Navigating the Landscape of Air Cleaning Technologies for COVID-19

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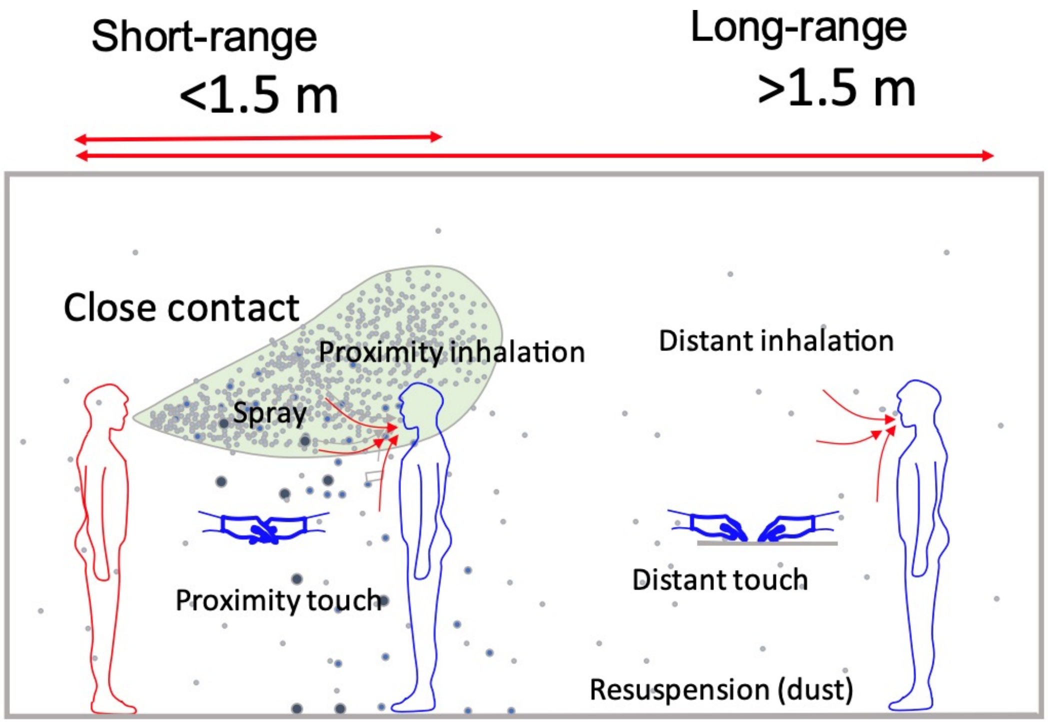
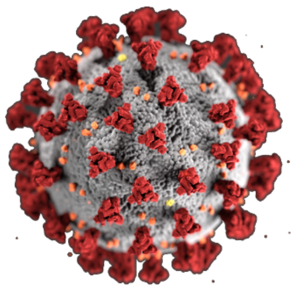
Transmission Routes of SARS-CoV-2



Li 2021, Indoor Air, 31:3–6

Possible routes of transmission:

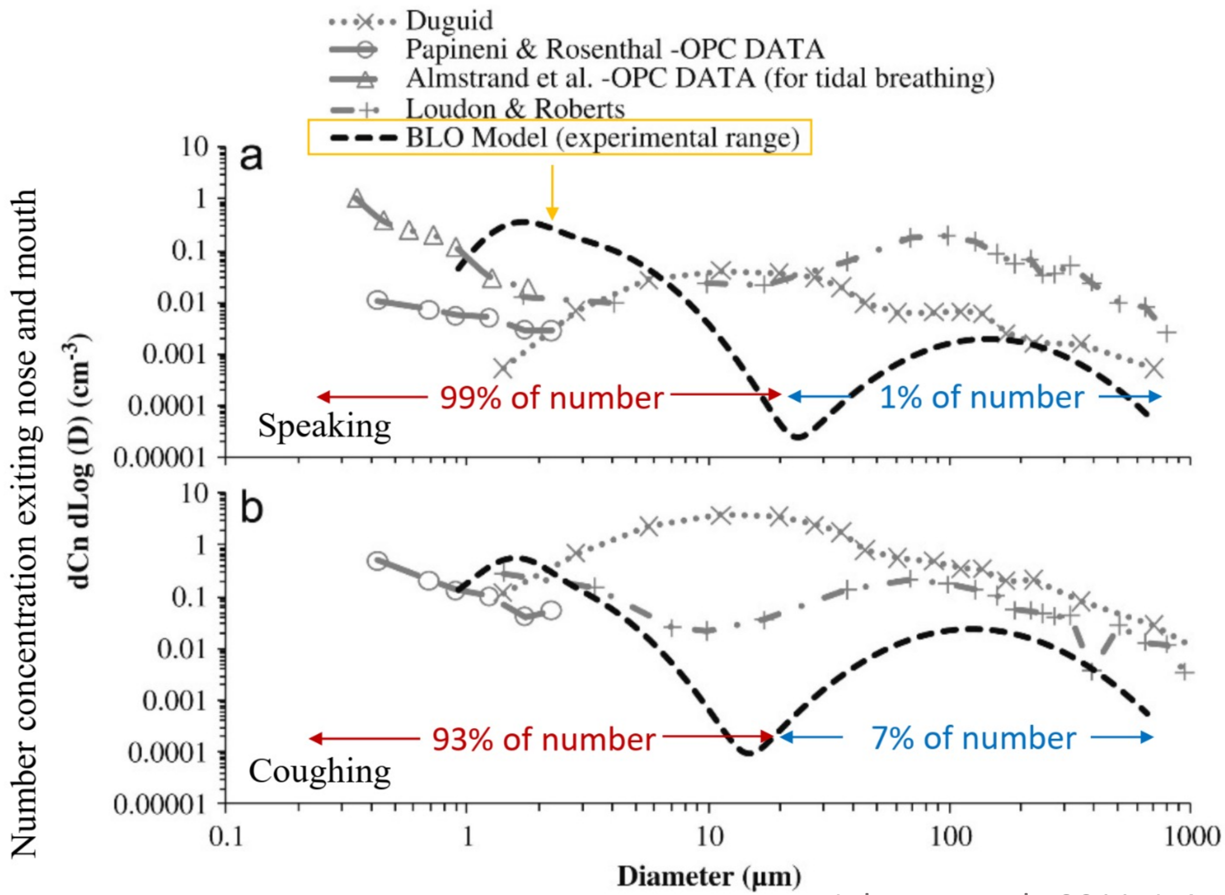
- Touching contaminated surfaces (both short and long rage)
  - *"Transmission of novel coronavirus to persons from surfaces contaminated with the virus has not been documented."* CDC, 2020[1]
- Large droplet spray (short range only)
- Aerosol inhalation (both short and long range)
  - *Aerosol inhalation is increasingly considered dominant.[2]*



Adapted from: cdc.gov

[1]CDC, 2020: www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cleaning-disinfection.html
[2]Greenhalgh et al. 2021 *The Lancet* 397(10285):P1603–1605

Human Respiratory Emissions of Particles



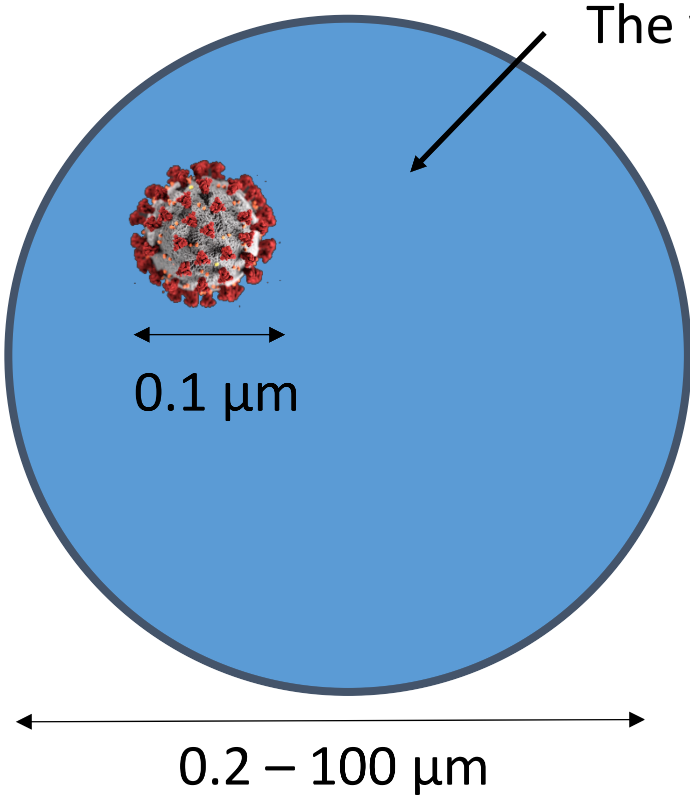
5 nl and 30 viral RNA copies from saying “Hello, World!”

125 nl and 900 viral RNA copies from one cough

Johnson et al., 2011, J. Aerosol Sci, 42, 839–851

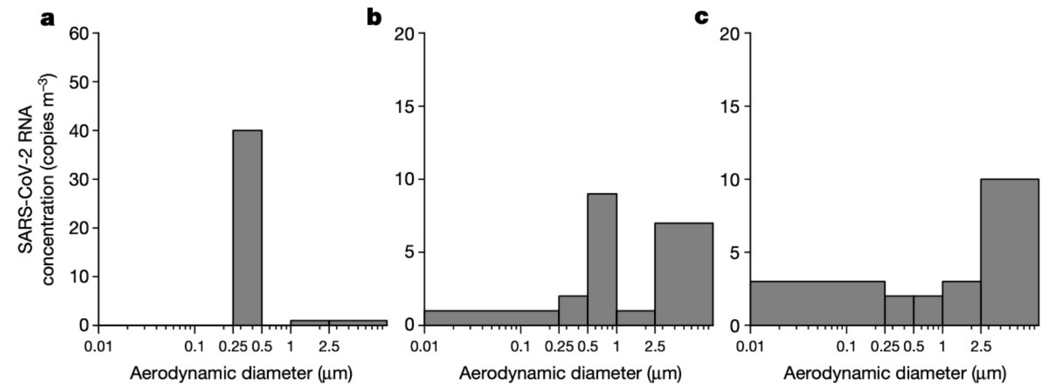
Slide source: Linsey Marr, Airborne Transmission of SARS-CoV-2: A Virtual Workshop, Aug. 26, 2020

SARS-CoV-2 in Indoor Air



The virus in air is enveloped in respiratory fluid.

There is evidence for SARS-CoV-2 in indoor particles across a range of sizes:



Liu et al., **2020** *Nature* 582:557-560

'A Smoking Gun': Infectious Coronavirus Retrieved From Hospital Air

Airborne virus plays a significant role in community transmission, many experts believe. A new study fills in the missing piece: Floating virus can infect cells.

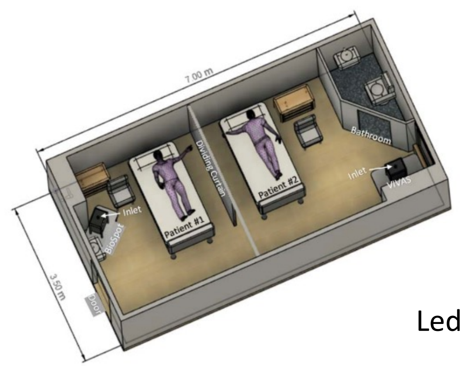


Table 3. Estimate of viable virus counts based on $TCID_{50}$ tests.

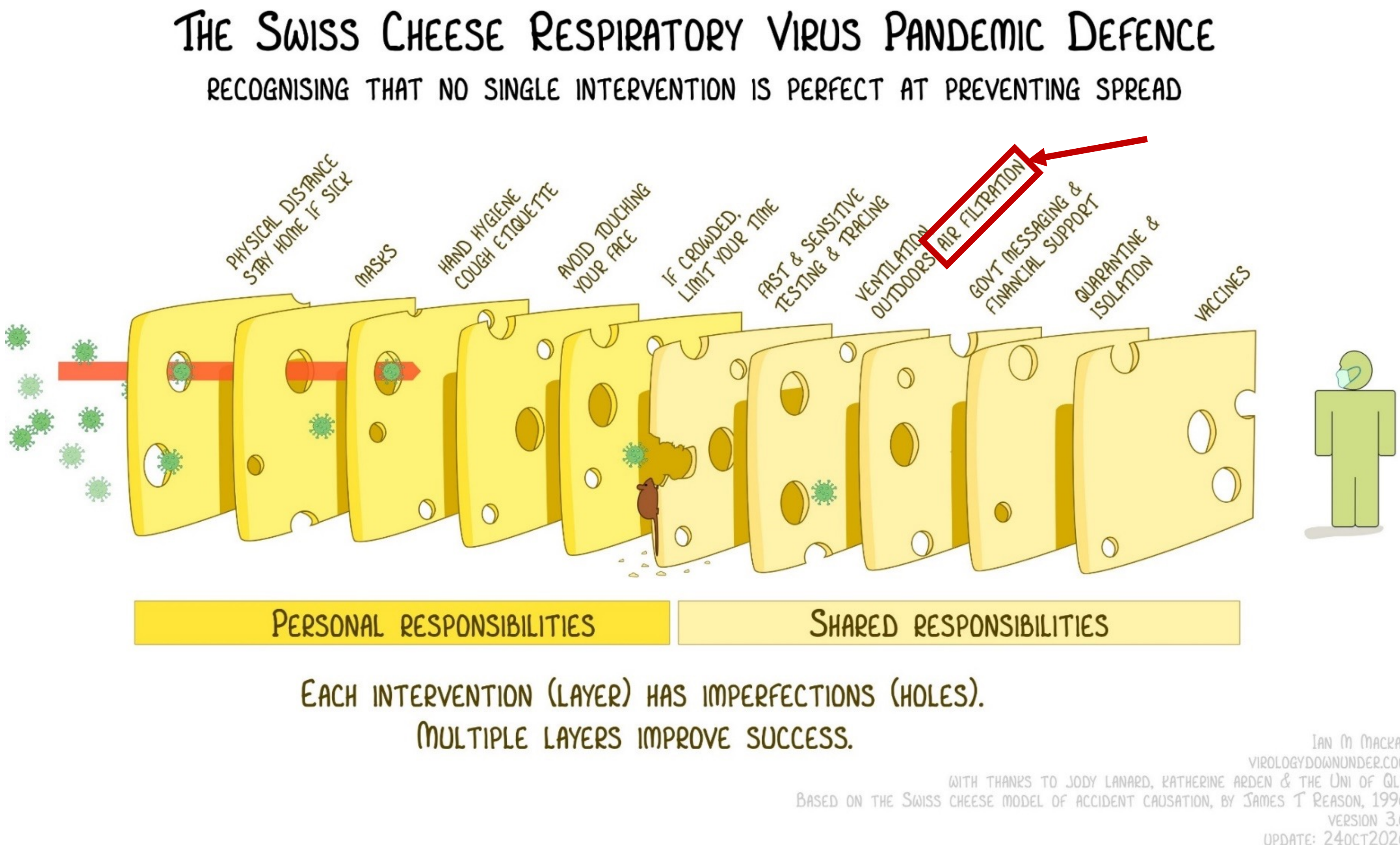
Sample ID	Virus genome equivalents/L of air[a]	$TCID_{50}$/100 µl	Viable virus count/L air
1-1 BioSpot	94	2.68E+04	74
1-2 BioSpot + HEPA	-	0	0
1-3 BioSpot	30	6.31E+03	18
2-1 VIVAS	44	1.00E+04	27
2-2 VIVA S+ HEPA	-	0	0
2-3 VIVAS	16	2.15E+03	6

[a]From Table 2.

Lednicky et al., **2020** *Int J Infectious Diseases* 100:P476-482

www.nytimes.com/2020/08/11/health/coronavirus-aerosols-indoors.html

Need for Layered Risk Reduction



www.nytimes.com/2020/12/05/health/coronavirus-swiss-cheese-infection-mackay.html

Navigating the Air Cleaning Landscape

Worries about COVID-19 spreading through the vents send Chicago building owners in search of cleaner air. 'You can't put a force field around your property.'

Chicago Tribune

By RYAN ORI
CHICAGO TRIBUNE | JUL 27, 2020 AT 10:41 AM

What will it take to make diners feel safe indoors? Nearly 60% feel uneasy eating inside, so restaurants try sterilizing UV wands, tabletop air purifiers as winter looms.

Chicago Tribune

By ALEXIA ELEJALDE-RUIZ
CHICAGO TRIBUNE | SEP 25, 2020 AT 7:11 AM

Do Air Filters In HVAC Systems Offer Protection Against Coronavirus Indoors? It Depends

DISCOVER

There are air filters that can catch particles laden with SARS-CoV-2. But whether or not the filtration happens depends on other factors.

By Leslie Nemo | Jul 17, 2020 11:45 AM

The New York Times

How to Keep the Coronavirus at Bay Indoors

By Apoorva Mandavilli

Sept. 27, 2020

Tips for dodging the virus as Americans retreat from colder weather: Open the windows, buy an air filter — and forget the UV lights.

Schools spending millions on air purifiers often sold using overblown claims

CNN health

By Lauren Weber and Christina Jewett, Kaiser Health News

Updated 6:06 PM ET, Tue May 11, 2021

Mother Jones

Caution to the Wind

Desperate to reopen and loaded with stimulus cash, schools are spending millions on high-tech purifiers. But are they safe?

MADISON PAULY MAY 27, 2021

Navigating the Air Cleaning Landscape

Air Cleaner Technology A uses **reactive molecules** to **destroy pathogens.**

Air Cleaner Technology B captures the **smallest viruses**, down to **100 nanometers.**

Air Cleaner Technology C delivers **50% more clean air** than HEPA filters.

Air Cleaner Technology D has been successfully installed in over 1,000 buildings, reducing particles by 20%.

Air Cleaner Technology D reduces viable SARS-CoV-2 by **over 99% in 60 minutes.**

Independent testing of Air Cleaner Technology E in a 15 ft^3 chamber demonstrates a **net 4 log reduction** of [*P. surrogate*] after 45 minutes.

Goals for This Talk

- Understand prevailing guidance on air cleaning
- Understand air cleaning mechanisms of action and their potential magnitude of impacts on COVID-19 transmission in indoor environments
- Understand air cleaner test standards and limitations
- Learn to critically review and interpret air cleaner test reports
- Learn to use tools to evaluate air cleaning technologies
- Answer common questions on air cleaning technologies

Prevailing Guidance on Air Cleaning for COVID

CDC Guidance

Centers for Disease Control and Prevention
CDC 24/7: Saving Lives, Protecting People™

Updates as of June 2, 2021

Ventilation in Buildings

"CDC recommends a layered approach to reduce exposures to SARS-CoV-2, the virus that causes COVID-19. This approach includes using multiple mitigation strategies":

Ventilation improvements, physical distancing, wearing face masks, hand hygiene, and vaccination.

- "…potential target benchmark for good ventilation is CO_2 readings below 800 ppm"

Several "tools in the mitigation toolbox" include:

Improve central air filtration
- To as high as possible
- Refers to ASHRAE

Use portable high-efficiency particulate air (HEPA) fan/filtration systems

Supplement with UVGI when options for increasing room ventilation and filtration are limited

+ Cautionary language on ionization, dry hydrogen peroxide and chemical fogging disinfection

www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

ASHRAE Guidance

ASHRAE EPIDEMIC TASK FORCE

1. Public health guidance:
   - Follow CDC guidance on hand hygiene, masks, occupancy, etc.
2. Ventilation, filtration, air cleaning
   - Minimum outdoor air (OA) flow rates, use MERV 13 or better filters
   - Only use air cleaners for which evidence of effectiveness and safety is clear
3. Air distribution
   - Promote mixing (when directional airflow not required)
4. HVAC System Operation
   - Maintain temperature, humidity, clean air supply, flush spaces
5. System Commissioning
   - Verify systems are functioning as designed

www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf

EPA Guidance

EPA United States Environmental Protection Agency

Indoor Air in Homes and Coronavirus (COVID-19)

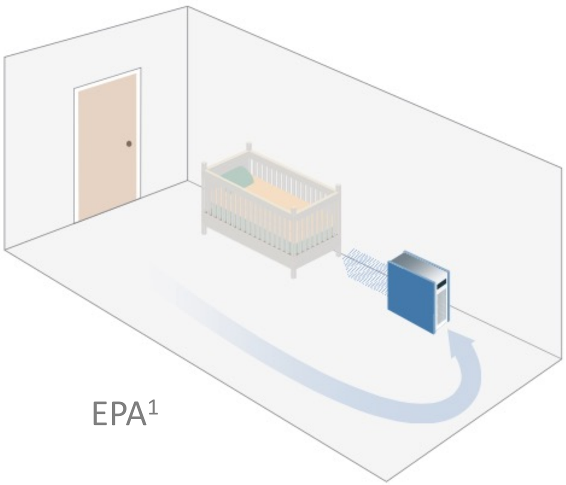
1. Increase ventilation with outside air
2. Improve natural ventilation
3. Use your HVAC system and consider upgrading filters
    - “By itself…not enough to protect yourself and your family”
    - Run continuously or for longer times
    - Upgrade to the highest efficiency filter that your system fan and filter slot can accommodate
4. Use a portable air cleaner if you have one
    - “By itself…not enough to protect people from COVID-19”
5. Increase ventilation with evaporative coolers/whole-house fans

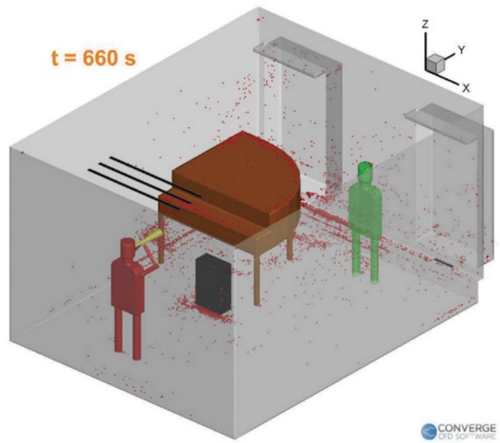
www.epa.gov/coronavirus/indoor-air-homes-and-coronavirus-covid-19

Air Cleaning Types and Terminology

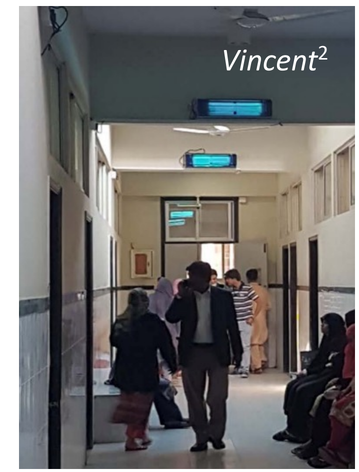
Types of Air Cleaners Available

Portable/stand-alone air cleaners

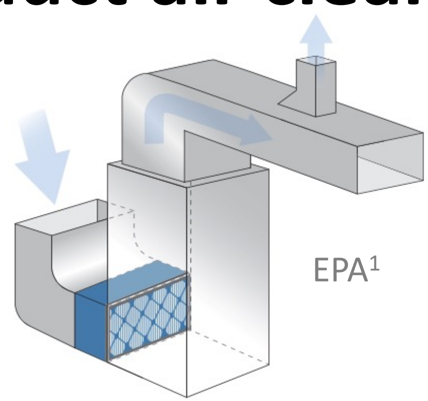


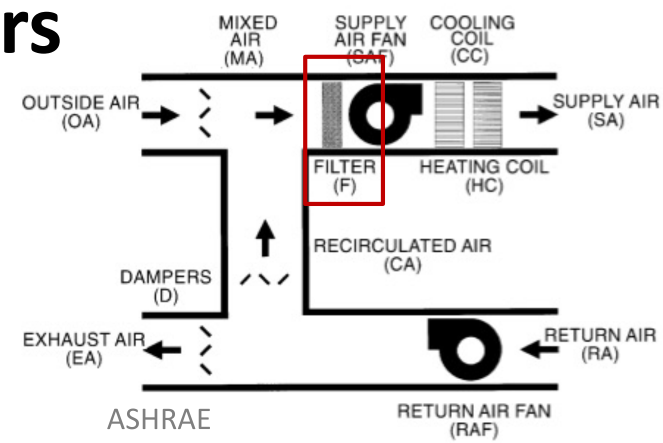


Narayanan and Yang 2021
Phys. Fluids 33, 033307



In-duct air cleaners





[1] www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home
[2] Vincent, 2020, Upper-room UVGI Air Disinfection, National Academies of Sciences

Types of Air Cleaning Technologies

"Subtractive" technologies

- Mechanism of action: removing or inactivating targeted contaminants from indoor air when they come in contact with the technology

Key parameters:

- Airflow rate
- Airflow relative to volume
- Single-pass efficiency
- Potential for byproduct formation (e.g., O_3 with ESP)

- Examples: filters, electrostatic precipitators (ESPs), sorbent media (for gases)

"Additive" technologies

- Mechanism of action: adding constituents to the air to remove particles, inactivate microorganisms and/or react with chemical contaminants

Key parameters:

- Type, concentration and dose of additives
- Potential toxicity of additives
- Potential for byproduct formation (particles/gases)

- Examples: ionizers, ozone, plasma, hydrogen peroxide, reactive oxygen species

Many air cleaners use a combination of technologies!

[1] https://www.epa.gov/indoor-air-quality-iaq/guide-air-cleaners-home

Common Air Cleaning Test Standards

Air Cleaning Technology	Target Pollutant(s)	Test Standards (Rating Metrics)
Fibrous media filters	**Particles**	**Filters:** ASHRAE 52.2 (MERV) ISO 16890 (ePM) ISO 29463 (HEPA) Proprietary standards (FPR,MPR) **Portable air cleaners:** AHAM AC-1 (CADR)
Electrostatic precipitators (ESPs)	**Particles**	**No rating; some ozone emission standards (UL 2998)**
Ionizers, plasma, etc.	**Particles**	**None specifically**
Ultraviolet germicidal irradiation (UVGI)	**Microbial particles**	**Air:** ASHRAE 185.1 **Surfaces:** ASHRAE 185.2

+ Many devices/technologies are tested in **non-standardized** ways.

[1] www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home

Air Cleaner Evaluation Matrix

- Ideal matrix of demonstrated performance metrics:

	Effectiveness	Byproduct formation
Particle	Yes	No
Chemical	Yes	No
Microbiological	Yes	n/a

- More common matrix of demonstrated performance metrics for a particular technology:

	Effectiveness	Byproduct formation
Particle	Yes*	Unknown
Chemical	Unknown	Unknown
Microbiological	Yes*	n/a

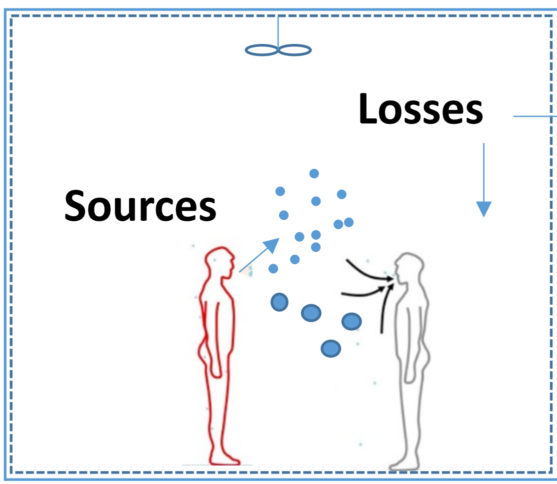
*Yes, but it's difficult to interpret the data (will revisit in subsequent slides).

Quantifying Air Cleaning Impacts

Mass Balances on Indoor Air

- Mass balance models allow for predicting the impacts of interventions on indoor contaminant concentrations.
- In words, a mass-balance is a statement of conservation of mass in which: **Accumulation = Inputs – Outputs**

General approach tracks sources and losses in time to predict concentration:

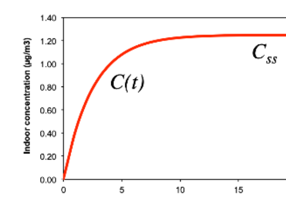


$$\frac{dC}{dt} = S - LC$$

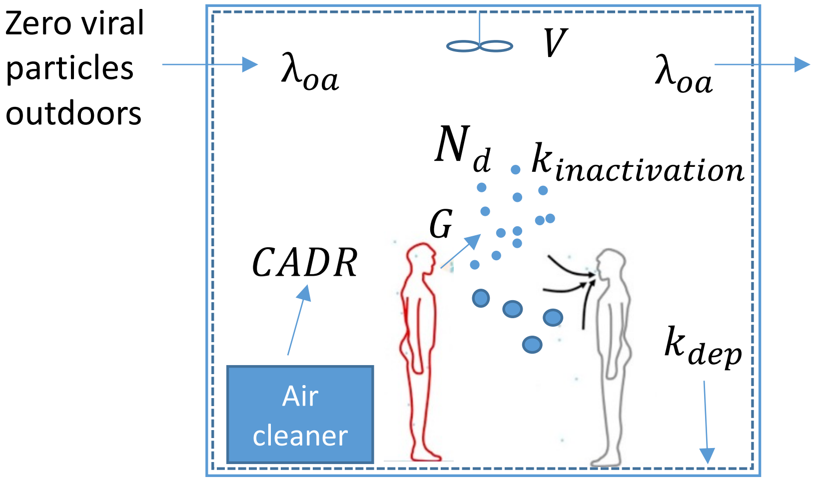
C = concentration (#/m^3)
t = time (h)
S = sources (#/(m^3-h))
L = losses (h^{-1})

Time-varying solution: $C(t) = C_0 e^{-Lt} + \frac{S}{L}\left(1 - e^{-Lt}\right)$

Steady-state solution: $C_{ss} = \frac{S}{L}$



Indoor Air Mass Balance on SARS-CoV-2



Where:
N_d = infectious virus in particles of diameter d (#/m^3)
G = infectious viral particle generation rate (#/h)
V = volume of the space (m^3)
λ_{oa} = outdoor air exchange rate (1/h)
k_{dep} = infectious particle deposition loss rate (1/h)
$k_{inactivation}$ = viral particle inactivation rate (1/h)
$CADR$ = clean air delivery rate (m^3/h)

$$\frac{dN_d}{dt} = \underbrace{\frac{G}{V}}_{\textbf{Sources}} \underbrace{- N_d\lambda_{oa} - k_{dep}N_d - k_{inactivation}N_d - \frac{CADR}{V}N_d}_{\textbf{Losses}}$$

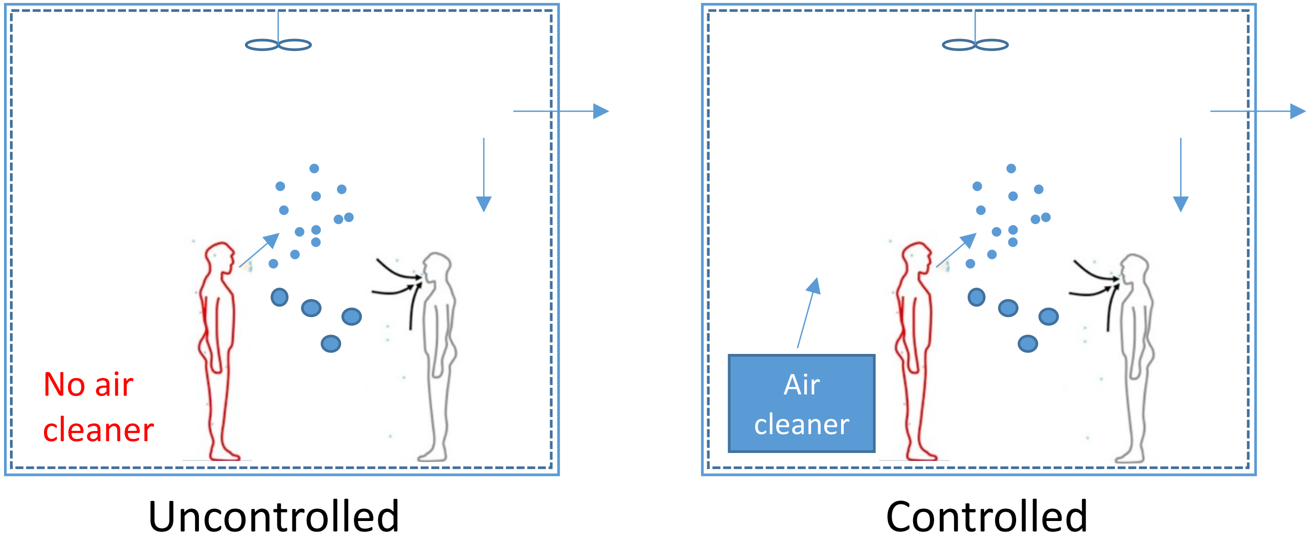
CADR: the volumetric flow rate of air (or equivalent), free of viral particles due to air cleaner

- *i.e., loss rate enhancement due to air cleaning*

Goal: High Effectiveness (ϵ)

- Ultimate goal: achieve a high level of effectiveness (ϵ)
  - Comparison of indoor concentrations (or indoor/outdoor concentration ratios) with and without an air cleaning technology operation:

The **effectiveness**, ϵ, of an air-cleaner is: $\epsilon = 1 - \frac{N_{d,controlled}}{N_{d,uncontrolled}}$



Loss Mechanisms "Layer"

The solution to the mass-balance equation is:

$$N = \left(\frac{G}{\boldsymbol{L}V}\right)\left(1 - e^{-\boldsymbol{L}t}\right) \qquad \text{Where: } \boldsymbol{L} = \lambda_{oa} + k_{inactivation} + k_{dep} + \frac{CADR}{V}$$

where L is the sum of the loss mechanisms: ventilation, inactivation, deposition, air cleaning

- All terms have units of h^{-1} (per hour): interventions are *additive* (i.e., they "layer")

Example at right:

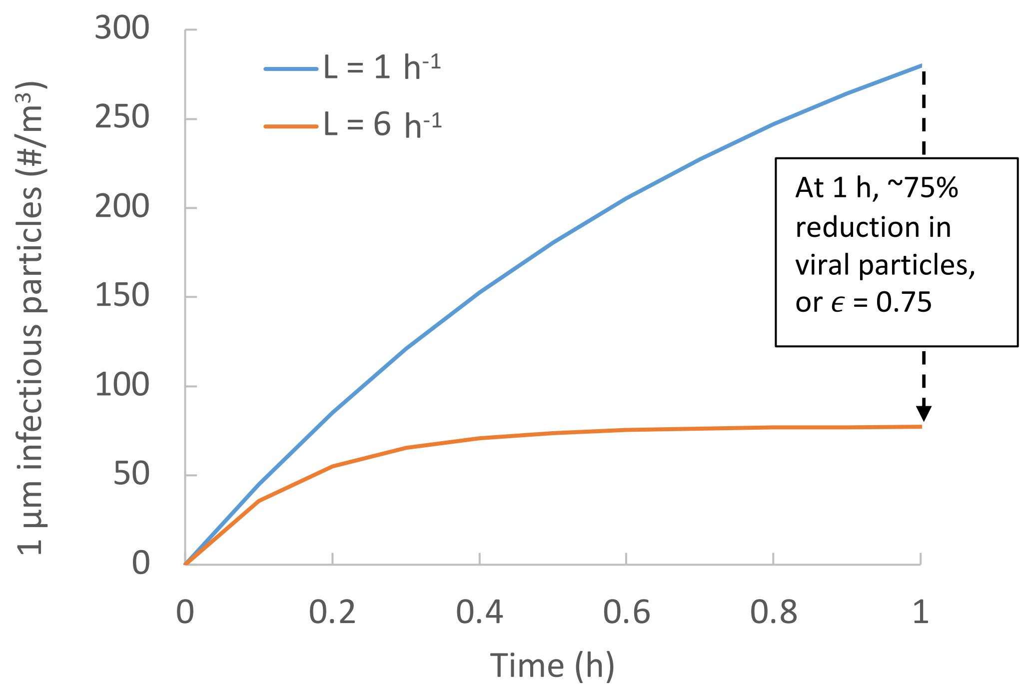
- 75 m^3 space
- No viral particles initially (t = 0)
- No viral particles outdoors
- Emissions of 1 µm particles containing infectious material (G = 600 #/min)

Baseline: $\boldsymbol{L}$ = 1 h^{-1}

with interventions: $\boldsymbol{L}$ = 6 h^{-1}

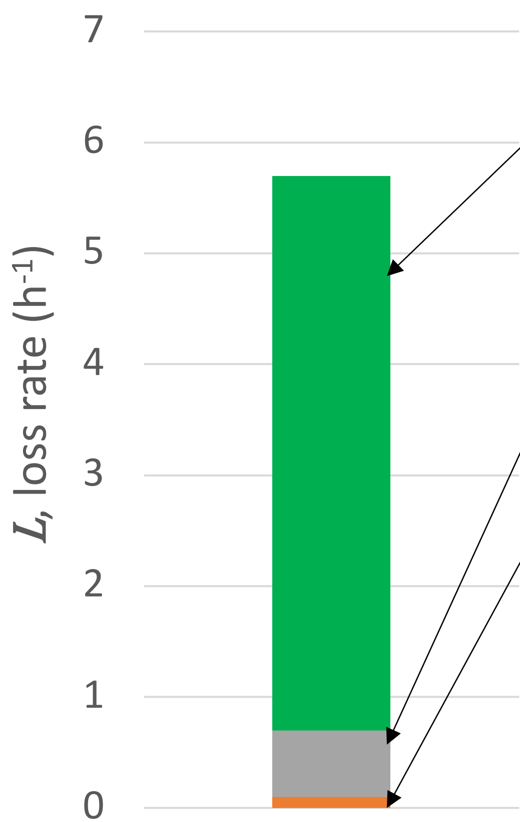
Higher $\boldsymbol{L}$ leads **to lower indoor particle concentrations**

- **Higher effectiveness (ϵ)**



Increasing Loss Mechanisms in Buildings

Losses, $\boldsymbol{L}$, in a residential space **with increased outdoor air**:



Outdoor air, open windows/doors[1], $\boldsymbol{\lambda_{oa}}$**: ~5 h^{-1}**

- Highly variable, not easily predicted

Virus inactivation[2], $k_{inactivation}$: ~0.6 h^{-1}

Particle deposition (1-4 μm)[3], k_{dep}: ~0.1-0.8 h^{-1}

No recirculation air cleaning[4], $\frac{CADR}{V}$: 0 h^{-1}

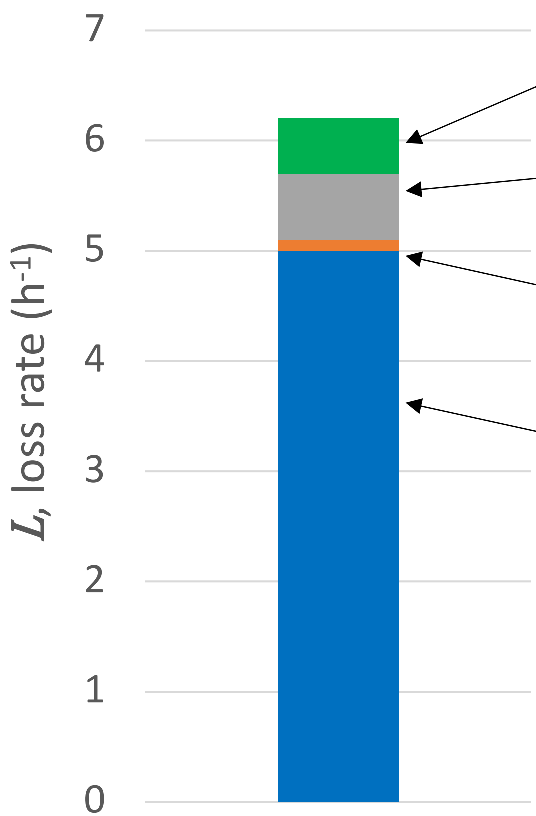
Outdoor air ventilation + air cleaning ($\lambda_{oa} + \frac{CADR}{V}$) are where largest increases in $\boldsymbol{L}$ can usually be realized

- **This sum may be referred to as eACH: equivalent air changes per hour (h^{-1})**

[1]Johnson et al. 2004, *JESEE* 14:1–22; [2] van Doremalen et al. 2020, N Eng J Med 382(16):1564–1567; [3]Hussein and Kulmala, 2008, *Water Air Soil Pollut*. 8:23–34 (2008); [4]ANSI/AHAM AC-1

Increasing Loss Mechanisms in Buildings

Losses, $\boldsymbol{L}$, in a residential space **with increased air cleaning**:



Outdoor air ventilation[1], λ_{oa}: ~0.5 h^{-1}

Virus inactivation[2], $k_{inactivation}$: ~0.6 h^{-1}

Particle deposition (1–4 µm)[3], k_{dep}: ~0.1-0.8 h^{-1}

Recirculation air cleaning[4], $\frac{CADR}{V}$**: ~5 h^{-1}**

Outdoor air ventilation + air cleaning ($\lambda_{oa} + \frac{CADR}{V}$) are where largest increases in $\boldsymbol{L}$ can usually be realized

- **This sum may be referred to as eACH: equivalent air changes per hour (h^{-1})**

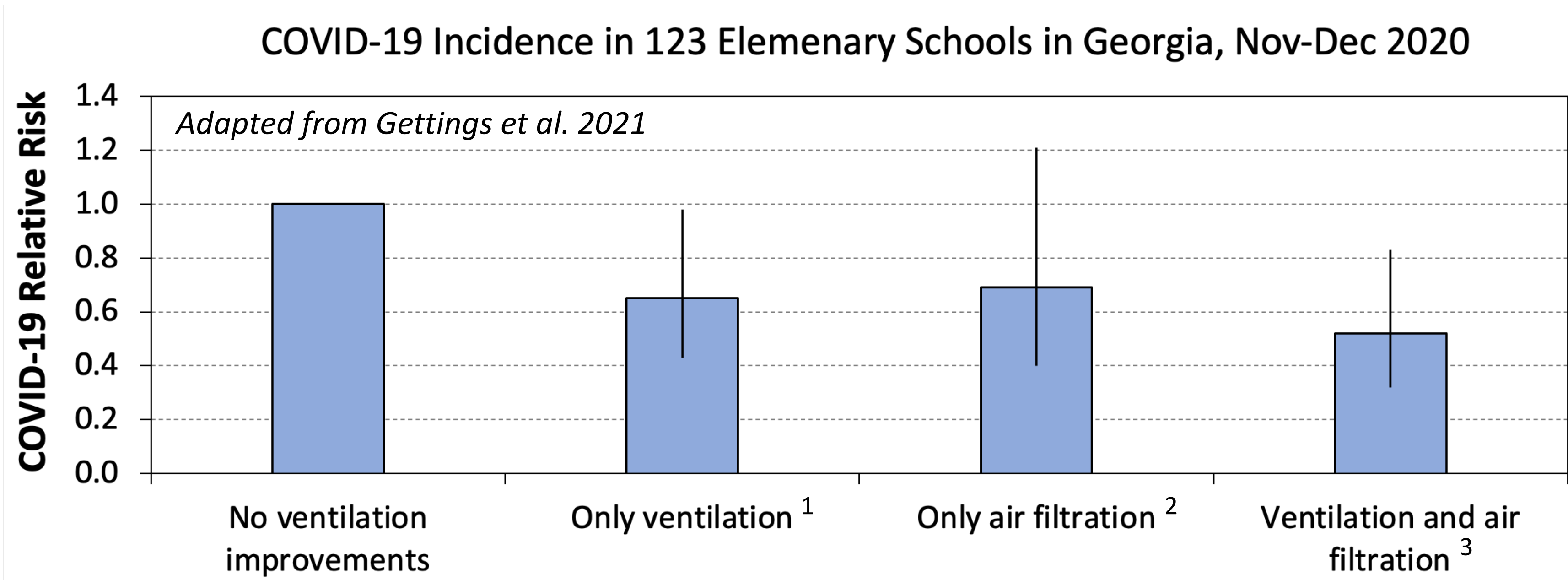
[1]Murray and Burrmaster 1995, Risk Analysis 15(4): 459–465; [2] van Doremalen et al. 2020, N Eng J Med 382(16):1564–1567; [3]Hussein and Kulmala, 2008, *Water Air Soil Pollut*. 8:23–34 (2008); [4]ANSI/AHAM AC-1

Risk Reduction Targets and Tools

Air Cleaning and Ventilation Are Additive

Improved ventilation and mask rules for staff in elementary schools resulted in fewer COVID-19 cases, CDC study finds CBS NEWS

www.cbsnews.com/news/covid-school-masks-ventilation/



[1]Ventilation only = open doors, open windows or fans

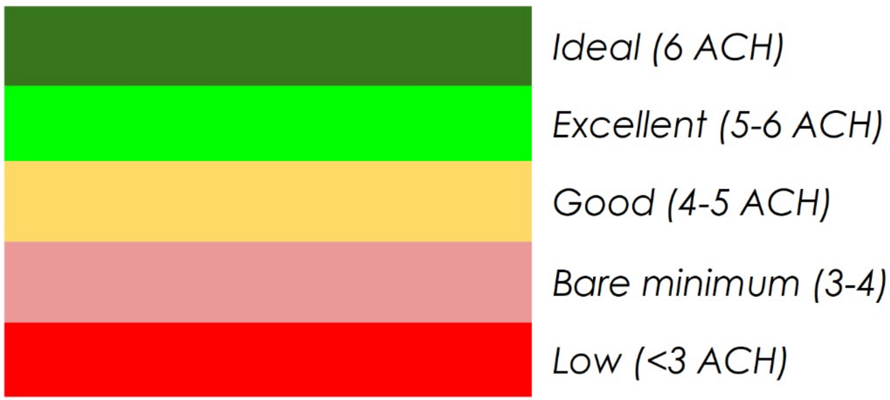
[2]Air filtration only = using HEPA filters with or without UVGI and no ventilation

[3]Ventilation and air filtration = both [1] and [2]

Suggested Targets for Loss Rate

Achievable using a combination of outdoor air ventilation and air cleaning

TARGET IS AT LEAST 5 TOTAL AIR CHANGES PER HOUR



Harvard Healthy Buildings[1]:
4–6 h^{-1}

schools.forhealth.org/wp-content/uploads/sites/19/2020/08/Harvard-Healthy-Buildings-program-How-to-assess-classroom-ventilation-08-28-2020.pdf

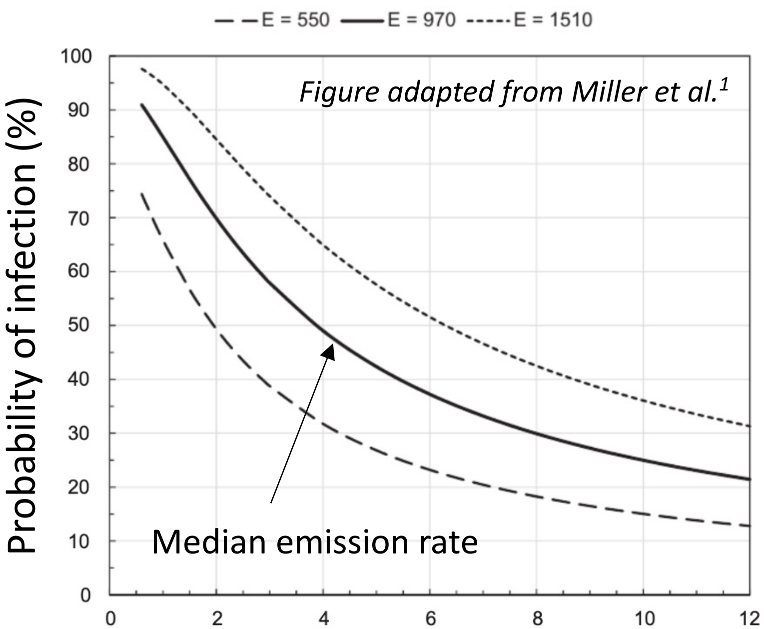
ASHRAE Standard 170:
Min. 6 h^{-1} total (OA + SA with MERV 14)
[Min. 2 h^{-1} from OA][2]

[1]Allen et al. 2021 *JAMA* 325(20):2112–2113; [2]ASHRAE Standard 170-2017

Reduce Risks by Increasing Loss Rate

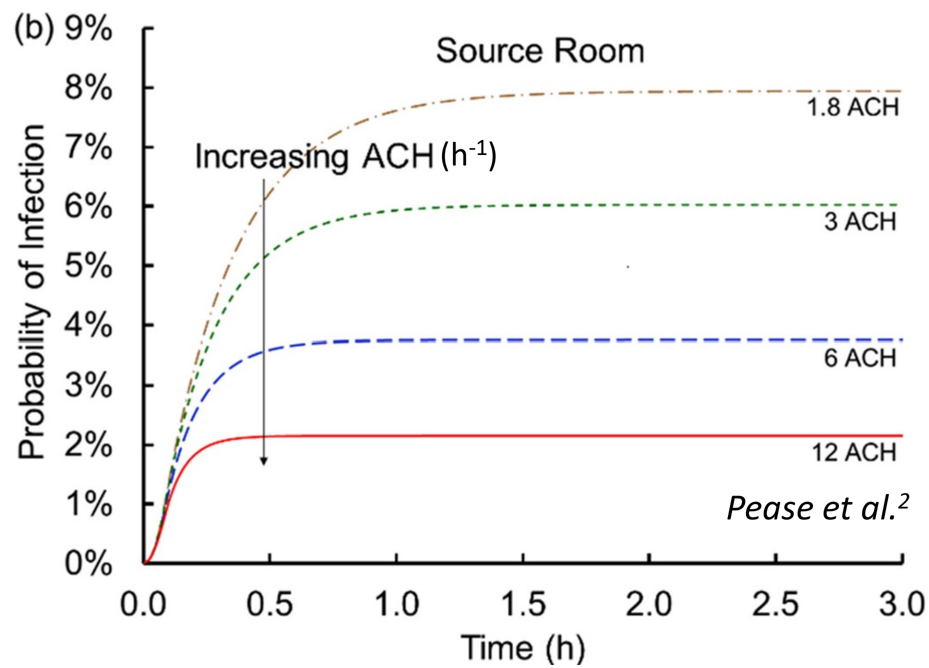
Mass-balance modeling informs risk models (e.g., using the Wells–Riley equation)[1]

During a choir practice[1]:



L (h^{-1}), total loss rate (ventilation, deposition, filtration, and inactivation)

In three rooms, connected by HVAC[2]:



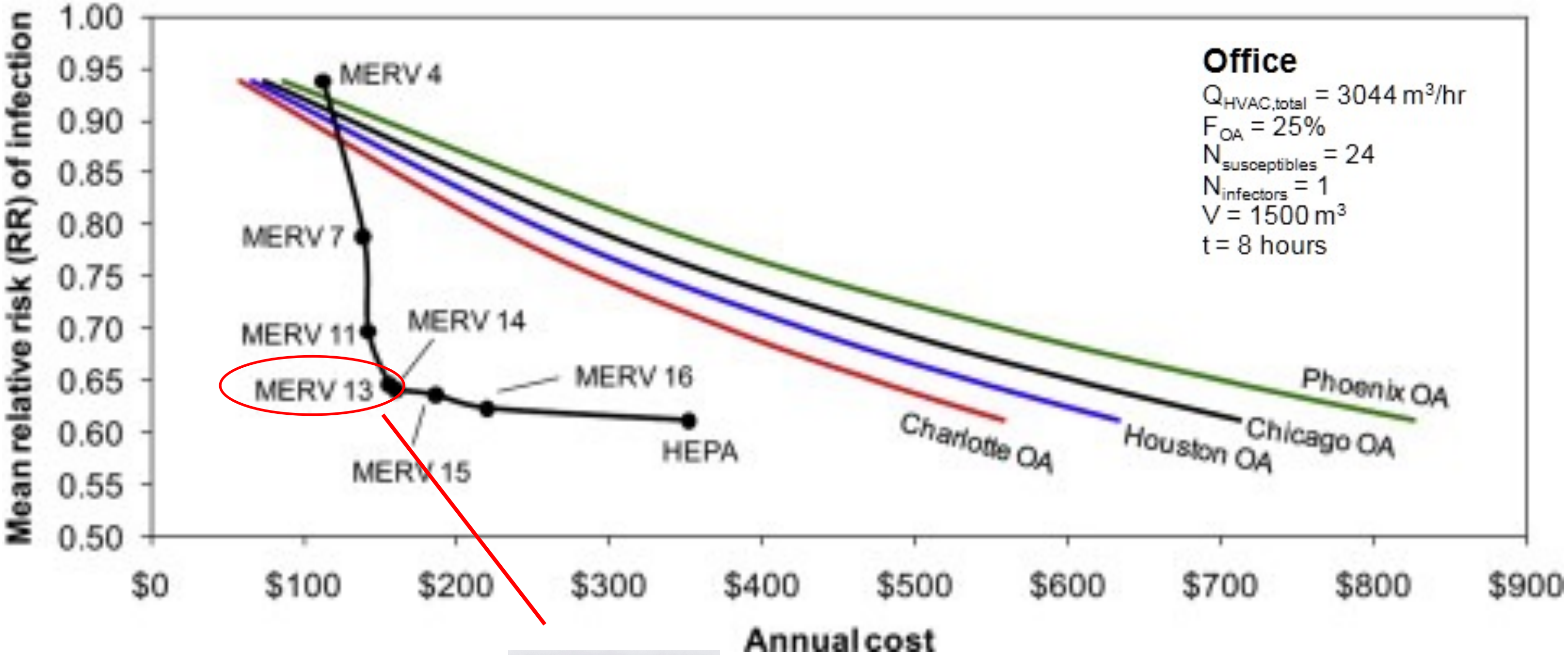
[1]Miller et al. 2021, *Indoor Air* 31(2): 314–323; [2]Pease et al. 2021, *Building and Environment* 107633

Air Cleaning vs. Ventilation: Cost Effectiveness

For influenza transmission:

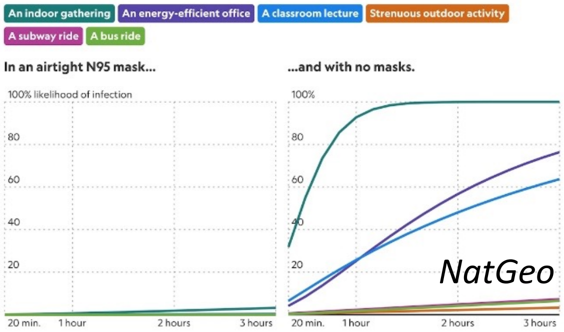
"HVAC filtration appears more cost effective than outdoor air ventilation."[1]

Figure adapted from: Azimi et al.[1]



MERV 13 at point of diminishing returns in cost/benefit trade-off

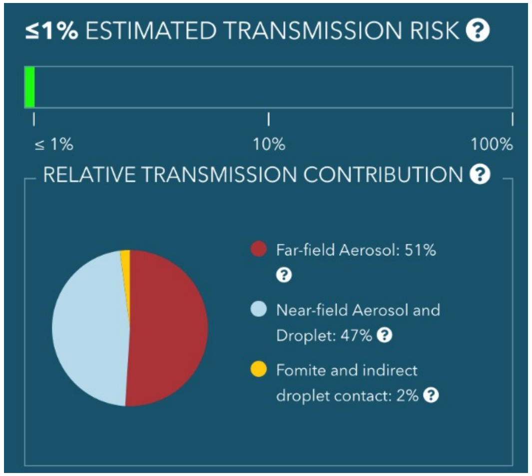
Online Tools for Risk Evaluation



Wells–Riley model calculator

tinyurl.com/covid-estimator

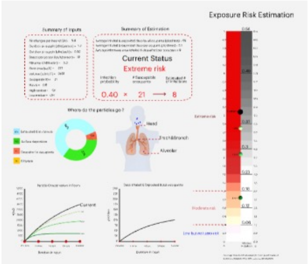
Multi-mode transmission model



covid-19.forhealth.org/covid-19-transmission-calculator/

Inhalation dose model

safeairspaces.com/safeairspaces-estimator

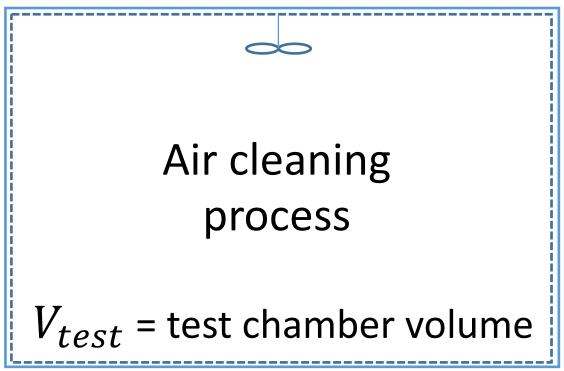


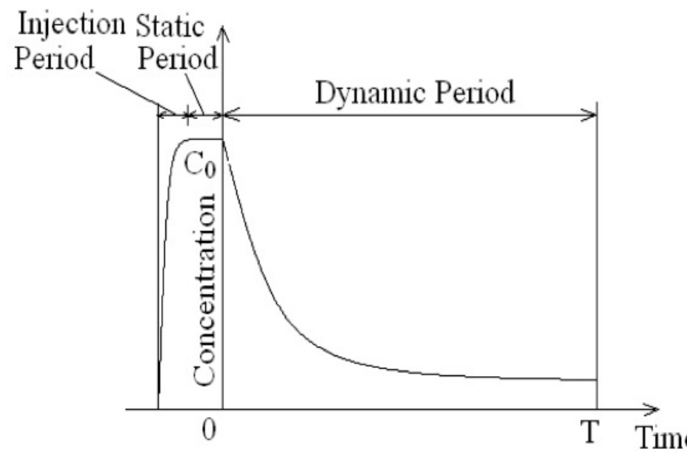
Interpreting Air Cleaner Performance Data

What Information Is Available to Increase $\boldsymbol{L}$?

All air cleaners can be evaluated with "pull down" test method.[1,2]

- In controlled chamber: injection, static, decay periods
  - With air cleaner on, repeat with air cleaner off
  - Used for particles,[1,2,3] gases,[4,5,6] microbes[7]





Compare loss rates with air cleaner ("$\boldsymbol{L_{ac}}$") on and off

- Change in loss rates is due to air cleaner, if other conditions held constant

$$\boldsymbol{L_{ac\ off}} = \lambda_{oa} + k_{inactivation} + k_{dep} \qquad \boldsymbol{L_{ac\ on}} = \lambda_{oa} + k_{inactivation} + k_{dep} + \frac{CADR}{V_{test}}$$

$$\boldsymbol{L_{ac\ on}} - \boldsymbol{L_{ac\ off}} = \frac{CADR}{V_{test}}$$

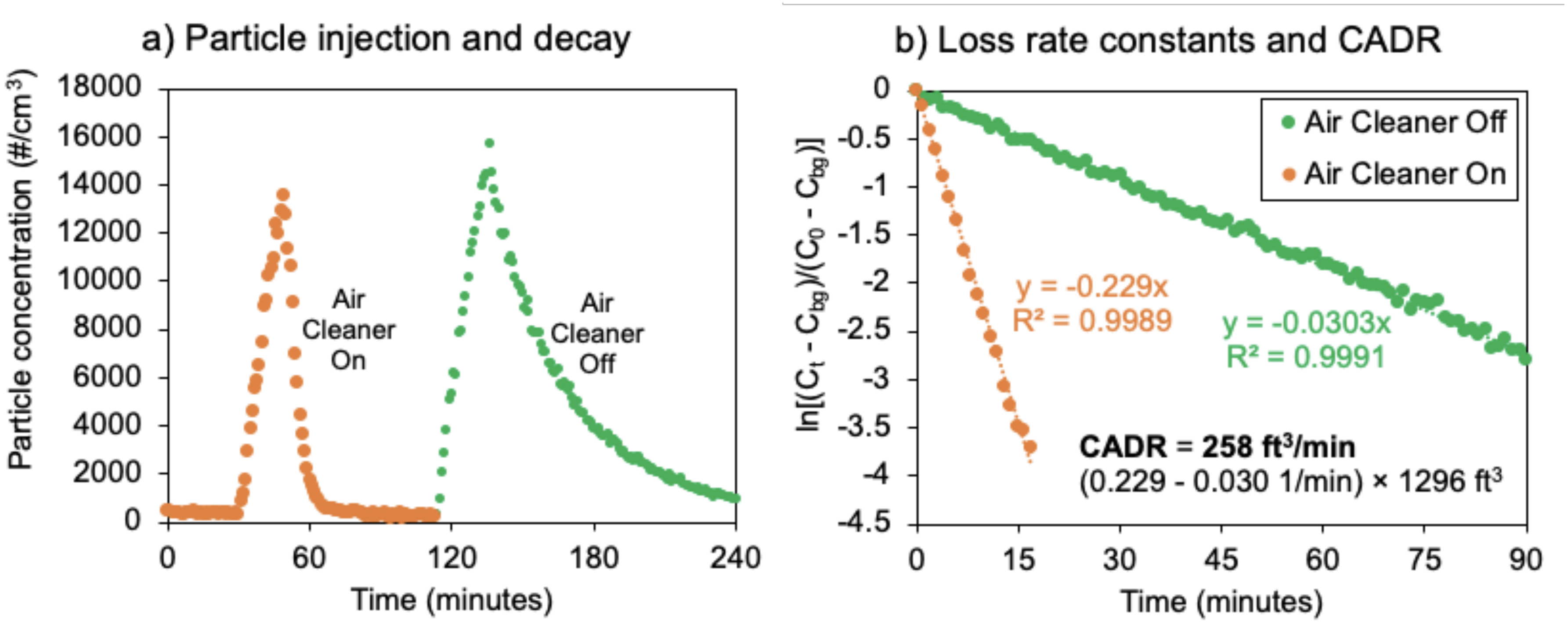
Where: "ac" = air cleaner

[1] ANSI/AHAM AC-1; [2]Offermann et al. 1985, *Atmos. Environ.* 19(11):1761–1771; [3]Sultan et al. 2011 *HVAC&R Res.* 17(4):513–525
[4]Daisey and Hodgson 1989, *Atmos. Environ.* 23(9):1885–1892; [5]Chen et al. 2005, *ASHRAE Trans.* 111 P1:1101–1114
[6]Howard-Reed et al. 2008 *Build Environ* 43(3):368–377; [7]Schuit et al. 2020, *J. Infectious Dis.* 222(4): 564–571

What Information Is Available to Increase L?

For a **subtractive portable air cleaner**:

Example testing of a mechanical filter portable air cleaner:



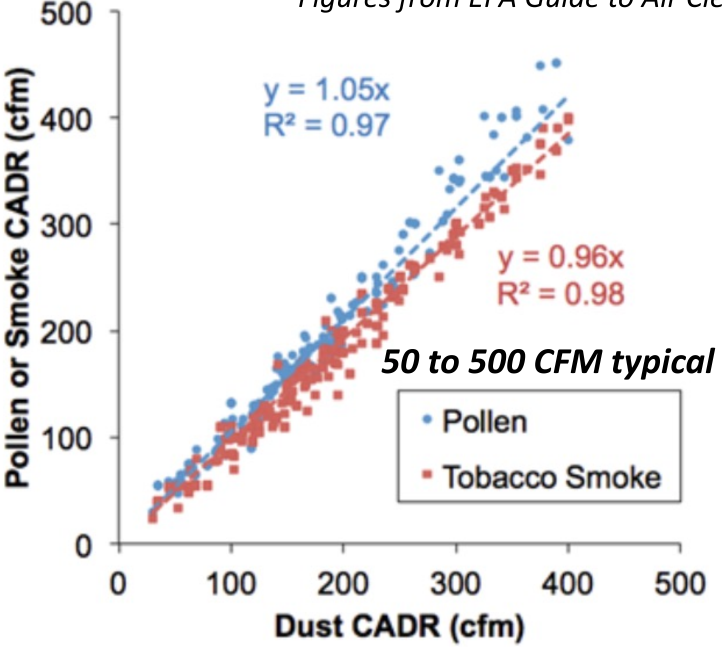
Outcome of testing: $L_{ac\ on} - L_{ac\ off} = \dfrac{CADR}{V_{test}}$ $\longrightarrow$ $CADR = V_{test}\left(L_{ac\ on} - L_{ac\ off}\right)$

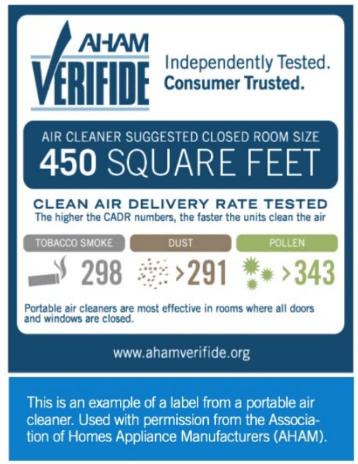
built-envi.com/portfolio/air-cleaner-testing/

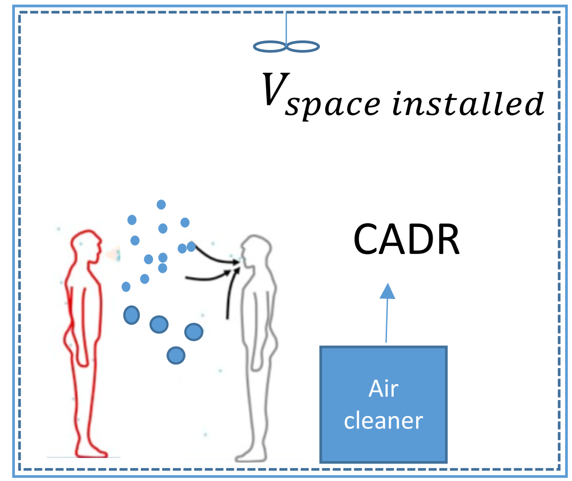
Example Portable Air Cleaner Test Data

For **portable air cleaners (additive or subtractive)**:

Figures from EPA Guide to Air Cleaners in the Home[1]







CADR required for 80% effectiveness @ steady state:

Portable Air Cleaner Sizing for Particle Removal						
Room area (square feet)	100	200	300	400	500	600
Minimum CADR (cfm)	65	130	195	260	325	390

Note this chart is for estimation purposes. The CADRs are calculated based on an 8-foot ceiling. If you have higher ceilings, you may want to select a portable air cleaner with a higher CADR.

L (or eACH) in space installed depends on sizing of air cleaner.

AHAM recommendation for 80% steady-state concentration reduction:

- $CADR\ (cfm) > \frac{2}{3} \times Area\ (ft^2)$

  Yields eACH of $\sim 5\ h^{-1}$

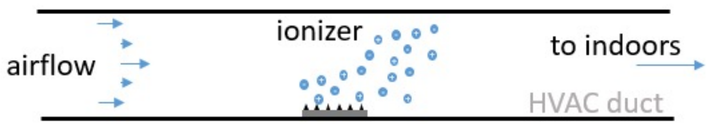
[1] www.epa.gov/indoor-air-quality-iaq/air-cleaners-and-air-filters-home

What information is available to increase *L*?

For **additive (in-duct and portable) air cleaners**

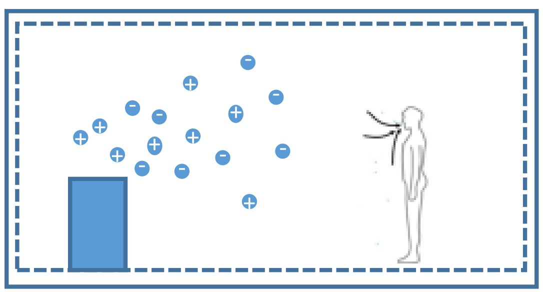
- Generally tested following a “pull down” method (similar to portable air cleaners)
- Albeit often via ***non-standardized*** test methods
- Potential for byproduct formation is seldom reported

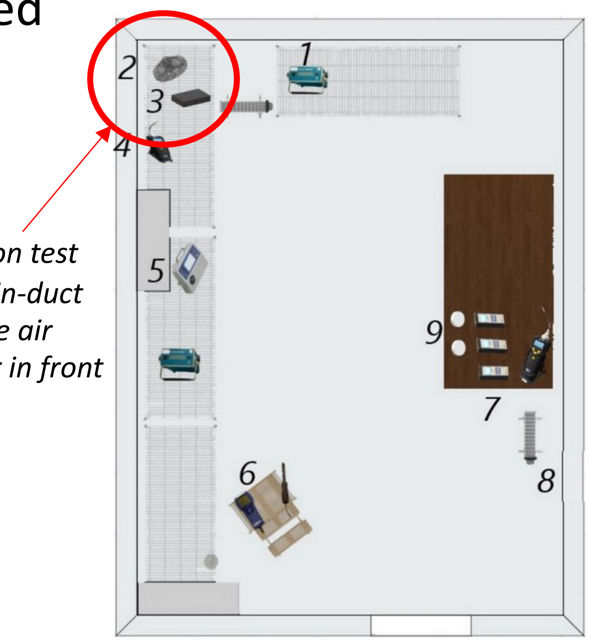
In-duct unit:



Example additive electronic air cleaner

Portable unit:





Common test setup: in-duct additive air cleaner in front of fan

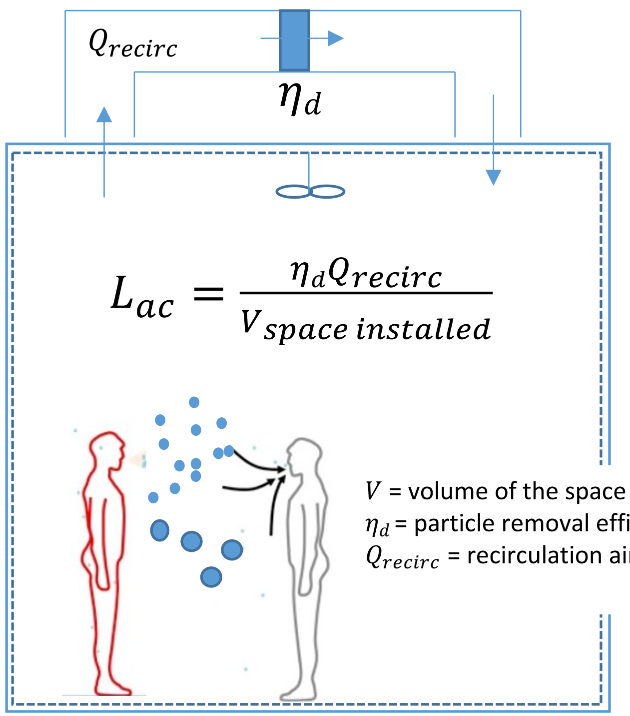
Boeing test report: Use of Bipolar ionization

Manufacturer-provided data may not be directly in the form of CADR

What Information Is Available to Increase L?

For **in-duct subtractive systems (e.g., filtration, UVGI)**

- L can be estimated from single-pass efficiency (η_d)[1,2] and flowrate (Q_{recirc}).



$$L_{ac} = \frac{\eta_d Q_{recirc}}{V_{space\ installed}}$$

V = volume of the space (m^3)
η_d = particle removal efficiency (%)
Q_{recirc} = recirculation air flow rate (m^3/h)

ASHRAE 52.2 MERV[1] Table from NAFA[2]

Standard 52.2 Minimum Efficiency Reporting Value (MERV)	Composite Average Particle Size Efficiency, % in Size Range, µm			Average Arrestance, %
	Range 1 (0.3-1.0)	Range 2 (1.0-3.0)	Range 3 (3.0-10.0)	
1	n/a	n/a	E3 < 20	A_{avg} < 65
2	n/a	n/a	E3 < 20	65 ≤ A_{avg} < 70
3	n/a	n/a	E3 < 20	70 ≤ A_{avg} < 75
4	n/a	n/a	E3 < 20	75 ≤ A_{avg}
5	n/a	n/a	20 ≤ E3	n/a
6	n/a	n/a	35 ≤ E3	n/a
7	n/a	n/a	50 ≤ E3	n/a
8	n/a	20 ≤ E_2	70 ≤ E3	n/a
9	n/a	35 ≤ E_2	75 ≤ E3	n/a
10	n/a	50 ≤ E_2	80 ≤ E3	n/a
11	20 ≤ E_1	65 ≤ E_2	85 ≤ E3	n/a
12	35 ≤ E_1	80 ≤ E_2	90 ≤ E3	n/a
13	50 ≤ E_1	85 ≤ E_2	90 ≤ E3	n/a
14	75 ≤ E_1	90 ≤ E_2	95 ≤ E3	n/a
15	85 ≤ E_1	90 ≤ E_2	95 ≤ E3	n/a
16	95 ≤ E_1	95 ≤ E_2	95 ≤ E3	n/a

L (or eACH) realized in space depends on:
- Increase MERV rating, if possible (MERV 13)
- Flow rate (and static pressure) for ↑ η_d

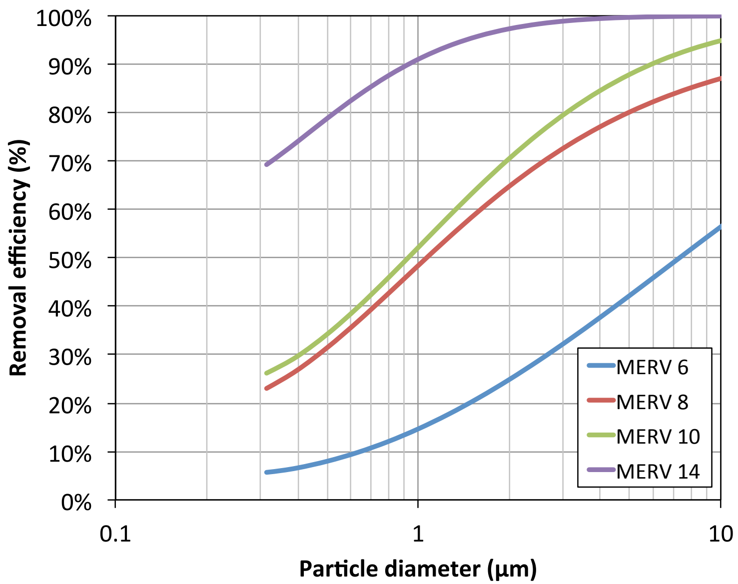
[1]ASHRAE 52.2-2017; [2]NAFA: www.nafahq.org/understanding-merv-nafa-users-guide-to-ansi-ashrae-52-2/

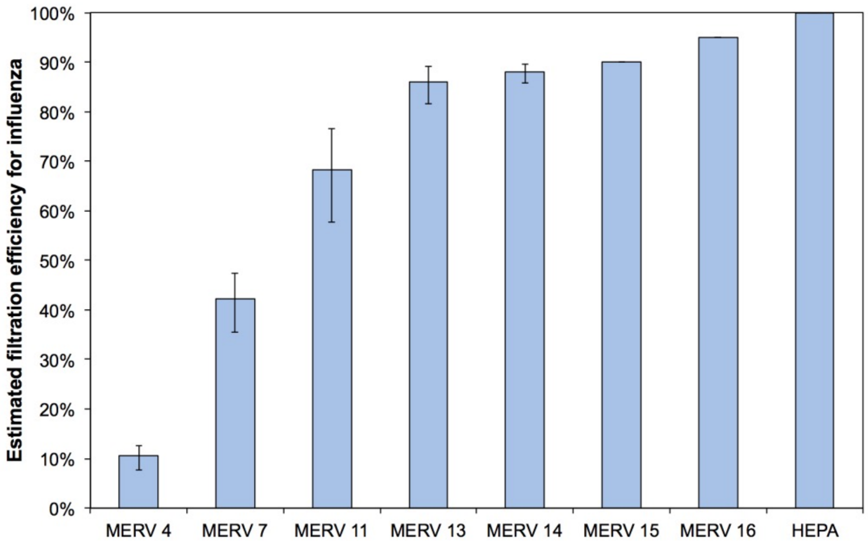
What Information Is Available to Increase *L*?

For **in-duct subtractive systems (e.g., filtration, UVGI)**

- Single-pass efficiency (η_d) can be estimated from MERV and viral particle distribution.[1]

Typical MERV efficiency curves: → Estimating viral particle removal efficiency:





For a range of typical commercial building supply airflow rates (0.3 to 1 CFM/ft^2):

- MERV 13 (~80% viral removal efficiency) offers ~0.25-0.8 CFM/ft^2 in CADR
- For a 1000 ft^2 space with 10 ft high ceilings: ~**250-800 CFM CADR** & ~**1.4-4.8 eACH**

$$eACH = \frac{\eta_d Q_{recirc}}{V_{space\ installed}}$$

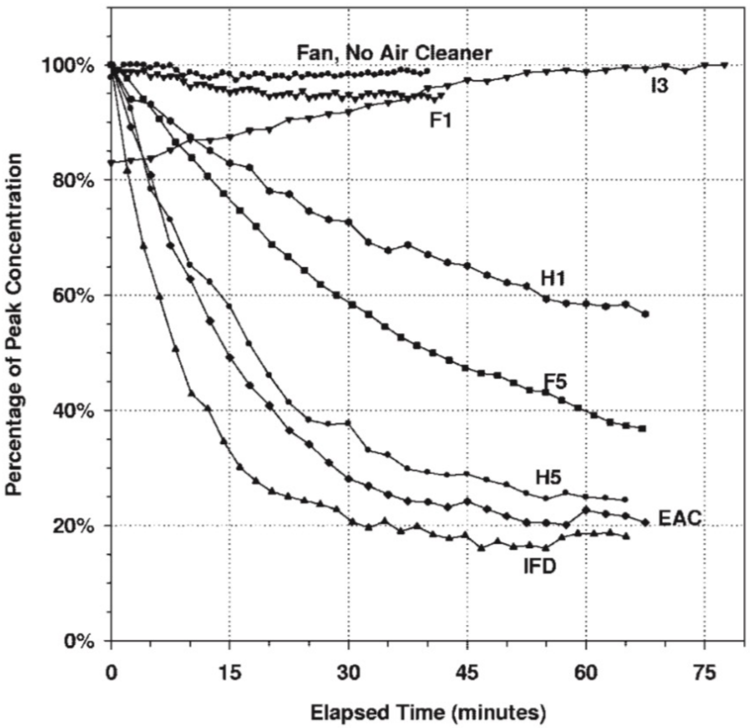
[1]Azimi et al. 2013 *Building and Environment* 70, 150-160

What Information Is Available to Increase L?

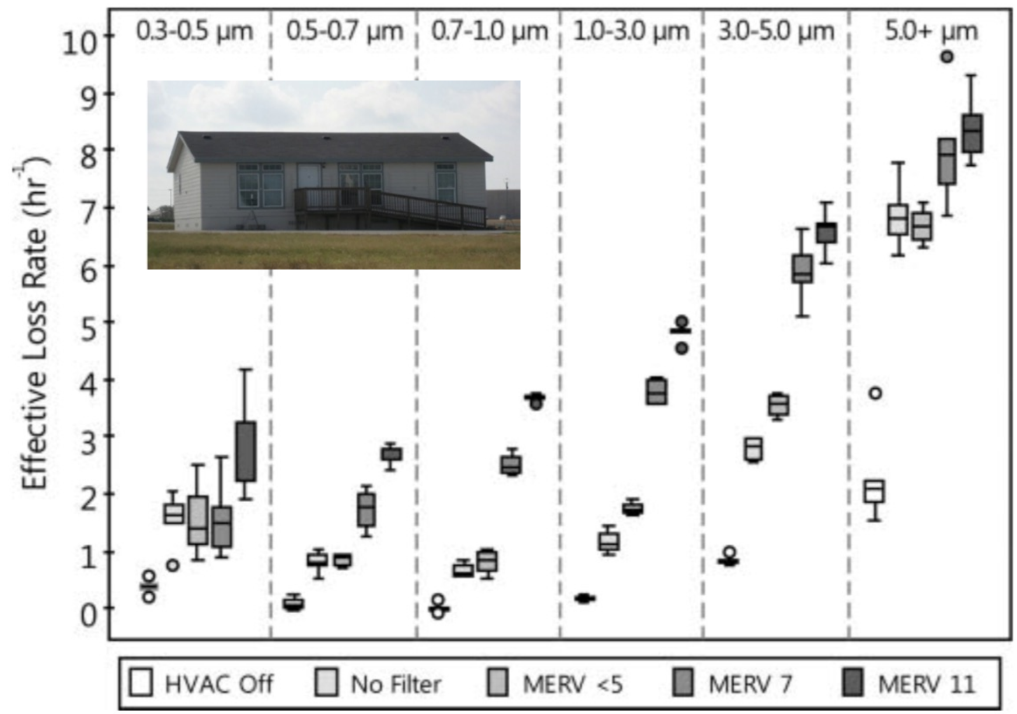
For **in-duct subtractive systems (e.g., filtration, UVGI)**

- L can also be estimated from an *in-situ* (*in the space installed*) pull down test.[1,2]

MacIntosh et al. 2008



Stephens and Siegel 2012



[1]MacIntosh et al. 2008, *J Air Waste Man Assoc* 58(11):1474–1482; [2]Stephens and Siegel 2012, *Aerosol Sci Technol* 46(5):504–513

What Information Is Available to Increase *L*?

- Knowing CADR (or *L*) of air cleaner allows design of intervention for target effectiveness.
  - Target effectiveness may not be realized.
  - Important to have design based on sound principles.
- What about air cleaners that don't report CADR?

Typical example:

99% removal of $PM_{2.5}$/SARS-CoV-2 in 1 hour

How can we translate this to evaluate whether the air cleaner will be effective in the target space?

Navigating Language of Test Reports

1. **Removal measurements, with air cleaner on (test) and off (control)**
    - Concentrations
    - % removal
    - log reduction
    - Net log reduction
2. **Time of each measurement of removal**
3. **Volume of test chamber**
4. **Ensure consistency of conditions between test and control**
    - Environmental conditions (e.g., temperature, humidity, light)
    - Challenge concentration
5. **Operating conditions during test**
    - What device settings?
    - For additive: added constituent concentrations and locations measured

Navigating Language of Test Reports

- Language used in test reports:
  - Concentration: *absolute* measurement

    $N_{d,at\ some\ time}$ for example: $1\times10^{6}\ \frac{TCID_{50}}{mL}$

  - % reduction: *relative* measurement

    $$\%\ reduction = \frac{N_{d,inital} - N_{d,later\ time}}{N_{d,inital}}$$

  - log reduction: *relative* measurement on log scale

    $$\text{log reduction} = -\log\left(\frac{N_{d,later\ time}}{N_{d,inital}}\right)$$

  - Net log reduction: *relative* measure, log scale, control accounted

    $$\text{Net log reduction} = \left[-\log\left(\frac{N_{d,later\ time}}{N_{d,inital}}\right)\right]_{test} - \left[-\log\left(\frac{N_{d,later\ time}}{N_{d,inital}}\right)\right]_{control}$$

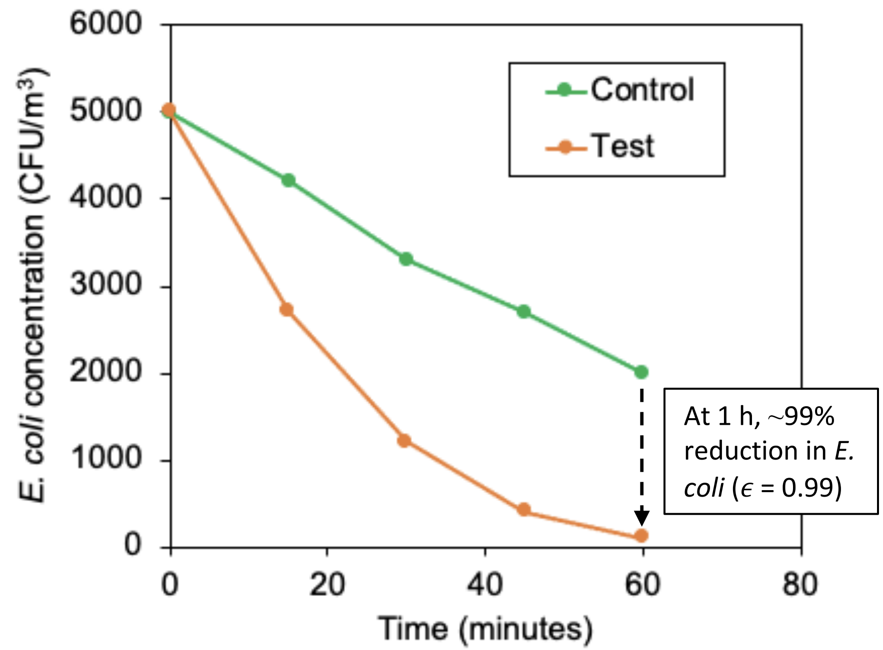
Collecting Test Data: Example 1

Aerosolized *Escherichia coli* inactivation test in a 500 ft^3 chamber

1. Collect performance data: concentration, time, chamber volume

Hypothetical air cleaner test results:

Time (min)	Test report data: Concentration (CFU/m^3)	
	Control	Test
0	5000	5000
15	4200	2700
30	3300	1200
45	2700	400
60	2000	100



Analyzing Test Data: Example 1

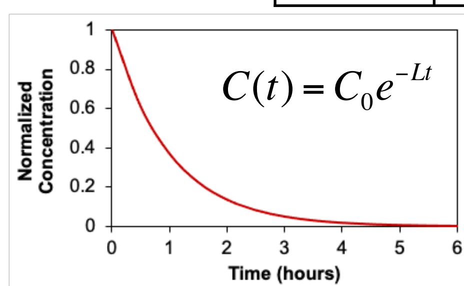
Aerosolized *E. coli* inactivation test in a 500 ft^3 chamber

2. Fit concentration data to a first-order exponential decay model:

Time (min)	Test report data: Concentration (CFU/m^3)	
	Control	Test
0	5000	5000
15	4200	2700
30	3300	1200
45	2700	400
60	2000	100

→

Time (min)	Loss rate calculations: $\ln(N_{d,t}/N_{d,t=0})$	
	Control	Test
0	0	0
15	-0.174	-0.616
30	-0.416	-1.427
45	-0.616	-2.526
60	-0.916	-3.912



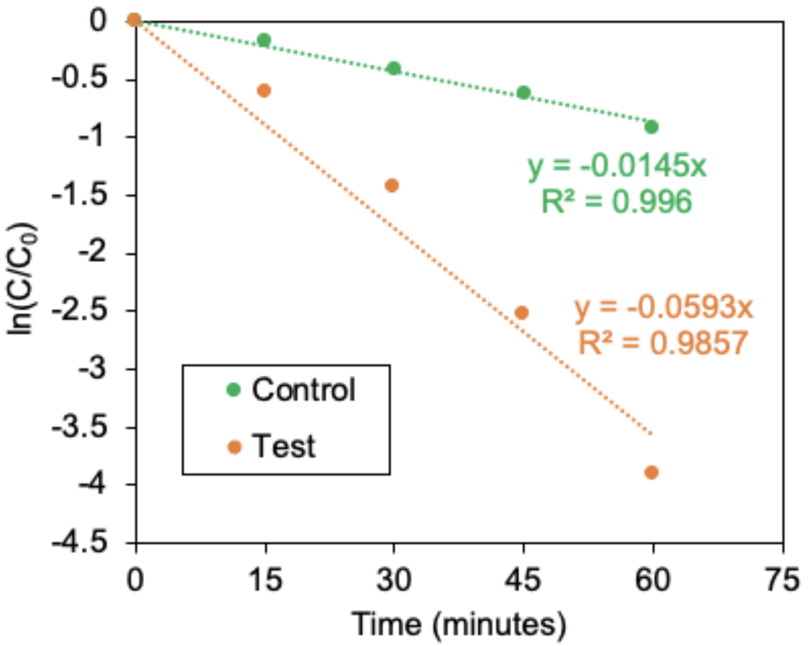
→

$$\ln \frac{N_{d,t}}{N_{d,t=o}} = -\boldsymbol{L}t$$

Interpreting Test Data: Example 1

Aerosolized *E. coli* inactivation test in a 500 ft³ chamber

3. Plot transformed data and estimate loss rates



4. Determine CADR from loss rates:

$$CADR = V_{test}\left(L_{ac\ on} - L_{ac\ off}\right)$$

$$CADR = 500\ ft^3 \times (0.0145 - 0.0593)$$

$$CADR = 22.4\ \frac{ft^3}{min} \approx \mathbf{22\ CFM}$$

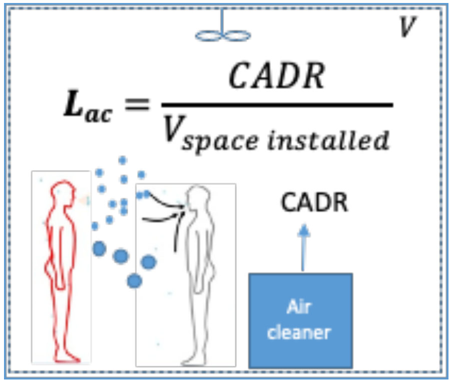
Scaling Test Data: Example 1

Aerosolized *E. coli* inactivation test in a 500 ft^3 chamber

5. Scale the results to the targeted installation space

- Use the volume of the *space the device will be installed*:

Assume we are designing this air cleaner for use in a conference room:
15 ft x 25 ft x 10 ft = 3750 ft^3



$$L_{ac} = \frac{CADR}{V_{space\ installed}} = \frac{22.4 \frac{ft^3}{min} \times \frac{60\ min}{1\ h}}{3750\ ft^3} = \mathbf{0.35\ h^{-1}}$$

- Typical target is $L_{ac} > 5\ h^{-1}$
- Air cleaner is **undersized** for the space

Key Issue: Test Chamber Volumes

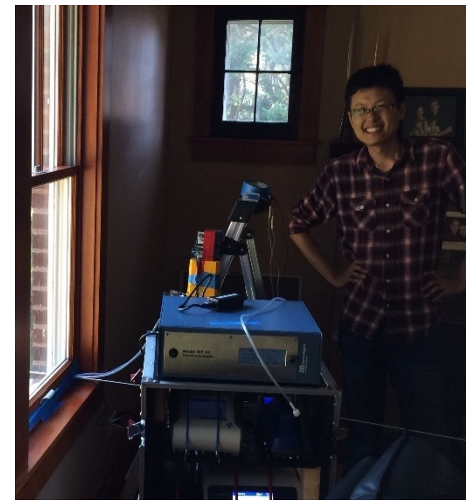
Resulting CADR scales with test chamber volume:

$$CADR = \boxed{V_{test}}\left(L_{ac\,on} - L_{ac\,off}\right)$$

Small chamber
(< 1 m³)
[< 35 ft³]

Medium chamber
(2-10 m³)
[70-350 ft³]

Large chamber
(10-50 m³)
[350-1750 ft³]



Field testing
(>50 m³)
[> 1750 ft³]

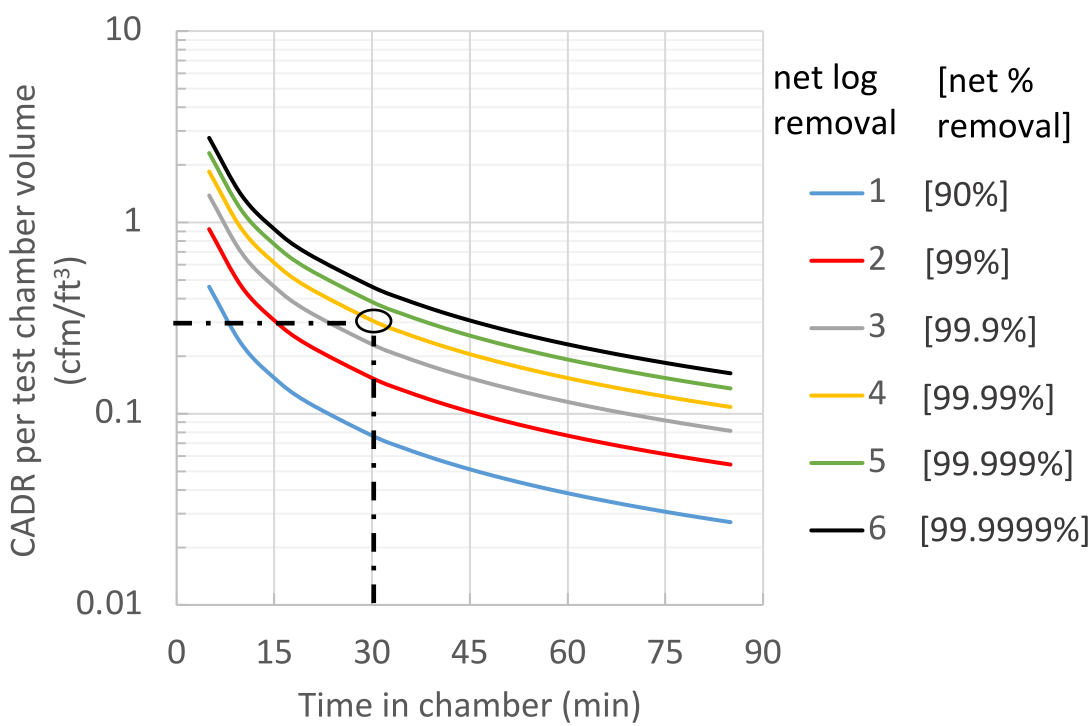
A wide range of chamber test volumes are used in practice

- Especially in **non-standardized** test approaches

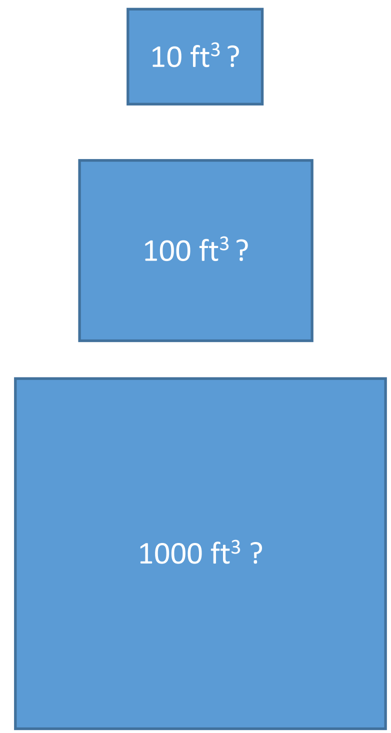
CADR Scales With Volume of Test Chamber

Consider the following test result:

- 99.99% removal in 30 minutes



What is the CADR if the tested in a chamber with volume…



CADR

3 cfm

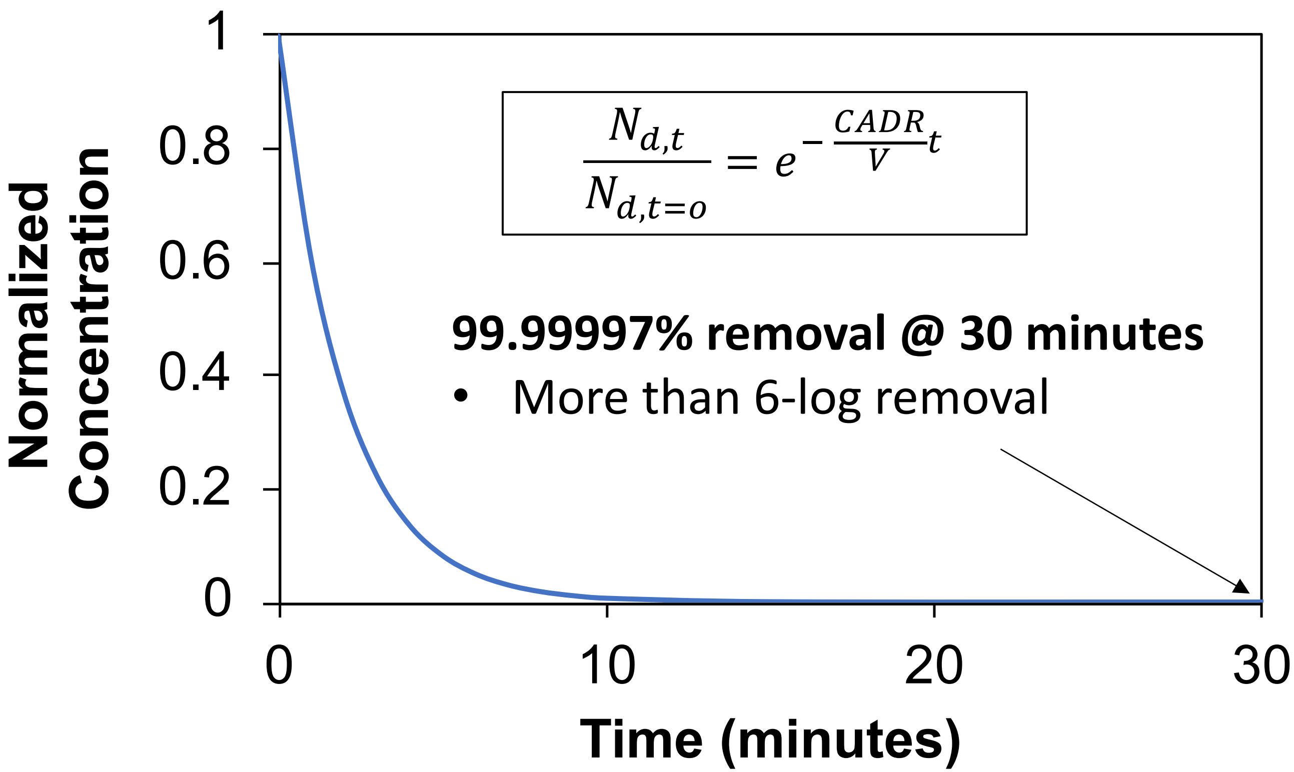
30 cfm

300 cfm

A wide range of CADRs can all claim 99.99% removal in 30 minutes, depending on test chamber volume.

Typical CADR in a 500 ft^3 Chamber

What % removal is achieved in a 500 ft^3 test chamber with a typical 250 CFM CADR air cleaner?



Tools to Support These Calculations

Many new air disinfection devices are marketed for their ability to inactivate SARS-CoV-2. How can I tell if they work as advertised?

*"As with all emerging technologies, consumers are encouraged to exercise caution and to **do their homework**."* CDC, Ventilation in Buildings, June 2, 2021

We developed **ACE IT** to help you do your homework

	A	B	C	D	E	F
1	**Air cleaner efficacy investigation tool (ACE IT)**					
2	**Developed by:**	Elliott T. Gall	Portland State University		gall@pdx.edu	
3		Brent Stephens	Illinois Institute of Technology		brent@iit.edu	
4		Mohammad Heidarinejad	Illinois Institute of Technology		muh182@iit.edu	
5		Delphine Farmer	Colorado State University		Delphine.Farmer@colostate.edu	
6		Marwa Zataari	D ZINE Partners		marwa.zaatari@gmail.com	
7	**Version:**	1.2				
8	**Date:**	6/1/2021	See Appendix D for changelog			
9	**Link:**	www.pdx.edu/healthy-buildings/ace-it				
10	**Goal: Provide a tool to interpret air cleaning tests results in the context of realistic indoor environments**					

www.pdx.edu/healthy-buildings/ace-it

Example with ACE IT

Example with ACE IT

SARS-CoV-2 inactivation test
conducted in a 1000 ft^3 chamber

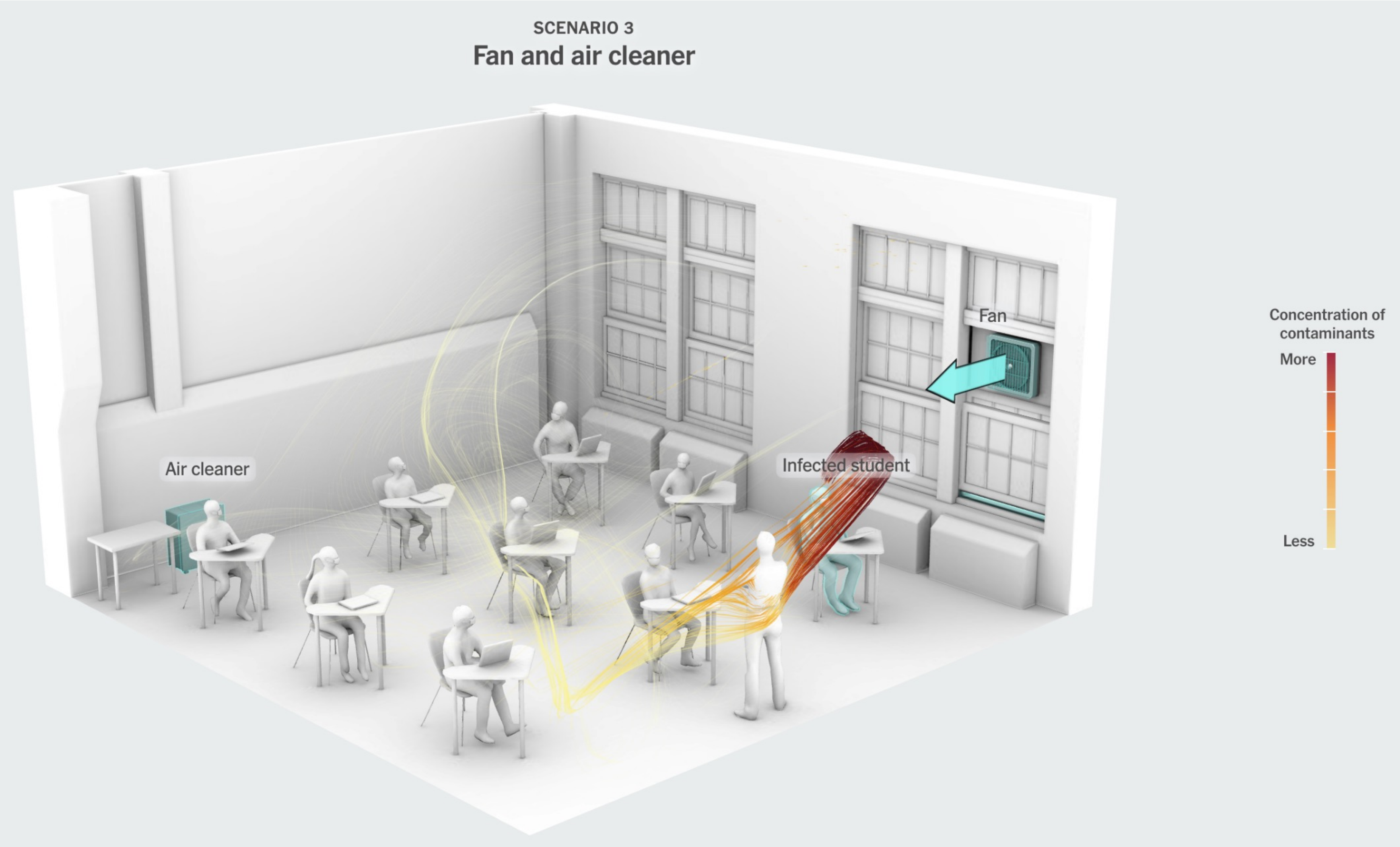
Time (min)	Test report data	
	Log reduction	
	Control	Test
0	0	0
10	0.4	2.2
20	0.9	4.6
30	1.4	6.1

To be installed in a 3750 ft^3 space

- e.g., 375 ft^2 w/ 10 ft ceilings

Other Considerations

Air Cleaner Placement and Performance



www.nytimes.com/interactive/2021/02/26/science/reopen-schools-safety-ventilation.html

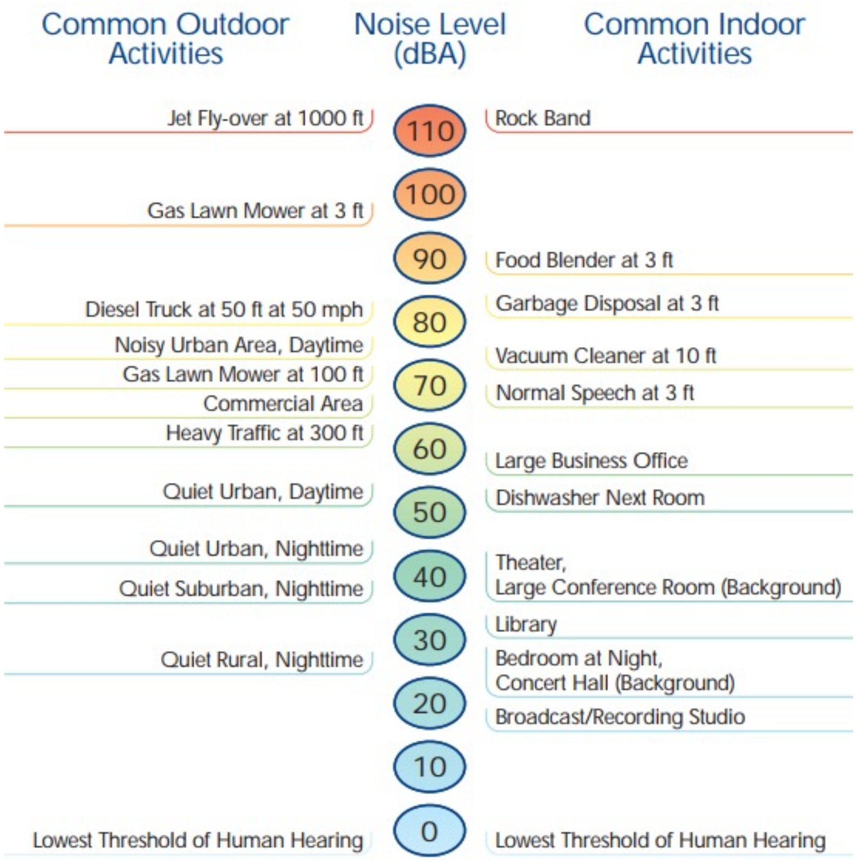
Noise Affects Use of Portable Air Cleaners

- Portable air cleaners are often used less frequently over time.
  - Some studies have noted/speculated that may be because of noise.

    Sulser et al. **2009** *Int Arch All Immunol*;
    Batterman et al. **2012** *Indoor Air*

- EPA maintains that interference and annoyance occurs at indoor noise levels above 45 dBA.*

- Many portable air cleaners exceed this threshold.
  - But quantified noise is not used as a standardized performance factor in the United States and is not routinely available on product packaging.

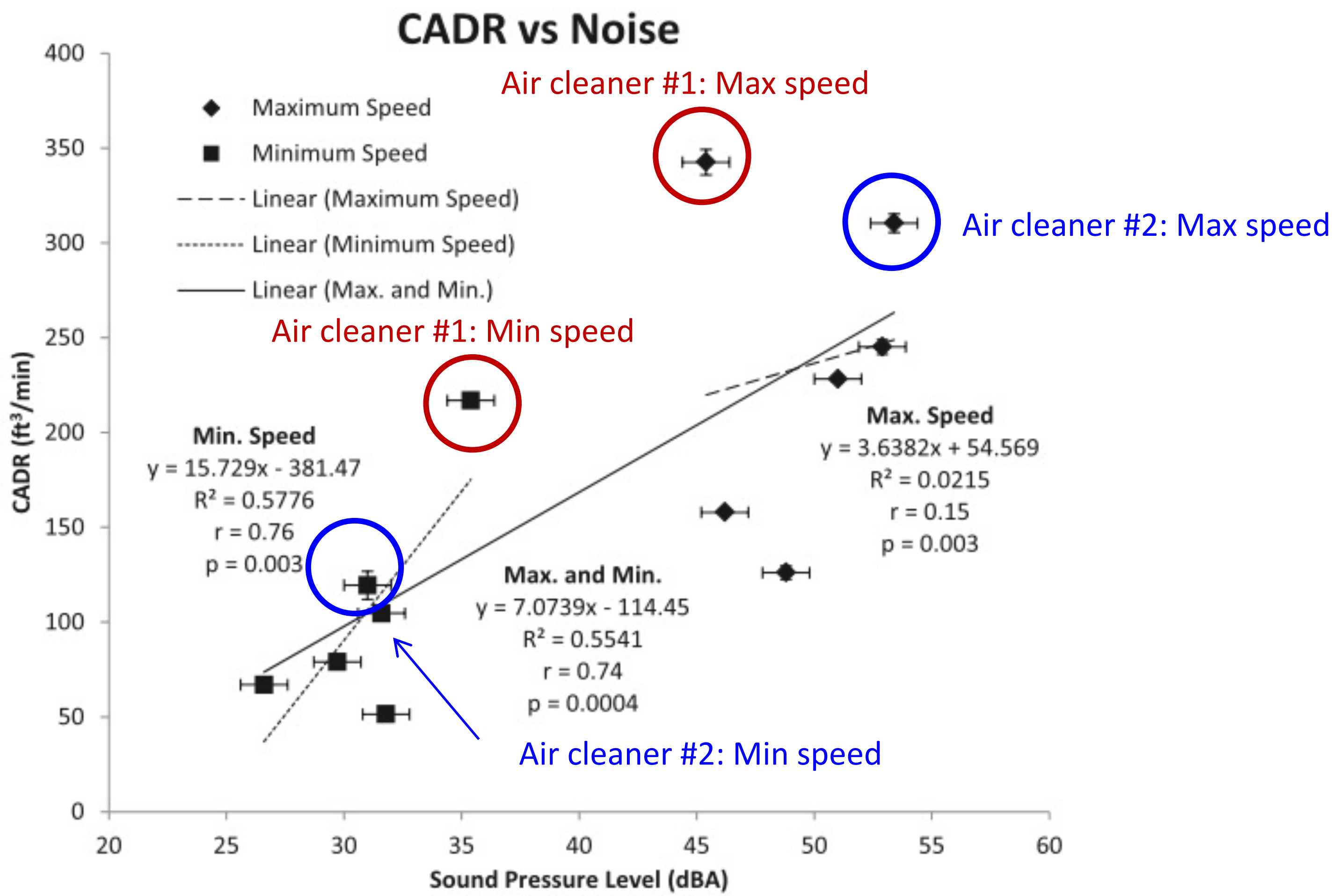


www.dot.ca.gov/dist2/projects/sixer/loud.pdf

*Source: archive.epa.gov/epa/aboutepa/epa-identifies-noise-levels-affecting-health-and-welfare.html

Noise Affects Use of Portable Air Cleaners

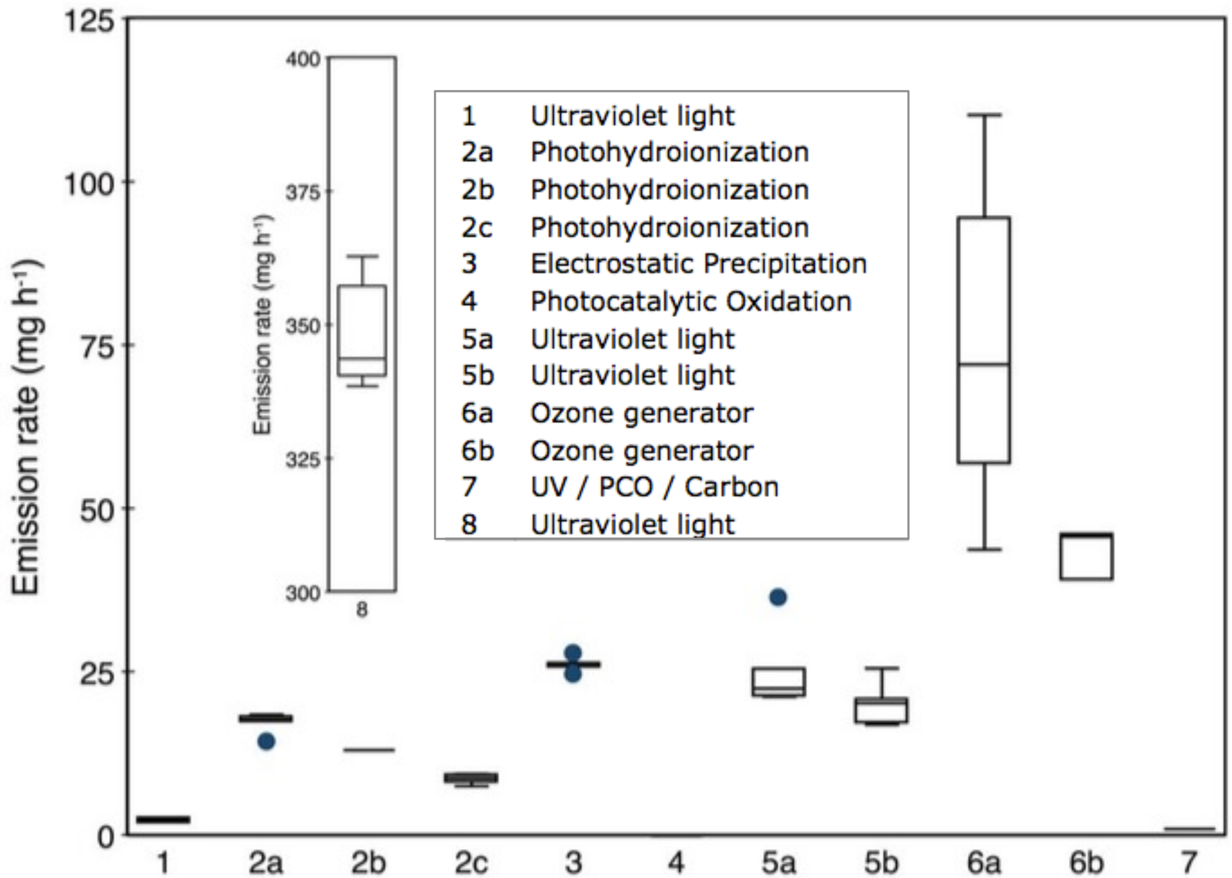
- Portable air cleaners are often loudest at their most effective setting (e.g., their highest flow setting).[1]



[1]Peck et al. 2016 *Building and Environ* 98:21–29

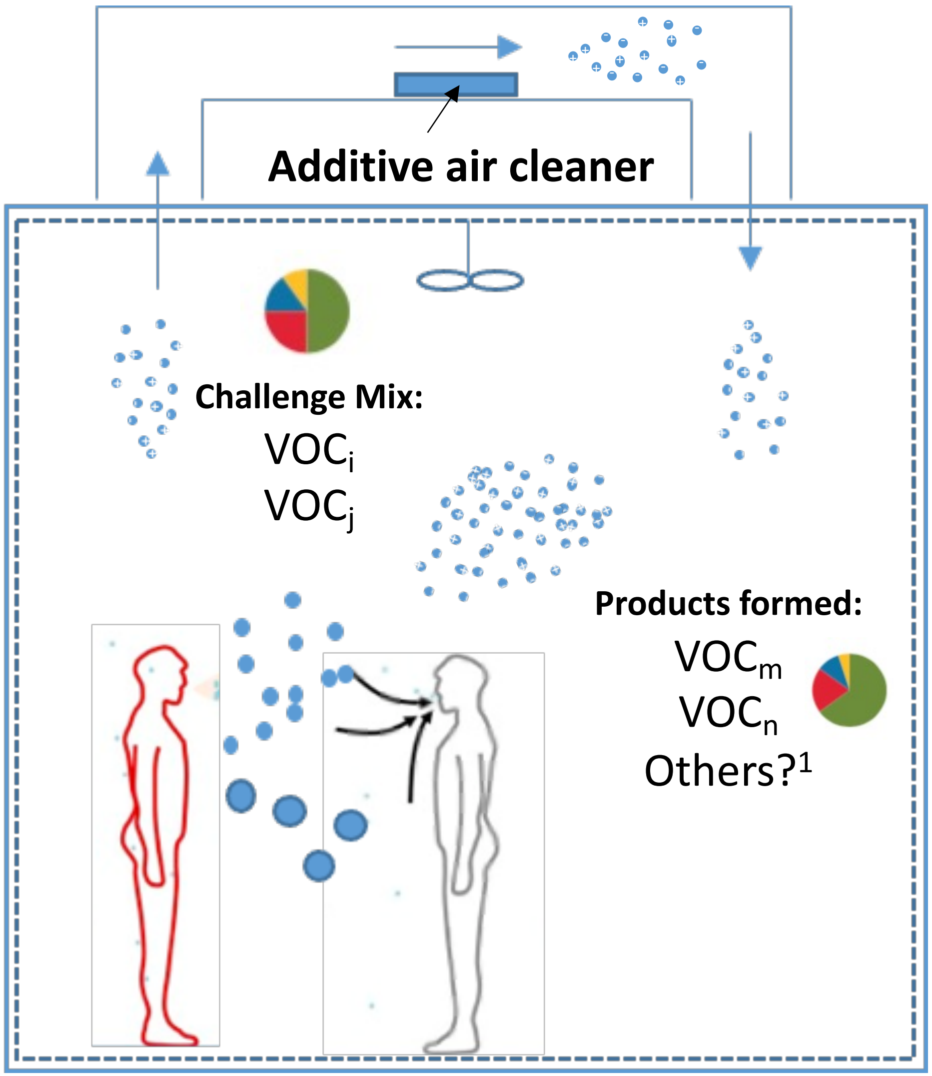
Ozone Emissions From Electronic Air Cleaners

- Some electronic air cleaners emit ozone (O_3) during operation.[1]
  - Ensure products meet UL 2998 standard (<5 ppb O_3 in chamber)

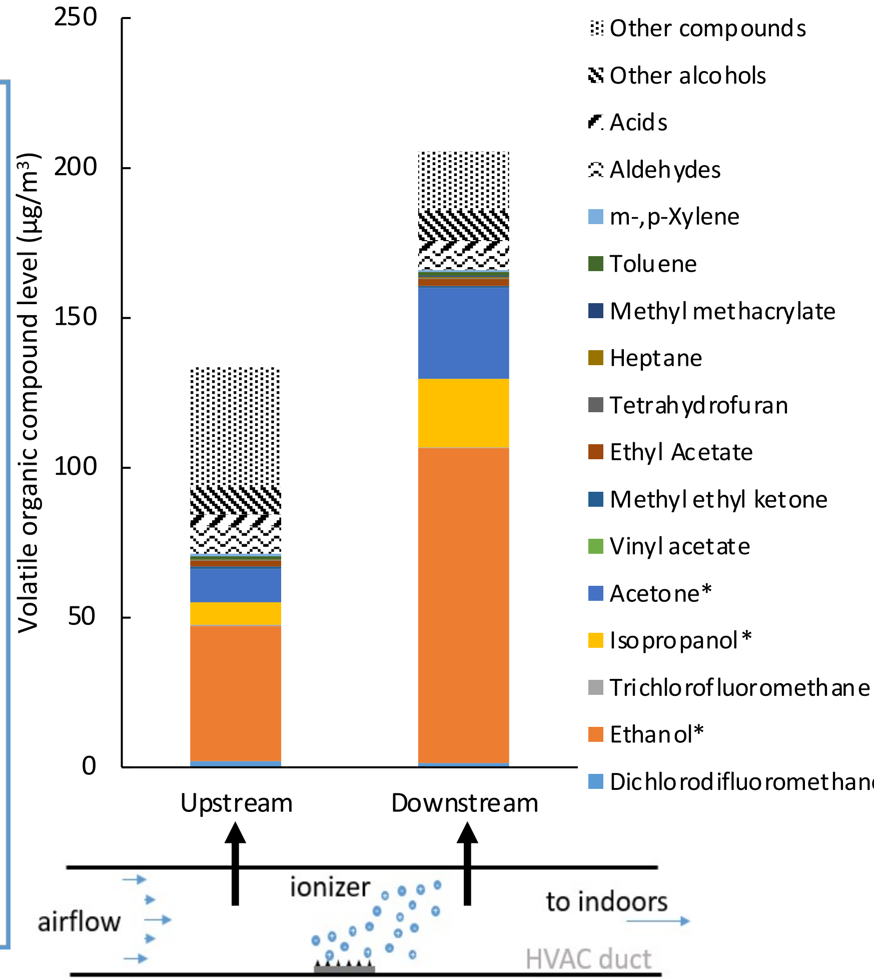


[1]Morrison et al., 2014 *CARB Report "In-duct air cleaning devices: Ozone emission rates and test methodology"*

Potential for Byproduct Formation



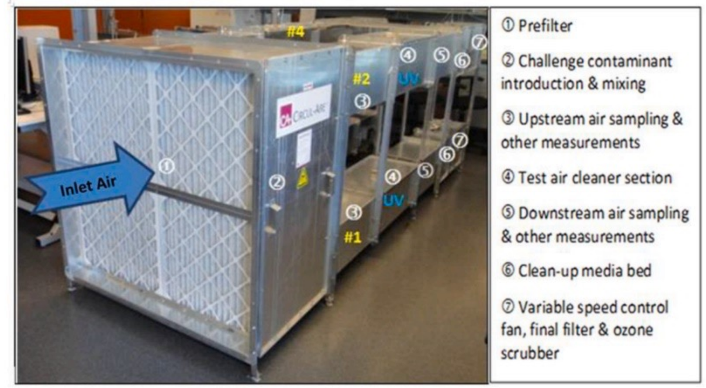
Example of byproduct measurements[2]



[1]Liu et al. 2020, *Indoor Air* 31:220-228; [2]Zeng et al. 2021, *Building and Environment* 195:107750

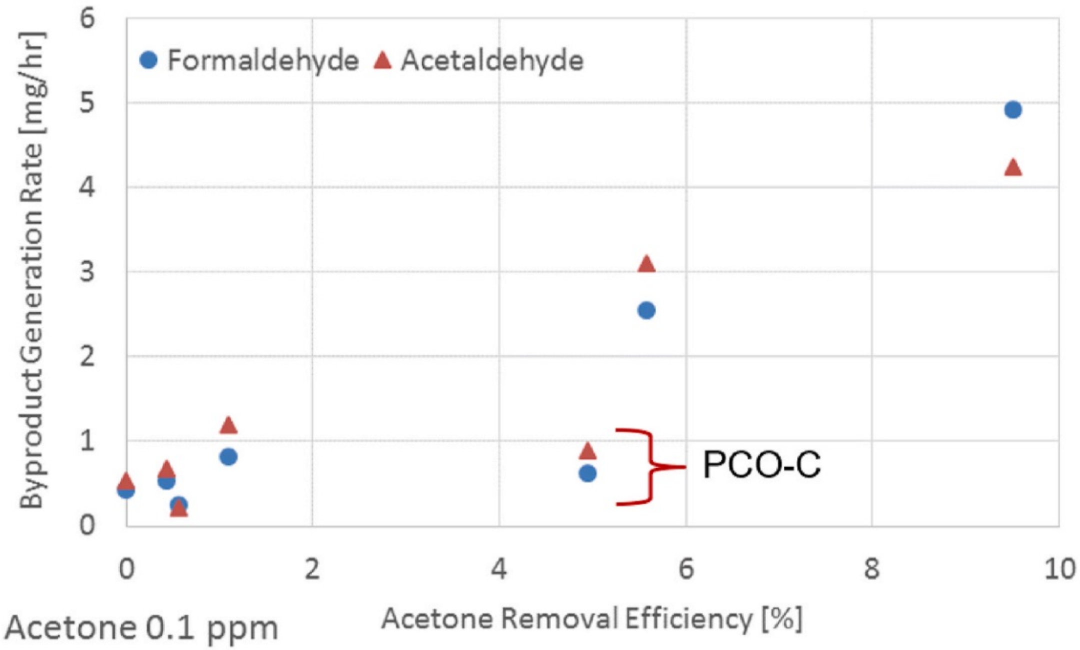
Potential for Byproduct Formation

- Tests of 12 electronic (**additive** air cleaners)[1]
- Three general mechanisms:
  1. Photocatalytic oxidation (PCO)
  2. Non-thermal plasma (NTP)
  3. Ozonation



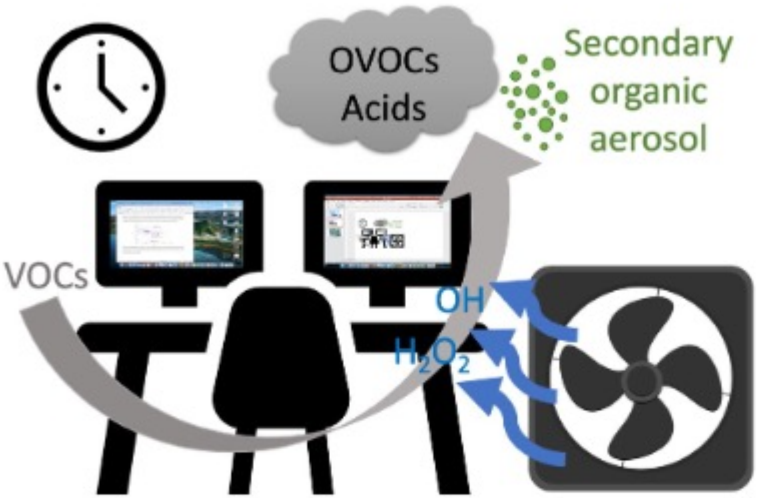
- Results show acetone removal efficiency to PCO systems scales linearly with byproduct generation rate[1]

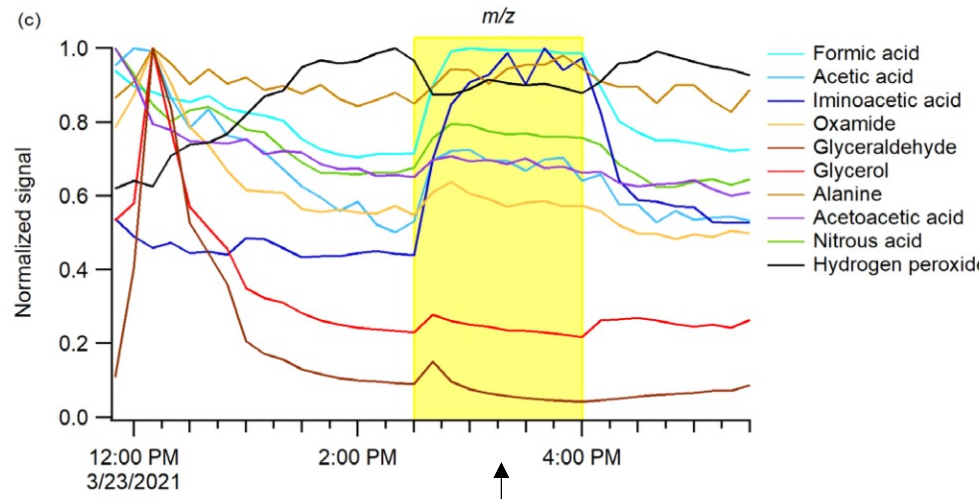
- **CADRs** across tested air cleaners for methyl ethyl ketone (MEK) ranged 0–68 m^3/h



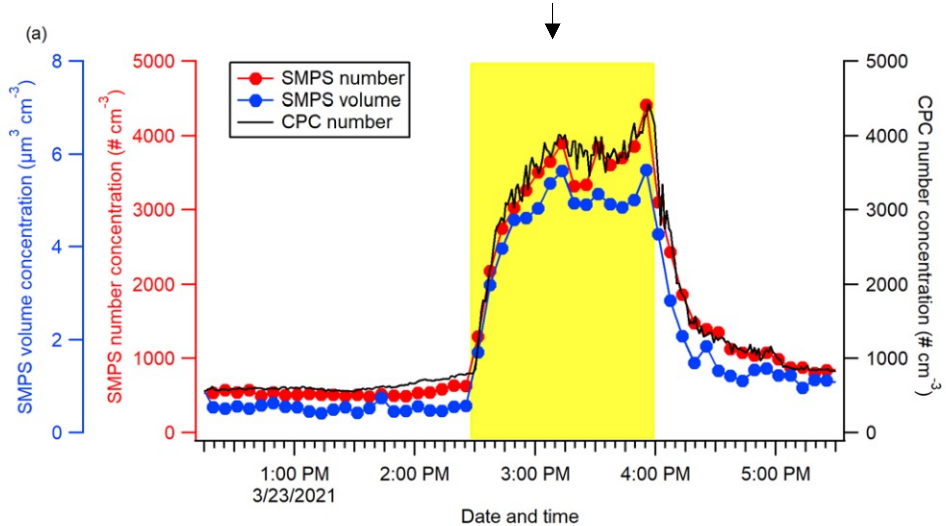
[1]Lee et al. 2021, *Building and Environment* 196(107782)

Potential Byproduct Formation





Yellow shading: device is on



Study (pre-print) of oxidant generating air cleaner operating **in an office**[1]:

- Enhanced low molecular weight OVOCs
  - Top, shown in yellow
- Increases in particle number + volume
  - Bottom, shown in yellow

[1]Joo et al., medrxiv, doi.org/10.1101/2021.06.01.21258186

Closing Thoughts and Recommendations

What to Ask of Laboratory Test Reports?

- **Seek the following details from <u>laboratory reports</u> provided on air cleaning technology efficacy:**
  - Were any standard test methods used? And were they appropriate?
  - Volume of test chamber/environment
  - Were air samples or surface samples collected?
  - What were the constituent types and concentrations used?
  - For additive technologies, how much of which additives were present?
  - Were byproduct tests performed (and under realistic) conditions?
  - What were the control and test loss rates?
  - What were the mixing conditions and airflow rates?
  - Did the test accurately reflect in-situ operation?
    - Air cleaner settings, e.g., fan flowrate
    - Added constituent concentration and locations of measurements
  - What instruments were used?
  - What is the equivalent CADR resulting from the test?

What to Ask of Field Test Reports?

- **Seek the following details from <u>field-test reports</u> provided on air cleaning technology efficacy:**
  - Were any field test method standards or guides used? [1,2,3]
  - Were indoor and outdoor measurements conducted simultaneously?
  - Were there appropriate controls?
  - Were there differences in test conditions with air cleaner on and off?
    - How was this verified? Air change rates controlled/constant? Occupancy patterns?
  - Were appropriate (i.e., sufficiently sensitive) instruments used?
  - Were there sufficient data and appropriate statistical significance tests?
  - Were upstream/downstream measurements made?
  - Were in-situ CADR measurements made?
  - Were mechanisms that contribute to loss rates teased out?
    - e.g., separating air cleaning, deposition, and inactivation?
  - For additive technologies, how much of which additives were present?
  - Were byproduct tests performed (and under realistic) conditions?

[1]AIHA, The IAQ Investigator's Guide; [2]NIOSH Guidance for indoor air quality investigations; [3]Chan and Singer 2014, LBNL-6607E

Air Cleaning: Charting a Path Forward

Ongoing Research Needs:

- **Fundamental studies** that elucidate underlying mechanisms of action of air cleaning technologies
    - o Manufacturers can support by endeavoring to as clearly as possible explain mechanism
    - o Manufacturers should explain mechanism to various stakeholders
        - – Distributors, purchasers, installers/operators and "end-users"
- **Studies in well-controlled environments**
    - o Chamber studies with test conditions, challenges clearly explained
- **Studies in less-well controlled environments**
    - o Field studies are needed to test understand, evaluate real-world efficacy and impacts

Suggestions for Improving Test Standards

- Standards are lacking for many aspects of air cleaners.

	Effectiveness	Byproduct formation
Particle	?	?
Chemical	?	?
Microbiological	?	-

Effectiveness:

- Standards and methods exist, but incomplete

Byproduct formation:

- Generally non-existent

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The Built Environment Research Group

advancing energy, environmental, and sustainability
research within the built environment
at Illinois Institute of Technology

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HEALTHY BUILDINGS
RESEARCH LAB AT
PORTLAND STATE

www.pdx.edu/healthy-buildings/indoor-air-quality-and-healthy-buildings

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