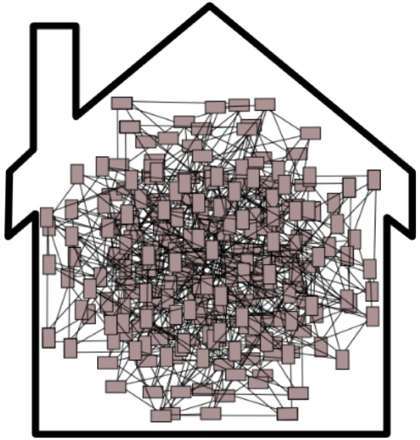
Air Cleaners & Indoor Chemistry



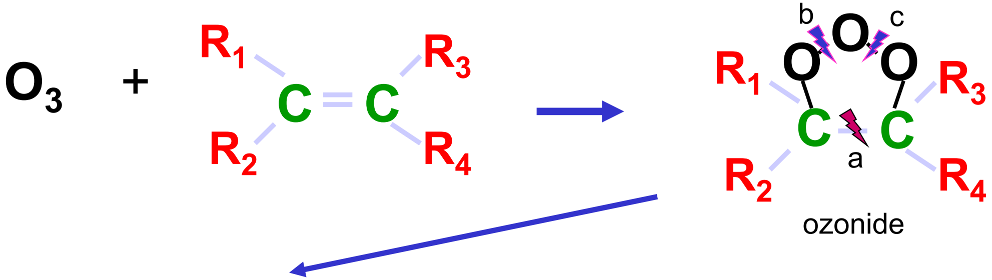
@CorsIAQ

Richard L. Corsi, Ph.D., P.E.

H. Chik M. Erzurumlu Dean
Maseeh College of Engineering and Computer Science
Portland State University

Joe J. King Chair in Engineering #2
Dept. of Civil, Architectural & Environmental Engineering
The University of Texas at Austin

Ozone + Unsaturated Organic Compounds



R_1R_2CO + $R_3R_4C^{*}OO^{*}$; **more rxn products**

R_3R_4CO + $R_1R_2C^{*}OO^{*}$; **more rxn products**

Free radicals (OH, HOO, ROO, ..)

Other short-lived intermediates

Carbonyls (mono-, di-)

Organic acids

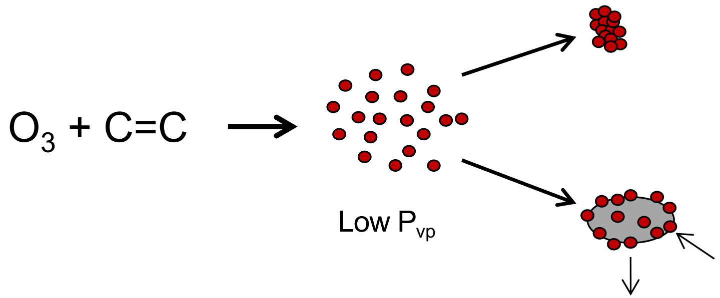
Peroxides

Indoor SOA (iSOA)

- Σ stable gaseous rxn products can be 2-3 x O_3
- Reactions occur in air & on surfaces
- Health effects of products not well understood

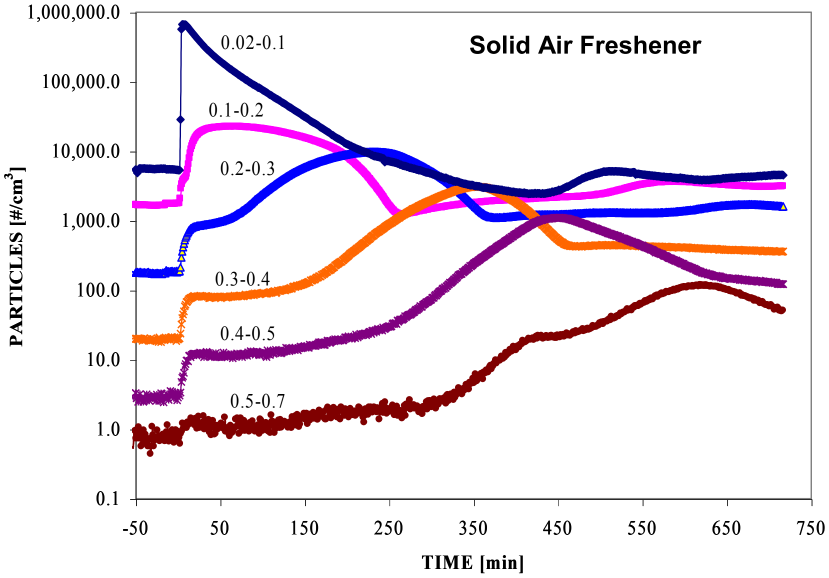
A lot of additional chemistry: OH, NO/NO_2, HONO, chlorine, ammonia ..

Indoor Secondary Organic Aerosols



Indoor SOA

- Ozone + alkenes present
- OH + HC present
- Charged VOCs (ions) present

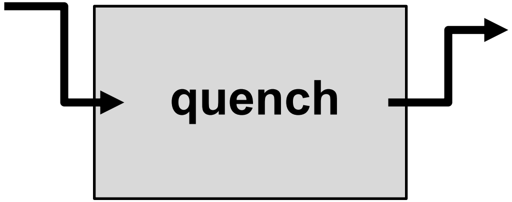


Sarwar G., et al., *J Air & Waste Man Assoc.*, 54: 367-377 (2004)

Quench (Control) vs. Create

In-duct or In-room

PM / VOCs / O_3

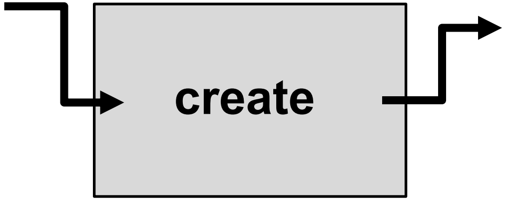


- Less PM
- Less VOCs
- Less ozone

$$C = \frac{pC_o + E/\lambda V}{1 + \sum k_b C_j/\lambda + k_d/\lambda + \eta Q_c/\lambda V}$$

ηQ_c = CADR

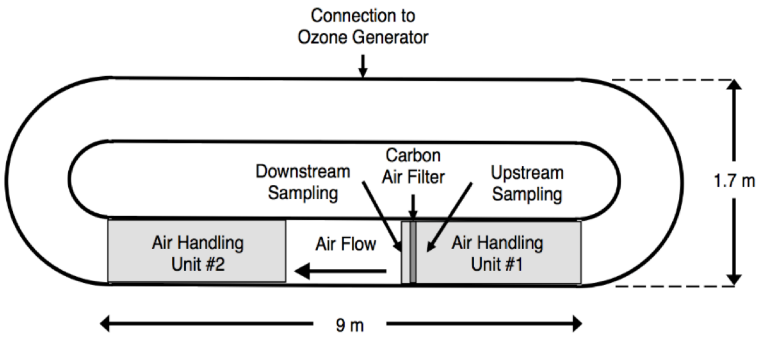
PM (w/ bacteria/viruses) / VOCs



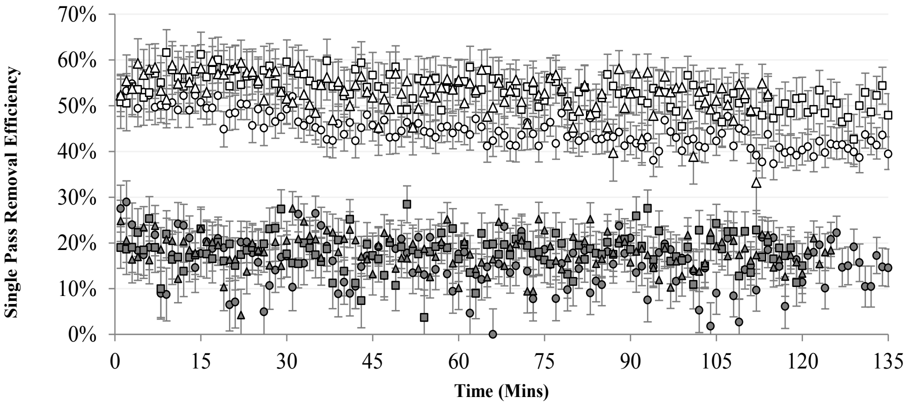
Ions
Ozone
OH*

- Less PM?
- Less VOCs?
- Bacteria kill?
- Virus inactivation?

Activated Carbon Filtration



University of Texas Duct Simulator



Bulk AC filter replicates

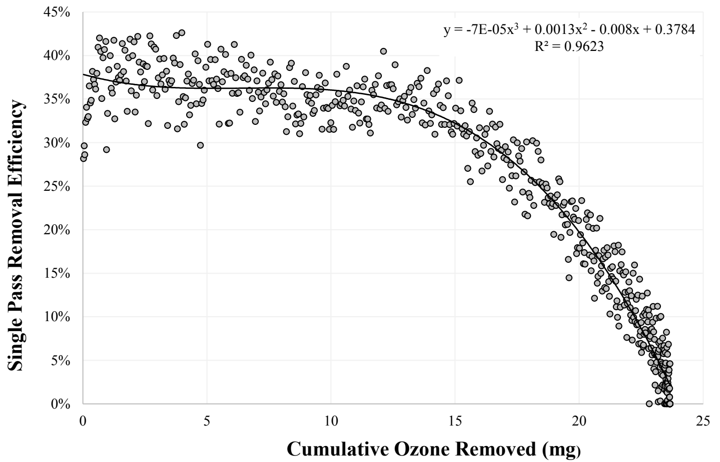
Slurry AC filter replicates

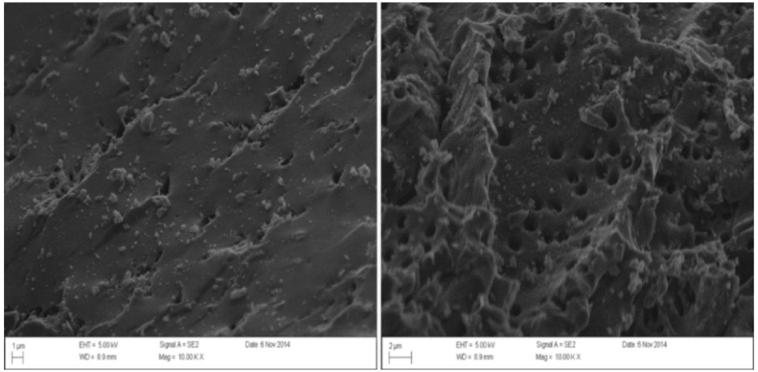
Aldred, J., Doctoral Dissertation, University of Texas at Austin (2015)

Activated Carbon Filtration

- Effectiveness for O_3 removal decreases with time
  - Consumption of reaction sites
  - Acidic surface oxidation complexes
  - Physical decomposition of AcC

Alvarez, P. M., et al. *Industrial & Engineering Chemistry Research, 47*(8), 2545–2553 (2008)

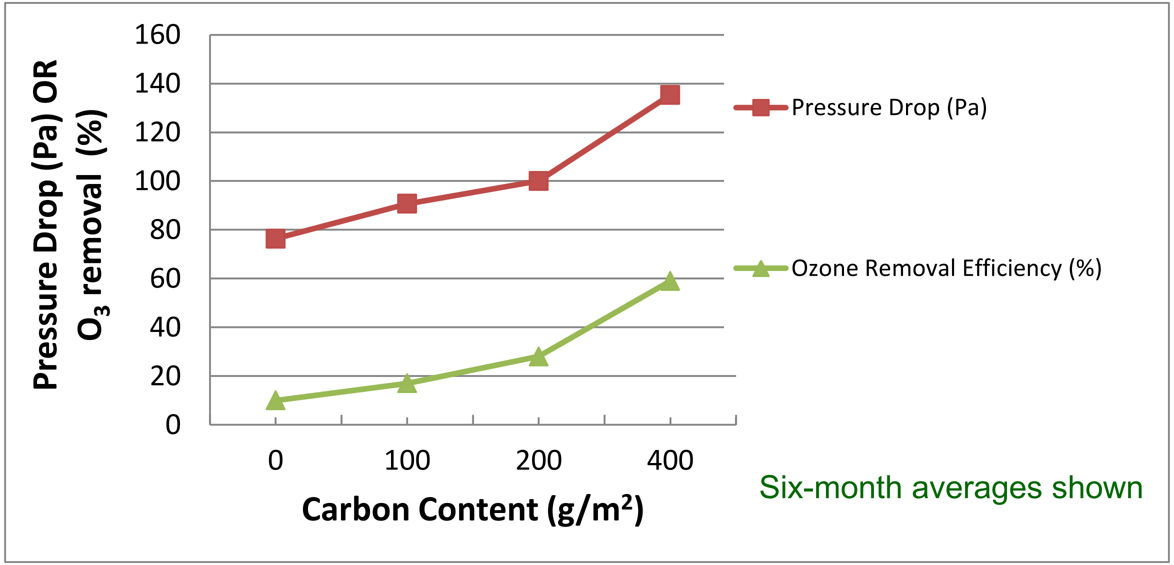




Aldred, J., Doctoral Dissertation, University of Texas at Austin (2015)

Amount of Activated Carbon / Area Matters

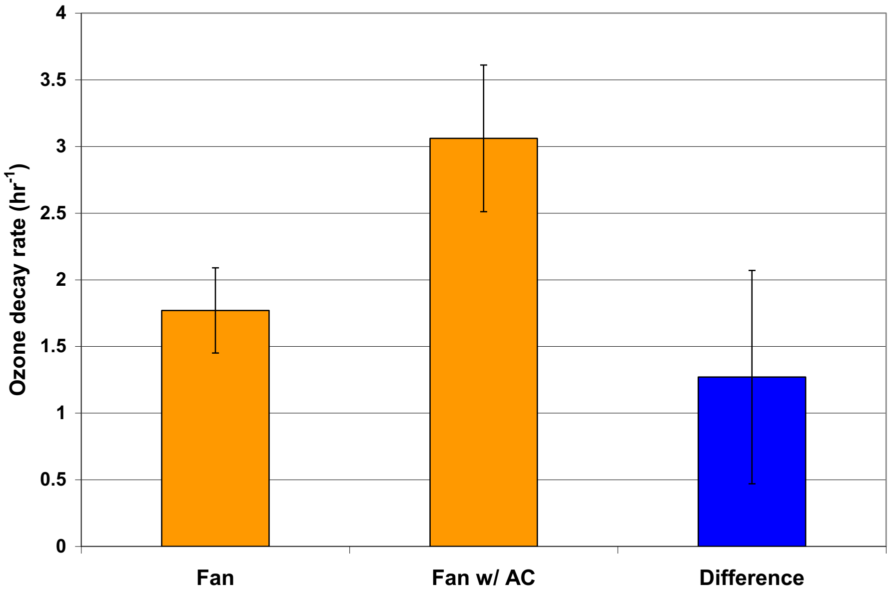
- Six months of continuous field testing (varied g/m²)
- (0.6 m x 0.6 m x 0.3 m) = (24" x 24" x 12") w/ ≈ 1,300 cfm



Bekö, G., et al., *Building and Environment*, *44*(10), 2114–2120 (2009)

Activated Carbon Fan Blade Sleeves

$$\frac{1}{v_d} = \frac{1}{v_t} + \frac{4}{\gamma \langle v_b \rangle}$$



- AC on fan blades: Mean O_3 decay increase = 1.25 hr^{-1}
- Average 33% decrease in indoor ozone

Kunkel D, *et al.*, *Building and Environment*, 45: 445-452 (2010)

Passive Removal Materials (PRMS)

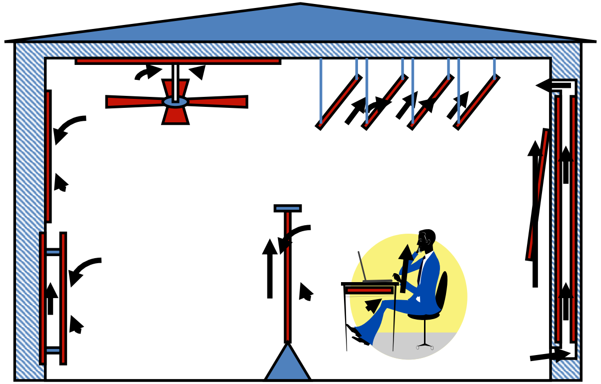
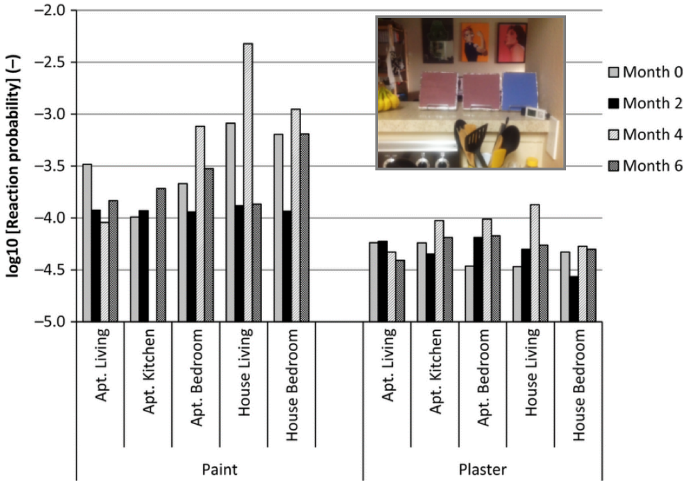


Image courtesy of Glenn Morrison



- High, sustained reactivity w/ O_3
- Minimal reaction product yield
- Large surface area
- Reduces other O_3 reactions

+

Clay paints & plasters (kaolinite)

- Removal of organic acids
- Buffers water vapor
- Improves PAQ

Lamble, SP, *et al.*, *Atmos Environ*, 45: 6965-6972 (2011); Darling, E, *et al.*, *Building and Environment*, 57: 370-376 (2012); Darling, E., et al., *Building and Environment*, 106: 33-44 (2016); Darling E. & Corsi RL, *Indoor Air*, 27 (3): 658-669 (2017)

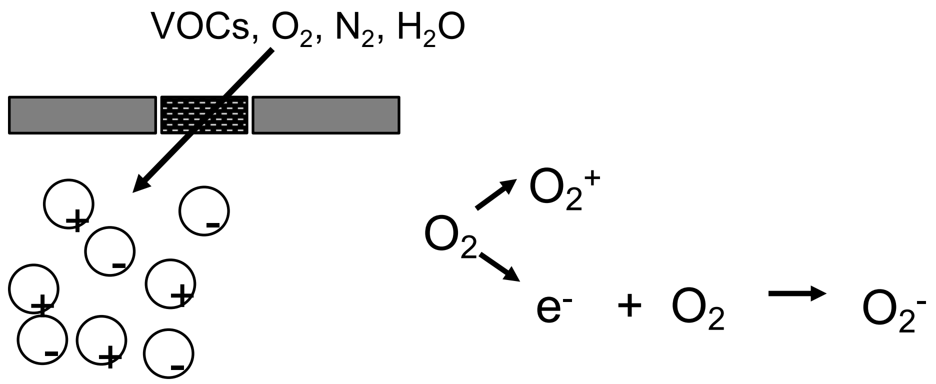
Ion Generators

- **Ionized hydrogen peroxide systems**
  "…contain a high concentration of Reactive Oxygen Species (ROS), consisting mostly of hydroxyl radicals (OH) as the killing agent."

- **Ion generators (plasma, unipolar, bipolar)**
  "…vastly superior to most air purification methods because it works "in the space" … doesn't wait for pollutants to find their way into the filter.."

Claims: Ion generators

- PM charged
  agglomerate → surfaces/filters
- Viruses inactivated
- Odors neutralized
  oxygen ions break down VOCs



Ion Generators

Ionization Energy (IE) = energy required to remove an electron from atom (molecule)

- High energy input = more ions = better performance = O_3 ↑
- Manufacturers that claim no O_3 generally aim for ≤ 12 eV
- Aged/dirty electrodes shown to increase O_3

Dorsey, JA., & Davidson, JH, *IEEE Transactions on Industry Applications*, 30(2): 370-378 (1994)

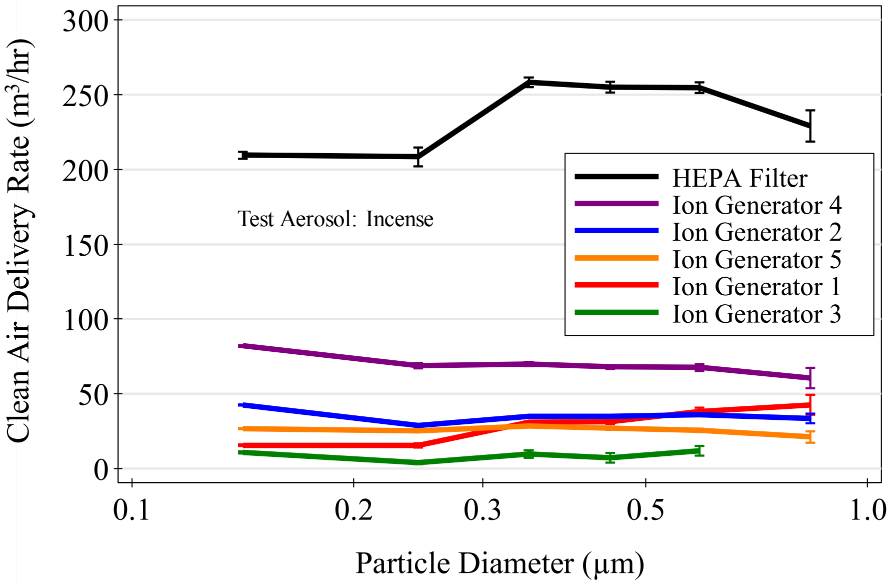
IE (eV): O_2 = 12.07; N_2 = 15.6; H_2O = 12.6

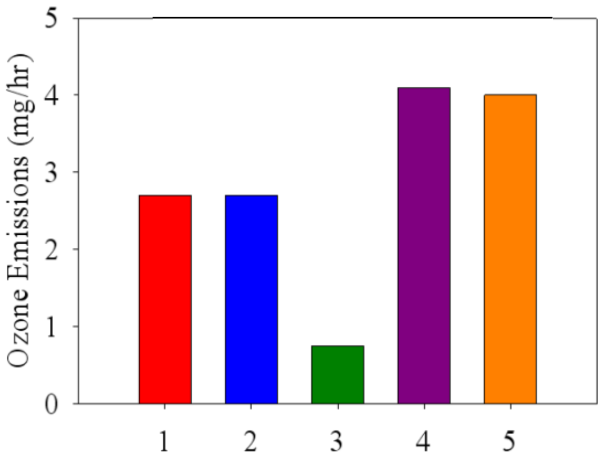
Ionizers designed to avoid ozone are insufficient to ionize major components of air

Most ions will be generated by VOCs

e.g., limonene (8.3); xylenes (8.6); toluene (8.8); HCHO (10.88); ethanol (10.48)

Ion Generators: Effectiveness & Ozone





O_3 Emissions – Ionizers

CADR: HEPA (not a great HEPA) > IG (CADR = ηQ_c)

Ion generators: lowest ozone emitter = worst CADR; highest ozone emitter = best CADR

Yu, X., et al., *Indoor Air 2005, Proc.10th Intl' Conf on Indoor Air Quality and Climate*, Beijing, China (2005)

Ion Generators

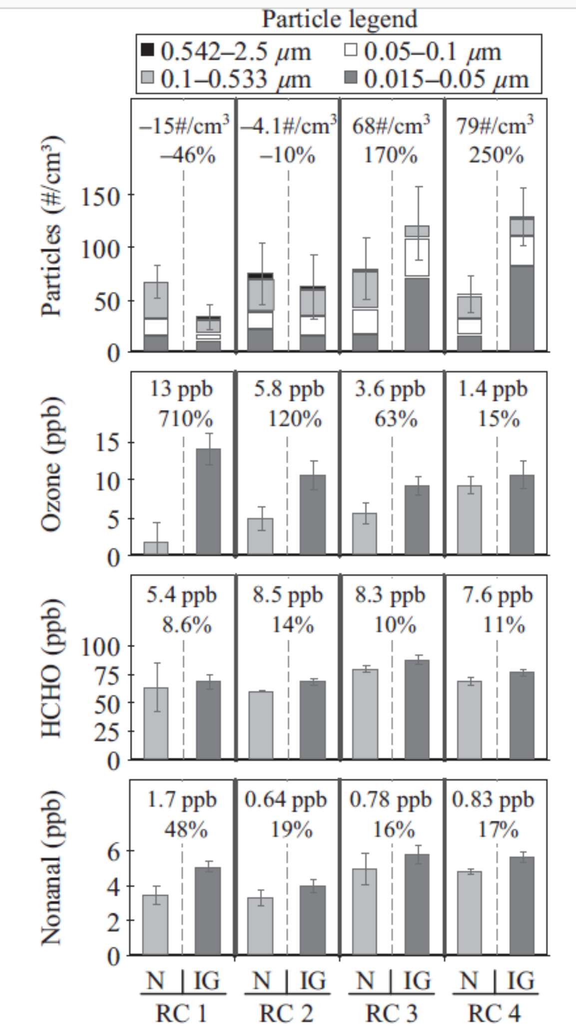
- Field study - 27 m^3 room in residence @ 0.5.h

RC 1: Original flooring of sealed/stained concrete, *without* air freshener

RC 2: Installed flooring of carpet with padding, *without* air freshener

RC 3: Original flooring of sealed/stained concrete, *with* air freshener

RC 4: Installed flooring of carpet with padding, *with* air freshener



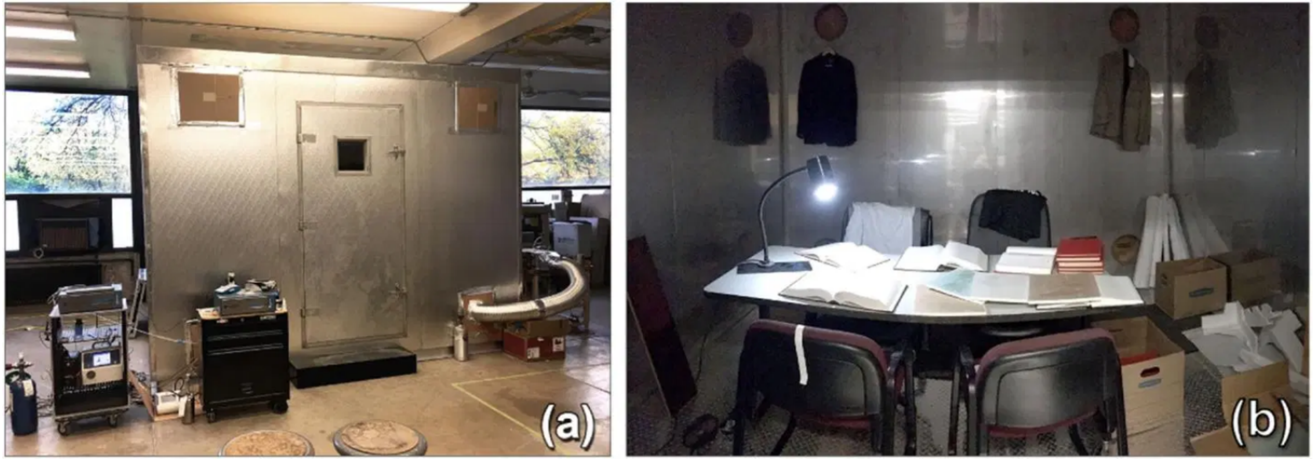
Waring, M.S. & Siegel, J.A., *Indoor Air, 21: 267-276* (2011)

Bipolar Ionization

- Several studies show benefits (PM, VOCs, pathogens)
  - Small volumes, near source
  - Extreme ion concentration = 10^6 – $10^7 cm^{-3}$
- Indoor air w/ in-room or in-duct ionizer: 2,000 – 20,000 cm^{-3}
  - Background ≈ 100 to 1,000 cm^{-3}
  - Context: 1 ppb VOC ≈ 2.5×10^{10} cm^{-3}
- Independent studies limited
  - **PM removal**: Translatable info?
  - **Viruses**: Inactivation mechanism(s)?
  - **VOCs**: Removal pathways? Adducts?
  - **Rxn Products**: Neglected. Pathways?

?

Chamber Test: Bipolar Ionizer (BPI)



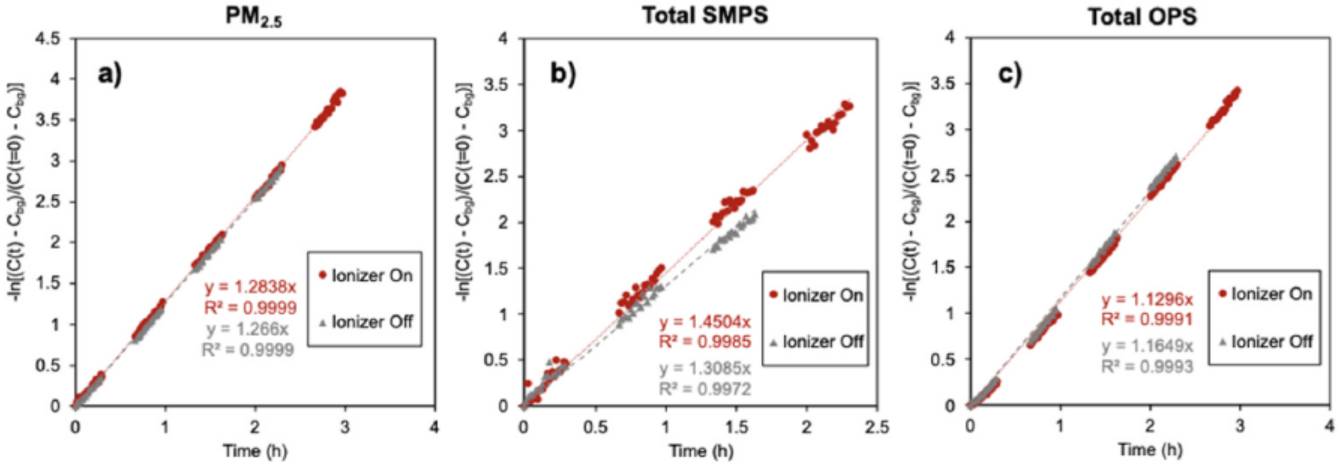
- Chamber: 36.7 m^3 equipped w/ aged emission sources
- Single pass ventilation w/ charcoal fiber filtered lab air @ 1.2 – 1.6/hr
- BPI system intended to ionize molecules w/ IE < 12.07 eV (less than O_2 = 12.07 eV)
- Ion concentration w/ ionizer off = 300 – 700 cm^{-3}; on = 1,400 to 2,000 cm^{-3}

Zheng, Y., et al., *Building and Environment*, 195 (2021) doi.org/10.1016/j.buildenv.2021.107750

Particle Decay: BPI On & Off

Particle decay (based on incense in chamber)

$PM_{2.5}$ estimated via SMPS + OPS | SMPS ≈ 0.01 to 0.3 μm | OPS = 0.3 to 10 μm



CADR (m^3/h): 0.7 | 5.2 | -0.3

Comparison: Good portable HEPA air cleaner: CADR = 500 m^3/h

Zheng, Y., et al., *Building and Environment*, 195 (2021) doi.org/10.1016/j.buildenv.2021.107750

BPI in Chamber: VOC Formation & Decay

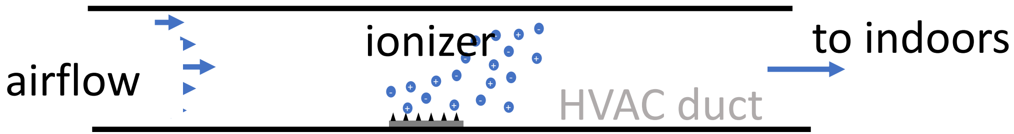
Analyte	% Change in I/O Ratio[1]
Formaldehyde	**+2%**
Acetaldehyde	**+13%**
Acetone	**+73%**
Butanal	**+28%**
Toluene	**+15%**
1,2-Dichloroethane	**< -42%**
Ethylbenzene	**< -64%**
m,p-Xylene	**< -78%**
Dichlorodifluoromethane	**< -17%**
Summed TOC	**-19%**

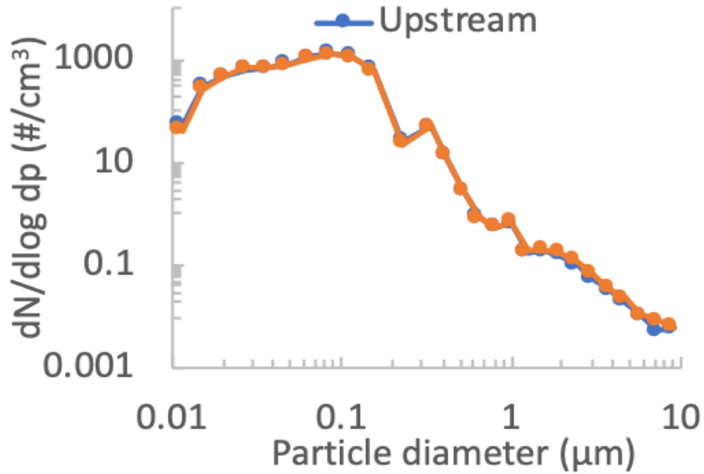
[1] values with < indicate measured value inside the chamber was below MDL

- Negligible particle removal
- Negligible ozone formation
- Higher MW VOC decay
- Toluene formation
- Low MW OVOC formation
  - IE < energy input
  - Rate of formation >> removal
  - Reaction pathway?

Zheng, Y., et al., *Building and Environment*, 195 (2021) doi.org/10.1016/j.buildenv.2021.107750

Application of BPI in Office Building

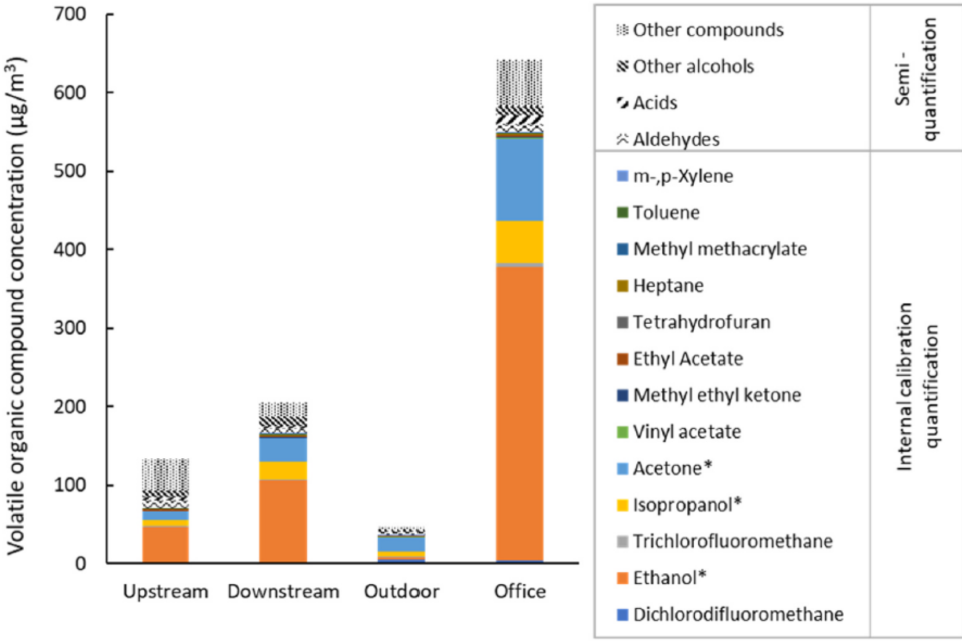




- Negligible particle removal
- Negligible O_3 formation
- Some OVOC production
- Some non-oxygenated HC removal

Plot/graphic courtesy of Elliott Gall, Portland State University

VOCs: BPI in Office Building



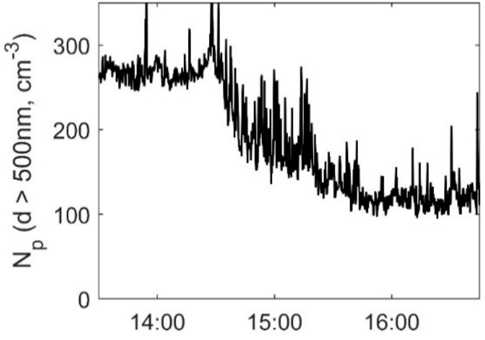
- Formed: several OVOCs
- Near vicinity of ionizer
  - 0.75 m downstream
- Significant increase out of duct

Zheng, Y., et al., *Building and Environment*, 195 (2021) doi.org/10.1016/j.buildenv.2021.107750

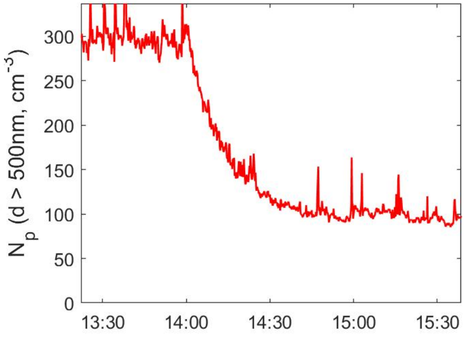
In-Room BPI v. Proven Approaches

Classroom: 363 m^3; NaCl aerosol particles (mean d_p = 2 µm); SS to intervention

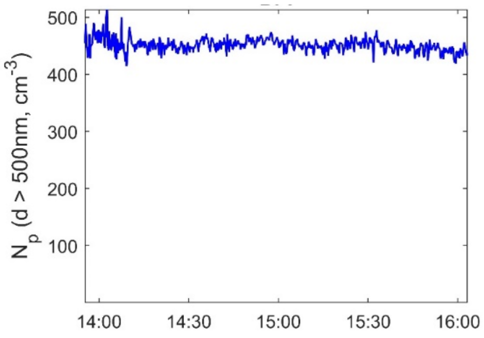
Test 1: Increase ventilation from 1.1 ACH – 4.6 ACH.



Test 2: Add in-room HEPA filtration equivalent to 1.1 ACH – 4 ACH.

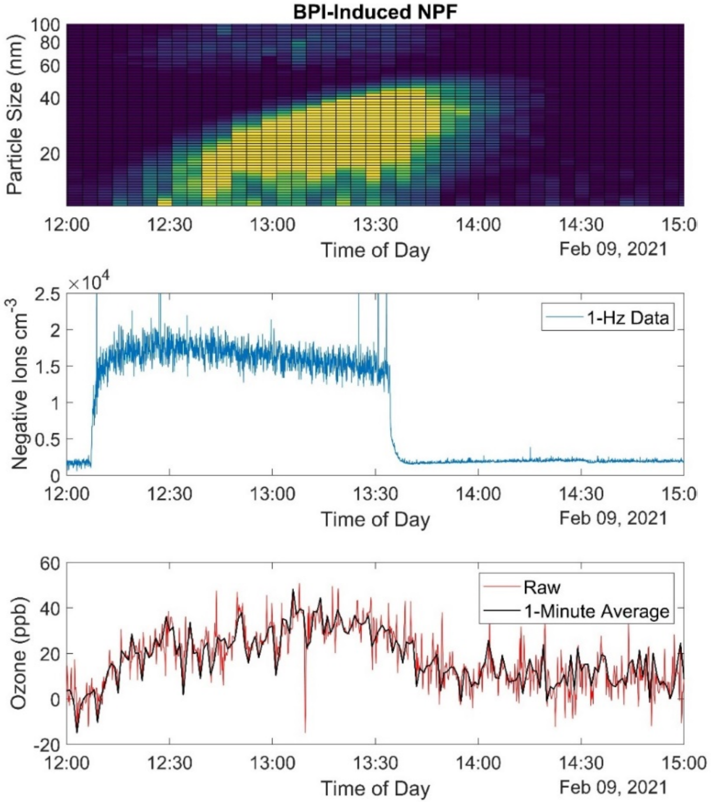


Test 3: Add in-room bipolar ionizer



Plots/findings courtesy of Bertram Research Group, U of Wisconsin-Madison

BPI in Classroom: UFP, Ions, Ozone



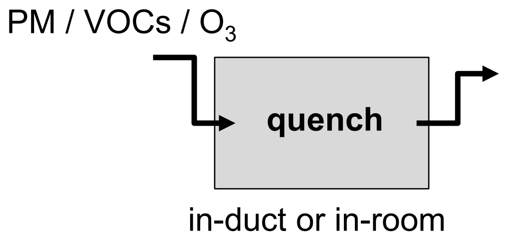
1. Strong UFP formation driven by ion-induced nucleation + in room VOC
2. UFP = *fn*(ion gen rate, existing aerosol A_{surf}, VOCs …)
3. In room ion lifetime < 1 min (Ion Decay rate > 110 h^{-1})
4. Rapid ion loss rates make in-duct ion delivery prohibitive
5. BPI can sustain in-room ion concentrations of 1-2 x 10^4 ions cm^{-3} with <u>strong</u> spatial gradients (ventilation 1 ACH)
6. No evidence of enhanced particle deposition by charging
7. BPI O_3 production

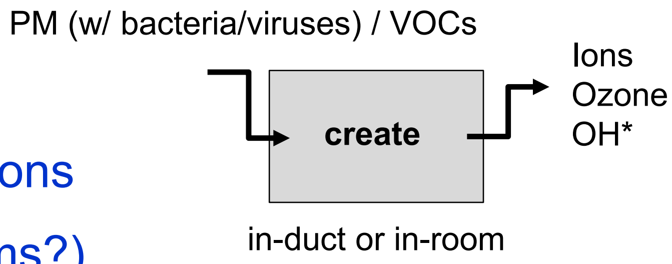
Red text added

Plots/findings courtesy of Bertram Research Group, U of Wisconsin-Madison

Summary

- Air cleaners can quench indoor ozone chemistry
- Ionizers cause some indoor chemistry
- Less energy = less O_3 = less ions = less effective
- Ionizers (becoming popular again)
  - Literature incomplete / problematic
  - Do not appear relevant for PM removal
  - Inactivation of viruses at extreme ion concentrations
  - Some VOCs degrade / OVOC form (mechanisms?)
  - Implications of by-products?
  - Speciation of ions?





Acknowledgements

Dr. Timothy Bertram, U of Wisconsin-Madison

Dr. Elliott Gall, Portland State University

Former students & colleagues who contributed to work herein:

Dr. Josh Aldred

Dr. Erin Darling

Donna Kunkel

Dr. Golam Sarwar

Dr. Michael Waring

Jeff Siegel

Glenn Morrison