Reducing In-Home Exposure to Air Pollutants

Brett Singer (PI)
Woody Delp, Doug Black, Hugo Destaillats, Iain Walker
Lawrence Berkeley National Lab

Sacramento, CA
March 24, 2016
Disclaimer

The statements and conclusions in this presentation are not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.
Acknowledgements

- Balance Point Home Performance: G. Healy, D. Perunko
- ARB: P. Jenkins, M. Gabor, Z. Zhang, HJ Lee
- System C Prototype Filter w/Catalyst: Frank Hammes of IQAir
- Technical Advisory Committee: Wenhao Chen, Rob Hammon, Marla Mueller, Maziar Shirakh, and Bruce Wilcox
Homes can be designed to reduce our exposure to air pollutants

- We spend most of our time indoors, much of it at home
- Many California homes impacted by ambient air pollution
- Pollutant loss and removal as air enters and resides in buildings reduces concentrations relative to outdoors
- Engineered ventilation and filtration can further reduce exposures
- California requires new homes to be airtight for energy efficiency and to have mechanical ventilation
- ARB concerned that some types of mechanical ventilation could increase in-home exposure to outdoor pollutants
Study Objectives

- Quantify effectiveness of ventilation and filtration systems at reducing in-home exposures to pollutants
- Focus on PM$_{2.5}$, ultrafine particles and black carbon (diesel PM) from outdoor sources
  - Secondary focus on ozone, VOCs and indoor generated particles
- Identify compatible low-energy systems suitable to California and quantify energy use of these systems relative to Reference
Residential Airflows

Windows closed: air enters via cracks & gaps

Recirculation through heating & cooling forced air unit (FAU) –

Envelope air-sealed for energy efficiency

Airtight homes have base mechanical ventilation
- Exhaust
- Supply
- Balanced
Enhanced air cleaning options

- **Indoor-generated pollutants**
  - Filter on forced air unit (FAU); helps when heating or cooling
  - Operate FAU specifically to clear air
  - Room air cleaners*

- **Outdoor pollutants**
  - Filter pollutants from indoor air after entry
  - Supply or balanced ventilation: Add filter in-line
  - Exhaust ventilation: Envelope acts as a filter

*Not a focus of this study; examined in other ARB sponsored studies
Filter effectiveness indicated by MERV rating

**MERV7**

- Filter Efficiency (%)
- Size (μm)

**MERV12**

- Filter Efficiency (%)
- Size (μm)
Ventilation & Enhanced Pollutant Removal

- Reference + 7 systems with enhanced removal
- Exhaust, supply and balanced ventilation
- Particle filtration:
  - MERV8 to MERV13 on supply
  - MERV4 to MERV16 or electrostatic precipitator on FAU
  - HEPA on FAU bypass, portables with HEPA
- VOC removal technologies
  - Activated carbon
  - Chemisorbent
  - Room temperature catalyst
Approach

- Compare systems with enhanced pollutant removal to each other and to a common, “reference” system
- Install in test house and operate 5-7 d in summer & fall/winter
- Measure air pollutants and energy
- Evaluate particle removal for indoor source (cooking)
- Key metrics are ratio of indoor-to-outdoor (I/O) concentrations, percent reductions in pollutant levels, and annual energy
Reference:
Exhaust ventilation; MERV4 on FAU t-stat control

Exhaust

Exhaust Fan

Return

1" Filter
(MERV 4)

Thermally Conditioned Supply

Bath fan draws 6.5W
A: MERV13 on continuous supply; MERV4 on FAU t-stat control

Extra power relative to Reference: 2W (est.)
B: MERV13 on continuous supply; electronic air cleaner (ESP) + MERV4 on FAU w/t-stat control

Extra power relative to Reference: 20 W
C: MERV16 w/catalyst\(^1\) on blended supply; MERV4 on FAU t-stat control

\(^1\)For VOC removal
D: MERV8 on supply, MERV16 + chemisorbent\(^1\) on FAU operating 20 min each hour

Extra power relative to Reference: 240 W*  
*Could be reduced with efficient FAU motor

\(^1\)For VOC removal
**E: Exhaust ventilation + MERV13 on FAU operating min. 20 min each hour**

Extra power relative to Reference: 235 W*

*Could be reduced with efficient FAU motor
F: Exhaust ventilation + MERV13 on “Mini-split”

Extra power relative to Reference: 100 W
G: MERV8 on supply; HEPA+ activated carbon\(^1\) on FAU operating 20 min each hour

Extra power relative to Reference: \(~300\) W\(^*\)

*Includes estimated energy recovery by HRV. Could be reduced with efficient blower motor.

\(^1\)For VOC removal
Reference + Portable Air Filtration Units:

Extra power relative to Reference: 8-30 W
Test House: Impacted by I-80, Sacramento
Test House – Typical California Construction

- Built 2006
- 1,200 ft²
- 3 bedroom, 2 bath
- One story slab foundation
- FAU in attic
Sampling locations

Outdoor

At roofline just above the main inlet

Indoor

Centrally located

Indoor & outdoor sample lines had equal length and turns!
Continuous pollutant measurements

CPCs

3787
Total count
6 nm - 2.5 μm

3781 w/ Size Selector
Total count
100 nm - 2.5 μm

Met One

OPC

0.3 μm - 0.4 μm
0.4 μm - 0.5 μm
0.5 μm - 0.7 μm
0.7 μm - 1.0 μm
1.0 μm - 2.5 μm

Aethalometer

BC & UV

2B Technologies
Ozone

DustTrak
PM$_{2.5}$

Mass estimated from size-resolved particle number concentrations
Speciated VOC and Volatile Aldehydes

- 31 VOCs, indoor and outdoor origin
- 24-h integrated samples for 2-4 d in summer
- 3 systems w/VOC removal technology and Reference
Robustness and data integrity

- Parallel systems switching indoor and outdoor
  - Continuous cross-checks of particle instruments
  - Continuity through any single instrument failure
Key parameter is indoor/outdoor ratio. Log scale shows consistent results as levels vary.

I/O 0.05
95% Reduction

I/O 0.75
25% Reduction

Illustrates the absolute reduction

Illustrates the relative reduction
Example Results: Reference

System Reference  0.5 - 0.7 μm

- Indoor
- Outdoor

Particles L⁻¹

Averaging
- 1 min
- 1 hr
Example Results: Reference

System Reference 0.5 - 0.7 μm

Particles L⁻¹

Indoor
Outdoor

Particles L⁻¹

Averaging
1 min
1 hr
24 hr

3 4 5 6 7 8 9
Jul

Thermally Conditioned
Supply
Exhaust
Return

Exhaust Fan

1" Filter (MERV 4)
Example Results: Reference

System Reference 0.5 - 0.7 μm

- Indoor/Outdoor
- 1 min
- 1 hr
- 24 hr
- 24 hr
- Peak 1 hr
- Averaging

Particles L⁻¹

Indoor
Outdoor

0.2
0.4
0.6

3 4 5 6 7 8 9

Jul

60-80%

Exhaust
Thermally Conditioned
Supply
Exhaust
Fan
1" Filter (MERV 4)
Return
Better Performance: System D (MERV16)

System D 0.5 - 0.7 μm

Averaging
1 min
1 hr
24 hr

Particles ·L⁻¹

Indoor
Outdoor

96-98%
Summary Results: Outdoor Particles

- Effectiveness varied: UFP > PM$_{2.5}$ > BC
- Best particle removal:
  - MERV16 on supply (C)
  - MERV16 on FAU (D)
  - MERV13 on minisplit (F)
  - Portables with HEPA
  - MERV13 on FAU (E)
- Similar results in summer & fall/winter, except for Sys B with ESP on t-stat

PM$_{2.5}$ estimated from size-resolved particle concs.
## Percent reductions in particle concentrations compared to outdoors (SU, F/W)

<table>
<thead>
<tr>
<th>System</th>
<th>PM$_{2.5}$</th>
<th>Black carbon</th>
<th>Ultrafine particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref: modestly tight shell + exhaust ventilation</td>
<td>73, 66</td>
<td>58, 48</td>
<td>87, 84</td>
</tr>
<tr>
<td>A: MERV13 on continuous supply</td>
<td>67, 63</td>
<td>40, 38</td>
<td>82, 76</td>
</tr>
<tr>
<td>B: MERV13 on cont. supply + ESP on FAU</td>
<td>81, 70</td>
<td>73, 50</td>
<td>90, 77</td>
</tr>
<tr>
<td>C: MERV16 on blended supply</td>
<td>97, 98</td>
<td>92, 84</td>
<td>97, 99</td>
</tr>
<tr>
<td>D: Supply ventilation into return of FAU with MERV16 filter and 20/60 timer</td>
<td>97, 97</td>
<td>93, 96</td>
<td>98, 97</td>
</tr>
<tr>
<td>E: MERV13 on return of FAU on 20/60 timer with exhaust ventilation</td>
<td>91, 88</td>
<td>84, 80</td>
<td>93, 93</td>
</tr>
<tr>
<td>F: MERV13 on continuous ducted heat pump and exhaust ventilation</td>
<td>96, 95</td>
<td>86, 92</td>
<td>96, 96</td>
</tr>
<tr>
<td>G: HRV into return of FAU with HEPA bypass operating on 20/60 timer</td>
<td>79, 78</td>
<td>65, 68</td>
<td>83, 83</td>
</tr>
<tr>
<td>Ref + Portable HEPA units</td>
<td>(na), 90</td>
<td>(na), 85</td>
<td>(na), 91</td>
</tr>
</tbody>
</table>
Removal during outdoor air entry to home

- All have lowest performance for 0.3-0.4 um particles as predicted by theory
- Tight shell looks better than the supply MERV13 and HRV
Performance for indoor particles

[Graph showing SF$_6$ and PM$_{2.5}$ levels during cooking and system operation phases.]

- SF$_6$ levels:
  - Cooking: 0.172 hr$^{-1}$
  - System Operation: 0.0632 hr$^{-1}$, 0.71 hr$^{-1}$, 0.616 hr$^{-1}$

- Estimated PM$_{2.5}$ (μg m$^{-3}$):
  - Cooking: 0.958 hr$^{-1}$
  - System Operation: 5.54 hr$^{-1}$, 5.47 hr$^{-1}$, 0.493 hr$^{-1}$
Summary Results: Cooking Particles

- Sys F and portables: continuous filtration of indoor air
- Sys D & E: intermittent filtration of indoor air — depends on timing
- B, D, E effective when operated continuously
- Sys C (MERV16 on blended supply) does almost nothing for indoor particles

Percent reduction in 1 h time-integrated PM$_{2.5}$ relative to reference conditions
Good performance requires high removal efficiency + airflow

- Filters from C (MERV16) and G (HEPA on bypass) have high removal efficiency, but not enough airflow
- ESP of Sys B and MERV16 of Sys D have both high removal efficiency and enough airflow
Ozone very low inside. Credit tight envelope.

Ozone was below quant limit indoors for Reference & other systems.
VOC levels were ~20 times higher indoors

- **Outdoor VOCs**: alkanes and aromatic hydrocarbons (motor vehicle emissions)
- **Indoor VOCs**: aldehydes, alcohols, terpenoids, siloxanes (material emissions, household products)
The relative difference in indoor concentrations between each system and the reference system, $\% \Delta C$, is defined as follows:

$$\% \Delta C = \frac{C\text{(System C/D/G)} - C\text{(Reference System)}}{C\text{(Reference System)}} \times 100$$

Main assumption: source strength of VOCs remained constant over the month during which measurements were carried out.
Experimental conditions during VOC tests

<table>
<thead>
<tr>
<th>System</th>
<th>ACH (h⁻¹)</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>T (°C)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>st dev</td>
<td>average</td>
<td>st dev</td>
<td>average</td>
</tr>
<tr>
<td>REF</td>
<td>0.29</td>
<td>0.00</td>
<td>24</td>
<td>0</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>26</td>
<td>0</td>
<td>44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>ACH (h⁻¹)</th>
<th>T (°C)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>0.31</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>0.28</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.25</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

Temp. and AER variations cannot account for observed VOC reductions. Lower AER for Sys C suggests performance for catalyst better than simple calculation.
**Limited removal efficiency for formaldehyde**

- Formaldehyde is difficult to remove with most air cleaning methods.

- The chart shows that formaldehyde removal efficiency varies among different methods:
  - Activated carbon: 7%
  - Chemisorbent: 5%
  - Catalyst: 15%

- **Formaldehyde**

- **Removal efficiency**

- **Activated carbon**: 7%
- **Chemisorbent**: 5%
- **Catalyst**: 15%
The three systems showed significant removal efficiencies for many VOCs.

<table>
<thead>
<tr>
<th>Removable Compound</th>
<th>Activated carbon</th>
<th>Chemisorbent</th>
<th>Catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>o-Xylene</td>
<td>29 %</td>
<td>49 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Hexanal</td>
<td>26 %</td>
<td>51 %</td>
<td>26 %</td>
</tr>
<tr>
<td>2-Butoxyethanol</td>
<td>24 %</td>
<td>29 %</td>
<td>23 %</td>
</tr>
<tr>
<td>d-Limonene</td>
<td>48 %</td>
<td>59 %</td>
<td>13 %</td>
</tr>
</tbody>
</table>
Estimate annual fan energy consumption

- Start with FAU run-time for heating and cooling, determine extra hours for intermittent systems.
  - Results from residential energy simulation models
  - Relatively consistent across state b/c systems sized to climate
  - Roughly 800 h baseline; +2400 for 20/60 intermittent

- Multiply by power when operating.
Estimated annual fan energy consumption

![Bar chart comparing energy consumption for different systems and motor types.](chart)

- **Standard PSC Motor**
  - System Ref: 15 kWh
  - System A: 34 kWh
  - System B: 259 kWh
  - System D: 1,454 kWh
  - System E: 1,439 kWh
  - System G: 2,116 kWh
  - Port: 173 kWh

- **BPM Motor (Efficient)**
  - System Ref: 15 kWh
  - System A: 34 kWh
  - System B: 259 kWh
  - System D: 635 kWh
  - System E: 588 kWh
  - System G: 1,756 kWh
  - Port: 173 kWh

The chart illustrates the energy consumption for different systems and motor types, with the BPM Motor being more efficient.
Key Results – Outdoor Particles

- The Reference configuration of exhaust ventilation in a moderately tight home reduced concentrations relative to outdoors by 66-73% for PM$_{2.5}$, 48-58% for BC and 84-87% for UFP.

- Supply ventilation with a MERV13 filter yielded slightly higher in-home concentrations of outdoor particles compared to Reference.

- MERV16 on supply ventilation or FAU operating intermittently lowered PM$_{2.5}$ by 97-98%, BC by 84-96% and UFP by 97-99%.

- MERV13 deep pleat filtration on continuous ducted heat pump reduced PM$_{2.5}$ by 95-96%, BC by 86-92% and UFP by 96%.

- A 1” MERV13 filter at the FAU return reduced PM$_{2.5}$ by 88-91%, BC by 80-84% and UFP by 83% compared to outdoors.

BC = Black carbon; UFP = Ultrafine particles
Filtration on supply ventilation provides no benefit for indoor generated particles.

For systems with intermittent filtration, reductions for cooking particles vary with timing of fan operation.

When operated continuously, all recirculating air systems had some benefits in reducing $1h\ PM_{2.5}$

- MERV4 on FAU reduced $1h\ PM_{2.5}$ by ~25%.
- ESP or MERV16 on FAU reduced $1h\ PM_{2.5}$ by ~75%
- MERV13 on FAU / heat pump reduced $1h\ PM_{2.5}$ by 65-70%
Available technologies can cut VOC levels
- Indoor BTEX levels reduced by three air cleaning systems between 8% and 49% with respect to Reference system

Need to consider both airflow and single pass removal efficiency for effectiveness

Possible to get high particle removal rates with low pressure drop filters

Filtration on ducted supply is lowest energy approach to cleaning outdoor air

Filtration on forced air system with standard blower motor uses a lot of energy for an efficient home

Efficient blower motors enable low-energy air cleaning; continuous low speed operation is most efficient