NATIONAL CENTER FOR ENERGY MANAGEMENT AND BUILDING TECHNOLOGIES

How Effective are Air Cleaners in Removing VOC's and Particulates from Indoor Air?

Davor Novosel
Chief Technology Officer

Acknowledgement

- This presentation reports on the work being performed at Syracuse University under NCEMBT Tasks 8 and 05-03
  - Task 8 has been completed and the final report (NCEMBT-061101) has been published and is available at www.ncembt.org for downloading
  - Task 05-03 is on-going and builds upon results of Task 8
- The Principal Investigator is Jianshun (Jensen) Zhang, Ph.D. with major contributions by Wenhao Chen, Ph.D.

Outline

- Objectives
- Significance of Research
- Research Methodology
- Results
  - Completed Task 8
    - → 6 portable devices
    - → 2 in-duct devices
  - Ongoing Task 05-03
    - → 4 in-duct devices

Objectives

- Develop/validate a chamber test procedure for air cleaner performance evaluation under combined challenges of volatile organic compounds (VOCs) and particles
- Generate performance data for selected residential scale air cleaning devices
  - 6 portable and 2 in-duct devices in original Task 8
  - 4 in-duct devices in the follow-up Task 05-03
- Assess the potential of air purification for IAQ improvement and impact on energy efficiency

Significance of Research

- Seeks to address issues contributing to:
  - Lack of standard test methods for combined VOC and particulate removal
  - Limited information on actual performance data of air cleaners
  - Limited detailed number estimates on potential of air cleaning technologies for improving IAQ and saving energy
  - Limited knowledge about the influence of product design (technology selection, flow arrangement, etc.) on the performance of air cleaners

Research Methodology

- Literature Review
  - Existing test standards
  - Available indoor air cleaning technologies/products
- Selection of Test Air Cleaners
- Development of Chamber Test Procedure
- Performance Testing and Analysis
  - Generate performance data
  - Identify effective and safe indoor air cleaning technologies
  - Compare with available product ratings (CADR of portable air cleaners and MERV of in-duct filters)
- Evaluation of Potential of Air Cleaners for Improving IAQ and Saving Energy
  - Contaminant reduction capability
  - Energy usage

Review of Existing Test Standards

Particles Removal		Gaseous Contaminants Removal	
Test Specimen	Applicable standard(s)	Test Specimen	Applicable standard(s)
		Sorbent media	ASHRAE Std. 145.1P
Portable air cleaner	ANSI/AHAM AC-1-2005	Portable air cleaner	None [a]
In-duct filter	ANSI/ASHRAE Std. 52.1-1992 and 52.2-1999	In-duct sorbent filter	ASHRAE Std. 145.2P [b]

(a) Literature reviews indicate that a test procedure similar to AHAM AC-1-2005 was most often used.

(b) ASHRAE Std. 145.2P is still in early development stage.

"Pull-down" vs. "Constant Source" Method

	"Pull-down" Method	"Constant-source" Method
Test apparatus	Test chamber	Test duct rig
Method description	Contaminant generations are stopped before turning on the air cleaner and the concentration decays of test contaminants in chamber from its initial value is measured	Contaminants are continuously generated during the experiment. Test contaminant concentrations at both upstream and downstream of the air cleaner are measured.
Performance parameter reported	CADR	Single-pass removal efficiency
Application category	Commonly used for portable air cleaners	Commonly used for in-duct filters/devices
Test Duration	*Initial* performance only (short-term)	Short-term or long-term performance evaluation
Test standards	AHAM AC-1-2005	ASHRAE Std. 52.2-1999 and ASHRAE Std. 145.2P

Review of Available Technologies

- Particles
  - Filtration
  - Electrostatic precipitators
  - Electronic air cleaner + charged-media filter
  - Ion generator (Ionizers)
- Gaseous contaminants (including VOCs)
  - Sorption filtration
  - Ultraviolet photocatalytic oxidation (UV-PCO)
  - Air ionization (or plasma decomposition)
  - Ozone oxidation (not recommended based on previous study)
  - Botanical air cleaning (no commercial products available)

Selection of Test Air Cleaners /1

Eight air cleaners tested in completed Task 8

Product Type	Device No.	Purchase Price	Major Technology for removing VOCs			Major Technology for removing particulates			
			Sorption Filtration	UV-PCO	Ionization	Mechanical Filtration	Electrostatic precipitator	Mechanical filtration with charged particles and/or media	Ionizer
Portable	P1	$249	✓			✓			
	P2	$795	✓			✓			
	P3	$499	✓				✓		
	P4	$565	✓					✓	
	P5	$349			✓				✓
	P6	~$470	✓			✓			
In-duct	D1	$510	✓			✓			
	D2	~$1400		✓		✓			

Note: Products P6 and D2 were directly provided by manufacturers. Sales prices for US market are estimated.

Selection of Test Air Cleaners /2

Four more in-duct air cleaners in ongoing Task 05-03

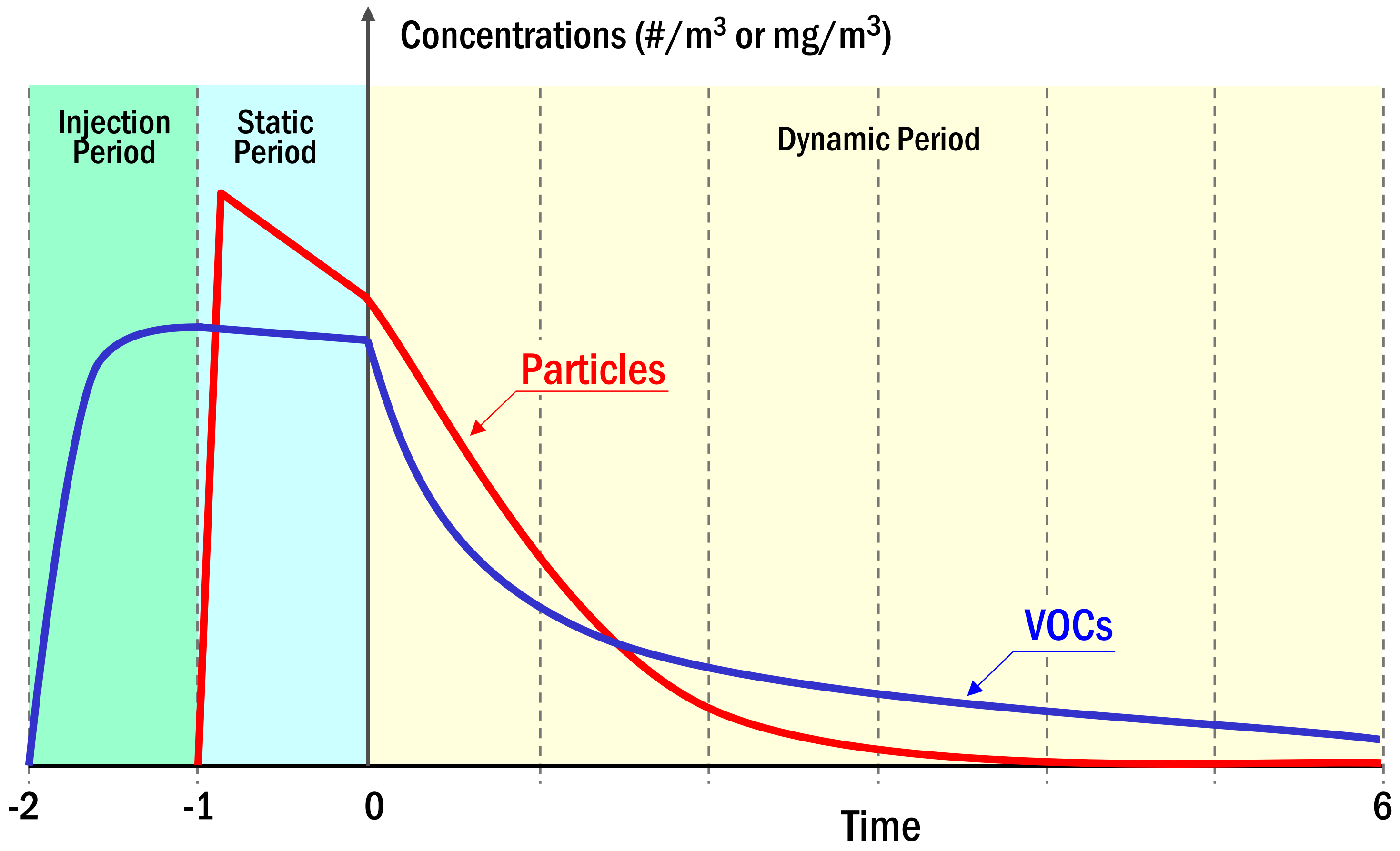
Device No.	Technology for particulate removal	Technology for VOCs removal
D3	2 inch. "combined" filter containing 250g activated carbon attached to cotton-polyester media (MERV 8)	
D4[a]	4 inch. thick MERV 13 mini pleat filtration media	1 inch. sorbent pad with blend sorbent media (50/50 blend of activated carbon and $KMnO_4$ impregnated alumina)
D5[a]	Electronic cell (to charge particles using point ionization) + charged media	1 inch. self-packed sorbent bed with granular activated carbon and potassium permanganate impregnated activated alumina (50/50 by weight, total 3.95 kg)[b]
D2[c]	MERV 9 filter	UV-PCO: six 17 watts UVA lamps and a honeycomb catalyst coated insert

(a) Although listed as one device, it was the combination of two products (one for particle removal and one VOC removal);

(b) Although such a sorbent bed is seldom used in residential houses due to its large pressure drop, it was designed to collect data for verification of the sorbent bed design model that can be used later in designing sorbent filter for residential houses

(c) Product D2 has been tested in Task 8 and will be used for further evaluation of potential byproduct generation from incomplete PCO reaction.

“Pull-down” Test Procedure /1



“Pull-down” Test Procedure /2

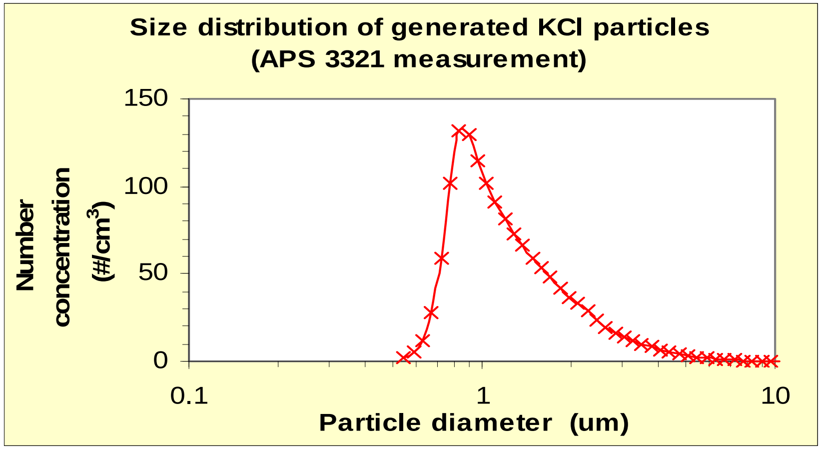
- Advantages
  - Applicable to both portable and in-duct air cleaners and to different types of technologies
  - Covers a wide range of test VOCs and particle concentrations within a reasonable experimental time
  - Easy to implement using existing environmental chambers
- Disadvantage
  - Only initial performance can be evaluated

Test Contaminants

A mixture of 8 VOCs …

Chemical Category	Chemical Name	Molecular Formula	Molecular Weight	Boiling Point (ºC)	Approximate Vapor Pressure at 25ºC (mm Hg)	Included in ASHRAE Std 145.1P
Alkane	n-Hexane	C_6H_{14}	86.2	69	151	yes
	n-Decane	$C_{10}H_{22}$	142.3	174	1.25	no
Aromatic	Toluene	C_7H_8	92.1	111	28.4	yes
Chlorocarbon	Dichloromethane	CH_2Cl_2	84.9	40	435	yes
	Tetrachloroethylene	C_2Cl_4	165.8	121	18.6	yes
Alcohol	iso-Butanol	$C_4H_{10}O$	74.1	108	9	yes
Ketone	2-Butanone	C_4H_8O	72.1	80	78	yes
Aldehyde	Formaldehyde	CH_2O	30.0	-19	3840	yes

… and KCl particles



Contaminant Generation, Sampling and Analysis

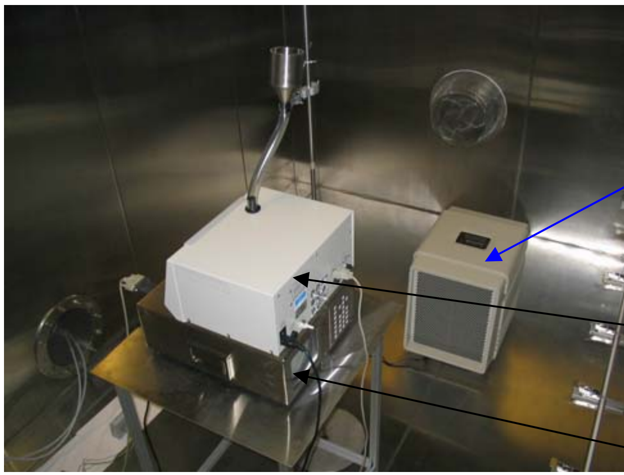
Large-particle aerosol generator

Sorbent tube sampling and ATD-GC/MS

On-line monitoring:
- SF_6
- TVOC as toluene & formaldehyde
- KCl particles
- O_3

Test Facility in Task 8

Full-scale stainless steel chamber (12 ft x 7 ft x 10 ft high)



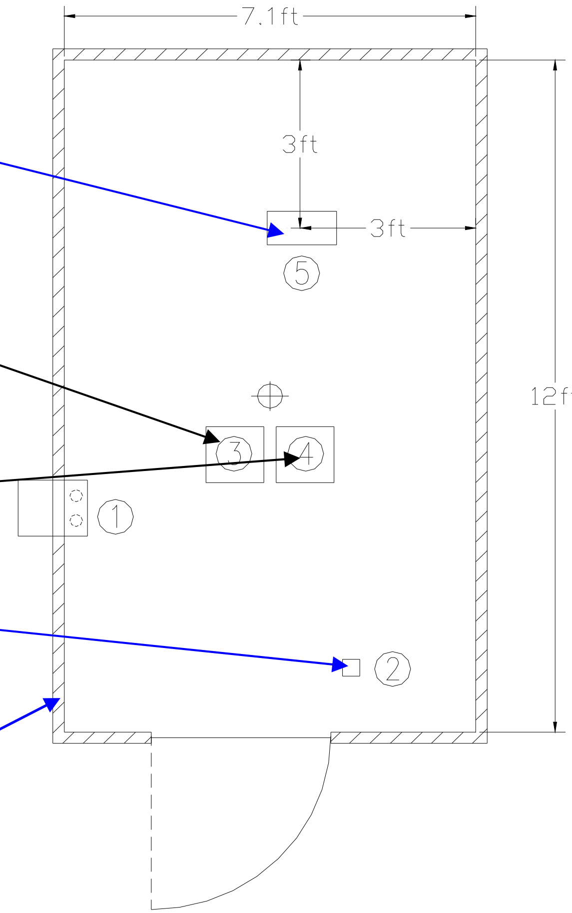
Test portable air cleaner

TSI model 3321 APS

LASAIR model 1003 APC

Hot plate for vaporizing test VOCs

Full-scale chamber with modified recirculation loop



Test Conditions in Task 8

- Target initial concentrations:
  - VOCs: 1mg/m^3 for each VOC except formaldehyde and 2mg/m^3 for formaldehyde
  - Particles: total 1000 ~ 2000 particles/cm^3 for KCl with 0.3-10 µm diameter (0.523 – 11.548µm of aerodynamic diameter from APS 3321 measurement)
- Temperature and RH
  - 21°C and 50% RH at the start of test
  - Temperature and RH not controlled but measured during the test
- Test Flow Rate
  - Maximum flow rate setting for portable air cleaners and 130 CFM (9 ACH) provided by the in-duct recirculating fan for well-mixing purpose
  - Approximate 700 CFM (49 ACH) provided by HVAC system of the chamber for in-duct devices
- Sampling location
  - Return duct adjacent to chamber outlet for VOCs and ozone
  - Center of room (approximate 1.6 m high) for particles

Data Analysis by a Well-mixed Single-zone Model

- **Mass balance equation in "pull-down" test**

$$V\frac{dC}{dt} = -(CADR + Q_{leak} + kV)\cdot C \qquad (C = C_0 \text{ at } t = 0) \qquad [E.1]$$

  - Without air cleaner operating: $\ln\left(\frac{C}{C_0}\right) = -(\frac{Q_{leak} + kV}{V})\cdot t = -k_n \cdot t$
  - With air cleaner operating: $\ln\left(\frac{C}{C_0}\right) = -(\frac{CADR + Q_{leak} + kV}{V})\cdot t = -k_e \cdot t$

- **Direct performance parameter obtained is CADR**
  - CADR is constant: $\mathrm{CADR} = \mathrm{V}(\mathrm{k_e} - \mathrm{k_n})$ [E.2]
  - CADR is not constant: $\frac{\int_0^T C dt}{T} = \frac{\int_0^T C_0 \cdot e^{-(k_n + \frac{CADR\_e}{V})\cdot t} dt}{T}$ [E.3]

T = length of dynamic test period,

CADR_e = equivalent CADR over test period (Equation [E.3] reduces to [E.2] for constant CADR)

Other Performance Parameters Measured

- Single-pass Removal Efficiency η

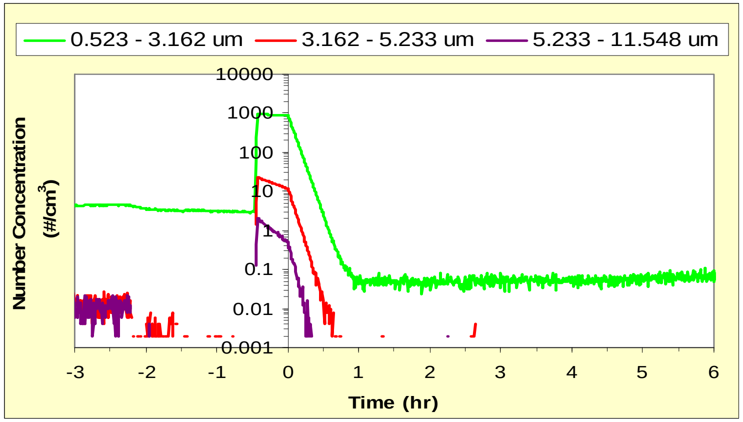
$$\eta = \frac{CADR}{G}$$

G = airflow rate through the air cleaner, CFM or m^3/h

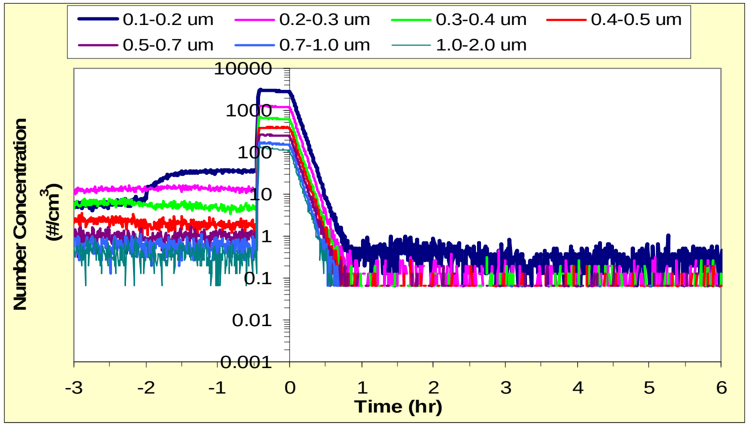
- Energy consumption index (Watts/CFM CADR)
- Ozone generation rate (mg/h)
- Noise level for portable air cleaners
- Pressure drop across in-duct air cleaners

Measured Particle Concentration Decay

Product P2 (sorption & mechanical filtration)

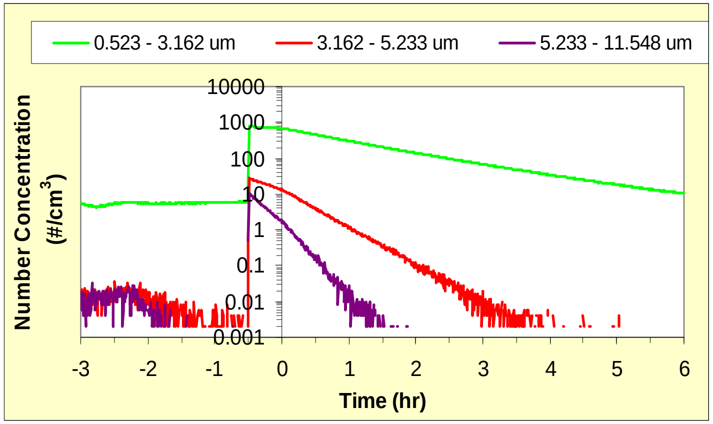


TSI APS 3321 Measurement

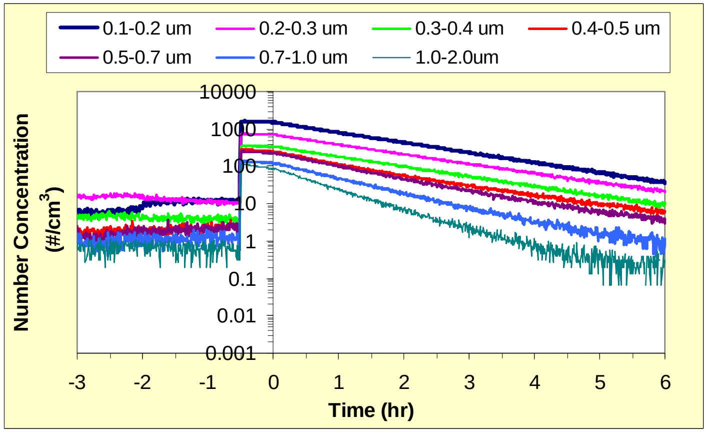


LASAIR 1003 APC Measurement

Product P5 (ionization)



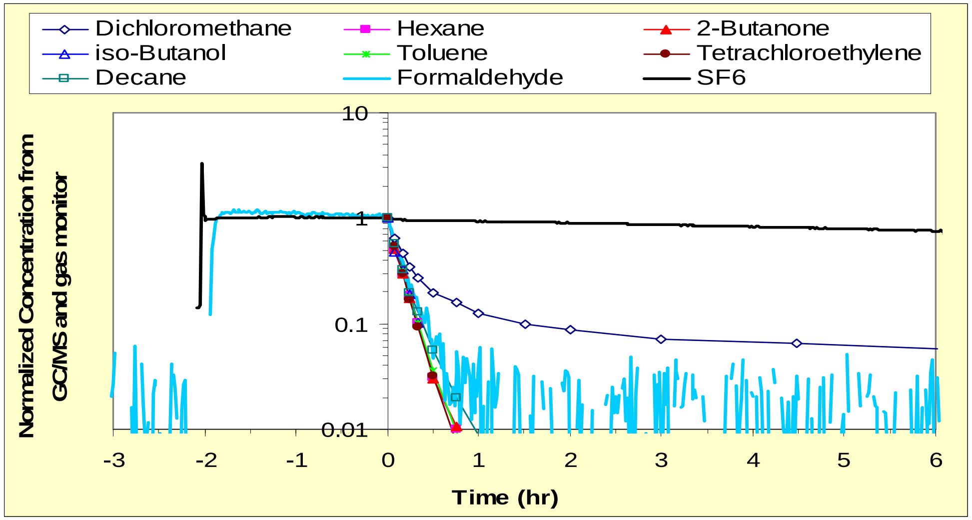
TSI APS 3321 Measurement



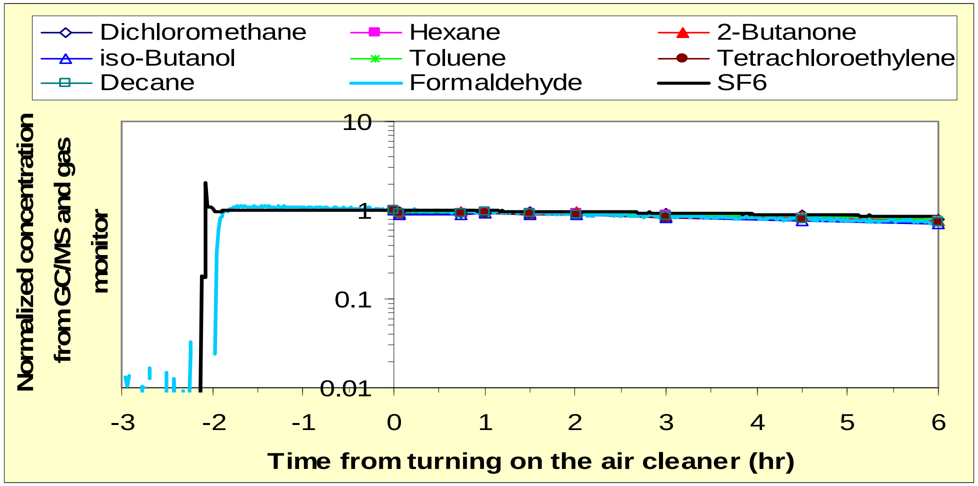
LASAIR 1003 APC Measurement

Measured VOC Concentration Decay

Product P2
(sorption & mechanical filtration)



Product P5
(ionization)



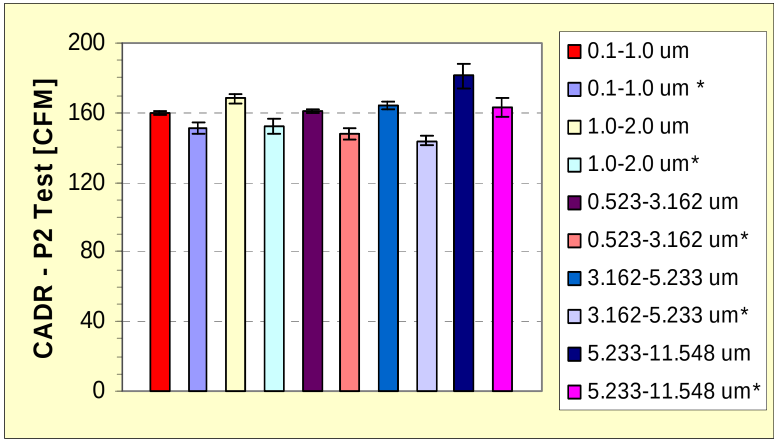
GC/MS and Gas Monitor Measurements (both products)

Summary of Test Results for Particles

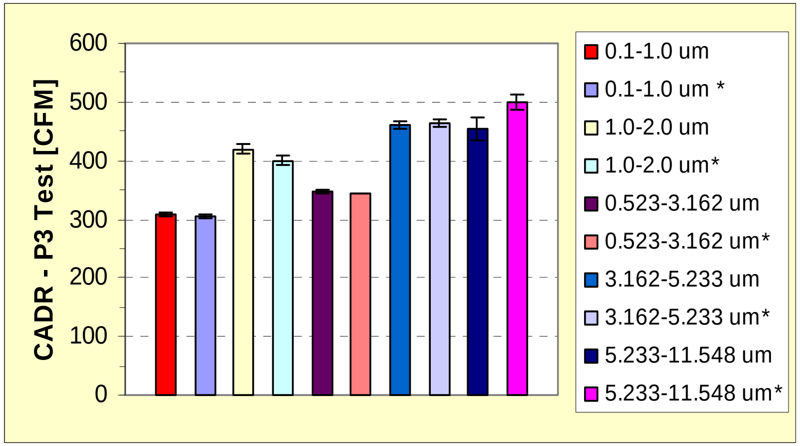
Device No.	Average CADR	Average removal efficiency (%)	Watts/CADR	Purchase $/CADR	Ozone generation
P1	169	68	0.8	1.5	No
P2	167	74	1.4	4.8	No
P3	370	96	0.2	1.3	Yes (1.696 mg/h)
P4	205	53	0.6	2.8	No
P5	9	-	0.8	37.4	Yes (2.267 mg/h)
P6	142	61	0.4	3.3	No
D1	555	84	0	0.9	No
D2	155	24	0.9	9.0	No

Notes: (1) Average CADR and removal efficiency were the average for 0.1 – 1.0 μm, 0.523 – 3.162 μm and 5.233 – 11.548 μm particles
(2) For column of ozone generation, values in "( )" were ozone concentration at the end of 6 hr test period and the estimated ozone generation rate, respectively.

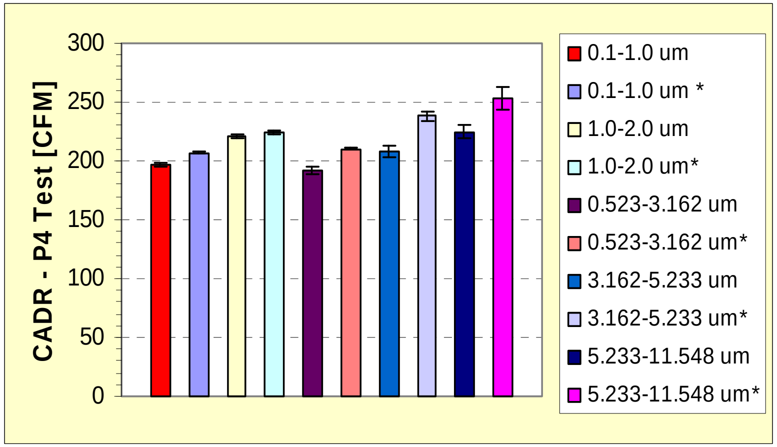
VOC+Particle vs. Particle Only Test



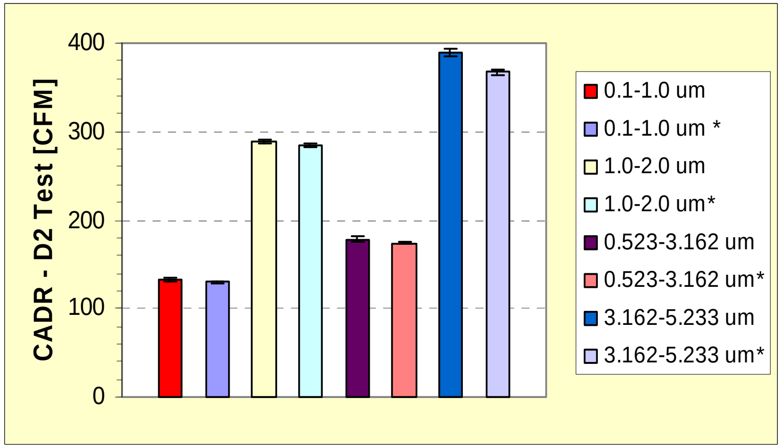
(a) Product P2



(b) Product P3



(c) Product P4



(d) Product D2

Note: Results from particle only tests are marked with "*"

Comparison with AHAM Certified CADR

CADR (CFM)		Product P1	Product P3	Product P4
AHAM certifications	Tobacco smoke (0.1 – 1.0 μm)	195	300	388
	Dust (0.5 – 3.0 μm)	155	325	377
	Pollen (5 – 11 μm)	155	370	378
Our measurements	KCl particle (0.1 – 1 μm)	163	308	197
	KCl particle (0.523 – 3.162 μm)*	159	348	192
	KCl particle (5.233 – 11.548 μm)*	184	454	225

Note: Diameter ranges marked with " * " are aerodynamic diameters

- No significant difference was observed for particulate removal between tests with particle injection only and with simultaneous injection of particles and VOCs
- Test results for portable air cleaners (except P4) were generally comparable with certified CADR

Comparison with Rated MERV

Efficiency (%)		Product D1 (MERV 15)	Product D2 (MERV 9)
Composite average particle size efficiency (ASHRAE 52.2)	0.3 – 1.0 μm	85% ≤ E < 95%	N/A
	1.0 – 3.0 μm	E ≥ 90%	E < 50%
	3.0 – 10.0 μm	E ≥ 90%	E ≤ 85%
Our measurements	0.1 – 1.0 μm	86%	25%
	0.523 – 1.0 μm*	84%	25%
	1.0 – 3.162 μm*	85%	33%
	3.162 – 10.0 μm*	74%	58%

Notes: (1) Diameter ranges marked with " * " are aerodynamic diameters;
(2) For particles with diameter range of 3.162 – 10.0μm, concentration decay was only measurable for 3.162 – 5.233μm particles during the dynamic period

- CADR was not measurable for particles in the size range of 5.233 –11.548μm due to the large natural decay rate
- Measured efficiency was smaller than ASHRAE MERV rating, especially for larger particles (> 3.162μm)

Summary of Test Results for VOCs /1

Toluene					
Device No.	CADR[1]	Removal efficiency[1] (%)	Watt/CADR[2]	Purchase $ /CADR	Ozone generation
P1	138 (133 ± 8)	55 (53 ± 3)	1.0	1.8	No
P2	95 (92 ± 7)	42 (40 ± 3)	2.5	8.4	No
P3	7 (7 ± 8)	2 (2 ± 2)	9.6	71.3	Yes (1.696 mg/h)
P4	216 (223 ± 20)	56 (58 ± 5)	0.6	2.6	No
P5	0.1 (0.2 ± 0.1)	-	72	3490	Yes (2.267 mg/h)
P6	124 (116 ± 24)	54 (50 ±10)	0.4	3.8	No
D1	588 (563 ± 52)	89 (85 ± 8)	0	0.9	No
D2	40 (40 ± 33)	6 (6 ± 5)	3.6	35.0	No

Notes:

1. Average and standard deviation for six VOCs
2. Only direct power consumption by in-duct air cleaner was measured and used to calculate Watt/CADR

Summary of Test Results for VOCs /2

Formaldehyde					
Device No.	CADR	Removal efficiency (%)	Watt / CADR[1]	Purchase $ / CADR	Ozone generation
P1	3	1	45.3	83	No
P2	77	34	3.0	10.3	No
P3	0.7	0.2	95.7	713	Yes (1.696 mg/h)
P4	28	7	4.4	20.2	No
P5	0.3	-	24	1163	Yes (2.267 mg/h)
P6	77	33	0.7	6.1	No
D1	440	67	0	1.2	No
D2	45	7	3.2	31.1	No

Note:

1. Only direct power consumption by in-duct air cleaner was measured and used to calculate Watt/CADR

Summary of Test Results for VOCs /3

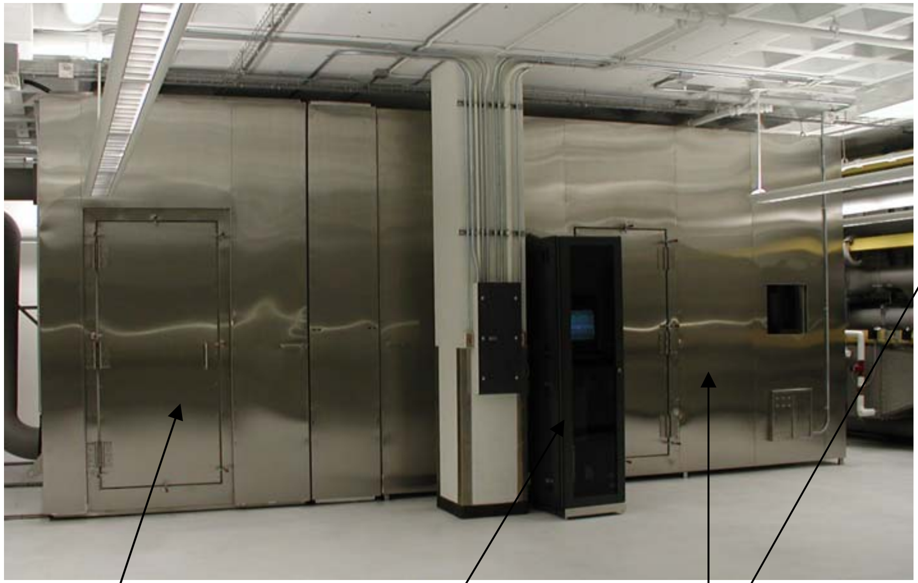
Dichloromethane					
Device No.	CADR	Removal efficiency (%)	Watt /CADR[1]	Purchase $ /CADR	Ozone generation
P1	10	4	13.6	24.9	No
P2	20	9	11.7	39.8	No
P3	0.6	0.2	112	832	Yes (1.696 mg/h)
P4	34	9	3.6	16.6	No
P5	0.1	-	72	3490	Yes (2.267 mg/h)
P6	8	4	6.4	58.8	No
D1	502	76	0	1.0	No
D2	4	1	35.5	350	No

Note:

1. Only direct power consumption by in-duct air cleaner was measured and used to calculate Watt/CADR

Test Facility in Task 05-03

Full-scale stainless steel chamber (16 ft x 12 ft x 10 ft high, larger volume)



Test chamber used in Task 8

Control station

Test chamber used in Task 05-03

Modified in-duct air cleaner test loop with bypass

Installation of test filter (standard size) inside the test box

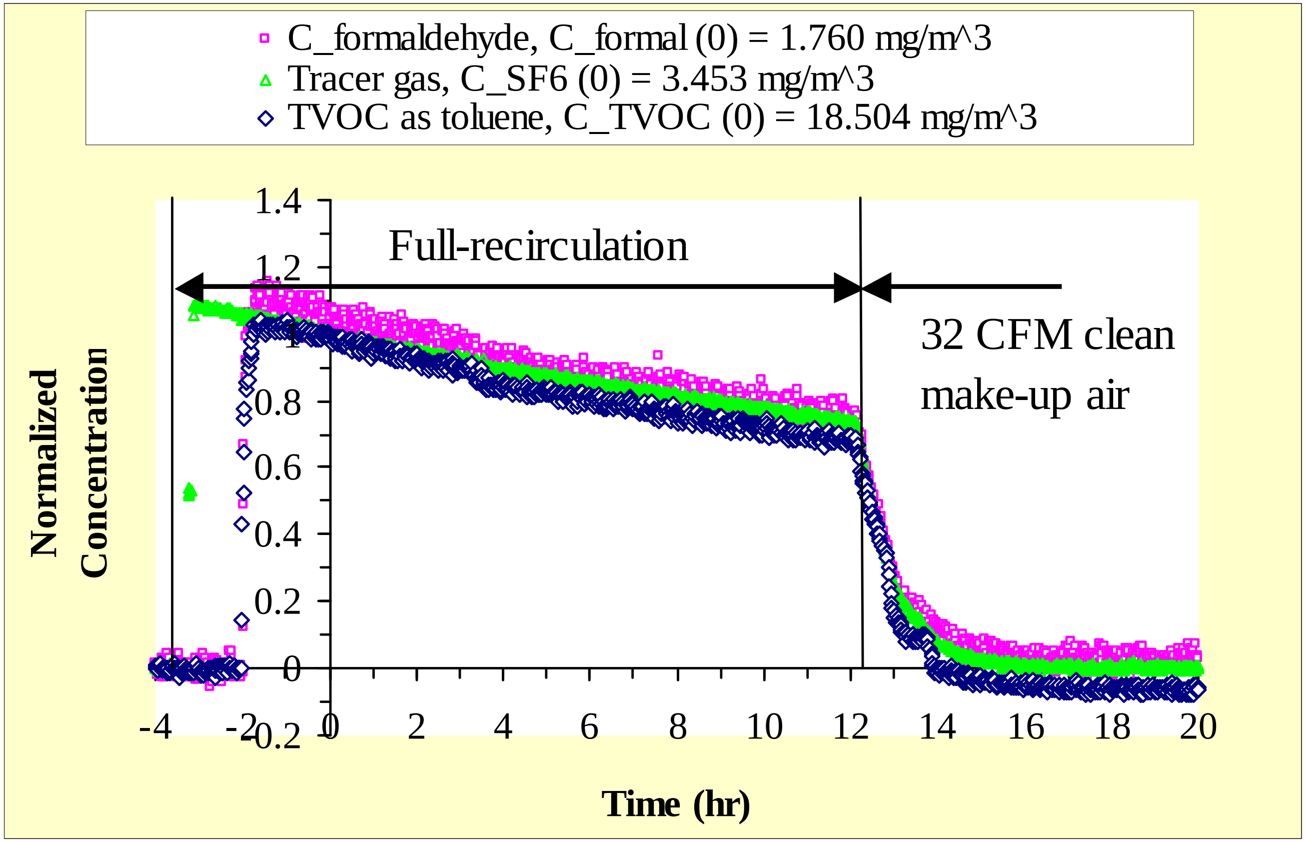
Refinement of Test Conditions in Task 05-03

- The test airflow rate was changed to 800 CFM, which is closer to realistic operating condition in a whole house ventilation system.
- The chamber with the larger volume was used to obtain more accurate data points during the "pull-down" test for high efficiency in-duct air cleaners under large operating flow rates.
- The chamber was conditioned during test runs to maintain a narrow temperature and RH range (23 ± 1°C, 50 ± 5% RH).

Test Progress to Date (Task 05-03)

- Empty chamber test conducted first as control test
- Products D3, D4 and D5 were tested with the standard test procedure
- Additional particle only tests conducted for products D3, D4 and D5 to estimate CADR for 5.233 – 11.548 µm particles, in which the system was switched from the by-pass loop to the in-duct air cleaner test loop right after particle injection

Empty Chamber Characterization (Task 05-03)



- Good air tightness (leakage rate < 0.03 ACH)
- Negligible sink effect for VOCs under test conditions

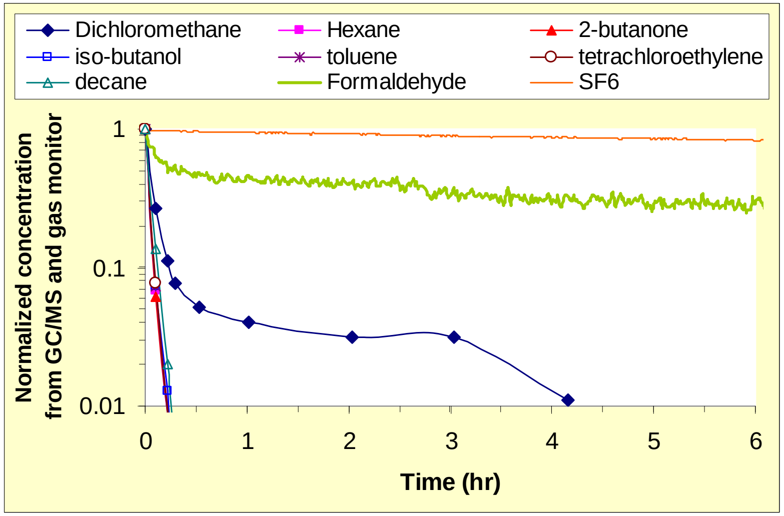
Empty Chamber Characterization (Task 05-03)

System status	Parameters	APS 3321 measurement			APC 1003 measurement	
		0.523-3.162 μm	3.162-5.233 μm	5.233-11.548 μm	0.1-1.0 μm	1.0-2.0 μm
By-pass loop (Injection and static period)	k (ACH)	0.826	9.266	15.065	0.409	2.715
	R^2	0.996	0.999	0.997	0.992	0.994
	$C_{\_ini}$ (#/cm^3)	1104.843	28.985	5.382	7792.149	266.080
In-duct test loop (Dynamic test period)	k (ACH)	0.730	8.697	-	0.465	2.562
	R^2	0.992	0.989	-	0.999	0.989
	C_0 (#/cm^3)	819.770	1.200	0.030	6708.053	101.899
Difference of k between the by-pass loop and in-duct test box loop (ACH)		-0.096	-0.569	-	0.056	-0.153

- Similar natural decay rates between by-pass loop and in-duct test loop
- Large natural decay rate for large particles (9 ACH for 3.162 – 5.233μm particles and 15 ACH for 5.233 – 11.548 μm particles) under test conditions

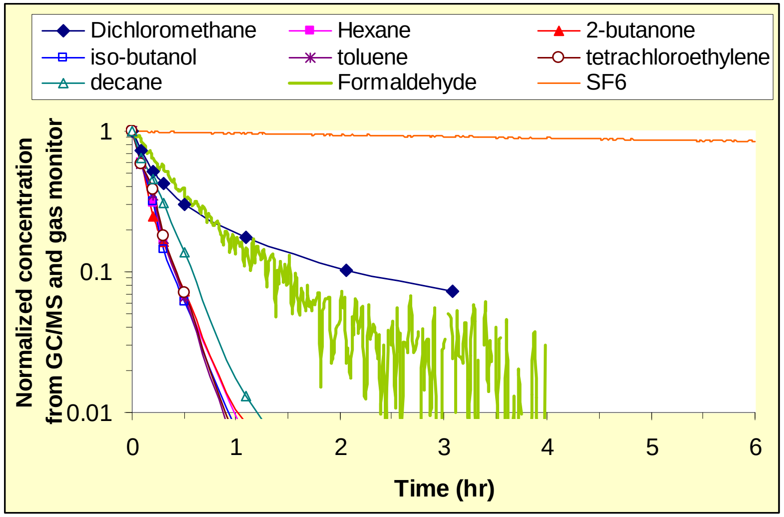
Example Results for VOCs (Task 05-03)

Product D3



VOC	CADR (CFM)	η (%)
Decane	571	71.3
Tetrachloroethylene	657	82.1
Toluene	668	83.5
Iso-Butanol	652	81.5
2-Butanone	653	81.7
Hexane	655	81.9
Dichloromethane	152	19.0
Formaldehyde	7	0.9

Product D4



VOC	CADR (CFM)	? (%)
Decane	125	15.7
Tetrachloroethylene	158	19.7
Toluene	162	20.2
Iso-Butanol	157	19.6
2-Butanone	148	18.5
Hexane	154	19.3
Dichloromethane	51	6.3
Formaldehyde	55	6.8

Example Results for Particles (Task 05-03)

Product D3 (MERV 8)

Particulate		Standard test with combined challenges of VOCs and particles		Particle only test		% Difference between two tests
		CADR (CFM)	η (%)	CADR (CFM)	η (%)	
LASAIR 1003 APC Measurement	0.1 – 1μm	80	10	67	8.4	-15.7
	1 - 2 μm	172	21.5	159	19.8	-7.7
TSI 3321 APS Measurement	0.523 – 3.162 μm	80	10	70	8.7	-13.1
	3.162 – 5.233 μm	151	18.9	177	22.1	17.0
	5.233 – 11.548 μm	-	-	115	14.4	-

Product D4 (MERV 13)

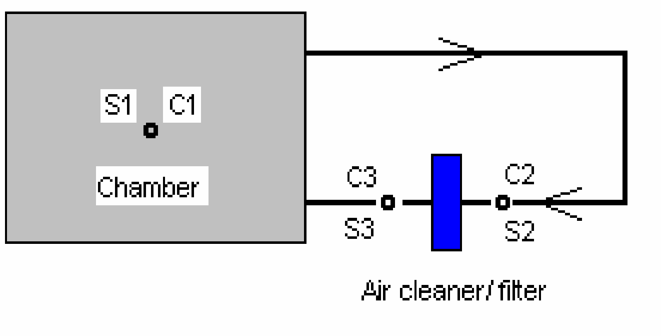
Particulate		Standard test with combined challenges of VOCs and particles		Particle only test		% Difference between two tests
		CADR (CFM)	η (%)	CADR (CFM)	η (%)	
LASAIR 1003 APC Measurement	0.1 – 1μm	342	42.7	349	43.6	2.1
	1 - 2 μm	420	52.5	429	53.7	2.3
TSI 3321 APS Measurement	0.523 – 3.162 μm	385	48.1	399	49.9	3.8
	3.162 – 5.233 μm	129	16.1	245	30.7	90.3
	5.233 – 11.548 μm	-	-	188	23.4	-

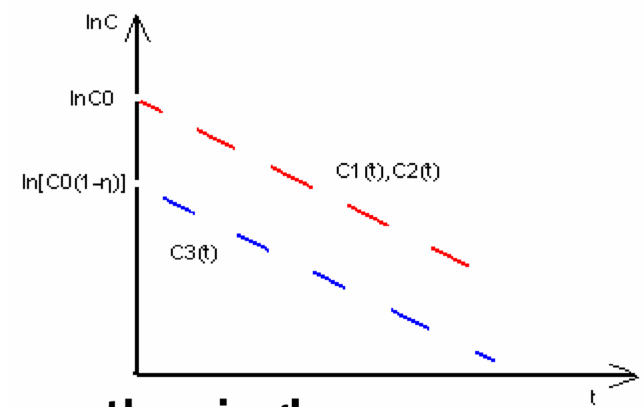
Technical Problems Identified (Task 05-03)

- For particles in the size range of 5.233 – 11.548μm, CADR could not be calculated from the standard combined injection test procedure.
- Big relative difference (90.3%) between CADR obtained from standard test and from particle only test was observed for 3.162 - 5.233μm particles in product D4 test.
- Single pass efficiencies calculated from current tests for the MERV 8 (product D3) and MERV 13 filter (product D4) do not agree well with the composite average particle size efficiency and typical shape of minimum efficiency vs. particle size curve defined per ASHRAE std. 52.2-1999.

Current Efforts for Addressing Technical Problems

- Directly determine the single pass efficiency as well as CADR from the chamber "pull-down" test by sequentially sampling the particle concentration at immediate upstream and downstream of the air cleaner/filter as well as in the middle of the chamber





- Examine the effect of test flow rate on the single-pass efficiency vs. particle size curve
- Conduct detailed experimental uncertainty analysis to determine the maximum diameter of particles for which the standard test procedure can apply under the specified test conditions for in-duct devices

Findings to Date – Technology Evaluation

- Media filtration and electronic precipitation are two effective methods to remove indoor particulate contaminants.
  - The single portable electronic air cleaner tested had better performance than other portable air cleaners with HEPA filters, but generated certain amount of ozone.
- Sorption and UV-photocatalytic oxidation are two effective methods to remove indoor VOC contaminants.
  - The tested ionizer only had very modest removal capacity for particulates, no significant removal effect for all the tested VOCs, and generated significant amounts of ozone.
  - More in-depth byproduct investigations with ethanol and butanol are needed for UV-PCO devices.

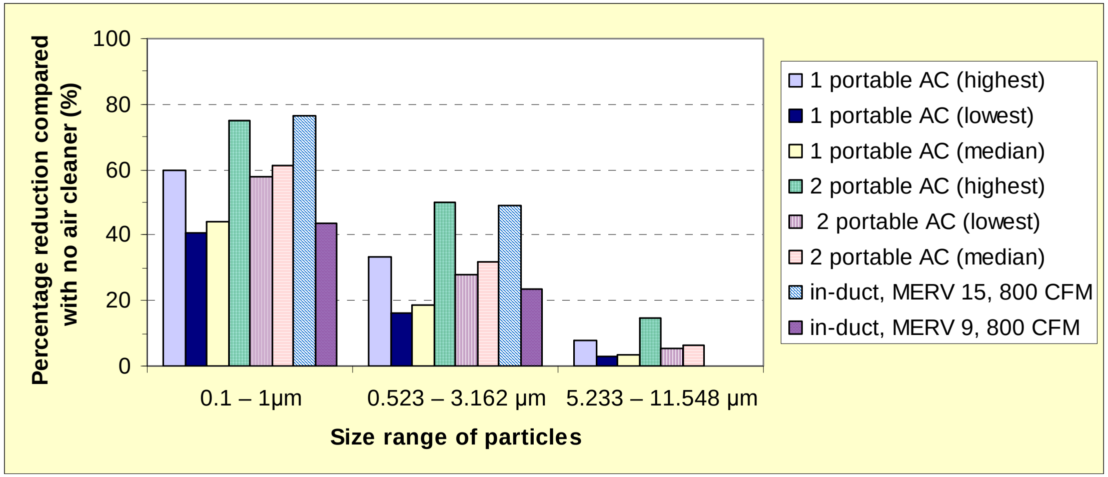
Findings to Date – Test Procedure Development

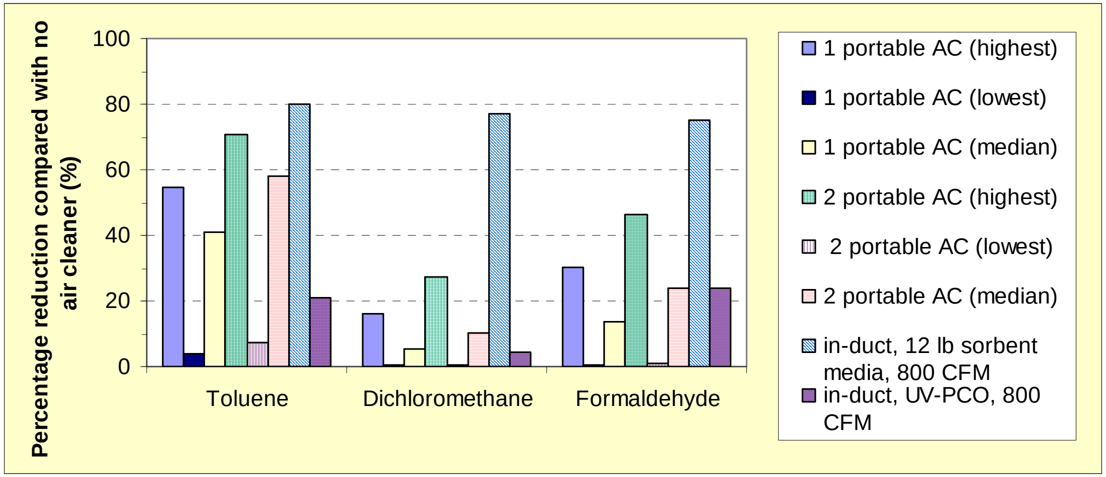
- The proposed test procedure with combined VOCs and particle injection worked well for portable air cleaners.
- Due to the large test airflow rate (800 CFM), CADR could not be determined or would have large uncertainties for particles with large diameters (i.e., >3.162µm).
- The maximum diameter of particles for which the proposed test procedure can be applied needs to be determined under the specified test conditions.
- There is a need to determine the removal efficiency as a function of airflow rate/air velocity through devices.

Effectiveness of Current Air Cleaners for Improving IAQ

- Seeks to address:
  - How much additional percentage reduction of contaminant concentration can be obtained above a ventilation only approach if an air cleaner is used?
  - If an air cleaner is to be used to substitute some mechanical ventilation to maintain a pre-defined concentration level, how much energy can be saved?
- As a first approximation, the initial performance data (CADR and watts/CFM CADR) obtained from this project were used assuming that the air cleaner maintains its initial removal efficiency during its service life
- In Task 8, steady-state well-mixed single zone model and degree day method were used
- In Task 05-03, IAQ software (i.e., MEDB-IAQ or CONTAMW) and energy simulation software (i.e., EnergyGauge) will be used for more accurate evaluation

Steady-state Calculation Results (Task 8) /1





Calculated percentage reductions in concentration for base-case of 0.35 ACH ventilation

Steady-state Calculation Results (Task 8) /2

Annual energy cost comparison of using an air cleaner to substitute 0.2 ACH of mechanical ventilation for Syracuse, NY

	Base case with 0.2 ACH mechanical ventilation	0.2 ACH equivalent clean air provided by a portable air cleaner (based on most efficient product tested)			
		Particulates	Toluene	Formaldehyde	Dichloromethane
Annual electricity (kWh)	403				
Annual natural gas (therms)	219				
Annual energy cost ($)	$72.30				
Annual electricity by air cleaner (kWh)		106	212	370	1904
Annual operation cost of air cleaner		$12.30	$24.50	$42.90	$220.60
HVAC benefit (or penalty) due to the heat release of air cleaner		Neglected	Neglected	Neglected	-$2.80
Annual cost savings compared to base case		$60.00	$47.70	$29.40	-$151.20

Notes: (1) Only ventilation-related or air cleaner-related energy consumptions (gain) were considered

(2) Negative numbers indicated that the use of air cleaner cost more compared to the base case.

References

- Final report published:
  Wenhao Chen, W., Gao, Z., Zhang, J., Kosar, D., Walker, C.E., Novosel, D. 2006. National Center For Energy Management And Building Technologies Task 8: Reduced Energy Use Through Reduced Indoor Contamination In Residential Buildings. Final Report NCEMBT-061101. Alexandria, VA: National Center For Energy Management And Building Technologies
  and available for download at http://www.ncembt.org/downloads.html;
- Scientific paper:
  Zhang, J. and W. Chen. 2006. Laboratory Testing of Air Cleaners for Removing Indoor Contaminants. Proceedings of International Specialty Conference: Indoor Environmental Quality - Problems, Research and Solutions. Pittsburgh, PA: Air & Waste Management Association

Thank you!