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Role of air cleaning in infection control

Preface

WILD WILD WEST of air cleaning...

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.

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

Chicago Tribune

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.

Study uncovers safety concerns with some air purifiers

EurekAlert!

Joint university research finds some air purifiers may actually increase harmful airborne chemicals

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CLEARING THE AIR

More Than 100 Missouri Schools Have Bought 'Often Unproven' Air-Cleaning Technology

KHN

ENVIRONMENT | MAR. 16, 2021

The Magic Molekule

There has never been a better business (or planetary) climate in which to calm and stoke your anxieties about dirty air.

By Reeves Wiedeman

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

Schools spending millions on air purifiers often sold using overblown claims

By Lauren Weber and Christina Jewett, Kaiser Health News

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

CNN health

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

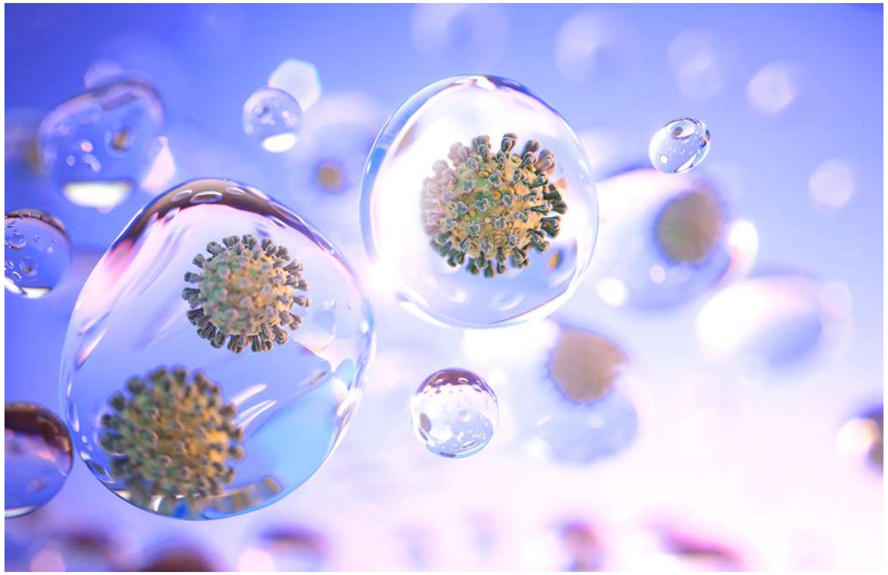
GREGORY BARBER SCIENCE 03.26.2021 WIRED

The Ionizer in Your School May Not Do Much to Fight Covid

Manufacturers say the devices remove 99 percent of viruses. Researchers say such claims are unproven, and cheaper air filters are more effective.

Objective

- The **true** (*I hope*) story about the effects of filtration and air cleaning on reducing the risk of infectious disease in occupied buildings (with no potential of adverse effects).



Introduction

Recommendations

ASHRAE EPIDEMIC TASK FORCE

Core Recommendations for Reducing Airborne Infectious Aerosol Exposure

The following recommendations are the basis for the detailed guidance issued by ASHRAE Epidemic Task Force. They are based on the concept that within limits ventilation, filtration, and air cleaners can be deployed flexibly to achieve exposure reduction goals subject to constraints that may include comfort, energy use, and costs. This is done by setting targets for equivalent clean air supply rate and expressing the performance of filters, air cleaners, and other removal mechanisms in these terms.

1. *Public Health Guidance* – Follow all current regulatory and statutory requirements and recommendations, including vaccination, wearing of masks and other personal protective equipment, social distancing, administrative measures, circulation of occupants, hygiene, and sanitation.
2. *Ventilation, Filtration, Air Cleaning*
   - 2.1 Provide and maintain at least required minimum outdoor airflow rates for ventilation as specified by applicable codes and standards.
   - 2.2 Use combinations of filters and air cleaners that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems.
   - 2.3 Only use air cleaners for which evidence of effectiveness and safety is clear.
   - 2.4 Select control options, including standalone filters and air cleaners, that provide desired exposure reduction while minimizing associated energy penalties.
3. *Air Distribution* - Where directional airflow is not specifically required, or not recommended as the result of a risk assessment, promote mixing of space air without causing strong air currents that increase direct transmission from person-to-person.
4. *HVAC System Operation*
   - 4.1 Maintain temperature and humidity design set points.
   - 4.2 Maintain equivalent clean air supply required for design occupancy whenever anyone is present in the space served by a system.
   - 4.3 When necessary to flush spaces between occupied periods, operate systems for a time required to achieve three air changes of equivalent clean air supply.
   - 4.4 Limit re-entry of contaminated air that may re-enter the building from energy recovery devices, outdoor air, and other sources to acceptable levels.
5. *System Commissioning – Verify that HVAC systems are functioning as designed.*

The *Lancet* COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel

The First Four Healthy Building Strategies Every Building Should Pursue to Reduce Risk from COVID-19

JULY 2022

3. UPGRADE AIR FILTERS TO MINIMUM EFFICIENCY REPORTING VALUE (MERV) 13

HVAC systems often have air filters to remove airborne particles from outdoor air that is brought indoors and from air that is recirculated within the building.

- **Benefits related to reducing the risk of COVID-19 and other infectious disease transmission:** Upgrading filters on recirculated air to those with ratings of MERV 13 or higher will reduce the transport of airborne particles while systems are operating, which may help reduce airborne infectious disease transmission within rooms and between rooms.
- **Benefits beyond disease transmission:** Enhanced filtration can reduce indoor concentrations of airborne particles of either indoor origin (e.g., cooking, cleaning or vacuuming, frequent use of printers) or outdoor origin (e.g., vehicle traffic, wildfires, desert dust storms). Exposure to fine particulate matter is associated with reduced cognitive function and reduced respiratory and cardiovascular health.[26,27,28,29,30,31,32,33,34,35,36,37]
- **Feasibility:** Filter upgrades may not be possible for all HVAC systems; HVAC professionals should be consulted before filter changes are made in a building. Annual material, labor, and fan energy costs associated with the use of MERV 13 filtration in a hypothetical 500 m^2 office are estimated to be $156.[38]

4. SUPPLEMENT WITH PORTABLE AIR CLEANERS, WHERE NEEDED

Free-standing, plug-in portable air cleaners with high efficiency particulate air (HEPA) filters capture airborne particles in rooms where they are deployed, when sized correctly.[39]

- **Benefits related to reducing the risk of COVID-19 and other infectious disease transmission:** Properly sized portable air cleaners with HEPA filters can reduce in-room concentrations of airborne particles, including those carrying viral material.
- **Benefits beyond disease transmission:** Portable air cleaners can reduce indoor concentrations of any airborne particles and reduce the risk of harmful particle-induced impacts on neurological/cognitive, respiratory, and cardiovascular health.
- **Feasibility:** Portable air cleaners are cost-effective, flexible solutions to reduce the risk of airborne infectious disease transmission in spaces where other ventilation and filtration modifications are impossible, or where building occupants seek additional reassurance about air quality.[40]

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Non-infectious air delivery rate (NADR)

The Lancet COVID-19 Commission
Task Force on Safe Work, Safe School, and Safe Travel

Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases

NOVEMBER 2022

TABLE 1.
Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Diseases; The Lancet COVID-19 Commission Task Force on Safe School, Safe Work, and Safe Travel

	Volumetric flow rate per volume	Volumetric flow rate per person		Volumetric flow rate per floor area	
	ACHe	cfm/person	L/s/person	cfm/ft²	L/s/m²
Good	4	21	10	0.75 + ASHRAE minimum outdoor air ventilation	3.8 + ASHRAE minimum outdoor air ventilation
Better	6	30	14	1.0 + ASHRAE minimum outdoor air ventilation	5.1 + ASHRAE minimum outdoor air ventilation
Best	> 6	> 30	> 14	>1.0 + ASHRAE minimum outdoor air ventilation	> 5.1 + ASHRAE minimum outdoor air ventilation

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May 12-2023: ASHRAE 241 and CDC

ASHRAE

ASHRAE Standard 241P

Advisory Public Review Draft

Control of Infectious Aerosols

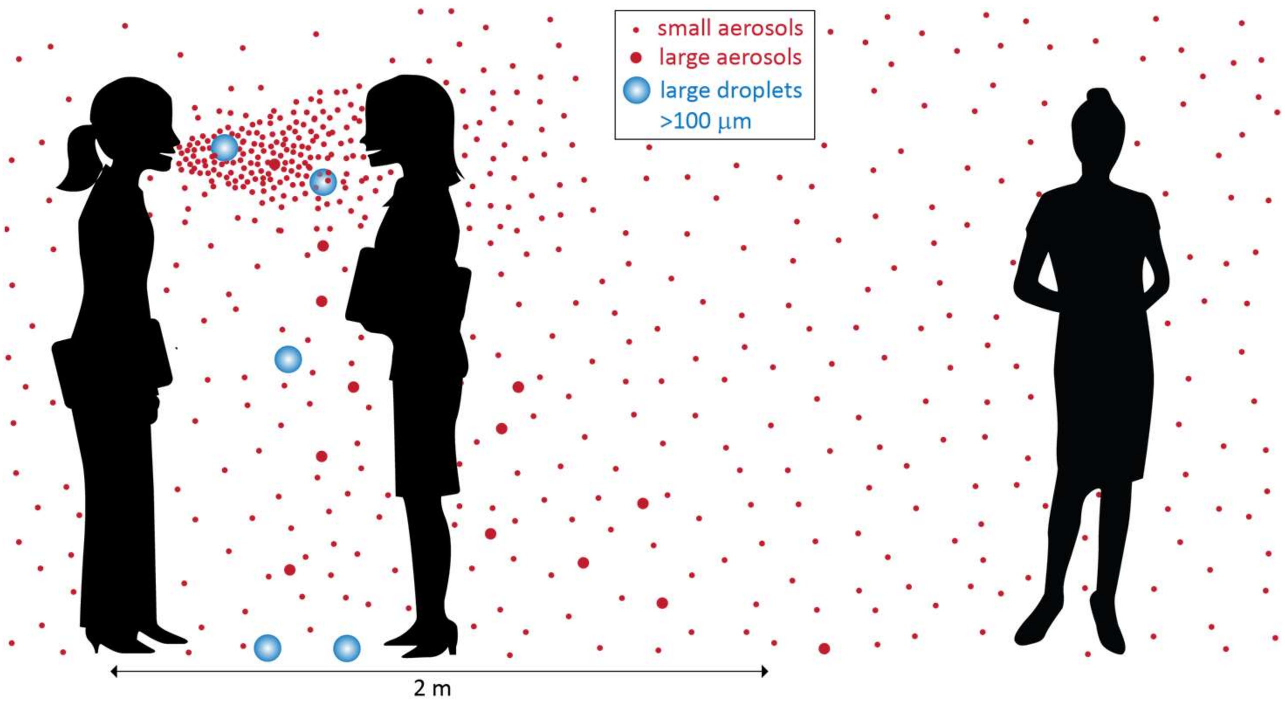
Table 5-1 Minimum Equivalent Outdoor Air per person for Infection Control Rates in *Breathing Zone*

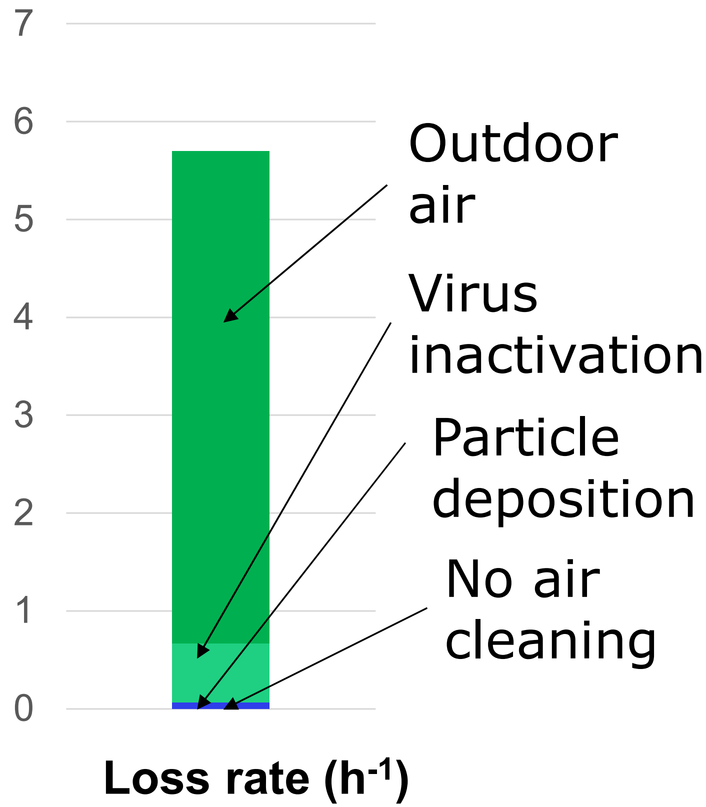
Occupancy Category	EOAi	
	CFM/person	L/s/person
Office	40	20
Educational Facilities	50	25
Food and Beverage Facilities	40	20
Residential	50	25
Retail	20	10
Gym	80	40
Public Assembly spaces	20	10
Place of religious worship	30	15
Healthcare exam room	60	30
Healthcare patient room	180	90
Healthcare resident room	80	40
Common treatment area	90	45
Healthcare waiting room	120	60

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

5 ach

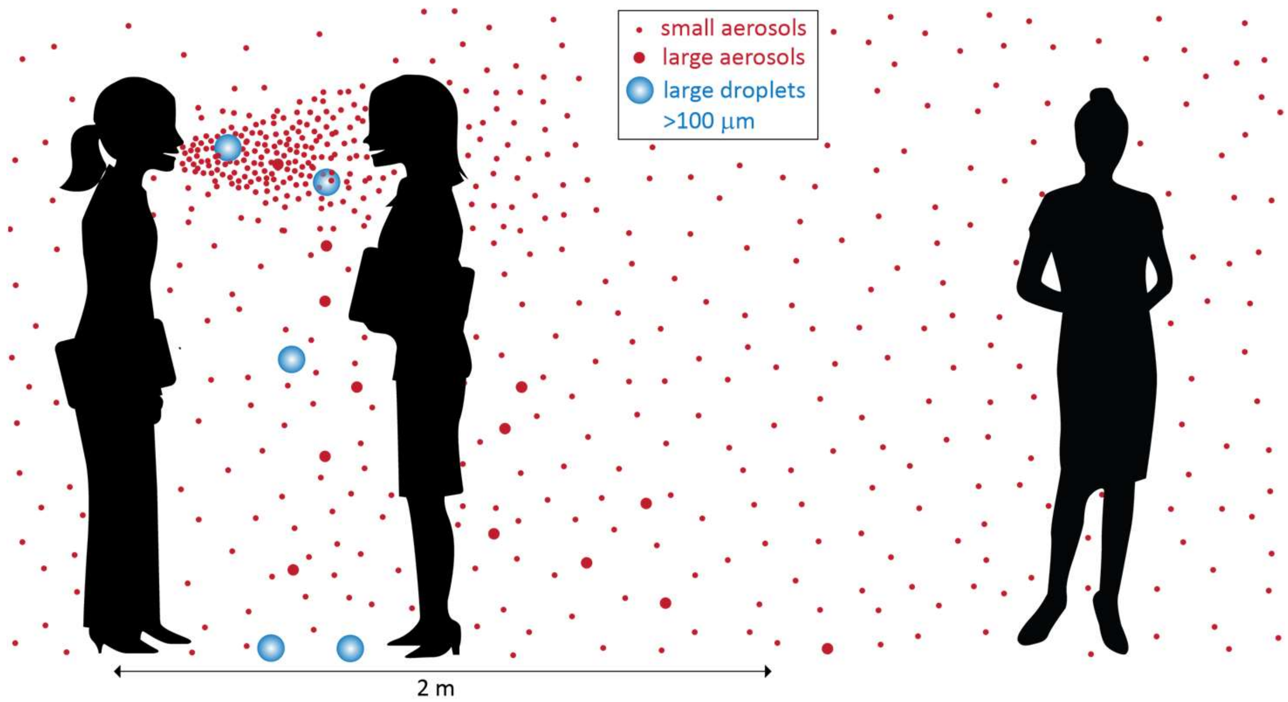
Aerosol transmission, long range

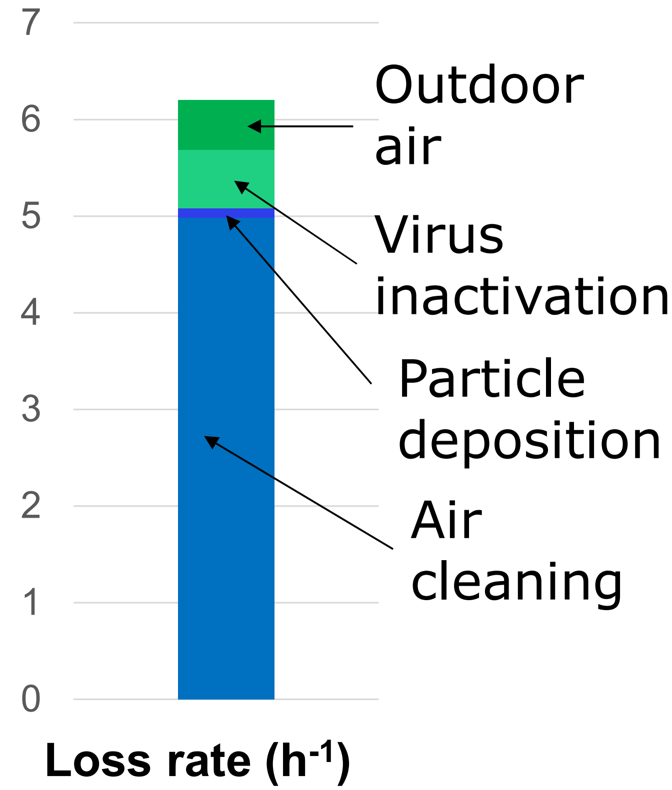




Sources: Morawska et al. (2020); Johnson et al. (2004); Van Dormalen et al. (2020); Hussein and Kulmala (2008); ANSI/AHAM AC-1

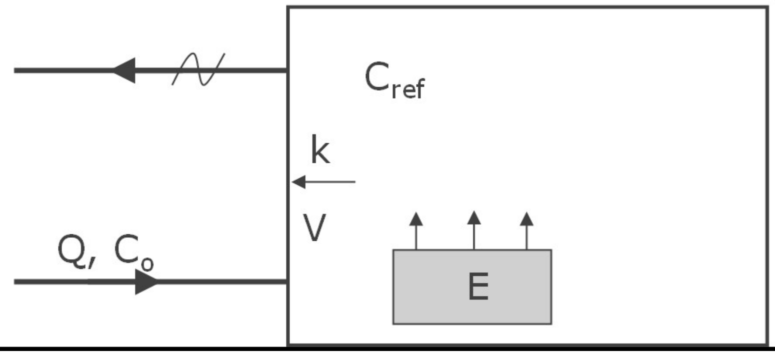
Aerosol transmission, long range



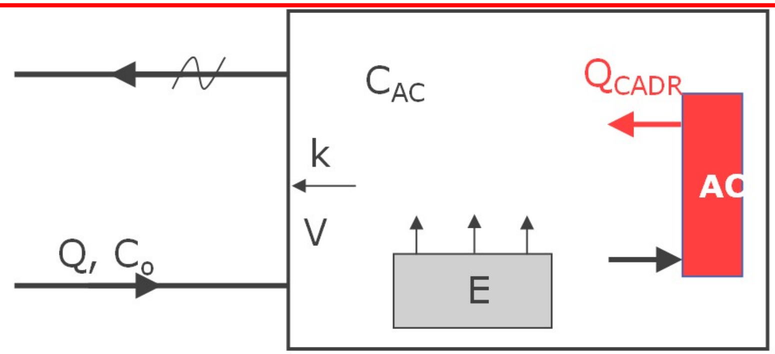


Air cleaning

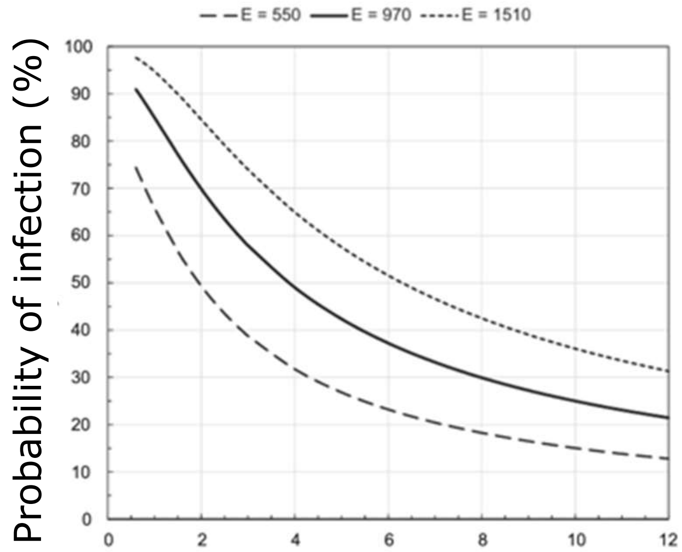
The effect of air cleaner => additional dilution/removal => lower risk



$$C_{ref} = \frac{Q \cdot C_o + E}{Q + k \cdot V}$$



$$C_{AC} = \frac{QC_0 + E}{Q + k \cdot V + Q_{CADR}}$$



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

Air cleaning technologies

Technology	Mechanism of action	Key parameters	Example
"Subtractive" technologies (filters, sorbents)	Removing or inactivating targeted contaminants from indoor air when they come in contact with the technology	• Airflow rate • Face velocity • Single-pass efficiency • Potential for by-product formation	Filters, electrostatic precipitators (ESPs), sorbent media (for gases), excitation media, UVGI
"Additive" technologies (electronic and reactive air cleaners)	Adding constituents to the air to remove particles, inactivate microorganisms and/or react with chemical contaminants	• Type, concentration and dose of additives • Potential toxicity of additives • Potential for by-product formation • Airflow • Face velocity • Location with respect to space • Recirculated vs 100% OA	Ionizers, bipolar ionization, needle point discharge, ozone, plasma, hydrogen peroxide, PCO, reactive oxygen species, oxidants, fumigation, UVGI
Hybrid	⊕		

Common test standards

Technology	Target Pollutant(s)	Test Standards (Rating Metrics)
Fibrous media filters	Particles	ASHRAE 52.2 (MERV) ISO 16890 (ePM) ISO 29463 (HEPA) Proprietary standards (FPR,MPR) Portable air cleaners: AHAM AC-1 (CADR)
Sorbent	Gases	ASHRAE 145.2
Ultraviolet germicidal irradiation (UVGI)	Microbial particles	Air: ASHRAE 185.1 Surfaces: ASHRAE 185.2
Electrostatic precipitators (ESPs)	Particles+	No rating; some ozone emission standards (UL 2998) ✖
Ionizers, plasma, PCO, H2O2, etc.	Particles+	No rating; some ozone emission standards (UL 2998) ✖

ASHRAE Standard 62.1-2019 requires any air cleaning technologies to comply with UL 2998 (0 ppb ozone)

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Position documents providing guidelines

All filtration and air-cleaning technologies should be accompanied by data documenting their performance regarding removal of contaminants; these data should be based on established industry test standards. If not available, scientifically controlled third-party evaluation and documentation should be provided.

Devices that use the reactivity of ozone for the purpose of cleaning the air should not be used in occupied spaces because of negative health effects that arise from exposure to ozone and its reaction products. Extreme caution is warranted when using devices that emit a significant amount of ozone as by-product of their operation, rather than as a method of air cleaning. These devices pose a potential risk to health.

Commissioning, active maintenance, and monitoring of filtration and air-cleaning devices are needed to ensure design performance.

In the absence of robust information regarding safe levels of ozone, the precautionary principle should be used. Any ozone emission (beyond a trivial amount that any electrical device can emit) should be seen as a negative and use of an ozone-emitting air cleaner, even though the ozoneis an unintentional by-product of operation, may represent a net negative impact on indoor air quality and thus should be used with caution. If possible, non-ozone-emitting alternatives should be used.

Attentionmust be paid to certain air-cleaning technologies that claim to produce radicals (e.g.,hydroperoxy, peroxy, and hydroxyl radicals) that become airborne (gaseous state) as a means of effecting air cleaning/treatment

ASHRAE Position Document on Filtration and Air Cleaning

Approved by ASHRAE Board of Directors
January 29, 2015

Expires
January 29, 2018

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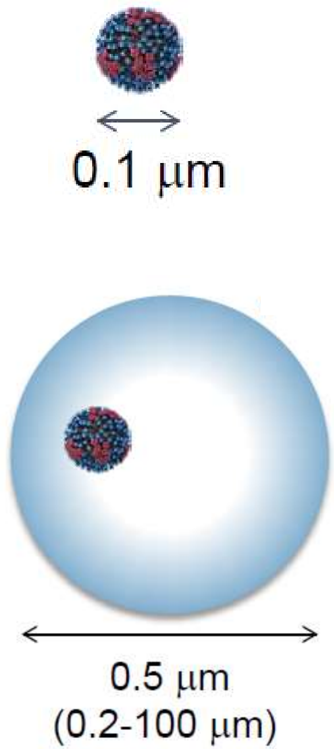
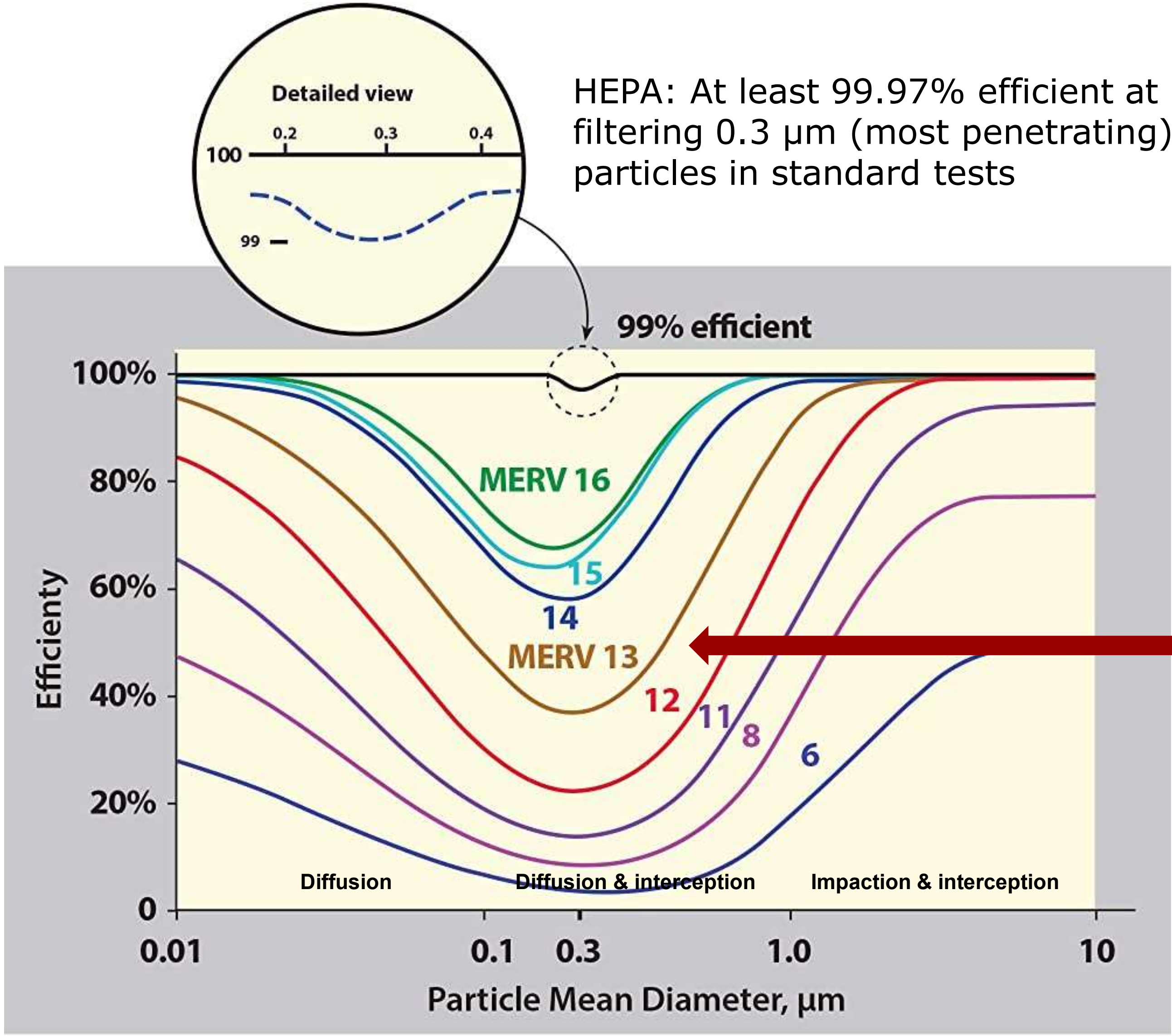
404-636-8400 • fax: 404-321-5478 • www.ashrae.org

Air filtration


THE RELATIVE SIZE
OF PARTICLES
From the COVID-19 pandemic to the U.S. West Coast wildfires, some of the biggest threats now are also the most microscopic.
A particle needs to be 10 microns (µm) or less before it can be inhaled into your respiratory tract. But just how small are these specks?
Here's a look at the relative sizes of some familiar particles
HUMAN HAIR 50-180µm
FOR SCALE
FINE BEACH SAND 90µm
GRAIN OF SALT 60µm
WHITE BLOOD CELL 25µm
GRAIN OF POLLEN 15µm
DUST PARTICLE (PM10) <10µm
RED BLOOD CELL 7-8µm
RESPIRATORY DROPLETS 5-10µm
DUST PARTICLE (PM2.5) 2.5µm
BACTERIUM 1-3µm
WILDFIRE SMOKE 0.4-0.7µm
CORONAVIRUS 0.1-0.5µm
T4 BACTERIOPHAGE 0.225µm
ZIKA VIRUS 0.045µm
Pollen can trigger allergic reactions and hay fever—which 1 in 5 Americans experience every year.
The visibility limits for what the naked eye can see hovers around 10-40µm.
Respiratory droplets have the potential to carry smaller particles within them, such as dust or coronavirus.
Wildfire smoke can persist in the air for several days, and even months.


0.1 µm
0.5 µm
(0.2-100 µm)

HEPA: At least 99.97% efficient at filtering 0.3 µm (most penetrating) particles in standard tests



ASHRAE Recommendations: MERV 13

MERV 8 + MERV 11 = **MERV 13**

MERV 11 + UVC 60% = **MERV 13**

MERV 8 + UVC 80% = **MERV 13**

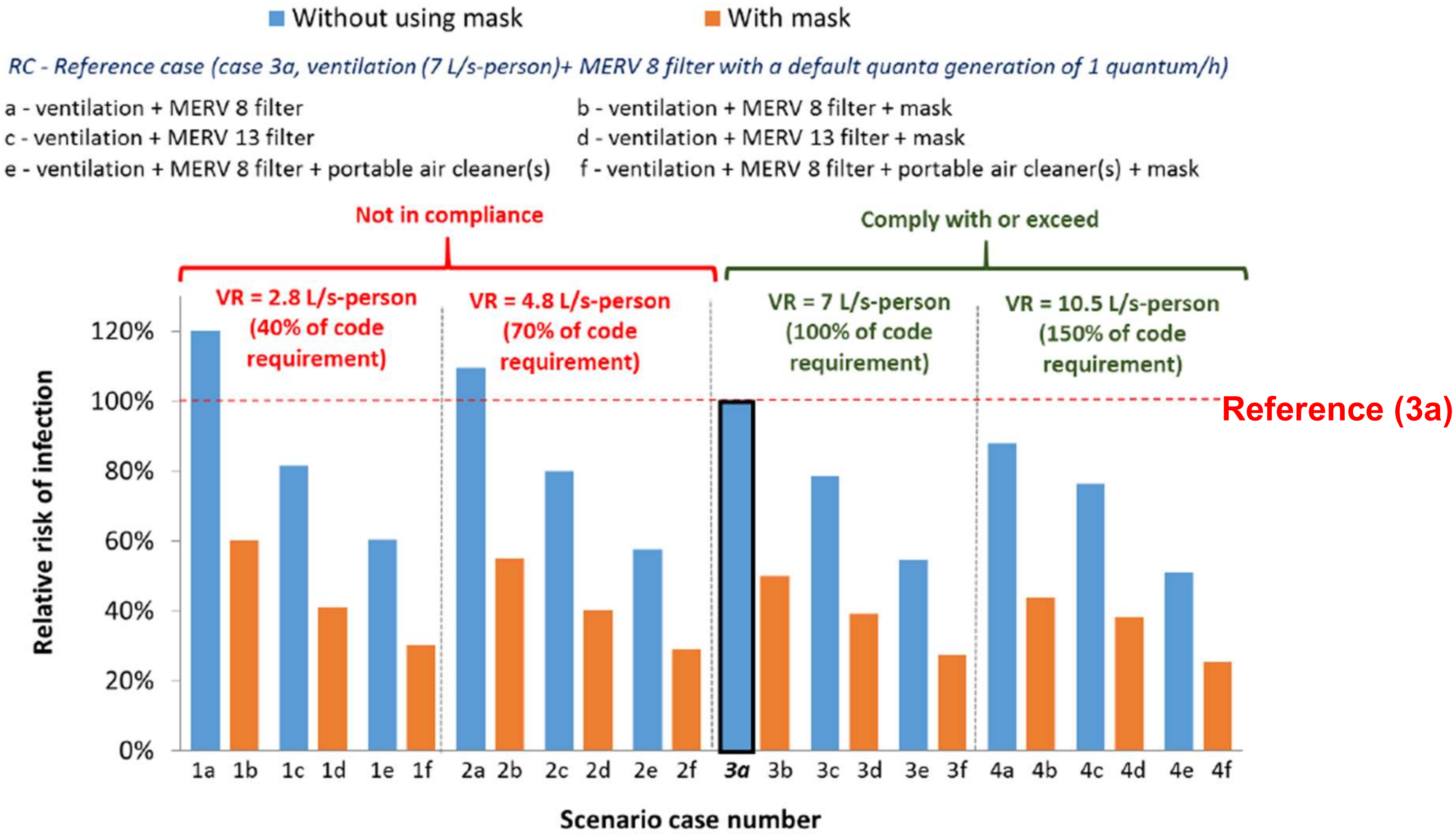
MERV 11 + HEPA CADR 150= **MERV 13**

MERV 8 + HEPA CADR 300= **MERV 13**

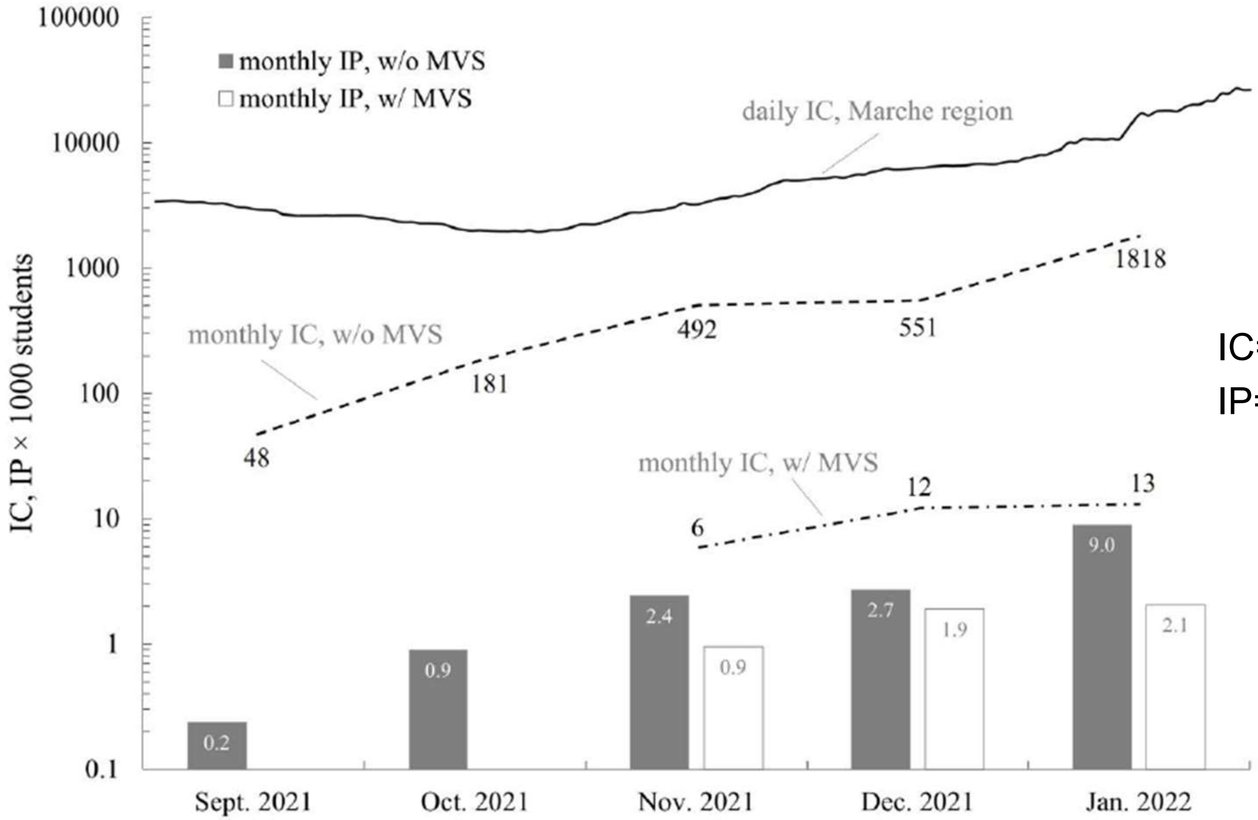
Do-it-yourself (DIY) portable air cleaners, e.g. Corsi-Rosenthal

Sources: Sactown Magazine

No field data, only modeling



Field validation with increased ventilation

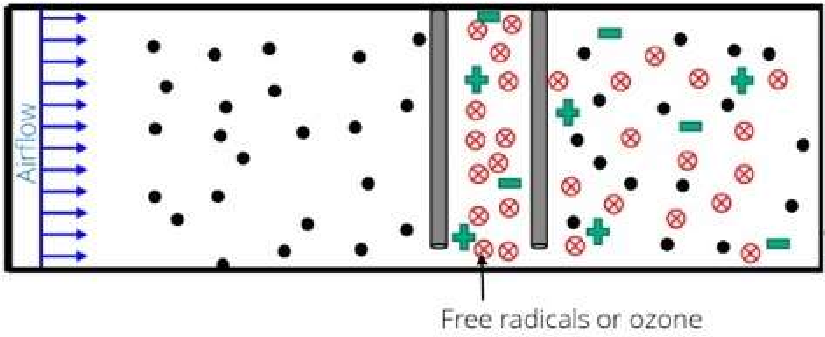


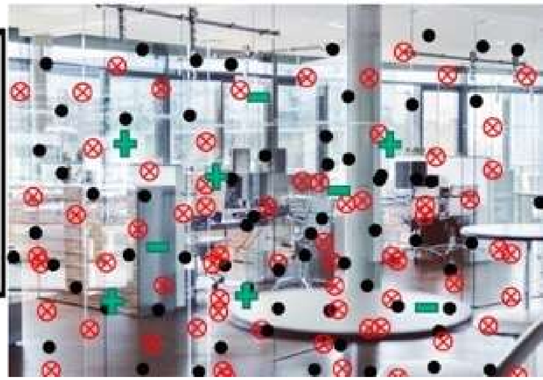
IC=incidence cases

IP=incidence proportion

Other air cleaners

Electronic Air Cleaners – EACs, or additive air cleaners





Names

4 broad categories and MANY MANY names

- Photocatalytic Oxidation (PCO) and Dry Hydrogen Peroxide (DHP)
- Bipolar Ionization/Corona Discharge/ Needlepoint Ionization
- Oxidants
- Fumigation

Mechanism

But the mechanism is the same:

Create reactive ions, mixtures of reactive oxygen species (ROS), ozone, hydroxyl radicals, superoxide anions, etc. in air that react with airborne contaminants

Facts

Fact 1: Free radicals and/or ozone produced

Fact 2: Indiscriminate and unpredictable reactions

Fact 3: unproven to be safe or effective

UVGI and UVC

UV-C energy: 265 nm optimum wavelength for damaging DNA and RNA.

What?

- Air and/or surface
- Upper room, in duct, portable

How much?

- On the fly air disinfection: Minimum target UVC dose (254 nm) of 1,500 μW•s/cm^2 (1,500 μJ/cm^2) to get 99% removal.
- Should be coupled with mechanical filtration

https://www.ashrae.org/technical-resources/filtration-disinfection

Challenges

Major misconceptions and problems

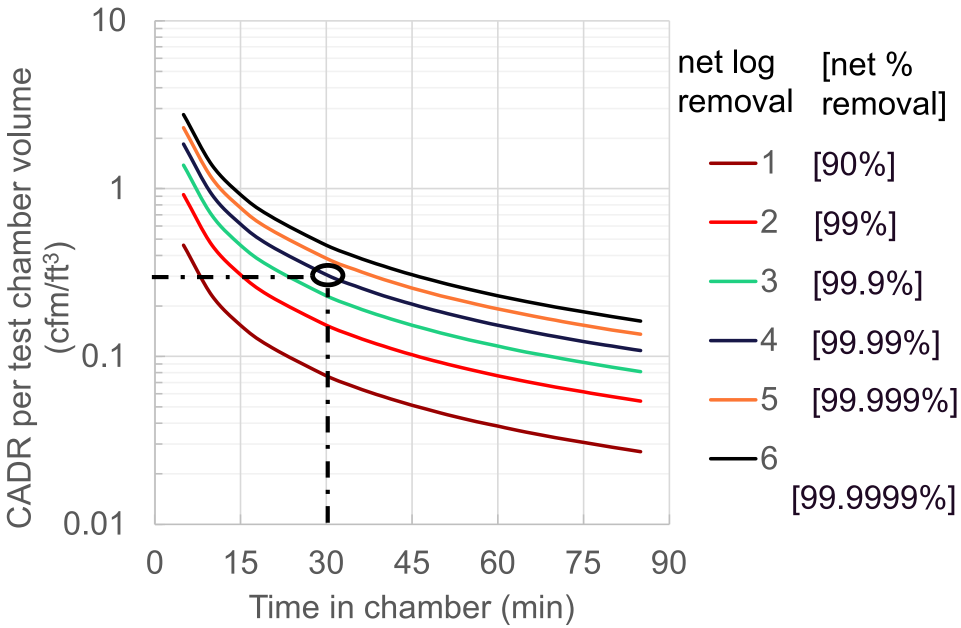
- Efficiency vs. effectiveness or efficiency vs. CADR
- Production of ozone or other reactive species
- Chemical transformations producing new species, (potentially) toxic pollutants
- CADR vs. noise, noise vs. Efficiency

- Commissioning, maintenance, operation, monitoring, documentation

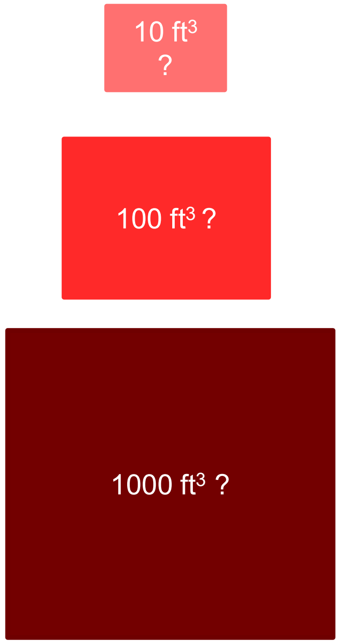
CADR Scales With Volume of Test Chamber

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

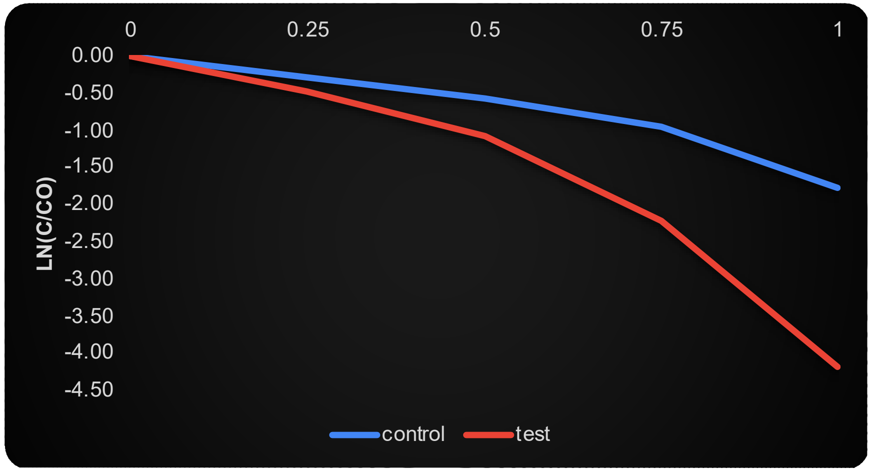
A wide range of CADRs can all claim 99.99% removal in 30 minutes, depending on test chamber volume

Calculation of efficiency in realistic indoor environments

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

Consider the following test result:

- 98.3% removal in 60 minutes
- Table/graph concentration: control, test



2) Comparison calculation		
	loss rate (1/h)	
control (w/ device off)	1.5	
test (w/ device on)	3.5	
Effect of device	2.0	

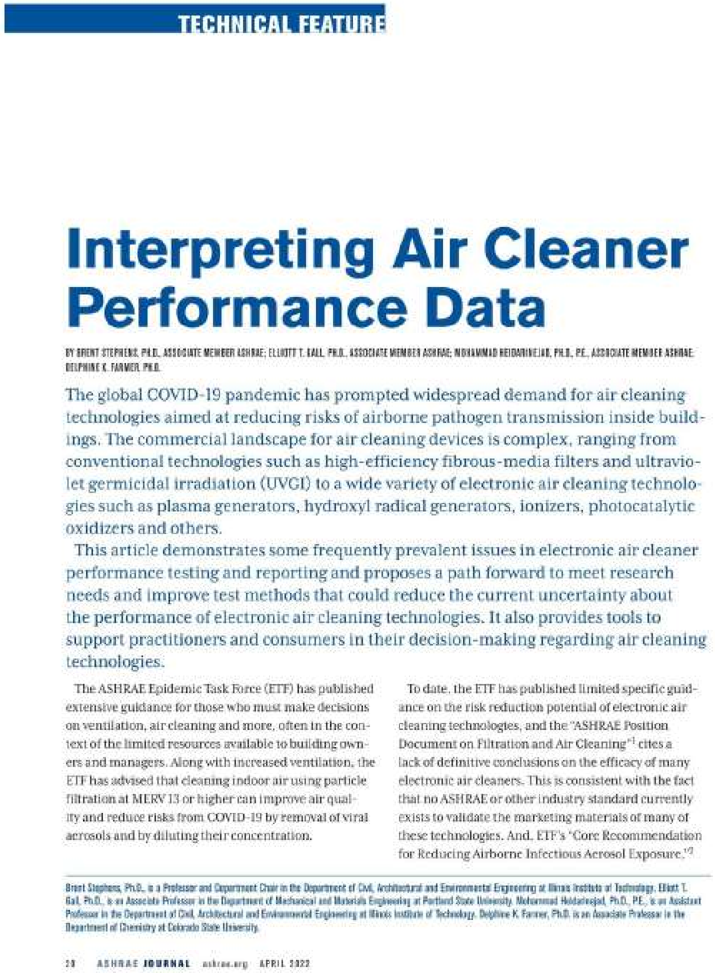
3) Scaling to indoor setting		
Floor area	1,000	ft²
Ceiling height	8	ft
Volume	8,000	ft3
Clean air changes per hour (ACH) provided by device	0.31	1/h

To get 5 ACH, we need to install in this classroom 16 units.

→ Manufacturer recommendation is 1 device for 4 classrooms:

→ For 4 classrooms to achieve 5 ACH, you would need 4 x 16 = 64 devices!!!

More examples



TECHNICAL FEATURE

Interpreting Air Cleaner Performance Data

BY BRENT STEPHENS, PH.D., ASSOCIATE MEMBER ASHRAE; ELLIOTT T. GALL, PH.D., ASSOCIATE MEMBER ASHRAE; MOHAMMAD HEIDARINEJAD, PH.D., P.E., ASSOCIATE MEMBER ASHRAE; DELPHINE K. FARMER, PH.D.

The global COVID-19 pandemic has prompted widespread demand for air cleaning technologies aimed at reducing risks of airborne pathogen transmission inside buildings. The commercial landscape for air cleaning devices is complex, ranging from conventional technologies such as high-efficiency fibrous-media filters and ultraviolet germicidal irradiation (UVGI) to a wide variety of electronic air cleaning technologies such as plasma generators, hydroxyl radical generators, ionizers, photocatalytic oxidizers and others.

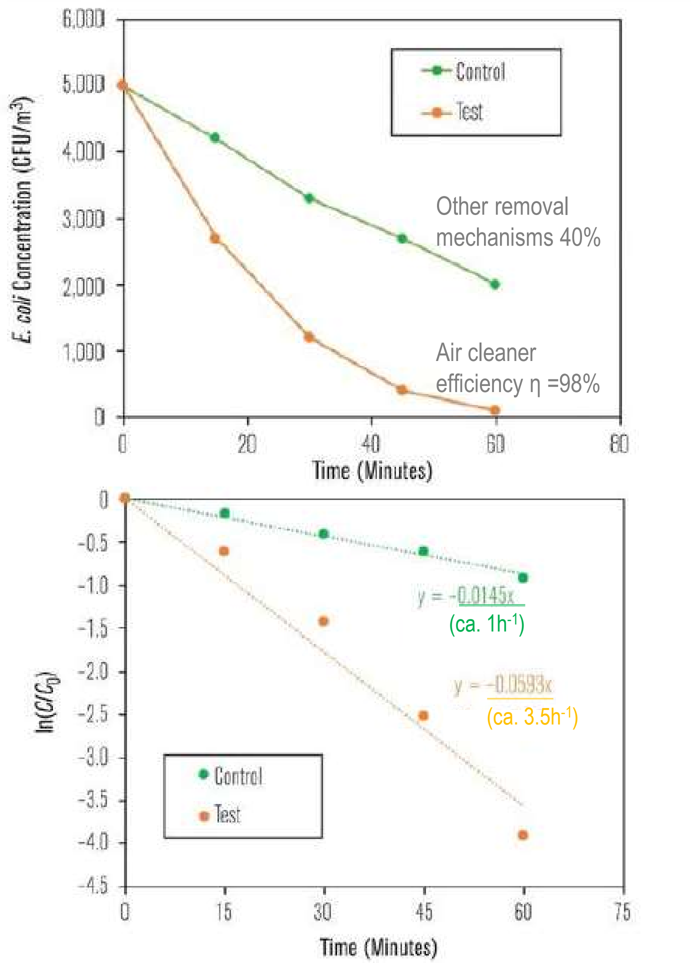
This article demonstrates some frequently prevalent issues in electronic air cleaner performance testing and reporting and proposes a path forward to meet research needs and improve test methods that could reduce the current uncertainty about the performance of electronic air cleaning technologies. It also provides tools to support practitioners and consumers in their decision-making regarding air cleaning technologies.

The ASHRAE Epidemic Task Force (ETF) has published extensive guidance for those who must make decisions on ventilation, air cleaning and more, often in the context of the limited resources available to building owners and managers. Along with increased ventilation, the ETF has advised that cleaning indoor air using particle filtration at MERV 13 or higher can improve air quality and reduce risks from COVID-19 by removal of viral aerosols and by diluting their concentration.

To date, the ETF has published limited specific guidance on the risk reduction potential of electronic air cleaning technologies, and the "ASHRAE Position Document on Filtration and Air Cleaning"[1] cites a lack of definitive conclusions on the efficacy of many electronic air cleaners. This is consistent with the fact that no ASHRAE or other industry standard currently exists to validate the marketing materials of many of these technologies. And, ETF's "Core Recommendation for Reducing Airborne Infectious Aerosol Exposure."[2]

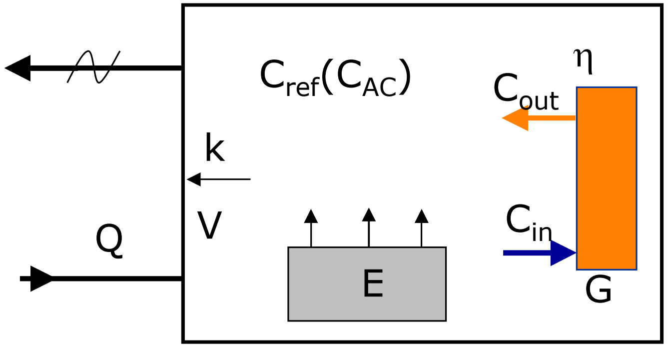
Brent Stephens, Ph.D., is a Professor and Department Chair in the Department of Civil, Architectural and Environmental Engineering at Illinois Institute of Technology. Elliott T. Gall, Ph.D., is an Associate Professor in the Department of Mechanical and Materials Engineering at Portland State University. Mohammad Heidarinejad, Ph.D., P.E., is an Assistant Professor in the Department of Civil, Architectural and Environmental Engineering at Illinois Institute of Technology. Delphine K. Farmer, Ph.D. is an Associate Professor in the Department of Chemistry at Colorado State University.

28 ASHRAE JOURNAL ashrae.org APRIL 2022



Removal rate difference in a 14.2 m^3 chamber: CADR=50-13=37 m^3/h (2.5 h^{-1})

Removal effect (ε) Effectiveness (f)



$$\varepsilon = \frac{C_{ref} - C_{AC}}{C_{AC}} \cdot 100\ [\%]$$

or

$$\varepsilon = \frac{f}{f+1}\ where\ f = \frac{CADR}{Q + k \cdot V}$$

- Fractional reduction in pollutant concentration that results from application of an air cleaner in indoor volume/space.
- Effectiveness is judged against other removal processes (by deposition rate and ventilation)

Ozone

Standard/Protocol	Methods	Measuring time	Measuring space /volume	Thresholds
Standards for Electric Air Cleaners, US Underwriters Laboratory (UL standard 867)	Measuring ozone concentration	24 h	Chamber/ $33.1m^3$	**50 ppb**
Electric Air Cleaners, Canadian Standard Association (CSA C-187 C1.7.4)	Measuring ozone concentration	24 h (8h time weight average)	Chamber/Similar to UL standard	**20 ppb**
Reduced Energy Use Through Reduced Indoor Contamination in Residential Buildings, NCEMBT (NCEMBT 061101), US report	Calculate ozone generation rate	-	Chamber/ $55m^3$	**-**
National Research Council Canada (NRC) standard	Calculate ozone generation rate	-	Chamber/ $55m^3$	**(suggest not exceed 50 ppb)**

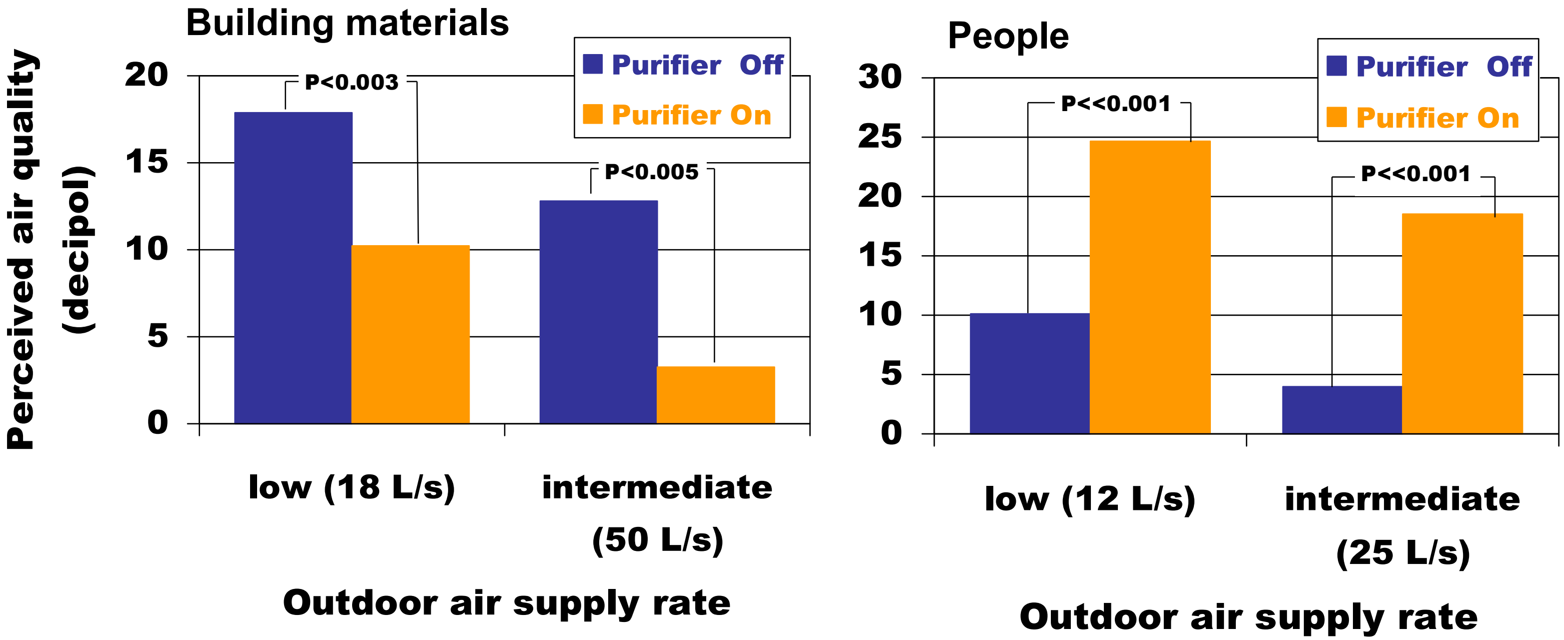
Sources: Afshari et al. (2022)

Byproduct generation, incomplete oxidation

- Aldehydes → **formaldehyde**, formic acid, CO
- **Alcohols** → aldehydes → acids → shorter carbon chain alcohols and acids →**formaldehyde**, methanol → CO_2 and H_2O
- Benzene → phenol
- 1-Butanol → butanal (butyraldehyde), butanoic acid, ethanol, acetaldehyde, (propanal (propionaldehyde) and propanol, propanoic acid) → (ethanol, **formaldehyde**) → methanol, **formaldehyde** and formic acid
- Ethanol → methanol, acetaldehyde, **formaldehyde**, acetic acid, formic acid
- Methanol → methyl formate (measured in liquid form only), **formaldehyde**, methylal (formaldehyde dimethyl acetal
- Toluene → benzaldehyde, benzoic acid, cresol, benzyl alcohol, phenol, benzene, formic acid

Sources: Mo et al. (2009)

By-product, example



New evidence: human oxidation field

- The presence of any ozone should be avoided (also in the reactor)
- Skin oils + ozone => non insignificant yields of OH radical => significant reactions in the air

INDOOR AIR QUALITY

The human oxidation field

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Hydroxyl (OH) radicals are highly reactive species that can oxidize most pollutant gases. In this study, high concentrations of OH radicals were found when people were exposed to ozone in a climate-controlled chamber. OH concentrations calculated by two methods using measurements of total OH reactivity, speciated alkenes, and oxidation products were consistent with those obtained from a chemically explicit model. Key to establishing this human-induced oxidation field is 6-methyl-5-hepten-2-one (6-MHO), which forms when ozone reacts with the skin-oil squalene and subsequently generates OH efficiently through gas-phase reaction with ozone. A dynamic model was used to show the spatial extent of the human-generated OH oxidation field and its dependency on ozone influx through ventilation. This finding has implications for the oxidation, lifetime, and perception of chemicals indoors and, ultimately, human health.

North Americans and Europeans spend, on average, ~90% of their time indoors (including home, workplace, and transport) (1, 2). Within this enclosed space, occupants are exposed to a multitude of chemicals from various sources, including outdoor pollutants that penetrate indoors, gaseous emissions from building materials and furnishings, and products of human activities such as cooking and cleaning (3). In addition, the occupants themselves are a potent mobile source of gaseous emissions from breath and skin (human bioeffluents) as well as primary and secondary particles (4). Characterization of these indoor sources and the main indoor removal mechanisms are key to understanding indoor air quality (5).

Chemical removal of gas-phase species in outside air during daytime is mostly initiated by hydroxyl (OH) radicals, which are formed when a short-wavelength photolysis product of ozone (O_3) [an excited oxygen atom, $O(^1D)$] reacts with water. Longer-wavelength photolysis of nitrous acid (HONO) and formaldehyde (HCHO) also provides small additional OH sources outside, as does the light-independent ozonolysis of alkenes via Criegee intermediate formation (6). By contrast, the indoor environment is less influenced by direct sunlight, in particular ultraviolet light, which is largely filtered out by glass windows, so that primary production of OH indoors via $O(^1D)$ is negligible. Although some OH can be generated by longer-wavelength artificial light by photolysis with natural light of formaldehyde and HONO if present, O_3 entering the building from outside is generally considered to be the principal oxidant indoors (7). Nevertheless, previous studies have highlighted the potential importance of alkene ozonolysis (8–11) in generating OH via Criegee intermediates in indoor environments, particularly when reactive molecules such as limonene from air fresheners or cooking are abundant. Previous estimates and measurements of indoor OH concentrations have ranged from 10^5 to 10^7 molecules cm^{-3}, which is substantially higher than outdoor nighttime concentrations and comparable to daytime atmospheric OH concentration levels in some regions (8–15).

None of the aforementioned model or measurement studies considered occupied indoor environments and therefore the underlying chemical influence of humans. Yet with every breath, humans exhale reactive alkenes such as isoprene, which can oxidize to further alkenes such as methyl vinyl ketone (MVK) and methacrolein (MACR) (16). Moreover, O_3 reacting at the skin surface with the skin-oil squalene ($C_{30}H_{50}$), a triterpene responsible for almost 50% of the unsaturated carbon atoms on human skin, releases a host of alkene-containing compounds to the air, including geranyl acetone, 6-methyl-5-hepten-2-one (6-MHO), OH-6-methyl-5-hepten-2-one (OH-6-MHO), 4-methyl-8-oxo-4-nonenal (4-MON), 4-methyl-4-octene-1,8-dial (4-MOD), and *trans*-2-nonenal (17). These species have the potential to react further in the gas phase, either to generate OH through reaction with O_3 or to deplete OH through direct reaction with the alkene. Therefore, humans have the potential to profoundly affect the oxidative environment indoors, particularly in areas of high occupancy (18), larger exposed body surface, and higher air temperature and humidity (19).

In this study, measurements were conducted in a climate-controlled stainless-steel chamber (see Fig. 1) with three different groups of four adult subjects on four separate days (including two replicates from the same group) (20). The air change rate (ACR) (3.2 $hour^{-1}$) and O_3 concentration [100 parts per billion (ppb) at the inlet and 35 ppb indoors] used in this experiment were chosen for reproducing a realistic scenario based on the expected O_3 decrease due to occupancy (21). (ACR is the number of times that the total air volume in a room or space is completely replaced by outdoor air in an hour.) From this data, we have determined the indoor concentrations and spatial distribution of OH radicals generated by humans upon exposure to O_3. This oxidative field is produced in isolation from other indoor sources or sinks of OH. A steady-state approach was applied, combining measured total OH reactivity (OH loss frequency in s^{-1}), measured concentrations of compounds containing an alkene double bond, and available literature values of OH yields from O_3 with alkene reactions. For comparison, the OH levels were also determined by an independent method using isoprene and its oxidation products. In the final step, the empirically derived OH levels and measurements were compared with those obtained from a detailed multiphase chemical kinetic model, and these results were used to simulate high spatial and time-resolved OH distributions in a room using a computational fluid dynamics (CFD) model. To investigate the existence and variability of spatial concentration gradients, we tested four scenarios: (i) an evaluation of the experimental results using the same underfloor air distribution from a perforated floor along with intensive air mixing at the average indoor O_3 concentration of 35 ppb as in the experiment, (ii) the same ventilation condition of the experiment without any mixing fans at an indoor O_3 concentration of 35 ppb to simulate a residential condition, (iii) air jets supplied at ceiling height and an indoor O_3 concentration of 35 ppb to simulate an office condition, and (iv) same as (iii) except the indoor O_3 concentration was 5 ppb.

Results

Total OH reactivity of human emissions

Figure 2 shows the OH loss frequency (total OH reactivity) measured directly in the chamber. The total OH reactivity of the gas-phase human bioeffluents was, on average, $8 \pm 4\ s^{-1}$ in the absence of O_3 and $34 \pm 16\ s^{-1}$ when O_3 was present (mean value ± measurement error, determined at equilibrium in the last 15 min before volunteers left the chamber). In the absence of O_3, the dominant OH sinks were reactive compounds in human breath (e.g., isoprene 64%), whereas in the presence of O_3,

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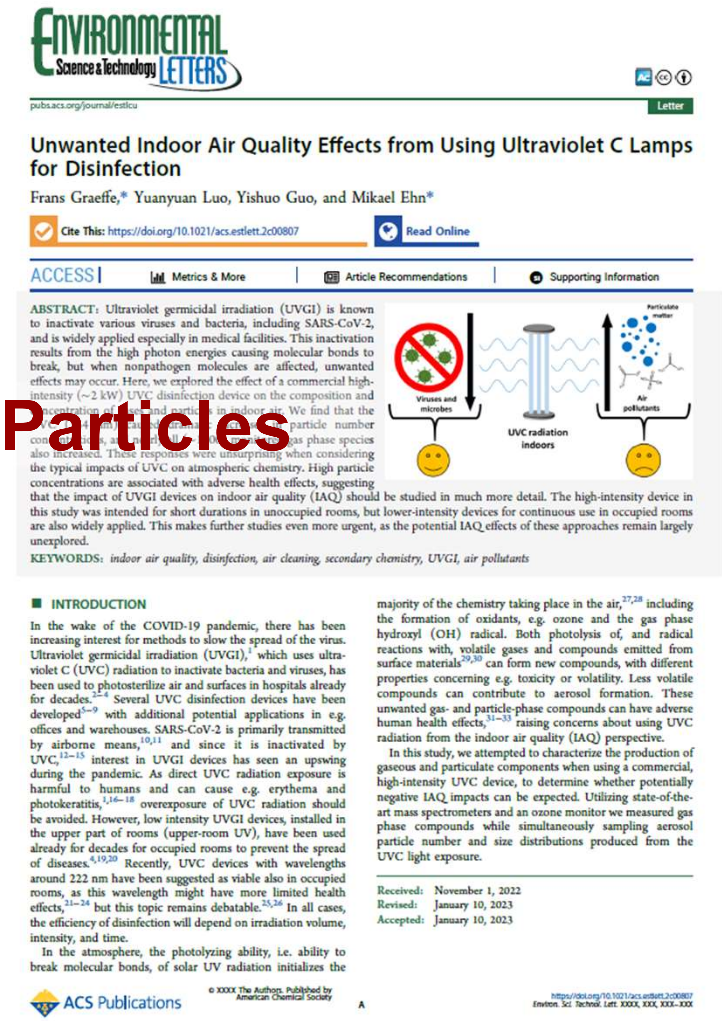
Toxic pollutants?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Letter

Unwanted Indoor Air Quality Effects from Using Ultraviolet C Lamps for Disinfection

Frans Graeffe,* Yuanyuan Luo, Yishuo Guo, and Mikael Ehn*

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KEYWORDS: indoor air quality, disinfection, air cleaning, secondary chemistry, UVGI, air pollutants

INTRODUCTION

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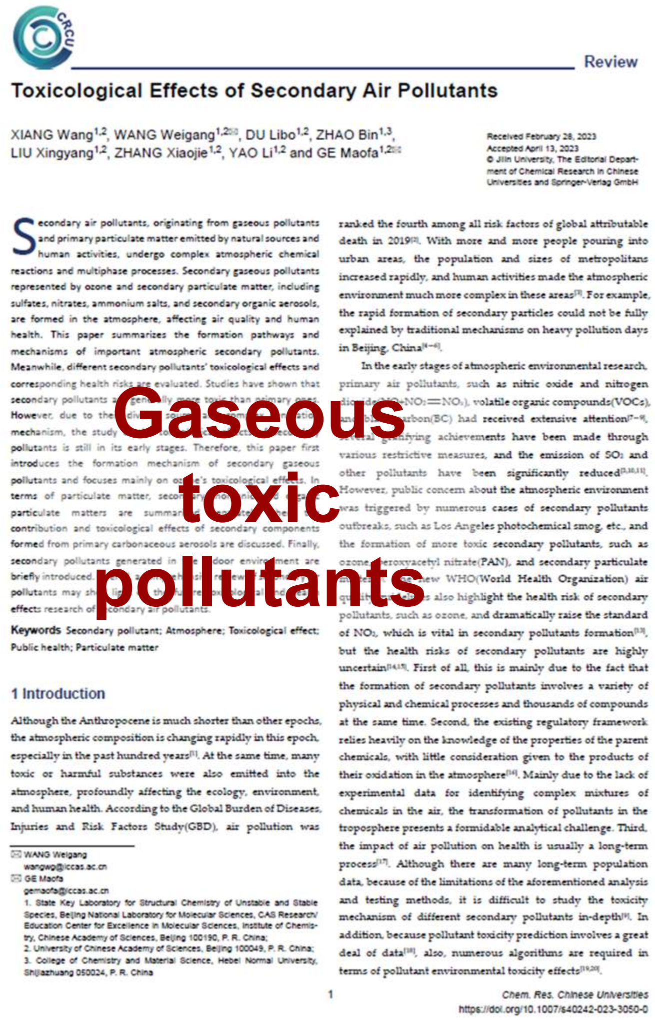
Particles


Review

Toxicological Effects of Secondary Air Pollutants

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1 Introduction

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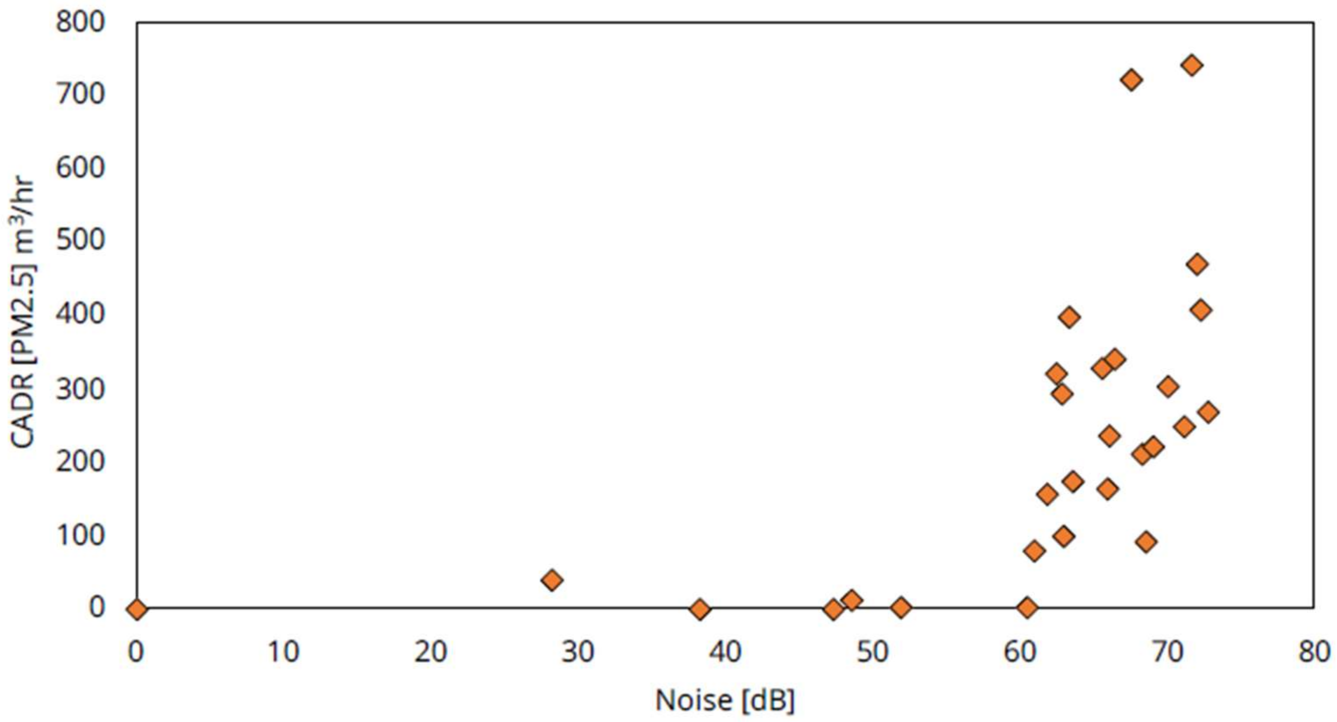
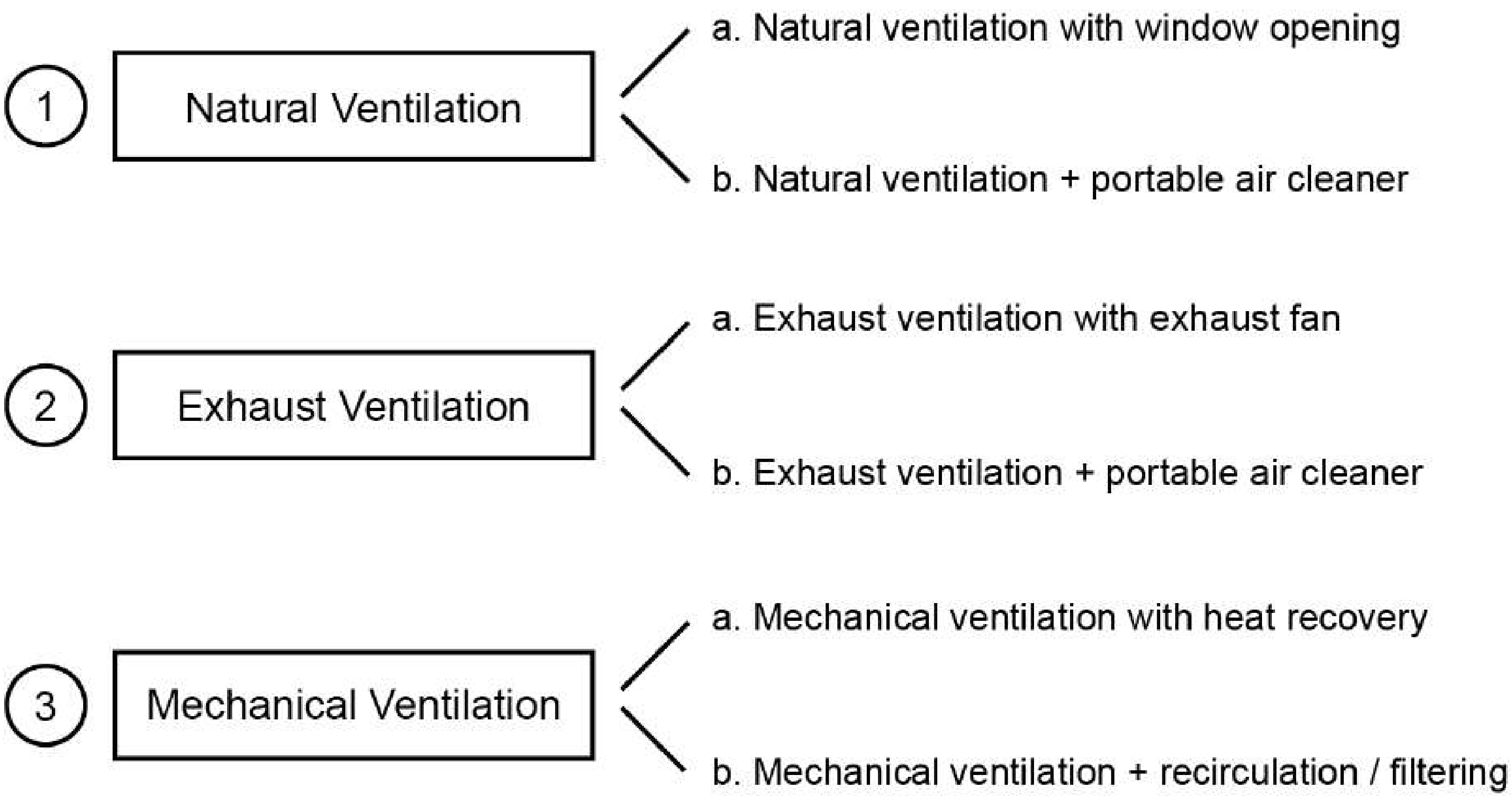
Gaseous toxic pollutants

Noise



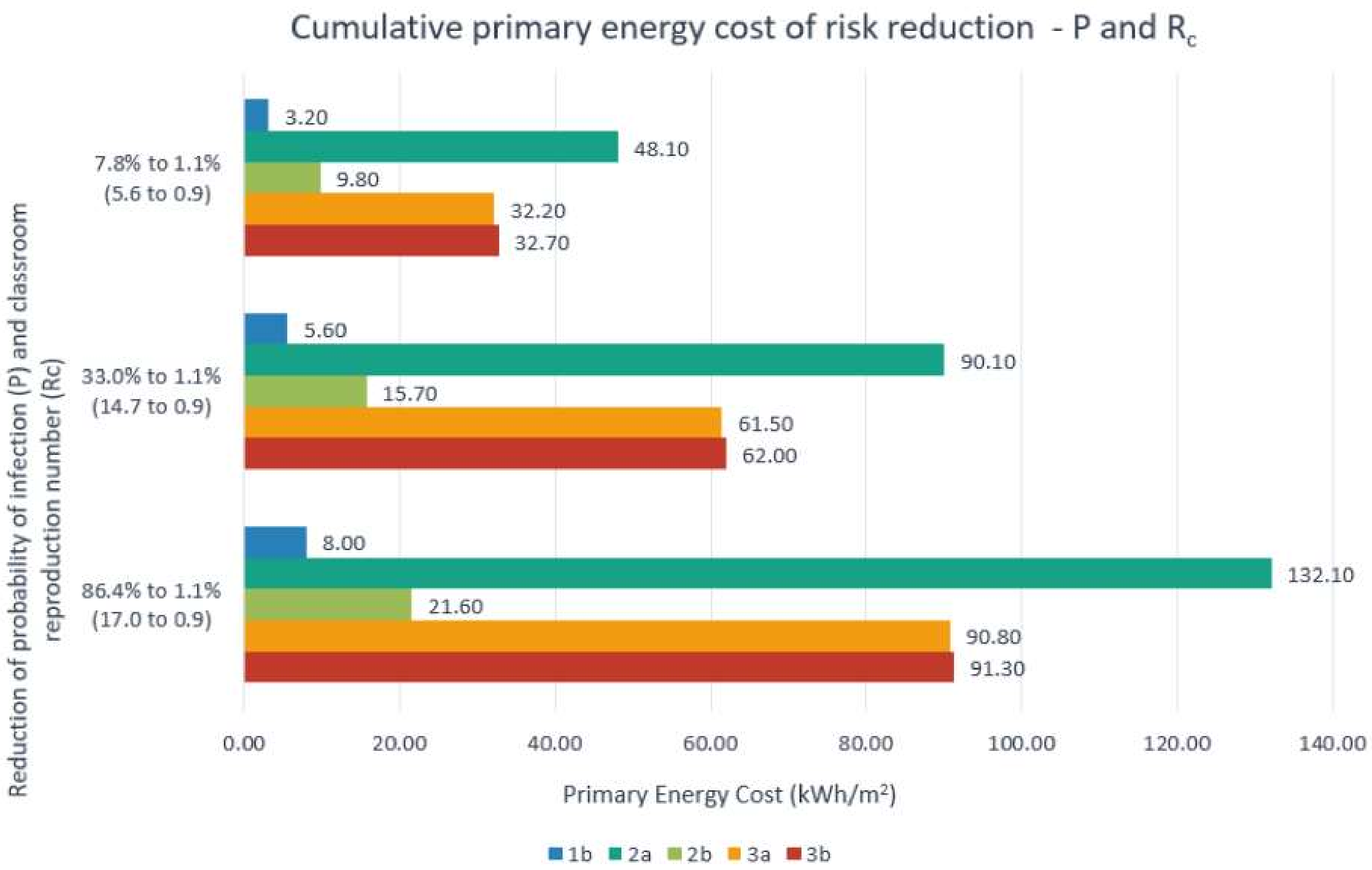
800
700
600
500
400
300
200
100
0
CADR [PM2.5] m³/hr
0
10
20
30
40
50
60
70
80
Noise [dB]

Impact on energy use, cost-benefit

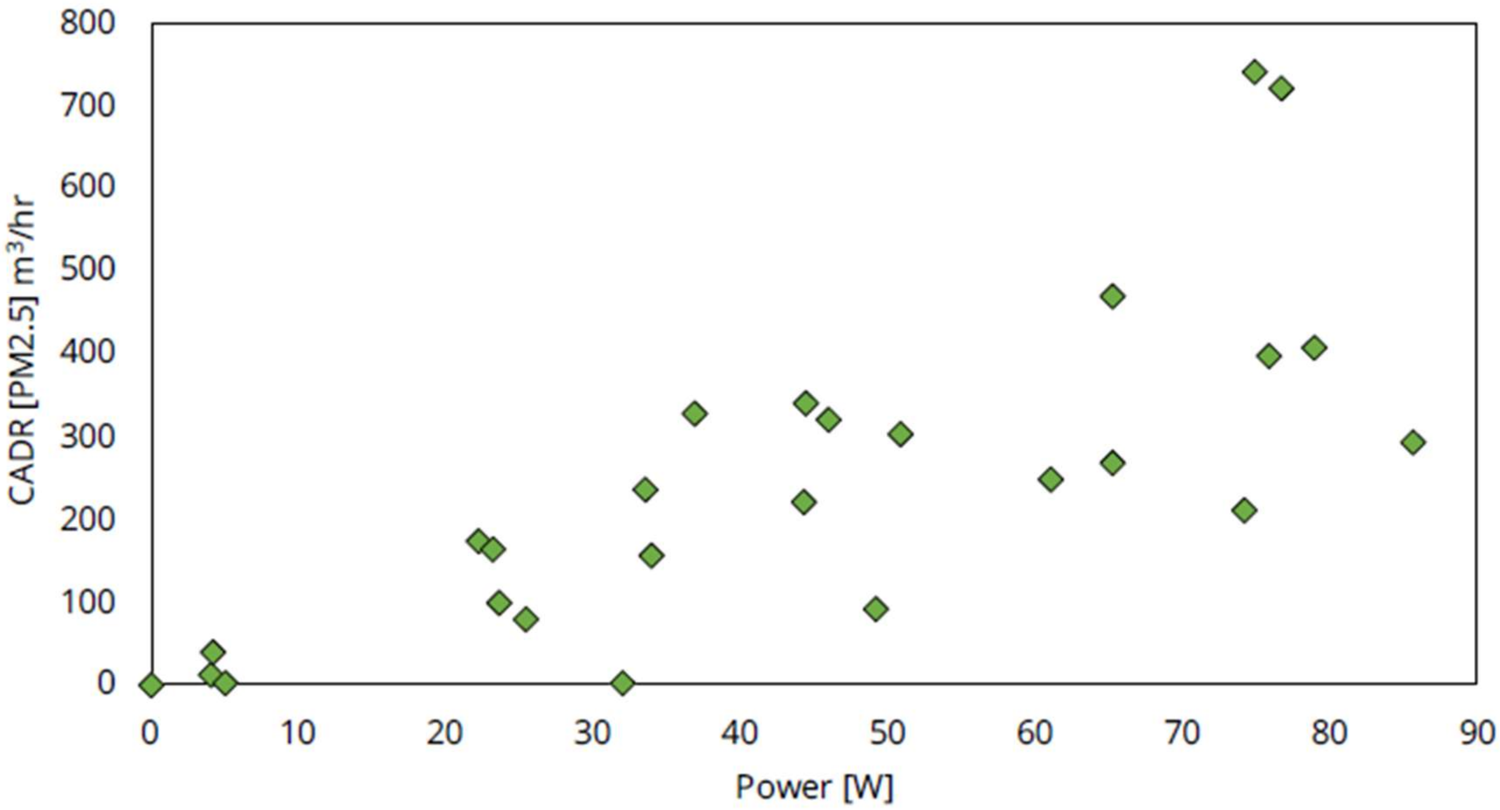


Unpublished: Tsafara (and Wargocki) (2021)

Energy Implications, Danish School



Power



800
700
600
500
400
300
200
100
0
CADR [PM2.5] m³/hr
0
10
20
30
40
50
60
70
80
90
Power [W]

Cost vs. Benefit - Boston 50k ft2, 250 Occupants

Total Annual Outside Air + Filtration Cost

	Bare Minimum (3-4 ACH)	Good (4-5 ACH)	Excellent (5-6 ACH)	Ideal (6 ACH)
100% OA	n/a	n/a	n/a	$85,827
	MERV 7	**MERV 11**	**MERV 13**	**HEPA**
VRP+30%	$18,100	$18,738	$19,834	$46,566
VRP	$15,384	$16,047	$17,182	$44,871
IAQP	$10,340	$11,050	$12,261	$41,838

Cost per Effective ACH

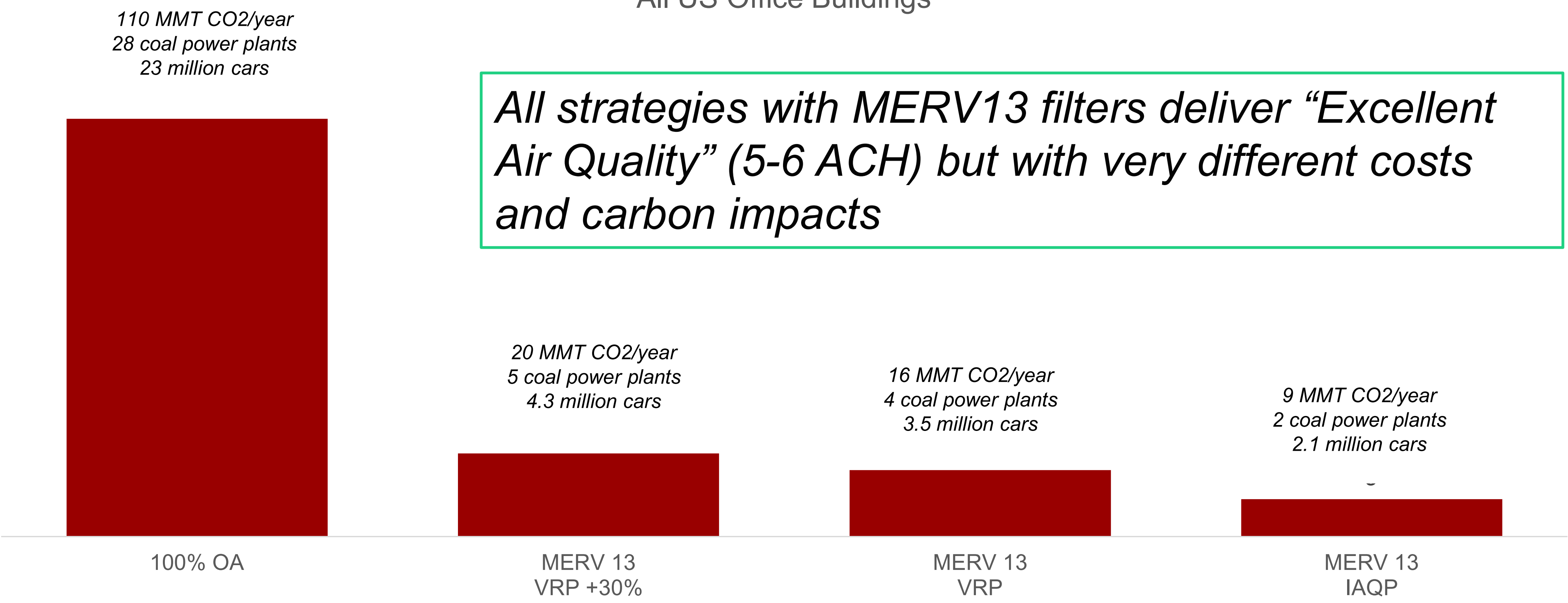
	Bare Minimum (3-4 ACH)	Good (4-5 ACH)	Excellent (5-6 ACH)	Ideal (6 ACH)
100% OA	n/a	n/a	n/a	$14,305
	MERV 7	**MERV 11**	**MERV 13**	**HEPA**
VRP+30%	$6,033	$4,685	$3,967	$7,761
VRP	$5,128	$4,012	$3,436	$7,479
IAQP	$3,447	$2,763	$2,452	$6,973

Courtesy of Zaatari

US Office Carbon Impact of Different Strategies

Million Metric tons of CO2/year
All US Office Buildings

All strategies with MERV13 filters deliver “Excellent Air Quality” (5-6 ACH) but with very different costs and carbon impacts



Epilogue

Take home messages (w/strong personal bias)

Air cleaning as a measure to reduce infection risk

- Outdoor air: yes (and no)
- Air cleaning and filtration: yes and no

- MERV13 and higher: yes
- Portable air cleaners (HEPA): probably yes
- UVC/UVGI: probably yes
- Additive technologies: (probably) no
- Reactive species: (probably) banned

- Lack of proper testing methods
- Lack of verification in actual applications
- Weighting risks

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Thank You

DTU