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AUTOMATED AIR INFILTRATION MEASUREMENTS IN LARGE BUILDINGS

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ABSTRACT

An automated air infiltration measurement system for large buildings is described. The system consists of a micro-computer, electron capture gas chromatograph, a ten port sampling manifold, and five tracer gas injection units. The system controls the injection and sampling of tracer gas in a multi-zone building, calculates the air infiltration rates of each zone, and measures the on-time of events such as HVAC fan operation, exhaust fan operation, and door/window openings. The measurements also include such analog variables as interior and exterior temperatures, wind speed, wind direction and pressure differentials across the building envelope. The data collected using the automated air infiltration system in large buildings will allow the determination of the relative importance of air leakage and forced ventilation on the energy requirements of the building, as well as evaluating the influence of meteorological conditions, HVAC fan operation, exhaust fan operation and exterior building pressure on the air leakage.

INTRODUCTION

It is generally assumed that the air exchange rate for large buildings is dominated by the requirements for ventilation of the building and that the air leakage into such buildings is only a small component of the total air exchange of the building. However, little data have been collected to verify that the air leakage in large buildings is indeed small, and that the ventilation rates that the building is experiencing under actual usage is that intended by the designers of the building and the designers of its HVAC system. Also, although the air leakage rate of a large building may be small compared to the ventilation requirements of the building, the energy requirements on the heating and cooling system imposed by air leakage in large buildings may be significant since such air leakage is uncontrollable and offers no opportunity for recovery of the energy lost. The parameters that influence air leakage in large buildings are also not well understood. It is not certain whether the air leakage is driven by the pressures induced by the operation of the mechanical system or by the natural driving forces of wind and temperature.

In an attempt to answer these questions, a project was started at the National Bureau of Standards under sponsorship of the U.S. Department of Energy to investigate the nature and causes of air infiltration in large buildings. The first building studied in this project was the 11-story administration building at the National Bureau of Standards in Gaithersburg, Maryland [1].

The air infiltration measurements initially made in the NBS administration building were accomplished using a semi-automated air infiltration measurement system [2-3]. The tracer gas was injected manually into the building. Tracer concentrations were measured using an electron capture gas chromatograph with the output recorded on a strip-chart. This system required large amounts of manual data reduction and required the frequent presence of technicians during the periods when measurements were being made. As part of the U.S. contribution to the International Energy Agency project to study the heating and cooling requirements of a large building near Glasgow, Scotland, the National Bureau of Standards was requested by the U.S. Department of Energy to provide the investigators of the Building Services Research Unit of the University of Glasgow* with an automated air infiltration measurement system and to assist them in the operation and analysis of the data collected using the system.

The building being studied in the I.E. A. project is a four story, approximately 2.4 million cubic foot structure called the Collins Building and is located is Bishopbriggs, an outlying area of Glasgow. It is occupied by the Collins Publishing Company. It stands on open terrain with no immediately surrounding buildings, no external shielding, and on a grade so that there is one more exposed floor on the north side, than on the south. The building is serviced by four mechanical systems: one handling the basement, ground, first and second floors; a second handling the third floor; a third

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*This investigation is being conducted by Dr. Jeremy Cockcroft, now with Honeywell, Inc., and Neale Veech of the Building Services Research Unit of the University of Glasgow.

dedicated to the computer room; and the fourth used for the sports area.

The U.S. Department of Energy also requested that NBS provide a second air infiltration measurement system to be installed in a 26-story building called the Park Plaza Building in Newark, N.J. This building is occupied by Public Service Electric and Gas Company of New Jersey and is located in an urban environment.

It was decided that the automated air infiltration systems for application to these studies of energy usage in large buildings should be based on the automated air infiltration system previously developed and used in residences by Princeton University and NBS [3-4]. However, the new requirements on the measurement system (due to the complexity of the air handling system and multi-zone nature of large buildings) necessitated a more sophisticated design. It was decided that the most feasible approach was to incorporate a micro-computer in the measurement system, capable of being programmed to make the many decisions needed to properly handle the injection and sampling from several zones. This paper will describe this micro-computer based automated air infiltration measurement system.

Description of the Automated Air Infiltration System

The automated air infiltration system for large buildings is shown schematically in Figure 1. The system consists of a S-100 Buss micro-computer with two 5 1/4 inch dual-sided floppy disc drives, a 100,000 day real-time clock, a CRT terminal, a parallel printer, an electron capture gas chromatograph, a ten-port sampling manifold, five injection units, and an analog interface. The interfacing of the gas chromatograph, the sampling manifold and the injection units is accomplished through two specially designed S-100 interface cards: the S-100 air infiltration interface card, and the S-100 Buss octal A-C relay card. Figure 2 shows a block diagram of the interfacing of each component with the micro-computer. The micro-computer has a Z-80 based CPU (which operates at 4 MHZ), 64K of RAM memory, a disc controller and a dual serial/parallel I/O interface. It is programmable in Fortran, Z-80 assembly language, and Basic. Disc drive "A" of the computer is used for storage of the air infiltration programs and for "booting" the system. Disc drive "B" is used for data storage. Each has a capacity for storing 173k bytes of data. The resident disc operating system (on a PROM located on the disc controller card) was modified to allow for the automatic booting of the system and for the initialization of the air infiltration interface. Drivers for the real-time clock were added to the disc operating system so that the clock could be used through system calls.

The S-100 Buss air infiltration board controlled the capturing of the tracer gas peak and thus allowed the determination of the tracer gas concentration. A block design for this interface is given in Figure 3. This interface board between the gas chromatograph and the S-100 Buss permits both software and hardware determination of the tracer gas concentration peak. The advantage of this flexibility is that in a system configuation where the computer is busy monitoring other variables, it is possible to output a short series of commands to the S-100 Buss air infiltration board. The peak detector will determine the tracer peak automatically, indicating to the computer when it has found the peak (usually about 25 seconds after initialization of the sequence). In a configuration in which the compiler is not busy with other functions, the peak can be detected by software. The software mode is more reliable and less sensitive to noise and adjustments to the gas chromatograph. The air infiltration board also has two 8-bit parallel output ports and can automatically control the activation of the rotary sample value on the gas chromotograph,although in the configuration for large buildings this function is accomplished by a S-100 octal A-C relay card. The system has two S-100 Buss octal A-C relay cards. The block diagram for this card is given in Figure 4. These two cards control the sample value manifold, the injection units and the rotary sample valve on the gas chromatograph. They also serve as input ports for events data.

In the Collins Building, flow switches were installed in the HVAC and the exhaust fan systems. The output from these flow switches were connected to the event status ports on the S-100 Buss octal A-C relay cards. The interrupt service routine of the monitoring program would check the status ports each second to determine which HVAC system was operating and which exhaust fans were on. If the HVAC system of a zone was not operating, no injection of tracer into the zone was permitted.

The tracer gas selected for the study of air exchange in large buildings is sulfur hexafluoride. Although there are several suitable tracer gases for residential buildings, practical constraints limit the choice when dealing with volumes of one million cubic feet and more. One cannot truck in large quantities of tracer gas, rather the choice is to use a tracer which can be detected in concentrations as low as several parts per billion. For example, in a one million cubic foot building, the largest available cylinder of Nitrous Oxide would produce only 10 seedings of the building. The corresponding cylinder of sulfur hexafluoride would produce 10,000 seedings.

To minimize the size of the air infiltration measurement system, maximum use was made of the micro-computer cabinet. For example, the election capture gas chromatograph was removed from its standard cabinet, and the pneumatic rotary actuator was connected to the sample valve (Figure 5). The unit was then installed in the redesigned front panel in the micro-computer cabinet. The units power supply, in turn, was placed in the power supply section at the rear of the cabinet. In this way no additional space was required.

The 10 port sample manifold is shown in the photograph in Figure 6. It was designed so that it would fit in the rear of the computer cabinet, thus fully utilizing the cabinet space. The solenoids of the 10 port sample valve manifold were connected to the first octal A-C relay card and to the first two relays of the second octal A-C relay card. In any application in large buildings, auxiliary pumps must be added to the sampling system since the pump of the gas chromatograph is not designed to pull samples through the long lengths of tubing required by the building sampling network.

The injection units for a large building vary according to the size of the zone being seeded by the unit. For zones in excess of 300,000 ft^3, the injection unit consists of an appropriately sized cylinder of tracer gas with a pressure regulator and leak-tight solenoid. For volumes less than 300,000 ft^3 a specially designed injection unit consisting of a low pressure tank, a low pressure regulator and a zero leakage solenoid valve is required (see Figure 7). The maximum size of the tracer gas container is based upon maximum safe concentration of the tracer gas to which the occupant of the building could be subjected without harmful effects. That is

$$(Q_t/V_z) < C_{max} \tag{1}$$

where Q_t is the quantity of gas contained in the injection unit tank, V_z is the volume of the zone served by the injection unit and C_{max} is the maximum safe tracer concentration, usually taken to be a factor of three or more lower than the OSHA eight hour maximum concentration (i.e., 1000 ppm for SF_6).

Equation (1) is based on the assumption that the tank of tracer gas exhausted its contents instantly. In practice, the most likely mode of failure is a leaking injection valve. In that case, the flow controlling orifice would spread the leakage over an extensive period of time further limiting concentration build-up. Table 1 gives the parameters pertinent in the selection of the injection unit tank size for the four injection zones of the Collins Building. The estimated duration of each reservoir was

TABLE 1

PARAMETERS AFFECTING TANK SELECTION FOR ZONES OF COLLINS BUILDING

	Volume of Zone Vz	Injection Tank Size Q_t	Maximum Concentration $Qt_{/Vz}$	Estimated Duration of Tracer Supply
Zone Supplied by Main HVAC	2.4×10^6 ft^3	95 lb (1A cyl.)	245 ppm	∿ 45 days
Zone Supplied by Third Floor HVAC	175,000 ft^3	10 lb (No. 3 cyl.)	360 ppm	∿ 60 days
Computer Area	74,000 ft^3	1.3 lb	70 ppm	∿ 22 days
Sports Area	68,000 ft	1.3 lb	80 ppm	∿ 24 days

derived by assuming an injection of 100 ppb of tracer every three hours, 24 hours a day, seven days a week.

The 16-channel analog A/D interface card also deserves special mention. This card monitors such interior and exterior parameters as temperature, wind speed, wind direction and exterior building envelope pressure differentials.

Description of Software of Operating the Automated Air Infiltration Unit

A group of programs was developed for operating the automated air infiltration unit in large buildings. Two general subroutine libraries were written. The first library contained the interrupt related subroutines that were needed for controlling the injection of tracer gas, the determination of the status events, and the control of the sampling manifold. Although these subroutines were written in assembly language, they are all Fortran callable and thus allow the development of programs by those familiar with Fortran. The second library consisted of subroutines which did not depend on the interrupt feature of the micro-computer. Several diagnostic programs for testing the functioning of the major components of the hardware were also written and the program for the calibration of the electron capture detector was developed so that air sample bags of known tracer concentration could be used to obtain the coefficients C_0 and β of the equation:

$$C = C_0 \,[\ln (S/P)]^{\beta} \qquad (2)$$

where S is the standing current P is the peak current, C is the concentration in ppb. For the gas chromatograph used in the systems installed in the Collins Building, the coefficients C_0 and β are approximately 80 ppb and 0.95 respectively.

Figure 8 shows a block diagram of the monitoring program for the Collins Building. Initially the program determines the parameters of the building, and then measures the initial concentration and injects tracer gas into the zones of the building.

The injection of tracer gas is controlled by the following considerations. In a large building with several interesting zones, it is desirable to keep the tracer gas concentrations of each zone approximately equal in order to minimize the error caused by the interchange of tracer between the zones. Also, in large buildings it is prudent to inject the tracer slowly into the ducts in order to ensure proper mixing. It was decided to design for an injection time of 5 minutes (about 4 times that used by the automated air infiltration system used in homes) and allow for possible injection times of up to 10 minutes. In order to insure that all zones at least started at approximately the same concentration level the injection time each hour was calculated from the following equations:

$$\frac{dC}{dt} = AIC + F \qquad \text{during injection } (o < t < t_o) \qquad (3)$$

$$\frac{dC}{dt} = - AIC \qquad \text{during mixing } (t_o < t) \qquad (4)$$

where AI is the air infiltration rate, C the tracer concentration and F the injection flow rate per unit volume.

The mixing period was specified as τ = 20 minutes after the start of injection.

Equation (3) and (4) can be solved to yield the expressions:

$$C(t) = (C_o - \frac{F}{AI})\, e^{-AIt} + \frac{F}{AI} \qquad c < t < t_o \qquad (5)$$

$$C(t) = [(C_o - \frac{F}{AI})e^{-AIt_o} + \frac{F}{AI}]\; e^{-AI\,(t-t_o)} \qquad (6)$$

$$t_o < t$$

If C_1 is the concentration at the end of the mixing period then:

$$C_1 = [C_o - \frac{F}{AI} + \frac{F}{AI} e^{AI\, t_o}] e^{-AI\tau} \tag{7}$$

The concentration C_1 is chosen so that it lies in the linear range of the gas chromatograph as determined by the calibration curve of the electron capture detector. In the case of the system installed in the Collins building $C_1 \approx 120$ ppb. The initial concentration C_o was chosen as the last measured concentration of the previous sample period. The injection time for each zone was then calculated by the following equation:

$$\begin{aligned} t_o &= \frac{1}{AI} \ln [1 + \frac{AI}{F} (C_1 e^{AI\tau} - C_o)] \text{ if } 0 < t_o < 10 \\ t_o &= 0 \text{ if } C_1 e^{AI\tau} < C_o \\ t_o &= 10 \text{ if } t_o \geq 10 \end{aligned} \tag{8}$$

The system then samples the zones once each ten minutes for the next 40 minutes. The air infiltration rates are determined by statistically fitting a semi-log curve

$$C = C' \exp (- AIt) \tag{9}$$

to each history of tracer concentration for each of the zones.

These data are then outputted to the discs and printer. Then the hourly cycle is repeated until the operator aborts the system.

Summary

The automated air infiltration measurement system described in this paper has proven to be capable of performing the complex tasks necessary for determining the air exchange rates in large buildings. Key components of the measurement system include: the micro-computer, the electron capture gas chromatograph, a ten port sampling manifold and five tracer gas injection units. How these components interact and the function each is performing have been discussed here in considerable detail. The programmed micro-computer is used: to control the injection of tracer gas, thus maintaining the building zones within chosen concentration limits; to selectively sample from the zones, thus accurately tracking the tracer gas concentration decay; and to store the resulting air exchange rate data on a floppy disc. The capacity of the micro computer allows storage of the event data (e.g. HVAC, fan operation and door/window openings), internal and external temperatures and the local weather data. With this vital information the air exchange rate measurements have that much more meaning, and thereby provide the basis for advancements in the understanding of the role of air infiltration in large buildings.

Although the initial application of this air infiltration measurement system has been in large multi-story commercial buildings, the built-in versatility allows wider application. For example, housing blocks with horizontal zoning and even tightly compartmentalized single-family houses often require air infiltration measurement systems with the capabilities described here. The compactness of the measurement system as illustrated in Figure 9 further aids its application potential in both large and small buildings.

Acknowledgements

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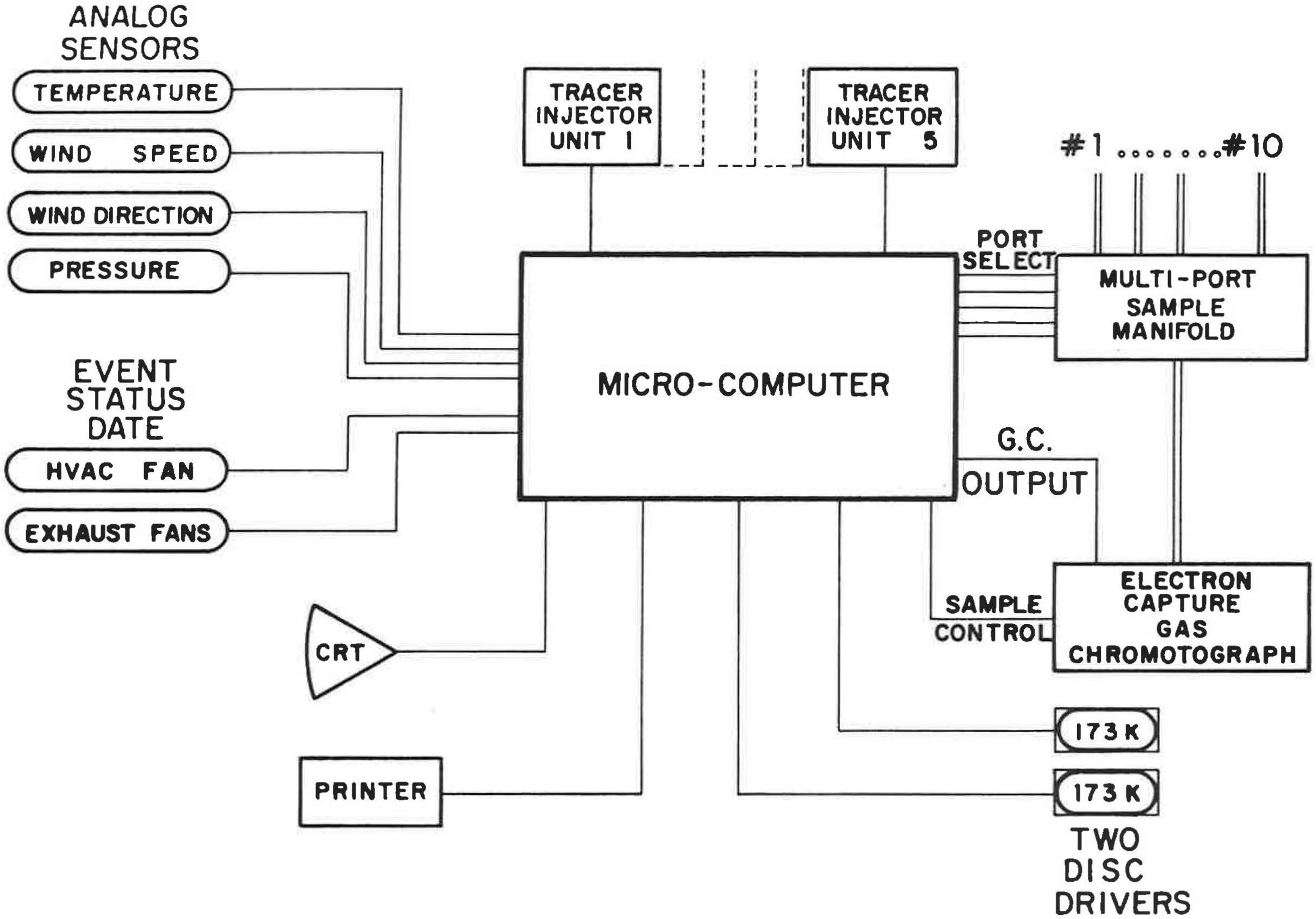
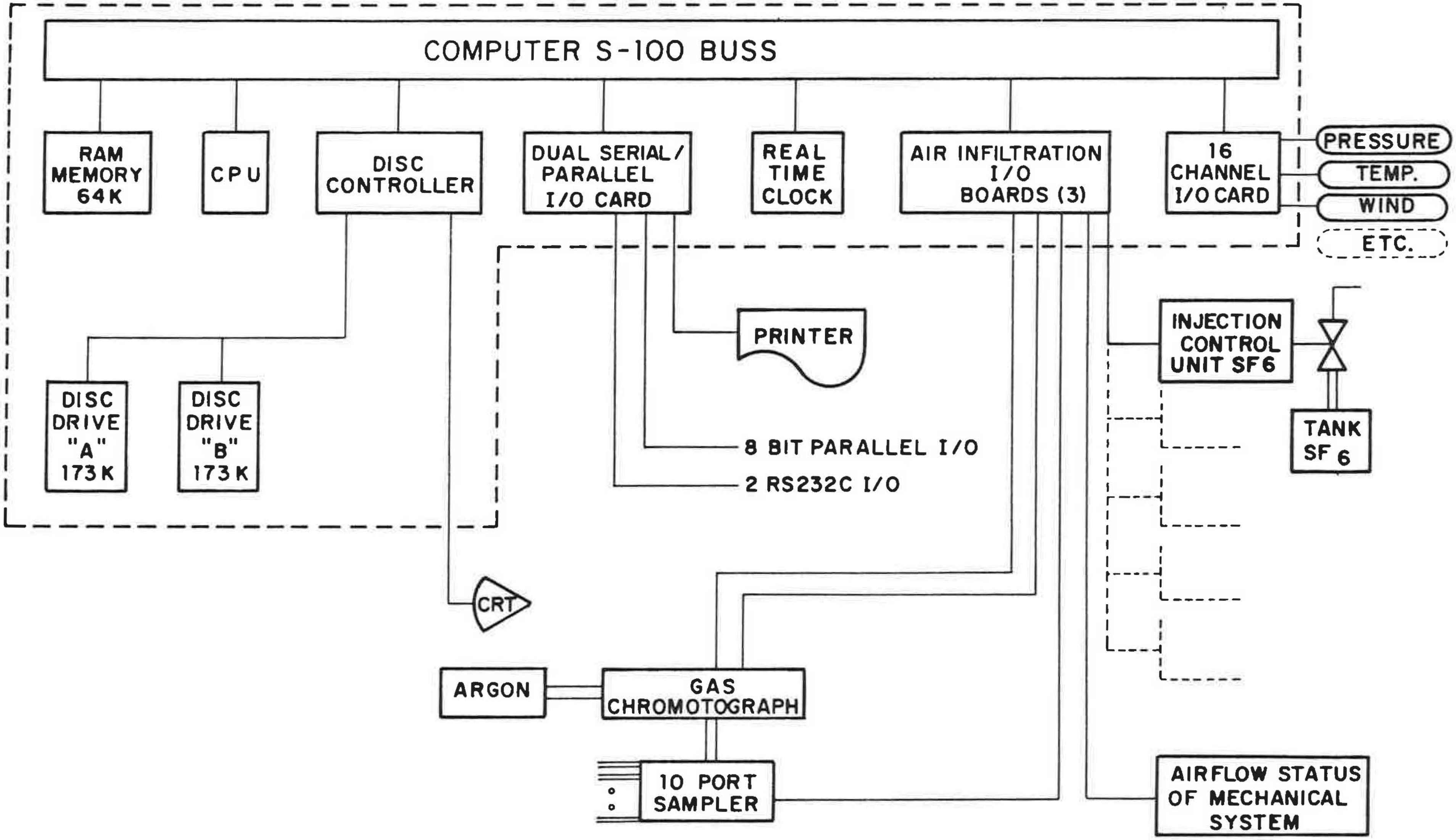


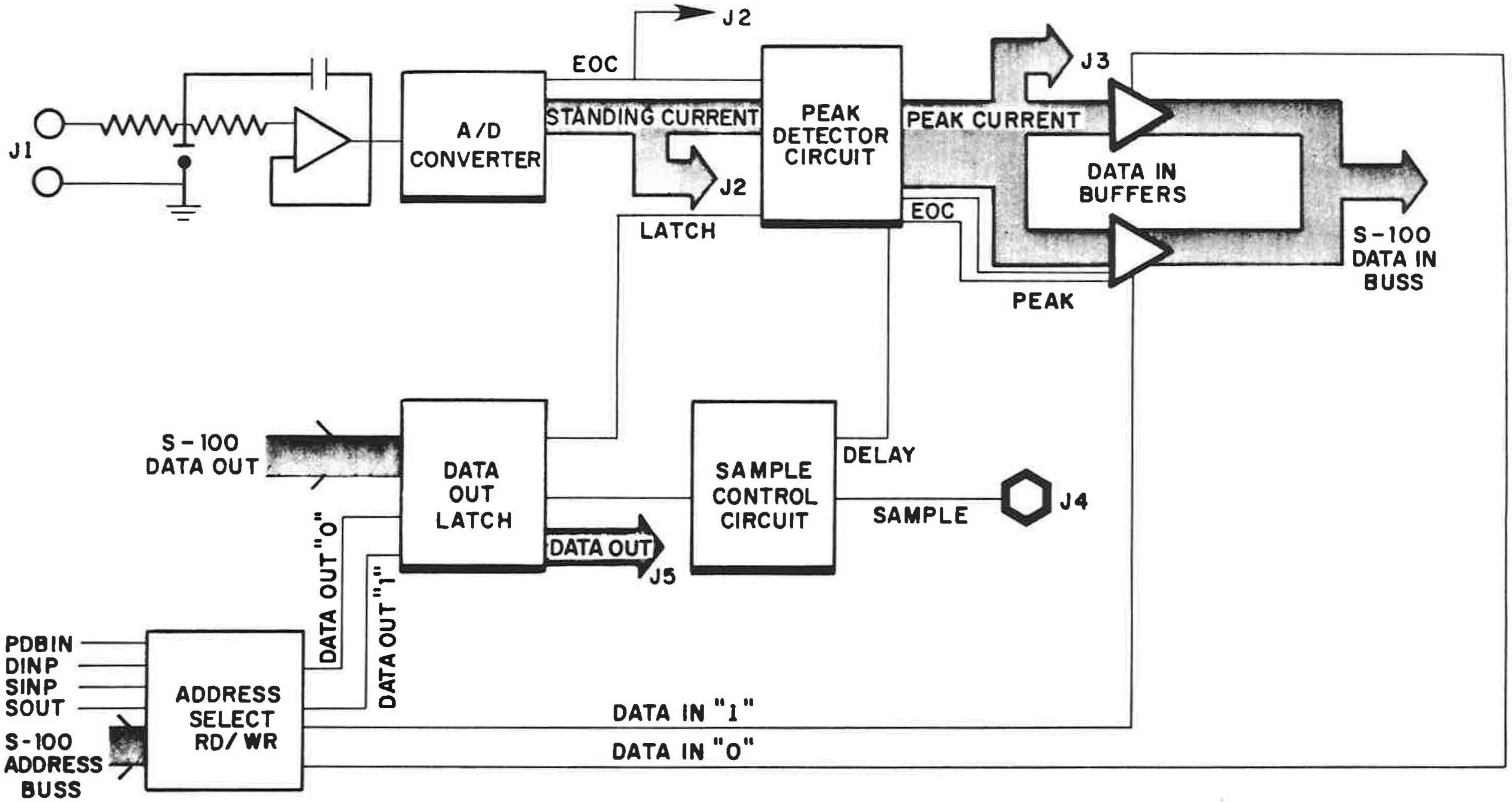
SCHEMATIC OF MAJOR COMPONETS OF AIR INFILTRATION MEASUREMENT SYSTEM FOR LARGE BUILDINGS

FIGURE 1

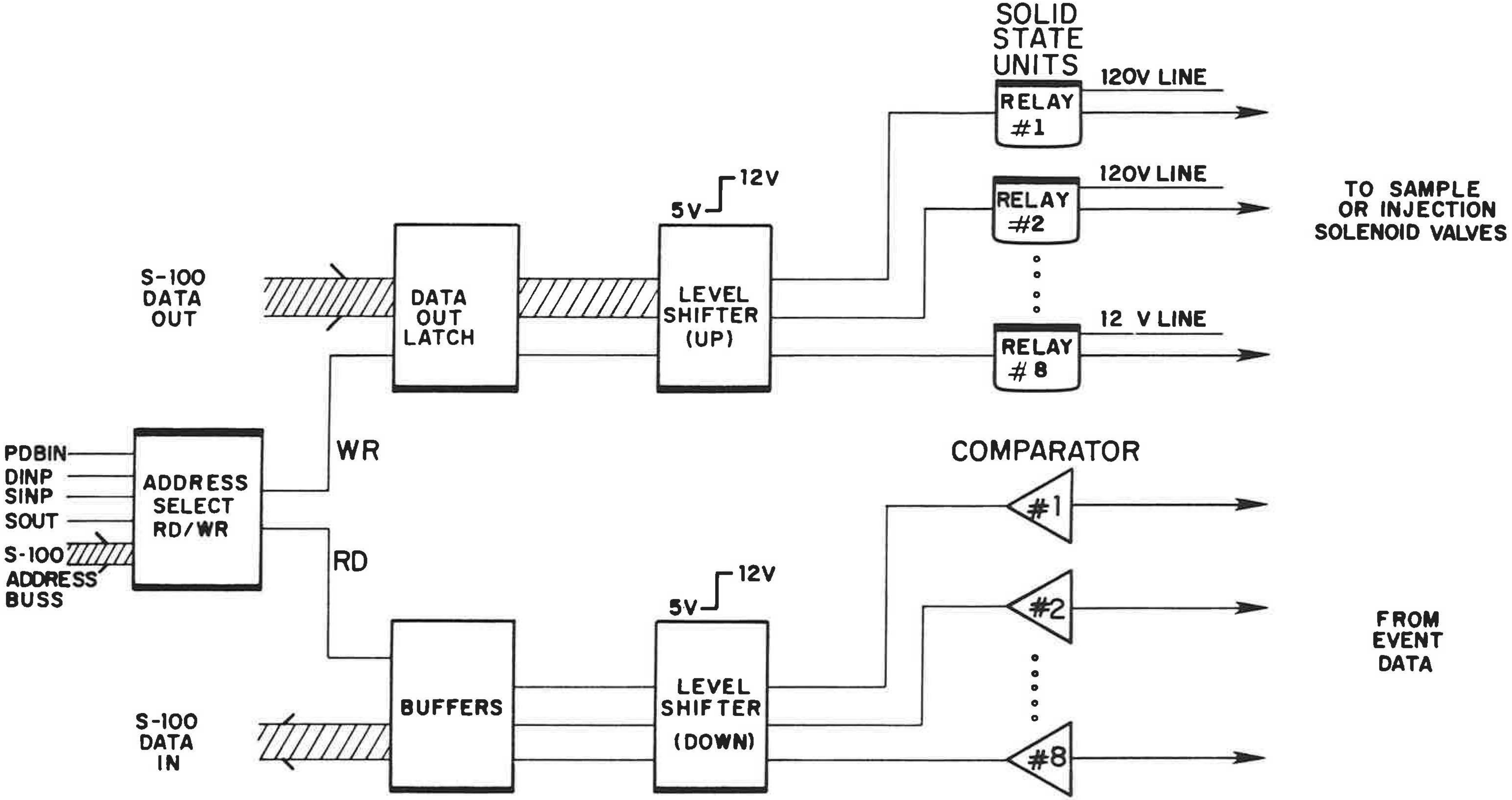


BLOCK DIAGRAM OF THE INTERFACING OF EACH COMPONENT WITH THE COMPUTER

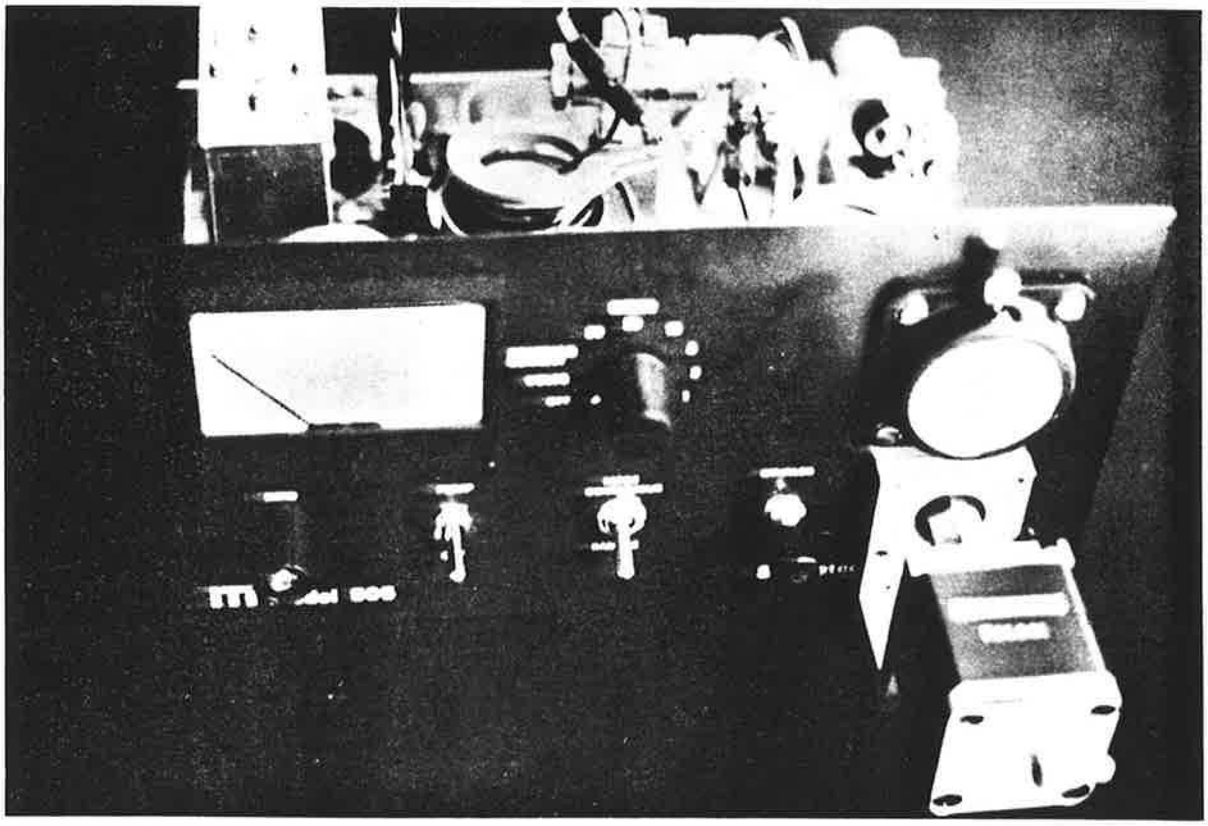
FIGURE 2



BLOCK DIAGRAM AIR INFILTRATION S-100 INTERFACE
FIGURE 3

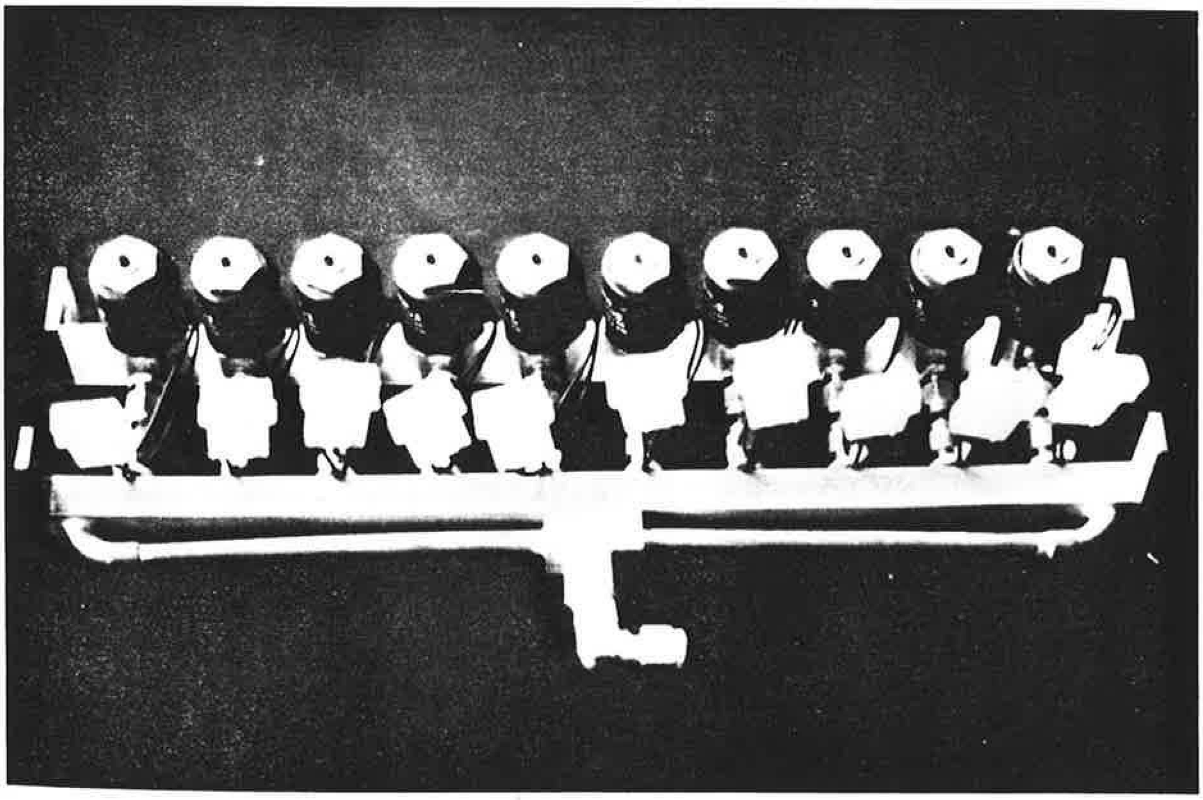


BLOCK DIAGRAM OF S-100 BUSS OCTAL A-C RELAY CARD
FIGURE 4



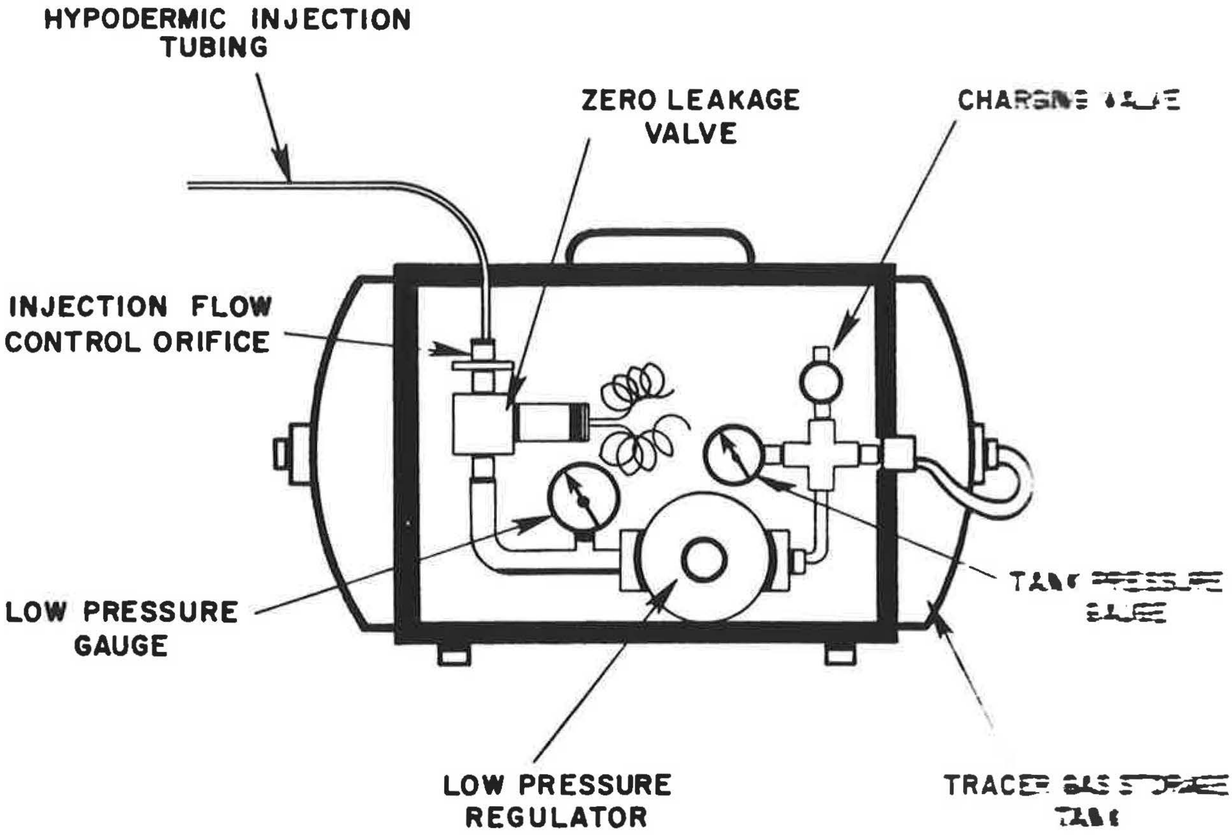
SF_6 DETECTOR USING AN ELECTRON CAPTURE GAS CHROMATOGRAPH AND ROTARY VALVE ACTUATOR

FIGURE 5



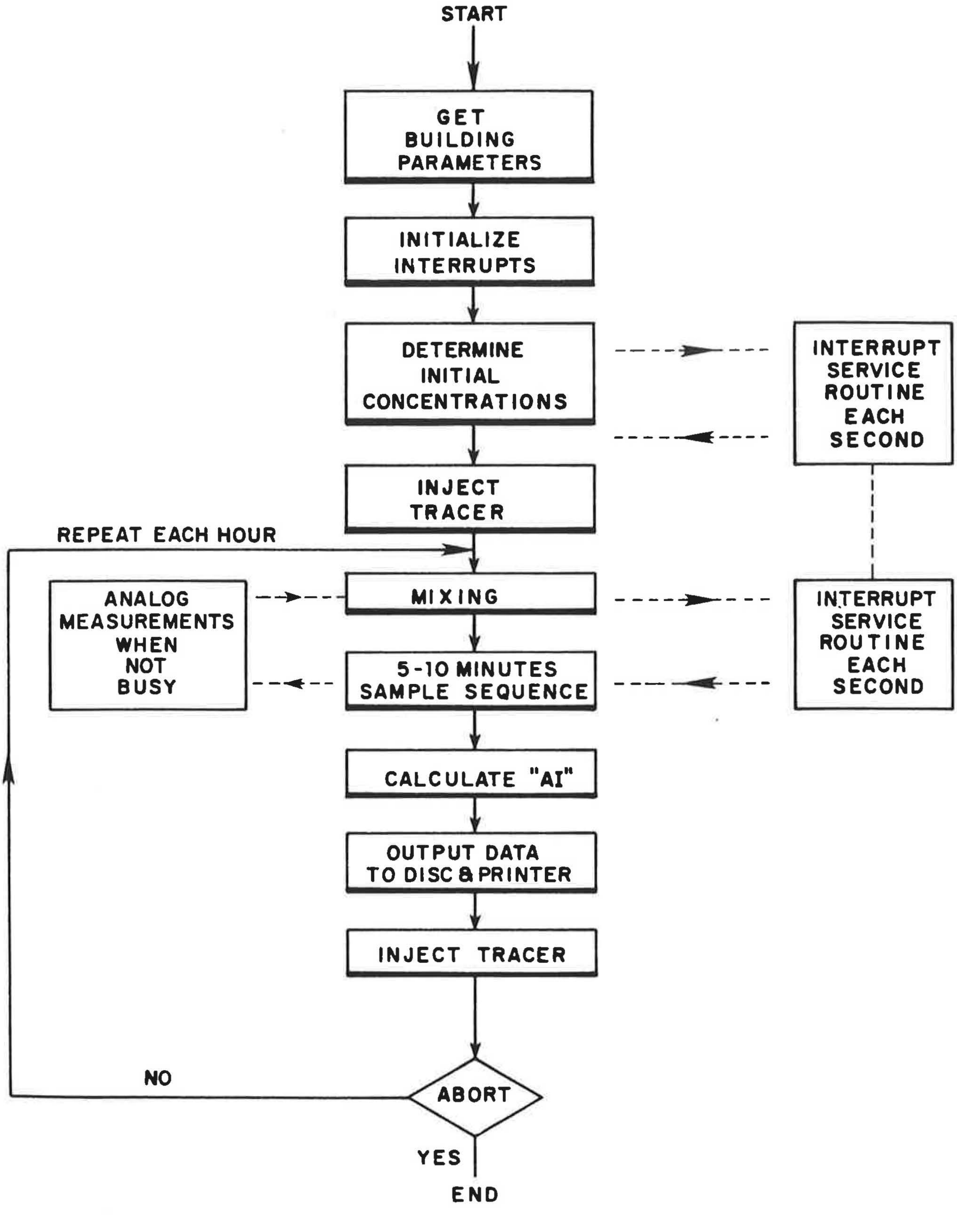
THE 10 PORT MANIFOLD USED FOR ZONE SAMPLING

FIGURE 6



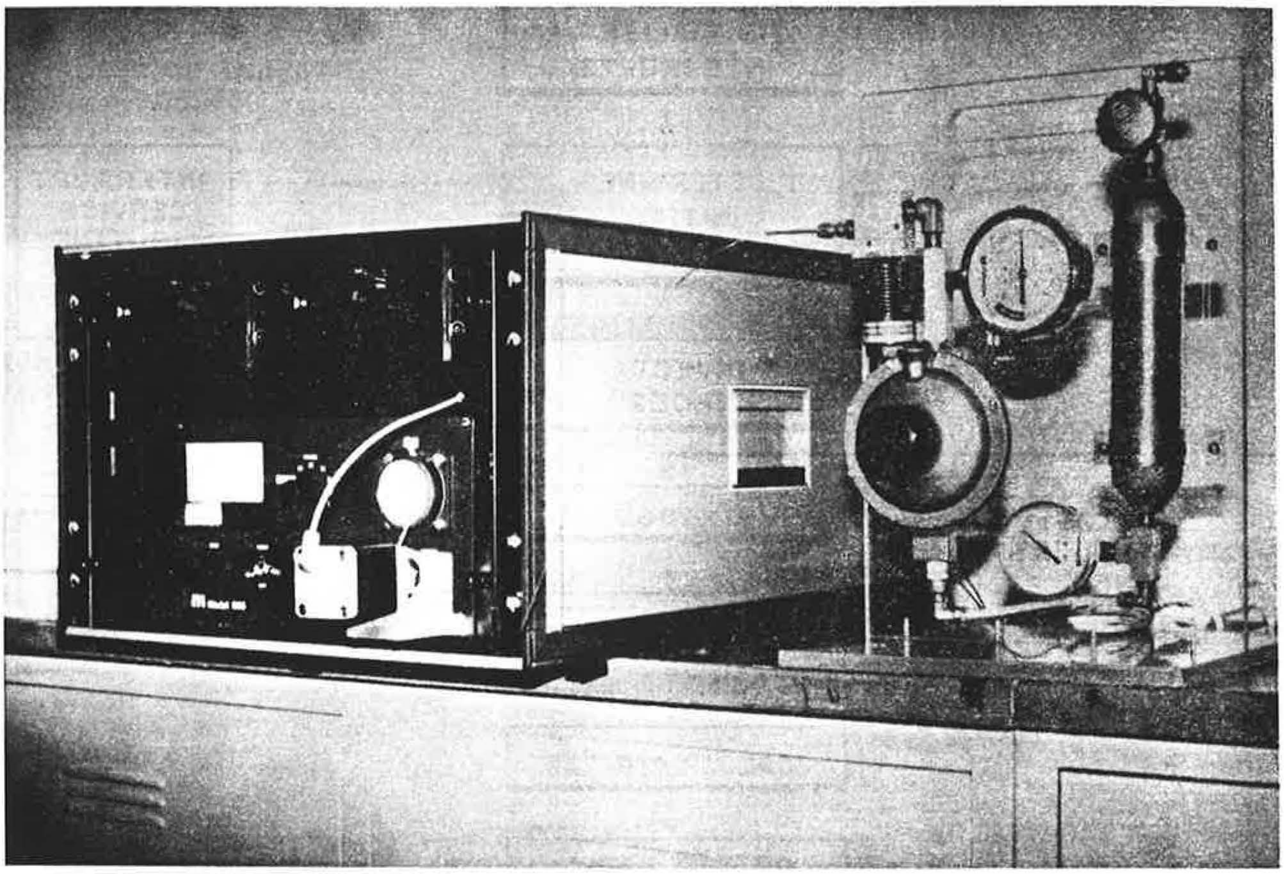
TRACER GAS INJECTION UNIT INCLUDING STORAGE TANK

FIGURE 7



SIMPLIFIED FLOW DIAGRAM FOR MONITORING AIR INFILTRATION IN LARGE BUILDING

FIGURE 8



THE ASSEMBLED AUTOMATED AIR INFILTRATION MEASUREMENT SYSTEM INCLUDING A SMALL ZONE TRACER GAS INJECTION SYSTEM

FIGURE 9