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April 1997

Presented at the
ASHRAE 1998
Winter Meeting,
San Francisco, CA,
January 17–21, 1998,
and to be published in
ASHRAE Transactions

Submitted for presentation at the ASHRAE 1998 Winter Meeting
and for publication in ASHRAE Transactions

LBNL-40223

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This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098.

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Abstract
A new method for characterizing ventilation in commercial buildings using the Pollutant Concentration Index (PCI) was evaluated via field studies in four buildings. The PCI parameter quantifies the effectiveness of ventilation in controlling air pollutant exposures for pollutants released continuously and spatially uniformly within the building. For the measurements, passive tracer gas sources spaced uniformly per unit floor area, simulated an indoor pollutant. The sources continuously released the tracer gas at a known rate. During the occupied periods of several days, air samples from seated breathing-level locations were collected in gas storage bags. The PCI values were based on the tracer gas concentrations in the sample storage bags and on the indoor tracer gas emission rate. The technique was successfully implemented in buildings ranging in floor area from 129 m^2 to 4475 m^2. Results of these studies indicated that the spacing of tracer gas sources, between 8 and 73 m^2/source, had little effect upon measured values of the PCI. The agreement between PCI values measured simultaneously with two different tracers was usually within 15%. The precision of PCI measurements made with a single tracer gas was approximately 5%. Measured PCI values were referenced to predicted values for buildings that meet minimum ventilation standards. PCI values also indicated the spatial and temporal variability of the effectiveness of ventilation in controlling pollutant exposures.

Introduction

Traditionally, the rate of ventilation in buildings has been characterized by the rate of outside air supply, normalized by either the indoor volume, the floor area, or the number of occupants. Measurements of these ventilation rates in commercial buildings generally serve one of the following purposes: (1) to compare actual ventilation rates to those specified in standards; (2) to determine ventilation rates for use in energy-related calculations; (3) to evaluate the spatial distribution of ventilation within a building. Research on the relationship between ventilation and occupant health in commercial buildings is another, less common, application for ventilation rate measurements.

Existing techniques for determining ventilation rates in commercial buildings include: tracer gas decays or stepups (Fisk and Faulkner 1992, Persily and Dols 1989); measurements of post-occupancy carbon dioxide (CO_2) decay rates (Persily and Dols 1990); measurement of air flow rates (SMACNA 1993); and mass-balance estimates based on measured CO_2 concentrations and estimates of the rates that occupants generate carbon dioxide (Persily and Dols 1990). Although ventilation rates are often temporally variable and long-term average ventilation rates are often desired, none of these measurement techniques provide an average ventilation rate for an extended time period (several days), unless the measurement process is repeated many times. Only the tracer gas decays and CO_2-procedures account properly for air infiltration and exfiltration. The stepup and decay tracer-gas techniques are labor intensive, impractical to implement in many buildings, and require stable ventilation rates (Fisk and Faulkner 1992, Fisk et al. 1993). Direct measurements of air flow rates, for example using flow hoods, pitot tubes, or hot-wire anemometers are labor intensive, often obtrusive and often inaccurate when air velocities are low or the velocity profiles in airstreams are irregular. Also, these direct measurements do not account for air infiltration. Post occupancy CO_2 decays are only applicable when virtually all occupants leave the building within a short period. Estimates of ventilation rate based on CO_2 mass balances are often inaccurate because of uncertainties in both occupancy and the rate of CO_2 emissions by occupants and because indoor CO_2 concentrations usually do not stabilize (Persily and Dols 1990).

A new method has been proposed (Fisk et al. 1993) to characterize ventilation in commercial buildings. This method overcomes many of the drawbacks of the existing techniques described above. The goal is to characterize the effectiveness of ventilation in controlling work-time exposures to a simulated indoor-generated air pollutant, rather than to determine a normalized rate of outside air supply. The method uses continuously-emitting tracer gas sources that simulate an indoor-generated pollutant source (e.g., building materials). The tracer gas sources are uniformly distributed per unit floor area in the occupied space. The air in the occupied space is sampled for about 9 hours per day (during work hours) for 2 to 7 workdays. From the concentrations in the samples and the tracer gas emission rate, the pollutant concentration index (PCI) is computed for each sample location.

To develop the PCI method, many aspects of the measurement process were studied (Fisk et al. 1993). The emission rates of tracers from tracer gas sources were investigated by trying different tracers using various methods for tracer gas release. Sample collection methods were tested as well as the integrity of sample storage. Tracer gas sorption and desorption on typical office furniture was investigated and found to have an insignificant effect on measured values of PCI. Finally, the accuracy and repeatability of measuring tracer gas concentrations was evaluated using a gas chromatograph-mass spectrometer (GC/MS) system and a gas chromatograph-electron capture detector (GC-ECD) system for analyses of samples.

The field test results presented in this paper were the next step in assessing the precision, accuracy, and practicality of the PCI measurement method. Field studies were undertaken in different types and sizes of buildings and in two climates. The results presented here provide information on the precision and accuracy of the PCI measurements in the field, characterize the dependence of measurement precision on the spacing of tracer sources (floor area per tracer source location), and demonstrate the utility of PCI measurements.

The Pollutant Concentration Index

The pollutant concentration index (PCI) is a tracer gas concentration normalized by the indoor tracer gas emission rate and scaled to have a value of 100 in a building with perfectly mixed air and continuous ventilation at the minimum rate specified for offices in ASHRAE Standard 62-1989 [10 l/s-occupant and 7 occupants per 100 m^2] (ASHRAE 1989). The equation for PCI is

$$PCI = \frac{70A_{floor}}{NE_{avg}} C_{avg}$$

where, A_{floor} is the floor area, N is the number of tracer gas sources, E_{avg} is the average emission rate of tracer gas sources during the period of deployment in the space and C_{avg} is the average tracer gas concentration measured during the sampling period. Since the PCI is an effective pollutant concentration, lower values of PCI indicate better ventilation.

Experimental Methods

Establishing Calibration Gas Concentrations
As defined above, the PCI is scaled to equal 100 when the air in a space is perfectly mixed and the ventilation rate is constant at 70 l/sec per 100 m^2 floor area. To calibrate the measurement method, vials of each tracer were placed in duct system with a constant and accurately (~2%) known air flow rate and a constant air temperature. The air flow rate was measured with a calibrated orifice plate flow meter. Fans in the duct system mixed the tracer gases in the air vigorously. The vials were weighed to determine tracer gas emission rates (determined within 5%) and tracer gas concentrations in the airstream were determined from a mass balance equation. Samples were then taken from the airstream and analyzed, yielding measured concentrations that could be compared to the calculated concentrations. Assuming, but not verifying, that the tracers in the vials were pure, the concentrations of the calibration gas standards provided by the manufacturer were validated or adjusted as necessary.

Study Spaces
The study spaces that were used to make the PCI measurements are described below and in Table 2. The spaces varied in size and ventilation type.

Space 1 was the top floor of a four story building. The perimeter of Space 1 contained some private offices and the center is open plan with cubicles. The floor is ventilated by two constant-volume ventilation systems plus a smaller system for a conference room. In the second phase the average percent outside air (%OA) in the supply air was 22% to 36% for one ventilation system and 47% for the other system. One of the larger ventilation systems failed during the first three sample periods. In the first study phase, tracer gas sources were installed about one per cubicle or office, then in the second phase the sources were paired producing one source for every two cubicles or offices. The space had operable windows but occupants were asked to keep them closed during sampling.

Space 2 was a large office trailer having a floor area of 264 m^2 with 15 cubicles and a few private offices. The ventilation system consisted of two heat pump units with economizers that varied the amount of outside air delivery as the outside air temperature varied. In the first study phase, there was one tracer gas source per cubicle or office, in the second phase the sources were placed about one per every two cubicles or offices. The trailer is not well insulated and the temperature was set back on the weekends, so that the temperature dropped to 12°C. Despite this large temperature variation which produced about a 50% change in emission rates for the tracer gas sources, the calculated PCI values for two tracers agreed very well.

Space 3 was a leaky building used as a laboratory/warehouse. The ceiling height was about 4 m high. The packaged constant-volume ventilation system supplied and removed air from a height of approximately 3.5 m. For this study, the economizer was adjusted to supply 100% outside air at all times. All three tracers were used simultaneously for all sample periods in Space 3. To determine measurement precision, vials with two different tracers were placed in the same locations for the first two sample periods. To serve as a reference, vials with one tracer gas remained in the same location for all sampling periods.

Space 4, a floor within a large office building, was the largest space studied with a floor area of 4475 m^2. The space was served by four variable air volume ventilation systems with air supply and removal from ceiling level. During the measurements, the ventilation system operated with minimum outside air supply, estimated to vary between approximately 10% and 20% of the supply air flow rate. While the vials with one tracer gas were not moved for the study, half of the vials of the second tracer gas were removed from the space for the 3rd sample period and paired during the 4th to 6th sample periods.

Tracer gases

In three of the four spaces studied, two tracers were chosen from the following three perfluorocarbon tracers: PDCB (Dodecafluorodimethylcyclobutane, C_6F_{12}), PMCH (perfluoromethylcyclohexane, C_7F_{14}), and mPDCH (perfluoro-1,3-dimethylcyclohexane, C_8F_{16}). The tracers are liquid at room temperature, non-toxic and have been used by researchers at Brookhaven National Laboratory (Dietz and Cote 1982) and in Sweden (Stymne and Eliasson 1991). The tracer gas sources (Figure 1) were made by adding approximately 5 ml of liquid tracer into 4 dram glass vials. The vials were sealed with screw caps with holes. Sandwiched between the vial and cap was a silicon rubber septa about 2 mm thick. The emission rate of the tracer gas from the vials was dependent upon: the temperature, the vial opening diameter, the septa material and thickness, the vial orientation (cap up or down) and the type of tracer. With each tracer, the emission rate at room temperature varied about 4% per degree C. The emission rates were determined from the weight loss of the vials. Before and after each sampling period some or all of the vials were weighed. Before each study, a sufficient number of vials were manufactured to produce a concentration of approximately 1 ppb at the expected ventilation rate in the study space. A few vials are usually discarded because they have atypical emission rates. After discarding such vials, the coefficient of variation in emission rates from sets of vials was about 5%.

Placement of tracer gas source vials

Using holders with magnets, the vials were spaced uniformly per unit floor area at 0.7 to 2 meters above the floor on file cabinets, partitions, and other office furniture. To provide information on the possible influence of specific tracer gas source locations on measured values of PCI, a second set of vials with a different tracer was again installed in a uniform manner but at different locations from the first set. In Space 3, three tracers were used simultaneously with various patterns of tracer gas source installation.

Sampler locations
For most of the studies, air samples were drawn from breathing-level locations and pumped, using small peristaltic pumps, into two-liter multilayer gas storage bags. About ten samplers (Figure 1) were placed in the occupied space with the inlet of the sample tubing located at approximately seated breathing height (1.1 m). Also, in Spaces 1 and 2, one or two samplers collected air from the return/exhaust air duct of the ventilation system. The distance between a sampler and a tracer gas source was maintained greater than 2 m. Samplers had programmable timers which started and stopped the sample pumps. Typically samples were collected from 9:00 to 18:00 on weekdays for two to seven days. This sampling pattern provided a relatively long-term measurement of an occupant's exposure to a simulated indoor pollutant. The samples within the bags were later analyzed using a gas chromatograph with an electron capture detector (GC-ECD) calibrated with ten calibration gases. For the first three sample periods in Space 1, samples were collected on solid sorbents and a gas chromatograph/mass spectrometer system was used to determine tracer gas concentrations. All subsequent measurements were made on the GC-ECD system which simplified the measurement process and increased measurement precision.

Results

PCI Values and their Spatial Variability
Table 1 contains a summary of PCI values for each sampling period. One advantage of the PCI technique is the ability to compare PCI values measured in a building to PCI values predicted for buildings that meet minimum ventilation standards (ASHRAE 1989). Most PCI values shown in Table 1 are less than 100, thus the spaces seem to have ventilation rates that meet or exceed the minimum requirements for offices in ASHRAE Standard 62-1989 (ASHRAE 1989). PCI values in Space 1 approximately doubled when one of two ventilation systems failed. Space 1 and Space 3 are much better ventilated than Space 4.

As currently defined, the reference value of 100 for PCI is strictly valid only if the indoor temperature in the building is constant and the building is an office building. For office buildings with large (e.g., > 5 °C) temporal variations in air temperature (e.g., between day and night), the tracer gas emission rate will vary significantly over time and significantly influence the measured value of PCI. For example, if sampling starts one hour after an instantaneous 5°C increase in temperature in a building with an air exchange rate of 1 hr^{-1}, then the true reference value of PCI should be 105. For buildings other than offices, the reference ventilation rates may differ from 70 l/sec per 100 m^2 floor area and different constants should be used in the PCI equation.

The ratio of the interquartile range (IQR) defined as the difference between the 75th percentile and the 25th percentile of the PCI values to the median of the PCI values is used as a measure of the variability in PCI caused by spatial variability in ventilation rates plus measurement imprecision. This ratio is generally less than 20% (Table 1). Except in Space 1, there was not a large spatial variability in the measured PCI values. The largest value of this ratio is 32%, which occurred in Space 1 during the time that one of the two ventilation systems failed. In the zone normally ventilated by the failed ventilation system, the PCI values were about 50% higher than in the zone with the working ventilation system. In Space 2, the reason for the nearly tripling of PCI values during the second set of measurements is unknown. It was the smallest space studied, thus any change in ventilation, such as an open door or failed ventilation unit, could cause large changes in the overall ventilation rate.

Bias in PCI values

Despite efforts described above to verify or, if needed, correct the calibration gas standards, comparisons of the median values of PCI measured with different tracer gases in the same tests indicated a bias. The following bias in the median PCI values were evident: mPDCH PCI values were always greater than PMCH PCI values by about 5% to 20%; PDCB PCI values were usually greater than PMCH PCI values by 6% to 19%; and PDCB PCI values were always greater than mPDCH PCI values by 7% to 14%. These biases in PCI values from different tracer gases, add to the uncertainty of measuring the true values of the PCI in a space. Thus, if comparisons of PCI values are to be made between two spaces, for maximum accuracy the PCI measurements should be made with the same tracer gas.

Table 1. Summary of measured PCI values in occupied space.

Space	Sample Period	Tracer	Min	25th%	Median	75th%	Max	IQR†/Median	PRE‡
1	7-9 Aug 95	mPDCH	49	56	66	75	80	29%	0.88
		PMCH	42	47	56	60	66	24%	0.89
1	10-11 Aug 95	mPDCH	34	43	56	61	70	32%	0.83
		PMCH	33	37	45	50	60	30%	0.90
1	16-17 Aug 95	mPDCH	38	42	55	59	62	30%	0.87
		PMCH	32	39	46	53	58	29%	0.90
1	11-12 Oct 95	mPDCH	23	27	27	31	34	17%	0.85
		PMCH	19	23	26	28	35	20%	0.85
1	17-19 Oct 95	mPDCH	32	34	37	43	49	24%	0.85
		PMCH	23	27	31	35	38	28%	1.01
1	24-25 Oct 95	mPDCH	24	25	28	29	33	15%	0.90
		PMCH	20	23	28	30	32	24%	1.01
2	11-12 Dec 95	mPDCH	64	67	71	74	77	9%	1.04
		PMCH	55	58	66	74	80	24%	1.02
2	13-14 Dec 95	mPDCH	61	63	69	71	75	11%	1.02
		PMCH	51	53	59	61	79	13%	1.01
2	18-19 Dec 95	mPDCH	169	180	185	192	208	7%	1.04
		PMCH	143	157	167	172	178	9%	1.08
2	20-21 Dec 95	mPDCH	130	137	143	149	161	9%	0.91
		PMCH	128	130	132	141	146	8%	1.04
3	4-10 Jun 96	mPDCH	43	50	53	56	68	11%	na
		PMCH*	41	46	51	53	63	14%	na
		PDCB*	46	50	57	60	85	18%	na
3	11-13 Jun 96	mPDCH	34	36	39	43	48	19%	na
		PMCH*	32	34	37	39	42	11%	na
		PDCB*	39	41	45	48	50	15%	na
3	21-25 Jun 96	mPDCH	36	41	43	45	48	10%	na
		PMCH	37	38	39	44	60	17%	na
		PDCB	37	45	47	48	49	6%	na
3	27-28 Jun 96	mPDCH	41	47	48	51	55	8%	na
		PMCH	40	42	43	53	60	25%	na
		PDCB	46	51	54	56	63	9%	na
4	8-9 Aug 96	PMCH	90	94	103	111	126	17%	na
		PDCB	97	106	115	119	125	12%	na
4	15-16 Aug 96	PMCH	85	96	103	111	118	15%	na
		PDCB	94	104	113	120	122	14%	na
4	22-23 Aug 96	PMCH	94	100	104	110	129	10%	na
		PDCB	92	96	102	107	114	11%	na
4	29-30 Aug 96	PMCH	92	96	103	111	113	15%	na
		PDCB	78	85	98	108	108	23%	na
4	5-6 Sep 96	PMCH	105	111	117	124	133	11%	na
		PDCB	111	118	125	135	140	14%	na
4	12-13 Sep 96	PMCH	159	170	179	191	205	12%	na
		PDCB	111	117	122	128	136	10%	na

* Sources with PMCH and PDCB tracers in same location

† IQR ≡ Interquartile Range = 75th percentile - 25th percentile.

‡ PRE ≡ Return PCI / Median PCI at Breathing Level

Measurement Precision and Influence of Tracer gas Source Spacing on PCI

The values of PCI from two or more tracers were compared in order to quantify measurement precision and to indicate the effects of tracer gas source spacing and specific tracer gas source locations on measured values of PCI. To quantify the differences in PCI values from different tracer gases measured at the same location and time, a PCI absolute percent deviation is computed, defined as follows

$$\text{PCI Absolute Percent Deviation}_{\text{Loc}}^{\text{Tracer}} = \frac{\left|PCI_{Loc}^{Tracer} - \overline{PCI}_{Loc}\right|}{\overline{PCI}_{Loc}} 100\%$$

where PCI_{Loc}^{Tracer} is the PCI value at a measurement location and sample period for one tracer and $\overline{PCI}_{Loc}$ is the average PCI value, over all tracers, at the same location and sample period. All PCI absolute percent deviations for a particular sample period are lumped together and the median, interquartile and maximum are listed in Table 2. For two tracers, the absolute percent deviations for each tracer will be the same at each location and sample period. In Space 3, three tracers were used, thus, in Table 2 the maximum values of all three absolute percent deviations are shown. The maximum absolute percent deviations in PCI values were usually less than 15%, with 35% being the largest for all four spaces.

To determine how much of the absolute percent deviation in PCI values was from measurement errors, i.e., from errors in determining tracer gas emission rates and tracer gas concentrations, measurements were made in Space 3 with the vials for two of the tracers installed in the same locations. Also, duplicate measurements were made from an airstream containing the tracer gases in which the air was well mixed, the flow rate steady and the temperature constant. For the first two sample periods in Space 3, the absolute percent deviation should reflect only measurement errors because differences in PCI values caused by different tracer source locations were eliminated. These measurement errors include a bias between tracers (discussed previously) and some measurement imprecision. If the measurement error consisted only of a constant bias, the PCI absolute percent deviation would be constant; therefore, the interquartile range of the PCI absolute percent deviation is an indicator of the measurement imprecision for measurements with a single tracer gas. For the two sampling periods, for the paired tracer gas sources, the IQR of the absolute percent deviation was 1% (the interquartile data listed in the Table 2 is for three tracers combined). Repeat measurements in a duct with well mixed air produced PCI values that varied about ±5%. Finally, to quantify an upper bound on measurement imprecision of PCI values, the IQR of the absolute percent deviations listed in Table 2 is generally less than 10%. Therefore, field measurements of PCI made with a single tracer gas are quite precise. Differences between two measured PCI values that exceed approximately 5% are more likely than not to be real and not the result of measurement imprecision.

Table 2. Summary of PCI Absolute Percent Deviations for each sampling period.

Space	Sample Period	Floor Area, m^2	1st Tracer locations	2nd Tracer locations	m^2/Tracer locations**	Median % Dev	Interquartile * % Dev	Max % Dev
1	7-9 Aug 95	996	73	73	14	8%	7% - 12%	14%
1	10,11 Aug 95	996	73	73	14	8%	8% - 10%	15%
1	16,17 Aug 95	996	73	73	14	5%	4% - 7%	12%
1	11,12 Oct 95	996	39	38	26	6%	4% - 11%	19%
1	17-19 Oct 95	996	39	38	26	6%	3% - 15%	34%
1	24,25 Oct 95	996	39	38	26	12%	9% - 20%	35%
2	11,12 Dec 95	264	18	18	15	8%	3% - 10%	12%
2	13,14 Dec 95	264	18	18	15	7%	5% - 8%	19%
2	18,19 Dec 95	264	9	9	29	5%	2% - 9%	11%
2	20,21 Dec 95	264	9	9	29	3%	2% - 7%	11%
3	4-10 Jun 96	129	16†	16	8	6%‡	3% - 6%‡	18%‡
3	11-13 Jun 96	129	16†	16	8	8%‡	4% - 10%‡	14%‡
3	21-25 Jun 96	129	8††	16	12	7%‡	4% - 11%‡	16%‡
3	27,28 Jun 96	129	8††	16	12	5%‡	3% - 11%‡	22%‡
4	8,9 Aug 96	4475	95	96	47	5%	3% - 5%	6%
4	15,16 Aug 96	4475	95	96	47	4%	2% - 5%	6%
4	22,23 Aug 96	4475	52	96	60	2%	1% - 5%	15%
4	29,30 Aug 96	4475	26	96	73	3%	2% - 10%	17%
4	5,6 Sep 96	4475	26	96	73	3%	2% - 3%	7%
4	12,13 Sep 96	4475	26	96	73	15%	12% - 18%	25%

* The interquartile is the 25th percentile to the 75th percentile

† Two sets of vials paired in same locations.

†† 16 original locations shared equally by two sets of vials but not paired.

‡ Combined values from three tracers. The IQR of the % deviation for two paired tracers was 1% during 4-10 Jun 96 and 11-13 Jun 96.

** Floor Area/Tracer locations/number of tracers.

Influence of Tracer gas Source Spacing on PCI Values

In each space, the tracer gas source spacing was changed to assess the effect of spacing on the precision of the measured PCI values. The spacing varied from a high of roughly one vial of each tracer per cubicle or office to a low of about one vial of each tracer per 15 cubicles or offices. To determine if tracer source spacing (over the range studied) significantly influenced the precision of PCI measurements, we plotted the IQR of the PCI absolute percent deviation versus the floor area per vial (Figure 2). As the vial spacing was increased there was no appreciable increase in the IQR of the PCI absolute percent deviations. Thus, to use this measurement method for a medium to large commercial building, similar to those used in this study, with non-operable windows and some recirculated supply air, the number of vials that need to be filled, weighed and deployed will be a manageable number. Further field studies are needed to determine the required tracer spacing for buildings with 100% outside air or open windows.

Pollutant Removal Efficiencies

In spaces with imperfect mixing, the ratio of tracer gas concentration in the air removed from the ventilated space to that at the breathing level is a measure of pollutant removal efficiency (PRE) of the ventilation system. A ventilation system is more efficiently removing pollutants if the return/exhaust air concentration is greater than the breathing level concentration. An inefficient short-circuiting of air between ceiling supply diffusers and ceiling-level return/exhaust grills will be reflected by the return/exhaust concentration being less than breathing level concentrations. Table 1 lists the PRE for Spaces 1 and 2, which indicate a slight tendency toward short-circuiting in Space 1. The PRE, measured in this manner, may be a practical substitute for the air change effectiveness (ASHRAE 1996). The air change effectiveness is the most commonly used parameter for characterizing indoor air flow patterns, however, measurements of air change effectiveness are impractical in many buildings (ASHRAE 1996, Fisk et al. 1993, Fisk and Faulkner 1992). In a previous laboratory study (Fisk et al. 1996), there was a very strong correlation between measured values of PRE and simultaneously measured values of air change effectiveness.

Conclusions

The PCI measurement method can be used practically in a broad range of building types including buildings with temporal variations in ventilation rate. Also, the measurement method can characterize the ventilation in a building for an extended period of time, such as a work-week. Thus, the PCI measurement method can be used to characterize a building's ventilation in situations where other measurement techniques are very difficult to implement.

The PCI measurement method provides information on several characteristics of ventilation including: (1) the effectiveness of controlling pollutant exposures in a study building relative to the effectiveness of controlling pollutant exposures in buildings that meet ventilation standards; (2) the spatial variability of pollutant exposure control; (3) the temporal (such as weekly or monthly) variability of pollutant exposure control; (4) the pollutant removal efficiency (a possible practical substitute for air change effectiveness).

The precision of PCI measurements made with a single tracer gas is quite good. Differences between two measured values of PCI that are greater than approximately 5% are more likely than not to be real differences. There is, however, a significant bias, generally less than 15%, between measurements made with different tracer gases, implying significant errors in absolute values of PCI.

In the sealed, mechanically ventilated buildings studied, the PCI values were affected slightly or not at all by tracer source spacing from 8 to 73 m^2 per source. Thus, the number of vials necessary to study a large building is a manageable number.

Acknowledgments

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Systems and Materials Division of the U.S. Department of Energy (DOE) under contract No. DE-AC03-76SF00098. The authors appreciate the comments of Richard Diamond and Charlie Huizenga on a draft of this paper.

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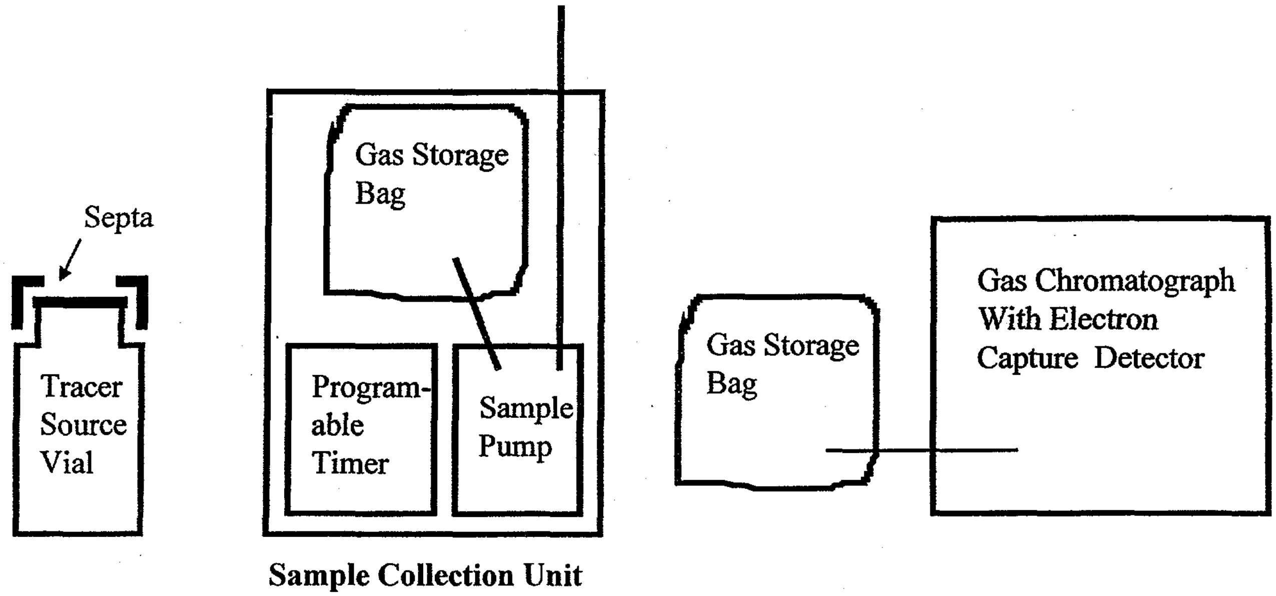

Figure 1. Diagram of experimental system

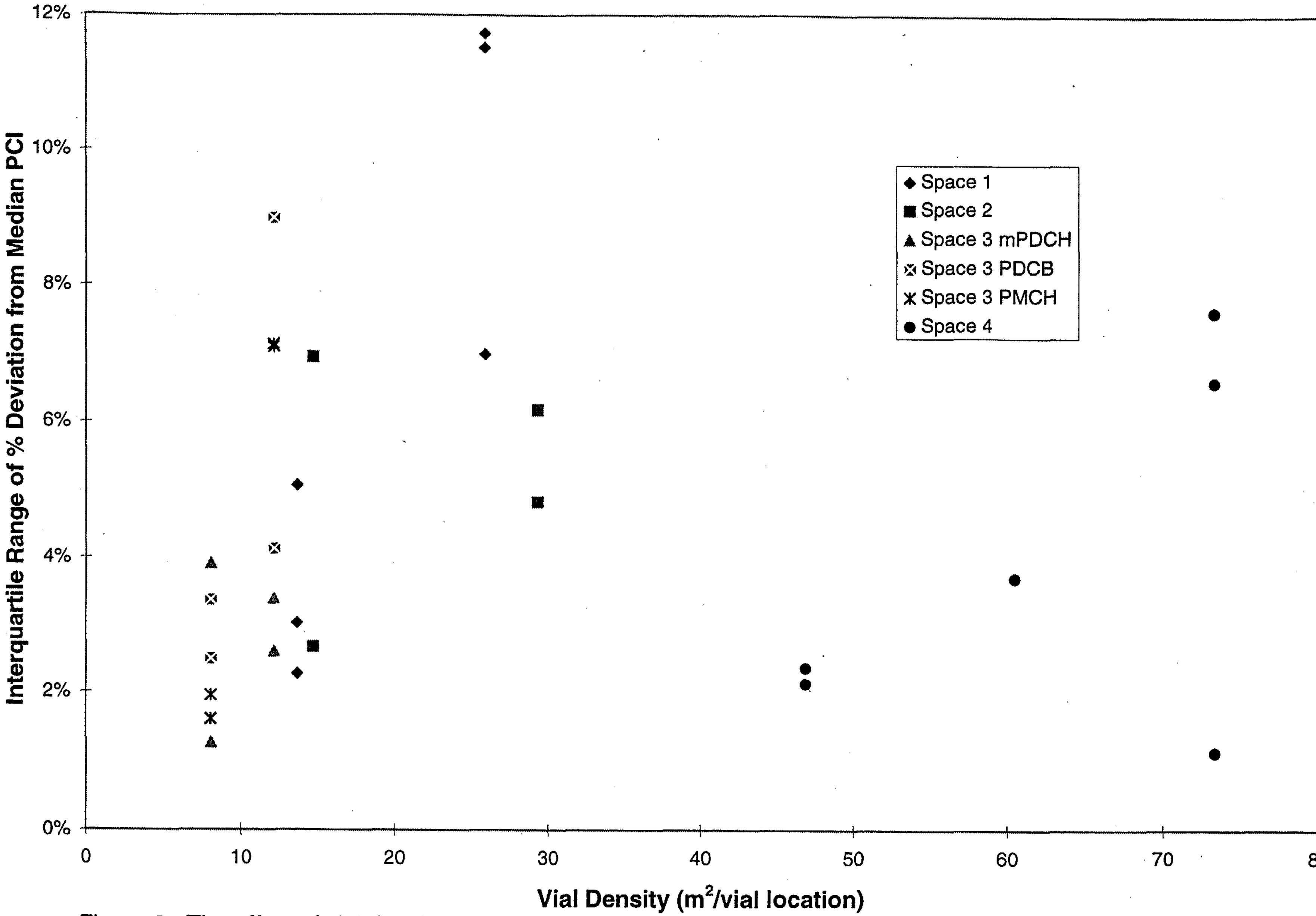

Figure 2. The effect of vial density on the interquartile range of the percent deviation from median PCI by Space.