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PAPER 25

IMPROVING THE ACCURACY OF A CONSTANT CONCENTRATION TRACER GAS SYSTEM

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SYNOPSIS

Air infiltration flows into different zones of a building can be measured with the constant concentration technique by injecting a metered amount of tracer gas to hold the concentration of the gas constant. The control and estimation algorithm used to calculate the injection rate is designed using classical transform and optimal estimation methods. The ability of the control algorithm to keep the concentration constant and to accurately measure time varying infiltration flows is demonstrated using digital computer simulations and laboratory experiments. Field demonstrations then complete the confirmation that all components of the total system are performing as designed, and that the desired accuracy targets have been achieved.

The details of how constant concentration system accuracy targets were attained in the Princeton constant concentration tracer gas measurement system are outlined in this paper. Before the total system accuracy goals could be achieved it was necessary to focus attention on the commercial SF_6 detection unit based upon the principles of gas chromatography and electron capture. Gas flow paths, sequencing and critical times in a given sample analysis all directly impinge on the total system function and ultimate accuracy. Some of the points discussed are: internal air leakage, valve switching, and calibration of various subsystems.

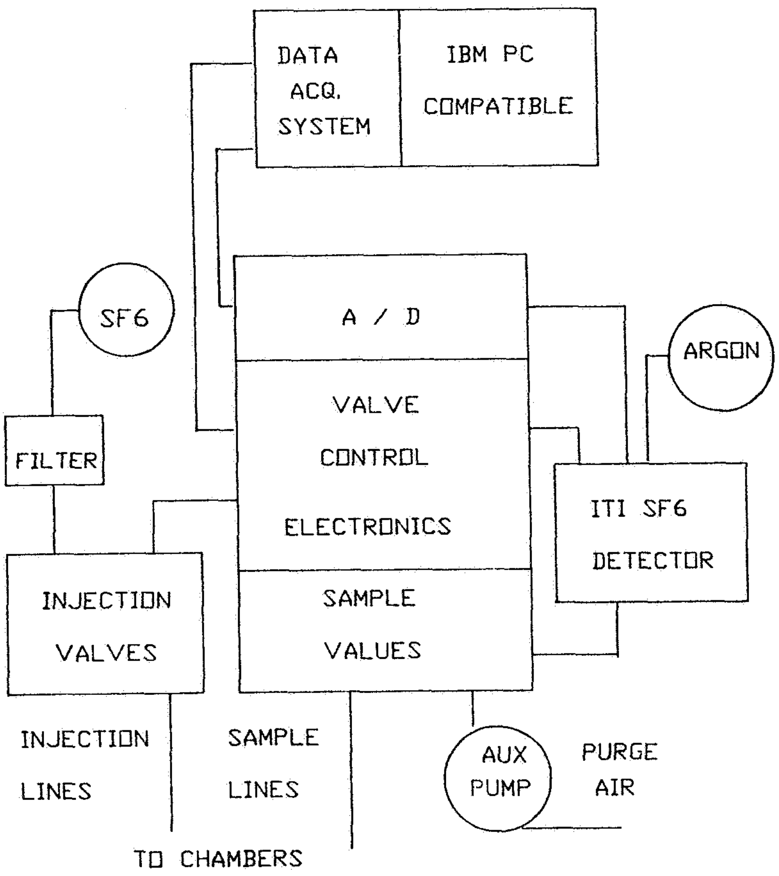
1.0 INTRODUCTION

The increased use of constant concentration tracer gas (CCTG) systems to provide the detailed measurements of air infiltration in multiple zones necessary to analyse building energy and indoor air quality performance is evident in AIC literature.[1-5] In addition numerous reports and conference proceedings point out that more than a decade of automated air infiltration system developments has taken place in the IEA countries[6-15] seeking improved air infiltration measurement approaches. This paper attempts to add to that literature related to CCTG systems in providing information on the use of control theory in the system design to aid in the achievement of the accuracy goals. The actual mechanical and electrical design considerations in the tracer gas detection system itself are also covered in some detail in order to document what has proven to be critical factors in the development of our CCTG system which is shown in the schematic of Figure 1.

In the June 1985 ASHRAE annual meeting, we attempted to place CCTG systems in prospective with other techniques for documenting air movements and infiltration in multi-cell buildings.[16] Further details on the control method used in the Princeton CCTG system, on accuracy evaluations using laboratory tests, field evaluations and computer simulations will be presented in December 1985, ASHRAE Florida conference. Detailed field studies of the Princeton CCTG system in a well-documented research house are presented as a companion paper in this conference.[17]

Figure 1

BLOCK DIAGRAM OF CONSTANT CONCENTRATION SYSTEM



2.0 CONTROL AND ESTIMATION ALGORITHM FOR CCTG SYSTEM

The constant concentration technique measures the air infiltration flow into each zone of a building. To make this measurement a metered amount of tracer gas is injected into each zone so that the concentration of the tracer gas is kept at a target level in all the zones. If the tracer concentration in a zone is not near the target the measured air infiltration rate (AIR) in that zone is in error and the air flowing from the zone causes the measured AIRs in the adjoining zones to be in error. To compute the rate of tracer injection, the control and estimation algorithm may consider the present and past level of the measured concentrations, the past injection rates, and the estimated air flow. The following section presents a detailed analysis of how to best compute the injection rate and estimate the air infiltration flow from the measured concentrations and previous injection rates.

2.1 Simplified Air Flow Model

The first step in the analysis of a control system is to form a accurate model of the process being controlled. The coupled set of first order differential equations which govern the level of tracer gas in a multi-zone building is [18]:

$$V_j \frac{dc_j}{dt} = -c_j \sum_{i=1}^{n} F_{ji} + \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \qquad (1)$$

where V_j = volume of zone j

F_{ji} = air flow from zone j to zone i

c_j = tracer gas concentration in zone j (state variable)

S_j = rate of tracer gas injection into zone j (control)

the n^{th} zone is the outside air

This model assumes that imperfect mixing in the zone does not introduce a time lag or delay in the system.

By keeping the concentration of the tracer gas at the concentration target (c_t) in all the zones, the tracer gas equations reduce to:

$$V_j \frac{dc_j}{dt} = c_t \{ - \sum_{i=1}^{n} F_{ji} + \sum_{k=1}^{n-1} F_{kj} \} + c_n \cdot F_{nj} + S_j \qquad (2)$$

For an appropriate choice of tracer gas, the outside concentration c_n is negligible compared to c_t. Assuming that the density of the gas in each zone is equal, the conservation of mass equation gives:

$$\sum_{i=1}^{n} F_{ij} = \sum_{i=1}^{n} F_{ji} \qquad (3)$$

Thus, in Equation (2) the sum of the flows leaving the zone can be replaced by the sum of the flows entering the zone. This reduces the flow terms in the brackets to F_{nj}, the air infiltration flow. By applying this simplification, assuming that dc_j/dt is negligible, and that $c_n << c_t$, the air infiltration flows are found to be:

$$F_{nj} = \frac{S_j}{c_t} \qquad (4)$$

Thus, by holding the concentration constant, the infiltration into a zone is simply the tracer injection rate into the zone divided by the steady concentration.

2.2 Discrete Model and Z-plane Analysis

The system of tracer gas concentrations and air flow rates is described in a continuous manner by the differential Equations (1). Although the goal of the system control is to keep the zone concentration steady at the target level, the concentration does at times deviate from the target level. These deviations occur during system startup and when there are changes in AIR. During these times the differential term is not negligible and must be retained in order to properly model the movement of the concentration. The nature of the constant concentration instrumentation requires that the concentration sampling and calculation of the level of the injection rate to be discrete. Thus, the system is modeled with difference equations, and the analysis of the control is carried out using discrete analysis techniques, Z-transforms and pole placement in the Z-plane.

By applying the assumptions that the tracer concentrations in the zones are near the target and that $c_n << c_t$ the levels of tracer gas in the j building zones are approximated by:

$$V_j \frac{dcj}{dt} = -cj \cdot F_{nj} + S_j \tag{5}$$

It is advantageous that the equations do not contain air flow rates between the building zones (interzone air flows) since the flow rates are not measurable by the system and are difficult to estimate. The remaining variables in the equations can either be estimated or are measured.

The differential Equations (5) are also separate. Thus, the modeling and analysis can be carried out on one zone and applied to the rest of the zones. Integrating the approximated differential equation over the sample period yields a difference equation for the tracer concentration:

$$c_{k+1} = a_k c_k + b_k u_k \tag{6}$$

where c_{k+1} = concentration at time (k+1) Ts [1/1]

u_k = S_k/V (control variable-injection rate) [1/t]

AIR_k = F_{nk}/V (air infiltration rate) [1/t]

a_k = $\exp(-AIR_k \; Ts)$ [1/1]

b_k = $(1 - a_k)/AIR_k$ [t]

Ts = time between samples [t]

AIR_k is assumed to be constant over Ts

- dimension of variable is shown in brackets -

The analysis of the control algorithm can be carried out by two methods. One method is to transform the difference equation to state space using Z-transforms and find the control which will give the desired pole placement (i.e., desired response) in the Z-plane. This method is applicable to systems whose difference equation is easily transformed (i.e., linear difference equations with constant coefficients). Often the control which yields the desired response can be found empirically. Another method is the simulation of the system response to each proposed control algorithm until the desired response is found. Without prior knowledge or intuition of which control is proper this can be a time consuming process. However, it may be necessary if the difference equation is not easily transformed. It also has the advantage of providing a qualitative view of the response. The analysis of the constant concentration system control utilizes both methods.

The constant concentration system operates in two modes: (1) the startup period and (2) continuous response to changes in air infiltration rate. The startup period is modeled as a step change in the desired concentration from 0 at the initial time to c_t at all following times. The control design during this period is a classic servodesign problem. The goal of the design is for the concentration to rapidly follow the change in the desired concentration with little or no overshoot. The response of the system to the step change in c_t is conveniently analyzed using pole placement (also called state-space method) in the Z-plane.

When there are changes in AIR the goal is to keep the concentration at the target level. This is a classic regulator problem The difference equation is not easily transformed into the Z-domain for the case of time varying values of a and b. However, the response of the system is similar for changes in c_t and AIR. Simulations confirm that the system response to a step change in c_t is similar in form to that of a step change in AIR. Thus, a state-space analysis of the startup period is used as an indicator of the form of the response of both the startup period and for changes in AIR. The simulations of changes in AIR are used to verify the state-space analysis and provide a qualitative analysis of the response.

2.3 Evaluation of the Control Algorithm

To accurately measure the air infiltration flows in a building the constant concentration measurement technique requires the level of tracer gas to remain near the target level in each zone while the air infiltration flow is changing. The criteria to meet this condition are:

1) fast response with little overshoot

2) low steady state error

3) low sensitivity to measurement errors

In the state-space analysis the first two criteria translate to having the transfer function poles located near the origin and the final value of c (found from the final value theorem) close to c_t. The sensitivity to measurement errors criterion is examined using monte carlo type simulations that include gaussian measurement errors.

The analysis has involved four proposed control methods - proportional (P), integral (I), proportional-integral (PI), and proportional-integral-derivative (PID). The discussion will focus on proportional adaptive and proportional integral methods. The analysis is carried out in the following way:

1) the difference equation is transformed into the Z-domain to find the poles of the transfer function $H(z) = C(z)/C_t(z)$,

2) the root locus of the poles is displayed in the Z-plane,

3) given the Z-transform of the target concentration- $C_t(z) = c_t\, z/(z-1)$, the final value of the concentration is found from the final value theorem,

4) the response to a step change in AIR from 0.2 to 0.5 ACH for selected values of control gains and Ts= 4 minutes is simulated,

5) the response to a step change in AIR from 0.2 to 0.5 ACH and a gaussian measurement error of 1% is simulated for the best control parameters- the average standard deviation of the concentration and the average of the concentration over five, simulations is computed as a measure of the ability of the control to keep the concentration near the target when measurement errors are present,

6) the change in response is studied when the level of AIR is different from the level used to compute the control parameters, and

7) the relative advantages and disadvantages of the method are discussed.

2.3.1 A Proportional Control

Proportional control is the most simple feedback control. For a first order system P control provides a fast response with little or no overshoot. Its one drawback is that there is a steady state error when the control parameters (i.e., control gains and constants) are kept constant. When the control parameters are continuously updated the steady-state error is eliminated and the speed of response is slightly decreased.

The proportional control feeds back the present error signal (the difference of the present concentration from the target concentration (c_t)) multiplied by a gain K_p [1/t]. The expression for the control is:

$$u_k = K_p\,(c_t - c_k) \tag{7}$$

The difference equation for the tracer concentration is:

$$c_{k+1} = a_k \cdot c_k + b_k \cdot K_p\,(c_t - c_k) \tag{8}$$

The analysis of the startup period assumes that a_k and b_k are constant and the response of concentration to a change in c_t is studied. Thus, the transfer function of interest is $H(z) = C(z)/C_t(z)$. By taking the Z-transform of both sides of Eqn.(8)

this is found to be:

$$H(z) = \frac{bKp}{(z - (a - bKp))} \tag{9}$$

This equation has one pole at (a - bKp), thus to place the pole at zero, Kp = a/b.

During the operation of the system the sample time does not vary. Thus, the transient response of the system will not significantly change for a constant value of K_p and changes in the levels of AIR from 0.1 to 2.0 ACH. However, the percent error of the final concentration reaches an unacceptable level for AIRs higher than 1.0 ACH. The error in c_f is caused by failing to reset the control level to the higher value required by higher AIRs. At higher AIR levels the system increases the proportional control term by settling at a level of concentration below the target.

The error in the final concentration does not have to be as large as the analysis indicates. The target concentration can be reached exactly by replacing the parameter c_t in the control Equation (7) with a larger value, ε_o, dependent on the level of AIR and the sample time. This method, called adaptive control, responds properly when the measured AIR is not greatly different than the true AIR. For slowly changing AIRs the measured AIR is within 10% of the true AIR and the concentration error is less than 1%. The concentration error is not as small, however, for sudden changes in AIR. The method of estimating the AIR by dividing the injection rate summed over a period of time by the desired concentration does not respond quickly to sudden changes in AIR. For a step increase in the AIR the estimated value of AIR lags behind the true value; which causes a lag in the concentration reaching the target concentration.

Proportional control is a simple method that provides a quick response with no overshoot to changes in AIR. The one drawback to the method is the presence of steady state error. By replacing c_t with a value dependent on AIR the proportional adaptive method is slightly oscillatory.

2.3.2 Proportional-Integral Control

Proportional-Integral control is a combination of proportional and integral terms. The addition of the integral term to the proportional method eliminates the final concentration error of proportional control and the need for adaptive control. When broken into parts, the proportional term can be thought of as providing the amount of control needed to bring the concentration from the measured to the target level and the integral terms adds an amount needed to counteract the drop in concentration that would result from air infiltration. By properly choosing the control gains the system response to changes in AIRs is a one step delay with no overshoot. Thus, PI control satisfies the two response criteria of a fast response with no overshoot and no steady state error.

The PI method feeds back the error signal multiplied by K_p [1/t] added to the integral of the error signal multiplied by Ki [1/t^2]. As in the analysis of the integral method, the difference equation is found by working back from the Z-transform equivalent of the control method. The Z-transform of PI control method is the sum of the transforms of the proportional and integral terms. Multiplying the PI control method transform by the error signal transform yields the control transform:

$$U(z) = E(z)\,[Kp + Ki\,Ts\,z/(z - 1)] \tag{10}$$

or

$$z\,U(z) - U(z) = E(z)\,[\,Kp(z - 1) + Ki \cdot Ts \cdot z]$$

Which is transformed into the discrete time domain to yield:

$$u_{k+1} = u_k + (K_p + Ki \cdot Ts)(c_t - c_{k+1}) - K_p(c_t - c_k) \tag{11}$$

or

$$u_{k+1} = u_k + Ki \cdot Ts(c_t - c_{k+1}) + K_p(c_k - c_{k+1})$$

Then Eqn. (11) is inserted into Eqn. (6) with the z transform providing the required transfer function:

$$H(z) = \frac{bz(Kp + Ki \cdot Ts) - bKp}{(z - 1)(z - a) + bz(Kp + Ki \cdot Ts) - bKp} \tag{12}$$

The Equations for the two poles are then:

$$p1,p2 = \frac{a + 1 - b(Kp + Ki \cdot Ts)}{2} \tag{13}$$

$$\pm \frac{[(a + 1 - b(Kp + Ki \cdot Ts))^2 - 4(a - bKp)]^{0.5}}{4}$$

By choosing Kp = a/b and Ki = 1/bTs, PI control satisfies the two response criteria of a fast response with little overshoot and no steady state error. The computation of the values of Kp and Ki to meet the two criteria is straightforward. The analysis has shown that the steady state error is zero for all values of Ts, Kp, and Ki and that using the values of Kp and Ki given by Kp = Ki·Ts = 1/Ts provides a fast response with little overshoot.

2.3.3 Comparison of the Control Methods

AP and PI control provide fast system response with little or no overshoot and no steady state error. The difference between the two controls is that the AIR feedback for AP is indirect while PI has direct feedback. AP control adjusts the level of control for varying AIRs by changing the magnitude of the control parameter c_o. The lag in the estimation of AIR introduces a time lag in the system. This causes concentrations to be below the target for increasing AIRs and above the target for decreasing AIRs. For PI control the integral term directly compensates for the level of AIR. This method has the drawback of being sensitive to measurement errors. The sensitivity of the control and the restriction on negative injection rates cause concentrations to be above the target.

2.4. System Model for Estimation

In order to evaluate the response of the system to different control methods the derivation of the tracer concentration model included only the injection rate as an input to the system. A complete model of the system includes the effect of uncontrolled inputs - these inputs are called system disturbances. An example of a system disturbance is the flow of air from an adjoining zone that has a concentration different than the target. The equation which models the tracer concentration in the presence of disturbances is:

$$c_{k+1} = a_k c_k + b_k u_k + w_k \tag{14}$$

where w_k is the disturbance into the system

A final addition to the system model is the equation describing concentration measurement:

$$cm_{k+1} = c_{k+1} + n_{k+1} \tag{15}$$

where cm_{k+1} is the measured concentration

n_{k+1} is the measurement error.

As stated earlier, the measurement error is due to detector measurement errors and the nonuniformity of the concentration caused by imperfect mixing.

A Kalman filter is a method of estimating the concentration so that the variance in the estimated concentration (c) from the true concentration is minimized. This is accomplished by properly computing the estimation gain (Ke_k) used to combine the measured (c_m) and extrapolated (*) concentration to form an estimation of the true concentration:

$$c_{k+1} = c^*_{k+1} + Ke_{k+1}\,(c_{mk+1} - c^*_{k+1}) \tag{16}$$

Ke^k is computed by considering the covariance of the past estimate of the concentration (P^k), the covariance of the disturbance into the system (Q^k), and the covariance of the measurement error (R^k). The Kalman filter equations provide for a concentration extrapolation:

$$c^*_{k+1} = a'_k\, c_k + b'_k\, u_k \tag{17}$$

The calculation of the Kalman filter gain has assumed that the disturbance and measurement errors are known and/or measurable. Unfortunately, for most structures these values are difficult to obtain. Measurement errors depend on the error in the detector and the uniformity of the concentration in the zone. The precision of the detector can be quantified and is approximately less than or equal to 1% of the measured value for the system in use. However, the uniformity of the concentration in the zone will be dependent on the strength and direction of air flow in the zone (intra-zone flow) and the rate of infiltration flow (i.e., larger AIRs will cause greater dilution near the exterior envelope). Since the natural intra-zone flow can show large fluctuations and is usually too low to provide adequate mixing small fans are placed in the room to accelerate the diffusion of the injected tracer gas and increase mixing[2,4,5].

The second value required for the computation of Ke is the covariance of the disturbance. The disturbance input to a zone is a result of the flow of air from an adjoining zone that has a concentration different than the target. Since it is not possible to measure the flow rate and concentration of each air stream entering and leaving a zone, it is not possible to directly measure the covariance of the disturbance input.

2.5 Air Infiltration Rate Estimation

The estimated specific air infiltration rate is used for three purposes: 1) the reported value of the outdoor air flow rate into the zone is equal to the AIR multiplied by the zone volume, 2) the AIR is used in the process of estimating the concentration, and 3) the AIR is used by the proportional adapative control method to compute c_o. Thus, any error in the estimated AIR not only causes incorrect values of the reported infiltration flow rate but also affects the control of the system. Three methods of AIR estimation are discussed in this section. The averaging method computes an estimate of the average infiltration flow rate by dividing the tracer injection rate averaged over a period of time by the target concentration. The assumption is made in the derivation of the averaging method that this concentration is held constant at the target level. Although the averaging method provides a fairly accurate estimation of the AIR[19] in general, neglecting the information of the movement of the concentration decreases the accuracy of the AIR estimation. The two alternatives to the averaging method, modified averaging and weighted least squares (WLS), do not neglect the movement of the concentration. Modified averaging includes the change in the concentration from the beginning to the end of the averaging time and divides by the average concentration instead of the target concentration. The WLS method computes the AIR which best fits the time history data of the control and concentration values. In addition to incorporating the concentration data, the WLS technique weights the most recent data more heavily than past data. As a result, the WLS method provides an estimate of time varying AIRs that is more accurate than the AIR estimated by the averaging method. Figures 2 and 3 illustrate the ability of methods described to follow a step change in AIR.

Figure 2
Simulation of AIR Estimation
for Averaging and Modified Averaging

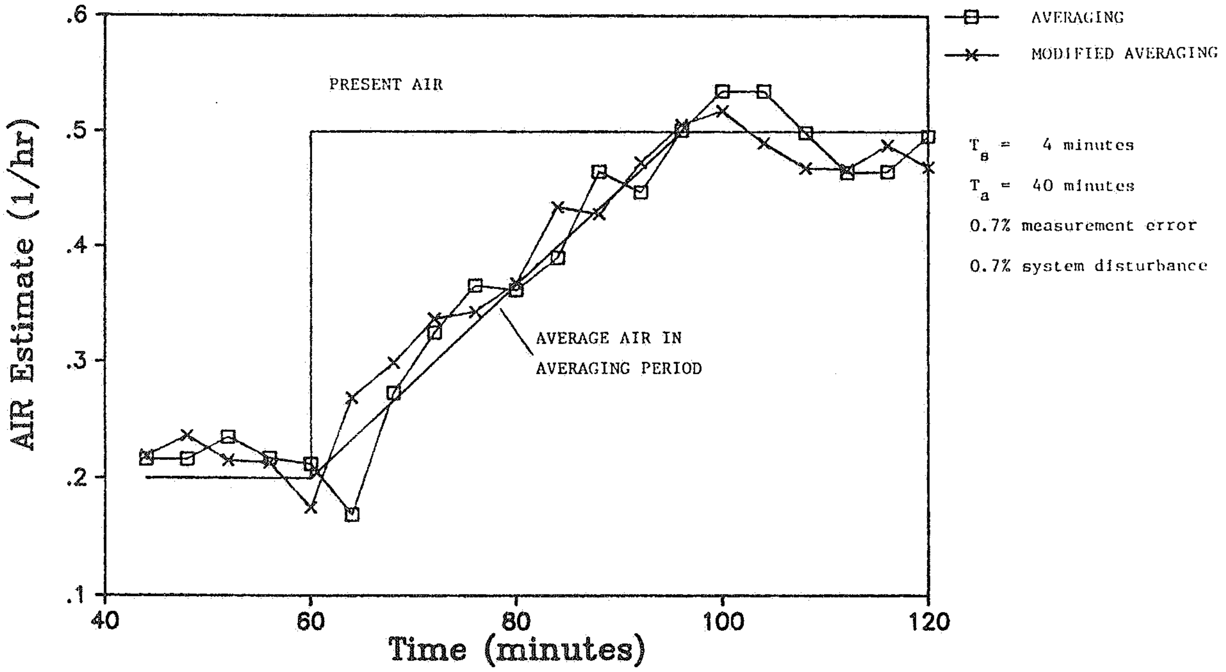
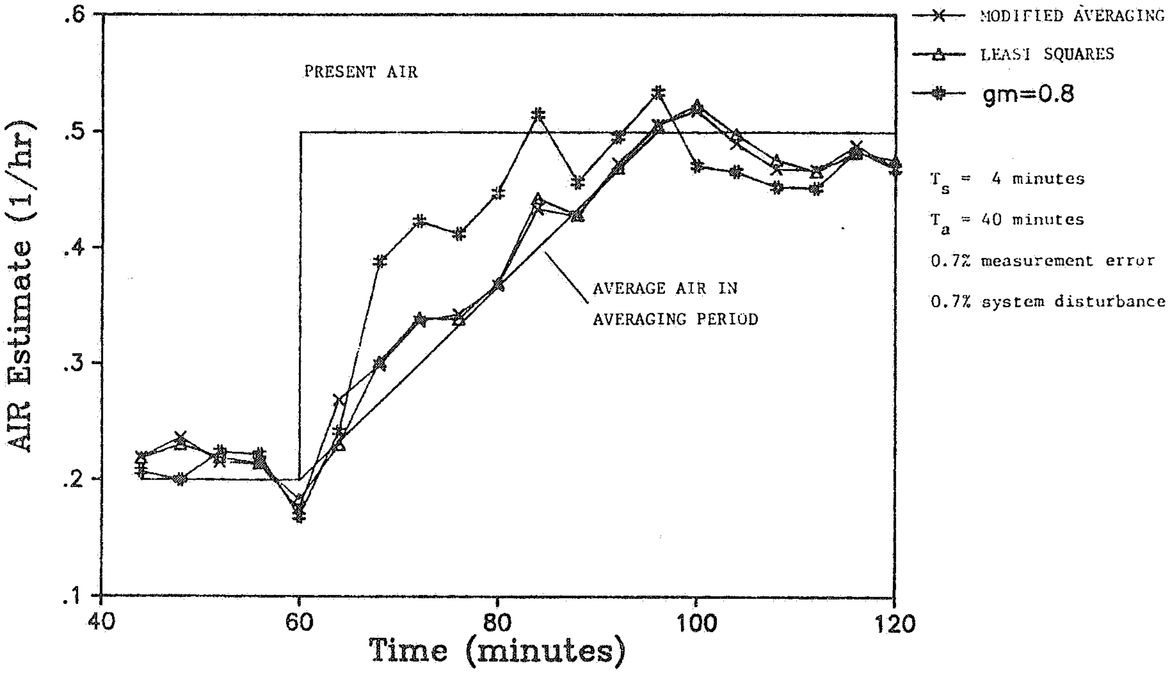


Figure 3
Simulation of AIR Estimation
for Averaging and Least Squares Methods



The analysis of the error of the estimated average AIR leads to the following general conclusions:

1) The modified averaging method is significantly more accurate than the averaging method.

2) Except at high levels of measurement error the accuracy of the modified averaging and least squares methods are nearly equivalent.

3) For disturbances less than 1.5% and measurement errors less than 3% the least squares and modified averaging methods estimate the average AIR within approximately 5% of the average AIR.

3.0 SF6 DETECTOR OPERATION AND MODIFICATIONS

3.1 Detector Operation

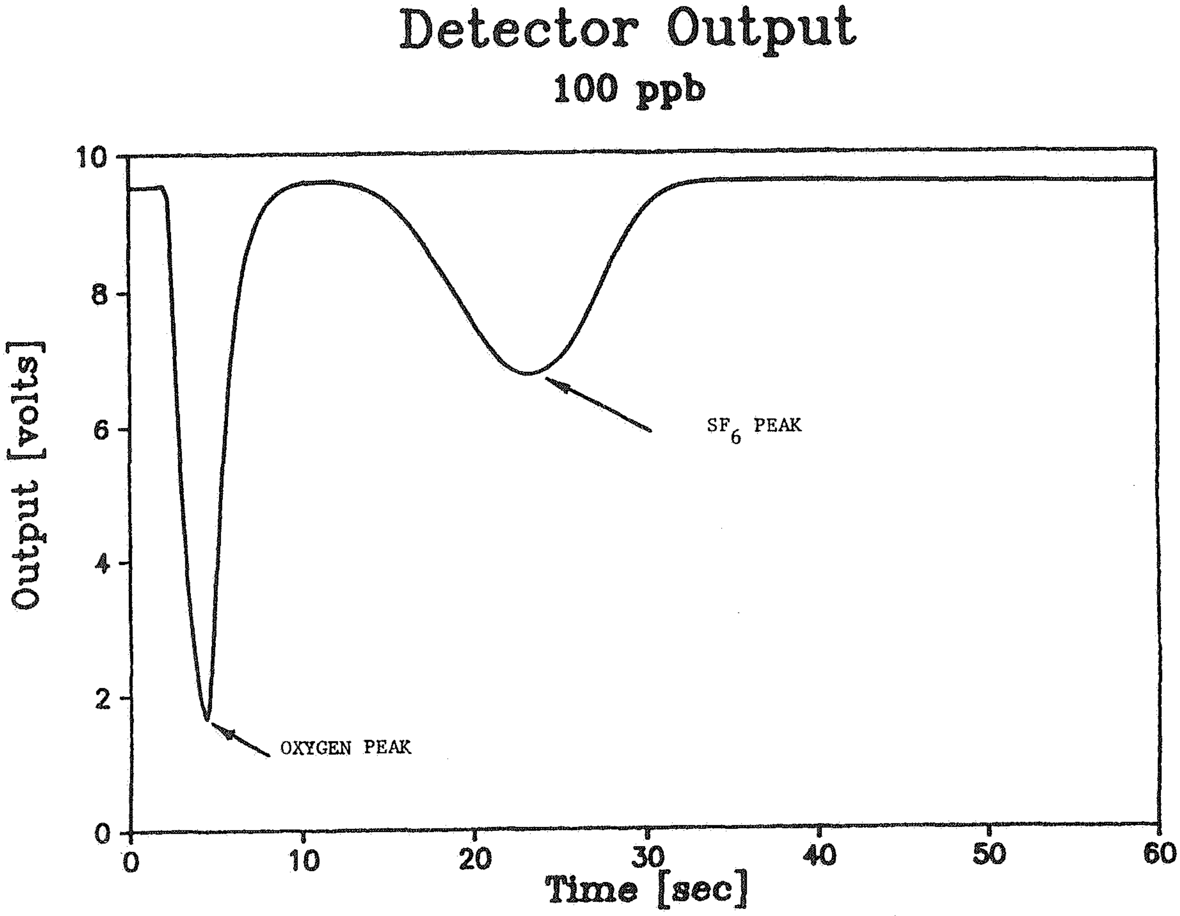
Before discussing the details of the improvements to the operation of a typical SF6 detector, we should review the existing equipment. Princeton's constant concentration system measures the SF6 concentration in the individual zones with an ITI model 505 SF6 electron capture gas chromatograph. The primary components in the chromatograph are an electron capture detector cell fitted with an Ni63 beta source, a 380mm long 100-120 mesh aluminum oxide packed column, three 3-way sample valves, and the electronic circuitry needed to convert the detector output into a voltage signal. The detector is able to precisely measure SF6 concentrations from 10 to 500 parts per billion with a 60 second cycle time between samples.

In the detector a source of electrons is provided by the stream of beta particles emitted from the Ni63. The strength of the electron flow is measured by the detector - this level is generally called the "standing current". As oxygen and SF6 flow through the detector they capture electrons in proportion to their concentration and decrease the output of the detector. Since these gases are separated in time by the packed column the magnitude of the decrease of the detector output can be measured for each gas. Figure 4 displays the typical conditioned output of the detector analyzing air with a concentration of 100 ppb SF6 that has been injected into the column. The oxygen peak occurs first at approximately five seconds and the SF6 peak occurs at about 23 seconds when argon pressures are maintained at three atmospheres. The concentration of SF6 is a function of the ratio of the standing current to the peak current.

The operation of the detector can be split into two phases: sample injection and sample detection. During the injection phase all 3-way sample valves are activated which causes the carrier gas to flow in the "ON" direction as shown in the flow diagram in Figure 5a. This allows the carrier gas to flush the sampled air in the sample loop into the column. After allowing two seconds for complete flushing, all the 3-way valves are deactivated and the detection phase begins. During this phase, air from the zone being sampled is pumped through the sample loop and out the exhaust port. The carrier gas (argon) now flows directly to the column where it continues to force the gas from the sample loop through the column.

The argon and sample gas then flow through the electron capture detector and are exhausted outside the detector enclosure.

Figure 4



3.2 Detector modifications

This commercial detector has been primarily designed for use in finding leaks in underground pipes. In this application the ease of use is emphasized rather than the accuracy of the instrument. Over the past year many modifications have been made to the plumbing and electrical system which limit the use of the detector to the sample mode but improve its reliability and accuracy.

Figures 5a, 6a, and 7a show the plumbing, wiring, and detector supply and amplifier diagrams of the original detector. Figures 5b, 6b, and 7b show the same diagrams for the modified detector. The following is a summary of the modifications and the reasons for the changes.

3.2.1 Plumbing System

Changes:

1) Eliminate by-pass valve, continuous/sample mode valve, and capillary restriction.

2) Bypass column and detector flushing outlets.

3) Replace rotary injection valve with three 3-way solenoid valves.
4) The detector output is exhausted directly to outside of the enclosure.

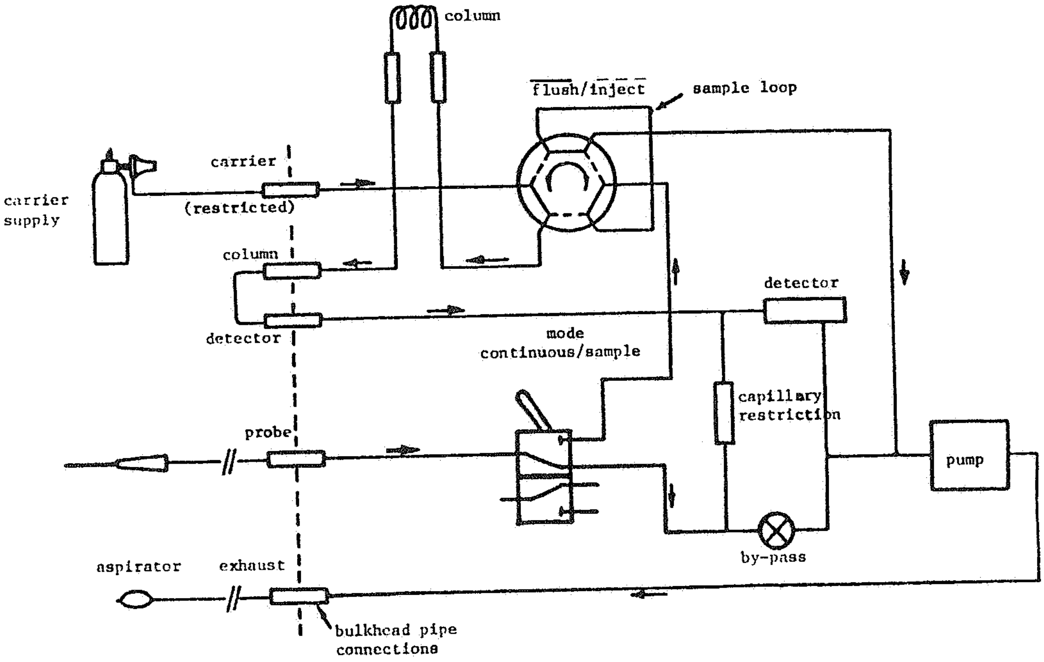


Figure 5a. Original pipework diagram.

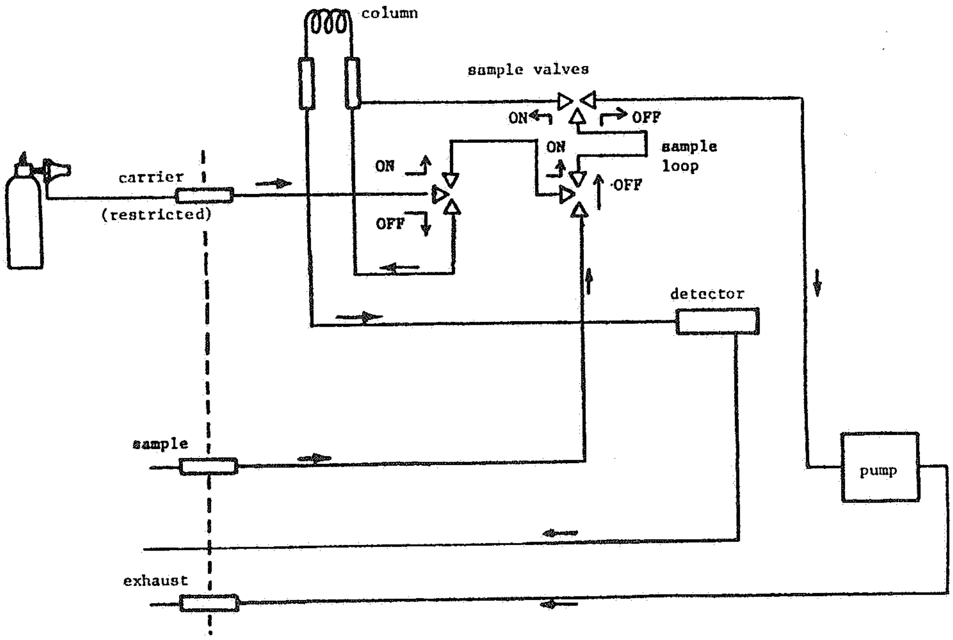


Figure 5b. Revised pipework diagram.

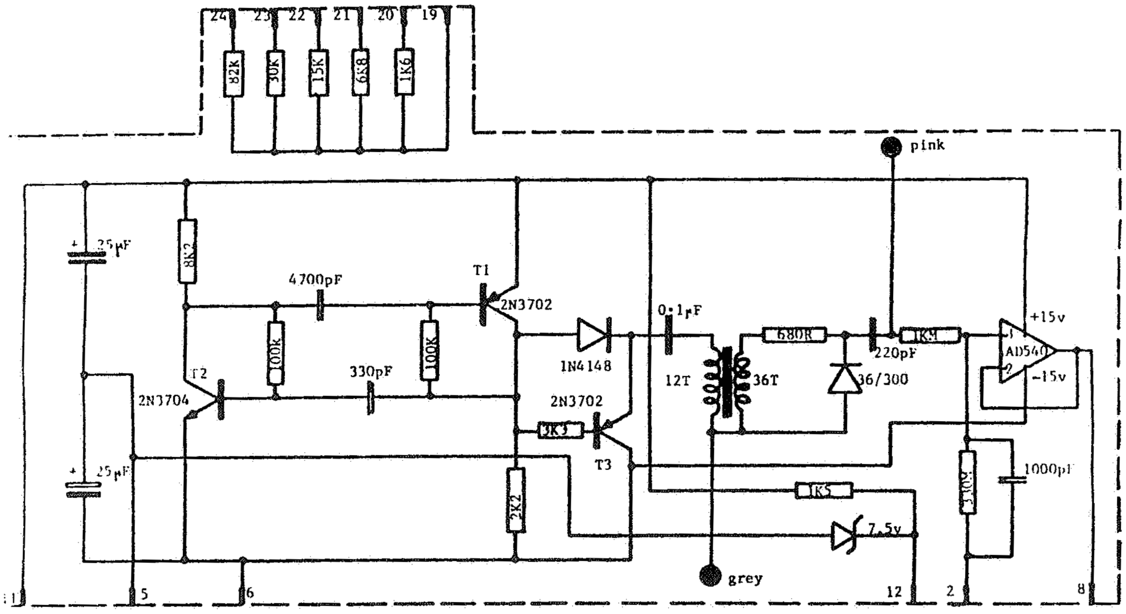


Figure 6a. Original detector supply and amplifier.

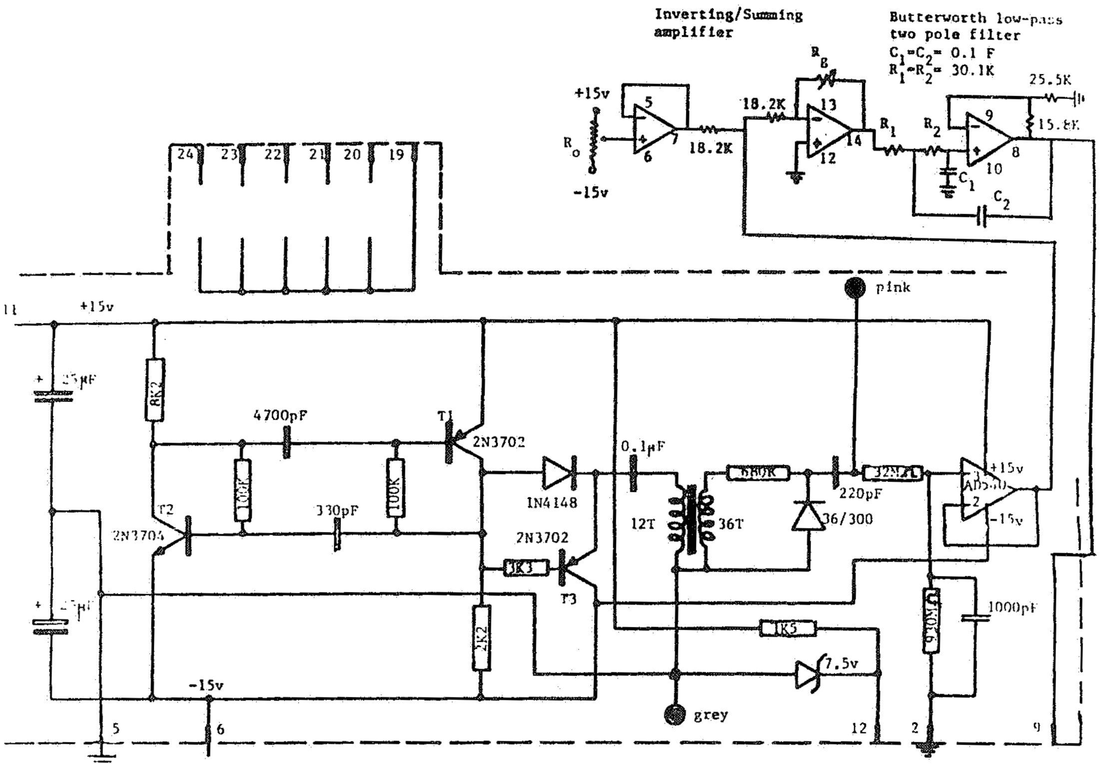
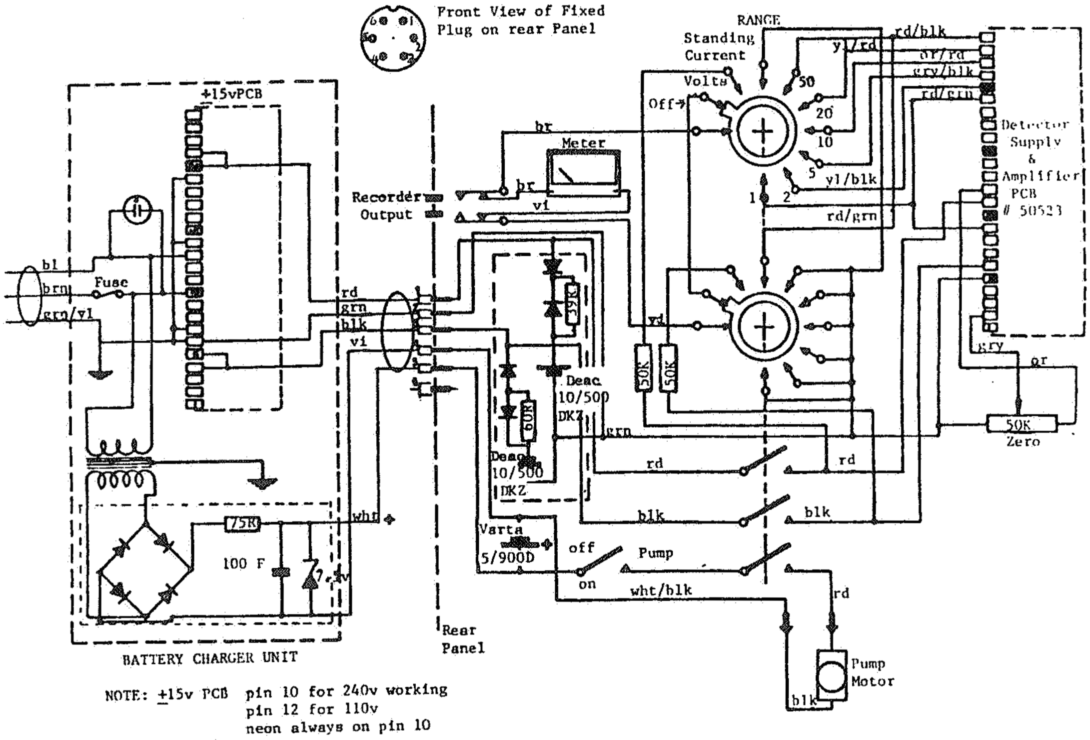
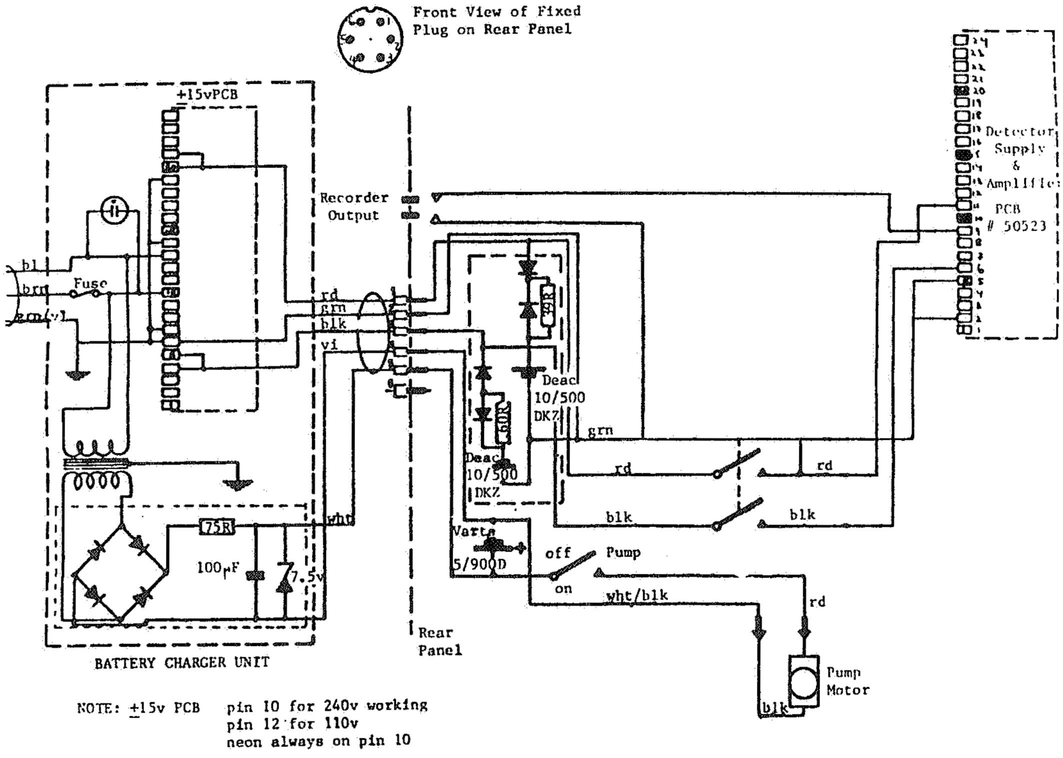


Figure 6b. Revised detector supply and amplifier.



NOTE: +15v PCB pin 10 for 240v working
pin 12 for 110v
neon always on pin 10

Figure 7a. Original wiring diagram.



NOTE: +15v PCB pin 10 for 240v working
pin 12 for 110v
neon always on pin 10

Figure 7b. Revised wiring diagram.

Reasons for changes:

1) The continuous/sample mode valve and by-pass valve are prone to leaks that are difficult to eliminate. Elimination of the capillary restriction reduces the level of the carrier gas flow needed to provide the proper standing current.

2) Bypassing the column and detector flushing outlets further eliminates connections that may be sources of leaks. It also leads to a more compact system.

3) The three 3-way solenoid valves are less prone to leaks than the rotary valve. The solenoid valves also eliminate the need for a high pressure gas source (usually) argon to actuate the rotary valve. This reduces the amount of argon used by the detector and allows the operator the option of using a lower argon pressure to the column.

4) The separation of the detector output from the pump input has two effects:

   a) The pressure in the lines through the column and detector are above instead of below atmospheric pressure. This eliminates the possibility of contamination of the sample by leaks through the plumbing.

   b) The pressure across the pump no longer affects the flow through the detector. Since the pump pressure will vary depending on the restriction in the sample line, the power provided to it, and the condition of the pump, the flow through the detector is more stable. This also allows the user to employ a variety of different flow rates through the sample loop without affecting the calibration of the detector. Thus, low flow rates can be used during calibration to decrease the amount of calibration gas, and high flow rates can be used during operation to decrease the transportation time from the zone to the detector.

3.2.2 Electrical System

Changes:

1) Voltage output signal

   a) Invert and provide adjustable offset and amplification of signal.

   b) Filter signal through a low-pass filter, frequency = 53Hz.

   c) Run signal from the detector supply and amplifier card to the output jack through a coaxial cable.

2) Replace rotary switch with a single pole double throw switch for the +15 and -15 volt lines.

3) Interrupt pump power with pump switch only.

4) Disconnect meter.

5) Disconnect "zero" potentiometer.

6) Remove wires and resistors for range output.

Reasons for Changes:

1) The output from the detector is a negative voltage with the standing voltage being from 1.5 to 3.2 volts. The voltage can be read as a positive voltage with the rotary switch in the standing current position. However, if the battery charger is connected and the device used to read the voltage is connected to the outlet ground the signal output is shorted out. Typically both these situations occur. In the particular example of the present system (a Techmar Lab Master system), the analog to digital converter is connected to ground and requires a 0 to +10 volt input. In order to achieve high resolution and convert the signal to a positive voltage, the signal from the detector supply and amplification card is passed through a op-amp inverting amplifier with offset.

2) Because of the changes in the plumbing system (conversion to dedicated sample mode system) it is no longer necessary to be able to adjust the level of the output voltage as needed in the continuous mode. Thus, the "zero" potentiometer, rotary switch, and range resistors have been eliminated. The output voltage is run directly from the card to the output jack and the voltage supplies are interrupted by a single throw switch. This has several advantages:

   a) Better noise protection through the coaxial cable.

   b) A very low output impedance (the original system had an impedance as high as 82K ohms).

   c) The level of the output voltage (which affects the detector's calibration) can not be accidentally changed by twisting the "zero" potentiometer. It can be adjusted internally to keep a high resolution of the SF6 peak.

   d) It provides easier switching, fewer connections, and less cluttered wiring.

3) The first half of the detector supply and amplifier circuit supplies a high voltage, high frequency (15 kHz) pulse to the detector. Although the pulses do not affect the detector's meter or a high inertia recorder, these pulses are passed through to the output signal (the input pulses and output signal are carried on the same line) and can be recorded by analog to digital converters. The addition of the op-amp filter with a cutoff frequency of 53 Hz. greatly reduces the magnitude of the pulses and does not distort the shape of the peaks.

4) The meter is not required for normal operation and the high output voltage could damage it.

5) The single pump power switch allows individual control of the pump.

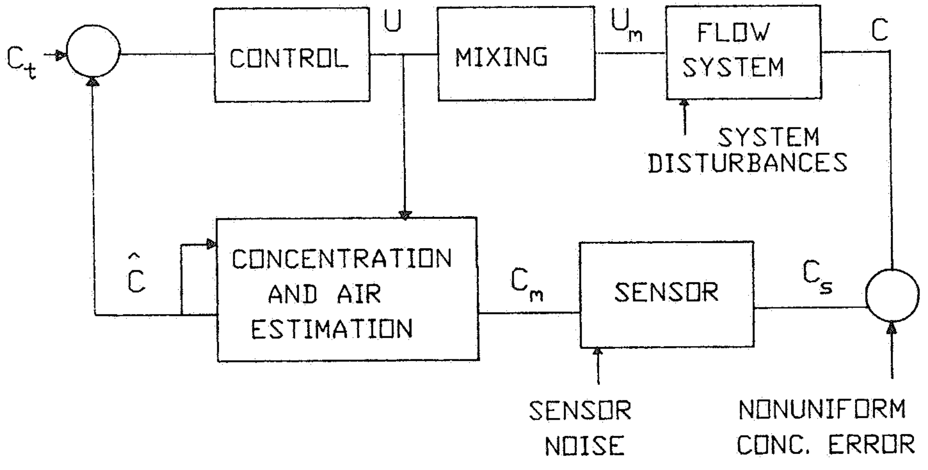
4.0 SYSTEM

The total system using the constant concentration principle was shown schematically in Figure 1. The block diagram indicates how the data acquistion system is integrated with the A/D, valve control electronics, injection system, sample system and SF6 detector. The tracer gas is actually SF6 diluted to a 0.1% concentration so that metering of the SF6 can be accurately performed. Flow rates through the injection lines to the individual zones are all carefully calibrated[16] to insure the valve open times can be related directly to the flow of SF6 to each zone.

Figure 8 is another block diagram, this time of the control and air infiltration rate estimation system. Seeking the target concentration c^t, the individual control system elements take care of system disturbances, sensor noise and nonuniform concentration errors.

Figure 8

BLOCK DIAGRAM OF SYSTEM CONTROL AND ESTIMATION



U - computed control value

U_m - control applied to system

C - average zone concentration

C_s - sampled concentration

C_m - measured concentration

$\hat{C}$ - estimated concentration

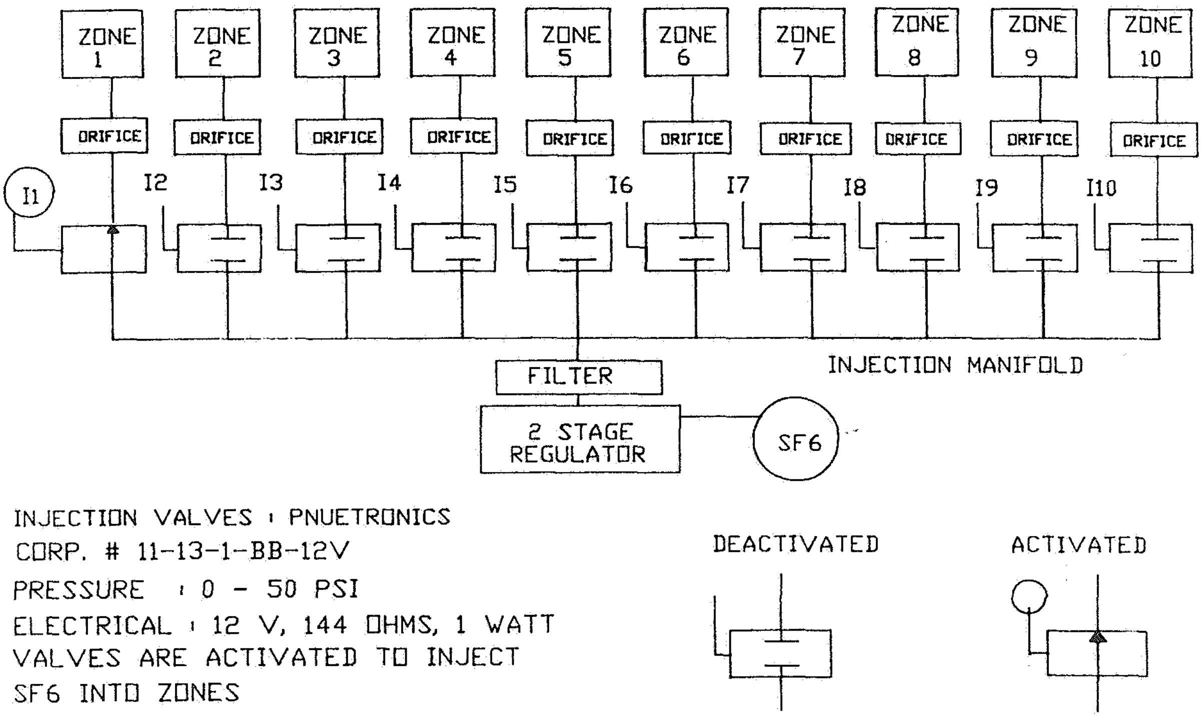
C_t - target concentration

AIR_e - estimated air

The sampling system pumping diagram and injection system diagrams have a number of similar characteristics. Valving is achieved with 10 subminiature DC valves (1 watt) protected by upstream filtering. In the injection system, Figure 9, flow rates are controlled with two stages of regulation on the dilute SF6. Each zone has a selected micro orifice to match zone volume tracer gas needs. The sampling schematic is shown in Figure 10 with details on the circuitry explained. When this system is deployed in larger zones sampling locations in the zone are multiplied by branching the sampling part to several locations[17].

Figure 9

INJECTION SYSTEM PLUMBING DIAGRAMS



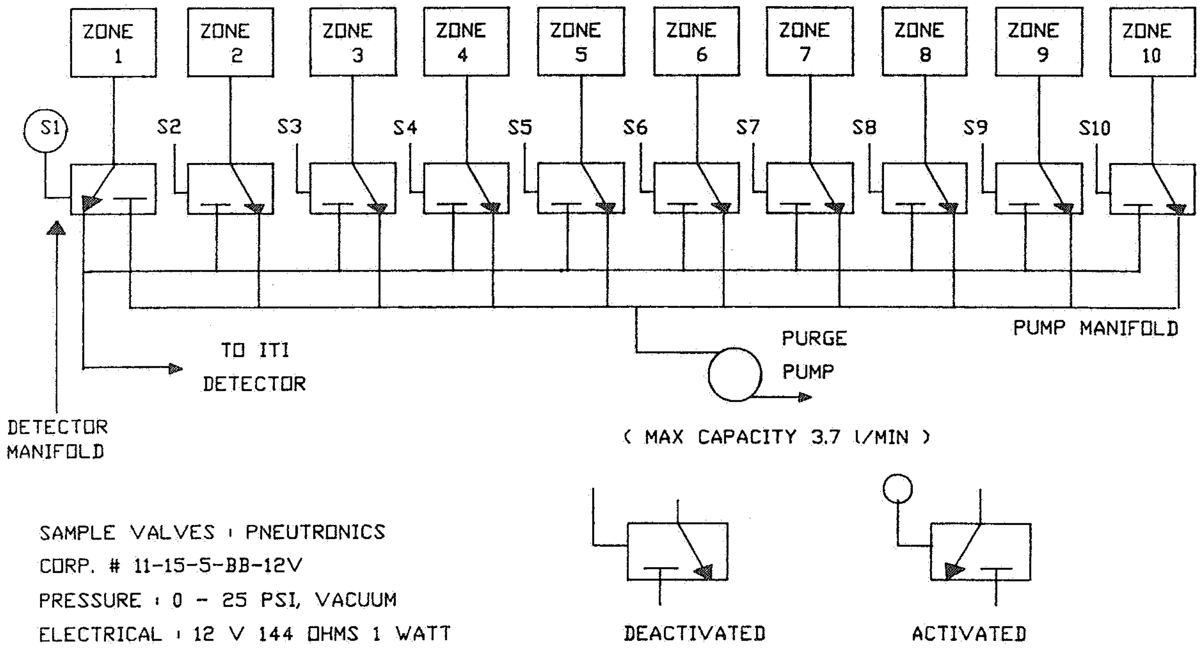
INJECTION VALVES : PNUETRONICS CORP. # 11-13-1-BB-12V
PRESSURE : 0 - 50 PSI
ELECTRICAL : 12 V, 144 OHMS, 1 WATT
VALVES ARE ACTIVATED TO INJECT SF6 INTO ZONES

5.0 CONCLUSIONS

The rationale for the design of the control system to achieve suitably rapid control response, while maintaining accurate values of the tracer gas concentration, in the constant concentration tracer gas measurement system was described. More than one choice of control and concentration averaging is acceptable and modified averaging or least squares methods can be used with the adaptive proportional and proportional integral control methods to achieve the system goals. The need is justified and the actions required for numerous modifications to the commerical SF6 detection system to raise the accuracy of SF6 concentration evaluation of the equipment. The total CCTG system incorporates a recommended control approach, the upgraded SF6 detection unit, individually calibrated micro orifices and subminiature DC valves to meter out the desired quantities of SF6. Finally, the sampling system, using similar valving arrangements, provides the individual zone samples

Figure 10

SAMPLE SYSTEM PUMPING DIAGRAM



to the SF6 detection system and associated data acquisition system operated by a microcomputer. The total system is operating very effectively in both field and laboratory tests, maintaining hourly SF6 concentrations at ± 0.6% with data scatter well within design limits.[17]

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