UNCERTAINTIES IN AIR EXCHANGE USING CONTINUOUS-INJECTION, LONG-TERM SAMPLING TRACER-GAS METHODS

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ABSTRACT

The PerFluorocarbon Tracer (PFT) method is a low-cost method commonly used for measuring air exchange in buildings. This is a specific instance of the more general *Continuous-Injection, Long-Term Sampling (CILTS)* approach for using tracer gasses. The technique is widely used but there has been little work on understanding the uncertainties (both precision and bias) associated with its use, particularly given that it is typically deployed by untrained or lightly trained people to minimize experimental costs. In this article we will conduct a first-principles error analysis to estimate the uncertainties and then compare that analysis to CILTS measurements that were over-sampled, through the use of multiple tracers and emitter and sampler distribution patterns, in three houses. We find that the CILTS method can have an overall uncertainty of 10-15% in ideal circumstances, but that even in highly controlled field experiments done by trained experimenters, one should expect more like 20%. There many realistic field conditions (such as open windows) where CILTS is not likely to provide any quantitative data. Even avoiding the worst situations CILTS should be considered as having a *factor of two* uncertainty for the broad field trials that it is typically used in. We provide guidance on how to deploy CILTS and design the experiment to minimize uncertainties.

1 INTRODUCTION

Building ventilation is the primary process used to insure acceptable indoor air quality by removing pollutants from indoor sources as well as conditioning the air for occupant comfort. In many buildings, ventilation occurs by the uncontrolled leakage of air through the building envelope termed infiltration. Efforts to improve building energy efficiency have focused on reducing infiltration by making homes more airtight. In the absence of designed ventilation, reduced infiltration can lead to elevated concentration of pollutants indoors. However, the use of mechanical ventilation can offset the energy gained thought improved airtightness. Thus, accurate measurement of the ventilation rate, or air exchange rate, is key to assess the energy and air quality impacts of infiltration. Having a reliable estimate of building ventilation can also be necessary to characterize other indoor phenomena, such as the emission rate of contaminants indoors.

The constant injection method involves placing a number of emission sources, whose emission rate is well known or controlled – often using sophisticated mass flow controllers - of one or more tracer gases in a house together with samplers to measure the concentration of the gas over a period of time that can range from hours to days. The time-averaged air exchange rate is determined from the volume of gas tracer emitted into the house and the concentration of that tracer measured by the sampler. Simpler methods utilize a passive technique to obtain relatively constant emission of tracer, such as the evaporation of a liquid through a controlling membrane. This method is often called the "PFT" method because it used PerFluorocarbon Tracer gases. The defining characteristic of this technique is not the tracer gasses themselves but the fact that they use Constant Injection and Long-Term Sampling in the field. We shall refer to this technique with a more generic title of CILTS.

The CILTS method is widely used due to the small size and low cost of the sources and samplers, the flexibility in measurement duration, and because to can be deployed using personnel with limited training. This is particularly important for applications such as field projects that require the measurement of the air exchange rate in large numbers of homes. There is general guidance regarding the number of gas sources that should be placed based on the total area of the space [ASTM E741 2000]; sources and samplers are largely placed in a locations within a home based on the convenience for occupants and engineering judgment.

Due to its widespread use, it is important to have a reasonably good idea of the uncertainties associated with the CILTS method, but limited analyses exist. The factors that affect measurement uncertainty include uncertainties in the tracer emission rate, the measured tracer concentration, the time rate of change in the tracer concentration, and the spatial variability of tracer concentration within the house. Some earlier research investigated some of these uncertainties [Dietz and Cole, 1982; Leaderer et al, 1985], but do not explicitly discuss the implications for the resulting air exchange rate. D'Ottavio et al, 1988, shows how to analyze the data but contains no error analysis. The objective of this work is to estimate the sources and magnitude of errors for a typical single-zone application of CILTS. These uncertainties will be examined thought analysis of field data using a theoretical uncertainty analysis method developed by Sherman (1989). Based on the analysis, recommendations for reducing the errors of using the CILTS method will be listed.

A more extensive version of this article has been submitted for publication.

2 UNCERTAINTIES ESTIMATES FOR THE CILTS METHOD

All tracer gas methods use the continuity equation to calculate the air exchange rate from the measured tracer concentrations and other experimental parameters. The continuity equation for a single zone is as follows:

$$V \times \dot{C} + Q \times C = S \quad \textbf{(1)}$$

where V is the zone volume (m^3), Q is the ventilation rate of the zone (m^3/h), C is the tracer concentration (g/m^3), $\dot{C}$ is the time rate of change of tracer concentration ($g/m^3/h$) and S is the tracer emission rate (g/h). The ventilation rate generally varies as a function of time, which is directly reflected in the term for the time rate of change of tracer concentration. However, the CILTS method results in a single measurement of tracer gas concentration averaged over the time period of the experiment. Therefore, the use of the continuity equation to calculate the air exchange rate measured using the CILTS method requires that sampling time period be sufficiently long that the transient changes in concentration can be neglected. When this is the case, an average air exchange rate, A (1/h) can be determined from the measured tracer emission rate and the measured concentration as follows

$$Q = S / C = A \times V \tag{2}$$

When the emitters are first placed in the building there is an additional transient period during which the tracer reaches equilibrium in the home. It is also important that the tracer sampling period either avoids this initial transient period or that the sampling period is long enough so that this transient period is inconsequential to use Eq. 2 to calculate the air exchange rate.

There are a number of errors to consider when calculating the air exchange rate using Eq. 2 with the CILTS method. The first types are instrumentation errors associated with the measurement of the tracer gas emission rate and concentration. The second type of errors are those arising from the simplified model of the continuity equation used to interpret the data. The subsequent discussion will discuss these different sources of error in detail.

2.1 Instrumentation Error

Instrumentation error encompasses all of the errors in the directly measured quantities of average emission and concentration. The contribution to the uncertainty to the calculated air exchange rate follows from Eq. 2 and can be expressed as:

$$\left(\frac{\delta Q}{Q}\right)^2 = \left(\frac{\delta A}{A}\right)^2 = \left(\frac{\delta S}{S}\right)^2 + \left(\frac{\delta C}{C}\right)^2 \tag{3}$$

There can also be an error term for the uncertainty in the volume of the space, but for this effort, we shall assume that is small.

Estimating the uncertainty of the average tracer emission rate, S, is a straightforward exercise. The total mass emitted is often measured gravimetrically by weighing the emitter before and after the tracer gas sampling period, and the result can be highly accurate. If the emitter is calibrated in the laboratory and an emission curve is used, it may be less accurate. The emission rate may not be constant, but if the changes in the emission rate are not correlated with variations in the air change rate, small variations in time will not affect the results. We will, therefore, consider the tracer emission rate to be constant in time.

The error in the measured tracer gas concentration is due to errors in both sample collection and analysis. The analytical technique used to measure the amount of tracer gas in the sample can have precision errors due to variability in instrument response and bias errors due to imperfect calibration. The errors in sample collection are primarily due to uncertainly in the value of sampling rate and a sampling rate that may not be constant. Both of these errors are of particular important with concentrating samplers (e.g. sorbent tubes) due to potential effects of temperature and potential sample saturation. Non-concentrating sampling techniques such as bag sampling are much less likely to experience non-constant sampling rates. There is a modelling error (discussed later) associated with assuming the concentration is spatially homogeneous at the spatial average, but there is also a measurement error associated with determining the average concentration. This uncertainty can be reduced by using multiple samplers, but the modelling error cannot.

Most experiments using the CILTS technique do not analyse the concentration data in the field, which can result in an additional source of measurement error. Transporting the sample to the laboratory for analysis allows for an opportunity for sample degradation. For instance, some of the sample may be lost in transit or storage through leaks. This is particularly important for concentrating samplers where the concentration measurement is a function of the total collected mass. For non-concentrating samplers, such as units that directly sample room air into a bag, the loss of part of the sample is less important because analysis results directly in a concentration. For concentrated samples any loss will create a negative bias. For all kinds of samples, contamination of the sample in transportation can result in error in either direction.

2.2 Model Errors

Model errors result from the fact that the model one is using to interpret the data is a simplification of reality. This is, of course, intrinsic in any scientific experiment, but it is important to recognize the simplifications that may lead to significant error and to reduce them or at least estimate their impact.

To analyse the data in the CILTS approach it is assumed that the system is in steady-state (i.e. that the concentration has had sufficient time to reach equilibrium that transient effects are unimportant), that the parameters are stationary (i.e. that the air exchange is truly a constant over the measurement period), and that space is a single-zone (i.e. that the concentration is homogenous throughout the space). Each of these assumptions has an intrinsic error that is dependent on the system being measured rather than the instruments measuring that system. We will examine each of these errors individually (i.e. assuming no instrumentation or other model errors contribute) and then combine them assuming they are independent.

2.3 Steady-State

The time dependent continuity equation, Eq. 1, includes the time rate of change of the tracer concentration, thus a complete solution will have include a term that accounts for the initial concentration. The CILTS method assumes that transient changes in concentration can be neglected, and so represents a source of error that depends on the difference between the initial and final concentrations.

$$\left(\frac{\delta Q}{Q}\right)_{steady-state} = \left(\frac{\delta A}{A}\right)_{steady-state} = -\frac{V}{S}\frac{\Delta C}{\Delta t} = -\frac{1}{A\Delta t}\frac{\Delta C}{C} \tag{4}$$

The bias from this error at could be corrected if we knew the initial and final concentration. Since CILTS only measures the average concentration over the sampling period, we cannot correct the result without some prior knowledge of the system. For instance, if we know that the initial concentration was zero, Eq. 4 can be used recursively to correct the CILTS result. However, as previously discussed, successful implementation of the CILTS method requires sufficiently long sampling times that these transient changes in concentration, which should make this error quite small. We shall assume this is the approach taken and that any calculable biases have been taking into account.

2.4 Constant Air Exchange

A sufficiently long sampling period is necessary to allow for the transient changes in concentration to be neglected. The air exchange rate, however, will most likely vary over the sampling period, so the tracer gas concentration will be varying over time. The CILTS method measures the average concentration, but the air exchange rate is inversely related to the concentration. Thus, the CILTS analysis will underestimate air exchange rather than providing in a true average air exchange rate. This effect has been previously investigated (Sherman LBL-23088). If the variation is small, the bias can be corrected for, however, the bias can be intractably large if the variation in air exchange is large - as might be the case for an experiment where windows are opened and closed during the testing or the weather changes significantly. This magnitude is important when the measured average air exchange rate is used for energy calculations. However, some analyses do not use the average air exchange, but rather the effective air exchange as described by Sherman and Wilson (1986). For instance, the effective air exchange is more useful for understanding the dilution of indoor contaminants. The CILTS method does not result in a bias in the effective air exchange rate from variations in tracer gas concentration that occur during the measurement period.

2.5 Homogeneity

The CILTS analysis assumes that the space can be treated as a single zone and that the concentration is the same everywhere in this zone. Incomplete mixing, however, can result in substantial variability in tracer concentration within the zone resulting in a measured concentration that may not be representative of the space as a whole. In addition, the average concentration measured in the zone may not be the representative concentration needed in the CILTS analysis. The continuity equation requires that the representative concentration must be the flow-weighted average concentration of the air flowing from the space to outside.

To investigate the errors due to inhomogeneity, we have broken down the putative single zone into a set of N interacting multizone spaces starting from the derivation of Sherman (1989). The results show that, even if the average concentration could be measured with minimum uncertainty, there would be an error in the calculated average air exchange rate induced from the spatial inhomogeneity as follows:

$$\left(\frac{dQ}{Q}\right)_o^2 = \left(\frac{dA}{A}\right)_o^2 = N\frac{d^2C_o}{C^2} + N\frac{d^2S}{S^2} \tag{5}$$

This is a new term not usually considered in error analysis, but can be combined with other errors in a straightforward manner

3 ERROR ANALYSIS OF CILTS DATA

An intensive investigation of the CILTS method was recently performed in three test homes (Lunden et al, 2012)), which can only be summarized herein. The tests used multiple simultaneous PFTs sampling at high spatial density in multiple configurations to evaluate the precision of the technique and to provide guidance on the best way to deploy it. This data set, hereafter referred to as the "Lunden data", is uniquely able to help us examine the errors that result from the CILTS method using the error analysis presented above. Each test house used four different PFTs with different sample densities and two different sampling methods essentially resulting in four separate experimental measurements of the same air exchange rate. The differences between the experiments serve to identify which factors are most important with regards to experimental uncertainty. In addition, the high spatial density of sampling locations in the experiments – larger than a typical experiment – will help to quantify the spatial variability in tracer concentration.

The experiments were designed to investigate a series of ventilation conditions. These experimental ventilation conditions included no forced air system operation, normal operation of an air conditioner, constant operation of the forced air system fan, and other variations. Estimates of precision and bias errors that are the same for each experiment are as follows:

- Emission source: The PFTs emission sources were the same for all experiments, and consisted of liquid in a glass vial with a septa through which the gas diffused. The vials were placed in dry block heaters to keep the emitters at a constant temperature. The emission rate for each vial was measured gravimetrically on site using a high precision scale, which generally give results on the order of 1% or better. The accuracy of these scales can be hard to assess, but can be assumed to be on the order of 1%. Sources can sometimes undergo more transport and handling that will affect the precision of the measured emission rate, i.e. when sources are shipped to and from experimental locations by mail. For these situations, the precision error may be on the order of 5%.

- Collection and Transport: In the Lunden data, there were large numbers of emitters and, most importantly, samplers. We shall assume that any precision errors due to sample collection will be reflected in any inhomogeneity of the measured concentrations, and will thus only consider bias errors. While there is no evidence of a significant bias in sample collection, for the purposes of this analysis, we shall assume a bias error of 3% and no transportation error.

- Analysis: The tracer gas analyser had a precision error of 5%. This uncertainty reduces as multiple sampler are used to estimate the mean concentration. During the analysis of the tracer gas samples, a significant bias was discovered and corrected, with no residual bias reported. For the purposes of this analysis, we shall assume a bias error of 2%, which is not reduced by multiple samples.

One of the samplers used in the experiment collected time resolved gas samples, resulting in 15 measurements of the tracer gas concentration every 24 hours. While these concentrations were averaged in order to calculate the average ACH over the experimental period, the time resolved results provide a measure of the size of the time varying concentration term. We estimate the magnitude of this variation as the average concentration plus and minus two times the standard deviation of the time resolved measurements. The variation in concentration generally occurs over a 24-hour period. Using these estimates, the magnitude of the time varying term ranges from 3% to 16%. For our experimental homes, the largest values tended to occur when there was no central air handling fan operating. The average value of the time varying term for all conditions with central forced air fan operation was 4%.

Putting this all together (assuming we have many samples), the Lunden study error becomes

$$\left(\frac{dQ}{Q}\right)^2_{effective} = \left(\frac{dA}{A}\right)^2_{effective} = \left(\frac{1}{A\Delta t}\frac{\Delta C}{C}\right)^2 + 0.0034 + N\left(0.0001 + \frac{d^2 C_o}{C^2}\right) \quad \textbf{(6)}$$

If we disregard the time varying term and assume that the space is truly a homogeneous single zone, the air exchange rate resulting from the CILTS method as deployed by Lunden et al (2012) would have an uncertainty of 6%. Assuming a value of 4% for the time varying term increases the uncertainty to 7%. These uncertainty estimates represent the minimum uncertainty in the measured air exchange rate. It is highly unlikely that the tracer gas concentration in a home would ever be truly homogeneous. The extent to which spatial homogeneity contributes to the uncertainty can be assessed for the Lunden data due to the relatively high spatial density of samplers deployed in their experiments.

3.1 House 1

House 1 in the experiments conducted by Lunden et al (2012) is a 93 m^2 single story house with a simple, compact floor plan. Four different PFTs were deployed, each with a different spatial distribution of emitters, and in some cases, samplers. The tracer gases were over-sampled (i.e., using more locations) compared to a typical CILTS measurement to allow a better estimate of the spatial variation. In their report, Lunden et al. (2012) divided the space into 9 zones. Some of the zones are small enough to ignore or sufficiently well coupled to be considered a single zone. As a result, we shall assume 4 zones in our error calculations, recognizing that this may be an under estimate. The air handler in house 1 turns over the air seven times per hour.

In the test in which the central air handler was not run the average air exchange rate from the four tracers was 0.5 ACH with a standard deviation from the different tracer approaches of 13%. The four tracer gasses all showed a spatial variation on the order of 20% (16%-22%). Using Equation 10 to estimate the error we expect an uncertainty of 40%. This value is much larger than the 6 to 7% uncertainty due to all other sources of error and bias, showing that the heterogeneity in the measured tracer concentration dominates the overall uncertainty of the measured air exchange rate. The air change rate measured with this data has an unknown bias, but the standard deviation of 13% between the four tracer gases is well within the 40% estimate of the overall uncertainty.

The average air exchange rate for the experiment with constant central forced air fan operation was 0.87ACH with a standard deviation of 29%. This is higher than with the air handler off likely due to the contribution of duct leakage and with a larger standard deviation between the four tracers. The average spatial variation, 12%, was smaller for this condition, but had a larger range of values. The larger range of spatial variation is largely due to the results from tracer 3, which had only two emitters in the house. Discounting this value, the total uncertainty we would expect in this test is 18% but because of the outlier we see 25%.

Lunden attributes the outlier to the fact that the concentrations analyzed were low and close to the detection threshold for the analyzer. This type of error can happen because of the difficulties of knowing the air exchange rate and therefore the required emission rate as well as the appropriate number and location of emitters and samplers before starting the experiments. This problem is particular to these passive measurements that lack the instant feedback from real time measurements.

3.2 House 2

House 2 was a 325 m^2 ranch style home with a long narrow floor plan. This house had two central forced air systems and with them both operating the air was circulated 4.3 times per hour. The house was divided into 9 zones. Unlike the more compact configuration of house 1, these zones do not combine so easily and 9 may be an under-estimate. In the error calculations, we shall use 9 as the physical number of zones.

During economizer operation, one of the central systems supplied air from outside at the airflow rate used by the central system in normal recirculation mode – in this case about 3 ACH. This is a much higher flow than natural infiltration or most mechanical ventilation. For the three experimental conditions, it appears that the results from the tracer which has only one emitter, has a higher spatial variability than that observed for the other three tracers.

This is similar to the results for house 1, where there was a significantly higher spatial variability for one of the experimental conditions for the tracer with only two emitters.

In normal operation, we see a tracer variation of 15%-28% averaging to 18%. An 18% variation corresponds to an estimate ACH total uncertainty of 55%. The average measured ACH from the 4 tracer gasses is 0.27 ACH with a standard deviation of 10%. Similarly, the concentration variation for the Continuous Fan data is between 12% and 22%, with an average of 15%, leading to an overall estimated uncertainty of 45%, while the measured air change is 0.42 ACH with a standard deviation of %. When the system utilizes an Economizer fan, which operates occasionally, the variation in concentration is between 10% and 25% with an average of 20%, leading to an estimated uncertainty of 60%. The measured air change rate is 0.29 ACH with a standard deviation of 7%.

We note that the standard deviations of our measured values are significantly smaller than our estimated uncertainty. If all one cared about were repeatability this would indicate that our error estimate was too large, but our error estimate includes errors caused by model violations—in particular the fact that the average concentration may not be the same as the exfiltration weighted concentration. An example of this from the House 2 experiments was that a couple of rooms on the windward side had slightly open windows. This resulted in a net flow of air across the house leaving the windward rooms at lower concentrations. These rooms likely had less exfiltration and the samples from these rooms should have been weighted less. Thus we might expect a positive bias in the results, i.e., the experiment overestimated the air change rate.

The increased mixing due to central forced air heating and cooling system air handler operation reduces the variability in concentrations from zone to zone. It also shows increased air exchange - probably due to leaky ducts. The improvement in homogeneity is most noticeable for the experiments that had the fewest number of emitters.

3.3 House 3

House 3 experiments were designed to evaluate the effects of different distributions of emitters. House 3 was a 237 m^2, 3 story, open-plan house. Unlike houses 1 and 2, the tracer gas emitters were placed differently in house 3. Each floor had a unique tracer associated with in order to quite clearly see distribution patterns. In addition, one tracer was evenly distributed. Operation of the air handler fan introduced 3.4 ACH of internal mixing. House 3 was divided into 12 zones within the space spread over 3 floors. Because of the large stack effect in this home, there are generally much larger differences in tracer gas concentration from floor to floor than between most rooms within a single floor. Since the spatial variability is driving by vertical stratification in the house, we shall the three floors as the number of zones.

If we look at the case where the tracer was emitted everywhere the air exchange was 0.26±40% when the air handler was not running and 0.3±29% when the air handler was running. (Based on a concentration inhomogeneity of 23% and 17% respectively.) Since the natural ventilation air change rate was stack dominated for this house we would expect that the single tracer emitted only on the lower floor would give results similar to the tracer emitted everywhere. The air exchange for this single tracer was 0.26±47% with the air handler off and 0.32±9% with the air handler on confirms that this is indeed the case. By contrast if we use the data from the tracer injected only on the upper floor the result is quite different: 1.3±211% with the air handler off and 0.98±124% with the air handler on. The very large positive bias is the result of there being very little third floor tracer on the lower two floors due to the internal stack driven airflow from the lower to upper floors. These results indicate that if sampler locations are poorly chosen the errors are so large that the results are not useable. Again, we have the problem for passive methods that we do not know a priori (or even during the experiment) that these errors are occurring. The best we can do to minimize this problem it to emit and sample tracers on all floors of buildings and in more than one location per floor.

Averaging tests for all four tracers gives an average of 0.56 ACH±156% (based on a 90% concentration inhomogeneity) with the air handler off and 0.48 ± 121% (based on a 70% inhomogeneity) with the air handler on. The vast majority of the differences between the tracer gases is due to the very high air flow rate estimate from the tracer emitted only on the upper floor. This also biases the mean of the four tracers to be much higher than for the tracer emitted everywhere or the tracer emitted on the ground floor.

Additional experiments were performed in house 3 with interior doors closed and a kitchen exhaust on the second floor operating. With no air handler fan, this mode of operation showed the biggest special variation for each tracer with a range of 68% to 196% and a mean of 114% for an estimated error of 197%. The mean of the four tracer gas results was 0.52 ACH. With the air handler fan operating the spatial variation was reduced to a mean of 64% with a range of 19% to 146% (for an error estimate of 111%) and the mean of the four tracer gas results was 0.48 ACH. This result shows that even with the air handler operating it could not overcome the compartmentalization due to closed doors combined with tracers not emitted uniformly throughout the house.

4 RECOMMENDATIONS FOR CILTS APPLICATIONS

CILTS can be an accurate and precise method for determining air exchange when the system being measured matches the model assumptions—in particular that the air exchange and source emission be constant and that the system is in fact a single, isolated, well-mixed zone. Such a situation may occur in the laboratory or field studies with low air exchange rates and high internal mixing (e.g., due to operating a central forced air heating or cooling system air handler).However, CILTS is most used in situations where we know the assumptions are violated to at least some non-trivial degree. The uncertainties associated with these violations can be minimized by careful experimental design and deployment. The recommendations below will reduce the uncertainty of the CILTS result:

- *Emission Rate*: The emitters typically used by CILTS are passive emitters whose rate changes slowly over time, but more importantly is a function of temperature. The emitters should be placed in a temperature controlled environment to keep their emission rate constant during the experiment. The emitters should be calibrated for each experiment or they should be gravimetrically weighed before and after each experiment such that the total amount of emission is determined and no extrapolation of the concentration calibration curve is necessary to analyse the samples.
- *Emitter Deployment*: Emitters should be deployed in proportion to the local ***in***filtration to improve homogeneity. Of course the infiltration is not actually known; so this becomes a judgment by the experimenter. In many instances the best strategy is to deploy them evenly around the perimeter on all floors of the building. In instances where we know the air flow patterns, such as in the winter in a stack-dominated building, we know that the infiltration will predominantly happen in the lower parts of the building; so our emitter deployment should be predominantly in the lower parts of the building
- *Sampler Deployment*: As with the emitters, if we have no a priori knowledge, the samplers should be deployed evenly throughout the building. However if we can predict some of

the air flow patterns in advance the emitters should be placed near areas of ***ex***filtration. For example, if there is a prevailing wind direction, the samplers should preferentially be placed away from the windward side.

- *Sampler Number*: At least four samplers should be used per floor, and more in a large or complex floorplan. We recommend using a sampler for every 25-30 sq. m). An advantage of using multiple samples in addition to improving special averaging is that we can use the results to improve uncertainty estimates based on the standard deviation of the sampler results.
- *Mechanical Mixing*: When additional mixing (e.g. by use of air handler) can be applied it will improve homogeneity and reduce uncertainty. Care must be taken, however, to assure that the mixing does not change the system being measured
- *Experiment Duration*: To avoid issues from initial equilibrium transient effects a good practice is to deploy emitters for 24 hours before sampling begins. If this cannot be done, the integration time for CILTS must be at least 24 hours and preferably longer—especially for low air change rates. The integration time, however, should not be so long that the fundamental flow paths have changed—for example going from a stack dominated to wind dominated pattern. In such a case there will be a bias to the results and the estimate of the uncertainty from the spatial concentration variance will be under estimated.

5 CONCLUSIONS

We have taken oversampled field measurements with multiple gases and sampler/emitter locations and combined them with an error analysis to show that the CILTS method can have an uncertainty of 10-15% under ideal conditions. Ideal conditions include quality calibration of experimental equipment, correct placement of samplers and emitters relative to air flow patterns in the building, and a constant ventilation rate.

Deviations from ideal conditions include several issues related to effective sampling. Overall the most important factor about the system is the degree of mixing. It is not enough to measure the average concentration correctly as spatial inhomogeneities themselves introduce additional uncertainties. The experimental data suggests that even with optimum emitter and sampler placement, CILTS uncertainties of 20-25% should be expected when no special provisions are made for mixing.

When the infiltrating and exfiltrating flows are not evenly distributed around the parts of the building errors increase. The induced errors can, in principle, be mitigated by careful placement of the samplers (near exfiltrating areas) and the emitters (near infiltrating areas). This requires that those patterns persist through the experiment and that the experimenter knows what the pattern is.

Another factor related to persistence is the errors caused by having the air exchange itself vary during the course of the experiment. Variations in the air exchange have a biased effect on the inferred average air change rate independent of the issues of mixing and the need to change the optimal deployment. CILTS measures the effective air exchange not the average air exchange. The effective air exchange is the value relevant for dilution and most IAQ purposes, but not for energy purposes.

In general CILTS is not a very good method for estimating air exchange when there are large intermittent air exchanges going on (e.g., through open windows). In most circumstances it will be practically impossible to deploy samplers and emitters to accommodate this situation and it is unlikely that sufficient mechanical mixing can be supplied to minimize its impact. CILTS is best deployed over a period of time where the weather conditions are stable such that the air exchange is reasonably constant..

The typical use of CILTS is in high-volume or low cost situations where it is deployed by technicians (or even occupants) who are not highly trained in its application. Very often no prior estimate of the air exchange (rate or pattern) has been made. Under these more typical conditions, one might consider CILTS to provide results in the range of a "factor of 2" of the right answer.

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