Development of a Field Test Method to Measure Gaseous Air Cleaner Performance in a Mulitzone Building

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ABSTRACT
The performance of gaseous air cleaners for commercial and residential buildings has typically been evaluated using test protocols developed for a controlled laboratory chamber or a test duct. It is currently unknown whether laboratory measurements reflect the actual performance of an air cleaner installed in a real building. However, to date, there are no air cleaner field test protocols available, thereby limiting the existing field data. The National Institute of Standards and Technology (NIST) has conducted a series of experiments to support test procedure development for evaluating the installed performance of gaseous air cleaning equipment, as well as metrics for characterizing field performance. To date, over 100 experiments have been completed, of which 23 portable air cleaner experiments and 6 in-duct air cleaner experiments are described in this paper. Experimental variables have included air cleaner location, isolation of zones by closing doors, and contaminant source location. For each experiment, air cleaner removal of decane was measured directly using the air cleaner inlet and outlet concentrations, as well as with mass balance analyses using measured room concentrations. The results provide insight into the protocols and metrics that might prove useful for characterizing the field performance of air cleaners as well as the impact of air cleaner removal on zonal concentration levels in a variety of situations.

INTRODUCTION
Gaseous air cleaning devices are being applied and promoted to remove gaseous contaminants from buildings in order to improve indoor air quality and to address some building security concerns.[1-3] However, there are currently no standard test methods to characterize the removal efficiency of such devices as there are for particulate filtration.[4-6] Efforts are underway within the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) to develop such a laboratory test method for sorbent media used in gaseous air cleaners,[7] and the plan is to move on to the development of test standards for measuring the performance of full-scale systems in the laboratory.

While test methods are not yet in place for laboratory performance testing, such tests are relatively straightforward in chamber and ducted installations. Laboratory tests can provide measures of air cleaning removal efficiency under controlled conditions and will serve as the basis for standard methods of test for rating systems and devices, and ultimately for making design decisions and understanding how various parameters impact performance (e.g., temperature, relative humidity, interferents, etc.).[8-10]

However, it is expected that installed performance of these devices may be different from these laboratory determinations. This is expected for a number of reasons: imperfect installation related primarily to air bypass around the sorbent media, "system" effects such as nonuniform airflows into a ducted device, within room and between room concentration nonuniformities, and the presence of other contaminants that might impact removal efficiency. Therefore it is critical to be able to reliably measure installed performance, and ultimately to have standard test methods for doing so, in order to better understand which factors affect installed performance relative to laboratory-determined values.

In order to investigate some of the issues associated with field performance measurements of gaseous air cleaners in residential buildings, NIST has conducted a series of experiments in two test houses. The first phase of this study was completed in a single zone test house where a test method was developed using a continuous source injection and mass balance model at steady-state conditions to determine removal rates of a portable gaseous air cleaner and an in-duct device.[11] Results from this first phase of the study also revealed important factors affecting field performance such as air cleaner contaminant loading and room air mixing.

The next phase of the study, and focus of this paper, is the extension of the single zone test method to a three-bedroom test house. The objectives of these tests include: 1) development and demonstration of protocols for field measurements in realistic buildings; 2) investigation of metrics for characterizing installed performance; and 3) assessment of these metrics by conducting tests under both "ideal" and less-than-ideal circumstances.

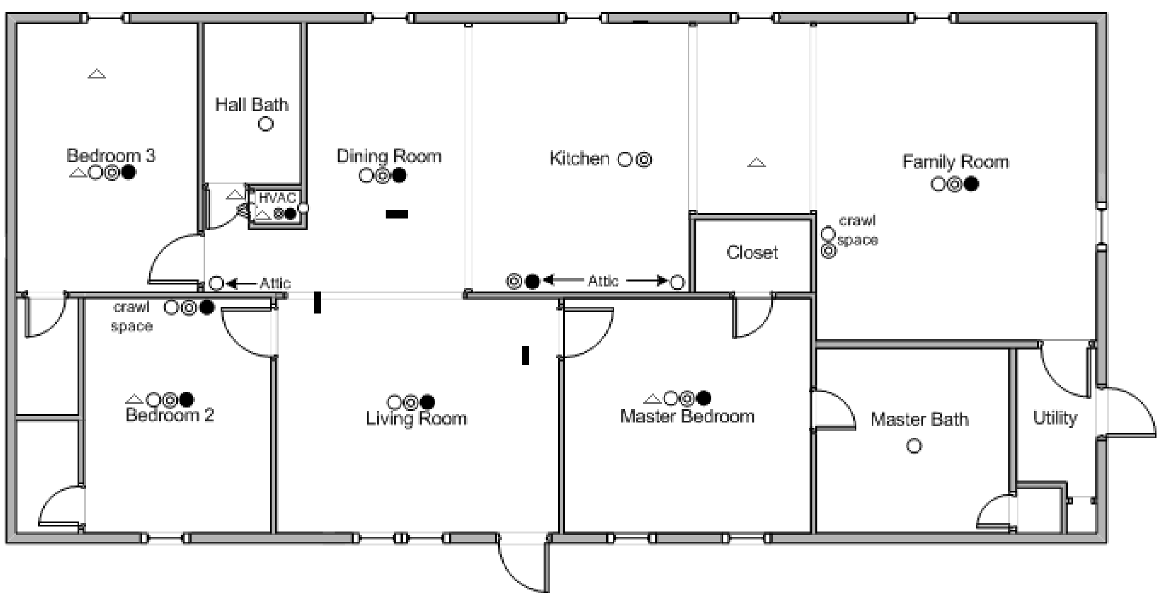
EXPERIMENTAL METHODOLOGY

The air cleaner experiments for this study were conducted in a double-wide manufactured home installed on the NIST campus in Gaithersburg, MD. A complete description of this house and its heating, cooling and ventilation systems is provided in Persily et al.[12] The conditioned space of the test house consists of three bedrooms with closets, two bathrooms, a utility room, and a contiguous living room, dining room, kitchen and family room (see floor plan in Figure 1). The house has a floor area of 140 m^2 and a volume of 340 m^3, with a cathedral ceiling over its full length that is 2.7 m high at the center and slopes down to 2.1 m at the front and back walls. The house has a heating, ventilating and air-conditioning (HVAC) system with a 22 kW gas furnace, a 15 kW air conditioner, and a forced air re-circulation fan with a design airflow rate of 500 L/s. For the air cleaner tests described here, the forced-air fan was either off or in recirculation mode with no outdoor air intake.

The whole house air change rates were measured using the tracer gas decay technique as described in ASTM test method E-741.[13] Sulfur hexafluoride (SF_6) was released into the house every 6 h and mixed for 10 min until a uniform concentration throughout the house (generally within ± 10 %) was achieved. After reaching a uniform concentration, the SF_6 concentration decay was monitored every 10 min in several locations (see Figure 1) using a gas chromatograph equipped with an electron capture detector (ECD). The ECD is capable of measuring SF_6 concentrations over a range of 0.018 mg/m^3 to 1.8 mg/m^3 with an uncertainty of about ± 5 % of the reading. The analyzer was calibrated weekly over this range with certified SF_6 calibration gas standards. The rate of decay of the logarithm of SF_6 concentration is equal to the air change rate of the house during the measurement period in units of air changes per hour (h^{-1}), and these rates are associated with a measurement uncertainty of ± 20 %.

Indoor and outdoor environmental conditions were monitored continuously during the air cleaner tests. Indoor and outdoor temperatures were measured with epoxy coated polymer thermistors (accuracy of approximately ± 0.4 °C) every 100 ms, with an average value recorded every minute. The house's thermostat was maintained at 21 °C resulting in a relatively constant indoor temperature for every test (see Table 1). The average relative humidity (RH) was also recorded every minute using bulk capacitive thin film polymer sensors with an accuracy of ± 2 % RH. Relative humidity did not vary significantly during tests but did vary between tests as shown in Table 1. However, earlier experiments did not show a significant impact of temperature or relative humidity in this range on portable air cleaner performance.[11]

Figure 1: Sample Locations of Manufactured House



○ = tracer gas concentration   ◎ = temperature

● = relative humidity   ▌ = mixing fan

Δ = decane sampling point

To remain consistent with the first phase of testing, decane was used as the test contaminant in this second phase of air cleaner tests. A more comprehensive test protocol would presumably include a wider range of contaminants to evaluate air cleaner performance. Decane was generated using a refillable permeation tube in the heated oven of a gas generator and injected into the test house at an average rate of 34 mg/h (± 2 %), which corresponded to a steady-state concentration in the test house ranging from 0.1 mg/m^3 to 10 mg/m^3, depending on air change rate and test conditions. To ensure complete distribution throughout the house for those tests where a uniform concentration was desired, decane was injected in the supply side of the HVAC fan. For tests where multizone effects were being examined, decane was injected into Bedroom #3. Decane concentrations were measured every 30 min using portable gas chromatographs equipped with flame ionization detectors (GC/FID). Samples were collected from four locations onto an inline sorbent sample tube for 10 min at an airflow rate of 0.006 m^3/h through polytetrafluoroethylene (PTFE) tubing. After collection the sample was ballistically desorbed directly onto the GC column for analysis over the next 20 min. The GC/FIDs were calibrated once per month with an uncertainty of ± 5 %. The measurement locations are shown in Figure 1 and included each of the bedrooms, between the kitchen and family room, and upstream and downstream of the air cleaner. The contaminant measurements in these sample locations accounted for about 93 % of the test house volume, with the remainder in assorted utility closets and other spaces.

Two types of air cleaners were tested: an in-duct model (DUCT) that was installed in the HVAC system return and a portable air cleaner (PAC) that was placed in different locations in the house. Based on earlier tests looking at air cleaner media capacity as a function of contaminant loading,[11] either new air cleaner media for the PAC or a new air cleaner for the DUCT cleaner was used for every test. As a result, this study only examines the initial capability of each air cleaner and long term performance will be addressed in a later study. The DUCT air cleaner media consisted of a pleated fiber matrix containing approximately 0.75 kg of activated carbon, alumina, and potassium permanganate in a 30.5 cm x 61.0 cm x 10.2 cm filter housing. The overall effective cleaning rate for this type of air cleaner is also dependent on the airflow rate through it, which was measured as 1380 m^3/h (± 7 %) using a differential pressure grid.

The portable air cleaner consisted of an inner sorbent cartridge with 500 g of carbon, potassium permanganate, and zeolite (CPZ). The air cleaner filtering system also included a high-efficiency particulate air (HEPA) filter, an activated carbon pre-filter, and an outer protective screen upstream of the CPZ filter. The air cleaner airflow rate was measured using a plastic shroud to enclose the device, and then performing a velocity traverse with a hot wire anemometer of a duct exiting the shroud. The maximum airflow setting corresponded to an average flow rate of 340 m^3/h with an uncertainty of ± 20 %. Additional measurements were made to determine whether the existence of any backpressure within the shroud impacted the airflow through the air cleaner, and no significant impact was found.

Field Test Protocol

The development of a field test protocol to evaluate the performance of gaseous air cleaners in a real building has involved over 100 field experiments to date. Earlier phases of this air cleaner work have focused on the use of a single zone two-phase mass balance model to evaluate the performance of an air cleaner in a one room test house.[11] For the earlier study, semi-real time volatile organic compound (VOC) concentrations were measured in the house along with the house air change rate and VOC source emission rate. These values were used in the following steady-state mass balance solution to estimate air cleaner removal:

Equation 1. Steady-state mass balance solution to estimate air cleaner removal.

$$\eta_{mb} Q_{ac} = \frac{G + Q(C_{out} - C)}{C}$$

where:

C = decane concentration indoors (mg/m^3)
G = VOC source emission rate (mg/h)
Q = outdoor ventilation rate (m^3/h)
C_{out} = decane concentration outdoors (mg/m^3)
η_{mb} = effective single pass removal efficiency of the installed air cleaner (-)
Q_{ac} = airflow rate recirculated through the air cleaner (m^3/h)

This approach compared the air cleaner's removal efficiency determined by the mass balance model to the air cleaner's single pass removal efficiency measured directly by comparing the upstream and downstream contaminant concentrations:

Equation 2. Air cleaner single pass removal efficiency.

$$\eta_{dir} = 1 - \frac{C_{down}}{C_{up}}$$

where:

η_{dir} = single pass removal efficiency of the device measured directly (-)
C_{down} = VOC concentration downstream of air cleaner (mg/m^3)
C_{up} = VOC concentration upstream of air cleaner (mg/m^3)

A multi-stage test protocol used in the earlier phase study provided the basis for the approach developed for measuring the performance of an air cleaner in a multizone building. In the first stage, a test contaminant (decane) is continuously injected into the house at a constant rate until a quasi steady-state concentration is achieved. For the test house, steady-state, defined as a concentration difference less than 5 % over at least a 2 h period, was typically achieved after 24 h of decane injection. Since there are sorptive surfaces (e.g., carpet, sheet flooring, wall covering, curtains, etc.) in the test house, contaminant adsorption and desorption affect the measured test house air concentrations. However, allowing the house to reach an equilibrium condition effectively eliminates the impact of sinks on the measured decane air concentrations.

The next stage adds the operation of the air cleaner and continues the decane injection. This stage is conducted until the decane concentration in the house is once again uniform and relatively constant, which typically occurred after another 24 h (48 h from the start of the test). For several tests, the air cleaner was operated from the beginning of the test, thereby combining Stages 1 and 2 for the first 48 h of testing. For tests with separate Stages 1 and 2, it is possible to compare the Stage 1 steady-state concentrations to the Stage 2 steady-state concentrations to characterize an air cleaner's effectiveness:[14]

Equation 3. Air cleaner effectiveness.

$$\varepsilon = 1 - \frac{C_{ctrl}}{C_{ref}}$$

where:

ε = air cleaner effectiveness, the fractional reduction in pollutant concentration that results from use of an air cleaner
C_{ctrl} = steady-state concentration of decane with an air cleaner operating (mg/m^3)
C_{ref} = steady-state concentration of VOC without air cleaner operating (mg/m^3)

At the end of this stage, the single pass removal efficiency of the air cleaner was also measured directly by comparing the air cleaner's upstream and downstream concentrations for at least two hours (see Equation 2).
In the final stage of testing, the decane source is removed but the air cleaner continues to operate to allow for examination of the decay of decane concentration. This stage continues until a background concentration level is achieved.

This field test protocol was first applied to the multizone test house to replicate the uniform concentration experiments completed in the one room test house.[11] The objective of these tests was to determine the ability to match an air cleaner removal efficiency determined from the single zone mass balance model to the single pass removal efficiency measured directly. To achieve a uniform concentration of decane throughout the house, the HVAC fan was operated continuously, three mixing fans were used, and the decane was injected into the return side of the HVAC system for even distribution to the house. Sulfur hexafluoride concentrations and decane concentrations measured in different locations in the house verified a uniform concentration condition. A summary of the test conditions is provided in Table 1.

Under ideal conditions of complete mixing and perfect air cleaner installation, the directly measured removal efficiency (Equation 2) should equal the removal efficiency based on the mass balance approach (Equation 1). A deviation between the two values is an indicator that non-ideal conditions exist (e.g., multizone conditions, improper air cleaner installation, short-circuiting, etc.) and the single zone mass balance model is not valid. It should be noted that achieving a single zone condition in a multizone building is not necessarily easy to do.[15-16] In fact, in many cases, it is not appropriate to apply a single zone mass balance to a real building.[17]

The field test protocol was also applied to the test house under non-uniform operating conditions. For example, tests were conducted by injecting the decane into Bedroom # 3, closing the door to Bedroom # 3, closing the other bedroom doors in the house, and turning the HVAC fan off (see Table 1). These tests followed the same two or three stage test protocol described above, but did not allow the use of the mass balance model to compare field performance to a direct efficiency value. However, decane concentrations were measured in several locations in the house allowing for zonal concentration comparisons and the use of a metric (described below) to characterize the impact of using an air cleaner on the mass of contaminant in the building.

This whole building impact metric, or mass ratio, compares the total mass measured in the house at steady-state to the predicted total mass that would be in the house at steady-state under ideal conditions using a single zone mass balance model and the directly measured removal efficiency. Thus, the metric compares an air cleaner's actual performance in a building to its predicted field performance based on the equivalent of a laboratory measured removal efficiency.

Equation 4. Air cleaner mass ratio.

$$\text{Mass Ratio} = \frac{\left(\dfrac{G + QC_{out}}{Q + \bar{\eta} Q_{ac}}\right)V}{M_{meas}}$$

where:

$\bar{\eta}$ = average effective single pass removal efficiency of the installed air cleaner (-)
V = volume of building air (m^3)
M_{meas} = VOC mass measured in whole building (mg).

For tests that achieve a single zone condition throughout the house, i.e., uniform concentration among the building zones, this ratio should approach one. If the mass ratio is less than one, the air cleaner is not achieving the same whole building performance as might be expected based on the direct removal efficiency. If the mass ratio is greater than one, then the air cleaner is surpassing its expected whole building effectiveness. Thus, this metric can reveal appropriate locations for a portable air cleaner relative to a source as well as installation problems for an in-duct air cleaner.

Table 1. Air cleaner test conditions.

Test # / AC Type	Air Cleaner Location	Source Location	Interior Door Status	HVAC Fan Status	Mixing Fans Status	Indoor Temp (° C)	Indoor RH (%)	Air Change Rate (h^{-1})
Uniform Concentration Tests								
33/PAC	Front of HVAC return	HVAC supply side	All open	On	On	22	24	0.36 ± 0.07
34/PAC	Front of HVAC return	HVAC supply side	All open	On	On	27	27	0.33 ± 0.07
35/PAC	Kitchen/dining room	HVAC supply side	All open	On	On	23	21	0.36 ± 0.07
36/PAC	Master bedroom	HVAC supply side	All open	On	On	25	23	0.40 ± 0.08
37/PAC	Bedroom #2	HVAC supply side	All open	On	On	22	17	0.41 ± 0.08
38/PAC	Bedroom #3	HVAC supply side	All open	On	On	22	21	0.39 ± 0.08
39/PAC	Kitchen/dining room	HVAC supply side	All open	On	On	25	21	0.28 ± 0.06
40/PAC	Bedroom #2	HVAC supply side	All open	On	On	27	24	0.42 ± 0.08
41/PAC	Master bedroom	HVAC supply side	All open	On	On	22	22	0.34 ± 0.07
42/PAC	Bedroom #3	HVAC supply side	All open	On	On	23	17	0.41 ± 0.08
43/DUCT	HVAC return	HVAC supply side	All open	On	On	22	16	0.45 ± 0.09
44/DUCT	HVAC return	HVAC supply side	All open	On	On	21	35	0.39 ± 0.08
Non-Uniform Concentration Tests								
27/PAC	Kitchen/dining room	Living/dining room	All open	On	On	22	21	0.40 ± 0.08
28/PAC	Family room	Living/dining room	All open	On	On	21	19	0.73 ± 0.15
29/PAC	Front of HVAC return	Living/dining room	All open	On	On	22	25	0.40 ± 0.08
45/PAC	Bedroom #3	Bedroom #3	All open	Auto*	Off	21	37	0.31 ± 0.06
48/PAC	Bedroom #3	Bedroom #3	Bedroom #3 closed	On	Off	21	57	0.21 ± 0.04
53/PAC	BR3	Bedroom #3	Bedroom #3 closed	Off	Off	29	46	0.14 ± 0.03
54/PAC	BR3	Bedroom #3	All closed	Off	Off	27	41	0.16 ± 0.03
55/PAC	MBR	Bedroom #3	All closed	Off	Off	29	44	0.23 ± 0.05
56/PAC	BR3	Bedroom #3	Bedroom #3 open, rest closed	Off	Off	29	39	0.38 ± 0.08
57/PAC	MBR	Bedroom #3	All open	Off	Off	23	31	0.32 ± 0.06
58/PAC	BR3	Bedroom #3	All open	Off	Off	26	32	0.29 ± 0.06
59/PAC	MBR	Bedroom #3	Bedroom #3 closed	Off	Off	26	39	0.29 ± 0.06
60/PAC	MBR	Bedroom #3	Bedroom #3 open, rest closed	Off	Off	22	39	0.37 ± 0.07
49/DUCT	HVAC Return	HVAC supply side	All open	On	Off	21	62	0.16 ± 0.03
50/DUCT	HVAC Return	Bedroom #3	Bedroom #3 closed	On	Off	21	56	0.16 ± 0.03
51/DUCT	HVAC Return	Bedroom #3	Bedroom #3 closed	On	Off	21	57	0.19 ± 0.04
52/DUCT	HVAC Return	Bedroom #3	Bedroom #3 closed	On	Off	21	54	0.19 ± 0.04

* The HVAC fan is on only when the cooling/heating device is operated by temperature controller.

RESULTS AND DISCUSSION

This paper includes results from 23 portable air cleaner (PAC) experiments and 6 in-duct air cleaner (DUCT) experiments (see Table 2). The first column of Table 2 lists the test number and air cleaner type that can be matched to the test conditions given in Table 1. The second and third columns in Table 2 report the directly measured removal efficiency (based on Equation 2) and the mass balance removal efficiency (based on Equation 1), respectively. The mass balance removal efficiency was only determined for uniform concentration tests and was not applicable for the non-uniform concentration tests. The fourth column shows the mass of decane in the test house at steady-state as predicted by a single zone mass balance model. The fifth column reports the total measured mass of decane (M_{meas}) at steady-state in the test house. Finally, the last column gives the mass ratio metric for each test (based on Equation 4).

For each test, the direct removal efficiency for the air cleaner was measured. The PAC direct removal efficiencies ranged from 0.38 to 0.65, with an average removal rate of 0.54 ± 0.08. In the earlier study,[11] a different model PAC was used but had similar decane removal rate results ranging from 0.27 to 0.56. The DUCT removal efficiencies measured here ranged from 0.20 to 0.73 with an average removal rate of 0.42 ± 0.18. A similar in-duct air cleaner was also studied earlier,[11] with an average decane removal rate of 0.38 ± 0.11. As noted earlier, a new in-duct air cleaner and new media for the PAC device were used in each test.

A total of 10 PAC tests and 2 DUCT tests were completed at uniform concentration conditions to compare the directly measured removal efficiency to the single zone mass balance removal efficiency. The results of an example experiment (Test # 39/PAC) for a single zone test are provided in Figure 2. For the single zone tests, the air cleaner was operating the entire experiment, so there is not a separate contaminant loading stage (Stage 1). The air cleaner operation stage shows the house reaching a steady-state decane concentration after approximately 36 h. This test exhibited a relative long time to steady-state due to the variations in air change rate, particularly the increase seen at about 18 h. The decane concentrations measured in four locations are similar and the air change rate is relatively constant except for the increase just noted.

Table 2. Air cleaner test results.

Test # AC Type	Direct Removal Efficiency	Mass Balance Removal Efficiency	Ideal "Whole House" Mass @ Steady-State (mg)	Measured "Whole House" Mass @ Steady-State (mg)	Ideal/Measured Mass Ratio Metric
Uniform Concentration Tests					
33/PAC	0.57 ± 0.06	0.55 ± 0.11	33 ± 6	31 ± 6	1.06 ± 0.28
34/PAC	0.54 ± 0.07	0.47 ± 0.10	42 ± 7	43 ± 9	0.96 ± 0.26
35/PAC	0.44 ± 0.08	0.50 ± 0.10	38 ± 7	37 ± 7	1.05 ± 0.28
36/PAC	0.38 ± 0.09	0.41 ± 0.09	37 ± 6	39 ± 8	0.94 ± 0.25
37/PAC	0.60 ± 0.06	0.43 ± 0.10	35 ± 6	37 ± 7	0.93 ± 0.24
38/PAC	0.38 ± 0.09	0.40 ± 0.10	37 ± 6	39 ± 8	0.94 ± 0.25
39/PAC	0.52 ± 0.07	0.44 ± 0.09	37 ± 6	41 ± 8	0.91± 0.24
40/PAC	057 ± 0.06	0.49 ± 0.10	41 ± 7	42 ± 8	0.98 ± 0.26
41/PAC	0.55 ± 0.06	0.43 ± 0.09	42 ± 7	42 ± 8	0.99 ± 0.26
42/PAC	0.53 ± 0.07	0.41 ± 0.09	40 ± 7	43 ± 9	0.92 ± 0.24
43/DUCT	0.33 ± 0.09	0.23 ± 0.04	8.7 ± 1.6	9.7 ± 2	0.90 ± 0.25
44/DUCT	0.20 ± 0.11	0.21 ± 0.04	9.9 ± 2.0	12 ± 2	0.83 ± 0.23
Non-Uniform Concentration Tests					
27/PAC	0.65 ± 0.05	N/A	21 ± 4	28 ± 6	0.77± 0.20
28/PAC	0.61 ± 0.05	N/A	21 ± 3	33 ± 7	0.64 ± 0.17
29/PAC	0.65 ± 0.05	N/A	22 ± 4	40 ± 8	0.57 ± 0.15
45/PAC	Not Meas.	N/A	12 ± 2	15 ± 3	0.82 ± 0.21
48/PAC	0.61 ± 0.06	N/A	49 ± 9	80 ± 16	0.61 ± 0.17
53/PAC	0.58 ± 0.05	N/A	50 ± 9	34 ± 7	1.44 ± 0.40
54/PAC	0.64 ± 0.05	N/A	47 ± 9	25 ± 5	1.88 ± 0.51
55/PAC	0.40 ± 0.08	N/A	43 ± 8	315 ± 63	0.14 ± 0.04
56/PAC	0.54 ± 0.05	N/A	36 ± 6	59 ± 12	0.61± 0.16
57/PAC	0.52 ± 0.07	N/A	40 ± 7	170 ± 34	0.23 ± 0.06
58/PAC	0.51 ± 0.07	N/A	42 ± 7	64 ± 13	0.66 ± 0.18
59/PAC	0.50 ± 0.07	N/A	36 ± 6	233 ± 47	0.16 ± 0.04
60/PAC	0.51 ± 0.07	N/A	36 ± 6	256 ± 51	0.14 ± 0.04
49/DUCT	0.43 ± 0.08	N/A	18 ± 4	44 ± 9	0.41 ± 0.12
50/DUCT	0.73 ± 0.03	N/A	17 ± 4	31 ± 6	0.56 ± 0.17
51/DUCT	0.43 ± 0.08	N/A	17 ± 4	31 ± 6	0.54 ± 0.16
52/DUCT	0.40 ± 0.08	N/A	34 ± 7	49 ± 10	0.69 ± 0.20

Mass balance results using the steady-state decane concentration for the single zone experiments are also shown in Table 2. In general, the mass balance approach resulted in removal efficiencies that are lower than those measured directly, but are still relatively close. All but three of the PAC direct removal efficiencies and mass balance removal efficiencies are within 15 % of one another. The similarity between the two numbers verifies that a single zone was achieved in the test house and that the air cleaner was operating without significant short-circuiting. There are only two single-zone DUCT removal efficiency results. In one case (#44), the removal efficiencies are in good agreement, while the other (#43) exhibits a roughly 30 % difference, perhaps indicating an installation problem for that test.

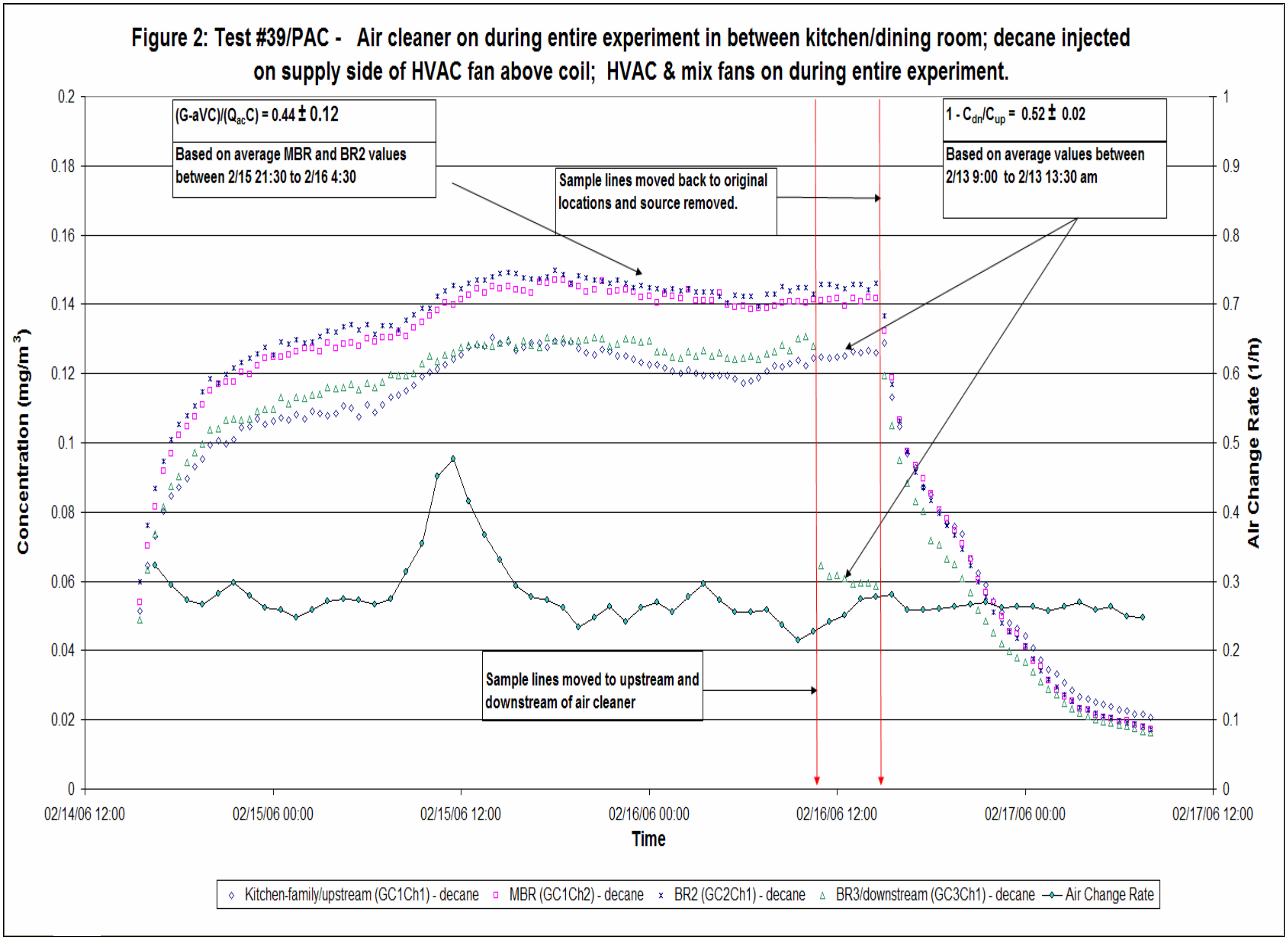


Figure 2: Test #39/PAC - Air cleaner on during entire experiment in between kitchen/dining room; decane injected on supply side of HVAC fan above coil; HVAC & mix fans on during entire experiment.
(G-aVC)/(QacC) = 0.44 ± 0.12
Based on average MBR and BR2 values between 2/15 21:30 to 2/16 4:30
Sample lines moved back to original locations and source removed.
1 - Cdn/Cup = 0.52 ± 0.02
Based on average values between 2/13 9:00 to 2/13 13:30 am
Sample lines moved to upstream and downstream of air cleaner
Concentration (mg/m3)
Air Change Rate (1/h)
Time
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
02/14/06 12:00
02/15/06 00:00
02/15/06 12:00
02/16/06 00:00
02/16/06 12:00
02/17/06 00:00
02/17/06 12:00
Kitchen-family/upstream (GC1Ch1) - decane
MBR (GC1Ch2) - decane
BR2 (GC2Ch1) - decane
BR3/downstream (GC3Ch1) - decane
Air Change Rate

Figures 3 and 4 show examples of so-called multizone experiments, where the house conditions and injection approach do not lead to a uniform decane concentration among the zones. In Figure 3, the decane was injected in Bedroom # 3 during Stage 1 and spread to other zones by the HVAC fan (Test # 48/PAC). The closed Bedroom # 3 door caused a higher steady-state concentration in this room than in other zones. In Stage 2, the portable air cleaner was operated in Bedroom # 3 while the decane source continued, and it was able to decrease the concentration in all of the zones of the house, with Bedroom # 3 remaining at a higher concentration. In the third stage, the decane source was removed and all the zones in the house are equalized and decreased to the background level. This test represents perhaps a more realistic scenario for a house and use of a portable type of air cleaner. As expected, the PAC was most effective at reducing the concentration of decane in Bedroom # 3. With the HVAC system on, the PAC was also able to reduce the overall decane concentration in the house.

Figure 4 shows a more extreme condition with the HVAC fan off (Test # 53/PAC). The source and the portable air cleaner are both in Bedroom # 3 and isolated from the rest of the house with the bedroom door closed without the HVAC fan operating. As a result, the rest of the house is almost unaffected. In spite of the high decane concentration reached in Bedroom # 3, once the decane source is removed, the portable air cleaner is able to lower the concentration to background level. At another extreme, four experiments were completed with the PAC located in a different room from the source (Tests # 55, 57, 59 and 60). These tests showed limited ability of the PAC to remove decane from the entire house.

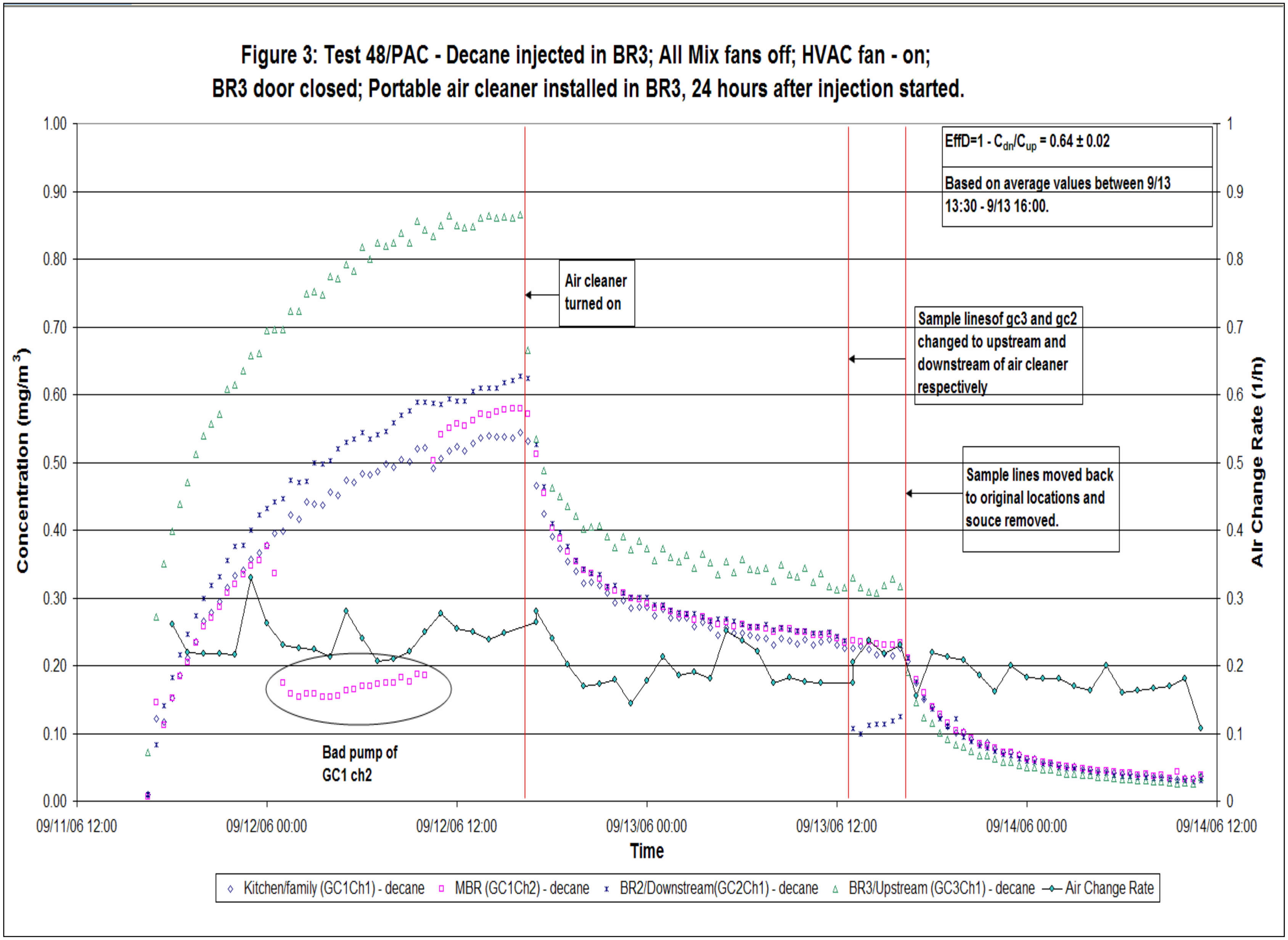


Figure 3: Test 48/PAC - Decane injected in BR3; All Mix fans off; HVAC fan - on;
BR3 door closed; Portable air cleaner installed in BR3, 24 hours after injection started.
EffD=1 - C_{dn}/C_{up} = 0.64 ± 0.02
Based on average values between 9/13 13:30 - 9/13 16:00.
Air cleaner turned on
Sample linesof gc3 and gc2 changed to upstream and downstream of air cleaner respectively
Sample lines moved back to original locations and souce removed.
Bad pump of GC1 ch2
Concentration (mg/m^3)
Air Change Rate (1/h)
Time
09/11/06 12:00
09/12/06 00:00
09/12/06 12:00
09/13/06 00:00
09/13/06 12:00
09/14/06 00:00
09/14/06 12:00
Kitchen/family (GC1Ch1) - decane
MBR (GC1Ch2) - decane
BR2/Downstream(GC2Ch1) - decane
BR3/Upstream (GC3Ch1) - decane
Air Change Rate

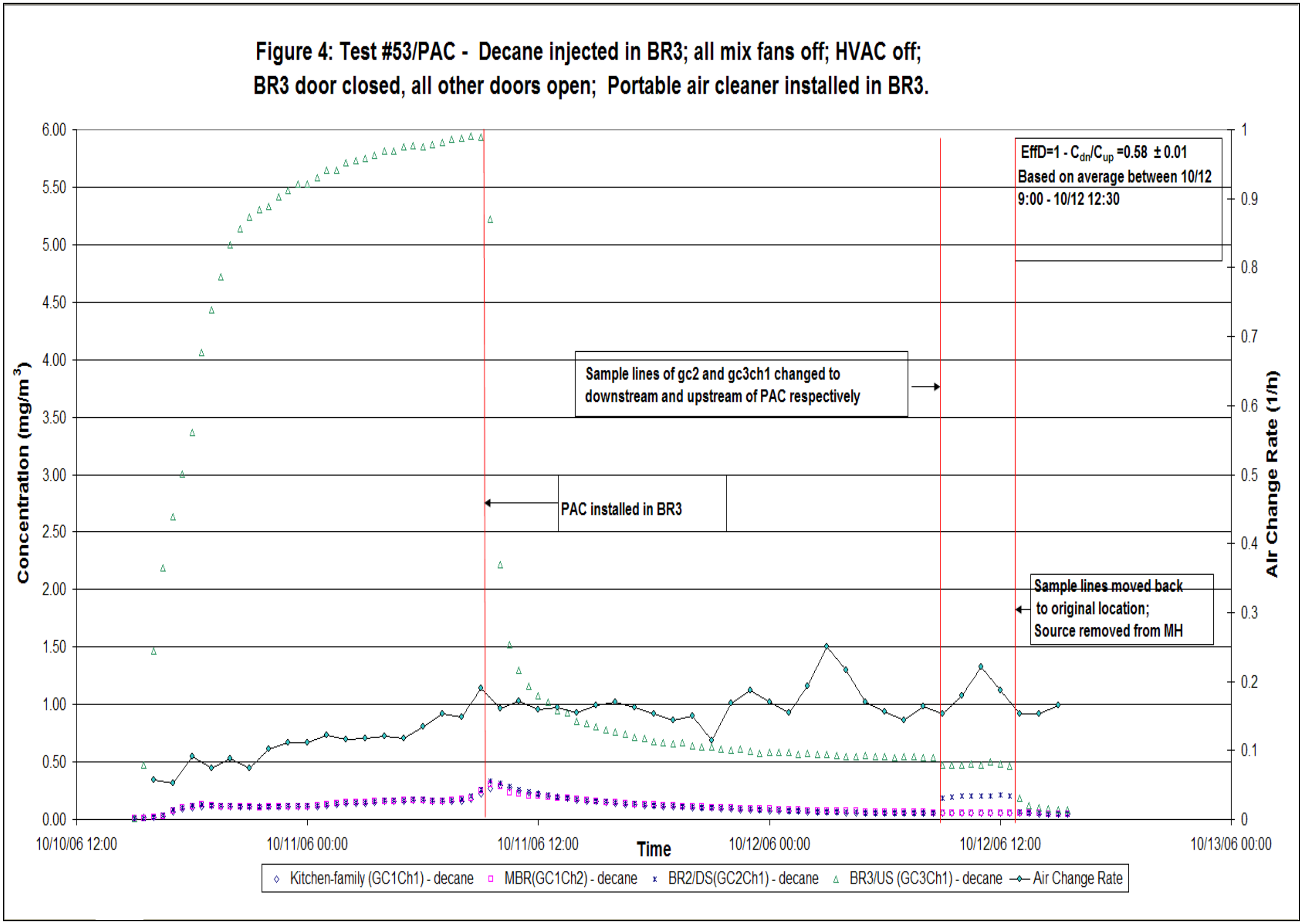


Figure 4: Test #53/PAC - Decane injected in BR3; all mix fans off; HVAC off;
BR3 door closed, all other doors open; Portable air cleaner installed in BR3.
EffD=1 - Cdn/Cup =0.58 ± 0.01
Based on average between 10/12
9:00 - 10/12 12:30
Sample lines of gc2 and gc3ch1 changed to
downstream and upstream of PAC respectively
PAC installed in BR3
Sample lines moved back
to original location;
Source removed from MH
Concentration (mg/m3)
Air Change Rate (1/h)
Time
6.00
5.50
5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10/10/06 12:00
10/11/06 00:00
10/11/06 12:00
10/12/06 00:00
10/12/06 12:00
10/13/06 00:00
Kitchen-family (GC1Ch1) - decane
MBR(GC1Ch2) - decane
BR2/DS(GC2Ch1) - decane
BR3/US (GC3Ch1) - decane
Air Change Rate

A summary of the mass ratio metric to characterize air cleaner performance in the field is also provided in Table 2. As shown in Table 2, the single zone PAC experiments result in mass ratios that are close to 1, with a range of 0.92 to 1.06 and a mean of 0.97 ± 0.05. Again, these values are consistent with the test house operating as a single zone and that the mass removed from the house is in agreement with the predictions based on the PAC direct removal efficiency. The single zone DUCT experiments resulted in slightly lower mass ratios of 0.90 and 0.83.

The mass ratios for the PAC non-uniform concentration experiments had a wide range from 0.14 to 1.88 depending on scenario conditions. The lowest mass ratios (0.14 to 0.23) correspond to scenarios with the decane source injected into a different room than the PAC. In these cases, the PAC had little impact on the decane concentration in the whole house. The highest mass ratios (1.44 to 1.88) correspond to tests with the decane source injection in a closed room with the PAC. In these cases, the PAC was able to remove most of the decane mass before it had much impact on the remainder of the house. Thus, any information regarding the location of the contaminant source and occupants can prove useful for placement of a portable air cleaner.

All of the DUCT mass ratios for the multizone tests were less than one, ranging from 0.41 to 0.69. This relatively narrow range of mass ratios indicates a lower variable impact of house conditions on the effectiveness of an in-duct air cleaner. Also, mass ratios less than one indicate that the DUCT air cleaner was not as effective at removing decane from the whole house as would be predicted by a laboratory determined removal efficiency. The DUCT mass ratios fall within the range of mass ratios measured for the PAC, which illustrates the advantage of a PAC for isolated point sources and the advantage of a DUCT air cleaner for more pervasive contaminant sources. It should also be noted that a DUCT air cleaner only removes contaminants when the HVAC fan is on. In cases when the HVAC system is cycling on and off, the DUCT air cleaner would be even less effective.

The mass ratio metric described here is specifically for cases when a steady-state concentration is reached. However, a similar metric could be developed for non-steady-state cases by comparing integrated mass or perhaps peak concentrations.

CONCLUSIONS

A field performance test is needed to fully understand the capabilities of a gaseous air cleaner in real buildings. This paper describes a protocol for conducting such tests in a multizone building and proposes a metric to characterize performance when the building cannot be characterized as a single zone. Field tests completed in this study provide data showing the impact that multizone conditions can have on gaseous air cleaner performance in a real building. When a building does not have a uniform concentration of contaminants, an in-duct air cleaner may not be as effective at reducing the whole building mass. Likewise, a portable air cleaner will also not be as effective at removing total mass when operated in rooms different from the contaminant source, but it can also effectively exceed predicted performance when the source and air cleaner are in the same room isolated from the remainder of the house. Such information can provide useful guidance for air cleaner use to best reduce building occupant exposure to VOCs and other contaminants. However, characterizing building specific air cleaner operating scenarios would require information on building air distribution, source emissions and source location.

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KEY WORDS
Gaseous air cleaning, volatile organic compounds, field test method, indoor air