probable that at some future period, viable commercial-grade CO_2 sensors will evolve from research efforts as described above. Detector technology is more mature than that of the emitter. Growing of the crystal is, at this time, an art rather than a science. It is difficult to predict the time frame

of a viable solid-state detector/emitter for CO_2. Market demands for this, and other frequency spectrum applications such as carbon monoxide, will be an important factor in this development.

Cost projections are similarly difficult to estimate; however, it may be reasonable to expect such devices to fall into the $200 range, in 1980 dollars.

Summarizing the previous cost estimates for the various CO_2 sensors gives the following comparison:

Sensor Type	System Installed Cost
Laboratory	$2400
Commercial Grade	$1000
IRLED	$ 200

6.5.1.3 Control Logic--In its simplest implementation, the CO_2 control logic will consist of specification of the throttling range, i.e., the range of CO_2 concentration over which the dampers will respond from fully closed to fully open to some given position. Generally, this open position will roughly agree to the nominal minimum position which is presumed to provide "adequate" ventilation for design loads. The electrical signal is converted to pneumatic and compared to the temperature control signal in a pneumatic switch (Figure 6-29). These functions were provided in the Fridley Junior High School tests by a Moore Products 0-to-10-mv/3-to-5-psi-millivolt converter at a cost of $450.

It is recognized that a throttling range control concept does not provide "precise" control. This issue is discussed more fully in another section.

6.5.1.4 Air Distribution System--One of the findings of the Fridley Junior High School test, which is perhaps typical of many existing buildings, is that the air distribution system is far from optimum with respect to ventilation

efficiency. The placement of air supplies and returns are such that short-circuiting of the air flow occurs. The effect of this situation on CO_2 control of ventilation may be to require additional fresh air, both for CO_2 control and temperature control. While ventilation efficiency can be addressed in new construction, little can be done in an existing duct system. Circulation fans could be used at the expense of the parasitic electricity required. An alternate means to increase ventilation efficiency is to unbalance the air pressure--forcing exfiltration. In a CO_2 system this could be achieved by controlling only the intake damper with the CO_2 signal. This implementation would result in nonsynchronous operation of the dampers and would require additional damper actuators, pneumatic switches and possibly variable speed control on the supply and return air fans.

This effect of ventilation efficiency was briefly investigated by simulation and this showed that during the test period some savings might be obtained if perfect ventilation efficiency was assumed. The results are not conclusive, however, and it will be assumed that no special means are taken to improve ventilation efficiency of existing duct systems.

6.5.2 Installation Costs

The previous discussion of installation elements is summarized below to develop projected total system installed costs. Current CO_2 sensors, commercial grade, are assumed:

CO_2 Sensor	$1,000
E/P Converter with Set Point and Gain Control	$ 450
Replace Dampers with Low Leak (including installation)	$ 940
Miscellaneous Parts	$ 100
Installation 8 hours @ $40	$ 320
Total	$2,810

This cost represents a typical installation with assumptions previously noted and also represents the simplest implementation. It would replicate the results obtained in the Fridley Junior High School study.

6.5.3 Other Installation Issues

Certain assumptions were made in developing a typical installation cost. Other factors that may affect any or all installations are briefly investigated in this section.

6.5.3.1 Reliability--The benefits of the CO_2 ventilation concept are derived from operating outside air dampers from a closed position rather than a design minimum position. Further benefits, of course, also accrue from constraining the dampers to open only to the extent necessary to satisfy existing rather than design loads. There is an implication, therefore, that failures within the system could result in closed dampers during periods when ventilation is required.

General implementation of the CO_2 ventilation concept is likely to be accompanied by codes or standards limiting the maximum CO_2 concentration in a building or space. Japan, for example, has a national standard limiting CO_2 concentration to 1000 ppm.

Failures in the ventilation system components may be hard (damper closed) or soft (performance degraded). It is possible to protect a system against such failures with readily available technology. Occupants, or maintenance personnel, also represent a failure detection capability--particularly with hard failures. If the issue is a maximum CO_2 concentration that cannot be exceeded--even for short periods of time--a redundancy in the CO_2 sensor is the most direct means of sensing failures or degradation in performance anywhere within the system.

When the value of CO_2 exceeds a specified maximum, the dampers could be forced to the design minimum opening, known to provide adequate ventilation. The redundant sensor merely protects against failure in the sensor itself.

The redundant sensor must also be accompanied by logic circuitry to monitor CO_2 levels, compare sensors and provide the failure mode of operation and annunciation of failure. Estimated costs of such additions are:

Second Sensor	$1000
Monitor Electronics	$ 250
Total	$1250

6.5.4 Summary

It is concluded that within the current state of the art, CO_2 ventilation systems could be implemented in a general building, at costs on the order of $2800. The system would consist of off-the-shelf parts, installed by trades-people familiar with air handling systems and their controls. A number of issues remain to be resolved before commercialization of the concept will, or should, occur:

- Institutional barriers--revision of codes and standards.
- Fail-safe operational requirements.
- Return on investment.

6.5.5 National Impact

It is presumed that for the CO_2 system to become a commercially viable product, it must be cost-effective. That is, return on investment, or other payback considerations must be satisfied by consequential energy cost savings resulting

from product implementation. The factors that enter into a determination of cost-effectiveness are, then, product installation and maintenance cost, energy savings, and payback requirements. These are investigated in this section with a view to determining product cost "goals" assuming the other two parameters are known within an adequate range. Using this and other parameters, the impact of commercialization will be determined.

6.5.5.1 Payback Requirements--Reference is made to a recent study* in which a market survey was made to determine, among other things, payback periods that would be acceptable to owners or managers of three classes of buildings: schools, apartments and offices. The results from the nationwide survey are summarized in Figure 6-31.

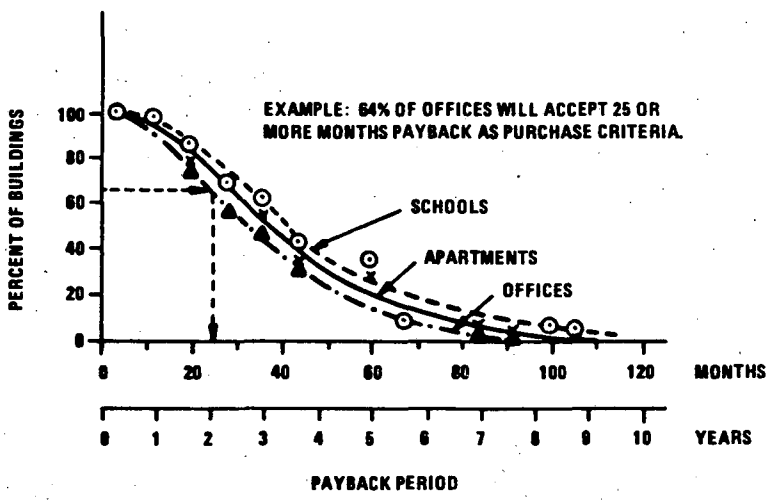

Figure 6-31. Payback Requirements by Building Sector

*DOE Report, BNL 50970, "Automated Energy Management Systems for Small Buildings," August 1978.

These data indicate that a three-year payback would be acceptable to more than 60 percent of the school sector. This figure will be used in subsequent analyses--recognizing the market limitation implied. Other payback/market limitation combinations could be used. Although return on investment calculations could contain many parameters such as the cost of money or depreciation, we will use the approach that a simple payback calculation will suffice, i.e.:

$$\text{Payback (years)} = \frac{\text{Installed Cost (\$)}}{\text{Energy Savings (\$/year)}}$$

It is further assumed that no significant additional maintenance is incurred from the addition of CO_2 control.

6.5.5.2 Energy Savings--From the Fridley Junior High School study we determined an annual percentage of energy savings during the heating season from variable ventilation control on the order of 20 percent. For this analysis, we will bracket that value with a range of savings potential from 10 to 30 percent to generalize the results. To apply the percentage savings, the base seasonal heating energy cost must be established. For any given existing building, the energy use is known. From a generalized approach, estimates may be made if the following conditions are known: building size, geographic location, energy rates and unit energy costs.

6.5.5.2.1 Unit Energy Costs--A useful energy cost figure is the total energy cost or usage per square foot per year for buildings. Two sources of such data are shown in Figures 6-32 and 6-33. These data, circa 1978, should be escalated at about 12 percent per annum to relate to the 1980 period of this study. From Figure 6-33, the average school energy cost (50 percent of the buildings) is about $0.72 per square foot per year, which escalated to 1980 is $0.90 per square foot per year. A market limitation is implied when using this average energy cost figure, which represents total energy used in a school.

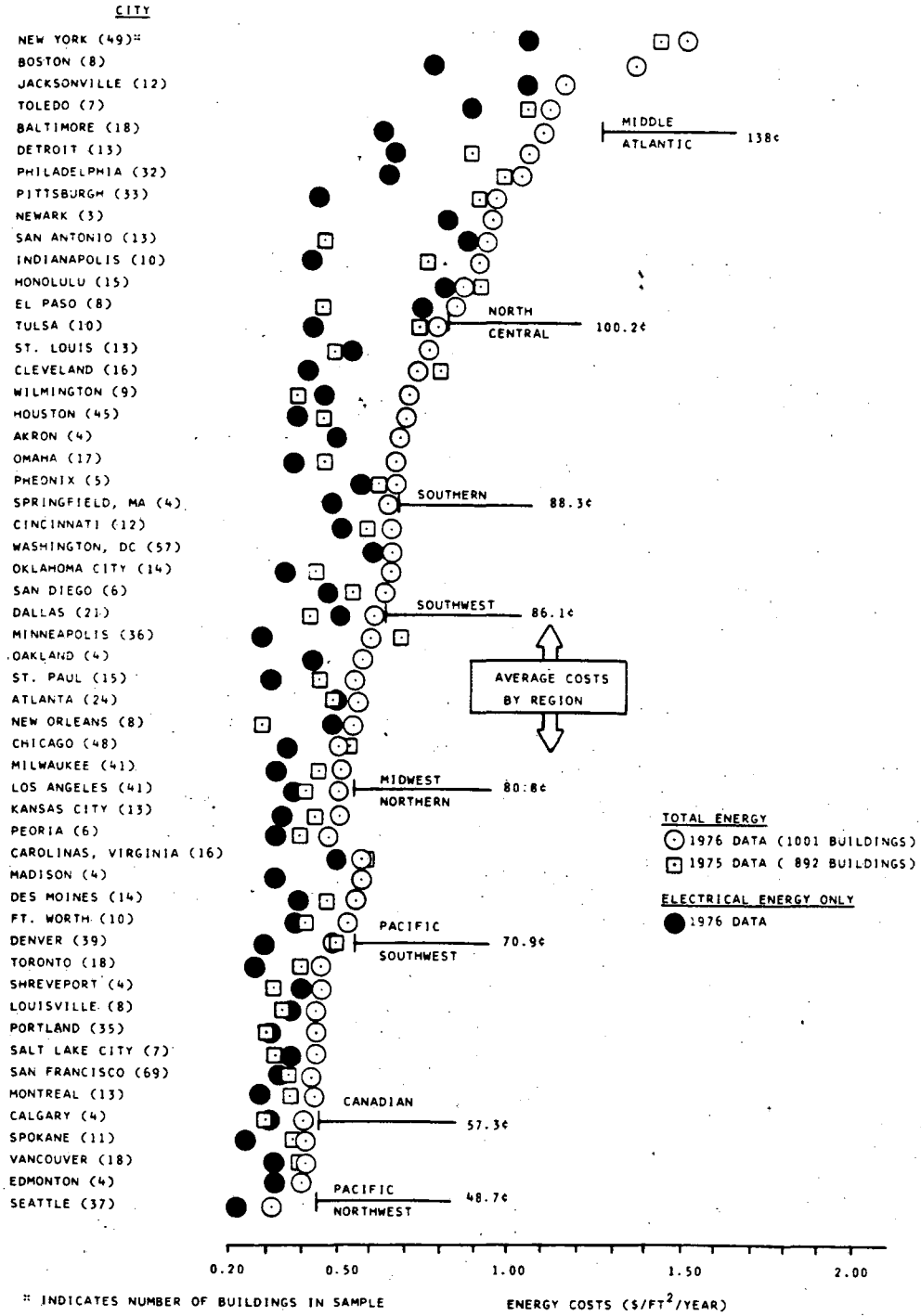

Figure 6-32. Annual Energy Costs, Office Buildings*

*Building Owners and Managers, International (BOMA), "Downtown and Suburban Office Building Experience Exchange Report," 1977.

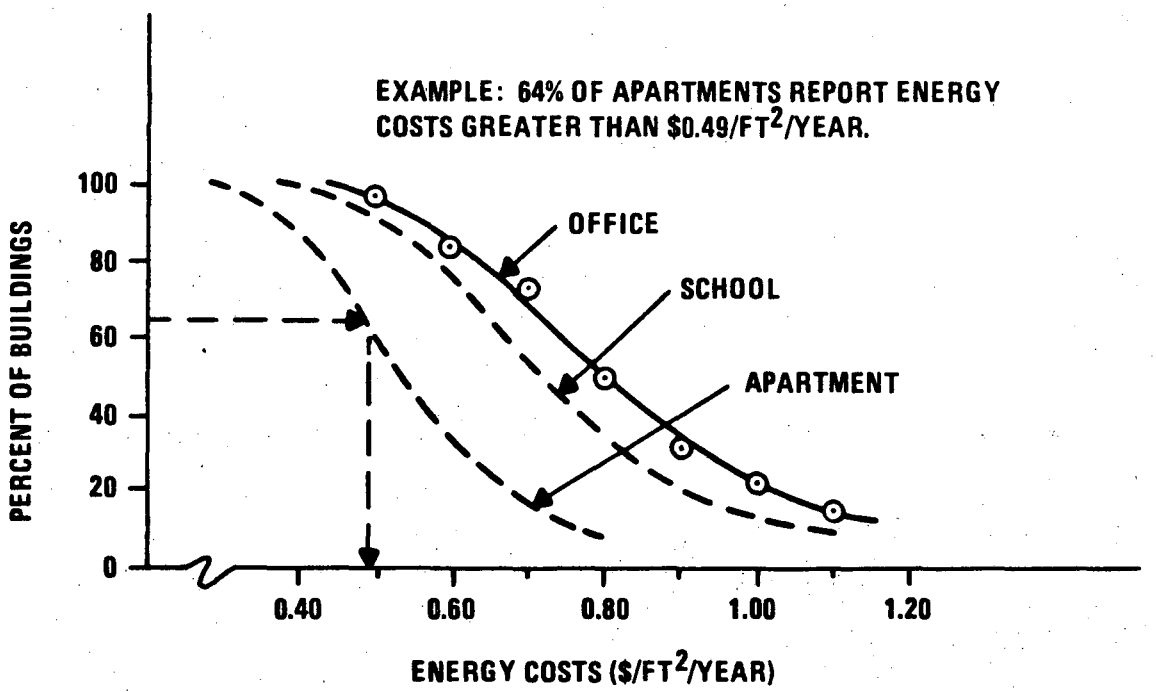

Figure 6-33. Percent of Market versus Total Energy Costs for Offices* and Schools and Apartments**

* Building Owners and Managers, International (BOMA), "Downtown and Suburban Office Building Experience Exchange Report, " 1977.

** U.S. Department of Energy, "Phase I/Base Data for the Development of Energy Performance Data for New Buildings," 12 January 1978.

Allocation of total energy to various end uses is discussed in "Residential and Commercial Energy Use Patterns, 1970-1990" (Federal Energy Administration, November 1974). A national average shows that about 72 percent of total energy, with small regional variations, is used for combined space heating and cooling in terms of Btu/ft^2.

Combining the above two figures, and assuming that regional energy rate variations are included in the average cost per square foot, space conditioning energy is (\$0.90) x (0.72) = \$0.65/ft^2/yr.

6.5.5.3 Generalized Cost Goals--Combining the above payback and energy costs in the relation:

Installed Cost Goal (\$) = Payback (3 years) x Energy Cost (\$0.65/ft^2/yr) x Energy Savings (%) x Building Size (ft^2)

gives the generalized cost goals illustrated in Figure 6-34. This figure forms one basis for subsequent evaluation of national impact of a CO_2 variable ventilation concept implementation.

Earlier estimated cost of a CO_2 ventilation system, single zone, was shown to be on the order of \$2800 using current state-of-the-art commercial-grade CO_2 sensors.

If we use an average estimate of 20 percent energy cost savings, the above installed price of a CO_2 ventilating system would be supported by buildings of greater than 8000 square feet gross floor area. From Figure 6-35, buildings exceeding this size consume approximately 90 percent of the total nationwide commercial building energy and represent 60 percent of all commercial buildings. Thus, the floor space limitation is not severe in terms of national energy savings potential.

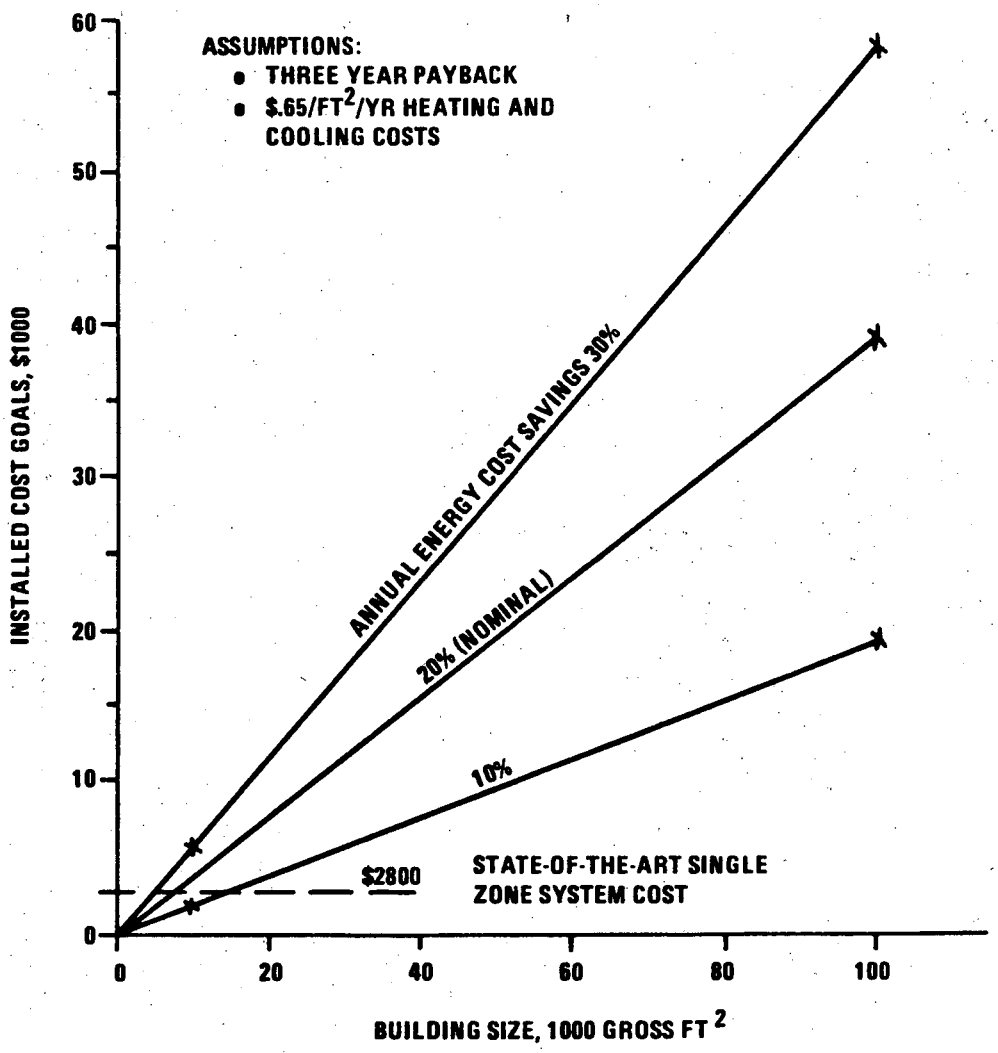

Figure 6-34. Cost Goals of Variable Ventilation System as a Function of Building Size and Energy Cost Savings

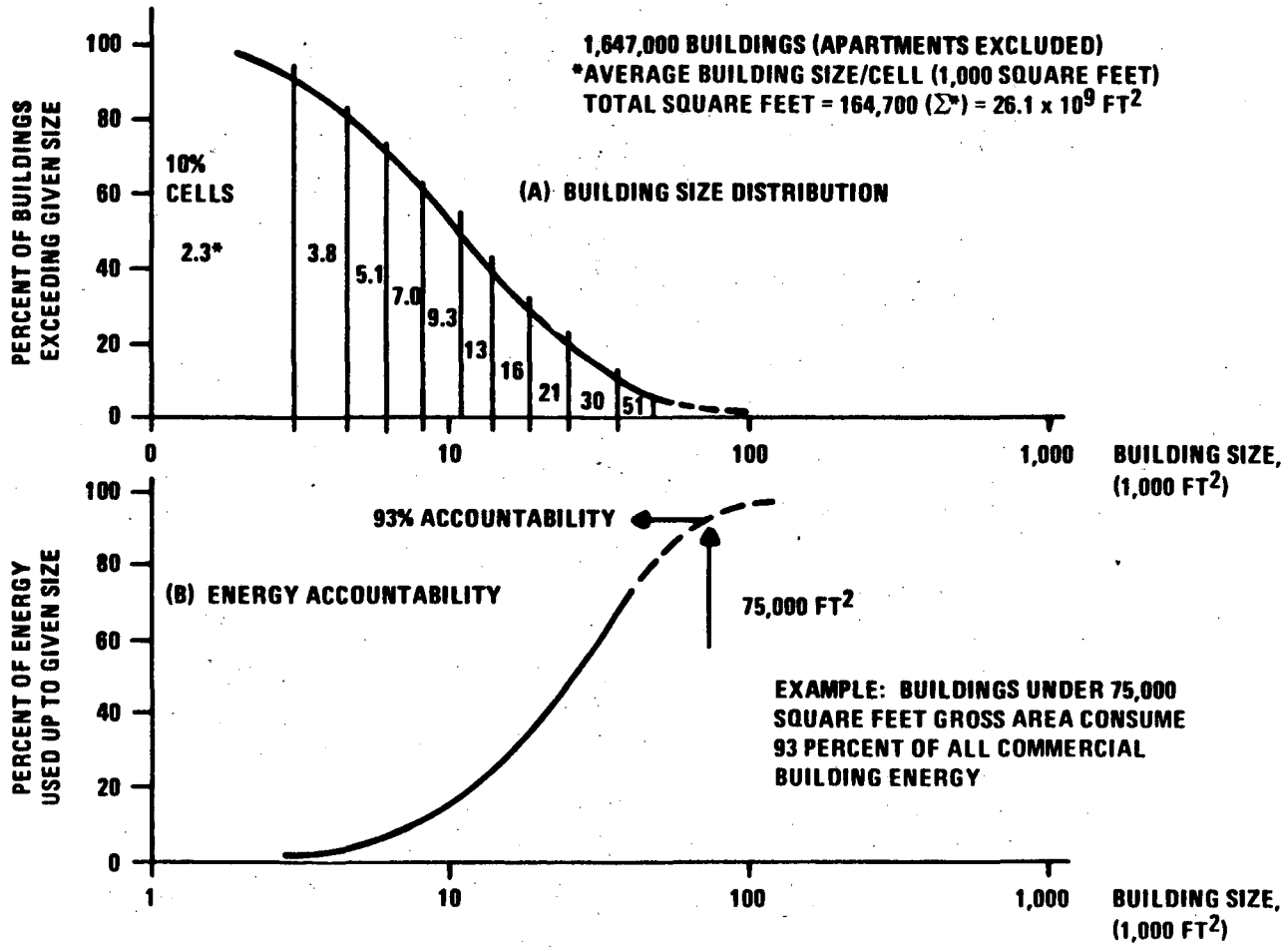

Figure 6-35. U.S. Commercial Buildings, 1975 Estimates of Size Distribution and Energy Accountability

6.5.5.4 HVAC System Limitations--From a technical viewpoint, the CO_2 ventilation concept could be applied to any ventilation system, even a through-the-wall unit in a motel room. From the data in the preceding paragraph, small single-zone systems will not justify the addition of the concept economically if return on investment is a criterion for installation. From Figure 3-5 (Section 3), it is seen that about 37 percent of the HVAC systems in schools are single-zone or through-the-wall units. Thus, about 63 percent of school systems are assumed to be commercially amenable to ventilation control.

6.5.5.5 National Implications--The implication of CO_2-based ventilation on national energy can be viewed from two approaches, one considering technical limitations only and the other accounting for economical limitations.

From a purely technical basis, it can be assumed that all commercial buildings provide fresh air ventilation according to existing codes and standards. A listing of commercial building categories is given in Table 6-16. Maximum savings accrue in buildings where the occupancy load widely varies over the period when ventilation is required. The Fridley Junior High School occupancy pattern is a good illustration of a large benefit application. Buildings with a level occupancy load or buildings which must ventilate to accommodate industrial processes which overshadow occupany requirements will be weak applications for CO_2 control.

No attempt has been made here to quantify or predict energy savings potential in the various building categories. One approach to accommodate varying energy savings potential is to assume a lower average percentage savings, for example, 10 percent.

Commercial energy use in 1980 has been forecast at 4.8 quadrillion Btu annually; about 72 percent of this amount is used to satisfy building heating and air

Table 6-16. Existing Business Building Inventory, 1975

BUILDING CATEGORY	NUMBER OF BUILDINGS	FLOOR SPACE ($FT^2 \times 10^6$)	INFORMATION SOURCE
BUSINESS RESIDENTIAL (APARTMENTS)			
MULTIFAMILY (MORE THAN 4 UNITS PER BUILDING) (11,792,000 UNITS)	865,000	12,971	U.S. HOUSING CENSUS ANNUAL HOUSING SURVEY, REF 2
LOW DENSITY (2 TO 4 UNITS PER BUILDING) (9,802,000 UNITS)	3,267,000	10,782	ESTIMATE ON NUMBER OF BUILDINGS
TOTAL RESIDENTIAL (21,594,000 UNITS)	(4,132,000)	(23,753)	
SCHOOLS (ELEMENTARY AND SECONDARY)	103,200	2,108	NAT. CENTER ED. STATISTICS
COLLEGE BUILDING	23,750	843	NAT. CENTER ED. STATISTICS
COLLEGE DORMITORY	11,400	276	NAT. CENTER ED. STATISTICS
OFFICES			
HIGH RISE (20 STORIES)	7,593		OFFICE OF INDUSTRIAL
LARGE OFFICE (5 TO 19 STORIES)	12,379	5,128	ECONOMICS (OIE)
SMALL OFFICE (5 STORIES)	247,403		
GOVERNMENT OFFICE	60,493	339	GENERAL SERVICES ADMINISTRATION (GSA)
RETAIL			
SHOPPING CENTER	47,500	3,100	OIE
STORES	378,750	1,899	OIE
WAREHOUSES	111,500	2,168	OIE
INDUSTRIAL PLANTS	138,700	4,920	OIE
PRIVATE INSTITUTION	79,980	1,637	RATIO TO SCHOOLS
HOTEL/MOTEL	29,750	796	OIE
MILITARY	77,553	614	GSA
GOVERNMENT INSTITUTION	14,074	320	STAT. ABSTRACT, 1975
HEALTH CARE	22,004	223	NATIONAL HEALTH STATISTICS
HOSPITAL	7,481	142	NATIONAL HEALTH STATISTICS
TERMINALS	10,875	137	OIE
LIBRARY/MUSEUM	24,832	798	STATISTICAL ABSTRACT, 1975
OTHER	238,750	1,532	OIE
TOTAL COMMERCIAL	(1,647,967)	(26,980)	
TOTALS, ALL CATEGORIES	(5,779,967)	(50,733)	

conditioning needs.* The net potential savings thus could be on the order of 0.34 quadrillion Btu (4.8 x 0.72 x 0.1), for national implementation of CO_2 ventilation control, assuming that there are no economic barriers to implementation. This is a barrel-of-oil equivalent of 58 x 10^6 barrels--about 7 days of the current import rate.

6.5.5.5.1 Economic Barriers--Several assumptions were made earlier in arriving at cost goals for a CO_2 ventilation system. These are summarized below relative to the market limitation inherent in those assumptions:

- Payback (3 years)--60 percent of buildings accept;
- Unit Energy Cost ($0.65/ft^2/yr)--50 percent of buildings exceed;
- HVAC Limitation--63 percent of buildings with amenable systems;
- Building Size (>8000 ft^2)--60 percent of commercial building energy.

The correlation between the above factors is unknown although by excluding buildings under 8000 ft^2, it is likely that a larger percentage of nonapplicable HVAC systems are included in that exclusion. The product of the above percentages is 16 percent, which represents the percentage of national commercial energy usage that would be affected by implementation of CO_2 ventilation control.

Thus, applying this economic limitation to the 0.34-quadrillion-Btu upper limit previously calculated gives a probable annual savings of (0.34) x (0.16) = 54 trillion Btu. The barrel-of-oil equivalent is 9.3 x 10^6 barrels--slightly more than the daily oil import rate.

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*Federal Energy Administration, "Residential and Commercial Energy Use Patterns, 1970-1990," November 1974, Figure 1-6.

SECTION 7.0
CONCLUSIONS AND RECOMMENDATIONS

Conventional building ventilation practices waste considerable energy by heating or cooling more ventilation air than actually is needed. Codes require a minimum amount of outdoor airflow based on designed occupancy. The common terminal reheat system exceeds the minimum outdoor airflow rate whenever outdoor air temperature is above the outdoor design temperature (-20°F in the case of Fridley Junior High School).

Two strategies exist for reducing this energy consumption:

- The mixed air temperature can be allowed to float so that excess outdoor air is not used unless it is needed for indoor cooling. This will result in a minimum of 10 percent energy reduction.

- The induction of outdoor air can be controlled on the basis of indoor CO_2 concentration. This technique will save about 20 percent additional energy.

Control based on indoor CO_2 concentration automatically compensates for infiltration, damper leakage, transient occupancy, and less than design loads.

The subjective tests showed a strong correlation between increasing CO_2 concentration and a subjective feeling of warmth. This leads to an unproven implication that a secondary energy savings benefit may derive from a downward heating temperature set point adjustment as CO_2 concentration levels reach their control level. This concept is recommended as a further potential research area.

Improper location of air supply and return outlets in rooms can lead to poor mixing and low ventilation efficiency. Some outdoor air may be conditioned, distributed to a space, passed from the supply outlet to the return without completely mixing with room air, and then exhausted. Lack of complete mixing in the room causes an unnecessary energy loss. Greater attention should be given to the number and location of return grill locations with respect to supply openings to assure good mixing within the rooms. Design of the return air distribution system is as important as the supply air distribution system.

A CO_2-controlled ventilation system maintains a closed outdoor air damper until outdoor air is required to dilute the indoor CO_2 concentration, or, if an economy cycle is used, until outdoor air is required for cooling. This will, in general, require modification of existing local building codes. Such codes today are based on the recommendations of ASHRAE Standard 62-73 (ANSI B194.1-1977), which specifically provides for minimum ventilation requirements. The reference standard has recently been revised (January 1981) and approved by ASHRAE (ASHRAE Standard 62-81, "Ventilation for Acceptable Indoor Air Quality") and makes provision for air quality methods of ventilation control. It is reasonable to expect that local building code authorities will adopt the provisions of ASHRAE Standard 62-81. The CO_2 concept described herein will meet the revised standard.

All components for a CO_2 ventilation control system are standard, off-the-shelf items except the CO_2 sensor. Industrial and laboratory-type CO_2 sensors are available, but these generally require special engineering for incorporation into a control system. At least two CO_2 sensor controllers that have been designed for control system applications (see Appendix G) are, however, available. The energy cost savings and control system costs appear to justify installations in buildings of about 8000 square feet floor area and greater.

Research is under way in at least three laboratories (Honeywell Corporate Technology Center, General Motors Research Center and Brown University) on infrared light-emitting diodes. IF these can be made reliable and inexpensive with a narrow emission band centered at 4.3 μm, they will be attractive for control devices. This research should be actively encouraged and accelerated.

Building HVAC systems usually have one outdoor air inlet and fan system that supplies several zones or rooms. A single control system with a multiplexed sampling system can be used. If room occupancy is transient, control of the outdoor air induction rate will shift to the zone of greatest load. This leads to overventilation of zones with lower occupancy. A variable-speed supply fan that increases the circulation rate when the loads are unevenly distributed or changed could relieve this situation. This also would improve mixing and ventilation efficiency. The subject of mixing and its effect on ventilation efficiency requires further research.

In summary, it is concluded that conditions are favorable for implementation of ventilation control systems based on demand as measured by room CO_2 concentration. The economics based on energy savings and return on investment appear favorable for buildings larger than 8000 square feet. The ASHRAE Ventilation Standard now supports this concept. The greatest benefit will be realized in buildings with transient occupancy.

APPENDIX A

PROCEDURE TO CALCULATE THE ENERGY CONTENT OF AN AIR VOLUME OR AN AIR STREAM

The energy content of a mass of moist air can be calculated using the following equations [1]:

$$Q = \rho\, h\, V \tag{A-1}$$

where:

$$\rho = \left[\frac{R_a T}{P} (1 + 1.6072\, w) \right]^{-1}$$

$$h = 0.240t + w(1061 + 0.444t)$$

where:

Q = Energy content of the moist air (Btu)

ρ = Moist air density (lb of dry air/ft^3)

h = Enthalpy of the moist air (Btu/lb of dry air)

V = Volume (ft^3)

R_a = Air constant (53.352 ft $lb_f/lb_m R$)

T = Air absolute temperature (^oF)

P = Total pressure (lb_f/ft^2)

t = Dry-bulb temperature (^oF)

w = Humidity ratio (lb of water/lb of dry air)

The humidity ratio, w, can be calculated from the partial pressure of water vapor in the air using the equation [1]:

$$w = 0.62198 \frac{P_w}{P - P_w} \tag{A-2}$$

where:

w = Humidity ratio (lb of water/lb of dry air)

P = Total pressure (lb_f/ft^2)

P_w = Partial pressure of water vapor (lb_f/fr^2)

The partial pressure of water vapor at saturation can be calculated using the following set of equations [2]:

$$Y_1 = 16.386396 + 0.00137804\ t - \frac{5656}{459.67 + t} \qquad \text{(A-3)}$$

$$Y_2 = \ln\ (459.67 + t)/100.0 \qquad \text{(A-4)}$$

$$P_w = 10^{(Y_1 - 3.560573\ Y_2)} \qquad \text{(A-5)}$$

where:

t = Dry-bulb temperature (^oF)

P_w = Partial pressure in inches of mercury

REFERENCES

1. ASHRAE Handbook of Fundamentals, Chapter 5, "Psychrometrics," published by ASHRAE, New York, 1977.

2. Woods, J.E., and Rohles, F.H., Psychrometric Tables for Human Factors Research, published by the Institute for Environmental Research, Kansas State University, Manhattan, Kansas, 1972.

APPENDIX B

CALCULATION OF THE DRY-BULB TEMPERATURE IN THE OCCUPIED SPACE OF THE BAND ROOM

The first method that was tried for estimating the dry-bulb temperature in the band room consisted of performing an energy balance on the occupied space of the band room. However, the constant factor, S, introduced in Subsection 5.5, Energy Analysis (Figure 5-7), was in reality a function of other factors such as temperature and flow rate of the supply air. The relationship between S and those factors could not be determined due to the impossibility of reproducing the heating season situation in the band room when the stratification problem became apparent. As a consequence, the errors committed by treating the factor S as a constant introduced a severe instability in the prediction of the band room dry-bulb temperature, and this method could not be used.

A second method, which provided some degree of success, was based on the fact that the amount of heat supplied to the band room was controlled by the room thermostat, which in turn sensed the room dry-bulb temperature.

Specifically, from the data recorded during the winter conditions, it was possible to determine the elevation in the temperature of the supply air across the reheat coils. These temperature elevations were related to the "percent open" position of the hot water valves, which were controlled by the thermostat in the band room (the maximum temperature elevations for the fully opened valves were measured by Honeywell). Finally, from the control range and set point, the temperature sensed by the thermostat was determined from the "percent open" position of the reheat coil valves.

Using the first 2 days of the Fridley data, all points that yielded a valve position between 0 percent and 100 percent open were regressed against the corresponding temperature measured at the exhaust grille. The resulting equation was:

$$T_T = 76.4 - 8.86 \times 10^{-2} \text{ TRM}$$

where:

T_T = Thermostat temperature

TRM = Room temperature (measured at the exhaust grille)

The correlation coefficient was $r^2 = 0.95$ for 144 points. A verification, listed in Table B-1, was made for one point per every hour of operation during 3 days of operation (i.e., the 2 days used to obtain the correlation and another day, selected from the remaining days for further verification; the day selected was February 4). As shown in Table B-1, the error between the "measured" and the "correlated" thermostat temperatures is small in most cases, but relatively large errors can occur in isolated points, especially near system start-up in the morning.

Table B-1. Comparison of Thermostat Temperatures (^{o}F)

DAY	HOUR	TRM	MEASURED T_T	CORRELATED T_T	ERROR ΔT
28	8	83.7	68.54	68.95	−0.41
28	9	85.6	68.54	68.78	−0.24
28	10	86.8	68.44	68.68	−0.24
28	11	87.7	68.46	68.60	−0.14
28	12	89.2	68.48	68.47	0.01
28	13	89.9	68.54	68.40	0.14
28	14	91.1	68.40	68.30	0.10
28	15	90.8	68.63	68.32	0.31
28	16	90.0	68.50	68.39	0.11
28	17	89.0	68.62	68.48	0.14
28	18	86.6	68.85	68.70	0.15
28	19	85.5	68.75	68.79	−0.04
28	20	80.1	69.49	69.27	0.22
28	21	78.8	69.45	69.39	0.06
29	6	58.2	70.62	71.21	−0.59
29	7	82.3	68.50	69.08	−0.58
29	8	85.4	68.51	68.80	−0.29
29	9	88.4	68.52	68.54	−0.02
29	10	88.9	68.60	68.49	0.11
29	11	89.9	68.48	68.40	0.08
29	12	90.1	68.47	68.39	0.08
29	13	90.3	68.58	68.37	0.21
29	14	80.2	69.34	69.26	0.08
29	15	79.8	68.64	69.30	−0.66
29	16	78.4	68.08	69.42	−1.34
29	17	72.2	69.63	70.46	−0.83
29	18	66.5	70.66	70.48	0.18
29	19	64.1	70.66	70.37	0.29
29	20	63.0	70.65	70.79	−0.14
29	21	61.9	70.65	70.88	−0.23
35	9	86.2	68.48	68.73	−0.25
35	10	88.8	68.54	68.50	0.04
35	11	89.6	68.57	68.43	0.14
35	12	88.1	68.86	68.56	0.30
35	13	80.3	69.57	69.25	0.32
35	14	79.8	69.58	69.30	0.28
35	15	78.4	69.57	69.42	0.15
35	16	78.5	69.59	69.41	0.18
35	17	78.2	69.60	69.44	0.16
35	18	77.7	69.55	69.48	0.07
35	19	77.9	69.60	69.47	0.13
35	20	78.5	69.64	69.41	0.23
35	21	79.1	69.67	69.36	0.31

APPENDIX C
COMPUTER PROGRAMS

PROGRAM THAT SIMULATES THE MUSIC WING OF FRIDLEY JUNIOR HIGH SCHOOL

DATE 80.271/11.01.05

```
LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 INTEGER HR,SEC,HR1,RMIN                                    4.
ISN 003                 REAL MASS,INF                                              5.
ISN 004                 DIMENSION QSV(156),SUPPLY(4),F(4),VOL(4),V(3),TIN(8),SUPCO2(156),   6.
                       /SUPDB(4,156),SUPW(156),RADG(7),DTMAX(8),SDG(8),QADB(156),DACO2(156   7.
                       /),RMDB(4,156),RHOUT(3,156),RMCO2(4,156),ADB(156),ACO2(156),BBT(3,1   8.
                       /56),DAW(156),AW(156),RMW(4,156),QLOSS(4,156),QTOTAL(4),CO2P          9.
                       /R(4,156),SETSTA(3,156),DAFLOW(156),QSH(156),WPROD(4,156),INF(4),    10.
                       /BOTRAN(4),TRAN(7),DELTB(4),BOTR(4),UA(150),UAP(150),TRMAX(4),SCPPL  11.
                       /Y(4)                                                              11.1
ISN 005                 COMMON LFAN,BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  12.
                       /DTRF,QADB,DAW,AW,DACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2,  13.
                       /F,SDG,SUPDB,DAFLOW,XMTOT,QADG,SUPW,SUPCO2,MASS,ALPHA,COLDSK,COLDCR  14.
                       /,SWEATL,SKINK,BODYTC,BLODTC,TSK,TCR,VSKBF,ERSW,ESK,HCP,HP,FCLP      15.
                       /,HRP,FPCLP,QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,LNDN,LDUP,DELTB,BOTR    16.
                       /,INTIME,XCTOT,SCPPLY,SUP,SUP3                                      17.
ISN 006                 EXTERNAL SATHUM,HVAC,Q                                             18.
ISN 007                 SUPPLY(1)=3440.                                                    19.
ISN 008                 SUPPLY(2)=2070.                                                    20.
ISN 009                 SUPPLY(3)=1700.                                                    21.
ISN 010                 SUPPLY(4)=2800.                                                    22.
ISN 011                 DO 730 J=1,4                                                       22.1
ISN 012             730 SCPPLY(J)=SUPPLY(J)*(1.-.15*PODMIN)                                22.2
ISN 013                 FBAND1=.5                                                          23.
ISN 014                 FBAND2=.5                                                          24.
ISN 015                 F(1)=1./7.                                                         25.
ISN 016                 F(2)=2.5/7.                                                        26.
ISN 017                 F(3)=2.5/7.                                                        27.
ISN 018                 F(4)=1./7.                                                         28.
ISN 019                 XMTOT=SUPPLY(1)+SUPPLY(2)+SUPPLY(3)+SUPPLY(4)                      29.
ISN 020                 XCTOT=XMTOT                                                        29.1
ISN 021                 CO2FL=2600.                                                        30.
ISN 022                 INF(1)=75.                                                         31.
ISN 023                 INF(2)=25.                                                         32.
ISN 024                 INF(3)=25.                                                         33.
ISN 025                 INF(4)=75.                                                         34.
ISN 026                 SUP=SUPPLY(4)/6.                                                   35.
ISN 027                 SUP3=SUP*3.                                                        36.
ISN 028                 VOL(1)=43320.                                                      37.
ISN 029                 VOL(2)=16340.                                                      38.
ISN 030                 VOL(3)=16340.                                                      39.
ISN 031                 VOL(4)=18240.                                                      40.
ISN 032                 V(1)=.03                                                           41.
ISN 033                 V(2)=.03                                                           42.
ISN 034                 V(3)=.03                                                           43.
ISN 035                 PROP=754./1354.                                                    44.
                  C                                                                        45.
                  C  NOMENCLATURE:                                                         46.
                  C                 SUPPLY - TOTAL SUPPLY AIR FLOW RATE INTO EACH SPACE    47.
                  C                 FBAND  - FRACTION OF THE SUPPLY AIR INTO EACH REHEAT   48.
                  C                          COIL OF THE BAND ROOM                         49.
                  C                 F      - SAME FOR REHEAT COILS IN OTHER SPACE          50.
                  C                 VOL    - VOLUME OF EACH OCCUPIED SPACE                 51.
                  C                 V      - AIR VELOCITY IN THE THREE ROOMS               52.
                  C                                                                        53.
                  C  NOW DEFINE CONSTANTS FOR SUBROUTINE STEADY                            54.
```

```
                                  ****    MAIN PROGRAM    ****
                  C
                  C
                  C  NOW INITIALIZE AND READ THE FOLLOWING AT TIME ZERO
                  C
                  C          TIN    - SUPPLY DRY BULB TEMPERATURE AFTER EACH REHEAT COIL
                  C                   CHANNELS 1&2 FOR BAND ROOM, 3 FOR ROOM 162, 4 FOR
                  C                   ROOM 164 AND 5-8 FOR OTHER SPACE
                  C          SUPDEW- SUPPLY DEW POINT -CHANNEL 25
                  C          SUPCO2- SUPPLY CO2 CONCENTRATION (PPM) - CHANNEL 34
                  C          HR,MIN,SEC- TIME ZERO
                  C          EXFLOW- OUTDOOR AIR FLOW RATE- CHANNEL 37
                  C
ISN 036                 WRITE(6,620)
ISN 037             620 FORMAT(5X,'*** EXECUTION  COMMENTS ***',///)
ISN 038                 NTIME=1
ISN 039                 DATA QTOTAL/4*0./
ISN 040                 READ(10,19)(TIN(I),I=1,8),SUPDEW,SUPCO2(1),EXFLOW,HR,MIN,SEC
ISN 041              19 FORMAT(9F6.1,F6.0,F7.1,3I2)
ISN 042                 SUPDB(1,1)=FBAND1*TIN(1)+FBAND2*TIN(2)
ISN 043                 SUPDB(2,1)=TIN(3)
ISN 044                 SUPDB(3,1)=TIN(4)
ISN 045                 SUPDB(4,1)=F(1)*TIN(5)+F(2)*TIN(6)+F(3)*TIN(7)+F(4)*TIN(8)
ISN 046                 HR2=FLOAT(HR)
                  C
                  C  NOW INPUT DETAILS OF THE AIR HANDLING UNIT AND CONTROL SYSTEM
                  C
                  C    LDUPH - HOUR WHEN DAY SETUP OCCURS
                  C    LDUPM - MINUTE "   "    "      "
                  C    LNDNH - HOUR WHEN NIGHT SETBACK OCCURS
                  C    LNDNM - MINUTE  "   "      "    "
                  C    LCO2 - FLAG (1 IF CO2 CONTROL IS USED, 0 OTHERWISE)
                  C    PODMIN - % OPEN FOR DAMPER AT MINIMUM SETTING
                  C    DTRF - TEMP. INCREASE ACCROSS RETURN AIR FAN
                  C    DTSF -   "       "       "    SUPPLY  "   "
                  C    SETN -   "   NIGHT SETBACK AMOUNT
                  C    BOTR - BOTTOM OF TEMP. RANGE DURING DAY (TEMP. CONTROL)
                  C    TRAN - TEMP. RANGE TO FULLY OPEN WATER FLOW IN A REHEAT COIL
                  C    CO2MIN - MAXIMUM LEVEL OF CO2 AT WHICH CO2 CONTROL OVERRIDES
                  C    CO2RAN - CO2 RANGE TO FULLY OPEN DAMPERS
                  C    RFW - RETURN FAN WATTS
                  C    SFW - SUPPLY  "    "
                  C    RADG - RETURN AIR DUCT GAINS (DRY BULB)
                  C    DTMAX - MAX. TEMP. RISE ACCROSS REHEAT COIL
                  C    OADG - OUTDOOR AIR DUCT GAIN
                  C    SDG - SUPPLY DUCT GAIN (DRY BULB)
                  C    LT - STATUS OF FAN ON OR OFF
                  C
ISN 047                 READ(5,1)LDUPH,LDUPM,LNDNH,LNDNM,LCO2,PODMIN,DTRF,DTSF,SETN,(BOTR(
                       /J),TRAN(J),J=1,4),CO2MIN,CO2RAN,(RADG(I),I=1,7),(DTMAX(I),I=1,8),
                       /(SDG(I),I=1,8),LT,OADG,PRESS,(DELTB(J),J=1,4),(TRAN(J),J=5,7)
ISN 048              1  FORMAT(4I2,I1,12F4.1,2F6.0,/,7F4.1,/,16F4.1,I1,F4.1,F5.1,/,5F4.1
                       /,2F4.2)
ISN 049                 TRU=TRAN(5)
ISN 050                 PWI=SATHUM((SUPDEW-32.)/1.8)
ISN 051                 SUPW(1)=.62198*PWI/(PRESS-PWI)
ISN 052                 PODMIN=PODMIN/100.
ISN 053                 LFAN=LT
ISN 054                 IF(LDUPH.GE.HR) GO TO 300
```

```
                                  ****    MAIN PROGRAM    ****

ISN 056          LDUP=(24-HR-1)*6+(60-MIN+LDUPM)/10+LDUPH*6                    113.
ISN 057          GO TO 310                                                     114.
ISN 058      300 IF(LDUPH.GT.HR) GO TO 301                                     115.
ISN 060          IF(MIN.GE.LDUPM) LDUP=24*6-(MIN-LDUPM)/10                     116.
ISN 062          IF(MIN.LT.LDUPM) LDUP=(LDUPM-MIN)/10                          117.
ISN 064          GO TO 310                                                     118.
ISN 065      301 LDUP=(LDUPH-HR-1)*6+(60-MIN+LDUPM)/10                         119.
ISN 066      310 IF(LNDNH.GE.HR) GO TO 302                                     120.
ISN 068          LNDN=(24-HR-1)*6+(60-MIN+LNDNM)/10+LNDNH*6                    121.
ISN 069          GO TO 309                                                     122.
ISN 070      302 IF(LNDNH.GT.HR) GO TO 303                                     123.
ISN 072          IF(MIN.GE.LNDNM) LNDN=24*6-(MIN-LNDNM)/10                     124.
ISN 074          IF(MIN.LT.LNDNM) LNDN=(LNDNM-MIN)/10                          125.
ISN 076          GO TO 309                                                     126.
ISN 077      303 LNDN=(LNDNH-HR-1)*6+(60-MIN+LNDNM)/10                         127.
ISN 078      309 CONTINUE                                                      128.
               C                                                               129.
               C  NOW INPUT THE DATA FROM THE DATALLOGGER FOR EACH 10 MIN. INTERVAL 130.
               C                                                               131.
               C     OADB  -OUTDOOR AIR DRY BULB TEMP.          -CHANNEL  17   132.
               C     DPOA  -     "     "  DEW POINT              -    "    26   133.
               C     OACO2 -     "     "  CO2 CONCENTRATION (PPM) -    "    35   134.
               C     RMDB  - ROOM DRY BULB TEMP.                 -    "    10,11,12 135.
               C     RHOUT -    "  RELATIVE HUMIDITY             -    "    21,22,23 136.
               C     RMCO2 -    "  CO2 CONCENTRATION (PPM)       -    "    32,31,30 137.
               C     ADB   -MAIN RETURN DRY BULB TEMP.           -    "    13   138.
               C     RHA   -  "      "   RELATIVE HUMIDITY       -    "    24   139.
               C     ACO2  -  "      "   CO2 CONCENTRATION (PPM) -    "    33   140.
               C     BBT   - ROOM BLACK BULB TEMPERATURE         -    "    18,19 20 141.
               C     E     -BTU METER READING                    -    "    36   142.
               C                                                               143.
ISN 079          I=1                                                           144.
ISN 080       17 READ(11,6,END=18)OADB(I),DPOA,OACO2(I),(RMDB(J,I),J=1,3),(RHOUT(J, 145.
                /I),J=2,3),(RMCO2(J,I),J=1,3),ADB(I),RHA,ACO2(I),(BBT(J,I),J=1,3),E 146.
ISN 081        6 FORMAT(2F6.1,F6.0,3F6.1,4X,2F4.1,3F6.0,F6.1,F4.1,F6.0,3F6.1,F6.0) 147.
ISN 082       63 READ(12,685,END=18)RHOUT(1,I)                                 148.
ISN 083      685 FORMAT(F4.1)                                                  149.
ISN 084          P=SATHUM((DPOA-32.)/1.8)                                      150.
ISN 085          OAW(I)=.62198*P/(PRESS-P)                                     151.
ISN 086          P=SATHUM((ADB(I)-32.)/1.8)*RHA/100.                           152.
ISN 087          AW(I)=.62198*P/(PRESS-P)                                      153.
ISN 088          DO 675 J=1,3                                                  154.
ISN 089          P=SATHUM((RMDB(J,I)-32.)/1.8)*RHOUT(J,I)/100.                 155.
ISN 090      675 RMW(J,I)=.62198*P/(PRESS-P)                                   156.
ISN 091          I=I+1                                                         157.
ISN 092          GO TO 17                                                      158.
ISN 093       18 NFINAL=I-1                                                    159.
ISN 094          IJK=0                                                         160.
ISN 095          GO TO 366                                                     161.
               C                                                               162.
               C  NOW THE MARCHING SOLUTION CAN START                          163.
               C                                                               164.
               C   - FIRST, DEFINE CONTROL VARIABLES                           165.
               C                                                               166.
ISN 096      367 BOTRAN(1)=BOTR(1)                                             167.
ISN 097          IF(LNDN.GT.LDUP) GO TO 320                                    168.
ISN 099          IF(NTIME.GT.LNDN.AND.NTIME.LT.LDUP) BOTRAN(1)=BOTR(1)-SETN    169.
ISN 101          L2C=LNDN+24*6                                                 170.
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                                    ****    MAIN PROGRAM    ****
ISN 102          IF(NFINAL.LT.L2C) GO TO 321                                171.
ISN 104          IF(NTIME.GT.L2C) BOTRAN(1)=BOTR(1)-SETN                    172.
ISN 106          GO TO 321                                                  173.
ISN 107      320 IF(NTIME.LT.LDUP.OR.NTIME.GT.LNDN) BOTRAN(1)=BOTR(1)-SETN  174.
ISN 109          L2C=LDUP+24*6                                              175.
ISN 110          IF(NFINAL.LT.L2C) GO TO 321                                176.
ISN 112          IF(NTIME.GT.L2C) BOTRAN(1)=BOTR(1)                         177.
ISN 114      321 DO 3446 J=2,4                                              178.
ISN 115          IF(BOTR(1).EQ.BOTRAN(1)) BOTRAN(J)=BOTR(J)                 179.
ISN 117     3446 IF(BOTR(1).NE.BOTRAN(1)) BOTRAN(J)=BOTR(J)-SETN            180.
ISN 119          IF(BOTRAN(1).EQ.BOTR(1)) GO TO 20                          181.
ISN 121          IF(BOTRAN(1).LT.BOTR(1)) LFAN=0                            182.
ISN 123          DO 1151 J=1,4                                              183.
ISN 124          BOT16=BOTRAN(J)+TRAN(J)*1.143                              184.
ISN 125          IF(RMDB(J,NTIME).LT.BOT16) GO TO 1152                      185.
ISN 127     1151 CONTINUE                                                   186.
ISN 128          GO TO 110                                                  187.
ISN 129     1152 DO 1155 J=1,4                                              188.
ISN 130          BOT14=BOTRAN(J)+TRAN(J)                                    189.
ISN 131     1155 IF(RMDB(J,NTIME).LT.BOT14) GO TO 20                        190.
ISN 133          IF(LT.EQ.0) LFAN=0                                         191.
ISN 135          IF(LT.EQ.1) LFAN=1                                         192.
ISN 137          GO TO 1999                                                 193.
ISN 138      110 LFAN=0                                                     194.
ISN 139          LT=0                                                       195.
ISN 140          GO TO 1999                                                 196.
ISN 141       20 LFAN=1                                                     197.
ISN 142          LT=1                                                       198.
ISN 143     1999 IJK=0                                                      199.
            C                                                               200.
            C  NOW, ENERGY, CO2, AND SETSTAR CALCULATIONS FOR THE 3 MAIN ROOMS 201.
            C                                                               202.
ISN 144          DO 5 J=1,3                                                 203.
ISN 145          IF(J.EQ.1) GO TO 8322                                      204.
ISN 147          IF(LFAN.EQ.0) FLOW=INF(J)                                  205.
ISN 149          IF(LFAN.EQ.1) FLOW=SCPPLY(J)                               206.
ISN 151          P=SATHUM((RMDB(J,NTIME)-32.)/1.8)*RHOUT(J,NTIME)/100.      207.
ISN 152          QIN=Q(FLOW,SUPW(NTIME),SUPDB(J,NTIME))*10.                 208.
ISN 153          QOUT=Q(FLOW,RMW(J,NTIME),RMDB(J,NTIME))*10.                209.
ISN 154          QST=Q(VOL(J),RMW(J,NTIME+1),RMDB(J,NTIME+1))-              210.
                /Q(VOL(J),RMW(J,NTIME),RMDB(J,NTIME))                       211.
ISN 155          QLOSS(J,NTIME)=QIN-QOUT-QST                                212.
ISN 156          QTOTAL(J)=QTOTAL(J)+QLOSS(J,NTIME)                         213.
ISN 157          R=(BST(J,NTIME)+(2.27*V(J)**.5)*(BBT(J,NTIME)-RMDB(J,NTIME))-32.)/ 214.
                /1.8                                                        215.
ISN 158          RT=(RMDB(J,NTIME)-32.)/1.8                                 216.
            C    IF(BOTRAN(1).EQ.BOTR(1)) CALL STEADY(BASEM,RT,CLO,0.,V(J),R,RHOUT( 217.
            C   /J,NTIME),SET,J,P)                                          218.
ISN 159     8322 IF(BOTRAN(1).EQ.BOTR(1)) SET=20.                           219.
ISN 161          IF(BOTRAN(1).NE.BOTR(1)) SET=0.                            220.
ISN 163        5 SETSTA(J,NTIME)=SET*1.8+32.                                221.
            C                                                               222.
            C  NOW PERFORM ENERGY AND CO2 CALCULATIONS IN THE OTHER OCCUPIED SPACE 223.
            C                                                               224.
ISN 164          NTIME=NTIME+1                                              225.
ISN 165      366 IF(LFAN.EQ.0.) GO TO 360                                   226.
ISN 167          T1=RMDB(1,NTIME)+RADG(1)                                   227.
ISN 168          Q1=Q(SCPPLY(1),RMW(1,NTIME),T1)                            228.
```

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                                  ****    MAIN PROGRAM    ****
ISN 169          T1=RMDB(2,NTIME)+RADG(5)                                    229.
ISN 170          Q2=Q(SCPPLY(2),RMW(2,NTIME),T1)                             230.
ISN 171          T1=RMDB(3,NTIME)+RADG(6)                                    231.
ISN 172          Q3=Q(SCPPLY(3),RMW(3,NTIME),T1)                             232.
ISN 173          QTOT=Q(XCTOT,AW(NTIME),ADB(NTIME))                          233.
ISN 174          QOTPDG=QTOT-Q1-Q2-Q3                                        234.
            C                                                                235.
            C  THE PROCEDURE TO CALCULATE THE DRY BULB TEMP. IN THE OTHER SPACE  236.
            C   MUST BE ITERATIVE                                            237.
            C   ANOTHER PROBLEM IS HOW TO CALCULATE RMW(4,NTIME).  IT DEPENDS 238.
            C   ON SUPW(NTIME) WHICH CAN ONLY BE EVALUATED AFTER RMDB(4,NTIME) 239.
            C   AND , THUS, RMW(4,NTIME), ARE KNOWN.  BUT , AS SUPW DOES NOT  240.
            C   VARY SIGNIFICANTLY IN 1 TIME STEP, SUPW(NTIME-1) WILL BE USED. 241.
            C                                                                242.
ISN 175          RMW(4,NTIME)=(AW(NTIME)*XCTOT-(RMW(1,NTIME)*PROP+(1.-PROP)*SUPW(NT 243.
                /IME-1))*SCPPLY(1)-RMW(2,NTIME)*SCPPLY(2)-RMW(3,NTIME)*SCPPLY(3))/ 244.
                /SCPPLY(4)                                                   245.
ISN 176          IF(RMW(4,NTIME).LT.0.) RMW(4,NTIME)=0.                      246.
ISN 178          RMCO2(4,NTIME)=(ACO2(NTIME)*XCTOT-RMCO2(1,NTIME)*SCPPLY(1)-RMCO2(2 247.
                /,NTIME)*SCPPLY(2)-RMCO2(3,NTIME)*SCPPLY(3))/SCPPLY(4)       248.
ISN 179          IF(RMCO2(4,NTIME).LT.0.) RMCO2(4,NTIME)=0.                  249.
            C                                                                250.
            C  ASSUMED VALUE HERE                                            251.
            C                                                                252.
ISN 181          RMDB(4,NTIME)=ADB(NTIME)-RADG(3)                            253.
ISN 182          A=0.                                                        254.
ISN 183      364 T1=RMDB(4,NTIME)+RADG(2)                                    255.
ISN 184          IJK=IJK+1                                                   256.
ISN 185          Q1=Q(SUP,RMW(4,NTIME),T1)                                   257.
ISN 186          T1=RMDB(4,NTIME)+RADG(3)                                    258.
ISN 187          Q2=Q(SUP,RMW(4,NTIME),T1)                                   259.
ISN 188          T1=RMDB(4,NTIME)+RADG(4)                                    260.
ISN 189          Q3=Q(SUP,RMW(4,NTIME),T1)                                   261.
ISN 190          T1=RMDB(4,NTIME)+RADG(7)                                    262.
ISN 191          QTOT=Q(SUP3,RMW(4,NTIME),T1)                                263.
ISN 192          QTOT=QTOT+Q1+Q2+Q3                                          264.
ISN 193          RATIO=(QTOT-QOTPDG)/QOTPDG                                  265.
ISN 194          IF(ABS(RATIO).LT..1) GO TO 361                              266.
ISN 196          IF(RATIO.LT.0.) GO TO 362                                   267.
ISN 198          IF(A.LT.0.) GO TO 363                                       268.
ISN 200          RMDB(4,NTIME)=RMDB(4,NTIME)-.2                              269.
ISN 201          A=1.                                                        270.
ISN 202          IF(IJK.GT.80) GO TO 363                                     271.
ISN 204          GO TO 364                                                   272.
ISN 205      362 IF(A.GT.0.) GO TO 363                                       273.
ISN 207          RMDB(4,NTIME)=RMDB(4,NTIME)+.2                              274.
ISN 208          A=-1.                                                       275.
ISN 209          IF(IJK.GT.80) GO TO 363                                     276.
ISN 211          GO TO 364                                                   277.
ISN 212      363 WRITE(6,365)RATIO,NTIME,IJK,Q1,Q2,QIN,QOUT,QREF             278.
ISN 213      365 FORMAT(2X,'CONVERGE ON RMDB(4)- RATIO=',F10.2,5X,'PERIOD',I5,' TRY 279.
                /#',I3,5E12.2)                                               280.
ISN 214          GO TO 361                                                   281.
ISN 215      360 IF(NTIME.NE.1) GO TO 370                                    282.
ISN 217          RMW(4,1)=(RMW(1,1)+RMW(2,1)+RMW(3,1))/3.                    283.
ISN 218          RMDB(4,1)=(RMDB(1,1)+RMDB(2,1)+RMDB(3,1))/3.                284.
ISN 219          RMCO2(4,1)=(RMCO2(1,1)+RMCO2(2,1)+RMCO2(3,1))/3.            285.
ISN 220          GO TO 367                                                   286.
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```
                                  ****    MAIN PROGRAM    ****

ISN 221          370  RMW(4,NTIME)=(RMW(4,NTIME-1)*VOL(4)+INF(4)*10.*(SUPW(NTIME-1)-RMW
                     /(4,NTIME-1)))/VOL(4)
ISN 222               IF(RMW(4,NTIME).LT.0.) RMW(4,NTIME)=0.
ISN 224               RMCO2(4,NTIME)=(RMCO2(4,NTIME-1)*VOL(4)+INF(4)*10.*(SUPCO2(NTIME
                     /-1)-RMCO2(4,NTIME-1)))/VOL(4)
ISN 225               IF(RMCO2(4,NTIME).LT.0.) RMCO2(4,NTIME)=0.
ISN 227               RMDB(4,NTIME)=(RMDB(1,NTIME)+RMDB(2,NTIME)+RMDB(3,NTIME))/3.
ISN 228          361  IF(NTIME.EQ.1) GO TO 367
ISN 230               IF(LFAN.EQ.0) FLOW=INF(4)
ISN 232               IF(LFAN.EQ.1) FLOW=SCPPLY(4)
ISN 234               QIN=Q(FLOW,SUPW(NTIME-1),SUPDB(4,NTIME-1))*10.
ISN 235               QOUT=Q(FLOW,RMW(4,NTIME-1),RMDB(4,NTIME-1))*10.
ISN 236               QST=Q(VOL(4),RMW(4,NTIME),RMDB(4,NTIME))-
                     /Q(VOL(4),RMW(4,NTIME-1),RMDB(4,NTIME-1))
ISN 237               QLOSS(4,NTIME-1)=QIN-QOUT-QST
ISN 238               IF(BOTR(1).EQ.BOTRAN(1)) QREF=QLOSS(4,NTIME-1)
ISN 240               QTOTAL(4)=QTOTAL(4)+QLOSS(4,NTIME-1)
ISN 241               CO2PR(4,NTIME-1)=VOL(4)*(RMCO2(4,NTIME)-RMCO2(4,NTIME-1))+FLOW
                     /*10.*(RMCO2(4,NTIME-1)-SUPCO2(NTIME-1))
ISN 242               WPROD(4,NTIME-1)=VOL(4)*(RMW(4,NTIME)-RMW(4,NTIME-1))+FLOW
                     /*10.*(RMW(4,NTIME-1)-SUPW(NTIME-1))
                C
                C  TO FINISH ENERGY CALCULATIONS, THE LOSS FROM THE FALSE CEILING HAD TO
                C   BE CALCULATED; BUT THE BTU METER IS NOT CALIBRATED, WHICH DOES NOT
                C   ALLOW THIS CALCULATION TO BE PERFORMED
                C
                C  NOW CALCULATE THE NEXT PERIOD SUPPLY QUANTITIES
                C
ISN 243               NTIME=NTIME-1
ISN 244               INTIME=NTIME
ISN 245               CALL HVAC
ISN 246               DO 4445 J=1,3
ISN 247               IF(LFAN.EQ.0) FLOW=INF(J)
ISN 249               IF(LFAN.EQ.1) FLOW=SCPPLY(J)
ISN 251               IF(LFAN.EQ.0) PROP1=1.
ISN 253               IF(LFAN.EQ.1) PROP1=PROP
ISN 255               IF(J.NE.1) GO TO 4444
ISN 257               QIN=Q(FLOW,SUPW(NTIME),SUPDB(J,NTIME))*10.
ISN 258               QOUT=Q(FLOW,RMW(J,NTIME)*PROP1+(1.-PROP1)*SUPW(NTIME),RMDB(J,NTIME
                     /))*10.
ISN 259               IF(LFAN.EQ.1) QST=Q(VOL(J),RMW(J,NTIME+1),
                     /1.5+((RMDB(J,NTIME+1)-828.3)/(-11.29)))-Q(VOL(1),RMW(J,NTIME)
                     /,1.5+((RMDB(J,NTIME)-828.3)/(-11.29)))
ISN 261               IF(LFAN.EQ.0) QST=Q(VOL(J),RMW(J,NTIME+1),RMDB(J,NTIME+1))
                     /-Q(VOL(1),RMW(1,NTIME),RMDB(1,NTIME))
ISN 263               QLOSS(J,NTIME)=QIN-QOUT-QST
ISN 264               QTOTAL(J)=QTOTAL(J)+QLOSS(J,NTIME)
ISN 265               CO2PR(J,NTIME)=VOL(J)*((RMCO2(J,NTIME+1)-(1.-PROP)*SUPCO2(NTIME+1)
                     /)/PROP-(RMCO2(J,NTIME)-(1.-PROP)*SUPCO2(NTIME))/PROP)+FLOW*
                     /10.*(RMCO2(J,NTIME)-SUPCO2(NTIME))
ISN 266               WPROD(J,NTIME)=VOL(J)*(RMW(J,NTIME+1)-RMW(J,NTIME))+FLOW*(PROP
                     /*RMW(J,NTIME)+(1.-PROP)*SUPW(NTIME)-SUPW(NTIME))*10.
ISN 267               GO TO 4445
ISN 268          4444 CO2PR(J,NTIME)=VOL(J)*(RMCO2(J,NTIME+1)-RMCO2(J,NTIME))+FLOW*
                     /10.*(RMCO2(J,NTIME)-SUPCO2(NTIME))
ISN 269               WPROD(J,NTIME)=VOL(J)*(RMW(J,NTIME+1)-RMW(J,NTIME))
                     /+FLOW*10.*(RMW(J,NTIME)-SUPW(NTIME))
ISN 270          4445 CONTINUE
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```
                                    ****    MAIN PROGRAM    ****

ISN 271          NTIME=NTIME+1                                                  345.
ISN 272          HR2=HR2+1./6.                                                  346.
ISN 273          IF(HR2.GT.24.) HR2=HR2-24.                                     347.
ISN 275          TRAN(5)=TRU                                                    348.
ISN 276          IF(RMDB(1,NTIME).LT.86.5.AND.HR2.GT.12.) TRAN(5)=TRAN(6)       349.
ISN 278          IF(RMDB(1,NTIME).LT.80.) TRAN(5)=TRAN(7)                       350.
ISN 280          IF(NTIME.LT.NFINAL) GO TO 367                                  351.
ISN 282          WRITE(6,450)LCO2,PODMIN,SETN,(BOTR(J),J=1,4),(TRAN(J),J=1,4),(DELT 352.
                /B(J),J=1,4),CO2M                                               353.
                /IN,CO2RAN,DTRF,DTSF,(I,RADG(I),I=1,7),OADG,(I,SDG(I),I=1,8),   354.
                /(I,DTMAX(I),I=1,8),PRESS,LNDN,LDUP                             355.
ISN 283      450 FORMAT(1H1,' SYSTEM CHARACTERISTICS',//,' LCO2=',I1,/,' PODMIN=', 356.
                /F4.2,//,' SETPOINTS:',//,' SETN=',F4.1,/,' BOTR=',4(F4.1,5X),/,' T 357.
                /RAN=',4(F4.1,5X),/,' DELTB=',4(F4.1,5X),/,' CO2MIN=',F6.0,/,' CO2R 358.
                /AN=',F6.0,//,' GAINS:',//,' DTRF=',F4.1,/,' DTSF=',F4.1,//,    359.
                /7(' DUCT #',I1,' RADG=',F4.1,/),/,' OADG=',F4.1,/,//,8(' SUPLY DUC 360.
                /T #',I1,' SDG=',F4.1,/),//,' COIL TEMP. RISE(MAX):',//,8(' COIL #' 361.
                /,I1,' DT=',F4.1,/),//,' PRESSURE=',F5.1,/,' LNDN=',I3,/,       362.
                /' LDUP=',I3)                                                   363.
ISN 284          WRITE(6,8)                                                     364.
ISN 285        8 FORMAT(1H1,2X,'TIME',14X,'ROOM #1',30X,'ROOM #2',30X,'ROOM #3',/, 365.
                /' HR-MIN  ',3('RMCO2  RMDB    RMW    SET*    QLOSS    '),/,    366.
                /8X,3('-----------------------------------',2X),//)             367.
C                                                                               368.
C  PRINT RESULTS                                                                369.
C                                                                               370.
ISN 286          K=0                                                            371.
ISN 287          UATOT=0.                                                       372.
ISN 288          DO 3392 J=1,NFINAL                                             373.
ISN 289          IF(QSH(J).GT.1.) GO TO 3392                                    374.
ISN 291          UA(J)=(QLOSS(1,J)+QLOSS(2,J)+QLOSS(3,J)+QLOSS(4,J))/(RMDB(4,J) 375.
                /-OADB(J))                                                      376.
ISN 292          K=K+1                                                          377.
ISN 293          UATOT=UATOT+UA(J)                                              378.
ISN 294     3392 CONTINUE                                                       379.
ISN 295          UATOT=UATOT/FLOAT(K)                                           380.
ISN 296          DO 3393 J=1,NFINAL                                             381.
ISN 297          IF(QSH(J).LT.1.) GO TO 3393                                    382.
ISN 299          UAP(J)=(QLOSS(1,J)+QLOSS(2,J)+QLOSS(3,J)+QLOSS(4,J))-UATOT     383.
                /*(ADB(J)-OADB(J))                                              384.
ISN 300          UA(J)=(QLOSS(1,J)+QLOSS(2,J)+QLOSS(3,J)+QLOSS(4,J))/(ADB(J)-    385.
                /OADB(J))                                                       386.
ISN 301     3393 CONTINUE                                                       387.
ISN 302          HR1=HR                                                         388.
ISN 303          RMIN=MIN                                                       389.
ISN 304          IPAGE=0                                                        390.
ISN 305          IFINAL=NFINAL-1                                                391.
ISN 306          DO 9 I=1,IFINAL                                                392.
ISN 307          WRITE(6,12)HR1,RMIN,RMCO2(1,I),RMDB(1,I),RMW(1,I),SETSTA(1,I),QLO 393.
                /SS(1,I),RMCO2(2,I),RMDB(2,I),RMW(2,I),SETSTA(2,I),QLOSS(2,I),  394.
                /RMCO2(3,I),RMDB(3,I),RMW(3,I),SETSTA(3,I),QLOSS(3,I)           395.
ISN 308     12   FORMAT(I3,I4,1X,3(F6.0,F7.1,F7.4,F7.1,2X,E9.2,2X))            396.
ISN 309          RMIN=RMIN+10                                                   397.
ISN 310          IF(RMIN.LT.60) GO TO 995                                       398.
ISN 312          RMIN=RMIN-60                                                   399.
ISN 313          HR1=HR1+1                                                      400.
ISN 314     995  IPAGE=IPAGE+1                                                  401.
ISN 315          IF(IPAGE.LT.53) GO TO 435                                      402.
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                                  ****    MAIN PROGRAM    ****

ISN 317              WRITE(6,8)                                                403.
ISN 318              IPAGE=0                                                   404.
ISN 319        435   IF(HR1.GT.23) HR1=HR1-24                                 405.
ISN 321          9   CONTINUE                                                 406.
               C                                                              407.
               C  NOW PRINT RESULTS FOR ROOM #4 AND ENERGY TOTALS (TOTALS)    408.
               C                                                              409.
ISN 322              IPAGE=0                                                   410.
ISN 323              HR1=HR                                                    411.
ISN 324              RMIN=MIN                                                  412.
ISN 325              WRITE(6,611)                                              413.
ISN 326        611   FORMAT(1H1,24X,'ROOM #4',/,3X,'  TIME      RMCO2       RMDB        RM 414.
                    /W       QLOSS',5X,'VENT. ENERG.',5X,'HEAT ENERG.',/,10X,'------',   415.
                    /'-----------------------------------',//)                 416.
ISN 327              DO 610 I=1,IFINAL                                         417.
ISN 328              WRITE(6,1212)HR1,RMIN,RMCO2(4,I),RMDB(4,I),RMW(4,I),QLOSS(4,I)     418.
                    /,QSV(I),QSH(I),UA(I),UAP(I)                               419.
ISN 329       1212   FORMAT(2X,2I4,F10.0,F10.1,F10.4,E12.2,2X,E12.2,5X,E12.2,2E12.3)    420.
ISN 330              RMIN=RMIN+10                                              421.
ISN 331              IF(RMIN.LT.60) GO TO 6100                                 422.
ISN 333              RMIN=RMIN-60                                              423.
ISN 334              HR1=HR1+1                                                 424.
ISN 335              IF(HR1.GT.23) HR1=HR1-24                                  425.
ISN 337       6100   IPAGE=IPAGE+1                                             426.
ISN 338              IF(IPAGE.LT.53) GO TO 610                                 427.
ISN 340              IPAGE=0                                                   428.
ISN 341              WRITE(6,611)                                              429.
ISN 342        610   CONTINUE                                                 430.
ISN 343              Q1=0.                                                     431.
ISN 344              Q2=0.                                                     432.
ISN 345              Q3=0.                                                     433.
ISN 346              DO 630 J=1,4                                              434.
ISN 347        630   Q1=Q1+QTOTAL(J)                                           435.
ISN 348              DO 631 J=1,IFINAL                                         436.
ISN 349              Q2=Q2+QSV(J)*10.                                          437.
ISN 350        631   Q3=Q3+QSH(J)*10.                                          438.
ISN 351              WRITE(6,632)(QTOTAL(I),I=1,4),Q1,Q2,Q3                    439.
ISN 352        632   FORMAT(1H1,5X,'ENERGY TOTALS',//,5X,'ROOM #1',F10.1,/,5X,'ROOM #2' 440.
                    /,F10.1,/,5X,'ROOM #3',F10.1,/,5X,'ROOM #4',F10.1,//,10X,'ROOM TOTA 441.
                    /L',F10.1,//,5X,'VENTILATION TOTAL',F10.1,/,5X,'HEATING      TOTAL'  442.
                    /,F10.1)                                                   443.
ISN 353              WRITE(6,650)                                              444.
ISN 354        650   FORMAT(1H1,2X,'CO2PR(1)     CO2PR(2)     CO2PR(3)     CO2PR(4)     WPR 445.
                    /OD(1)       WPROD(2)     WPROD(3)     WPROD(4)          NTIME      LFAN 446.
                    /',/,' ------------------------------------------------------------ 447.
                    /-----------------------------------',//)                 448.
ISN 355              IPAGE=0                                                   449.
ISN 356              DO 651 I=1,IFINAL                                         450.
ISN 357              LFAN=1                                                    451.
ISN 358              IF(QSH(I).EQ.0.) LFAN=0                                   452.
ISN 360              WRITE(6,652)(CO2PR(J,I),J=1,4),(WPROD(J,I),J=1,4),I,LFAN  453.
ISN 361        652   FORMAT(1X,8(E10.3,2X),5X,2I8)                            454.
ISN 362              IPAGE=IPAGE+1                                             455.
ISN 363              IF(IPAGE.LT.54) GO TO 651                                 456.
ISN 365              IPAGE=0                                                   457.
ISN 366              WRITE(6,650)                                              458.
ISN 367        651   CONTINUE                                                 459.
ISN 368              DO 2934 I=1,NFINAL                                        460.
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                                    ****    MAIN PROGRAM    ****

ISN 369          WRITE(9,2933)I,(CO2PR(J,I),J=1,4),(WPROD(J,I),J=1,4),(QLOSS(J,I),J
                /=1,4)
ISN 370       2933 FORMAT(I4,12E12.5)
ISN 371       2934 CONTINUE
              C
              C  NOW COMPARE  CALIBRATION QUANTITIES - THE SAME AS THOSE READ TO
              C   INITIALIZE THE PROGRAM
              C
ISN 372          WRITE(6,350)
ISN 373        350 FORMAT(1H1,24X,'SUPPLY DRY BULB TEMP(F) TO ROOM #',8X,'CO2',5X,'HU
                /MID',11X,'TIME',/,25X,'1',9X,'2',9X,'3',9X,'4',9X,'CONC',5X,'RATIO
                /',10X,'HR,MN,SC',6X,'OUT.AIR FLOW',/,'      ----------------------
                /-------------------------------------------------------------
                /--------------------------',//)
ISN 374          IPAGE=0
ISN 375          HR1=HR
ISN 376          RMIN=MIN
ISN 377          DO 351 J=1,IFINAL
ISN 378          A=FBAND1*TIN(1)+FBAND2*TIN(2)
ISN 379          B=TIN(3)
ISN 380          C=TIN(4)
ISN 381          D=F(1)*TIN(4)+F(2)*TIN(6)+TIN(7)*F(3)+F(4)*TIN(8)
ISN 382          P=SATHUM((SUPDEW-32.)/1.8)
ISN 383          E=.62198*P/(PRESS-P)
ISN 384          WRITE(6,352)A,B,C,D,SUPCO2(1),E,EXFLOW,(SUPDB(K,J),K=1,4),SUPCO2
                /(J),SUPW(J),HR1,RMIN,SEC,OAFLOW(J)
ISN 385        352 FORMAT(6X,'MEASURED',4X,4F10.1,F10.0,F10.4,25X,F9.1,/,5X,'CALCULAT
                /ED',3X,4F10.1,F10.0,F10.4,11X,I2,2I3,6X,F9.1,/)
ISN 386          READ(10,353)(TIN(I),I=1,8),SUPDEW,SUPCO2(1),EXFLOW
ISN 387        353 FORMAT(9F6.1,F6.0,F7.1,6X)
ISN 388          RMIN=RMIN+10
ISN 389          IF(RMIN.LT.60) GO TO 3510
ISN 391          RMIN=RMIN-60
ISN 392          HR1=HR1+1
ISN 393          IF(HR1.GT.23) HR1=0
ISN 395       3510 IPAGE=IPAGE+1
ISN 396          IF(IPAGE.LT.18) GO TO 351
ISN 398          IPAGE=0
ISN 399          WRITE(6,350)
ISN 400        351 CONTINUE
              C
              C   CALCULATIONS FOR ALTERNATE CONTROL STRATEGY
              C
              C
ISN 401          WRITE(6,3378)
ISN 402          READ(5,4761)PK,ADBMAX,(TRMAX(I),I=2,4)
ISN 403       4761 FORMAT(F3.1,4F4.1)
ISN 404          KLM=0
ISN 405       3378 FORMAT(1H1)
ISN 406       5016 CCO2=RMCO2(1,1)
ISN 407          HR2=FLOAT(HR)
ISN 408          CW=RMW(1,1)
ISN 409          TI15=1.5+((RMDB(1,1)-828.3)/(-11.29))
ISN 410          IF(BOTR(1).NE.BOTRAN(1).OR.RMDB(1,1).LT.70.) TI15=RMDB(1,1)
ISN 412          Q2=0.
ISN 413          Q3=0.
ISN 414          ICLFAN=0
ISN 415          IF(KLM.NE.1) GO TO 3334
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                                  ****    MAIN PROGRAM    ****
ISN 417          IF(LCO2.EQ.1) GO TO 3333                                    519.
ISN 419          LCO2=1                                                      520.
ISN 420          PODMIN=0.                                                   521.
ISN 421          GO TO 3334                                                  522.
ISN 422     3333 LCO2=0                                                      523.
ISN 423          PODMIN=.862                                                 524.
ISN 424     3334 NTIME=1                                                     525.
ISN 425     4140 KTENTH=NTIME                                                526.
ISN 426     4138 KTENTH=KTENTH+1                                             527.
ISN 427     3236 BOTRAN(1)=BOTR(1)                                           528.
ISN 428          IF(LNDN.GT.LDUP) GO TO 3352                                 529.
ISN 430          IF(NTIME.GT.LNDN.AND.NTIME.LT.LDUP) BOTRAN(1)=BOTR(1)-SETN  530.
ISN 432          L2C=LNDN+24*6                                               531.
ISN 433          IF(NFINAL.LT.L2C) GO TO 3353                                532.
ISN 435          IF(NTIME.GT.L2C) BOTRAN(1)=BOTR(1)-SETN                     533.
ISN 437          GO TO 3353                                                  534.
ISN 438     3352 IF(NTIME.LT.LDUP.OR.NTIME.GT.LNDN) BOTRAN(1)=BOTR(1)-SETN   535.
ISN 440          L2C=LDUP+24*6                                               536.
ISN 441          IF(NFINAL.LT.L2C) GO TO 3353                                537.
ISN 443          IF(NTIME.GT.L2C) BOTRAN(1)=BOTR(1)                          538.
ISN 445     3353 DO 3354 J=2,4                                               539.
ISN 446          IF(BOTR(1).EQ.BOTRAN(1)) BOTRAN(J)=BOTR(J)                  540.
ISN 448     3354 IF(BOTR(1).NE.BOTRAN(1)) BOTRAN(J)=BOTR(J)-SETN             541.
ISN 450          IF(BOTRAN(1).EQ.BOTR(1)) GO TO 3359                         542.
ISN 452          IF(BOTRAN(1).LT.BOTR(1)) LFAN=0                             543.
ISN 454          DO 3355 J=1,4                                               544.
ISN 455          BOT16=BOTRAN(J)+TRAN(J)*1.43                                545.
ISN 456          IF(RMDB(J,KTENTH-1).LT.BOT16) GO TO 3356                    546.
ISN 458     3355 CONTINUE                                                    547.
ISN 459          GO TO 3359                                                  548.
ISN 460     3356 DO 3357 J=1,4                                               549.
ISN 461          BOT14=BOTRAN(J)+TRAN(J)                                     550.
ISN 462     3357 IF(RMDB(J,KTENTH-1).LT.BOT14) GO TO 3359                    551.
ISN 464          IF(LT.EQ.0) LFAN=0                                          552.
ISN 466          IF(LT.EQ.1) LFAN=1                                          553.
ISN 468          GO TO 3360                                                  554.
ISN 469     3358 LFAN=0                                                      555.
ISN 470          LT=0                                                        556.
ISN 471          GO TO 3360                                                  557.
ISN 472     3359 LFAN=1                                                      558.
ISN 473          LT=1                                                        559.
ISN 474     3360 ADB(KTENTH-1)=0.                                            560.
ISN 475          AW(KTENTH-1)=0.                                             561.
ISN 476          ACO2(KTENTH-1)=0.                                           562.
ISN 477          IF(BOTRAN(1).LT.BOTR(1).AND.LFAN.EQ.1) ICLFAN=ICLFAN+1      563.
            C                                                                564.
            C    NOW CALCULATE THE SUPPLY CONDITIONS FOR THE NEXT INTERVAL   565.
            C                                                                566.
ISN 479          DO 3335 J=1,4                                               567.
ISN 480          IF(J.EQ.1) I=1                                              568.
ISN 482          IF(J.EQ.2) I=5                                              569.
ISN 484          IF(J.EQ.3) I=6                                              570.
ISN 486          IF(J.EQ.4) I=2                                              571.
ISN 488          IF(LFAN.EQ.1) FLOW=SCPPLY(J)                                572.
ISN 490          IF(LFAN.EQ.0) FLOW=INF(J)                                   573.
ISN 492          ADB(KTENTH-1)=ADB(KTENTH-1)+(RMDB(J,KTENTH-1)+RADG(I))*FLOW 574.
ISN 493          AW(KTENTH-1)=AW(KTENTH-1)+RMW(J,KTENTH-1)*FLOW              575.
ISN 494     3335 ACO2(KTENTH-1)=ACO2(KTENTH-1)+RMCO2(J,KTENTH-1)*FLOW        576.
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                                  ****    MAIN PROGRAM    ****

ISN 495          ADB(KTENTH-1)=ADB(KTENTH-1)/(XCTOT*FLOAT(LFAN)+200.*FLOAT(1-LFAN))  577.
ISN 496          AW(KTENTH-1)=AW(KTENTH-1)/(XCTOT*FLOAT(LFAN)+200.*FLOAT(1-LFAN))    578.
ISN 497          ACO2(KTENTH-1)=ACO2(KTENTH-1)/(XCTOT*FLOAT(LFAN)+200.*FLOAT(1-LFAN  579.
                /))                                                                   580.
ISN 498          IF(ADB(KTENTH-1).GT.ADBMAX) ADB(KTENTH-1)=ADBMAX                     581.
ISN 500          INTIME=NTIME                                                         582.
ISN 501          NTIME=KTENTH-1                                                       583.
ISN 502          CALL HVAC                                                            584.
ISN 503          NTIME=INTIME                                                         585.
            C                                                                         586.
            C   NOW CALCULATE ROOM QUANTITIES FOR THE NEXT INTERVAL                   587.
            C                                                                         588.
ISN 504          DO 5006 J=1,4                                                        589.
ISN 505          IF(LFAN.EQ.1) FLOW=SCPPLY(J)                                         590.
ISN 507          IF(LFAN.EQ.0) FLOW=INF(J)                                            591.
ISN 509          IF(J.EQ.1) GO TO 3337                                                592.
ISN 511          RMCO2(J,KTENTH)=(FLOW*SUPCO2(KTENTH-1)*PK-FLOW*RMCO2(J,KTENTH-1)*P  593.
                /K+CO2PR(J,NTIME)/10.*PK+RMCO2(J,KTENTH-1)*VOL(J))/VOL(J)             594.
ISN 512          IF(RMCO2(J,KTENTH).LT.0.) RMCO2(J,KTENTH)=0.                         595.
ISN 514          RMW(J,KTENTH)=(FLOW*SUPW(KTENTH-1)*PK-FLOW*RMW(J,KTENTH-1)*PK+WPRO  596.
                /D(J,NTIME)/10.*PK+RMW(J,KTENTH-1)*VOL(J))/VOL(J)                     597.
ISN 515          IF(RMW(J,KTENTH).LT.0.) RMW(J,KTENTH)=0.                             598.
ISN 517          QROOMF=Q(FLOW,SUPW(KTENTH-1),SUPDB(J,KTENTH-1))*PK-Q(FLOW,RMW(J,KT  599.
                /ENTH-1),RMDB(J,KTENTH-1))*PK-QLOSS(J,NTIME)/10.*PK+Q(VOL(J),RMW(J,  600.
                /KTENTH-1),RMDB(J,KTENTH-1))                                          601.
ISN 518     3344 N=0                                                                  602.
ISN 519          M=0                                                                  603.
ISN 520          RMDB(J,KTENTH)=RMDB(J,KTENTH-1)                                      604.
ISN 521     3341 Q1=Q(VOL(J),RMW(J,KTENTH),RMDB(J,KTENTH))                            605.
ISN 522          IF(Q1-QROOMF)3338,5005,3340                                          606.
ISN 523     3338 IF(N.EQ.2) GO TO 5005                                                607.
ISN 525          RMDB(J,KTENTH)=RMDB(J,KTENTH)+.01                                    608.
ISN 526          N=1                                                                  609.
ISN 527          M=M+1                                                                610.
ISN 528          IF(M.GT.1000) GO TO 3342                                             611.
ISN 530          GO TO 3341                                                           612.
ISN 531     3340 IF(N.EQ.1) GO TO 5005                                                613.
ISN 533          RMDB(J,KTENTH)=RMDB(J,KTENTH)-.01                                    614.
ISN 534          N=2                                                                  615.
ISN 535          M=M+1                                                                616.
ISN 536          IF(M.GT.1000) GO TO 3342                                             617.
ISN 538          GO TO 3341                                                           618.
ISN 539     3342 WRITE(6,3343)Q1,QROOMF,N,NTIME,J,KTENTH                              619.
ISN 540     3343 FORMAT(3X,'**CONVERGENCE PROBLEM***',2E12.2,4I8)                     620.
ISN 541          GO TO 5005                                                           621.
ISN 542     3337 CCO2=(FLOW*SUPCO2(KTENTH-1)*PK-RMCO2(1,KTENTH-1)*FLOW*PK+CO2PR(1,N  622.
                /TIME)/10.*PK+CCO2*VOL(1))/VOL(1)                                     623.
ISN 543          IF(CCO2.LT.0.) CCO2=0.                                               624.
ISN 545          RMCO2(1,KTENTH)=PROP*CCO2+(1.-PROP)*SUPCO2(KTENTH)                   625.
ISN 546          IF(RMCO2(1,KTENTH).LT.0.) RMCO2(1,KTENTH)=0.                         626.
ISN 548          CW1=(FLOW*SUPW(KTENTH-1)*PK-RMW(1,KTENTH-1)*FLOW*PK+WPROD(1,NTIME)  627.
                //10.*PK+CW*VOL(1))/VOL(1)                                            628.
ISN 549          IF(CW1.LT.0.) CW1=0.                                                 629.
ISN 551          RMW(1,KTENTH)=PROP*CW+(1.-PROP)*SUPW(KTENTH)                         630.
ISN 552          IF(RMW(1,KTENTH).LT.0.) RMW(1,KTENTH)=0.                             631.
ISN 554          QROOMF=Q(FLOW,SUPW(KTENTH-1),SUPDB(1,KTENTH-1))*PK-Q(FLOW,RMW(1,KT  632.
                /ENTH-1),RMDB(1,KTENTH-1))*PK-QLOSS(1,NTIME)/10.*PK+Q(VOL(1),CW,TI1  633.
                /5)                                                                   634.
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                                    ****    MAIN PROGRAM    ****

ISN 555          QROOMF=(PROP*QROOMF/VOL(1)+(1.-PROP)*Q(1..SUPW(KTENTH).
                /SUPDB(1,KTENTH)))*VOL(1)
ISN 556          GO TO 3344
ISN 557     5005 RMDB(J,KTENTH)=RMDB(J,KTENTH)+(FLOAT(N)-1.5)*.01
ISN 558          IF(J.NE.1.AND.RMDB(J,KTENTH).GT.TRMAX(J))RMDB(J,KTENTH)=TRMAX(J)
ISN 560     5006 IF(BOTR(I).EQ.BOTRAN(1).AND.RMDB(J,KTENTH).LT.65.)RMDB(J,KTENTH)=
                /65.
ISN 562          TI15=1.5+((RMDB(1,KTENTH)-828.3)/(-11.29))
ISN 563          IF(BOTR(I).NE.BOTRAN(1).OR.RMDB(1,KTENTH).LT.70.) TI15=RMDB(1,KTEN
                /TH)
ISN 565          Q2=Q2+QSV(KTENTH-1)*PK
ISN 566          Q3=Q3+QSH(KTENTH-1)*PK
ISN 567          IK=IFIX(10./PK+.1)
ISN 568          IF(KTENTH.LT.(NTIME+IK)) GO TO 4138
ISN 570          DO 4139 J=1,4
ISN 571          RMDB(J,NTIME+1)=RMDB(J,KTENTH)
ISN 572          RMW(J,NTIME+1)=RMW(J,KTENTH)
ISN 573          RMCO2(J,NTIME+1)=RMCO2(J,KTENTH)
ISN 574     4139 SUPDB(J,NTIME+1)=SUPDB(J,KTENTH)
ISN 575          SUPW(NTIME+1)=SUPW(KTENTH)
ISN 576          SUPCO2(NTIME+1)=SUPCO2(KTENTH)
ISN 577          OAFLOW(NTIME+1)=OAFLOW(KTENTH)
ISN 578          QSV(NTIME+1)=QSV(KTENTH)
ISN 579          QSH(NTIME+1)=QSH(KTENTH)
ISN 580          NTIME=NTIME+1
ISN 581          HR2=HR2+1./6.
ISN 582          IF(HR2.GT.24.) HR2=HR2-24.
ISN 584          TRAN(5)=TRU
ISN 585          IF(RMDB(1,NTIME).LT.86.5.AND.HR2.GT.12.) TRAN(5)=TRAN(6)
ISN 587          IF(RMDB(1,NTIME).LT.80.) TRAN(5)=TRAN(7)
ISN 589          IF(NTIME.LE.NFINAL) GO TO 4140
            C
            C  NOW PRINT RESULTS
            C
ISN 591          IF(LDUP.GT.LNDN) ITOFF=10*(LDUP-LNDN)
ISN 593          IF(LNDN.GT.LDUP) ITOFF=10*(NFINAL-LNDN+LDUP)
ISN 595          TFON=FLOAT(ICLFAN)/FLOAT(ITOFF)*100.
ISN 596          WRITE(6,3345)LCO2,Q2,Q3,TFON
ISN 597     3345 FORMAT(1H1,5X,'***RESULTS FOR ALTERNATE CONTROL STRATEGY***',/,8X,
                /'_____________________________________',//,' LCO2=',I1,///,5X,'EN
                /ERGY TOTALS',//,9X,'VENTILATION TOTAL',F10.1,/,9X,'HEATING      TOT
                /AL',F10.1,/////,10X,'FAN ON AT NIGHT=',F6.2,'%')
ISN 598          WRITE(6,3346)(I,I=1,4)
ISN 599     3346 FORMAT(1H1,2X,'TIME',2X,4(13X,'ROOM #',I1,10X),/,1X,'HR-MIN',1X,4(
                /' RMCO2  RMDB    RMW    SUPDB    '),2X,'ADB',/,8X,4('_______________
                /_____________  '),//)
ISN 600          HR1=HR
ISN 601          RMIN=MIN
ISN 602          IPAGE=0
ISN 603          DO 3348 I=1,IFINAL
ISN 604          WRITE(6,3347)HR1,RMIN,(RMCO2(J,I),RMDB(J,I),RMW(J,I),SUPDB(J,I),J=
                /1,4),ADB(I)
ISN 605     3347 FORMAT(I3,I4,1X,4(F6.0,F6.1,F8.4,F7.1,3X),F5.1)
ISN 606          RMIN=RMIN+10
ISN 607          IF(RMIN.LT.60) GO TO 3382
ISN 609          RMIN=RMIN-60
ISN 610          HR1=HR1+1
ISN 611     3382 IPAGE=IPAGE+1
```

```
                                    ****    MAIN PROGRAM    ****

ISN 612              IF(IPAGE.LT.53) GO TO 3388                                693.
ISN 614              WRITE(6,3346)(J,J=1,4)                                    694.
ISN 615              IPAGE=0                                                   695.
ISN 616         3389 IF(HR1.GT.23) HR1=HR1-24                                  696.
ISN 618         3348 CONTINUE                                                  697.
ISN 619              WRITE(6,3349)                                             698.
ISN 620         3349 FORMAT(1H1,5X,,'SUPW',5X,'SUPCO2',5X,'DAFLOW',5X,'QSV',10X,'QSH'   699.
                    /,7X,'TIME',8X,'NTIME',/,5X,71('_'),//)                    700.
ISN 621              HR1=HR                                                    701.
ISN 622              RMIN=MIN                                                  702.
ISN 623              IPAGE=0                                                   703.
ISN 624              DO 3350 I=1,IFINAL                                        704.
ISN 625              WRITE(6,3351)SUPW(I),SUPCO2(I),DAFLOW(I),QSV(I),QSH(I),HR1,RMIN,I   705.
ISN 626         3351 FORMAT(3X,F7.4,4X,F6.0,5X,F6.1,2E12.2,3X,I3,I4,5X,I5)     706.
ISN 627              RMIN=RMIN+10                                              707.
ISN 628              IF(RMIN.LT.60) GO TO 3383                                 708.
ISN 630              RMIN=RMIN-60                                              709.
ISN 631              HR1=HR1+1                                                 710.
ISN 632         3383 IPAGE=IPAGE+1                                             711.
ISN 633              IF(IPAGE.LT.53) GO TO 3384                                712.
ISN 635              WRITE(6,3349)                                             713.
ISN 636              IPAGE=0                                                   714.
ISN 637         3384 IF(HR1.GT.23) HR1=HR1-24                                  715.
ISN 639         3350 CONTINUE                                                  716.
ISN 640              IF(KLM.EQ.1) GO TO 5015                                   717.
ISN 642              KLM=1                                                     718.
ISN 643              GO TO 5016                                                719.
ISN 644         5015 STOP                                                      720.
ISN 645              END                                                       721.

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =     644 ,PROGRAM SIZE =    34114

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******
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                                                        DATE   80.271/11.01.49

LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-15

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOOBJECT
ISN 002                 SUBROUTINE HVAC                                                722.
ISN 003                 REAL MADB,MAW,MACO2                                            723.
ISN 004                 DIMENSION QSV(156),SUPPLY(4),F(4),SUPCO2(156),                 724.
                       /SUPDB(4,156),SUPW(156),DTMAX(8),SDG(8),QADB(156),QACO2(156     725.
                       /),RMDB(4,156),RMCO2(4,156),ADB(156),ACO2(156),BOTR(4),         726.
                       /QAW(156),AW(156),RMW(4,156),QLOSS(4,156),QTOTAL(4),SCPPLY(4)   727.
                       /,QAFLOW(156),TBRC(8),TARC(8),QSH(156),BOTRAN(4),TRAN(7),DELTB(4) 728.
ISN 005                 COMMON LFAN,BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  729.
                       /DTRF,QADB,QAW,AW,QACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2, 730.
                       /F,SDG,SUPDB,QAFLOW,XMTOT,QADG,SUPW,SUPCO2,MASS,ALPHA,COLDSK,COLDCR 731.
                       /,SWEATL,SKINK,BODYTC,BLODTC,TSK,TCR,VSKBF,ERSW,ESK,HCP,HP,FCLP     732.
                       /,HRP,FPCLP,QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,LNDN,LDUP,DELTB,BOTR   733.
                       /,INTIME,XCTOT,SCPPLY,SUP,SUP3                                      734.
ISN 006                 EXTERNAL Q                                                     735.
ISN 007                 IF(LFAN.EQ.0) GO TO 99                                         736.
ISN 009                 IF(BOTR(1).NE.BOTRAN(1)) POD=PODMIN                            737.
ISN 011                 IF(BOTR(1).NE.BOTRAN(1)) PODCO2=0.                             738.
ISN 013                 IF(BOTR(1).NE.BOTRAN(1)) GO TO 30                              739.
ISN 015                 TMAX=0.                                                        740.
ISN 016                 CO2MAX=0.                                                      741.
ISN 017                 DO 10 J=1,4                                                    742.
ISN 018                 TOPRAN=BOTRAN(J)+DELTB(J)                                      743.
ISN 019                 IF(J.NE.1)GO TO 120                                            744.
ISN 021                 T115=1.5+((RMDB(1,NTIME)-828.3)/(-11.29))                      745.
ISN 022                 IF(RMDB(1,NTIME).LT.70.) T115=RMDB(1,NTIME)                    746.
ISN 024                 PD=(T115-TOPRAN)/TRAN(1)                                       747.
ISN 025                 POD=PD                                                         748.
ISN 026                 GO TO 10                                                       749.
ISN 027             120 PD=(RMDB(J,NTIME)-TOPRAN)/TRAN(J)                              750.
ISN 028                 IF(PD.GT.POD) POD=PD                                           751.
ISN 030              10 CONTINUE                                                       752.
ISN 031                 IF(POD.LT.PODMIN) POD=PODMIN                                   753.
ISN 033                 IF(POD.GT.1.) POD=1.                                           754.
ISN 035                 DO 20 J=1,4                                                    755.
ISN 036              20 IF(RMCO2(J,NTIME).GT.CO2MAX) CO2MAX=RMCO2(J,NTIME)             756.
ISN 038                 PODCO2=(CO2MAX-CO2MIN)/CO2RAN                                  757.
ISN 039                 IF(PODCO2.LT.0.) PODCO2=0.                                     758.
ISN 041                 IF(PODCO2.GT.1.) PODCO2=1.                                     759.
ISN 043                 IF(LCO2.EQ.0) PODCO2=0.                                        760.
ISN 045                 IF(POD.GE.0..AND.POD.LE..825) GO TO 30                         761.
ISN 047                 TEMFL=720.+3680.*(POD-.825)/.175                               762.
ISN 048                 GO TO 35                                                       763.
ISN 049              30 TEMFL=400.+320.*(POD/.825)                                     764.
ISN 050              35 QAFLOW(NTIME)=TEMFL+CO2FL*PODCO2                               765.
ISN 051                 DO 730 J=1,4                                                   765.1
ISN 052             730 SCPPLY(J)=SUPPLY(J)*(1.-.15*POD)                               765.2
ISN 053                 XCTOT=XMTOT*(1.-.15*POD)                                       765.3
ISN 054                 SUP=SCPPLY(4)/6.                                               765.4
ISN 055                 SUP3=SUP*3.                                                    765.5
ISN 056                 RADB=ADB(NTIME)+DTRF                                           766.
ISN 057                 MAD3=(QAFLOW(NTIME)*(QADB(INTIME)+QADG)+(XCTOT-QAFLOW(NTIME))*RADB 767.
                       /)/XCTOT                                                        768.
ISN 058                 SUPW(NTIME+1)=(QAFLOW(NTIME)*QAW(INTIME)+(XCTOT-QAFLOW(NTIME))*AW 769.
                       /(NTIME))/XCTOT                                                 770.
ISN 059                 SUPCO2(NTIME+1)=(QAFLOW(NTIME)*QACO2(INTIME)+(XCTOT-QAFLOW(NTIME) 771.
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                                        **** SUBPROGRAM   HVAC ****

                        /)*ACO2(NTIME))/XCTOT                                          772.
                    C  CALL COOL                                                       773.
ISN 060                 MADB=MADB+DTSF                                                 774.
ISN 061                 DO 40 J=1,8                                                    775.
ISN 062              40 TBRC(J)=MADB+SDG(J)*2./3.                                      776.
ISN 063                 DTRH1=1.-((TI15-BOTRAN(1))/TRAN(5))                            777.
ISN 064                 DTRH2=1.-((TI15-BOTRAN(1))/TRAN(1))                            778.
ISN 065                 IF(DTRH1.LT.0.) DTRH1=0.                                       779.
ISN 067                 IF(DTRH1.GT.1.) DTRH1=1.                                       780.
ISN 069                 IF(DTRH2.LT.0.) DTRH2=0.                                       781.
ISN 071                 IF(DTRH2.GT.1.) DTRH2=1.                                       782.
ISN 073                 DO 70 I=1,8                                                    783.
ISN 074                 IF(I.LE.2) J=1                                                 784.
ISN 076                 IF(I.EQ.3) J=2                                                 785.
ISN 078                 IF(I.EQ.4) J=3                                                 786.
ISN 080                 IF(I.GT.4) J=4                                                 787.
ISN 082                 DTRHT=1.-((RMDB(J,NTIME)-BOTRAN(J))/TRAN(J))                   788.
ISN 083                 IF(I.EQ.1) DTRHT=DTRH1                                         789.
ISN 085                 IF(I.EQ.2) DTRHT=DTRH2                                         790.
ISN 087                 IF(DTRHT.LT.0.) DTRHT=0.                                       791.
ISN 089                 IF(DTRHT.GT.1.) DTRHT=1.                                       792.
ISN 091              70 TARC(I)=TBRC(I)+DTMAX(I)*DTRHT                                 793.
ISN 092                 QSH(NTIME)=Q(SCPPLY(1)*FBAND1,SUPW(NTIME),TARC(1))-Q(SCPPLY(1)  794.
                       /*FBAND1,SUPW(NTIME),MADB)+Q(SCPPLY(1)*FBAND2,SUPW(NTIME),TARC(2  795.
                       /))-Q(SCPPLY(1)*FBAND2,SUPW(NTIME),MADB)+Q(SCPPLY(2),SUPW(NTIME  796.
                       /),TARC(3))-Q(SCPPLY(2),SUPW(NTIME),MADB)+Q(SCPPLY(3),SUPW(NTIME  797.
                       /),TARC(4))-Q(SCPPLY(3),SUPW(NTIME),MADB)+Q(SCPPLY(4)*F(1),SUPW(  798.
                       /NTIME),TARC(5))-Q(SCPPLY(4)*F(1),SUPW(NTIME),MADB)               799.
ISN 093                 QSH(NTIME)=QSH(NTIME)+Q(SCPPLY(4)*F(4),SUPW(NTIME),TARC(8))-     800.
                       /Q(SCPPLY(4)*F(4),SUPW(NTIME),MADB)+Q(SCPPLY(4)*                  801.
                       /F(2),SUPW(NTIME),TARC(6))-Q(SCPPLY(4)*F(2),SUPW(NTIME),MADB)+Q(  802.
                       /SCPPLY(4)*F(3),SUPW(NTIME),TARC(7))-Q(SCPPLY(4)*F(3),SUPW(NTIME),  803.
                       /MADB)                                                            804.
ISN 094                 SUPDB(1,NTIME+1)=FBAND1*TARC(1)+FBAND2*TARC(2)                   805.
ISN 095                 SUPDB(2,NTIME+1)=TARC(3)                                         806.
ISN 096                 SUPDB(3,NTIME+1)=TARC(4)                                         807.
ISN 097                 SUPDB(4,NTIME+1)=F(1)*TARC(5)+F(2)*TARC(6)+F(3)*TARC(7)+         808.
                       /F(4)*TARC(8)                                                     809.
ISN 098                 QSV(NTIME)=Q(OAFLOW(NTIME),AW(NTIME),RADB)-                      810.
                       /Q(OAFLOW(NTIME),OAW(NTIME),OADB(NTIME)+OADG)                     811.
ISN 099             661 FORMAT(I3,4(F10.4,5X))                                           812.
ISN 100                 GO TO 999                                                        813.
ISN 101              99 DO 80 J=1,4                                                      814.
ISN 102                 IF(J.EQ.1) I=1                                                   815.
ISN 104                 IF(J.EQ.2) I=3                                                   816.
ISN 106                 IF(J.EQ.3) I=4                                                   817.
ISN 108                 IF(J.EQ.4) I=5                                                   818.
ISN 110              80 SUPDB(J,NTIME+1)=ADB(NTIME)+SDG(I)                               819.
ISN 111                 SUPW(NTIME+1)=AW(NTIME)                                          820.
ISN 112                 SUPCO2(NTIME+1)=ACO2(NTIME)                                      821.
ISN 113                 QSH(NTIME)=0.                                                    822.
ISN 114                 OAFLOW(NTIME)=300.                                               823.
ISN 115                 QSV(NTIME)=Q(OAFLOW(NTIME),AW(NTIME),RADB)-                      824.
                       /Q(OAFLOW(NTIME),OAW(NTIME),OADB(NTIME)+OADG)                     825.
ISN 116             999 RETURN                                                           826.
ISN 117                 END                                                              827.

*OPTIONS IN EFFECT*       NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
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                                        **** SUBPROGRAM   HVAC ****
*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
*OPTIONS IN EFFECT*       NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
*STATISTICS*     SOURCE STATEMENTS =      116 ,PROGRAM SIZE =      3378
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                  129K BYTES OF CORE NOT USED
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                                                                    DATE   80.271/11.01.59

LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 FUNCTION SATHUM(T)                                                    828.
ISN 003                 Y1=16.386396+.00137804*(T*1.8+32.)-5656./(459.67+(T*1.8+32.))         829.
ISN 004                 Y2=ALOG((459.67+(T*1.8+32.))/100.)                                    830.
ISN 005                 VP=10.**(Y1-(3.560573*Y2))                                            831.
ISN 006                 SATHUM=VP*25.4                                                        832.
ISN 007                 RETURN                                                                833.
ISN 008                 END                                                                   834.

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =        7 ,PROGRAM SIZE =      384

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                   165K BYTES OF CORE NOT USED
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                                                                DATE  80.271/11.02.11

LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 FUNCTION Q(V,W,T)                                          835.
ISN 003                 DIMENSION QSV(156),SUPPLY(4),F(4),VOL(4),TIN(8),SUPCO2(156),   836.
                       /SUPDB(4,156),SUPW(156),RADG(7),DTMAX(8),SDG(8),OADB(156),OACO2(156 837.
                       /),RMDB(4,156),RMOUT(3,156),RMCO2(4,156),ADB(156),ACO2(156),BBT(3,1 838.
                       /56),OAW(156),AW(156),RMW(4,156),QLOSS(4,156),QTOTAL(4),CO2P       839.
                       /R(4,156),SETSTA(3,156),OAFLOW(156),QSH(156),WPROD(4,156),INF(4),  840.
                       /BOTRAN(4),TRAN(7),DELTB(4),BOTR(4),UA(150),UAP(150),TRMAX(4),SCPPL 841.1
                       /Y(4)                                                              841.2
ISN 004                 COMMON LFAN,BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  842.
                       /DTRF,OADB,OAW,AW,OACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2, 843.
                       /F,SDG,SUPDB,OAFLOW,XMTOT,OADG,SUPW,SUPCO2,MASS,ALPHA,COLDSK,COLDCR 844.
                       /,SWEATL,SKINK,BODYTC,BLODTC,TSK,TCR,VSKBF,ERSW,ESK,HCP,HP,FCLP     845.
                       /,HRP,FPCLP,QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,LNDN,LDUP,DELTB,BOTR   846.
                       /,INTIME,XCTOT,SCPPLY,SUP,SUP3                                      847.
ISN 005                 RO=1./(53.352*(T+460.)*(1.+1.6078*W)/2116.224/PRESS*760.)          848.
ISN 006                 H=.24*T+W*(1061.+.444*T)                                           849.
ISN 007                 Q=RO*H*V                                                           850.
ISN 008                 RETURN                                                             851.
ISN 009                 END                                                                852.

*OPTIONS IN EFFECT*       NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*       NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*      SOURCE STATEMENTS =        8 ,PROGRAM SIZE =       364

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                   161K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
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PROGRAM THAT SIMULATES THE "CORRECTED" WING OF FRIDLEY JUNIOR HIGH SCHOOL

DATE 80.271/11.02.56

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LEVEL 21.8/3.2 (24FEB78)                    OS/360    UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 INTEGER HR,SEC,HR1,RMIN                                          4.
ISN 003                 REAL MASS,INF,KP                                                 5.
ISN 004                 DIMENSION QSV(156),SUPPLY(4),F(4),VOL(4),TIN(8),SUPCO2(156),     6.
                       /SUPDB(4,156),SUPW(156),RADG(7),DTMAX(8),SDG(8),OADB(156),UACO2(156  7.
                       /),RMDB(4,156),RMCO2(4,156),ADB(156),ACO2(156),SCPPLY(4),         8.
                       /OAW(156),AW(156),RMW(4,156),QLOSS(4,156),CO2P                    9.
                       /R(4,156),OAFLOW(156),QSH(156),WPROD(4,156),INF(4),              10.
                       /BOTRAN(4),TRAN(4),DELTB(4),BOTR(4),TRMAX(4)                     11.
ISN 005                 COMMON LFAN,BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  12.
                       /DTRF,OADB,OAW,AW,OACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2, 13.
                       /F,SDG,SUPDB,OAFLOW,XMTOT,OADG,SUPW,SUPCO2,                      14.
                       /QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,LNDN,LDUP,DELTB,BOTR           16.
                       /,INTIME,SCPPLY,XCTOT,SUP,SUP3                                   17.
ISN 006                 EXTERNAL SATHUM,HVAC,Q                                          18.
ISN 007                 SUPPLY(1)=3440.                                                 19.
ISN 008                 SUPPLY(2)=2070.                                                 20.
ISN 009                 SUPPLY(3)=1700.                                                 21.
ISN 010                 SUPPLY(4)=2800.                                                 22.
ISN 011                 FBAND1=.5                                                       23.
ISN 012                 FBAND2=.5                                                       24.
ISN 013                 F(1)=1./7.                                                      25.
ISN 014                 F(2)=2.5/7.                                                     26.
ISN 015                 F(3)=2.5/7.                                                     27.
ISN 016                 F(4)=1./7.                                                      28.
ISN 017                 XMTOT=SUPPLY(1)+SUPPLY(2)+SUPPLY(3)+SUPPLY(4)                   29.
ISN 018                 CO2FL=2600.                                                     30.
ISN 019                 INF(1)=75.                                                      31.
ISN 020                 INF(2)=25.                                                      32.
ISN 021                 INF(3)=25.                                                      33.
ISN 022                 INF(4)=75.                                                      34.
ISN 023                 VOL(1)=43320.                                                   37.
ISN 024                 VOL(2)=16340.                                                   38.
ISN 025                 VOL(3)=16340.                                                   39.
ISN 026                 VOL(4)=18240.                                                   40.
ISN 027                 READ(10,19)(TIN(I),I=1,8),SUPDEW,SUPCO2(1),EXFLOW,HR,MIN,SEC    45.
ISN 028              19 FORMAT(9F6.1,F6.0,F7.1,3I2)                                     46.
ISN 029                 SUPDB(1,1)=FBAND1*TIN(1)+FBAND2*TIN(2)                          47.
ISN 030                 SUPDB(2,1)=TIN(3)                                               48.
ISN 031                 SUPDB(3,1)=TIN(4)                                               49.
ISN 032                 SUPDB(4,1)=F(1)*TIN(5)+F(2)*TIN(6)+F(3)*TIN(7)+F(4)*TIN(8)      50.
ISN 033                 READ(5,1)LDUPH,LDUPM,LNDNH,LNDNM,LCO2,PODMIN,DTRF,DTSF,SETN,(BOTR(  52.
                       /J),TRAN(J),J=1,4),CO2MIN,CO2RAN,(RADG(I),I=1,7),(DTMAX(I),I=1,8),  53.
                       /(SDG(I),I=1,8),LT,OADG,PRESS,(DELTB(J),J=1,4)                   54.
ISN 034               1 FORMAT(4I2,I1,12F4.1,2F6.0,/,7F4.1,/,16F4.1,I1,F4.1,F5.1,/,4F4.1) 55.
ISN 035                 PWI=SATHUM((SUPDEW-32.)/1.8)                                    58.
ISN 036                 SUPW(1)=.62198*PWI/(PRESS-PWI)                                  59.
ISN 037                 PODMIN=PODMIN/100.                                              60.
ISN 038                 LFAN=LT                                                         61.
ISN 039                 IF(LDUPH.GE.HR) GO TO 300                                       62.
ISN 041                 LDUP=(24-HR-1)*6+(60-MIN+LDUPM)/10+LDUPH*6                      63.
ISN 042                 GO TO 310                                                       64.
ISN 043             300 IF(LDUPH.GT.HR) GO TO 301                                       65.
ISN 045                 IF(MIN.GE.LDUPM) LDUP=24*6-(MIN-LDUPM)/10                       66.
ISN 047                 IF(MIN.LT.LDUPM) LDUP=(LDUPM-MIN)/10                            67.
ISN 049                 GO TO 310                                                       68.
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                                  ****    MAIN PROGRAM    ****

ISN 050          301  LDUP=(LDUPH-HR-1)*6+(60-MIN+LDUPM)/10                    69.
ISN 051          310  IF(LNDNH.GE.HR) GO TO 302                                70.
ISN 053               LNDN=(24-HR-1)*6+(60-MIN+LNDNM)/10+LNDNH*6               71.
ISN 054               GO TO 309                                                72.
ISN 055          302  IF(LNDNH.GT.HR) GO TO 303                                73.
ISN 057               IF(MIN.GE.LNDNM) LNDN=24*6-(MIN-LNDNM)/10                74.
ISN 059               IF(MIN.LT.LNDNM) LNDN=(LNDNM-MIN)/10                     75.
ISN 061               GO TO 309                                                76.
ISN 062          303  LNDN=(LNDNH-HR-1)*6+(60-MIN+LNDNM)/10                    77.
ISN 063          309  LDUP2=LDUP+2                                             78.
ISN 064               READ(5,3106)(RMDB(J,1),J=1,4),(RMW(J,1),J=1,4),(RMCO2(J,1),J=1,4)  79.
ISN 065          3106 FORMAT(4F5.1,4F10.4,/,4F10.1)                            80.
ISN 066               I=1                                                      81.
ISN 067           17  READ(11,6,END=18)OADB(I),DPOA,OACO2(I)                  82.
ISN 068            6  FORMAT(2F6.1,F6.0,88X)                                  83.
ISN 069               P=SATHUM((DPOA-32.)/1.8)                                 84.
ISN 070               OAW(I)=.62198*P/(PRESS-P)                                85.
ISN 071               I=I+1                                                    86.
ISN 072               IF(I.GT.144) GO TO 18                                    86.5
ISN 074               GO TO 17                                                 87.
ISN 075           18  NFINAL=I-1                                              88.
ISN 076               IFINAL=NFINAL-1                                          88.1
ISN 077               DO 2934 I=1,IFINAL                                       90.
ISN 078               READ(9,2933)(CO2PP(J,I),J=1,4),(WPROD(J,I),J=1,4),(QLOSS  91.
                     /(J,I),J=1,4)                                             92.
ISN 079          2933 FORMAT(4X,12E12.5)                                       93.
ISN 080          2934 CONTINUE                                                 94.
ISN 081               WRITE(6,3378)                                            95.
ISN 082               READ(5,4761)PK,ADBMAX,(TRMAX(I),I=1,4)                   96.
ISN 083          4761 FORMAT(F3.1,5F4.1)                                       97.
ISN 084               KP=PK/10.                                                97.1
ISN 085               KLM=0                                                    98.
ISN 086          3378 FORMAT(1H1)                                              99.
ISN 087               DO 730 J=1,4                                             99.01
ISN 088           730 SCPPLY(J)=SUPPLY(J)*(1.-.15*PODMIN)                      99.02
ISN 089               SUP=SCPPLY(4)/6.                                         99.03
ISN 090               SUP3=SUP*3.                                              99.04
ISN 091               XCTOT=XMTOT*(1.-.15*PODMIN)                              99.05
                 C                                                             99.1
                 C   SIMULATION STARTS                                         99.2
                 C                                                             99.3
ISN 092          5016 CCO2=RMCO2(1,1)                                          100.
ISN 093               HR2=FLOAT(HR)                                            101.
ISN 094               CW=RMW(1,1)                                              102.
ISN 095               Q2=0.                                                    105.
ISN 096               Q3=0.                                                    106.
ISN 097               ICLFAN=0                                                 107.
ISN 098               IF(KLM.NE.1) GO TO 3334                                  108.
ISN 100               IF(LCO2.EQ.1) GO TO 3333                                 109.
ISN 102               LCO2=1                                                   110.
ISN 103               PODMIN=0.                                                111.
ISN 104               GO TO 3334                                               112.
ISN 105          3333 LCO2=0                                                   113.
ISN 106               PODMIN=.862                                              114.
ISN 107          3334 NTIME=1                                                  115.
ISN 108          4140 KTENTH=NTIME                                             116.
ISN 109          4138 KTENTH=KTENTH+1                                          117.
ISN 110          3336 BOTRAN(1)=BOTR(1)                                        118.
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```
                                  ****    MAIN PROGRAM    ****

ISN 111          IF(LNDN.GT.LDUP) GO TO 3352                                119.
ISN 113          IF(NTIME.GT.LNDN.AND.NTIME.LT.LDUP) BOTRAN(1)=BOTR(1)-SETN 120.
ISN 115          L2C=LNDN+24*6                                              121.
ISN 116          IF(NFINAL.LT.L2C) GO TO 3353                               122.
ISN 118          IF(NTIME.GT.L2C) BOTRAN(1)=BOTR(1)-SETN                    123.
ISN 120          GO TO 3353                                                 124.
ISN 121     3352 IF(NTIME.LT.LDUP.OR.NTIME.GT.LNDN) BOTRAN(1)=BOTR(1)-SETN  125.
ISN 123          L2C=LDUP+24*6                                              126.
ISN 124          IF(NFINAL.LT.L2C) GO TO 3353                               127.
ISN 126          IF(NTIME.GT.L2C) BOTRAN(1)=BOTR(1)                         128.
ISN 128     3353 DO 3354 J=2,4                                              129.
ISN 129          IF(BOTR(1).EQ.BOTRAN(1)) BOTRAN(J)=BOTR(J)                 130.
ISN 131     3354 IF(BOTR(1).NE.BOTRAN(1)) BOTRAN(J)=BOTR(J)-SETN            131.
ISN 133          IF(BOTRAN(1).EQ.BOTR(1)) GO TO 3359                        132.
ISN 135          IF(BOTRAN(1).LT.BOTR(1)) LFAN=0                            133.
ISN 137          DO 3355 J=1,4                                              134.
ISN 138          BOT16=BOTRAN(J)+TRAN(J)*1.43                               135.
ISN 139          IF(RMDB(J,KTENTH-1).LT.BOT16) GO TO 3356                   136.
ISN 141     3355 CONTINUE                                                   137.
ISN 142          GO TO 3358                                                 138.
ISN 143     3356 DO 3357 J=1,4                                              139.
ISN 144          BOT14=BOTRAN(J)+TRAN(J)                                    140.
ISN 145     3357 IF(RMDB(J,KTENTH-1).LT.BOT14) GO TO 3359                   141.
ISN 147          IF(LT.EQ.0) LFAN=0                                         142.
ISN 149          IF(LT.EQ.1) LFAN=1                                         143.
ISN 151          GO TO 3360                                                 144.
ISN 152     3358 LFAN=0                                                     145.
ISN 153          LT=0                                                       146.
ISN 154          GO TO 3360                                                 147.
ISN 155     3359 LFAN=1                                                     148.
ISN 156          LT=1                                                       149.
ISN 157     3360 ADB(KTENTH-1)=0.                                           150.
ISN 158          AW(KTENTH-1)=0.                                            151.
ISN 159          ACO2(KTENTH-1)=0.                                          152.
ISN 160          IF(BOTRAN(1).LT.BOTR(1).AND.LFAN.EQ.1) ICLFAN=ICLFAN+1     153.
            C                                                               154.
            C    NOW CALCULATE THE SUPPLY CONDITIONS FOR THE NEXT INTERVAL  155.
            C                                                               156.
ISN 162          DO 3335 J=1,4                                              157.
ISN 163          IF(J.EQ.1) I=1                                             158.
ISN 165          IF(J.EQ.2) I=5                                             159.
ISN 167          IF(J.EQ.3) I=6                                             160.
ISN 169          IF(J.EQ.4) I=2                                             161.
ISN 171          IF(LFAN.EQ.1) FLOW=SUPPLY(J)                               162.
ISN 173          IF(LFAN.EQ.0) FLOW=INF(J)                                  163.
ISN 175          ADB(KTENTH-1)=ADB(KTENTH-1)+(RMDB(J,KTENTH-1)+RADG(I))*FLOW 164.
ISN 176          AW(KTENTH-1)=AW(KTENTH-1)+RMW(J,KTENTH-1)*FLOW             165.
ISN 177     3335 ACO2(KTENTH-1)=ACO2(KTENTH-1)+RMCO2(J,KTENTH-1)*FLOW       166.
ISN 178          ADB(KTENTH-1)=ADB(KTENTH-1)/(XMTOT*FLOAT(LFAN)+200.*FLOAT(1-LFAN)) 167.
ISN 179          AW(KTENTH-1)=AW(KTENTH-1)/(XMTOT*FLOAT(LFAN)+200.*FLOAT(1-LFAN)) 168.
ISN 180          ACO2(KTENTH-1)=ACO2(KTENTH-1)/(XMTOT*FLOAT(LFAN)+200.*FLOAT(1-LFAN 169.
                /))                                                         170.
ISN 181          IF(ADB(KTENTH-1).GT.ADBMAX) ADB(KTENTH-1)=ADBMAX           171.
ISN 183          INTIME=NTIME                                               172.
ISN 184          NTIME=KTENTH-1                                             173.
ISN 185          CALL HVAC                                                  174.
ISN 186          NTIME=INTIME                                               175.
            C                                                               176.
```

```
                                  ****    MAIN PROGRAM    ****

                 C   NOW CALCULATE ROOM QUANTITIES FOR THE NEXT INTERVAL                  177.
                 C                                                                        178.
ISN 187                 DO 5006 J=1,4                                                     179.
ISN 188                 IF(LFAN.EQ.1) FLOW=SUPPLY(J)                                      180.
ISN 190                 IF(LFAN.EQ.0) FLOW=INF(J)                                         181.
ISN 192                 RMCO2(J,KTENTH)=(FLOW*SUPCO2(KTENTH-1)*PK-FLOW*RMCO2(J,KTENTH-1)*P 183.
                       /K+CO2PR(J,NTIME)/10.*PK+RMCO2(J,KTENTH-1)*VOL(J))/VOL(J)          184.
ISN 193                 IF(RMCO2(J,KTENTH).LT.0.) RMCO2(J,KTENTH)=0.                      185.
ISN 195                 RMW(J,KTENTH)=(FLOW*SUPW(KTENTH-1)*PK-FLOW*RMW(J,KTENTH-1)*PK+WPRO 186.
                       /D(J,NTIME)/10.*PK+RMW(J,KTENTH-1)*VOL(J))/VOL(J)                  187.
ISN 196                 IF(RMW(J,KTENTH).LT.0.) RMW(J,KTENTH)=0.                          188.
ISN 198                 QROOMF=Q(FLOW,SUPW(KTENTH-1),SUPDB(J,KTENTH-1))*PK-Q(FLOW,RMW(J,KT 189.
                       /ENTH-1),RMDB(J,KTENTH-1))*PK-QLOSS(J,NTIME)/10.*PK+Q(VOL(J),RMW(J, 190.
                       /KTENTH-1),RMDB(J,KTENTH-1))                                       191.
ISN 199            3344 N=0                                                               192.
ISN 200                 M=0                                                               193.
ISN 201                 RMDB(J,KTENTH)=RMDB(J,KTENTH-1)                                   194.
ISN 202            3341 Q1=Q(VOL(J),RMW(J,KTENTH),RMDB(J,KTENTH))                         195.
ISN 203                 IF(Q1-QROOMF)3338,5005,3340                                       196.
ISN 204            3338 IF(N.EQ.2) GO TO 5005                                             197.
ISN 206                 RMDB(J,KTENTH)=RMDB(J,KTENTH)+.01                                 198.
ISN 207                 N=1                                                               199.
ISN 208                 M=M+1                                                             200.
ISN 209                 IF(M.GT.1000) GO TO 3342                                          201.
ISN 211                 GO TO 3341                                                        202.
ISN 212            3340 IF(N.EQ.1) GO TO 5005                                             203.
ISN 214                 RMDB(J,KTENTH)=RMDB(J,KTENTH)-.01                                 204.
ISN 215                 N=2                                                               205.
ISN 216                 M=M+1                                                             206.
ISN 217                 IF(M.GT.1000) GO TO 3342                                          207.
ISN 219                 GO TO 3341                                                        208.
ISN 220            3342 WRITE(6,3343)Q1,QROOMF,N,NTIME,J,KTENTH                           209.
ISN 221            3343 FORMAT(3X,'**CONVERGENCE PROBLEM**',2E12.2,4I8)                   210.
ISN 222            5005 RMDB(J,KTENTH)=RMDB(J,KTENTH)+(FLOAT(N)-1.5)*.01                  228.
ISN 223                 IF(NTIME.GE.LDUP.AND.NTIME.LT.LDUP2) GO TO 5021                   228.11
ISN 225                 DIFF=ABS(RMDB(J,KTENTH)-RMDB(J,KTENTH-1))                         228.3
ISN 226                 IF(DIFF.LT.KP) GO TO 5021                                         228.4
ISN 228                 RMDB(J,KTENTH)=RMDB(J,KTENTH-1)+KP*DIFF/(RMDB(J,KTENTH)-RMDB      228.5
                       /(J,KTENTH-1))                                                     228.6
ISN 229            5021 IF(RMDB(J,KTENTH).GT.TRMAX(J))RMDB(J,KTENTH)=TRMAX(J)             229.
ISN 231            5006 IF(BOTR(1).EQ.BOTRAN(1).AND.RMDB(J,KTENTH).LT.65.)RMDB(J,KTENTH)= 230.
                       /65.                                                               231.
ISN 233                 Q2=Q2+QSV(KTENTH-1)*PK                                            235.
ISN 234                 Q3=Q3+QSH(KTENTH-1)*PK                                            236.
ISN 235                 IK=IFIX(10./PK+.1)                                                237.
ISN 236                 IF(KTENTH.LT.(NTIME+IK)) GO TO 4138                               238.
ISN 238                 DO 4139 J=1,4                                                     239.
ISN 239                 RMDB(J,NTIME+1)=RMDB(J,KTENTH)                                    240.
ISN 240                 RMW(J,NTIME+1)=RMW(J,KTENTH)                                      241.
ISN 241                 RMCO2(J,NTIME+1)=RMCO2(J,KTENTH)                                  242.
ISN 242            4139 SUPDB(J,NTIME+1)=SUPDB(J,KTENTH)                                  243.
ISN 243                 SUPW(NTIME+1)=SUPW(KTENTH)                                        244.
ISN 244                 SUPCO2(NTIME+1)=SUPCO2(KTENTH)                                    245.
ISN 245                 OAFLOW(NTIME+1)=OAFLOW(KTENTH)                                    246.
ISN 246                 QSV(NTIME+1)=QSV(KTENTH)                                          247.
ISN 247                 QSH(NTIME+1)=QSH(KTENTH)                                          248.
ISN 248                 NTIME=NTIME+1                                                     249.
ISN 249                 IF(NTIME.LE.NFINAL) GO TO 4140                                    255.
```

```
                                    ****    MAIN PROGRAM    ****
                  C
                  C   NOW PRINT RESULTS
                  C
ISN 251                IF(LDUP.GT.LNDN) ITOFF=10*(LDUP-LNDN)
ISN 253                IF(LNDN.GT.LDUP) ITOFF=10*(NFINAL-LNDN+LDUP)
ISN 255                TFON=FLOAT(ICLFAN)/FLOAT(ITOFF)*100.
ISN 256                WRITE(6,3345)LCO2,Q2,Q3,TFON
ISN 257             3345 FORMAT(1H1,5X,'***RESULTS FOR ALTERNATE CONTROL STRATEGY***',/,8X,
                       /'_____________________________________',//,' LCO2=',I1,///,5X,'EN
                       /ERGY TOTALS',//,9X,'VENTILATION TOTAL',F10.1,/,9X,'HEATING      TOT
                       /AL',F10.1,/////,10X,'FAN ON AT NIGHT=',F6.2,'%')
ISN 258                WRITE(6,3346)(I,I=1,4)
ISN 259             3346 FORMAT(1H1,2X,'TIME',2X,4(13X,'ROOM #',I1,10X),/,1X,'HR-MIN',1X,4(
                       /' RMCO2  RMDB    RMW    SUPDB    '),2X,'ADB',/,8X,4('_____________
                       /_____________  '),//)
ISN 260                HR1=HR
ISN 261                RMIN=MIN
ISN 262                IPAGE=0
ISN 263                DO 3348 I=1,IFINAL
ISN 264                WRITE(6,3347)HR1,RMIN,(RMCO2(J,I),RMDB(J,I),RMW(J,I),SUPDB(J,I),J=
                       /1,4),ADB(I)
ISN 265             3347 FORMAT(I3,I4,1X,4(F6.0,F6.1,F8.4,F7.1,3X),F5.1)
ISN 266                RMIN=RMIN+10
ISN 267                IF(RMIN.LT.60) GO TO 3382
ISN 269                RMIN=RMIN-60
ISN 270                HR1=HR1+1
ISN 271             3382 IPAGE=IPAGE+1
ISN 272                IF(IPAGE.LT.53) GO TO 3388
ISN 274                WRITE(6,3346)(J,J=1,4)
ISN 275                IPAGE=0
ISN 276             3388 IF(HR1.GT.23) HR1=HR1-24
ISN 278             3348 CONTINUE
ISN 279                WRITE(6,3349)
ISN 280             3349 FORMAT(1H1,5X,,'SUPW',5X,'SUPCO2',5X,'OAFLOW',5X,'QSV',10X,'QSH'
                       /,7X,'TIME',8X,'NTIME',/,5X,71('_'),//)
ISN 281                HR1=HR
ISN 282                RMIN=MIN
ISN 283                IPAGE=0
ISN 284                DO 3350 I=1,IFINAL
ISN 285                WRITE(6,3351)SUPW(I),SUPCO2(I),OAFLOW(I),QSV(I),QSH(I),HR1,RMIN,I
ISN 286             3351 FORMAT(3X,F7.4,4X,F6.0,5X,F6.1,2E12.2,3X,I3,I4,5X,I5)
ISN 287                RMIN=RMIN+10
ISN 288                IF(RMIN.LT.60) GO TO 3383
ISN 290                RMIN=RMIN-60
ISN 291                HR1=HR1+1
ISN 292             3383 IPAGE=IPAGE+1
ISN 293                IF(IPAGE.LT.53) GO TO 3384
ISN 295                WRITE(6,3349)
ISN 296                IPAGE=0
ISN 297             3384 IF(HR1.GT.23) HR1=HR1-24
ISN 299             3350 CONTINUE
ISN 300                IF(KLM.EQ.1) GO TO 5015
ISN 302                KLM=1
ISN 303                GO TO 5016
ISN 304             5015 STOP
ISN 305                END

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
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                                        ****     MAIN PROGRAM    ****
*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
*OPTIONS IN EFFECT*       NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
*STATISTICS*      SOURCE STATEMENTS =      304 ,PROGRAM SIZE =     16812
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                        85K BYTES OF CORE NOT USED
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DATE 80.271/11.03.13

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LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 SUBROUTINE HVAC                                                  312.
ISN 003                 REAL MADB,MAW,MACO2                                              313.
ISN 004                 DIMENSION QSV(156),SUPPLY(4),F(4),VOL(4),TIN(8),SUPCO2(156),     314.
                       /SUPDB(4,156),SUPW(156),RADG(7),DTMAX(8),SDG(8),OADB(156),OACO2(156 315.
                       /),RMDB(4,156),RMCO2(4,156),ADB(156),ACO2(156),TBRC(8),TARC(8),    316.
                       /OAW(156),AW(156),RMW(4,156),QLOSS(4,156),CO2P                    317.
                       /R(4,156),OAFLOW(156),QSH(156),WPROD(4,156),INF(4),SCPPLY(4),     318.
                       /BOTRAN(4),TRAN(4),DELTB(4),BOTR(4),TRMAX(4)                      319.
ISN 005                 COMMON LFAN,BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB, 320.
                       /DTRF,OADB,OAW,AW,OACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2, 321.
                       /F,SDG,SUPDB,OAFLOW,XMTOT,OADG,SUPW,SUPCO2,                       322.
                       /QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,LNDN,LOUP,DELTB,BOTR            323.
                       /,INTIME,SCPPLY,XCTOT,SUP,SUP3                                    324.
ISN 006                 EXTERNAL Q                                                       325.
ISN 007                 IF(LFAN.EQ.0) GO TO 99                                           326.
ISN 009                 IF(BOTR(1).NE.BOTRAN(1)) POD=PODMIN                              327.
ISN 011                 IF(BOTR(1).NE.BOTRAN(1)) PODCO2=0.                               328.
ISN 013                 IF(BOTR(1).NE.BOTRAN(1)) GO TO 30                                329.
ISN 015                 TMAX=0.                                                          330.
ISN 016                 CO2MAX=0.                                                        331.
ISN 017                 POD=0.                                                           331.1
ISN 018                 DO 10 J=1,4                                                      332.
ISN 019                 TOPRAN=BOTRAN(J)+DELTB(J)                                        333.
ISN 020                 PD=(RMDB(J,NTIME)-TOPRAN)/TRAN(J)                                340.
ISN 021                 IF(PD.GT.POD) POD=PD                                             341.
ISN 023              10 CONTINUE                                                         342.
ISN 024                 IF(POD.LT.PODMIN) POD=PODMIN                                     343.
ISN 026                 IF(POD.GT.1.) POD=1.                                             344.
ISN 028                 DO 20 J=1,4                                                      345.
ISN 029              20 IF(RMCO2(J,NTIME).GT.CO2MAX) CO2MAX=RMCO2(J,NTIME)               346.
ISN 031                 PODCO2=(CO2MAX-CO2MIN)/CO2RAN                                    347.
ISN 032                 IF(PODCO2.LT.0.) PODCO2=0.                                       348.
ISN 034                 IF(PODCO2.GT.1.) PODCO2=1.                                       349.
ISN 036                 IF(LCO2.EQ.0) PODCO2=0.                                          350.
ISN 038                 IF(POD.GE.0..AND.POD.LE..825) GO TO 30                           351.
ISN 040                 TEMFL=720.+3680.*(POD-.825)/.175                                 352.
ISN 041                 GO TO 35                                                         353.
ISN 042              30 TEMFL=400.+320.*(POD/.825)                                       354.
ISN 043              35 OAFLOW(NTIME)=TEMFL+CO2FL*PODCO2                                 355.
ISN 044                 DO 730 J=1,4                                                     355.1
ISN 045             730 SCPPLY(J)=SUPPLY(J)*(1.-.15*POD)                                 355.2
ISN 046                 XCTOT=XMTOT*(1.-.15*POD)                                         355.3
ISN 047                 SUP=SCPPLY(4)/6.                                                 355.4
ISN 048                 SUP3=SUP*3.                                                      355.5
ISN 049                 RADB=ADB(NTIME)+DTRF                                             356.
ISN 050                 MADB=(OAFLOW(NTIME)*(OADB(INTIME)+OADG)+(XMTOT-OAFLOW(NTIME))*RADB 357.
                       /)/XMTOT                                                          358.
ISN 051                 SUPW(NTIME+1)=(OAFLOW(NTIME)*OAW(INTIME)+(XMTOT-OAFLOW(NTIME))*AW 359.
                       /(NTIME))/XMTOT                                                   360.
ISN 052                 SUPCO2(NTIME+1)=(OAFLOW(NTIME)*OACO2(INTIME)+(XMTOT-OAFLOW(NTIME) 361.
                       /)*ACO2(NTIME))/XMTOT                                             362.
                     C  CALL COOL                                                        363.
ISN 053                 MADB=MADB+DTSF                                                   364.
ISN 054                 DO 40 J=1,8                                                      365.
ISN 055              40 TBRC(J)=MADB+SDG(J)*2./3.                                        366.
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                                    **** SUBPROGRAM   HVAC ****

ISN 056                 DO 70 I=1,8                                                    373.
ISN 057                 IF(I.LE.2) J=1                                                 374.
ISN 059                 IF(I.EQ.3) J=2                                                 375.
ISN 061                 IF(I.EQ.4) J=3                                                 376.
ISN 063                 IF(I.GT.4) J=4                                                 377.
ISN 065                 DTRHT=1.-((RMDB(J,NTIME)-BOTRAN(J))/TRAN(J))                   378.
ISN 066                 IF(DTRHT.LT.0.) DTRHT=0.                                       381.
ISN 068                 IF(DTRHT.GT.1.) DTRHT=1.                                       382.
ISN 070              70 TARC(I)=TBRC(I)+DTMAX(I)*DTRHT                                 383.
ISN 071                 QSH(NTIME)=Q(SUPPLY(1)*FBAND1,SUPW(NTIME),TARC(1))-Q(SUPPLY(1)  384.
                       /*FBAND1,SUPW(NTIME),MADB)+Q(SUPPLY(1)*FBAND2,SUPW(NTIME),TARC(2  385.
                       /))-Q(SUPPLY(1)*FBAND2,SUPW(NTIME),MADB)+Q(SUPPLY(2),SUPW(NTIME  386.
                       /),TARC(3))-Q(SUPPLY(2),SUPW(NTIME),MADB)+Q(SUPPLY(3),SUPW(NTIME  387.
                       /),TARC(4))-Q(SUPPLY(3),SUPW(NTIME),MADB)+Q(SUPPLY(4)*F(1),SUPW(  388.
                       /NTIME),TARC(5))-Q(SUPPLY(4)*F(1),SUPW(NTIME),MADB)               389.
ISN 072                 QSH(NTIME)=QSH(NTIME)+Q(SUPPLY(4)*F(4),SUPW(NTIME),TARC(8))-     390.
                       /Q(SUPPLY(4)*F(4),SUPW(NTIME),MADB)+Q(SUPPLY(4)*                  391.
                       /F(2),SUPW(NTIME),TARC(6))-Q(SUPPLY(4)*F(2),SUPW(NTIME),MADB)+Q(  392.
                       /SUPPLY(4)*F(3),SUPW(NTIME),TARC(7))-Q(SUPPLY(4)*F(3),SUPW(NTIME),  393.
                       /MADB)                                                            394.
ISN 073                 SUPDB(1,NTIME+1)=FBAND1*TARC(1)+FBAND2*TARC(2)                    395.
ISN 074                 SUPDB(2,NTIME+1)=TARC(3)                                          396.
ISN 075                 SUPDB(3,NTIME+1)=TARC(4)                                          397.
ISN 076                 SUPDB(4,NTIME+1)=F(1)*TARC(5)+F(2)*TARC(6)+F(3)*TARC(7)+          398.
                       /F(4)*TARC(8)                                                     399.
ISN 077                 QSV(NTIME)=Q(OAFLOW(NTIME),AW(NTIME),RADB)-                       400.
                       /Q(OAFLOW(NTIME),OAW(NTIME),OADB(NTIME)+OADG)                     401.
ISN 078             661 FORMAT(I3,4(F10.4,5X))                                            402.
ISN 079                 GO TO 999                                                         403.
ISN 080              99 DO 80 J=1,4                                                       404.
ISN 081                 IF(J.EQ.1) I=1                                                    405.
ISN 083                 IF(J.EQ.2) I=3                                                    406.
ISN 085                 IF(J.EQ.3) I=4                                                    407.
ISN 087                 IF(J.EQ.4) I=5                                                    408.
ISN 089              80 SUPDB(J,NTIME+1)=ADB(NTIME)+SDG(I)                                409.
ISN 090                 SUPW(NTIME+1)=AW(NTIME)                                           410.
ISN 091                 SUPCO2(NTIME+1)=ACO2(NTIME)                                       411.
ISN 092                 QSH(NTIME)=0.                                                     412.
ISN 093                 OAFLOW(NTIME)=300.                                                413.
ISN 094                 QSV(NTIME)=Q(OAFLOW(NTIME),AW(NTIME),RADB)-                       414.
                       /Q(OAFLOW(NTIME),OAW(NTIME),OADB(NTIME)+OADG)                     415.
ISN 095             999 RETURN                                                            416.
ISN 096                 END                                                               417.

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =      95 ,PROGRAM SIZE =     3110

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                  133K BYTES OF CORE NOT USED
```
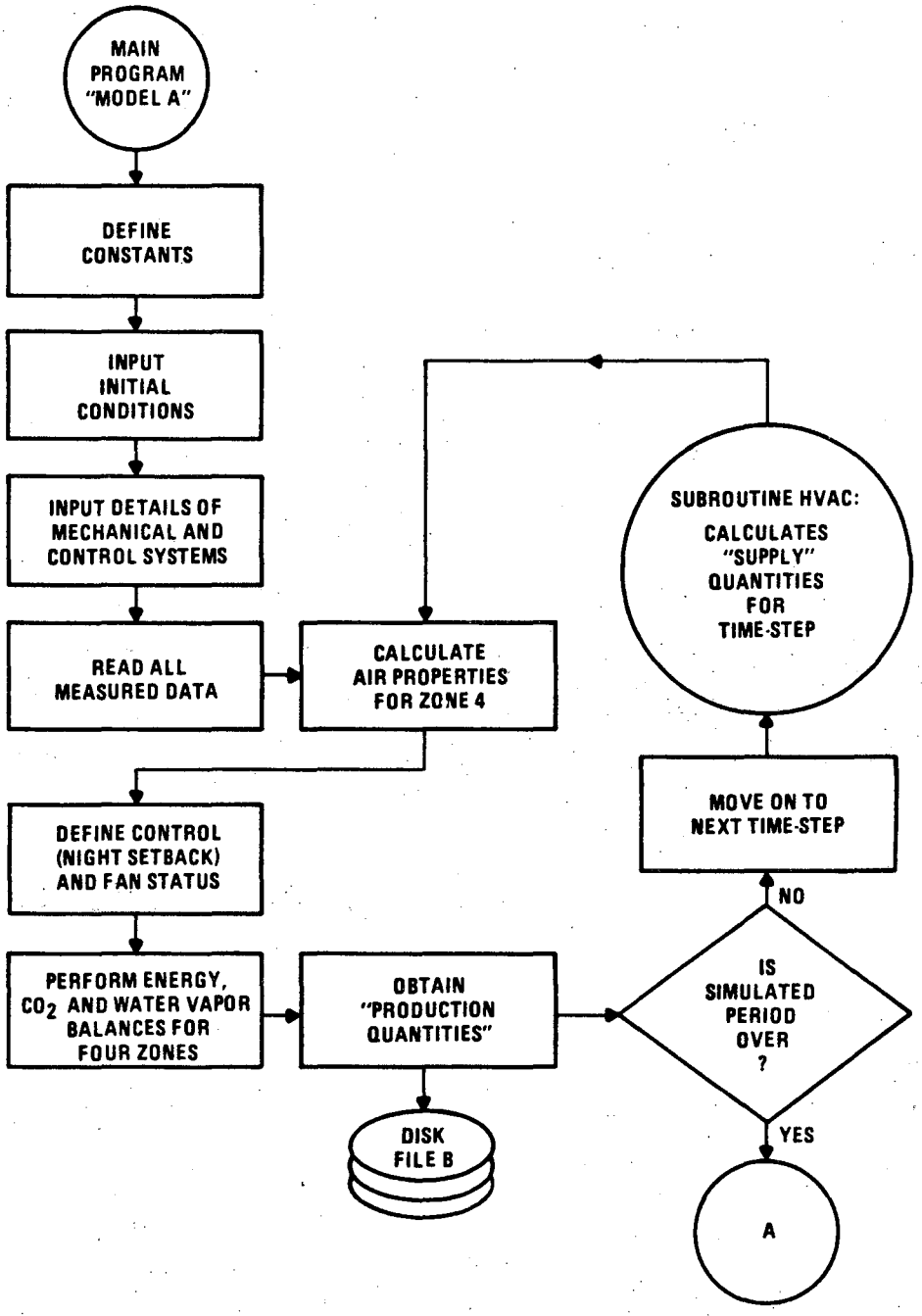
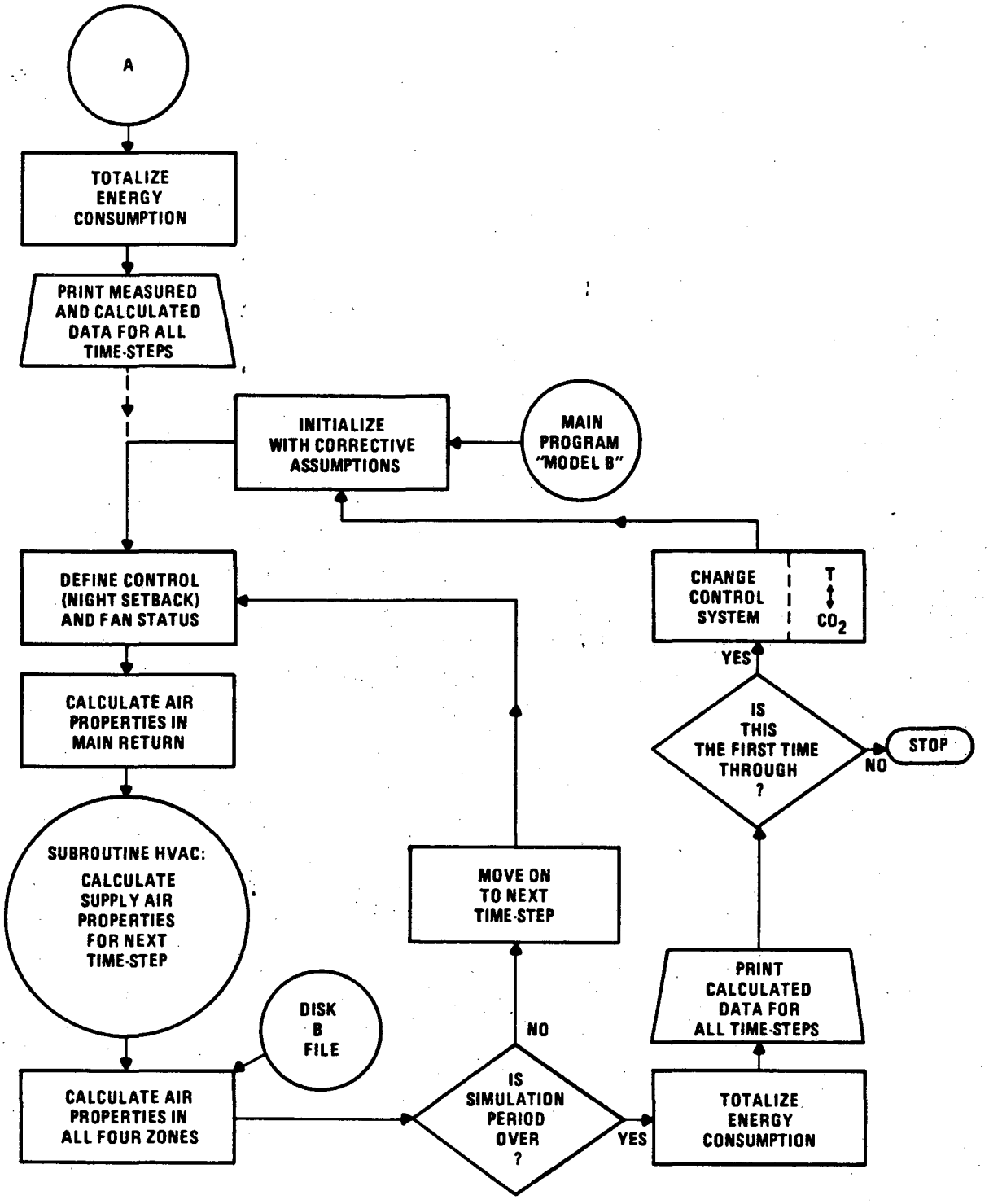

```
                                                                    DATE   80.271/11.03.25

LEVEL 21.8/3.2 (24FEB78)                    OS/360    UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 FUNCTION SATHUM(T)                                                    418.
ISN 003                 Y1=16.386396+.00137804*(T*1.8+32.)-5656./(459.67+(T*1.8+32.))         419.
ISN 004                 Y2=ALOG((459.67+(T*1.8+32.))/100.)                                    420.
ISN 005                 VP=10.**(Y1-(3.560573*Y2))                                            421.
ISN 006                 SATHUM=VP*25.4                                                        422.
ISN 007                 RETURN                                                                423.
ISN 008                 END                                                                   424.

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =        7 ,PROGRAM SIZE =       384

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    165K BYTES OF CORE NOT USED
```

```
                                                        DATE  80.271/11.03.38

LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                  FUNCTION Q(V,W,T)                                          425.
ISN 003                  DIMENSION QSV(156),SUPPLY(4),F(4),VOL(4),TIN(8),SUPCO2(156),  426.
                        /SUPDB(4,156),SUPW(156),RADG(7),DTMAX(8),SDG(8),OADB(156),OACO2(156 427.
                        /),RMDB(4,156),RMCO2(4,156),ADB(156),ACO2(156),            428.
                        /OAW(156),AW(156),RMW(4,156),QLOSS(4,156),CO2P             429.
                        /R(4,156),OAFLOW(156),QSH(156),WPROD(4,156),INF(4),SCPPLY(4),  430.
                        /BOTRAN(4),TRAN(4),DELTB(4),BOTR(4),TRMAX(4)               431.
ISN 004                  COMMON LFAN,BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  432.
                        /DTRF,OADB,OAW,AW,OACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2,  433.
                        /F,SDG,SUPDB,OAFLOW,XMTOT,OADG,SUPW,SUPCO2,                434.
                        /QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,LNDN,LDUP,DELTB,BOTR     435.
                        /,INTIME,SCPPLY,XCTOT,SUP,SUP3                             436.
ISN 005                  RO=1./(53.352*(T+460.)*(1.+1.6078*W)/2116.224/PRESS*760.)  438.
ISN 006                  H=.24*T+W*(1061.+.444*T)                                   439.
ISN 007                  Q=RO*H*V                                                   440.
ISN 008                  RETURN                                                     441.
ISN 009                  END                                                        442.

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =       8 ,PROGRAM SIZE =       348

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                  161K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
```

FLOW CHART FOR ENERGY ANALYSIS PROGRAMS




A
TOTALIZE ENERGY CONSUMPTION
PRINT MEASURED AND CALCULATED DATA FOR ALL TIME-STEPS
INITIALIZE WITH CORRECTIVE ASSUMPTIONS
MAIN PROGRAM "MODEL B"
DEFINE CONTROL (NIGHT SETBACK) AND FAN STATUS
CHANGE CONTROL SYSTEM
T
CO2
YES
CALCULATE AIR PROPERTIES IN MAIN RETURN
IS THIS THE FIRST TIME THROUGH ?
NO
STOP
SUBROUTINE HVAC: CALCULATE SUPPLY AIR PROPERTIES FOR NEXT TIME-STEP
MOVE ON TO NEXT TIME-STEP
PRINT CALCULATED DATA FOR ALL TIME-STEPS
DISK B FILE
NO
CALCULATE AIR PROPERTIES IN ALL FOUR ZONES
IS SIMULATION PERIOD OVER ?
YES
TOTALIZE ENERGY CONSUMPTION

APPENDIX D

FORTRAN PROGRAM TO CALCULATE SET*

```
                                                        DATE  80.273/10.28.36

LEVEL 21.8/3.2 (24FEB78)                    OS/360   JOB FORTRAN H          360/56-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 REAL M,I,MSK
ISN 003                 EXTERNAL STEADY,SET,SATHUM
ISN 004                 COMMON TIME,H,FCL,FPCL,HC,PDP,HR,TDEW,FCLP,FPCLP,HP,HCP,TSOH,DRIP
                  C
                  C
                  C ***********************************************************
                  C *                                                         *
                  C *INPUT THE FOLLOWING VARIABLES (ONE CARD PER OBSERVATION)*
                  C *                                                         *
                  C *EACH VALUE ON 10 SPACE FIELD   XXXXXX.XXX  =F10.3        *
                  C *                                                         *
                  C *M - METABOLIC ACTIVITY (W/M2)                            *
                  C *ETA - WORK EFFICIENCY (FRACTION)                         *
                  C *T - AMBIENT TEMPERATURE (DEGREES CELSIUS)                *
                  C *R - MEAN RADIANT TEMP. (DEGREES CELSIUS)                 *
                  C *RH - RELATIVE HUMIDITY (PERCENT)                         *
                  C *I - CLOTHING INSULATION VALUE (CLO)                      *
                  C *V - AIR VELOCITY (M/S)                                   *
                  C *                                                         *
                  C *OPTION: READ VAPOR PRESSURE INSTEAD OF RELATIVE          *
                  C *        HUMIDITY                                         *
                  C *        ALSO CHANGE ISN005 - RH REPLACED BY PDP          *
                  C *                    ISN007 - RH=PDP/SATHUM(T)*100.       *
                  C *        NOTE: PDP IN MILIMETERS OF MERCURY               *
                  C *                                                         *
                  C ***********************************************************
                  C
                  C
ISN 005             10  READ(5,1,END=999)M,ETA,T,R,RH,I,V
ISN 006             1   FORMAT(7F10.3)
ISN 007                 PDP=SATHUM(T)*RH/100.
ISN 008                 CALL STEADY(M,T,I,ETA,V,R,RH,TSK,PWET)
ISN 009                 SETS=SET(PWET,TSK,T)
ISN 010             2   WRITE(6,4)M,ETA,T,TSK,SETS,R,PWET,TSOH,V,TIME,PDP,RH,I
ISN 011             4   FORMAT(' METABOLIC RATE=',F10.2,/,' WORK EFFICIEN.=',F10.2,/,' AMB
                       IENT  TEMP.=',F10.2,34X,'TSKIN=',F10.2,24X,'SET*=',F10.2,/,' MEAN
                       RAD. TEMP=',F10.2,34X,'PWET =',F10.2,24X,'TSOH=',F10.2,/,' AIR VEL
                       OCITY  =',F10.2,34X,'TIME =',F10.2,/,' VAPOR PRESSURE=',F10.2,/,'
                       DRELATIVE HUMID=',F10.2,/,' CLOTHING INS.=',F10.2,////)
ISN 012                 GO TO 10
ISN 013             999 STOP
ISN 014                 END

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =      13 ,PROGRAM SIZE =      840

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                  101K BYTES OF CORE NOT USED
```

DATE 80.273/10.28.39

```
LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-15

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 SUBROUTINE STEADY(M,T,I,ETA,V,R,RH,TSK,PWET)
ISN 003                 REAL M,I,MASS
ISN 004                 COMMON TIME,H,FCL,FPCL,HC,PDP,HR,TDEW,FCLP,FPCLP,HP,HCP,TSOH,DRIP
ISN 005                 EXTERNAL SATHUM
                  C
                  C  DEFINE STANDARD MAN'S CHARACTERISTICS
                  C
ISN 006                 MASS=70.
ISN 007                 ALPHA=.1
ISN 008                 COLDSK=0.
ISN 009                 COLDCR=0.
ISN 010                 SWEATL=.58
ISN 011                 SKINK=5.28
ISN 012                 BODYTC=.97
ISN 013                 BLOOTC=1.163
                  C
                  C  DEFINE INITIAL CONDITIONS
                  C
ISN 014                 TSK=34.
ISN 015                 TCR=37.
ISN 016                 HC=12.7*SQRT(V)
ISN 017                 IF(HC.LT.2.9) HC=2.9
ISN 019                 FACL=1.+.15*I
ISN 020                 VSKBF=6.3
ISN 021                 ERSW=0.
ISN 022                 ESK=5.
ISN 023                 TIME=0.
ISN 024             100 DTIME=1./60.
                  C
                  C  START  CALCULATIONS OF STEADY-STATE CONDITIONS
                  C
ISN 025                 SKINM=ALPHA*MASS
ISN 026                 COREM=(1.-ALPHA)*MASS
ISN 027                 HR=5.
ISN 028             130 H=HC+HR
ISN 029                 FCL=1./(1.+.155*H*I)
ISN 030                 TO=(HR*R+HC*T)/H
ISN 031                 TCL=TO+FCL*(TSK-TO)
ISN 032                 H1=4.*5.97E-08*((TCL+TO)/2.+273.)**3.*FACL*.72
ISN 033                 H2=ABS(H1-HR)
ISN 034                 IF(H2.LT..1) GO TO 120
ISN 036                 HR=H1
ISN 037                 GO TO 130
ISN 038             120 FPCL=1./(1.+.143*HC*I)
ISN 039                 TDEW=(PDP+25.3)/1.92
ISN 040                 CSK=SKINM*BODYTC
ISN 041                 CCR=COREM*BODYTC
ISN 042                 HSK=(SKINK+BLOOTC*VSKBF)*(TCR-TSK)-ESK-H*FCL*(TSK-T)
ISN 043                 HCR=(M+19.4*COLDSK*COLCR)*(1.-ETA-0.0023*(44.-PDP)-0.0012*(34.-T))
                       A-(SKINK+BLOOTC*VSKBF)*(TCR-TSK)
ISN 044               3 DTSK=1.8*HSK*DTIME/CSK
ISN 045                 DTCR=1.8*HCR*DTIME/CCR
ISN 046                 ATSK=ABS(DTSK)
ISN 047                 ATCR=ABS(DTCR)
ISN 048                 IF(ATSK.GT..1.OR.ATCR.GT..1) GO TO 1
```

```
                                        **** SUBPRUGRAM STEADY ****
ISN 050                 GO TO 2
ISN 051            1    DTIME=DTIME/10.
ISN 052                 GO TO 3
ISN 053            2    TIME=TIME+DTIME
ISN 054                 TSK=TSK+DTSK
ISN 055                 TCR=TCR+DTCR
ISN 056                 SIGSK=TSK-34.
ISN 057                 SIGCR=TCR-37.
ISN 058                 IF(SIGSK)5,5,6
ISN 059            5    COLDSK=-SIGSK
ISN 060                 GO TO 7
ISN 061            6    COLDSK=0.
ISN 062            7    IF(SIGCR)8,8,9
ISN 063            8    WARMCR=0.
ISN 064                 COLDCR=-SIGCR
ISN 065                 GO TO 10
ISN 066            9    WARMCR=SIGCR
ISN 067           10    STRIC=.5*COLDSK
ISN 068                 DILAT=150.*WARMCR
ISN 069                 VSKBF=(6.3+DILAT)/(1.+STRIC)
ISN 070                 IF(VSKBF.GT.90.) VSKBF=90.
ISN 072                 TBP=ALPHA*TSK+(1.-ALPHA)*TCR
ISN 073                 SDOT=285.*(ALPHA*SIGSK+(1.-ALPHA)*SIGCR)
ISN 074                 ERSW=.68*SDOT*EXP(SIGSK/10.)
ISN 075                 IF(ERSW.GT.670.) ERSW=670.
ISN 077                 IF(ERSW.LT.0.) ERSW=0.
ISN 079                 EMAX=4.22*HC*(TSK-TDEW)*FPCL
ISN 080                 WRSW=ERSW/EMAX
ISN 081                 IF(ERSW.GT.EMAX) WRSW=1.
ISN 083                 PWET=.06+.94*WRSW
ISN 084                 ESK=PWET*EMAX
ISN 085                 DRIP=ERSW-ESK
ISN 086                 IF(ERSW.GT.EMAX) ESK=ERSW
ISN 088                 ALPHA=.0442+.3509/(VSKBF-.01386)
                  C
                  C  CHANGE TO A NEW ITERATIVE STEP IF NECESSARY
                  C
ISN 089         1000 IF(TIME.GT.6.) GO TO 200
ISN 091                 IF(ATCR.LT..001.AND.ATSK.LT..001) GO TO 201
ISN 093                 GO TO 100
ISN 094          200    WRITE(6,202)
ISN 095          202    FORMAT(2X,'TIME EXCEEDED - PROBABLY ZONE OF BODY HEATING OR COOLIN
                       AG:',/)
ISN 096          201    RETURN
ISN 097                 END

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =      96 ,PROGRAM SIZE =     1928

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    89K BYTES OF CORE NOT USED
```

DATE 80.273/10.28.43

```
LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 FUNCTION SET(PWET,TSK,T)
ISN 003                 COMMON TIME,H,FCL,FPCL,HC,PDP,HR,TDEW,FCLP,FPCLP,HP,HCP,TSOH,DRIP
ISN 004                 EXTERNAL SATHUM
ISN 005                 HCP=2.91
ISN 006                 HRP=4.9
ISN 007                 HP=HCP+HRP
ISN 008                 FCLP=.57
ISN 009                 FPCLP=.8
ISN 010                 SLOPE=-HP*FCLP/PWET/2.2/HCP/FPCLP
ISN 011                 A=H*FCL+4.22*PWET*HC*FPCL
ISN 012                 AP=HP*FCLP+4.22*PWET*FPCLP*HCP
ISN 013                 TOH=(H*FCL*T+PWET*4.22*HC*FPCL*TDEW)/A
ISN 014                 TSOH=A/AP*TOH+(1.-A/AP)*TSK
ISN 015                 STSOH=SATHUM(TSOH)
ISN 016                 IF(PWET.GT..999.AND.DRIP.GT.0.) GO TO 10
ISN 018                 IF(PWET.EQ..06.AND.DRIP.LT.0.) GO TO 11
                  C
                  C   SET* IS AN ITERATRIVE PROCESS
                  C
ISN 020                 N=0
ISN 021                 SET=TSOH
ISN 022                 IF(SET.LT.-100.) GO TO 3
ISN 024             2   PSET=SATHUM(SET)
ISN 025                 SET1=(AP*TSOH-PWET*4.22*HCP*FPCLP*(.5*PSET+25.3)/1.92)/HP/FCLP
ISN 026                 ASET=ABS(SET-SET1)
ISN 027                 SET=SET+2./3.*(SET1-SET)
ISN 028                 IF(SET.LT.-100.) GO TO 3
ISN 030                 N=N+1
ISN 031                 IF(N.GT.50) GO TO 3
ISN 033                 IF(ASET.GT..001) GO TO 2
ISN 035                 GO TO 5
ISN 036             3   WRITE(6,4)N,SET,SET1
ISN 037             4   FORMAT(' CONVERGENCE #ITER=',I2,5X,'SET=',F10.2,5X,'SET1=',F10.2,/
                       A)
ISN 038                 GO TO 51
ISN 039            11   WRITE(6,14)
ISN 040            14   FORMAT(' BODY COOLING',/)
ISN 041            51   SET=TSOH
ISN 042                 GO TO 20
ISN 043            10   WRITE(6,13)
ISN 044            13   FORMAT(' BODY HEATING',/)
ISN 045                 SET=TSOH+5.
ISN 046            20   SET1=TSOH+(.5*SATHUM(SET)-STSOH)/SLOPE
ISN 047                 ASET=ABS(SET-SET1)
ISN 048                 IF(ASET.LT..01) GO TO 5
ISN 050                 IF(SET1.LT.SET) GO TO 5
ISN 052                 SET=SET+.01
ISN 053                 GO TO 20
ISN 054             5   RETURN
ISN 055                 END

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
```

```
                                        **** SUBPROGRAM    SET ****
*STATISTICS*     SOURCE STATEMENTS =      54 *PROGRAM SIZE =     1078
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                    97K BYTES OF CORE NOT USED
```

```
                                                                    DATE   80.273/10.28.46

LEVEL 21.8/3.2 (24FEB78)                    OS/360    UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                  FUNCTION SATHUM(T)
ISN 003                  Y1=16.386396+.00137804*(T*1.8+32.)-5656./(459.67+(T*1.8+32.))
ISN 004                  Y2=ALOG((459.67+(T*1.8+32.))/100.)
ISN 005                  VP=10.**(Y1-(3.560573*Y2))
ISN 006                  SATHUM=VP*25.4
ISN 007                  RETURN
ISN 008                  END

*OPTIONS IN EFFECT*       NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*       NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =        7 ,PROGRAM SIZE =       384

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    101K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
```

APPENDIX E

CALCULATION SHEETS FOR ENERGY SAVINGS BY CITY

Table E-1. Energy Savings Calculations for Glasgow

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
−33	−33	1	0	0.286	0.375	1.524	1.889	0.286	0.375
−28	−28	3	1	0.277	0.364	1.467	1.817	2.298	2.909
−23	−23	11	4	0.269	0.342	1.408	1.747	8.591	8.356
−18	−18	31	12	0.259	0.325	1.349	1.692	24.217	30.379
−13	−13	52	26	0.250	0.312	1.283	1.611	46.358	58.110
− 8	− 8	37	26	0.235	0.298	1.209	1.539	40.129	51.040
− 8	− 9	20	23	0.236	0.298	1.213	1.545	32.619	41.495
− 4	− 4	68	60	0.220	0.286	1.152	1.473	84.080	107.828
2	2	55	53	0.206	0.259	1.071	1.370	68.093	86.855
2	1	29	33	0.206	0.261	1.071	1.370	41.317	52.779
2	0	1	0	0.206	0.261	1.070	1.379	0.206	0.261
7	7	94	75	0.193	0.242	0.993	1.284	92.617	119.048
12	11	14	12	0.179	0.224	0.919	1.184	13.534	17.344
12	12	92	77	0.179	0.223	0.917	1.180	87.077	111.376
17	16	123	101	0.164	0.208	0.837	1.072	104.709	133.856
17	17	9	1	0.165	0.208	0.830	1.072	2.315	2.944
22	21	177	123	0.151	0.189	0.743	0.965	148.116	152.148
27	26	26	28	0.138	0.170	0.662	0.846	22.124	28.108
27	25	203	124	0.138	0.171	0.660	0.846	109.854	139.617
32	29	113	130	0.124	0.151	0.575	0.739	88.762	113.133
32	30	79	59	0.124	0.150	0.575	0.735	43.721	55.215
37	32	37	54	0.110	0.135	0.497	0.634	30.908	39.231
37	33	94	102	0.111	0.135	0.494	0.632	60.822	77.154
42	36	63	105	0.099	0.114	0.421	0.539	50.442	63.777
42	37	57	37	0.099	0.114	0.420	0.542	21.183	26.552
47	38	0	1	0.088	0.099	0.359	0.443	0.359	0.443
47	39	23	80	0.088	0.099	0.359	0.445	30.744	37.877
47	41	0	3	0.088	0.099	0.354	0.442	1.062	1.326
52	42	4	59	0.077	0.085	0.298	0.355	17.890	21.285
57	44	0	6	0.067	0.072	0.237	0.288	1.422	1.728
57	45	2	33	0.067	0.072	0.237	0.283	7.955	9.483
62	47	0	17	0.058	0.060	0.224	0.225	3.808	3.825
62	48	2	32	0.058	0.060	0.223	0.225	7.252	7.320
57	46	10	38	0.067	0.072	0.237	0.282	9.676	11.436
57	47	24	41	0.067	0.072	0.234	0.286	11.202	13.454
22	22	9	3	0.151	0.189	0.748	0.958	3.603	4.413
27	24	3	1	0.137	0.171	0.657	0.851	1.068	1.364
57	48	34	32	0.067	0.072	0.234	0.285	9.766	11.568
27	26	2	0	0.138	0.170	0.662	0.846	0.276	0.340
32	30	67	18	0.124	0.150	0.575	0.735	18.658	23.280
37	33	50	18	0.111	0.135	0.494	0.632	14.442	18.126
37	34	58	15	0.110	0.134	0.492	0.635	13.760	17.297
42	38	39	11	0.099	0.114	0.423	0.539	8.514	10.375
42	39	59	17	0.099	0.113	0.421	0.538	12.998	15.813
47	40	38	40	0.088	0.098	0.357	0.443	17.624	21.444
47	42	107	55	0.088	0.099	0.359	0.439	29.161	34.738
52	43	25	40	0.077	0.085	0.301	0.352	13.965	16.205
52	45	89	66	0.077	0.086	0.297	0.357	26.455	31.216
62	49	10	38						
								1456.04	1834.25

DIFFERENCE = 378.21
PERCENT SAVINGS = 20.62

Table E-2. Energy Savings Calculations for Minneapolis

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
−28	−28	1	0	0.277	0.364	1.467	1.817	0.277	0.364
−23	−23	4	0	0.269	0.342	1.408	1.747	1.076	1.368
−18	−18	10	2	0.259	0.325	1.349	1.692	5.288	6.634
−13	−13	25	9	0.250	0.312	1.283	1.611	17.797	22.299
− 8	− 8	40	18	0.235	0.298	1.209	1.539	31.162	39.622
− 3	− 3	42	25	0.219	0.284	1.143	1.464	37.773	48.528
− 3	− 4	16	7	0.219	0.284	1.139	1.462	11.477	14.778
2	1	76	56	0.206	0.261	1.071	1.370	75.632	96.556
7	6	87	69	0.194	0.241	0.998	1.284	85.740	109.56
7	7	7	3	0.193	0.242	0.993	1.284	4.330	5.546
12	11	121	88	0.179	0.224	0.919	1.184	102.53	131.30
12	10	1	0	0.179	0.224	0.915	1.184	0.179	0.224
17	16	136	115	0.164	0.208	0.837	1.072	118.56	151.57
22	21	121	119	0.151	0.189	0.743	0.965	106.69	137.70
22	20	51	26	0.151	0.189	0.745	0.960	27.071	34.589
27	26	38	43	0.138	0.170	0.662	0.846	33.710	42.838
27	25	169	139	0.138	0.171	0.660	0.846	115.06	146.49
32	30	154	143	0.124	0.150	0.575	0.735	101.32	128.21
32	29	40	54	0.124	0.151	0.575	0.739	36.010	45.946
37	33	4	12	0.111	0.135	0.494	0.632	6.372	8.124
37	34	132	147	0.110	0.134	0.492	0.635	86.844	111.03
42	38	65	82	0.099	0.114	0.423	0.539	34.785	51.608
42	37	11	34	0.099	0.114	0.420	0.542	14.280	19.682
42	36	0	3	0.099	0.114	0.421	0.539	1.263	1.617
47	40	1	16	0.088	0.098	0.357	0.443	5.800	7.186
47	41	28	35	0.088	0.099	0.354	0.442	14.854	18.242
47	42	11	28	0.088	0.099	0.359	0.439	11.020	13.381
47	44	1	2	0.088	0.097	0.360	0.440	0.808	0.977
52	43	0	1	0.077	0.085	0.301	0.352	0.301	0.352
52	44	1	10	0.077	0.086	0.301	0.354	3.087	3.626
52	45	20	33	0.077	0.086	0.297	0.357	11.341	13.501
52	47	7	18	0.077	0.084	0.296	0.355	5.867	6.978
52	49	2	1	0.077	0.085	0.297	0.353	0.451	0.523
57	47	0	1	0.067	0.072	0.234	0.286	0.234	0.286
57	48	12	26	0.067	0.072	0.234	0.285	6.888	8.274
57	50	2	12	0.067	0.071	0.239	0.284	3.002	3.550
62	51	5	21	0.058	0.060	0.224	0.224	4.994	5.004
62	52	0	1						
62	53	0	6	0.058	0.060	0.220	0.220	1.320	1.320
22	21	4	0	0.151	0.189	0.743	0.965	0.604	0.756
27	25	9	1	0.138	0.171	0.660	0.846	1.902	2.385
32	30	23	6	0.124	0.150	0.575	0.735	6.302	7.860
37	34	38	11	0.110	0.134	0.492	0.635	9.592	12.077
42	39	43	26	0.099	0.113	0.421	0.538	15.203	18.847
47	43	50	33	0.089	0.098	0.358	0.442	16.264	19.486
52	47	37	37	0.077	0.084	0.296	0.355	13.801	16.243
57	51	27	37	0.067	0.072	0.238	0.284	10.615	12.452
								1199.48	1529.50

DIFFERENCE = 330.02
PERCENT SAVINGS = 21.58

Table E-3. Energy Savings Calculations for Albany

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
−18	−18	3	0	0.259	0.325	1.349	1.692	0.777	0.975
−13	−13	5	0	0.250	0.312	1.283	1.611	1.250	1.560
− 8	− 8	10	0	0.235	0.298	1.209	1.539	2.350	2.980
− 3	− 3	26	3	0.219	0.284	1.143	1.464	9.123	11.776
− 3	− 4	1	0	0.219	0.284	1.139	1.462	0.219	0.284
2	2	29	11	0.206	0.259	1.071	1.370	17.755	22.581
2	1	8	5	0.206	0.261	1.071	1.370	7.003	8.938
7	7	16	6	0.193	0.242	0.993	1.284	9.046	11.576
7	6	44	21	0.194	0.241	0.998	1.284	29.494	37.568
12	12	2	0	0.179	0.223	0.917	1.180	0.358	0.446
12	11	82	43	0.179	0.224	0.919	1.184	54.195	69.280
17	15	42	26	0.166	0.208	0.833	1.078	28.630	36.764
17	16	62	52	0.164	0.208	0.837	1.072	53.692	68.640
17	17	6	1	0.165	0.208	0.830	1.072	1.820	2.320
22	20	141	110	0.151	0.189	0.745	0.960	103.241	132.249
22	21	20	2	0.151	0.189	0.743	0.965	4.506	5.710
27	25	206	156	0.138	0.171	0.660	0.846	131.388	167.202
32	30	260	219	0.124	0.150	0.575	0.735	158.165	199.965
37	33	36	55	0.111	0.135	0.494	0.632	31.166	39.620
37	34	164	179	0.110	0.134	0.492	0.635	106.108	135.641
42	37	14	45	0.099	0.114	0.420	0.542	20.286	25.986
42	38	106	123	0.099	0.114	0.423	0.539	62.523	78.381
42	39	8	15	0.099	0.113	0.421	0.538	7.107	8.974
47	41	5	27	0.088	0.099	0.354	0.442	9.998	12.429
47	42	38	49	0.088	0.099	0.359	0.439	20.935	25.273
47	43	31	53	0.089	0.098	0.358	0.442	21.733	26.464
47	45	2	3	0.088	0.098	0.356	0.438	1.244	1.510
52	45	27	54	0.077	0.086	0.297	0.357	18.117	21.600
52	47	1	3	0.077	0.084	0.296	0.355	0.965	1.149
52	48	20	39	0.077	0.084	0.299	0.353	13.201	15.447
52	49	1	2	0.077	0.085	0.297	0.353	0.671	0.791
57	49	12	38	0.067	0.071	0.238	0.284	9.772	11.644
57	50	0	1	0.067	0.071	0.239	0.284	0.239	0.284
57	52	7	18	0.067	0.071	0.237	0.282	4.735	5.573
57	54	3	4	0.067	0.071	0.233	0.285	1.133	1.353
62	51	5	28	0.058	0.060	0.224	0.224	6.562	6.572
62	56	2	11	0.058	0.059	0.220	0.220	2.536	2.538
								952.04	1202.04

DIFFERENCE = 250.00
PERCENT SAVINGS = 20.80

Table E-4. Energy Savings Calculations for Toledo

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
−13	−13	1	0	0.250	0.312	1.283	1.611	0.250	0.312
− 8	− 8	9	1	0.235	0.298	1.209	1.539	3.324	4.221
− 3	− 3	18	4	0.219	0.284	1.143	1.464	8.514	10.968
2	2	38	12	9.206	0.259	1.071	1.370	20.680	26.282
7	7	5	0	0.193	0.242	0.993	1.284	0.965	1.210
7	6	40	24	0.194	0.241	0.998	1.284	31.712	40.456
12	12	1	0	0.179	0.223	0.917	1.180	0.179	0.223
12	11	78	46	0.179	0.224	0.919	1.184	56.236	71.936
17	17	1	0	0.165	0.208	0.830	1.072	0.165	0.208
17	16	117	45	0.164	0.208	0.837	1.072	56.853	72.576
22	21	94	68	0.151	0.189	0.743	0.965	64.718	83.386
22	20	74	68	0.151	0.189	0.745	0.960	61.834	79.266
27	26	82	62	0.138	0.170	0.662	0.846	52.360	66.392
27	25	149	118	0.138	0.171	0.660	0.846	98.442	125.307
32	30	271	243	0.124	0.150	0.575	0.735	173.329	219.255
37	35	28	35	0.110	0.135	0.494	0.633	20.370	25.935
37	34	162	180	0.110	0.134	0.492	0.635	106.380	136.008
42	39	44	59	0.099	0.113	0.421	0.538	29.195	36.714
42	38	64	107	0.099	0.114	0.423	0.539	51.597	64.969
47	43	29	64	0.089	0.098	0.358	0.442	25.493	31.130
47	42	29	33	0.088	0.099	0.359	0.439	14.399	17.358
47	41	8	19	0.088	0.099	0.354	0.442	7.430	9.190
52	49	2	5	0.077	0.085	0.297	0.353	1.639	1.935
52	48	4	7	0.077	0.084	0.299	0.353	2.401	2.807
52	47	15	26	0.077	0.084	0.296	0.355	8.851	10.490
52	46	28	47	0.077	0.086	0.298	0.355	16.162	19.093
57	55	1	0	0.067	0.071	0.236	0.284	0.067	0.071
57	53	14	26	0.067	0.071	0.239	0.283	7.152	8.352
57	52	1	7	0.067	0.071	0.237	0.282	1.726	2.045
57	50	15	34	0.067	0.071	0.239	0.284	9.131	10.721
62	55	21	37	0.058	0.059	0.220	0.221	9.358	9.416
62	54	0	1						
62	53	0	5	0.058	0.060	0.220	0.220	1.100	1.100
								942.012	1189.332

DIFFERENCE = 247.320
PERCENT SAVINGS = 20.79

Table E-5. Energy Savings Calculations for Tacoma

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
2	1	1	0	0.206	0.261	1.071	1.370	0.206	0.261
7	6	1	0	0.194	0.241	0.998	1.284	0.194	0.241
12	11	7	2	0.179	0.224	0.919	1.184	3.091	3.936
17	14	1	0	0.166	0.208	0.832	1.074	0.166	0.208
17	15	11	3	0.166	0.208	0.833	1.078	4.325	5.522
17	16	1	0	0.164	0.208	0.837	1.072	0.164	0.208
22	19	7	2	0.151	0.188	0.746	0.960	2.549	3.236
22	20	23	6	0.151	0.189	0.745	0.960	7.943	10.107
22	21	3	0	0.151	0.189	0.743	0.965	0.453	0.567
27	24	66	21	0.137	0.171	0.657	0.851	22.839	29.157
27	25	13	2	0.138	0.171	0.660	0.846	3.114	3.915
32	29	164	57	0.124	0.151	0.575	0.739	53.111	66.887
37	33	69	21	0.111	0.135	0.494	0.632	18.033	22.587
37	34	152	87	0.110	0.134	0.492	0.635	59.524	75.613
42	38	232	156	0.099	0.114	0.423	0.539	88.956	110.532
47	42	181	154	0.088	0.099	0.359	0.439	71.214	85.525
47	43	25	42	0.089	0.098	0.358	0.442	17.261	21.014
52	46	42	17	0.077	0.086	0.298	0.355	8.300	9.647
52	47	136	182	0.077	0.084	0.296	0.355	64.344	76.034
57	50	30	45	0.067	0.071	0.239	0.284	12.765	14.910
57	51	45	72	0.067	0.072	0.238	0.284	20.151	23.688
57	52	67	55	0.067	0.071	0.237	0.282	17.524	20.267
57	53	17	29	0.067	0.071	0.239	0.283	8.070	9.414
62	55	7	25	0.058	0.059	0.220	0.221	5.906	5.938
62	56	73	79	0.058	0.059	0.220	0.220	21.614	21.687
								511.817	621.101

DIFFERENCE = 109.284
PERCENT SAVINGS = 17.60

Table E-6. Energy Savings Calculations for Albuquerque

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
−3	−4	1	0	0.219	0.284	1.139	1.462	0.219	0.284
2	1	1	0	0.206	0.261	1.071	1.370	0.206	0.261
7	5	4	1	0.194	0.241	0.997	1.292	1.773	2.256
7	6	2	0	0.194	0.241	0.998	1.284	0.388	0.482
12	10	15	2	0.179	0.224	0.915	1.184	4.515	5.728
12	11	7	0	0.179	0.224	0.919	1.184	1.253	1.568
17	15	49	8	0.166	0.208	0.833	1.078	14.798	18.816
22	19	61	9	0.151	0.188	0.746	0.960	15.925	20.108
22	20	55	9	0.151	0.189	0.745	0.960	15.010	19.035
27	23	31	2	0.138	0.170	0.663	0.848	5.604	6.966
27	24	199	50	0.137	0.171	0.657	0.851	60.113	76.579
32	27	99	27	0.124	0.151	0.574	0.738	27.774	34.875
32	28	179	77	0.124	0.151	0.580	0.745	66.856	84.394
37	31	183	135	0.111	0.134	0.499	0.639	87.678	110.787
37	32	89	21	0.110	0.135	0.497	0.634	20.227	25.329
42	34	111	159	0.099	0.114	0.424	0.543	78.405	98.991
42	35	106	36	0.099	0.113	0.422	0.542	25.686	31.490
47	36	33	40	0.088	0.100	0.358	0.441	17.224	20.940
47	37	74	137	0.088	0.099	0.353	0.445	54.873	68.291
47	38	29	40	0.088	0.099	0.359	0.443	16.912	20.591
52	39	16	136	0.077	0.086	0.298	0.360	41.760	50.336
52	40	58	69	0.077	0.086	0.299	0.356	25.097	29.552
57	41	3	42	0.067	0.072	0.237	0.287	10.155	12.270
57	42	30	88	0.067	0.071	0.237	0.288	22.866	27.474
57	43	0	43	0.067	0.071	0.236	0.277	10.148	11.911
62	43	0	36	0.058	0.060	0.227	0.230	8.172	8.280
62	44	9	70						
62	45	0	29						
								633.64	787.59

DIFFERENCE = 153.95
PERCENT SAVINGS = 19.55

Table E-7. Energy Savings Calculations for Atlanta

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
2	2	1	0	0.206	0.259	1.071	1.370	0.206	0.259
7	7	3	0	0.193	0.242	0.993	1.284	0.579	0.726
12	11	3	1	0.179	0.224	0.919	1.184	1.456	1.856
17	17	2	0	0.165	0.208	0.830	1.072	0.330	0.416
17	16	7	2	0.164	0.208	0.837	1.072	2.822	3.600
22	22	11	1	0.151	0.189	0.748	0.958	2.409	3.037
22	21	19	4	0.151	0.189	0.743	0.965	5.841	7.451
27	26	24	13	0.138	0.170	0.662	0.846	11.918	15.078
27	27	83	7	0.139	0.170	0.660	0.845	16.157	20.025
32	31	247	72	0.124	0.151	0.575	0.733	72.028	90.073
37	35	173	98	0.110	0.135	0.494	0.633	67.442	85.389
37	36	151	73	0.110	0.134	0.497	0.637	52.891	66.735
42	39	71	52	0.099	0.113	0.421	0.538	28.921	35.999
42	40	249	205	0.099	0.113	0.424	0.535	111.571	137.812
42	41	60	43	0.099	0.114	0.421	0.537	24.043	29.931
47	43	62	143	0.089	0.098	0.358	0.442	56.712	69.282
47	44	93	105	0.088	0.097	0.360	0.440	45.984	55.221
47	45	95	131	0.088	0.098	0.356	0.438	54.996	66.688
52	46	25	148	0.077	0.086	0.298	0.355	46.029	54.690
52	47	10	45	0.077	0.084	0.296	0.355	14.090	16.815
52	48	14	26	0.077	0.084	0.299	0.353	8.852	10.354
52	49	37	100	0.077	0.085	0.297	0.353	32.549	38.445
57	48	0	25	0.067	0.072	0.234	0.285	5.850	7.125
57	49	1	47	0.067	0.071	0.236	0.284	11.159	13.419
57	50	2	15	0.067	0.071	0.239	0.284	3.719	4.402
57	51	2	5	0.067	0.072	0.238	0.284	1.324	1.564
57	52	5	27	0.067	0.071	0.237	0.282	6.734	7.969
62	50	0	9	0.058	0.060	0.221	0.224	1.989	2.016
62	51	0	23	0.058	0.060	0.224	0.224	5.152	5.152
62	52	0	1						
62	54	0	4						
								693.78	851.53

DIFFERENCE = 157.75
PERCENT SAVINGS = 18.53

Table E-8. Energy Savings Calculations for Dallas

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
12	11	6	2	0.179	0.224	0.919	1.184	2.912	3.712
17	17	1	0	0.165	0.208	0.830	1.072	0.165	0.208
17	15	8	4	0.166	0.208	0.833	1.078	4.660	5.976
22	21	5	1	0.151	0.189	0.743	0.965	1.498	1.910
22	20	23	10	0.151	0.189	0.745	0.960	10.923	13.947
27	24	27	11	0.137	0.171	0.657	0.851	10.926	13.978
27	25	41	9	0.138	0.171	0.660	0.846	11.598	14.625
32	32	1	0	0.124	0.152	0.574	0.735	0.124	0.152
32	29	127	53	0.124	0.151	0.575	0.739	46.223	58.344
37	33	131	60	0.111	0.135	0.494	0.632	44.181	55.605
37	34	47	23	0.110	0.134	0.492	0.635	16.486	20.903
42	37	46	31	0.099	0.114	0.420	0.542	17.574	22.046
42	38	181	97	0.099	0.114	0.423	0.539	58.950	72.917
47	41	36	32	0.088	0.099	0.354	0.442	14.496	17.708
47	42	179	118	0.088	0.099	0.359	0.439	58.114	69.523
52	45	66	61	0.077	0.086	0.297	0.357	23.199	27.453
52	46	91	100	0.077	0.086	0.298	0.355	36.807	43.326
52	47	31	10	0.077	0.084	0.296	0.355	5.347	6.154
57	49	34	88	0.067	0.071	0.236	0.284	23.046	27.406
57	50	32	33	0.067	0.071	0.239	0.284	10.031	11.644
57	51	77	54	0.067	0.072	0.238	0.284	18.011	20.880
62	53	9	24	0.058	0.060	0.220	0.220	5.802	5.820
62	55	24	35	0.058	0.059	0.220	0.221	9.092	9.151
62	56	56	30	0.058	0.059	0.220	0.220	9.848	9.904
								440.01	533.29

DIFFERENCE = 93.28
PERCENT SAVINGS = 17.49

Table E-9. Energy Savings Calculations for Yuma

BIN AVERAGE TEMPERATURES (°F)		NUMBER OF OCCURRENCES		ENERGY REQUIREMENTS PER BIN (10^6 Btu)				TOTAL ENERGY REQUIRED (10^6 Btu)	
				BIN 1		BIN 2			
DRY BULB	WET BULB	BIN 1	BIN 2	CO_2	TEMPERATURE	CO_2	TEMPERATURE	CO_2	TEMPERATURE
32	27	9	0	0.124	0.151	0.574	0.738	1.116	1.359
32	29	1	0	0.124	0.151	0.575	0.739	0.124	0.151
37	30	9	0	0.111	0.134	0.497	0.638	0.999	1.206
37	31	13	0	0.111	0.134	0.499	0.639	1.443	1.742
37	32	24	2	0.110	0.135	0.497	0.634	3.634	4.508
37	33	3	0	0.111	0.135	0.494	0.632	0.333	0.405
42	35	28	1	0.099	0.113	0.422	0.542	2.996	3.480
42	36	120	11	0.099	0.114	0.421	0.539	16.511	19.609
42	38	1	0	0.099	0.114	0.423	0.539	0.099	0.114
47	39	138	18	0.088	0.099	0.359	0.445	18.606	21.672
47	40	145	20	0.088	0.098	0.357	0.443	19.900	23.070
47	41	7	0	0.088	0.099	0.354	0.442	0.616	0.693
52	42	134	39	0.077	0.085	0.288	0.355	21.940	25.235
52	43	199	43	0.077	0.085	0.301	0.352	28.266	32.051
52	44	25	0	0.077	0.086	0.301	0.354	1.925	2.150
57	46	251	146	0.067	0.072	0.237	0.282	51.419	59.244
57	47	53	2	0.067	0.072	0.234	0.286	4.019	4.388
62	48	66	176	0.058	0.060	0.223	0.225	43.076	43.560
62	49	43	30						
62	50	70	9	0.058	0.060	0.221	0.224	6.049	6.216
								223.071	250.853

DIFFERENCE = 27.782
PERCENT SAVINGS = 11.08

APPENDIX F

FORTRAN PROGRAM TO PERFORM THE BIN ANALYSIS

DATE 80.271/10.59.05

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LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                   INTEGER HR,HR1,RMIN                                          4.
ISN 003                   REAL KP                                                      5.
ISN 004                   DIMENSION QSV(75),SUPPLY(4),F(4),VOL(4),SUPCO2(75),          6.
                         /SUPDB(4,75),SUPW(75),RADG(7),DTMAX(8),SDG(8),QBIN1(2),QBIN2(2),  7.
                         /RMDB(4,75),RMCO2(4,75),ADB(75),ACO2(75),ITEMP(2),ICO2(2),ICON(2),  8.
                         /AW(75),RMW(4,75),QLOSS(4,75),CO2P                           9.
                         /R(4,75),OAFLOW(75),QSH(75),WPROD(4,75),QLOSC(4,75)          10.
                         /,BOTRAN(4),TRAN(4),DELTB(4),TRMAX(4)                        11.
ISN 005                   COMMON BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  12.
                         /DTRF,OADB,OAW,AW,OACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2,  13.
                         /F,SDG,SUPDB,OAFLOW,XMTOT,OADG,SUPW,SUPCO2,ITEMP,ICO2,       14.
                         /QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,DELTB                      16.
                         /,INTIME,SUP,SUP3                                            17.
ISN 006                   EXTERNAL SATHUM,HVAC,Q                                       18.
ISN 007                   SUPPLY(1)=3440.                                              19.
ISN 008                   SUPPLY(2)=2070.                                              20.
ISN 009                   SUPPLY(3)=1700.                                              21.
ISN 010                   SUPPLY(4)=2800.                                              22.
ISN 011                   FBAND1=.5                                                    23.
ISN 012                   FBAND2=.5                                                    24.
ISN 013                   F(1)=1./7.                                                   25.
ISN 014                   F(2)=2.5/7.                                                  26.
ISN 015                   F(3)=2.5/7.                                                  27.
ISN 016                   F(4)=1./7.                                                   28.
ISN 017                   XMTOT=SUPPLY(1)+SUPPLY(2)+SUPPLY(3)+SUPPLY(4)                29.
ISN 018                   CO2FL=2600.                                                  30.
ISN 019                   SUP=SUPPLY(4)/6.                                             31.
ISN 020                   SUP3=SUP*3.                                                  32.
ISN 021                   VOL(1)=43320.                                                37.
ISN 022                   VOL(2)=16340.                                                38.
ISN 023                   VOL(3)=16340.                                                39.
ISN 024                   VOL(4)=18240.                                                39.1
ISN 025                   HR=6                                                         40.
ISN 026                   MIN=0                                                        41.
ISN 027                   SUPDB(1,1)=104.7                                             42.
ISN 028                   SUPDB(2,1)=75.2                                              43.
ISN 029                   SUPDB(3,1)=74.9                                              44.
ISN 030                   SUPDB(4,1)=83.                                               45.
ISN 031                   SUPW(1)=.0023                                                46.
ISN 032                   SUPCO2(1)=520.                                               47.
ISN 033                   NFINAL=67                                                    48.
ISN 034                   IFINAL=66                                                    49.
ISN 035                   IPAGE=0                                                      50.
ISN 036                   READ(5,1)LCO2,PODMIN,DTRF,DTSF,(BOTRAN(                      52.
                         /J),TRAN(J),J=1,4),CO2MIN,CO2RAN,(RADG(I),I=1,7),(DTMAX(I),I=1,8),  53.
                         /(SDG(I),I=1,8),OADG,PRESS,(DELTB(J),J=1,4)                  54.
ISN 037                 1 FORMAT(I1,11F4.1,2F6.0,/,7F4.1,/,16F4.1,F4.1,F5.1,/,4F4.1)   55.
ISN 038                   PODMIN=PODMIN/100.                                           60.
ISN 039                   READ(5,3106)(RMDB(J,I),J=1,4),(RMW(J,I),J=1,4),(RMCO2(J,I),J=1,4)  79.
ISN 040              3106 FORMAT(4F5.1,4F10.4,/,4F10.1)                                80.
ISN 041                   DO 2934 I=1,NFINAL                                           90.
ISN 042                   READ(9,2933)(QLOSC(J,I),J=1,4),(WPROD(J,I),J=1,4),(CO2PR     91.
                         /(J,I),J=1,4)                                                92.
ISN 043              2933 FORMAT(1X,12E11.4)                                           93.
ISN 044              2934 CONTINUE                                                     94.
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                                  ****    MAIN PROGRAM    ****
ISN 045          WRITE(6,3378)                                                95.
ISN 046          READ(5,4761)PK,ADBMAX,(TRMAX(I),I=1,4)                       96.
ISN 047     4761 FORMAT(F3.1,5F4.1)                                           97.
ISN 048          KP=PK/10.                                                    97.1
ISN 049          IK=IFIX(10./PK+.1)                                           97.2
ISN 050          OACO2=300.                                                   97.21
ISN 051       17 READ(5,6,END=5015)OADB,WBOA                                  97.3
ISN 052        6 FORMAT(2F6.1)                                                97.4
ISN 053          P=SATHUM((WBOA-32.)/1.8)                                     97.5
ISN 054          WSS=.62198*P/(PRESS-P)                                       97.6
ISN 055          OAW=((1093.-.556*WBOA)*WSS-.240*(OADB-WBOA))/(1093.+.444*    97.7
                /OADB-WBOA)                                                   97.8
ISN 056          KLM=0                                                        98.
ISN 057          ICON(1)=0                                                    98.1
ISN 058          ICON(2)=0                                                    98.2
ISN 059          ITEMP(1)=0                                                   98.3
ISN 060          ITEMP(2)=0                                                   98.4
ISN 061          ICO2(1)=0                                                    98.5
ISN 062          ICO2(2)=0                                                    98.6
ISN 063     3378 FORMAT(1H1,6X,'BIN',10X,'ENERGY  FOR  BIN 1 (6-8 AM)',6X,'ENERGY   99.
                /FOR  BIN 2 (8AM-5PM)',11X,'O.A. DAMPERS OPEN',12X,'CONVERGENCE',/,  99.01
                /93X,'CO2  CONT  TEMP. C',/,2X,'OADB',4X,'WBOA',6X,2('CO2',5X,'TEMP  99.02
                /',4X,'SAVE',5X,'X',7X),5X,'CD  TD',7X,'CD  TD',12X,'CO2   TEMP',    99.03
                //,1X,14('-'),2(4X,29('-')),9X,9('-'),5X,7('-'),11X,11('-'),//)     99.04
            C                                                                     99.1
            C    SIMULATION STARTS                                                99.2
            C                                                                     99.3
ISN 064     5016 CCO2=RMCO2(1,1)                                                 100.
ISN 065          HR2=FLOAT(HR)                                                  101.
ISN 066          CW=RMW(1,1)                                                    102.
ISN 067          Q2=0.                                                          105.
ISN 068          Q3=0.                                                          106.
ISN 069          IF(KLM.NE.1) GO TO 3334                                        108.
ISN 071          IF(LCO2.EQ.1) GO TO 3333                                       109.
ISN 073          LCO2=1                                                         110.
ISN 074          PODMIN=0.                                                      111.
ISN 075          GO TO 3334                                                     112.
ISN 076     3333 LCO2=0                                                         113.
ISN 077          PODMIN=.862                                                    114.
ISN 078     3334 NTIME=1                                                        115.
ISN 079     4140 KTENTH=NTIME                                                   116.
ISN 080     4138 KTENTH=KTENTH+1                                                117.
ISN 081     3360 ADB(KTENTH-1)=0.                                               150.
ISN 082          AW(KTENTH-1)=0.                                                151.
ISN 083          ACO2(KTENTH-1)=0.                                              152.
            C                                                                   154.
            C    NOW CALCULATE THE SUPPLY CONDITIONS FOR THE NEXT INTERVAL      155.
            C                                                                   156.
ISN 084          DO 3335 J=1,4                                                  157.
ISN 085          IF(J.EQ.1) I=1                                                 158.
ISN 087          IF(J.EQ.2) I=5                                                 159.
ISN 089          IF(J.EQ.3) I=6                                                 160.
ISN 091          IF(J.EQ.4) I=2                                                 161.
ISN 093          FLOW=SUPPLY(J)                                                 162.
ISN 094          ADB(KTENTH-1)=ADB(KTENTH-1)+(RMDB(J,KTENTH-1)+RADG(I))*FLOW    164.
ISN 095          AW(KTENTH-1)=AW(KTENTH-1)+RMW(J,KTENTH-1)*FLOW                 165.
ISN 096     3335 ACO2(KTENTH-1)=ACO2(KTENTH-1)+RMCO2(J,KTENTH-1)*FLOW           166.
ISN 097          ADB(KTENTH-1)=ADB(KTENTH-1)/(XMTOT)                            167.
```

```
                                    ****    MAIN PROGRAM    ****
ISN 098              AW(KTENTH-1)=AW(KTENTH-1)/(XMTOT)                                  168.
ISN 099              ACO2(KTENTH-1)=ACO2(KTENTH-1)/(XMTOT)                              169.
ISN 100              IF(ADB(KTENTH-1).GT.ADBMAX) ADB(KTENTH-1)=ADBMAX                   171.
ISN 102              DO 3359 J=1,4                                                      171.1
ISN 103         3359 QLOSS(J,NTIME)=QLOSC(J,NTIME)*(ADB(KTENTH-1)-DADB)                 171.2
ISN 104              INTIME=NTIME                                                       172.
ISN 105              NTIME=KTENTH-1                                                     173.
ISN 106              CALL HVAC                                                          174.
ISN 107              NTIME=INTIME                                                       175.
                C                                                                       176.
                C    NOW CALCULATE ROOM QUANTITIES FOR THE NEXT INTERVAL                177.
                C                                                                       178.
ISN 108              DO 5006 J=1,4                                                      179.
ISN 109              FLOW=SUPPLY(J)                                                     180.
ISN 110              RMCO2(J,KTENTH)=(FLOW*SUPCO2(KTENTH-1)*PK-FLOW*RMCO2(J,KTENTH-1)*P 183.
                    /K+CO2PR(J,NTIME)/10.*PK+RMCO2(J,KTENTH-1)*VOL(J))/VOL(J)           184.
ISN 111              IF(RMCO2(J,KTENTH).LT.0.) RMCO2(J,KTENTH)=0.                       185.
ISN 113              RMW(J,KTENTH)=(FLOW*SUPW(KTENTH-1)*PK-FLOW*RMW(J,KTENTH-1)*PK+WPRO 186.
                    /D(J,NTIME)/10.*PK+RMW(J,KTENTH-1)*VOL(J))/VOL(J)                   187.
ISN 114              IF(RMW(J,KTENTH).LT.0.) RMW(J,KTENTH)=0.                           188.
ISN 116              QROOMF=Q(FLOW,SUPW(KTENTH-1),SUPDB(J,KTENTH-1))*PK-Q(FLOW,RMW(J,KT 189.
                    /ENTH-1),RMDB(J,KTENTH-1))*PK-QLOSS(J,NTIME)/10.*PK+Q(VOL(J),RMW(J, 190.
                    /KTENTH-1),RMDB(J,KTENTH-1))                                        191.
ISN 117         3344 N=0                                                                192.
ISN 118              M=0                                                                193.
ISN 119              RMDB(J,KTENTH)=RMDB(J,KTENTH-1)                                    194.
ISN 120         3341 Q1=Q(VOL(J),RMW(J,KTENTH),RMDB(J,KTENTH))                          195.
ISN 121              IF(Q1-QROOMF)3338,5005,3340                                        196.
ISN 122         3338 IF(N.EQ.2) GO TO 5005                                              197.
ISN 124              RMDB(J,KTENTH)=RMDB(J,KTENTH)+.01                                  198.
ISN 125              N=1                                                                199.
ISN 126              M=M+1                                                              200.
ISN 127              IF(M.GT.1000) GO TO 3342                                           201.
ISN 129              GO TO 3341                                                         202.
ISN 130         3340 IF(N.EQ.1) GO TO 5005                                              203.
ISN 132              RMDB(J,KTENTH)=RMDB(J,KTENTH)-.01                                  204.
ISN 133              N=2                                                                205.
ISN 134              M=M+1                                                              206.
ISN 135              IF(M.GT.1000) GO TO 3342                                           207.
ISN 137              GO TO 3341                                                         208.
ISN 138         3342 ICON(LCO2+1)=ICON(LCO2+1)+1                                        209.
ISN 139         5005 RMDB(J,KTENTH)=RMDB(J,KTENTH)+(FLOAT(N)-1.5)*.01                   228.
ISN 140              DIFF=ABS(RMDB(J,KTENTH)-RMDB(J,KTENTH-1))                          228.3
ISN 141              IF(DIFF.LT.KP) GO TO 5021                                          228.4
ISN 143              RMDB(J,KTENTH)=RMDB(J,KTENTH-1)+KP*DIFF/(RMDB(J,KTENTH)-RMDB       228.5
                    /(J,KTENTH-1))                                                      228.6
ISN 144         5021 IF(RMDB(J,KTENTH).GT.TRMAX(J))RMDB(J,KTENTH)=TRMAX(J)              229.
ISN 146         5006 IF(RMDB(J,KTENTH).LT.65.)RMDB(J,KTENTH)=65.                        230.
ISN 148              Q2=Q2+QSV(KTENTH-1)*PK                                             235.
ISN 149              Q3=Q3+QSH(KTENTH-1)*PK                                             236.
ISN 150              IF(KTENTH.LT.(NTIME+IK)) GO TO 4138                                238.
ISN 152              DO 4139 J=1,4                                                      239.
ISN 153              RMDB(J,NTIME+1)=RMDB(J,KTENTH)                                     240.
ISN 154              RMW(J,NTIME+1)=RMW(J,KTENTH)                                       241.
ISN 155              RMCO2(J,NTIME+1)=RMCO2(J,KTENTH)                                   242.
ISN 156         4139 SUPDB(J,NTIME+1)=SUPDB(J,KTENTH)                                   243.
ISN 157              SUPW(NTIME+1)=SUPW(KTENTH)                                         244.
ISN 158              SUPCO2(NTIME+1)=SUPCO2(KTENTH)                                     245.
```

```
                                        ****    MAIN PROGRAM    ****

ISN 159                 QAFLOW(NTIME+1)=QAFLOW(KTENTH)                                    246.
ISN 160                 QSV(NTIME+1)=QSV(KTENTH)                                          247.
ISN 161                 QSH(NTIME+1)=QSH(KTENTH)                                          248.
ISN 162                 IF(NTIME.EQ.12) QBIN1(LCO2+1)=Q3/1.E6                             248.1
ISN 164                 NTIME=NTIME+1                                                     249.
ISN 165                 IF(NTIME.LE.NFINAL) GO TO 4140                                    255.
                  C                                                                       256.
                  C  NOW PRINT RESULTS                                                    257.
                  C                                                                       258.
ISN 167                 QBIN2(LCO2+1)=(Q3-QBIN1(LCO2+1)*1.E6)/1.E6                        262.
ISN 168                 IF(KLM.EQ.1) GO TO 6022                                           307.
ISN 170                 KLM=1                                                             308.
ISN 171                 GO TO 5015                                                        309.
ISN 172            6022 S1=(QBIN1(1)-QBIN1(2))/QBIN1(1)*100.                              310.01
ISN 173                 S2=(QBIN2(1)-QBIN2(2))/QBIN2(1)*100.                              310.02
ISN 174                 S3=QBIN1(1)-QBIN1(2)                                              310.03
ISN 175                 S4=QBIN2(1)-QBIN2(2)                                              310.04
ISN 176                 WRITE(6,6020)QADB,WBOA,QBIN1(2),QBIN1(1),S3,S1,QBIN2(2),QBIN2(1),  310.05
                       /S4,S2,ICO2(2),ITEMP(2),ICO2(1),ITEMP(1),ICON(2),ICON(1)           310.06
ISN 177            6020 FORMAT(F7.2,F8.2,2(4X,F5.3,2F8.3,F8.2),9X,I3,I5,I7,I5,12X,I3,I6)  310.07
ISN 178                 IPAGE=IPAGE+1                                                     310.08
ISN 179                 IF(S3.LT..01.AND.S4.LT..01) GO TO 5015                            310.09
ISN 181                 IF(IPAGE.LE.50) GO TO 17                                          310.1
ISN 183                 IPAGE=0                                                           310.11
ISN 184                 WRITE(6,3378)                                                     310.12
ISN 185                 GO TO 17                                                          310.13
ISN 186            5015 STOP                                                              310.14
ISN 187                 END                                                               310.15

*OPTICNS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTICNS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTICNS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*      SOURCE STATEMENTS =      186 ,PROGRAM SIZE =     10260

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    53K BYTES OF CORE NOT USED
```

DATE 80.271/10.59.36

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LEVEL 21.8/3.2 (24FEB78)                    OS/360   UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 SUBROUTINE HVAC                                          312.
ISN 003                 REAL MADB,MAW,MACO2                                      313.
ISN 004                 DIMENSION QSV(75),SUPPLY(4),F(4),VOL(4),SUPCO2(75),      314.
                       /SUPDB(4,75),SUPW(75),RADG(7),DTMAX(8),SDG(8),ITEMP(2),ICO2(2),  315.
                       /RMDB(4,75),RMCO2(4,75),ADB(75),ACO2(75),TARC(8),TBRC(8),  316.
                       /AW(75),RMW(4,75),QLOSS(4,75),CO2P                         317.
                       /R(4,75),OAFLOW(75),QSH(75),WPROD(4,75),QLOSC(4,75)        318.
                       /,BOTRAN(4),TRAN(4),DELTB(4),TRMAX(4)                      319.
ISN 005                 COMMON BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,  320.
                       /DTRF,OADB,OAW,AW,OACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2,  321.
                       /F,SDG,SUPDB,OAFLOW,XMTOT,OADG,SUPW,SUPCO2,ITEMP,ICO2,     322.
                       /QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,DELTB                    323.
                       /,INTIME,SUP,SUP3                                          324.
ISN 006                 EXTERNAL Q                                               325.
ISN 007                 TMAX=0.                                                  330.
ISN 008                 CO2MAX=0.                                                331.
ISN 009                 POD=0.                                                   331.1
ISN 010                 DO 10 J=1,4                                              332.
ISN 011                 TOPRAN=BOTRAN(J)+DELTB(J)                                333.
ISN 012                 PD=(RMDB(J,NTIME)-TOPRAN)/TRAN(J)                        340.
ISN 013                 IF(PD.GT.POD) POD=PD                                     341.
ISN 015              10 CONTINUE                                                 342.
ISN 016                 IF(POD.LT.PODMIN) POD=PODMIN                             343.
ISN 018                 IF(POD.GT.1.) POD=1.                                     344.
ISN 020                 IF(POD.GT.PODMIN) ITEMP(LCO2+1)=ITEMP(LCO2+1)+1          344.1
ISN 022                 DO 20 J=1,4                                              345.
ISN 023              20 IF(RMCO2(J,NTIME).GT.CO2MAX) CO2MAX=RMCO2(J,NTIME)       346.
ISN 025                 PODCO2=(CO2MAX-CO2MIN)/CO2RAN                            347.
ISN 026                 IF(PODCO2.LT.0.) PODCO2=0.                               348.
ISN 028                 IF(PODCO2.GT.1.) PODCO2=1.                               349.
ISN 030                 IF(LCO2.EQ.0) PODCO2=0.                                  350.
ISN 032                 IF(PODCO2.GT.0.) ICO2(LCO2+1)=ICO2(LCO2+1)+1             350.1
ISN 034                 IF(POD.GE.0..AND.POD.LE..825) GO TO 30                   351.
ISN 036                 TEMFL=720.+3680.*(POD-.825)/.175                         352.
ISN 037                 GO TO 35                                                 353.
ISN 038              30 TEMFL=400.+320.*(POD/.825)                               354.
ISN 039              35 OAFLOW(NTIME)=TEMFL+CO2FL*PODCO2                         355.
ISN 040                 RADB=ADB(NTIME)+DTRF                                     356.
ISN 041                 MADB=(OAFLOW(NTIME)*(OADB+OADG*(ADB(NTIME)-OADB)/70.)+(XM  357.
                       /TOT-OAFLOW(NTIME))*RADB)/XMTOT                           358.
ISN 042                 SUPW(NTIME+1)=(OAFLOW(NTIME)*OAW+(XMTOT-OAFLOW(NTIME))*AW  359.
                       /(NTIME))/XMTOT                                           360.
ISN 043                 SUPCO2(NTIME+1)=(OAFLOW(NTIME)*OACO2+(XMTOT-OAFLOW(NTIME)  361.
                       /)*ACO2(NTIME))/XMTOT                                     362.
                  C  CALL COOL                                                   363.
ISN 044                 MADB=MADB+DTSF                                           364.
ISN 045                 DO 40 J=1,8                                              365.
ISN 046              40 TBRC(J)=MADB+SDG(J)*2./3.                                366.
ISN 047                 DO 70 I=1,8                                              373.
ISN 048                 IF(I.LE.2) J=1                                           374.
ISN 050                 IF(I.EQ.3) J=2                                           375.
ISN 052                 IF(I.EQ.4) J=3                                           376.
ISN 054                 IF(I.GT.4) J=4                                           377.
ISN 056                 DTRHT=1.-((RMDB(J,NTIME)-BOTRAN(J))/TRAN(J))             378.
ISN 057                 IF(DTRHT.LT.0.) DTRHT=0.                                 381.
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                                  **** SUBPROGRAM   HVAC ****

ISN 059                 IF(DTRHT.GT.1.) DTRHT=1.                                    382.
ISN 061            70   TARC(I)=TBRC(I)+DTMAX(I)*DTRHT                              383.
ISN 062                 QSH(NTIME)=Q(SUPPLY(1)*FBAND1,SUPW(NTIME),TARC(1))-Q(SUPPLY(1)   384.
                       /*FBAND1,SUPW(NTIME),MADB)+Q(SUPPLY(1)*FBAND2,SUPW(NTIME),TARC(2   385.
                       /))-Q(SUPPLY(1)*FBAND2,SUPW(NTIME),MADB)+Q(SUPPLY(2),SUPW(NTIME   386.
                       /),TARC(3))-Q(SUPPLY(2),SUPW(NTIME),MADB)+Q(SUPPLY(3),SUPW(NTIME   387.
                       /),TARC(4))-Q(SUPPLY(3),SUPW(NTIME),MADB)+Q(SUPPLY(4)*F(1),SUPW(   388.
                       /NTIME),TARC(5))-Q(SUPPLY(4)*F(1),SUPW(NTIME),MADB)                389.
ISN 063                 QSH(NTIME)=QSH(NTIME)+Q(SUPPLY(4)*F(4),SUPW(NTIME),TARC(8))-      390.
                       /Q(SUPPLY(4)*F(4),SUPW(NTIME),MADB)+Q(SUPPLY(4)*                   391.
                       /F(2),SUPW(NTIME),TARC(6))-Q(SUPPLY(4)*F(2),SUPW(NTIME),MADB)+Q(   392.
                       /SUPPLY(4)*F(3),SUPW(NTIME),TARC(7))-Q(SUPPLY(4)*F(3),SUPW(NTIME),  393.
                       /MADB)                                                             394.
ISN 064                 SUPDB(1,NTIME+1)=FBAND1*TARC(1)+FBAND2*TARC(2)                    395.
ISN 065                 SUPDB(2,NTIME+1)=TARC(3)                                          396.
ISN 066                 SUPDB(3,NTIME+1)=TARC(4)                                          397.
ISN 067                 SUPDB(4,NTIME+1)=F(1)*TARC(5)+F(2)*TARC(6)+F(3)*TARC(7)+          398.
                       /F(4)*TARC(8)                                                      399.
ISN 068                 QSV(NTIME)=Q(OAFLOW(NTIME),AW(NTIME),MADB)-                        400.
                       /Q(OAFLOW(NTIME),OAW,OADB+OADG*(ADB(NTIME)-OADB)/70.)              401.
ISN 069                 RETURN                                                             416.
ISN 070                 END                                                                417.

*OPTIONS IN EFFECT*      NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*      SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*      NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*     SOURCE STATEMENTS =      69 ,PROGRAM SIZE =     2580

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                   73K BYTES OF CORE NOT USED
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                                                                    DATE   80.271/11.00.09

LEVEL 21.9/3.2 (24FEB78)                    OS/360    UOR FORTRAN H          360/58-IS

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 FUNCTION SATHUM(T)                                                    418.
ISN 003                 Y1=16.386396+.00137804*(T*1.8+32.)-5656./(459.67+(T*1.8+32.))         419.
ISN 004                 Y2=ALOG((459.67+(T*1.8+32.))/100.)                                    420.
ISN 005                 VP=10.**(Y1-(3.560573*Y2))                                            421.
ISN 006                 SATHUM=VP*25.4                                                        422.
ISN 007                 RETURN                                                                423.
ISN 008                 END                                                                   424.

*OPTIONS IN EFFECT*       NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*       NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*      SOURCE STATEMENTS =        7 ,PROGRAM SIZE =       384

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                        101K BYTES OF CORE NOT USED
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                                                                    DATE   80.271/11.00.25

LEVEL 21.8/3.2 (24FEB78)                    OS/360    UCR FORTRAN H          360/58-15

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID
                             NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT
ISN 002                 FUNCTION Q(V,W,T)                                                  425.
ISN 003                 DIMENSION QSV(75),SUPPLY(4),F(4),VOL(4),SUPCO2(75),                426.
                       /SUPDB(4,75),SUPW(75),RADG(7),DTMAX(8),SDG(8),                      427.
                       /RMDB(4,75),RMCO2(4,75),ADB(75),ACO2(75),ITEMP(2),ICO2(2),          428.
                       /AW(75),RMW(4,75),QLOSS(4,75),CO2P                                  429.
                       /R(4,75),QAFLOW(75),QSH(75),WPROD(4,75),QLOSC(4,75)                 430.
                       /,BOTRAN(4),TRAN(4),DELTB(4),TRMAX(4)                               431.
ISN 004                 COMMON BOTRAN,RMDB,TRAN,PODMIN,RMCO2,CO2MIN,CO2RAN,LCO2,ADB,       432.
                       /DTRF,QADB,QAW,AW,QACO2,ACO2,DTSF,NTIME,SUPPLY,DTMAX,FBAND1,FBAND2, 433.
                       /F,SDG,SUPDB,QAFLOW,XMTOT,QADG,SUPW,SUPCO2,ITEMP,ICO2,              434.
                       /QSV,QSH,PRESS,TEMFL,CO2FL,TOPRAN,DELTB                             435.
                       /,INTIME,SUP,SUP3                                                   436.
ISN 005                 RO=1./(53.352*(T+460.)*(1.+1.6078*W)/2116.224/PRESS*760.)          438.
ISN 006                 H=.24*T+W*(1061.+.444*T)                                           439.
ISN 007                 Q=RO*H*V                                                           440.
ISN 008                 RETURN                                                             441.
ISN 009                 END                                                                442.

*OPTIONS IN EFFECT*       NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,CALIGN=00

*OPTIONS IN EFFECT*       SOURCE,EBCDIC,NOLIST,NODECK,LOAD,NOMAP,NOEDIT,ID

*OPTIONS IN EFFECT*       NOXREF,NOXL,NOTERM,PRINT,COMMENT,SUMMARY,NOEJECT

*STATISTICS*      SOURCE STATEMENTS =        8 ,PROGRAM SIZE =       344

*STATISTICS*  NO  DIAGNOSTICS GENERATED

****** END OF COMPILATION ******                                    97K BYTES OF CORE NOT USED

*STATISTICS*  NO  DIAGNOSTICS THIS STEP
```

APPENDIX G
CARBON DIOXIDE SENSOR VENDORS

The following firms are known to have developed carbon dioxide sensors/controllers specifically for application to ventilation systems:

ACME Engineering Products
Trimex Ind. Bldg.
Route 11
Moers, N.Y. 12958
Tel.: (518) 236-5659
Telex: 055-60546

MDA Scientific, Inc.
1815 Elmdale Ave.
Glenview, Illinois 60025
Tel: (312) 998-1600
Telex: 72-6399 MDA-PRID
(Fuji Electric of Japan makes this device.)

In 1980 prices ranged from $1100 to $2500 and up for various models and options.

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720