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MEASURING AIRFLOW RATES WITH PULSE TRACER TECHNIQUES

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ABSTRACT: New tracer gas techniques for measuring airflow rates in HVAC ducts and building airflow systems are described. These pulse tracer techniques are based upon the application of integral mass balance equations to the tracer gas concentration response of an airflow system to pulse injections of tracer. For building airflow systems, or portions of them, the airflow system is first idealized by an appropriate multi-zone model, pulse injections of tracer are applied to each zone independently, and the concentration response of each of the zones is measured. The multi-zone integral mass balance equations are formed and solved to determine the airflow rates between the zones. The airflows that are determined and the accuracy of these determinations are dependent not only upon the air exchange characteristics of the building, but also on the appropriateness of the system idealization employed.

This paper presents the theoretical basis of the pulse techniques for measuring airflows in ducts, and for studying single-zone and multi-zone building airflow systems. Procedures for formulating appropriate multi-zone idealizations of building air flow systems are described and practical details of pulse testing outlined. A series of field studies are reviewed, providing examples of procedures used to formulate system idealizations, experimental techniques employed to conduct the tests, and airflow rate measurement results.

KEY WORDS: air exchange, airflow, infiltration, measurement, multi-zone, tracer gas, ventilation.

Introduction

Indoor air quality and energy use in buildings are both closely related to airflow into, out of, and within a building system. Consequently, indoor air quality and building energy analysis both depend critically upon obtaining complete and detailed information about these airflows. In most cases these airflow rates will be unknown due to uncertainties in envelope infiltration and the performance of the HVAC system, and due to the inherently complex nature of inter-zone airflows. One may attempt to determine these flows using network flow analysis methods [*1*,*2*] or, for existing buildings, using tracer gas measurement techniques. Perera [*3*] and Lagus [*4*] provide comprehensive reviews of existing tracer gas techniques for measuring airflows in buildings. This paper presents an alternative to these existing techniques, the pulse injection tracer techniques.

Tracer gas techniques attempt to determine building airflow rates from the measured tracer concentration response of building airflow systems to carefully controlled injections of tracer gases. Mass balance relations are used to relate measured tracer concentrations to these airflow rates, and tracer techniques can be classified by both the injection strategy employed and the form of the mass balance equations. Three different injection strategies are commonly used: *decay*, in which a suitable amount of tracer gas is injected to establish an initial condition of uniform concentration throughout the space; *constant injection*, in which the injection rate is constant; and *constant concentration*, in which the injection rate is controlled in an attempt to maintain a constant tracer concentration throughout the building system. The mass balance relations may be formulated in either an instantaneous form, which, for the multi-zone case, leads to systems of ordinary differential equations, or an integral form that accounts for tracer mass conservation over a given interval of time. While most researchers have historically tended to use instantaneous mass balance relations in the development of tracer gas techniques, a few have explored integral formulations of concentration response data [5-9].

In principal, a unique tracer technique may be developed for each injection strategy using either instantaneous or integral mass balance formulations. For the three injection strategies outlined above we may consider an array of six basic tracer techniques, as shown in Table 1. Furthermore, it is useful to distinguish single-zone techniques (SZ) from multi-zone techniques (MZ). The tracer techniques based upon instantaneous formulations have been applied with varying degrees of success. The tracer techniques based upon the integral formulations have been largely ignored until recently, and have yet to be studied thoroughly.

Tracer Injection Strategy	Mass Balance Formulation	
	Instantaneous	Integral
• Decay	SZ: yields infiltration MZ: yields all flows	(see Pulse Injection)
• Constant Injection	SZ: yields infiltration** MZ: yields all flows**	SZ: yields infiltration* MZ: yields all flows*
• Constant Concentration	SZ: yields infiltration MZ: yields only infiltration	SZ: yields infiltration* MZ: yields only infiltration*
• Pulse Injection	(see Decay)	SZ: yields infiltration MZ: yields all flows

SZ=single-zone; MZ=multi-zone; *=presently under consideration; **=tends to underestimate

Table 1 Classification of Tracer Techniques

The decay technique may be used to effectively determine infiltration airflows in buildings that behave as a single zone, and is the subject of the ASTM Practice for Measuring Air Leakage Rate by Tracer Dilution Method (E 741-83). It has also been applied to determine the details of infiltration, exfiltration, and zone-to-zone flows in buildings that behave as multi-zone systems. Several multi-zone decay techniques based upon instantaneous formulations have been considered [*3,5,8,10-12*]. Difficulties in measuring the first time derivative of the concentration response have limited the success of some of these approaches. Others appear to result in poorly conditioned systems of mass balance equations. Most multi-zone decay techniques rely on data collected very soon after the tracer gas injection. For this data to be reliable, the tracer gas concentration must be uniform in each of the building zones immediately after the injection. This is a difficult initial condition to achieve, and the accuracy of the results will be degraded by deviations from these assumed initial conditions.

The constant injection technique may be applied to single and multi-zone situations to determine the details of infiltration, exfiltration, and zone-to-zone flows. The constant injection technique based upon an instantaneous formulation tends, however, to significantly underestimate infiltration airflows as commonly implemented (i.e., using average concentrations measured over relatively long time periods as in the so-called Perfluorocarbon Tracer (PFT) method [*13*]) [*14-15*]. An integral formulation of the constant injection technique provides a means to mitigate this shortcoming and is presented in Axley [*16*]. The constant concentration technique is a reliable technique for single and multi-zone situations, providing accurate determinations of outdoor airflow rates into each of the building zones [*17*], but does not provide any information regarding zone-to-zone airflows. It is believed that the integral formulation of the constant concentration technique, presently under consideration by the authors, will provide a means to implement this technique without the need for the careful control that is required in the instantaneous formulation.

In this paper we shall consider the *pulse injection technique* that was presented by Walker as the *decay integral method* [*8*] and further developed by Afonso and his colleagues [*18-20*]. This technique is based upon an injection strategy of separate, short-duration, pulse injections of tracer into each zone of the building system and the application of integral mass balance equations to the reduction of the measured concentration response data. Although decay techniques have employed pulse injections to establish initial concentrations, they have not used data collected during the time interval of the pulse injection to solve for airflows. Nor have they used integral mass balance equations in analyzing the concentration response data. It is for these reasons that we distinguish the pulse injection techniques from traditional decay techniques. This paper will first consider the simplest case, the application of pulse injection techniques to the determination of flows in ducts, then move on to building applications involving both single-zone and multi-zone building idealizations. We then discuss experimental procedures and the results of the application of these techniques to the study of airflows in a large office building.

Duct Pulse Technique

The application of the pulse injection technique to the measurement of airflow rates in ducts provides a straightforward introduction to the pulse techniques. Measuring airflow rates in ductwork in building ventilation systems is difficult using traditional airflow rate measurement techniques (e.g. pitot tubes and hot-wire anemometers), due to insufficient lengths of straight ductwork for the establishment of fully-developed flow profiles. Constant injection tracer gas techniques have been used to measure these airflow rates [*4*], but they require one to wait for equilibrium and to measure very low tracer gas flow rates. The duct pulse technique is a quick and simple alternative for measuring these quantities in even the most complex duct configurations.

Theory

Consider the duct segment illustrated in Figure 1. Air flows into the duct from the left at a time-varying mass flow rate of $w(t)$. We inject a short duration tracer pulse at a rate $G(t)$ into the duct and measure the time variation of tracer concentration $C(t)$ at the exit. Assuming that the tracer injection results in only trace concentrations and, therefore, does not contribute significantly to the air mass flow rate, then the exit air mass flow rate will equal $w(t)$. Furthermore, if the exit concentration measurement is a flow-averaged concentration (e.g., the concentration is well-mixed across the section) then the mass flow rate of tracer exiting the duct will simply be equal to the product of the flow rate and the exit concentration, $w(t)C(t)$, where concentration is expressed in terms of the mass fraction of tracer relative to air. Recognizing that after some time, say t_2, all tracer is purged from the duct, we may account for tracer mass conservation through the use of the following integral mass balance:

$$\int_{t_1}^{t_2} w(t)\, C(t)\, dt = \int_{t_1}^{t_2} G(t)\, dt \quad ; \; w(t) \geq 0 \tag{1}$$

which simply asserts that the tracer mass leaving the duct segment equals the amount injected. t_1 is a point in time before the tracer gas injection.

We may apply the *integral mean value theorem* to the expression on the left, as the concentration variation does not involve a sign change, and simplify to obtain the governing equation for the duct pulse injection tracer technique:

$$w(\xi) = \left[\int_{t_1}^{t_2} C(t)\, dt\right]^{-1} \int_{t_1}^{t_2} G(t)\, dt \quad ; \; t_1 \leq \xi \leq t_2 \tag{2}$$

In words, the air mass flow rate that occurred at some time, ξ, during the time interval (t_1, t_2) is the ratio of the mass of tracer injected to the integral of the concentration response downstream from the injection point. Clearly if the air mass flow rate is constant, the determination will yield this constant value. If the air mass flow rate changes very little during the interval, then $w(\xi)$ will be a good estimate of the average flow rate during that interval.

Experimental Procedures

In applying the duct pulse technique there are several practical experimental considerations. The most important issues are knowing the mass of tracer that is injected and obtaining an accurate determination of the concentration integral. Since one only requires the integral of $G(t)$, the actual injection profile is irrelevant. It is only important to know the injection mass. This mass can be measured before or during the injection, but it is crucial that all of the tracer gas is injected into the duct.

The duct pulse measurement technique requires the determination of the integral of the concentration at the downstream measurement point, not the concentration time history. The determination of this integral relies on more than just accurate measurement of tracer gas concentrations. This integral must be based on a cross-sectional average concentration, or the concentration at the point of measurement must be varying only along the length of the duct, not across the duct cross-section. A multi-point injection across a duct cross-section will assist in achieving a uniform concentration at the concentration measurement point.

Because the concentration response will be relatively short-lived, it will be difficult to determine the concentration integral from numerical integration of real-time concentration measurements unless one's concentration measuring equipment has a high sampling frequency and covers a wide range of measurable concentrations. Therefore, it is advantageous to determine the concentration integral through the measurement of the average tracer gas concentration at the measurement point. This average concentration can be determined by filling an appropriate air sample container, beginning well before the pulse is injected and continuing until the pulse is completely purged from the duct. The concentration integral simply equals the average concentration multiplied by the length of time over which the sample container is filled.

In applying this technique to a particular system there will be some initial uncertainty in the amount of tracer gas that should be injected into the ductwork and in the appropriate length of time for averaging. The primary requirement is that the average concentration in the air sample container is in the accurately measurable range of one's tracer gas concentration measurement equipment. Meeting this requirement depends on choosing an appropriate combination of injection mass and concentration averaging time. In general, there may be some "trial-and-error" in determining these quantities. Since each measurement requires only a few minutes, it is not difficult to find appropriate values for these quantities. An estimate of the airflow rate obtained with a traditional measurement technique, e.g. a pitot tube, can be used to estimate the injection mass and the concentration averaging time. Because the time required to make a measurement is so short, an airflow measurement can be repeated several times, thereby providing an estimate of the repeatability of the results.

Measured Results

Some preliminary applications of the duct pulse technique have been conducted in the HVAC system of an office building. A comparison between the results of these duct pulse measurements and the airflow rates measured by hot-wire traverse is shown in Figure 2. These results lie in three distinct regions, depending on the type of duct that was studied.

In the ducts corresponding to the two lower airflow rates, a premeasured amount of tracer gas (sulfur hexafluoride, SF_6) was injected by hand. Plastic syringes were filled with SF_6, and the gas was injected into a hole in the duct. In the measurements corresponding to the higher airflow rates, the tracer gas was injected through a calibrated flow meter. The injections lasted no more than one minute. In all of these tests,, the concentration integral was based on an average concentration determined by filling an air sample bag with a battery operated pump over a period beginning at least one minute before the injection and lasting several minutes after the injection was complete. The air sample was taken from the duct as far downstream from the injection point as possible in order for the SF_6 to have the opportunity to mix with the air. In these tests, the injection mass and sampling period were varied to examine the sensitivity of the results to these variables, and the measurements were repeatable to within about 5%. The sampling times ranged from 3 to 10 minutes.

The agreement between the duct pulse results and the results of the hot-wire traverses are encouraging given the errors in the hot-wire readings, and uncertainties in the flow profile at the duct walls and the inside area of the duct. A detailed, laboratory study of the duct pulse technique is still necessary to provide a rigorous validation of the technique. The duct pulse technique provides a rapid and convenient means to measure a wide range of airflow rates in ducts. It is, however, based on the assumption that there is no leakage of air into or out of the duct, which in many cases is not true. However, the technique could be used to quantify duct leakage by employing a series of injections and samples at various points along the length of the duct.

Single-Zone Pulse Technique Theory

Consider the single-zone idealization illustrated in figure 3. Air flows into the zone at a mass flow rate of $w(t)$ and is assumed to be instantaneously and uniformly mixed within the zone. A short duration tracer pulse is injected into the zone and the zone concentration response to the pulse, $C(t)$, is measured.

Again we assume that the tracer injection rate is small relative to the air mass flow rate so that the exit air mass flow rate is practically equal to the inlet rate. We may write an instantaneous mass balance relation for this single-zone idealization, with M equal to the mass of air within the zone, as:

$$w(t)C(t) + M\frac{dC(t)}{dt} = G(t) \quad ; \quad w(t) \geq 0 \tag{3}$$

where we have assumed the tracer concentration outside of the zone to be zero. In words, at any instant in time the mass flow rate of tracer out of the zone, $w(t)C(t)$, plus the accumulation of tracer within the zone, $M\, dC/dt$, is equal to the rate of generation (i.e., injection) of the tracer, $G(t)$.

We may also demand that tracer mass be conserved over any arbitrary time interval, say (t_1, t_2), by directly integrating equation (3) over the time interval to obtain;

$$\int_{t_1}^{t_2} w(t)C(t)\, dt + M\,\Delta C = \int_{t_1}^{t_2} G(t)\, dt \tag{4}$$

where $\Delta C \equiv C(t_2) - C(t_1)$. We apply the integral mean value theorem to the first integral and simplify to obtain the governing equation for the single-zone pulse injection tracer technique:

$$w(\xi) = \left[\int_{t_1}^{t_2} C(t)\, dt\right]^{-1} \left[\int_{t_1}^{t_2} G(t)\, dt - M\,\Delta C\right] \quad ; \quad t_1 \leq \xi \leq t_2 \tag{5}$$

For single-zone systems, we may determine the air mass flow rate that occurred at some time, ξ, during the time interval (t_1, t_2) by simply computing the ratio of the mass of tracer injected, corrected by the amount of tracer accumulated $-M\Delta C$, to the integral of the concentration response within the zone. Again, if the air mass flow rate is constant the determination will yield this constant value. If the air mass flow rate changes very little during the time interval, then $w(\xi)$ will be a good estimate of the average flow rate during that interval.

By explicitly accounting for the accumulation of tracer we are able to consider any time interval we desire; we do not require complete purging of the tracer as before. This widens the possible experimental options as discussed below. We may consider a time interval sufficiently long to allow complete purging, or short time intervals that in the limit approach an instant in time, which would in principal provide instantaneous determinations of airflow rates.

Afonso et. al. [*18-19*] report the results of single zone pulse tests conducted in a laboratory test facility in which the airflow rate into the zone was measured with nozzles. Four tests were conducted at four different supply airflow rates into the zone. The measurements of the space air exchange rate were generally repeatable within 3%, and the agreement with the supply airflow rates measured with the nozzles ranged from 10 to 17%. The values calculated from the pulse tests were always less than the measured airflow rates, perhaps due to air leakage from the supply ducts. In these experiments, the room mass M was treated as an unknown and was solved for by evaluating equation (5) both before and after the tracer gas injection.

Multi-Zone Pulse Technique Theory

The development of the theory of the multi-zone pulse technique that follows is presented for the technique as currently proposed and is specific to this case. A more general development of multi-zone tracer gas theory in general, and the pulse technique in particular, is contained in Axley [*16*]. In the multi-zone case, we have to consider systems of equations and, consequently, the solution for airflows involve matrix, rather than scalar, algebraic operations. As a result, the issues of *singularity* and *conditioning* of the resulting equations become a central concern and will largely determine the success or failure of any pulse test.

Consider a multi-zone idealization of a building airflow system, with the air within each zone being instantaneously and uniformly mixed. This idealization consists of n well-mixed building zones and a well-mixed exterior (i.e., outdoor) "zone," with single flow paths linking each of these zone to all others. The exterior zone is designated as zone "0" and the building zones as 1 through n. The mass of air in the exterior zone "0" is considered infinite, and we assume that airflow from zone-to-zone is practically instantaneous. A three-zone example of such an idealization is illustrated in Figure 4.

The dispersal of tracer in this multi-zone idealization may be described by the following instantaneous mass balance equations (see [*21-22*] for complete details):

$$[W]\{C\} + [M]\frac{d\{C\}}{dt} = \{G\} \tag{6}$$

where;

$\{C\}^T = \{C_0, C_1, C_2, \ldots C_n\}$, where C_i is the tracer gas concentration in zone i,

$[M] = \mathrm{diag}\{m_0, m_1, m_2, \ldots m_n\}$, where m_i is the mass of air contained in zone i,

$\{G\}^T = \{G_0, G_1, G_2, \ldots G_n\}$, where G_i is the tracer mass generation rate in zone i,

and [W] is the *system mass transport matrix:*

$$[W] \equiv \begin{bmatrix} \left(\sum_{j=0;\neq 0}^{n} w_{0j}\right) & -w_{10} & \cdots & -w_{n0} \\ -w_{01} & \left(\sum_{j=0;\neq 1}^{n} w_{1j}\right) & \cdots & -w_{n1} \\ \cdots & \cdots & \cdots & \cdots \\ -w_{0n} & -w_{1n} & \cdots & \left(\sum_{j=0;\neq n}^{n} w_{nj}\right) \end{bmatrix} \tag{7}$$

where w_{ij} is the air mass flow rate from zone i to zone j. We admit only positive values for w_{ij}, and it should be noted that the diagonal terms are equal to the total air mass flow rate out of each zone.

The injection and measurement strategy used for the multi-zone pulse injection technique is illustrated in Figure 5 for a three-zone case. We first subject one zone to an individual, short-duration tracer pulse and measure the tracer concentration responses in all zones. A second zone is excited and, again, we measure the response in all zones. The process of excitation and response measurement is continued until all zones have been independently pulsed. These independent zone pulses may be done in series using a single tracer, simultaneously using multiple tracers, or as a series of multiple-tracer pulses.

As in the single-zone case, we require that tracer gas mass is conserved over any arbitrary time interval, say (t_1, t_2), by integrating equation (6). Applying the integral mean value theorem for an injection into zone i yields:

$$\{\int C_0, \ldots \int C_i, \ldots \int C_n\}[\mathbf{W}([\xi])]^T = \{(-m_0 \Delta C_0), \ldots (\int G_i - m_i \Delta C_i), \ldots (-m_n \Delta C_n)\} \tag{8}$$

where we have introduced the short-hand notation:

$$\int C_i \equiv \int_{t_1}^{t_2} C_i \, dt \ ; \ \int G_i \equiv \int_{t_1}^{t_2} G_i \, dt \ ; \ \Delta C_i \equiv C_i(t_2) - C_i(t_1)$$

Here, we must consider a separate unknown time, ξ_{ij}, for each element of the mass transport matrix [W].

The $\int C_i$'s, $\int G_i$'s, ΔC_i's, and ξ_{ij}'s depend on the nature of the measured data and constitute a data set. To distinguish one data set, from all others we use a superscript i as follows:

Integral Data Set i

$$\{\int C_0^i, \int C_1^i, \ldots \int C_n^i\}, \{\Delta C_0^i, \Delta C_1^i, \ldots \Delta C_n^i\}, \int G_i^i, [\xi^i]$$

Since the exterior zone, which will be involved in all building idealizations, can not be excited by tracer injection (due to its practically infinite volume), it must be handled differently. For this zone we use the requirement of the conservation of total air mass flow. This may be realized by recognizing that the mass concentration for air in all zones is unity and unchanging, that is:

$${}^{air}C_i = 1 \quad ; \quad {}^{air}G_i = 0$$

and, thus the integral data set for air alone is:

$$\int {}^{air}C_i = 1\Delta t \quad ; \quad \Delta\, {}^{air}C_i = 0 \quad ; \quad \int {}^{air}G_i = 0$$

Designating this data set as set "0" and substituting these values into equation (8), we obtain the integral mass balance relation corresponding to the conservation of total air mass flow:

$$\{1, 1, \ldots 1\}[W([\xi^0])]^T = \{0, 0, \ldots 0\} \tag{9}$$

The formation of the first term of the right side of equation (8), $-m_0\Delta C_0^i$ $(i \neq 0)$, corresponding to the exterior environment, presents a problem since the mass of air in the exterior zone, m_0, is considered infinite. We derive this term by requiring conservation of tracer mass for each injection, concluding that:

$$m_0\Delta C_0^i = \int G_i^i + \sum_{k=1}^{n} (-m_k \Delta C_k^i) \tag{10}$$

That is to say, the infinitesimal change in tracer concentration in the exterior zone is simply equal to the net generation of tracer in zone i less the net accumulation tracer in all zones of the building.

Based on the n injections into the n zones and data set 0, we obtain n+1 integral data sets. From these data sets n+1 separate, underdetermined systems of algebraic equations may be formed:

$$\begin{aligned}
\{1, 1, \ldots 1\}[W([\xi^0])]^T &= \{0, 0, \ldots 0\} \\
\{0, \int C_1^1, \ldots \int C_n^1\}[W([\xi^1])]^T &= \{(-m_0 \Delta C_0^1), (\int G_1^1 - m_1 \Delta C_1^1), \ldots (-m_n \Delta C_n^1)\} \\
&\cdots \\
\{0, \ldots \int C_i^i, \ldots \int C_n^i\}[W([\xi^i])]^T &= \{(-m_0 \Delta C_0^i), \ldots (\int G_i^i - m_i \Delta C_i^i), \ldots (-m_n \Delta C_n^i)\} \\
&\cdots
\end{aligned} \tag{11}$$

These equations can be assembled into a single determined system of algebraic equations if the following condition is satisfied:

$$[W([\xi^0])] \equiv [W([\xi^1])] \equiv [W([\xi^2])] \equiv \ldots [W([\xi^n])] \equiv [\overline{W}] \tag{12}$$

The resulting system of equations, after substitution of equation (10), is the basis of the multi-zone pulse injection technique:

$$[\int C]\,[\overline{W}]^T = [\int T] \tag{13a}$$

where;

$$[\int C] = \begin{bmatrix} \{1 & 1 & \cdots & 1\,\} \\ \{0 & \int C_1^1 & \cdots & \int C_n^1\,\} \\ & & \vdots & \\ \{0 & \int C_1^i & \cdots & \int C_n^i\,\} \\ & & \vdots & \\ \{0 & \int C_1^n & \cdots & \int C_n^n\,\} \end{bmatrix} \tag{13b}$$

$$[\int T] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ \left(\sum_{k=1}^{n} m_k \Delta C_k^1 - \int G_1^1\right) & \left(\int G_1^1 - m_1 \Delta C_1^1\right) & \cdots & \left(-m_i \Delta C_i^1\right) & \cdots & \left(-m_n \Delta C_n^1\right) \\ \vdots & \vdots & \ddots & \vdots & & \vdots \\ \left(\sum_{k=1}^{n} m_k \Delta C_k^i - \int G_i^i\right) & \left(-m_1 \Delta C_1^i\right) & \cdots & \left(\int G_i^i - m_i \Delta C_i^i\right) & \cdots & \left(-m_n \Delta C_n^i\right) \\ \vdots & \vdots & & \vdots & \ddots & \vdots \\ \left(\sum_{k=1}^{n} m_k \Delta C_k^n - \int G_n^n\right) & \left(-m_1 \Delta C_1^n\right) & \cdots & \left(-m_i \Delta C_i^n\right) & \cdots & \left(\int G_n^n - m_n \Delta C_n^n\right) \end{bmatrix} \tag{13c}$$

It must be emphasized that the formulation of equation (13) depends critically on the algebraic condition imposed by equation (12), i.e., the values of each w_{ij} are essentially the same at each value of ξ_{ij}. In practical situations we expect the system airflow rates to vary with time. If all airflows in the system do not vary greatly over the time period spanning all pulse tests, then this condition will essentially be met. If the variation of these airflows about their mean values is of relatively small amplitude, high frequency, or a combination of the two, then we should expect that the condition of equation (12) will also be met. For these cases the mass transport matrix will correspond to a mean flow condition in the system, thus, we have chosen to use the overbar (i.e., signifying a mean value) notation, $[\overline{W}]$, above.

It is conceivable that other special cases of airflow variation will also satisfy the condition of equation (12), thus, strictly speaking, equation (13) is not limited to the determination of a mean flow condition. From a practical point of view, however, it is best to attempt to determine airflows for a mean flow condition, thus, tracer injection and data collection strategies should be employed that may be completed rapidly. Both the pulse injection strategy and an integral constant injection strategy [*16*] can meet this objective. The use of multiple tracers will enable the test to be completed even more quickly.

It may be shown [*16*] that if the air mass flow rates are steady and the pulse injections are of short duration relative to the integral time intervals, then the integral concentration matrix $[\int \mathbf{C}]$ will be nonsingular. Therefore, the pulse injection technique as proposed will, in principal, lead to equations that may be solved to determine airflow rates (i.e., with infinite precision computation and data sets without error). These equations may, however, be expected to be ill-conditioned (i.e., especially sensitive to data errors) and, therefore, in some cases the flows that result from the solution of these equations may be overwhelmed by error. The use of independent injections (i.e., the pulse injection strategy) in each building zone, for an appropriate multi-zone idealization of the building, will tend to minimize the ill conditioning of the system and provide a near-optimal determination of the air flows for the given idealization. The ill-conditioning will be further minimized by idealizations and injection strategies for which the rows of $[\int \mathbf{C}]$ are characterized by large values of $\int C_i^i$ relative to the rest of the $\int C_i$'s. In those cases where ill-conditioning (i.e., as measured by the condition number of the system of equations, discussed below) remains a problem, the analyst should consider alternative idealizations of the building airflow system.

Solution of the Inverse Analysis Equations and Error Evaluation

Errors in the estimation of airflows by tracer techniques may be attributed to an inappropriate idealization of the building system being investigated, uncertainties introduced via flow variations, and/or error introduced via measurement error. The idealization of a given building airflow system may, to a great extent, determine the success or failure of the application of tracer techniques to the determination of airflows in the building. For example, the idealization of a very well-mixed portion of a building system as a collection of multiple zones will, in itself, result in a poorly conditioned system of inverse equations that will tend to amplify measurement error. Although we attempt to provide some guidance in this paper, the process of system idealization remains an art that requires experience and skill.

In the single-zone case, flow variation can result in very large errors in the estimation of mean airflows [*16*]. It must be expected that even greater errors will result in multi-zone cases due to the numerical phenomena of ill-conditioning that is intrinsically associated with the inverse problems being considered here. It is the primary responsibility of the analyst to attempt to conduct a given tracer test in such a way that the underlying assumptions of the tracer technique are satisfied. With this done, numerical techniques exist to deal with solution errors resulting from measurement error.

Equation (12) must be solved with special care to avoid unnecessary amplification of data errors due to ill-conditioning. Conventional elimination or iterative equation solving techniques may be expected to fail for very ill-conditioned problems and, thus, the analyst is well-advised to employ numerically more stable algorithms. *Singular value decomposition* has become the method of choice for solving ill-conditioned problems and is recommended here [*23*]. (Solution techniques based upon Cramer's Rule are computationally inferior to the elimination and iterative techniques and should not be considered).

Furthermore, as the degree of ill-conditioning that might be associated with any given problem will not, in general, be evident, the analyst is well-advised to not only compute the solution; but also compute and report a measure of the error associated with the solution. D'Ottavio [*24*] and Walker [*8*] have discussed error analysis techniques relating to the solution of both the constant injection technique and the pulse injection technique (Walker's *decay integral method)*, and their results apply here as well. Three error estimation techniques are offered; a) error estimation based upon perturbation analysis of systems of linear equations involving vector and matrix norms, b) error estimation based upon Monte Carlo error analysis, and c) error estimation based upon first order error analysis using Taylor expansions.

The perturbation analysis approach provides an upper-bound error estimation, but is sensitive to the scaling of the inverse equations. D'Ottavio employed *optimal scaling* of the equations, based upon scaling individual equations by the inverse of their row Euclidean norm to provide a (near) minimum of this upper bound error estimation. Central to perturbation analysis of systems of linear equations is the so-called *condition number*, which, in simple terms, provides an upper bound estimate of the ratio of the maximum relative solution error to the maximum relative data error (i.e., an error amplification factor). Thus, reporting the condition number of the integral concentration matrix $[\int C]$ provides one means of characterizing the error associated with the solution of a given problem. In the studies considered below, the solution was achieved using the robust and stable numerical method known as singular value decomposition [*23*]. The condition number of the system is obtained as a by-product of the singular value decomposition.

Application of the Pulse Injection Technique

The pulse injection techniques provide powerful tools for the determination of building airflow rates, however, to realize their potential they must be part of a systematic building investigation. Such an investigation involves a) the qualitative analysis of the building airflow system required to form an idealization of the building airflow system and to plan the experimental procedures, and b) the quantitative tasks of conducting the tests, reducing the data, and analyzing the results. In this section we discuss the investigative approach we have taken, the experimental procedures used to make these airflow rate measurements, and the results of several field applications.

Investigative Approach

The successful application of the pulse injection techniques demands a clear understanding of the building being studied and its airflow systems. Based on this understanding the analyst/experimentalist develops an "idealization" of the building as a series of well-mixed zones and formulates an appropriate pulse injection strategy in order to determine the airflow rates between these zones. Forming this idealization is a crucial step, determining not only the injection and sampling strategies, and consequently the experimental effort and cost, but also affecting the conditioning of the system of mass balance equations and, thereby, the accuracy of results. To the extent possible, the analyst/experimentalist should attempt to formulate an idealization and related injection strategy that will allow testing that satisfies the condition of equation (12) (i.e., practically speaking, to design a test that can be completed in a minimum of time). Thus, in general, simple idealizations will be preferred and multiple tracers may be advantageous.

An idealization of a building airflow system consists of a series of well-mixed zones connected by airflow paths, but need not include every airflow and every zone in the building. In fact, such an all-inclusive model of a building will generally be unmanageably complex from an experimental point of view and involve the determination of more airflow rates than are necessarily of interest. In many cases, several distinct building zones can be considered as a single zone with no degradation in the accuracy of the results if a tracer gas injection strategy can be employed that results in these separate zones having the same integral response to the tracer gas injections. In certain circumstances, a selected subsystem of the building can be investigated, providing useful information without consideration of the rest of the building. In this situation the rest of the building is being combined with the outdoors to form zone 0.

The development of a multi-zone idealization begins with a qualitative analysis of the building layout and the ventilation system equipment and zoning to identify the major zones and system airflow paths of the building. In addition to the air handler zoning and physical layout, the multi-zone idealization can be based on an interest in airflows between particular portions of the building, or other aspects of the building's air exchange performance. In the process of forming an idealization, the existence of unexpected or undesired airflows due to envelope leakage, poor system performance or inadequate separation between zones are investigated. A qualitative airflow diagnosis, using hand-held instrumentation (e.g. anemometers), "smoke-sticks", or tracer gas pulses, can serve to elucidate such building airflow characteristics. For example, exhaust airflows may be verified as such or shown to be not flowing in the expected direction. Specific airflow rates may be shown to be zero, and need not be included in the idealization.

Once the building idealization has been developed, tracer gas injection and air sampling strategies are defined. The injection strategies include the manner in which the tracer will be delivered to each zone, the mass of tracer to be injected and a means for determining this mass, and the timing of the injections into the various zones. The air sampling strategies include the number and location of air sampling points in each zone, and the manner in which they will be sampled. Specific issues regarding injection and sampling are discussed below. Once the data is collected it is converted into the form of equation (13), which is then solved for the unknown airflows and analyzed to provide an evaluation of the error.

Experimental Procedures

In addition to the use of an appropriate multi-zone idealization, a pulse measurement requires careful injection and sampling procedures. To a large degree, these procedures relate to the important assumption that each zone is well-mixed, more specifically, that the value of $\int C_i$ is uniform throughout each zone. The appropriateness of this assumption is increased by injecting the tracer gas as uniformly as possible throughout the zone. The gas can be released directly into the zone itself using a multi-point injection scheme or by moving the injection outlet through the space during the release. Such a "within-the-space" injection can be difficult in a large or complex zone, in which case the gas can instead be injected into the supply air distribution system serving that zone, if one exists. Using the air distribution system to inject the tracer can provide a uniform dispersal of the tracer gas, but one must be sure that all of the gas gets to the space (i.e., the supply ductwork does not leak). In many systems this assumption can not be justified, but, as discussed below, one can still use the supply air system for injection in this situation but not include the injection period in the concentration integral. The injection should last a short period of time relative to the airflow system time constants in order to approach the ideal post-injection conditions of a nonzero tracer gas concentration in the injection zone and zero concentrations in all other zones. Post-injection conditions of this type tend to minimize the ill-conditioning of $[\int \mathbf{C}]$.

As with the duct pulse technique, one only needs the integral of the tracer gas concentration in each zone. This can be determined with real-time monitoring or with an average air sample taken during the integration period. Real-time monitoring must be conducted with consideration given to the sampling frequency of the tracer gas monitor and the transport of air samples from the zones to the monitor. Since the pulse technique employs the assumption that the integral of the concentration response is uniform throughout each zone, the tracer gas concentration must be sampled at several locations in each zone in order to verify this assumption.

The time interval over which the integral is determined need not include the tracer gas injection, nor need it last until the tracer gas concentration goes to zero. If the integral includes the tracer gas injection, then the injection mass must be known precisely and be well dispersed throughout the test space. If the injection period is not included in the integral, then the injection mass need not be known, though it needs to be controlled such that the concentration within the zone is in the measurable range of the tracer gas detector. In this case, $\int G_i$ will equal zero, but the value of $- m_i \Delta C_i^i$ will be large and positive due to the significant tracer gas concentration at $t=t_1$.

The duration of the integration period involves a balance between one's ability to accurately measure low concentrations and one's knowledge of the zone masses m_i. Towards the end of the concentration response, the tracer concentrations will be very low and may be difficult to measure accurately. One can avoid this source of error in the integral by choosing t_2 to be a time when the concentrations are still within a range that can be accurately determined. In this case, the $m_i \Delta C_i$ terms may be significant, and if they are, an accurate knowledge of the m_i will be important. The importance of knowing m_i accurately depends on the relative magnitudes of the $\int G_i$ and $- m_i \Delta C_i$ terms.

In some cases, the concentration response in the injection zone will be very short lived, corresponding to a high air exchange rate. In these cases, one should employ an average concentration to determine the integral. This averaging should begin well before the tracer gas injection, and continue until the concentration within the zone has decreased to essentially zero. One can determine the air exchange rate of a single zone with such an average, but must be certain that the tracer gas concentration is zero at $t=t_2$. If it is not, then an air sample taken at t_2 is needed to compute the $M\Delta C$ term. This approach enables the low-cost determination of single zone air exchange rates with on-site air sampling and off-site tracer gas concentration analysis

Field Tests Using the Pulse Techniques

The integral pulse techniques were applied to two multi-zone idealizations of a fifteen-story office building. This building has four separate air handlers serving the fifteen-story tower section, two for the fourteenth and fifteenth floors, and two more serving floors one through thirteen. These air handlers run on 100% outdoor air and are located in a penthouse mechanical room. The air from the building is exhausted through a relief air system directly to the outdoors, with no provision for the recirculation of return air. On each floor, air from the supply air shafts is forced into an unducted ceiling plenum by booster fans. This supply air enters the occupied space through diffusers in the suspended ceiling as shown in figure 6. Based on an on-site inspection of the building and its systems, it was noted that there were significant amounts of supply air leaking from the pressurized ceiling plenum directly to the relief air shafts, to other service shafts, and presumably through the exterior envelope, without reaching the occupied space below the suspended ceiling. This leakage led to the question of how much of the supply air was actually reaching the occupied space on the floors. In addition, strong airflows were noted in the two stairways in the building, flowing up to the penthouse mechanical room. These airflows and other flows into the penthouse from the building led to the question of what were the airflow rates between the building zones and the penthouse.

Based on the inspection of the building and its systems, two different idealizations of the building were investigated with pulse tests. As shown in figures 7 and 8, one idealization is of the whole building and the second is of an individual floor. In the first idealization, the tower is modeled as three zones, based on the air handler zoning and the observed importance of the penthouse. Zone 1 consists of the penthouse mechanical room, the fourteenth and fifteenth floors are modeled as a single zone – zone 2, and zone 3 includes floors three through thirteen. The lower two floors were left out of zone 3 because they did not respond to the tracer gas injections and were therefore considered part of zone 0. The second idealization models an individual floor as two zones, a supply zone and an occupied zone, and is an example of a building subsystem that enables the investigation of specific aspects of a building's air exchange characteristics. The supply zone includes the supply air distribution system for a floor and the occupied zone includes the space below the suspended ceiling. The supply zone is a conceptualization, not a physical zone contained within well-defined boundaries. Therefore, the mass of the supply zone can not be used in analyzing the data. The first idealization is intended to determine the airflow rates between the main air handling zones, the penthouse and the outdoors. The second idealization is intended to determine how much of the floor's supply air actually reaches the occupied space.

The tower model depicted in figure 7 was investigated using successive pulse injections of sulfur hexafluoride (SF_6) into the penthouse (zone 1), the fourteenth and fifteenth floors (zone 2), and floors three through thirteen (zone 3). A premeasured amount of SF_6 was injected into the penthouse by hand while walking throughout the space over a period of about two minutes. The injections into the other two zones were made by injecting SF_6 into the air handlers serving these zones through flowmeters at a known rate for a known length of time (about one minute). The concentration response to the penthouse pulse was measured every five minutes in the penthouse and on floors 7, 11, 14 and 15. Only two floors in zone 3 were monitored because the zone 3 response to the penthouse injection was minimal and in order to enable more frequent sampling of the short-lived penthouse response. The concentration responses to the zone 2 and 3 pulses were measured every ten minutes in the penthouse, on floors 14 and 15, and on the odd-numbered floors from 3 to 13. The penthouse concentration was based on a mixture of air from two locations in the penthouse. The individual floor concentrations were based on a mixture of air from four locations on each floor. It must be emphasized that the floors in zones 2 and 3 behaved as single well-mixed zones in these tests, i.e., they responded with practically uniform concentration integrals for this particular injection strategy. For other injection strategies, these floors will, in general, behave differently.

Because the penthouse injection was released directly into the zone and because the penthouse concentration response was very short-lived, the tracer gas injection period was included in the concentration integral. Because of leakage in the supply air distribution system serving the building, the injection periods were not included in the integrals of the concentration response to the injections in zones 2 and 3.

The results of one of the tower pulse tests are shown in figure 7. The airflow rates from the outdoors (zone 0) into zones 2 and 3 include intentional outdoor air intake through the air handlers and air infiltration through leaks in the exterior envelope of the building. Due to leaks in the supply air distribution system, not all of the outdoor airflow through the air handlers necessarily reaches the space and therefore only a fraction of the outdoor air intake will contribute to the measured airflow rates from the outdoors to zones 2 and 3. The airflow rate through the air handlers serving zone 2 is about 7 m^3/s, as measured with a duct pulse test, but not all of this supply air gets to the zone due to leaks in the supply air system. The difference between the measured airflow rate from the outdoors to zone 2, 8.5 m^3/s, and the measured airflow rate through the air handlers is a lower limit on the infiltration airflow through leaks in the building envelope into zone 2, i.e., 1.5 m^3/s or about 0.5 air changes per hour. Similarly, the airflow rate through the air handlers serving zone 3 is about 20 m^3/s. Only 18.7 m^3/s of outdoor airflow into zone 3 was measured, and therefore no estimate of the minimum infiltration rate into that zone can be made. The measured airflow rates from the penthouse to zones 2 and 3 were larger than expected, possibly due to airflow down elevator shafts and large openings on the negative pressure side of the air handling systems within the penthouse. Two additional pulse tests were conducted on the idealization in figure 7 and the resultant airflow rates and condition numbers of all three tests are similar. In two of the tests a small negative value was obtained for the airflow rate from zone 2 to zone 3. Inasmuch as negative flows violate the assumption of the underlying theory, we must conclude that these values have resulted from data measurement errors amplified by the ill-conditioning of the system and are probably a manifestation of the data and analysis errors discussed earlier. More specifically, we may, by perturbation analysis, place an upper-bound error estimate on all flows equal to the product of the condition number, the relative data error, and the maximum flow determined. Representative values for these three quantities were 4, 1%, and 20 m^3/s, thus a reasonable upper-bound error estimate would be $\pm$ 0.8 m^3/s, a value on the order of the negative flows obtained.

The floor model depicted in figure 8 was investigated with a pulse test in order to determine the amount of supply air that was bypassing the occupied space of the floor. In this idealization of a floor of this building, zone 0 includes the outdoors and the rest of the building, zone 1 is the supply air distribution system, and zone 2 is the occupied space of the floor. The inclusion of the rest of the building in zone 0 is appropriate because the floors of this building are well separated from each other in terms of airflow. During these tests the SF_6 concentration was measured on the floors above and below the floor being tested, and there was essentially no SF_6 response on the surrounding floors. The injection into zone 1 was made by hand into the supply air ductwork, and the concentration response in this ductwork was determined by filling an air sample container to determine the average concentration. This was essentially a duct pulse test to determine the supply airflow rate to the floor. The concentration response was measured in real-time at four locations in the occupied space (zone 2). The integral of the concentration response to the supply zone injection included the injection period in order to determine the airflow rate in the supply ductwork. The tracer gas was injected directly into zone 2 by hand; a known amount of SF_6 was released while walking through the occupied space. Since there was no backflow from the occupied space into the supply air system there was no need to measure the concentration response in zone 1.

The results for a set of repeated "floor-bypass" tests are presented in figure 8 for the fifth floor of the building. These results are based upon a series of three injections; the supply zone was subject to a single injection and the occupied space was subjected to two separate injections. The test A results were computed using concentration data for the single supply zone injection and the first of the occupied space injections; the test B results were computed using concentration data for the supply zone injection and the second of the occupied space injections. A comparison of these results provides an indication of the uncertainty of the computed flows. Another floor-bypass pulse test was conducted on the fifth floor of the building, and two additional floors were tested twice each. The test results were all comparable, as were the condition numbers. The fraction of supply airflow that bypassed the occupied zone ranged from about one-third to one-half. The airflow rate from zone 0 to zone 2 was generally small and in some cases assumed a small negative value, but again these negative values were not significant relative to estimates of the uncertainty in flow based on perturbation analysis.

Summary and Discussion

The pulse injection tracer techniques provide useful tools for studying building airflow systems. The duct pulse application is a rapid and convenient means of measuring airflows in ventilation system ductwork. The building pulse applications are capable of determining the airflows in multi-zone building systems in relatively short time periods (i.e., on the order of the dominant system time constants), and can be conducted with a single tracer gas. Pulse injection determinations of airflow rates may be expected to be relatively insensitive to variations in airflow rates, and the analysis of data from field studies to date indicate that the multi-zone pulse injection technique may be expected to yield relatively well-conditioned equations. In the multi-zone pulse injection technique, as in all multi-zone tracer gas techniques, the manner in which the building airflow system is idealized as a series of inter-connected zones is pivotal in obtaining a well-conditioned system of equations and, thereby, reasonable estimates of the system airflow rates.

The field tests discussed above have served as preliminary applications of the pulse injection techniques, and the process of planning and conducting the tests and analyzing the data have raised several issues. A primary factor in obtaining accurate test results is minimizing the ill-conditioning of the system of mass balance equations. The degree of ill-conditioning of this system of equations is affected by the appropriateness of the building idealization, the accuracy of the test data, and the analysis of the data to obtain the terms of the $[\int C]$ and $[\int T]$ matrices. As discussed earlier there are two major variables in analyzing the test data, the inclusion of the injection period in the concentration response integrals and the length of the integration intervals. It has already been stated that if the tracer is injected directly into the zone and dispersed in a fairly uniform manner, than the injection can be included in the integration interval. If the tracer is "sent" to the zone via a supply air distribution system, it is best to begin the integration interval after the injection is complete, unless one is absolutely certain that the supply air system does not leak between the injection point and the zone. Including the injection period in the injection interval will generally minimize the ill-conditioning of $[\int C]$ because the value of $\int C$ in the injected zone will generally be larger than $\int C$ in the other zones, as compared to the case in which the injection is not included[1]. Including the injection does require knowledge of the injection mass $\int G$ and that the injection is uniform throughout the zone.

An important assumption in the pulse technique is that all zones are well-mixed, that is, the integral of the tracer gas concentration response within each zone is uniform. Therefore, all of the zones should start out with a uniform concentration profile, and the beginning of the integration interval should be delayed until the injection has mixed sufficiently to realize these conditions. If these initial conditions can not be achieved by a well distributed injection, even if the tracer in injected directly into the zone, then the injection should not be included in the integration interval. If the injection is not included, it is advisable to delay the start of the integration interval so that the tracer gas can mix within each zone. The longer one allows for the tracer gas to mix, the difference between the integral response, $\int C$, in the injected zone and all other zones will decrease, increasing the ill-conditioning of the system of equations.

The data collected in each of the above field tests were analyzed several times, varying the inclusion of the injection period in the integration interval and varying the length of this interval. The airflow rates calculated with these various data sets from the same test were compared. It was found that some of the calculated airflows rates were quite insensitive to which data set of a particular test was used, while others varied significantly for different data sets. For some tests, all of the calculated airflow rates varied by only 5 to 10% as the length of the injection interval and the inclusion of the injection was varied. For other tests, some airflow rates were insensitive to these variations while others were not. Including or not including the injection in the integration interval for zone i generally had a lesser effect on the airflows involving zones other than zone i than on the airflows involving zone i. It is not clear whether these differences in the sensitivity of the data from an individual test is due to the quality of the test data or to some other effect.

The pulse injection techniques are relatively new and there have been only limited applications in the field. Additional study in both the laboratory and the field is needed to more completely examine sources of errors and to better establish experimental procedures for their practical application. Several specific items are proposed for additional study including a laboratory study of the duct pulse technique designed to assess the experimental errors associated with the procedure. A laboratory

[1] Algebraically, having larger values of $\int C$ in the injected zone will insure that the rows of $[\int C]$ will be independent and, thus, $[\int C]$ will be nonsingular while large relative differences between $\int C$ in the injected and the other zones will tend to increase the orthogonality of the rows of $[\int C]$ and, thereby, reduce the ill-conditioning of $[\int C]$.

investigation of the multi-zone technique employing a facility in which inter-zonal airflows could be modulated and measured would enable the verification of the airflow rate determination by the pulse technique and an examination of the errors associated with data analysis and solution of the system of the mass balance equations. Additional field applications of the pulse technique are also appropriate at this time, using experimental procedures that are refined based on the experience discussed above and employing new building idealizations.

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References

[1] Walton, G.N., "Estimating Interroom Contaminant Movements", NBSIR 85-3229, National Bureau of Standards, Gaithersburg, MD, 1985.

[2] Axley, J., "Indoor Air Quality Modeling: Phase II Report", NBSIR 87-3661, National Bureau of Standards, Gaithersburg, MD, 1987.

[3] Perera, M.D.A.E.S., "Review of Techniques for Measuring Ventilation Rates in Multi-Celled Buildings," *Proceedings*, EEC Contractors Meeting on Natural Ventilation, Brussels, September, 1982.

[4] Lagus, P. and Persily, A.K., "A Review of Tracer-Gas Techniques for Measuring Airflows in Buildings," *ASHRAE Transactions*, Vol. 91, Pt. 2, 1985, pp. 1075-1087.

[5] Sinden, F.W., "Multi-Chamber Theory of Air Infiltration," *Building and Environment*, Vol. 13, 1978, pp. 21-28.

[6] Turiel, I. and Rudy, J., "Occupant-Generated CO_2 as an Indicator of Ventilation Rates", LBL-10496, Lawrence Berkeley Laboratory, Berkeley, CA., 1980.

[7] Penman, J.M. and Rashid, A.A.M., "Experimental Determination of Air-flow in a Naturally Ventilated Room Using Metabolic Carbon Dioxide," *Building and Environment*, Vol. 17, No. 4, 1982.

[8] Walker, R.R., "Interpretation and Error Analysis of Multiple-Tracer Gas Measurements to Determine Air Movements in a House," *Proceedings*, 6th Air Infiltration Centre Conference - Ventilation Strategies and Measurement Techniques, Het Meerdal, Park, Netherlands, 1985.

[9] Waters, J.R. and Simons, M.W., "The Evaluation of Contaminant Concentrations and Air Flows in a Multizone Model of a Building", *Building and Environment*, Vol. 22, No. 4, 1987, pp. 305-315.

[10] Dick, J.B., "Experimental Studies in Natural Ventilation of Houses," *Journal of the Institute of Heating and Ventilating Engineers*, December, 1949, pp. 421-466.

[11] I'Anson, S.J., Irwin, C., and Howarth, A.T., "Air Flow Measurement Using Three Tracer Gases," *Building and Environment*, Vol. 12, No. 4, 1982, pp.245-252.

[12] Irwin, C., Edwards, R.E., and Howarth, A.T., "The Measurement of Airflows Using a Rapid Response Tracer Gas Technique," *Building Services Engineering Research and Technology*, Vol. 6, No. 4, 1985, pp. 146-152.

[13] Dietz, R.N., Goodrich, R.W., Cote, E.A., and Wieser, R.F., "Detailed Description and Performance of a Passive Perfluorocarbon Tracer System for Building Ventilation and Air Exchange Measurements", in *Measured Air Leakage of Buildings*, Trechsel, H.R., and Lagus, P.L., Editors, STP 904, American Society for Testing and Materials, Philadelphia, 1986, pp..

[14] Bohac, D., Harrje, D.T., and Horner, G.S., "Field Study Comparisons of Constant Concentration and PFT Infiltration Measurements," *Proceedings*, 8th Air Infiltration and Ventilation Centre Conference - Ventilation Technology Research and Application, Uberlingen, Germany, September, 1987.

[15] Sherman, M.H., "Variation-Induced Bias in Passive Ventilation Measurement," LBL-23088, Lawrence Berkeley Laboratory, Berkeley, CA, 1987.

[16] Axley, J. and Persily, A., "Integral Mass Balances and Pulse Injection Tracer Techniques," *Proceedings*, 9th Air Infiltration and Ventilation Centre Conference, Effective Technology - Research and Application, Novotel Gent, Belgium, September, 1988.

[17] Sandberg, M. and Blomqvist, C., "A Quantitative Estimate of the Accuracy of Tracer Gas Methods for the Determination of the Ventilation Flow Rate in Buildings,", *Building and Environment*, Vol. 20, No. 3, 1985, pp. 139-150.

[18] Afonso, C.F.A., Maldonado, E.A.B., and Skåret, E., "A Single Tracer-gas Method to Characterize Multi-room Air Exchanges," *Energy and Buildings*, Vol. 9, 1986, pp. 273-280.

[19] Afonso, C.F.A., and Maldonado, E.A.B., "A Tracer-Gas Procedure for the Simultaneous Evaluation of Effective Volumes and Multizone Airflows," *Proceedings*, 3rd International Congress on Building Energy Management, Lausanne, Switzerland, September, 1987.

[20] Afonso, C.F.A., Maldonado, E.A.B., and Skåret, E., "Measuring Indoor Air Movement: An Essential Task to Characterize Indoor Air Quality," *Proceedings*, IAQ '86, American Society of Heating Refrigerating and Air-Conditioning Engineers, Atlanta, GA, April, 1986, pp. 592-601.

[21] Axley, J., "Progress Toward a General Analytical Method for Predicting Indoor Air Pollution in Buildings: Indoor Air Quality Modeling: Phase III Report", NBSIR 88-3814, National Bureau of Standards, Gaithersburg, MD, 1988.

[22] Axley, J., "Multi-Zone Dispersal Analysis by Element Assembly", (submitted for publication to *Building and Environment*, May, 1988).

[23] Press, W.H., Flannery, B.P., Teukolsky, S.A., and Vetterling, W.T., Numerical Recipes: The Art of Scientific Computing, Cambridge University Press, Cambridge, 1986.

[24] D'Ottavio, T.W., Senum, G.I., and Dietz, R.N., "Error Analysis Techniques for Perfluorocarbon Tracer Derived Multizone Ventilation Rates," BNL 39867, Brookhaven National Laboratory, Upton, NY, 1987.

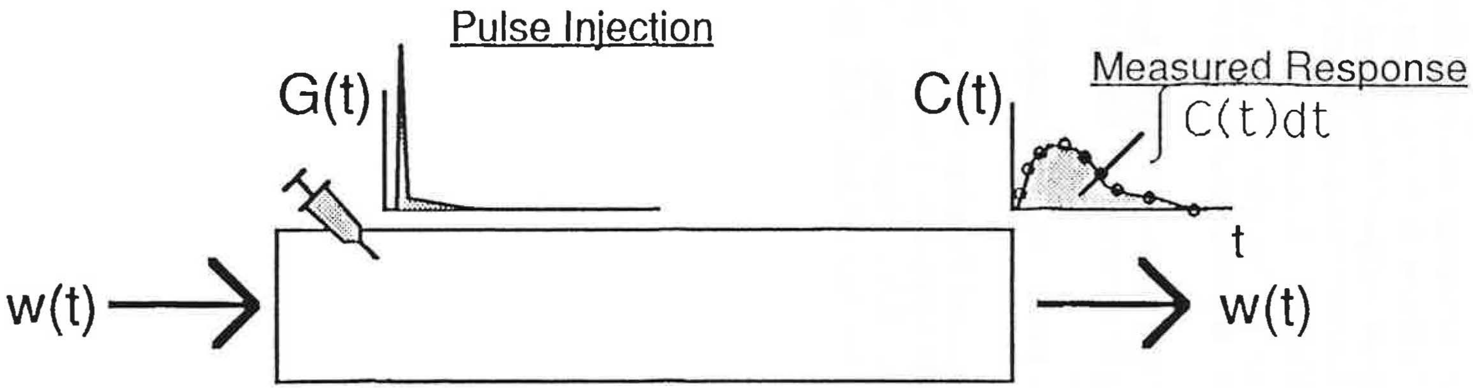


Figure 1 Duct Pulse Injection Technique

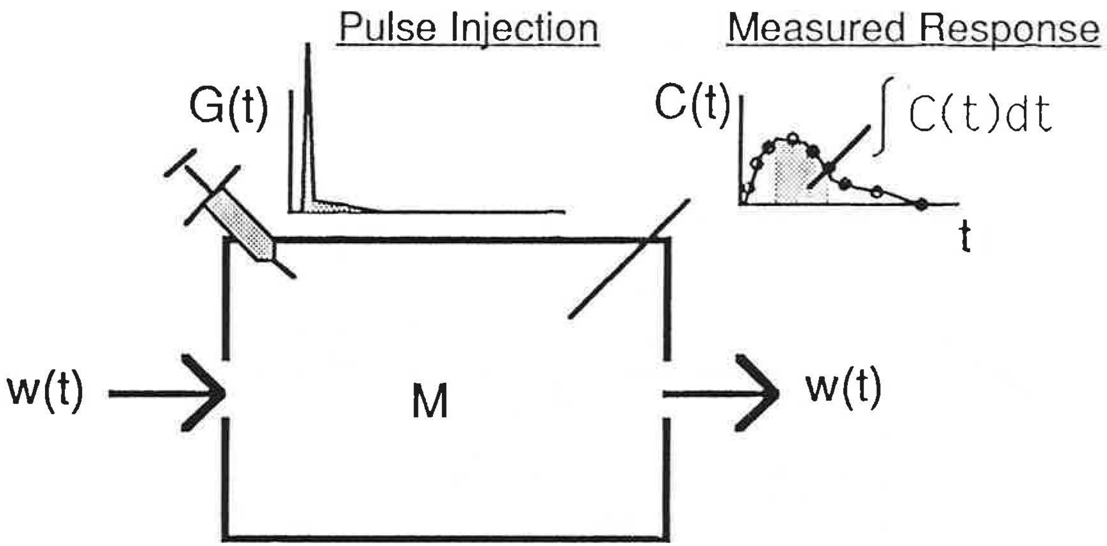


Figure 3 Single Zone Pulse Injection Technique

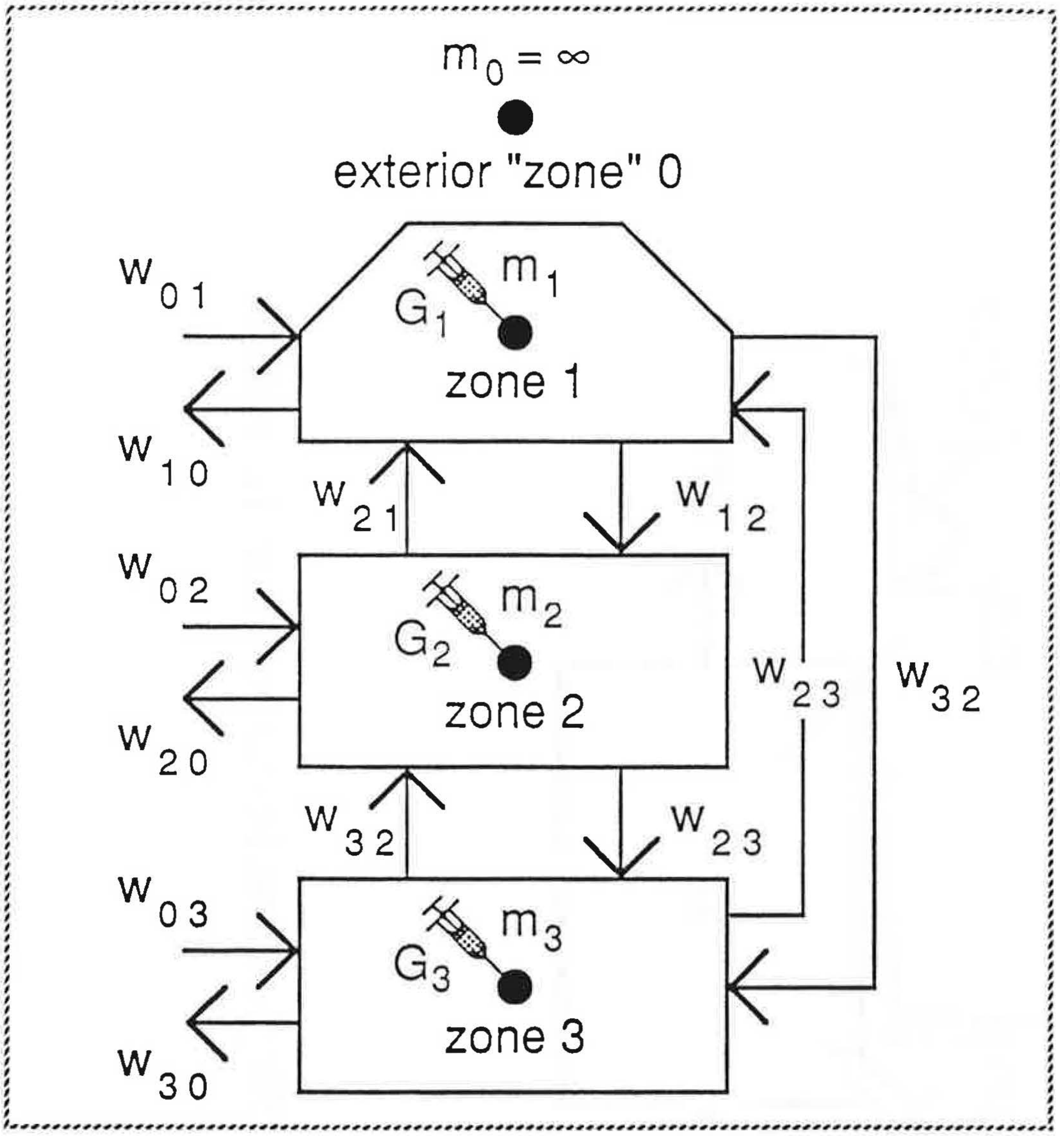


Figure 4 Three-Zone Building Idealization

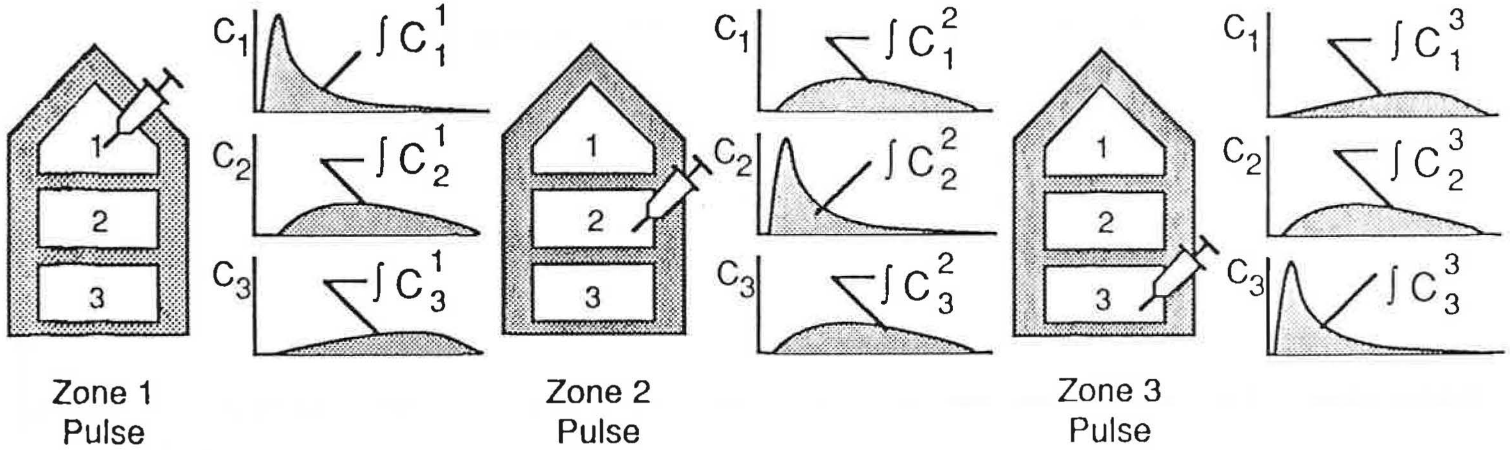


Figure 5 Multi-Zone Pulse Injection Technique

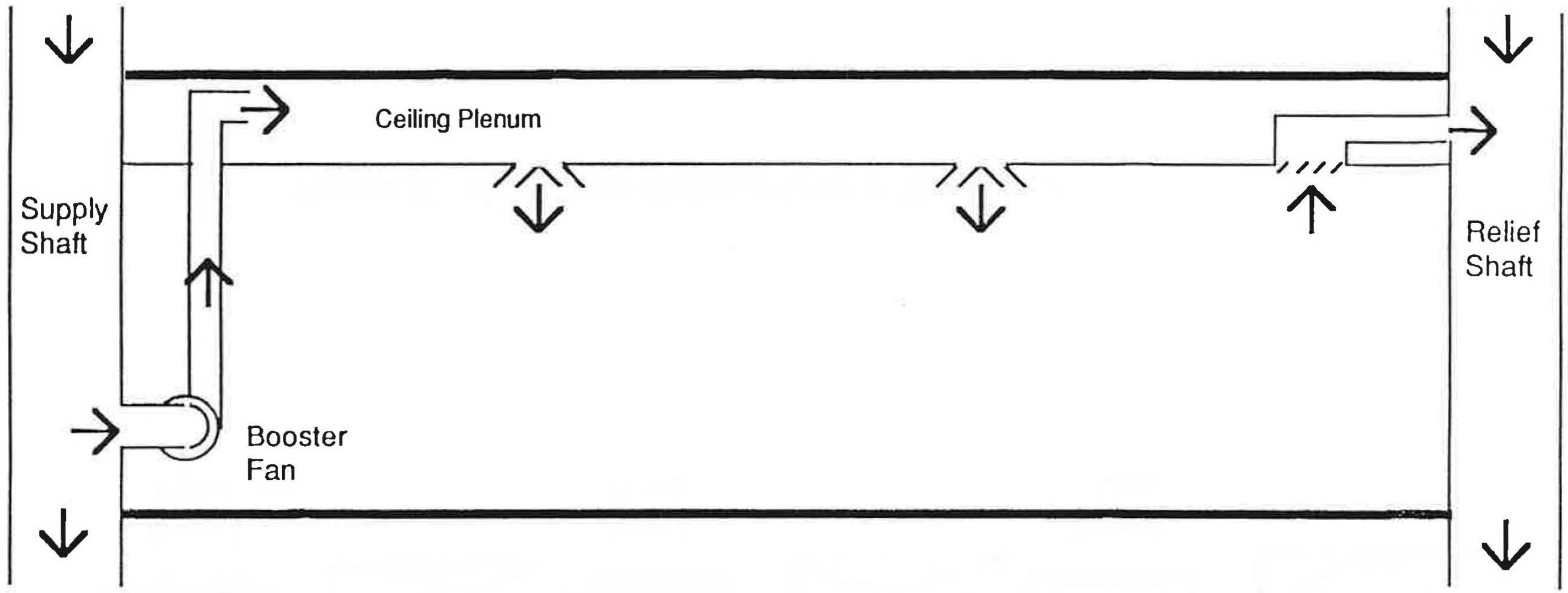


Figure 6   Simplified Section of an Individual Floor of Tower

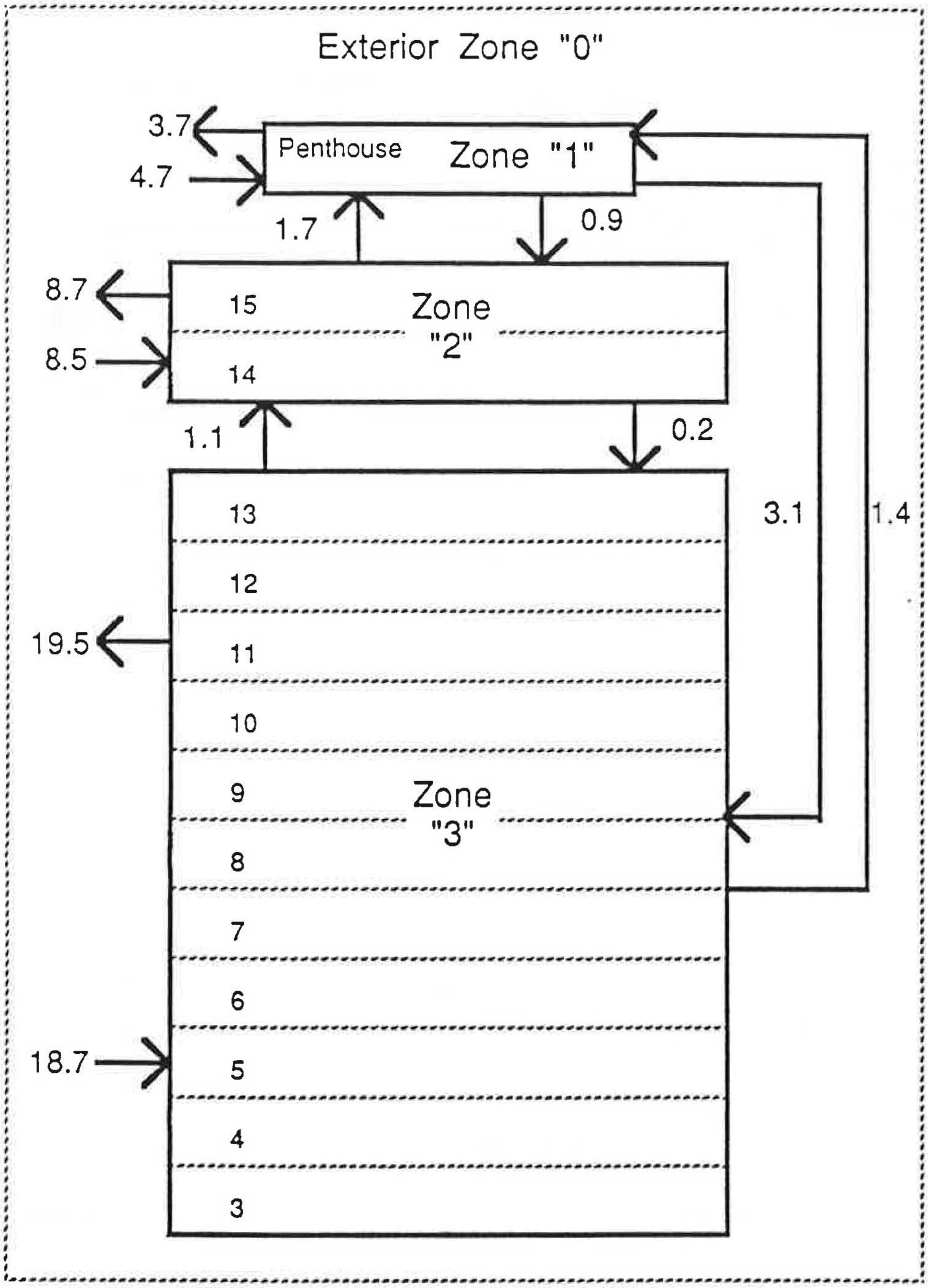
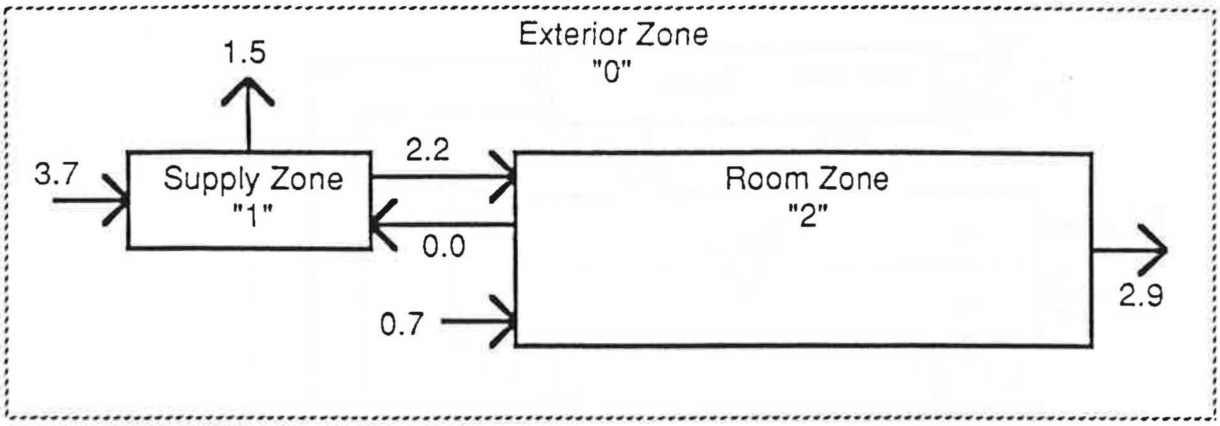
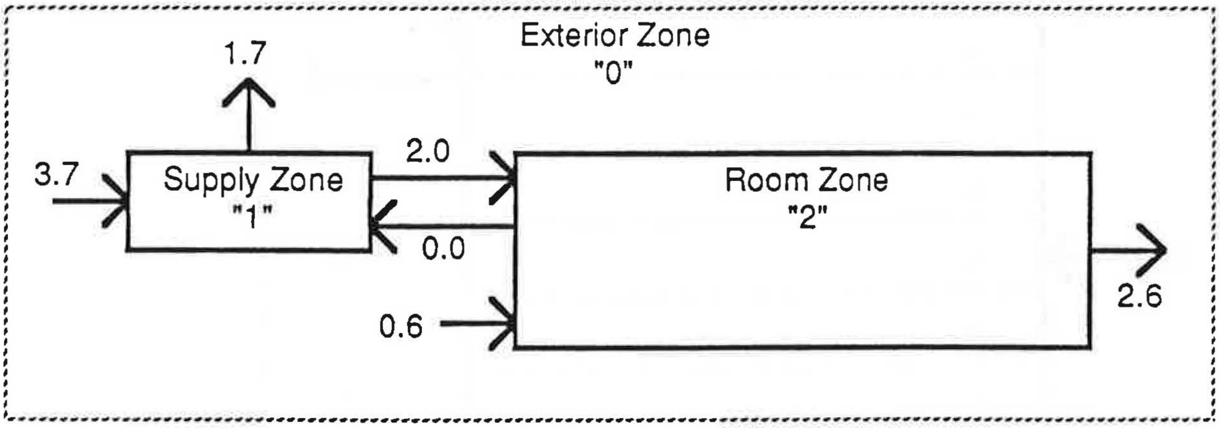


Figure 7 Three-Zone Idealization and Results for 12/1/87
(all flows in m^3/s)



Test A Results

Condition Number = 3.2



Test B Results

Condition Number = 3.4

Figure 8 Floor Idealization and Results for 12/17/87
(all flows in m^3/s)