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To Air is Human...but is it the Best Way to Control IAQ?

William Bahnfleth, PhD, PE

Professor, The Pennsylvania State University



PennState
College of Engineering

**ARCHITECTURAL
ENGINEERING**

One of my earliest AIVC memories is a presentation by Andrew Persily where he casually shared his insight that **we design our ventilation ‘for no particular reason’**. The precise underpinning for many of the requirements included in prescriptive ventilation standards is unclear and this is on purpose. The consensus process from which they originate is a cherished resource to create support and consistent adoption but is not conducive to clear scientific reasoning. An insight that would haunt me ever since.



Jelle Laverge, Ghent University (July 2025)

<https://www.aivc.org/sites/default/files/CR22.pdf>

Why ventilate? Conventional wisdom...

- Ventilation means dilution with outdoor air
- Many air contaminants have indoor sources
 - Building materials
 - Indoor processes
 - Occupants
- Consequences of exposure are bad
 - Odors
 - Chronic toxicity
 - Oncogenesis
 - Productivity loss
- Outdoor air is “fresh” – bring in lots of it to make indoor air fresh, too!



Dilution

$$C_{ss} = C_o + \frac{S}{Q}$$

- C_{ss} = Steady state concentration of a contaminant
- C_o = Concentration of contaminant in ventilation air
- S = Source strength (emission rate of a contaminant)
- Q = Flow rate of uncontaminated ventilation air (e.g., cfm or L/s)

Dilution has diminishing returns, exponentially growing costs

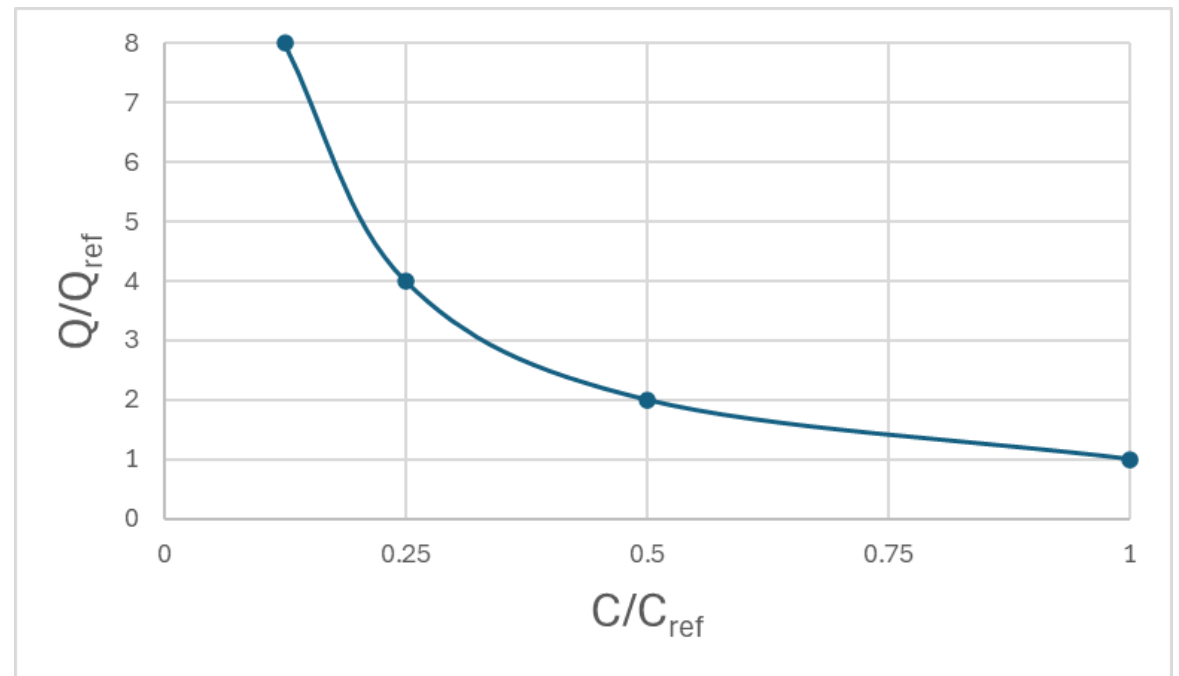
Suppose ventilation air is contaminant-free ($c_0 = 0$)

$$C_{ss} = \frac{S}{Q}$$

$$\frac{1}{2} C_{ss} = \frac{S}{2Q}$$

$$\frac{1}{4} C_{ss} = \frac{S}{4Q}$$

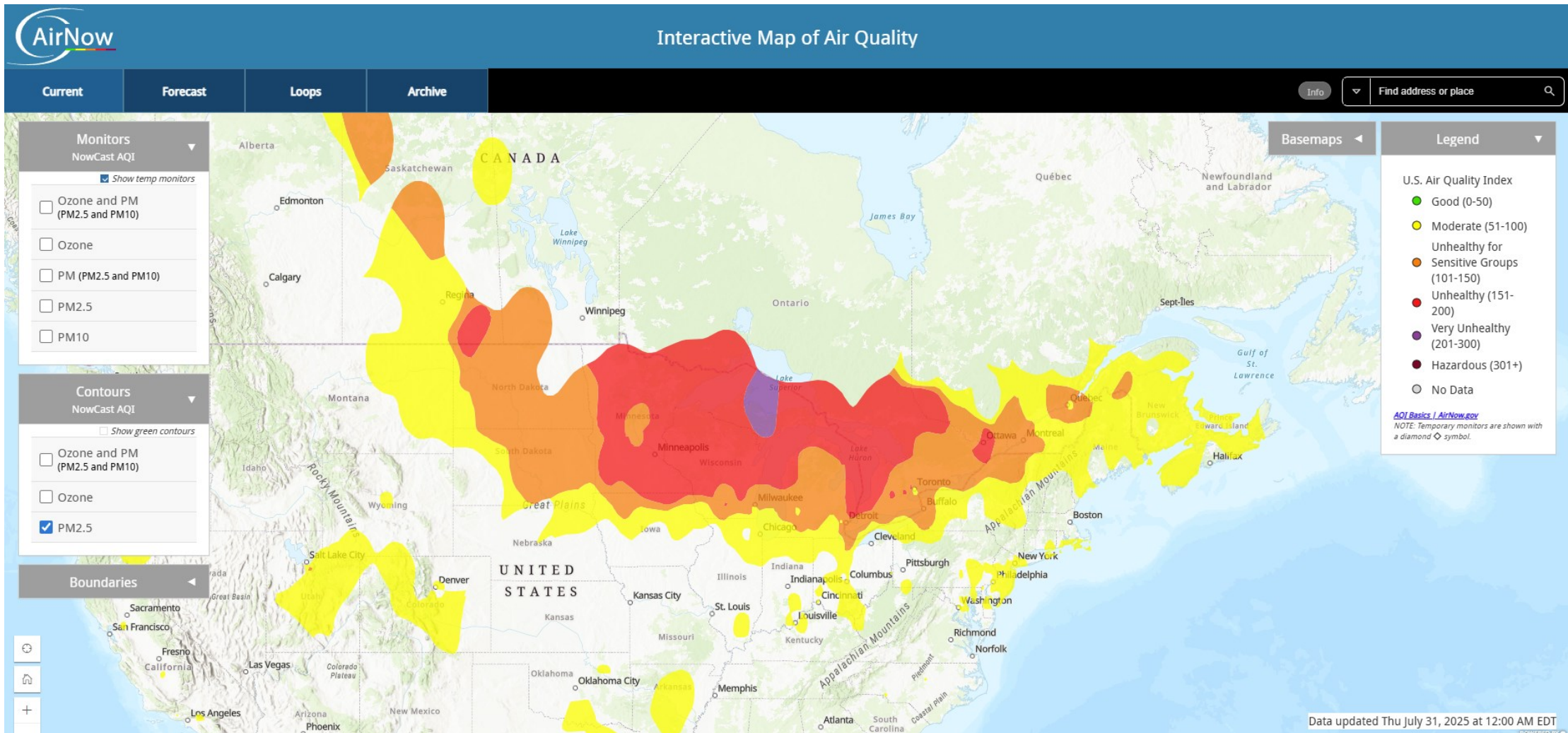
$$\frac{1}{8} C_{ss} = \frac{S}{8Q}$$



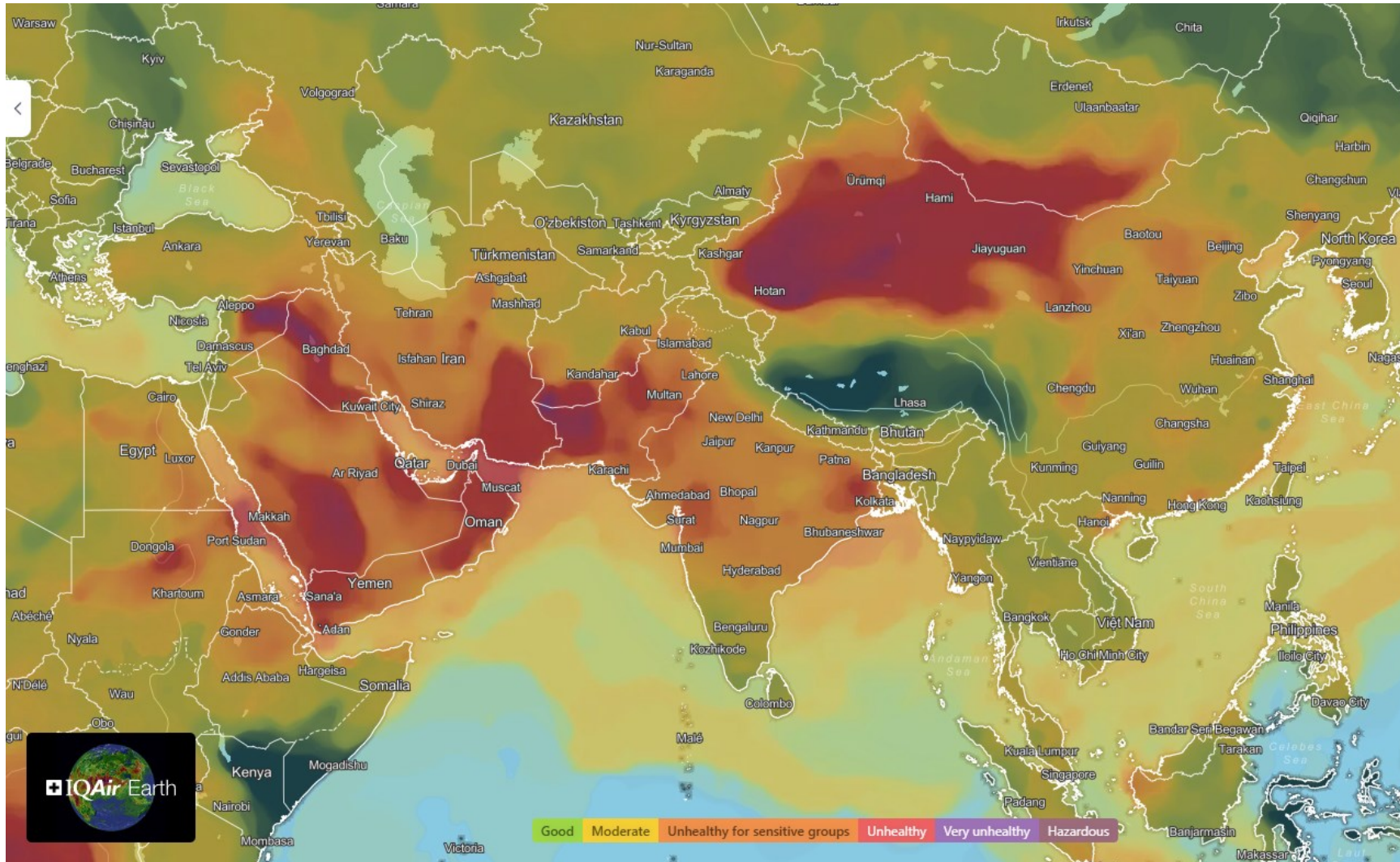
Outdoor air frequently isn't fresh



“Delhi residents can breathe in ‘moderate’ air quality”



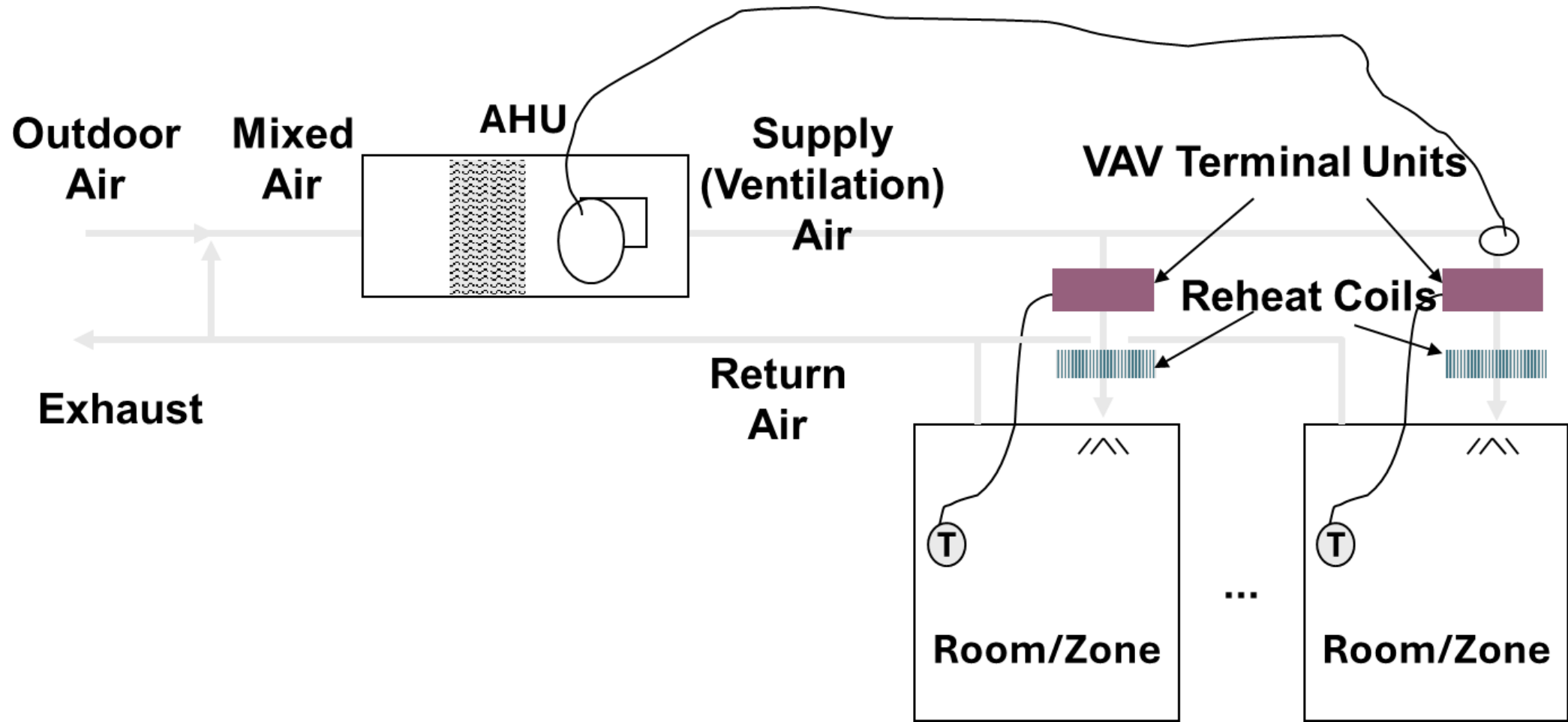
<https://gispub.epa.gov/airnow/>



<https://www.iqair.com/in-en/air-quality-map>

Ventilation \neq outdoor air

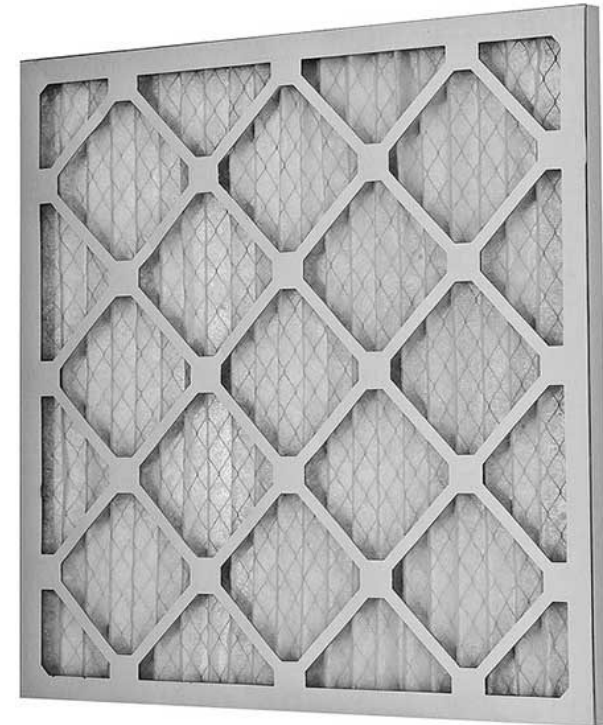
- Definitions of ventilation in standards:
 - (T)he process of supplying air to or removing air from a space for the purpose of controlling air contaminant levels, humidity, or temperature within the space. (ASHRAE Standard 62.1)
 - (T)he process of supplying or removing air by natural or mechanical means to or from any space. Such air may or may not have been conditioned. (ASHRAE Standard 62.2)
- Related concept - *ventilation air*:
 - (T)hat portion of supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable IAQ



Recirculating systems supply outdoor air, filter particles

- Outdoor air acts similarly (sort of) on many contaminants
- Mechanical filters remove particles – outdoor and indoor sources
- Can add other controls for gases and infectious aerosols

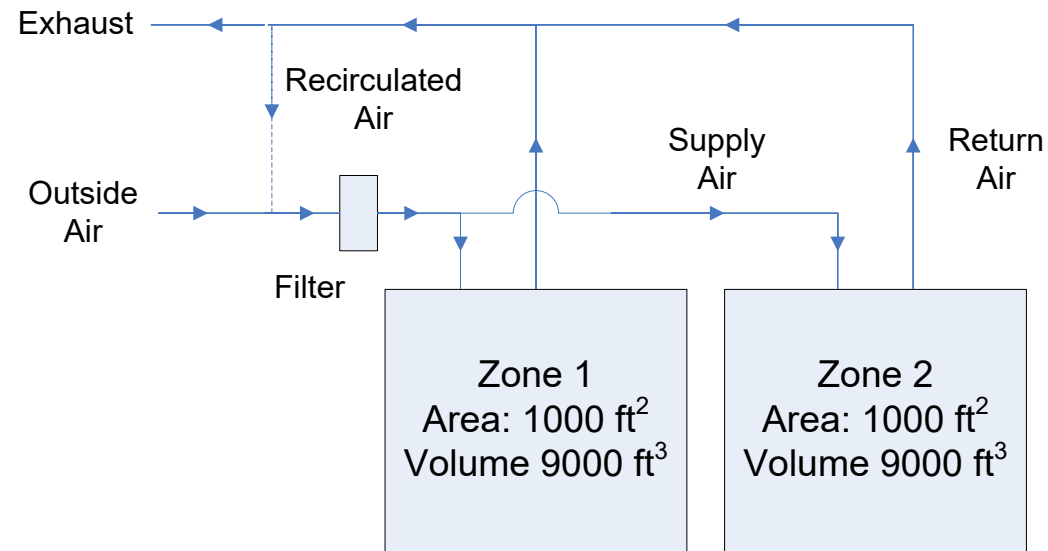
Usually, combined effect isn't quantified



Recirculation is a mixed blessing

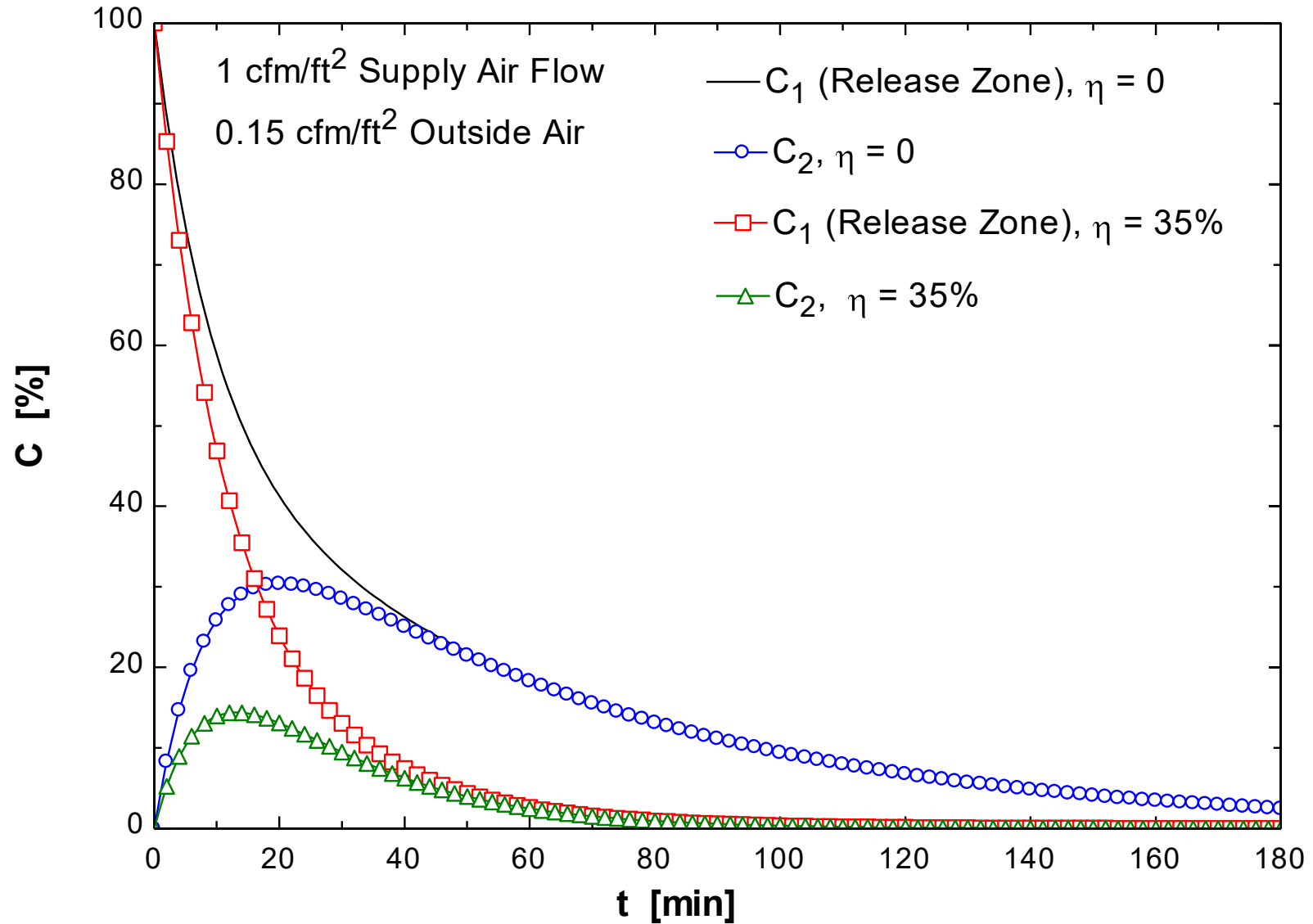
- Good
 - Higher air change rate clears contaminants faster
 - Enables control of indoor contaminant sources with air cleaning
 - Air economizer capacity increased
- Not so good
 - Multiple space recirculation spreads contaminants
 - Transport energy increased compared to dual path (DOAS) systems

Two-Zone Example



*Release in Zone 1-Initial
concentration of 100%*

Recirculation spreads contaminant to other space, but recirculation through filter speeds up clearance



Equivalent clean airflow (ECA) – a better measure of control?

- The effect of any control can be expressed in terms of dilution with uncontaminated air
- If all controls and removal rates are expressed as ECAs, performance-based IAQ becomes more attainable
- Must also rate performance of controls in terms of ECA

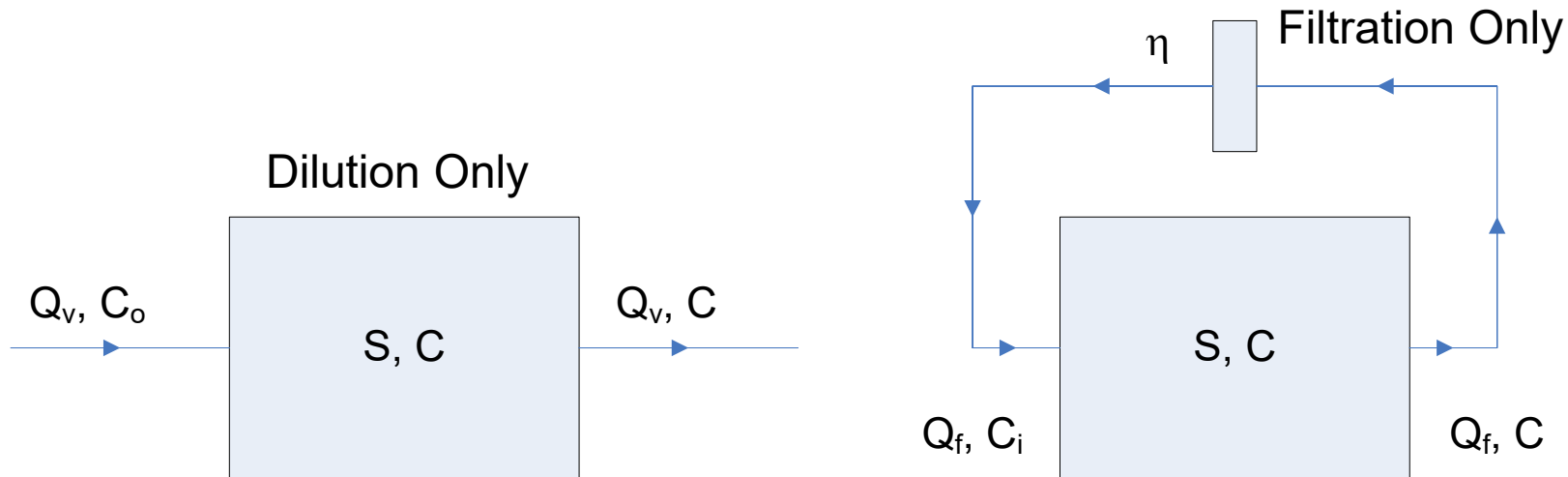
If used comprehensively, need at least three types – gas, particle, infectious aerosol

Equivalent clean airflow of a filter

Filter has *actual* airflow Q_f and efficiency η

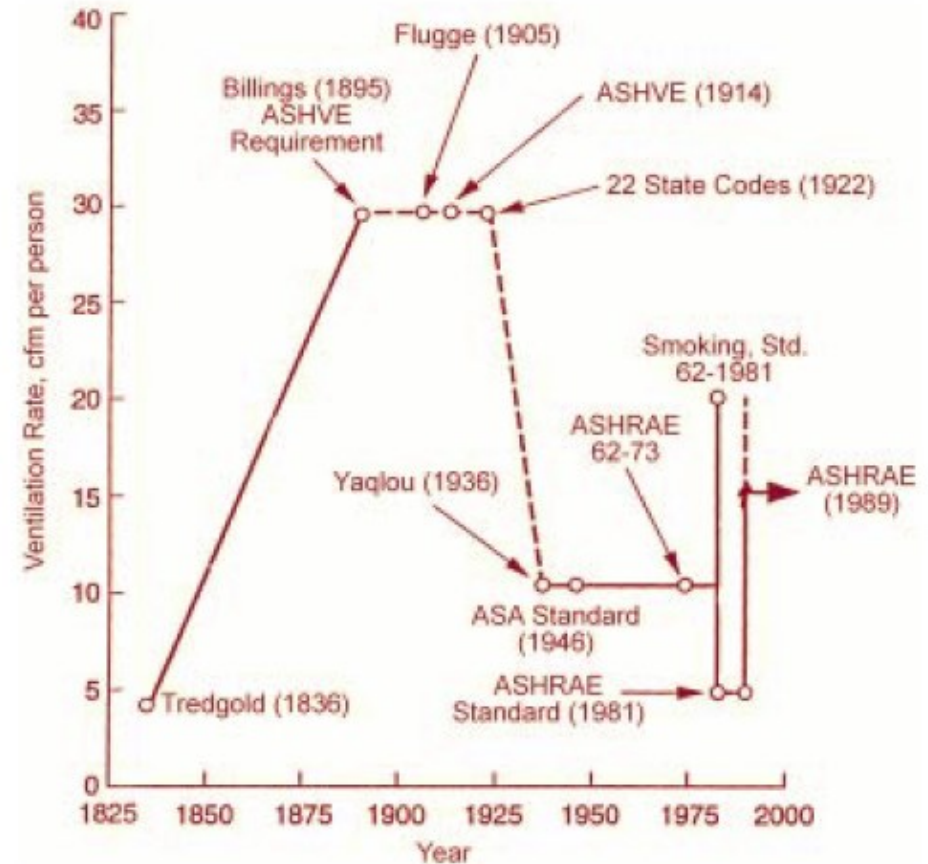
If Q_v is equivalent clean air for filter, $C_0 \equiv 0$.
can show for a well-mixed space:

$$Q_v = \eta Q_f$$



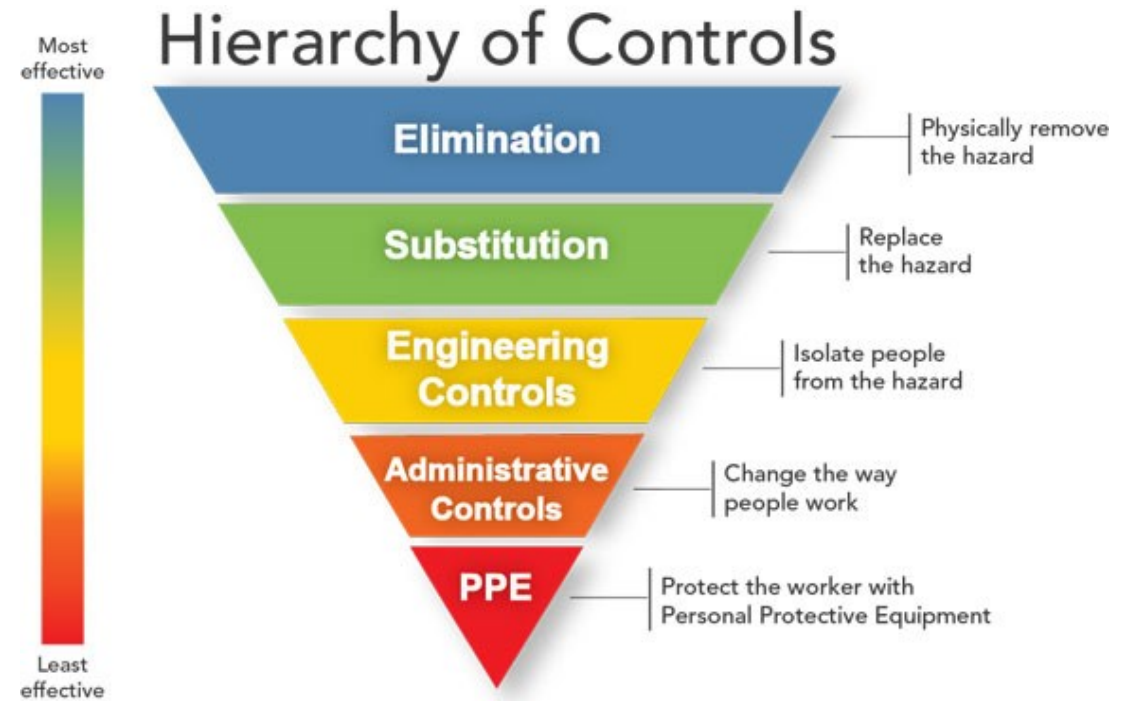
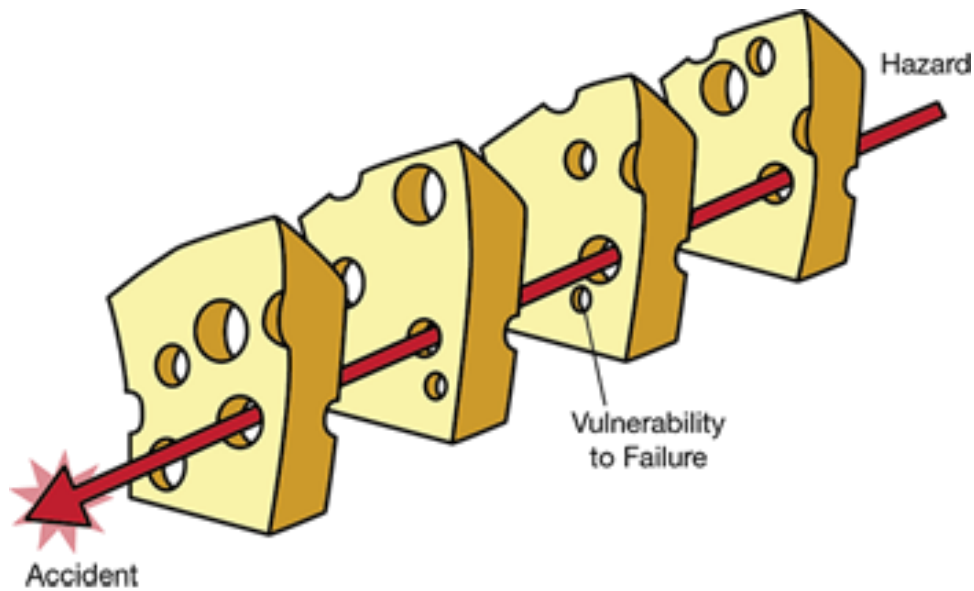
How much ventilation?

- Recommendations have varied widely over two centuries
 - Physiological
 - Limit infection risk
 - Perceived air quality
 - Safe contaminant exposures
- Stated in terms of outdoor air
- Emphasis on energy impact increasing over time



Janssen, J.E., 1999. The history of ventilation and temperature control: The first century of air conditioning. ASHRAE Journal, 41(10), p.48.

Ventilation is only one way to improve IAQ



Reason, J., 2000. Human error: models and management. *Bmj*, 320(7237), pp.768-770.

2019



ANSI/ASHRAE Standard 62.1-2019
 (Supersedes ANSI/ASHRAE Standard 62.1-2016)
 Includes ANSI/ASHRAE addenda listed in Appendix O

Ventilation for Acceptable Indoor Air Quality

See Appendix O for approval dates by ASHRAE and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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2022



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PDF includes hyperlinks for convenient navigation. Click on a reference to a section, table, figure, or equation to jump to its location. Return to the previous page via the bookmark menu.



Perception + safety have prevailed for ~100 years in non-healthcare facilities

- Acceptable indoor air quality (ASHRAE Standard 62.1):

air in which there are **no known contaminants at harmful concentrations**, as determined by cognizant authorities, and with which **a substantial majority (80% or more) of the people exposed do not express dissatisfaction.**

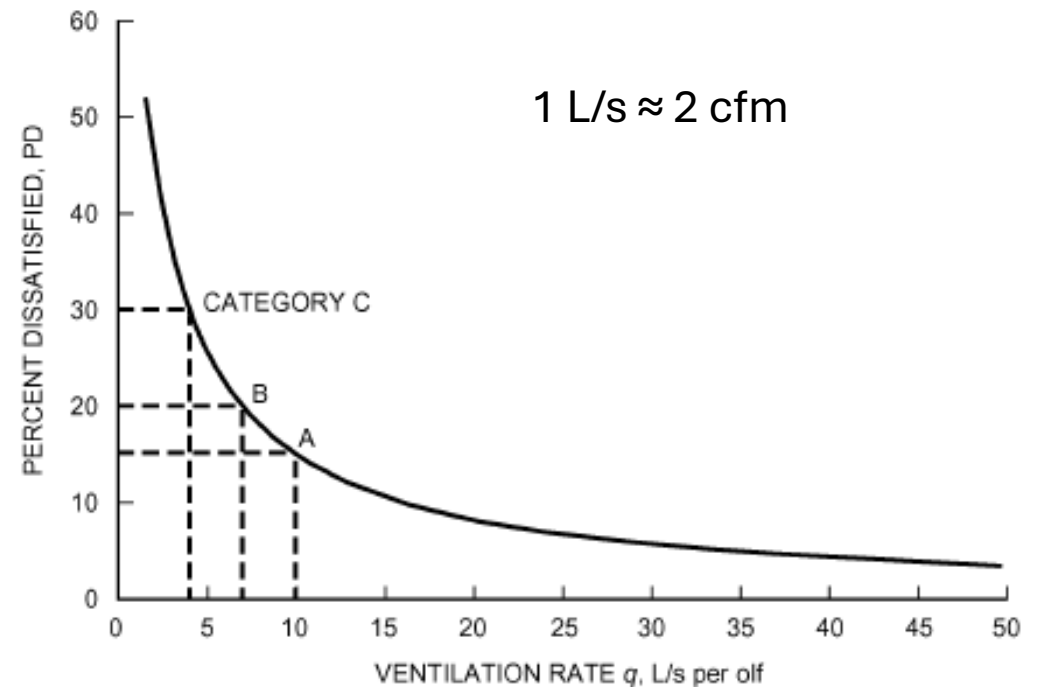


Fig. 5 Percentage of Dissatisfied Persons as a Function of Ventilation Rate per Standard Person (i.e., per Olf) (CEN 1998)

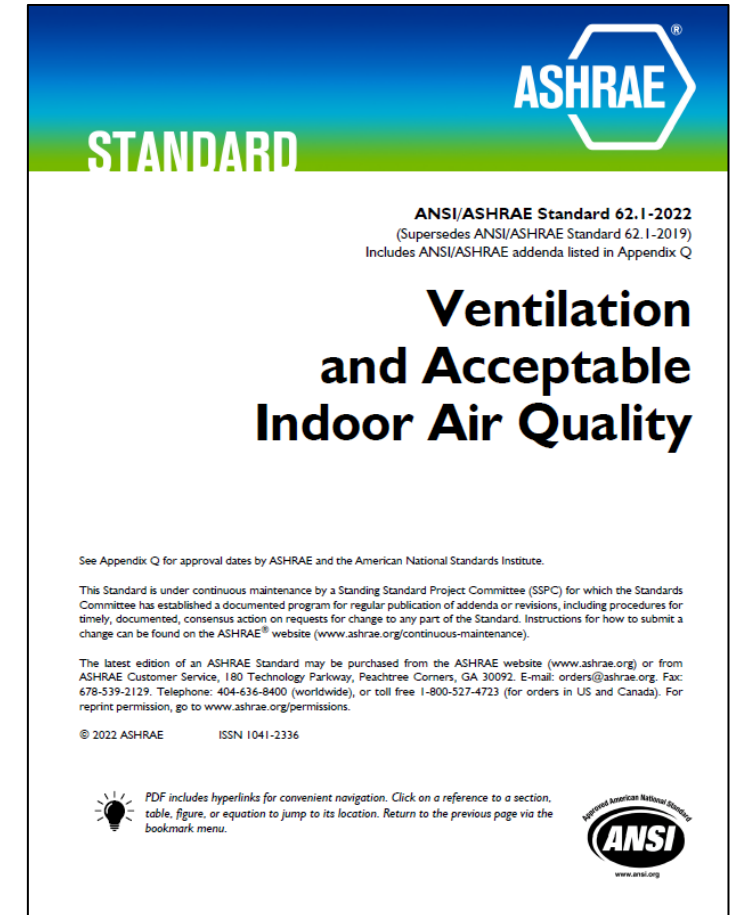
Current non-residential standards

- Ventilation Rate Procedure (VRP, prescriptive)
- Per-person rate (R_p) and area rate (R_a)

$$V_{bz} = R_p \times P_z + R_a \times A_z$$

Table 6-1 Minimum Ventilation Rates in Breathing Zone (Continued)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Default Values		
	cfm/ person	L/s· person	cfm/ft ²	L/s·m ²	Occupant Density		
					#/1000 ft ² or #/100 m ²	Air Class	OS (6.2.6.1.4)
Cafeteria/fast-food dining	7.5	3.8	0.18	0.9	100	2	
Kitchen (cooking)	7.5	3.8	0.12	0.6	20	2	
Restaurant dining rooms	7.5	3.8	0.18	0.9	70	2	
General							
Break rooms	5	2.5	0.06	0.3	25	1	✓



Current non-residential standards

- Indoor Air Quality Procedure (IAQP, performance)
- Design compounds (14 chemicals, 3 mixtures) and PM 2.5
- Designer specifies controls – outdoor air, air treatment – to comply with design limits
- Must also satisfied perceived air quality requirement
- Subjective and objective verification required

Table 6-5 Design Compounds, PM2.5, and Their Design Limits

Compound or PM2.5	Cognizant Authority	Design Limit
Acetaldehyde	Cal EPA CREL (June 2016)	140 µg/m ³
Acetone	AgBB LCI	1,200 µg/m ³
Benzene	Cal EPA CREL (June 2016)	3 µg/m ³
Dichloromethane	Cal EPA CREL (June 2016)	400 µg/m ³
Formaldehyde	Cal EPA 8-hour CREL (2004)	33 µg/m ³
Naphthalene	Cal EPA CREL (June 2016)	9 µg/m ³
Phenol	AgBB LCI	10 µg/m ³
Tetrachloroethylene	Cal EPA CREL (June 2016)	35 µg/m ³
Toluene	Cal EPA CREL (June 2016)	300 µg/m ³
1,1,1-trichloroethane	Cal EPA CREL (June 2016)	1000 µg/m ³
Xylene, total	AgBB LCI	500 µg/m ³
Carbon monoxide	U.S. EPA NAAQS	9 ppm
PM2.5	U.S. EPA NAAQS (annual mean)	12 µg/m ³
Ozone	U.S. EPA NAAQS	70 ppb
Ammonia	Cal EPA CREL (June 2016)	200 µg/m ³

For mixtures, “mixed exposure sum” < 1

$$E_m = \sum \frac{C}{DL}$$

Table 6-6 Mixtures of Compounds

Upper Respiratory Tract Irritation	Eye Irritation	Central Nervous System
Acetaldehyde	Acetaldehyde	Acetone
Acetone	Acetone	Dichloromethane
Xylene, total	Formaldehyde	Xylene, total
Ozone	Xylene, total	1,1,1-trichloroethane
	Ozone	Toluene

Source: ACGIH (2017) (See Informative Appendix P, “Informative References”).

Current residential standards

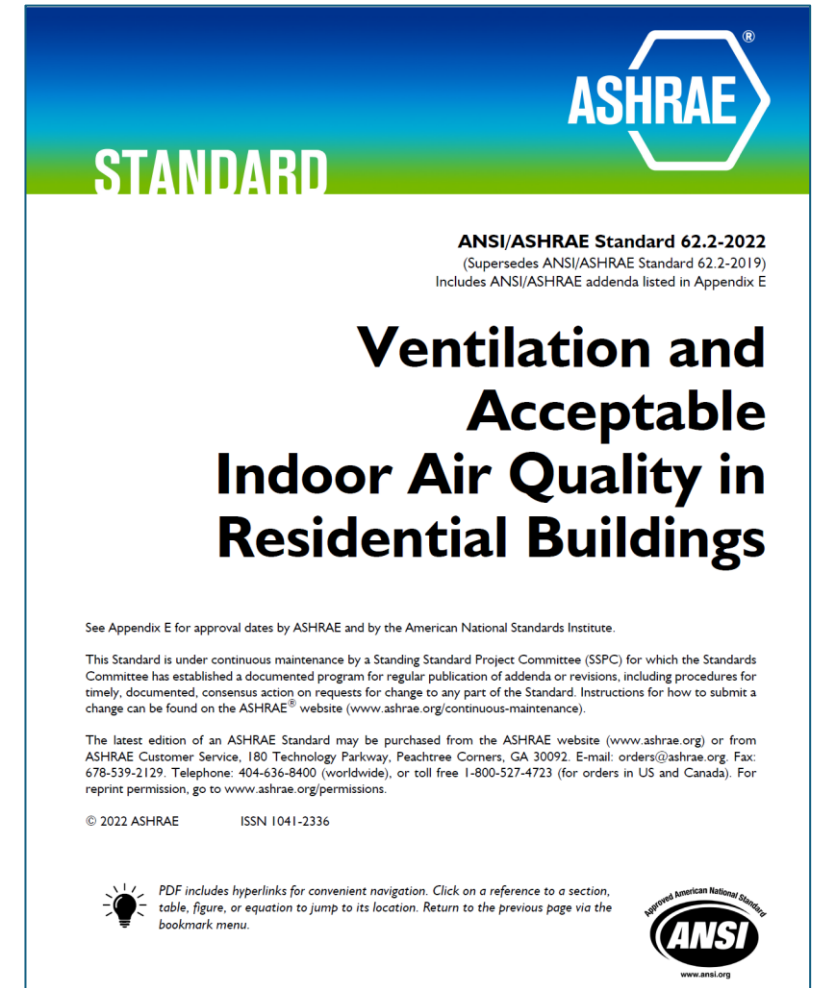
- Same definition of acceptability as 62.1
- Similar prescriptive approach
 - # Bedrooms (= people) + area

$$Q_{tot} [cfm] = 0.03A_{floor} [ft^2] + 7.5(N_{br} + 1)$$

- Credit for infiltration

Table 4-1a (I-P) Ventilation Air Requirements, cfm

Floor Area, ft ²	Bedrooms				
	1	2	3	4	5
<500	30	38	45	53	60
501 to 1000	45	53	60	68	75
1001 to 1500	60	68	75	83	90
1501 to 2000	75	83	90	98	105
2001 to 2500	90	98	105	113	120



Current residential standards

- Recent addenda have addressed
 - Use of equivalent clean air approach
 - Performance compliance path...but different than 62.1 IAQP
 - Control of infectious aerosols by adaptation of ASHRAE Standard 241 requirements (informative appendix)

Observations on the status quo

- We generally know what the rationale is
- Quantitative details are hard to come by...if they exist
- Ironically, evidence basis is weaker for health care ventilation
- Many would like to see the bar raised on what is acceptable
 - More transparency regarding basis for requirements
 - Performance approach or evidence-based prescriptive
 - Expand requirements to new areas – health and productivity
 - Bigger role for air cleaning/disinfection – but are we ready to do it?

Recent research seeks to rationalize IAQ control for chemical and particulate contaminants

- Built on work of Logue, et al. (2012)
- Objectives
 - Quantify and compare harm from indoor air contaminants
 - Disability-Adjusted Life-Year basis
- Analysis suggests that a small number of contaminants are significant

Research

A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences

Jennifer M. Logue, Phillip N. Price, Max H. Sherman, and Brett C. Singer

Environmental Energy Technologies Division, Lawrence Berkeley National Lab, Berkeley, California, USA

BACKGROUND: Indoor air pollutants (IAPs) cause multiple health impacts. Prioritizing mitigation options that differentially affect individual pollutants and comparing IAPs with other environmental health hazards require a common metric of harm.

OBJECTIVES: Our objective was to demonstrate a methodology to quantify and compare health impacts from IAPs. The methodology is needed to assess population health impacts of large-scale initiatives—including energy efficiency upgrades and ventilation standards—that affect indoor air quality (IAQ).

METHODS: Available disease incidence and disease impact models for specific pollutant–disease combinations were synthesized with data on measured concentrations to estimate the chronic health impact, in disability-adjusted life-years (DALYs) lost, due to inhalation of a subset of IAPs in U.S. residences. Model results were compared with independent estimates of DALYs lost due to disease.

RESULTS: Particulate matter $\leq 2.5 \mu\text{m}$ in aerodynamic diameter ($\text{PM}_{2.5}$), acrolein, and formaldehyde accounted for the vast majority of DALY losses caused by IAPs considered in this analysis, with impacts on par or greater than estimates for secondhand tobacco smoke and radon. Confidence intervals of DALYs lost derived from epidemiology-based response functions are tighter than those derived from toxicology-based, interspecies extrapolations. Statistics on disease incidence in the United States indicate that the upper-bound confidence interval for aggregate IAP harm is implausibly high.

CONCLUSIONS: The approach demonstrated in this study may be used to assess regional and national initiatives that affect IAQ at the population level. Cumulative health impacts from inhalation in U.S. residences of the IAPs assessed in this study are estimated at 400–1,100 DALYs lost annually per 100,000 persons.

KEY WORDS: air toxics, criteria pollutants, DALYs, exposure, impact assessment, indoor air pollutants, indoor air quality. *Environ Health Perspect* 120:216–222 (2012). <http://dx.doi.org/10.1289/ehp.1104035> [Online 17 November 2011]

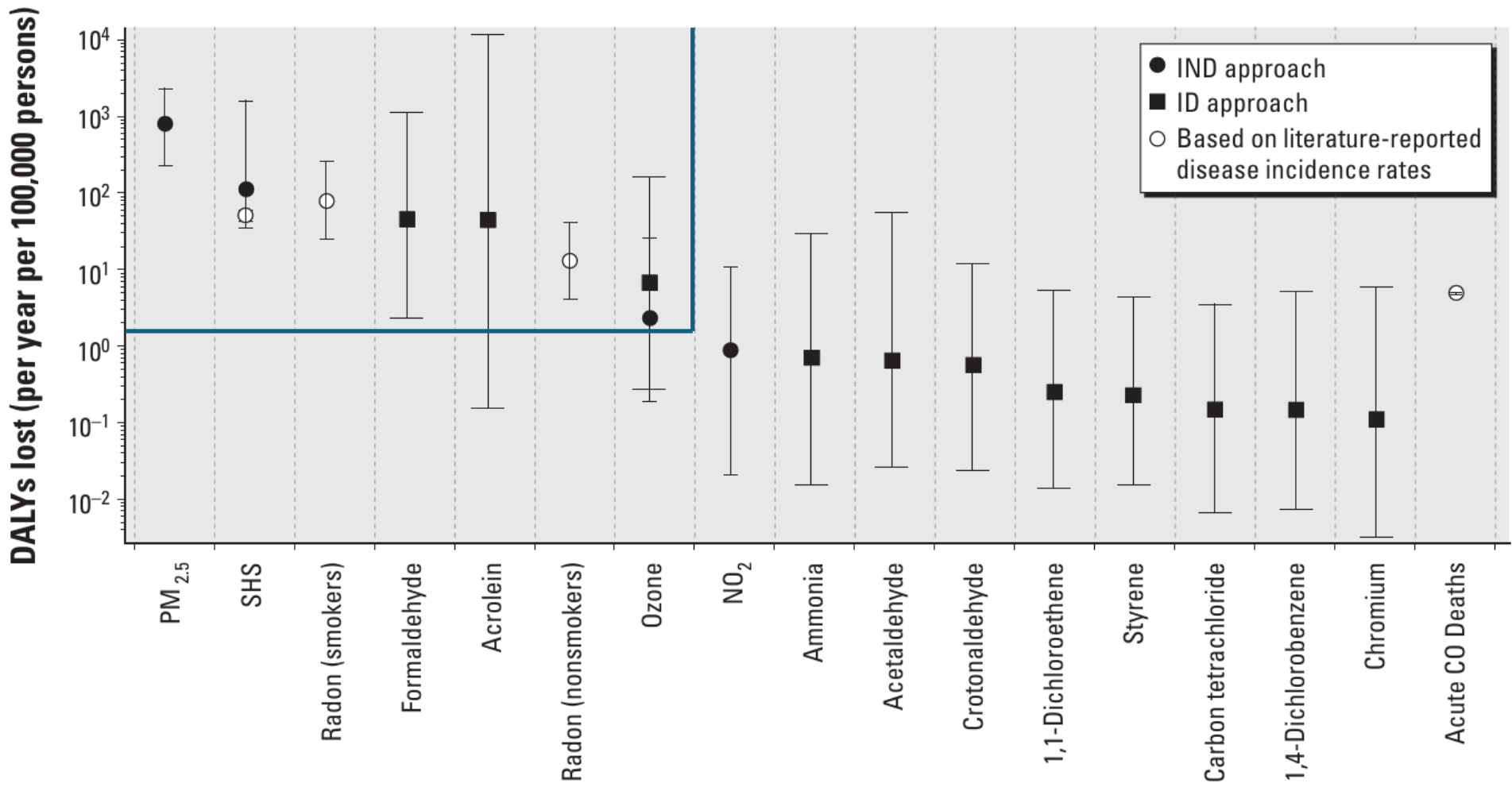
Air pollutant concentrations in many homes exceed health-based standards for chronic and acute exposures (Logue et al. 2011). On aver-

that impact. The U.S. EPA and the California EPA (CalEPA) each publish health standards or guidelines for long-term exposure concen-

disease incidence models for use in the cost-benefit analysis of the Clean Air Act (U.S. EPA 1999). Several studies have estimated the health impact per incidence of specific diseases (Hong et al. 2010; Lvovsky et al. 2000; Melse et al. 2010). Huijbregts et al. (2005) published cumulative impact and effect factors for exposure to air pollutants, including air toxics and ozone. These models provide the basis for performing a human health impact assessment for inhalation of IAPs.

In this study we combined disease incidence and DALY-based health impact models to develop a methodology for estimating the population-average health costs due to chronic inhalation of a broad suite of air pollutants in U.S. residences. We first analyzed published data to calculate mean exposure concentrations and estimated age-dependent inhalation intakes. We used disease incidence and disease impact models to predict pollutant-specific impacts and total DALY-based health costs to identify the residential IAPs that have the greatest impact on health in the United States. As a check on the method, and the estimated aggregate impact of IAP, we compared our findings with independent estimates of DALY losses related to secondhand smoke (SHS) to diseases that could potentially result from air pollutant

Environmental Health Perspectives 120:2 CID: <https://doi.org/10.1289/ehp.1104035>



Morantes, et al. reexamined residential data

- Screened over 300 indoor air contaminants to obtain 25 with useable data
- Considered harm (toxicology and epidemiology data)
- Quantified harm in DALY per unit of exposure
- Applied estimates of typical indoor concentrations
- Similar results to Logue, et al.
- Proposed basis for an IAQP in ASHRAE Standard 62.2

Harm from Residential Indoor Air Contaminants

Gioberti Morantes, Benjamin Jones,* Constanza Molina, and Max H. Sherman

Cite This: *Environ. Sci. Technol.* 2024, 58, 242–257

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Supporting Information

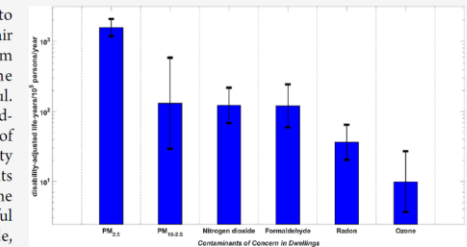
ABSTRACT: This study presents a health-centered approach to quantify and compare the chronic harm caused by indoor air contaminants using disability-adjusted life-year (DALY). The aim is to understand the chronic harm caused by airborne contaminants in dwellings and identify the most harmful. Epidemiological and toxicological evidence of population morbidity and mortality is used to determine harm intensities, a metric of chronic harm per unit of contaminant concentration. Uncertainty is evaluated in the concentrations of 45 indoor air contaminants commonly found in dwellings. Chronic harm is estimated from the harm intensities and the concentrations. The most harmful contaminants in dwellings are PM_{2.5}, PM_{10–2.5}, NO₂, formaldehyde, radon, and O₃, accounting for over 99% of total median harm of 2200 DALYs/10⁵ person/year. The chronic harm caused by all airborne contaminants in dwellings accounts for 7% of the total global burden from all diseases.

KEYWORDS: DALY, dwelling, harm intensity, harm budget, ranking, acceptable indoor air quality

1. INTRODUCTION

There is strong evidence that exposure to harmful airborne contaminants commonly found in dwellings, such as volatile organic compounds (VOCs), particulate matter (PM), bio-

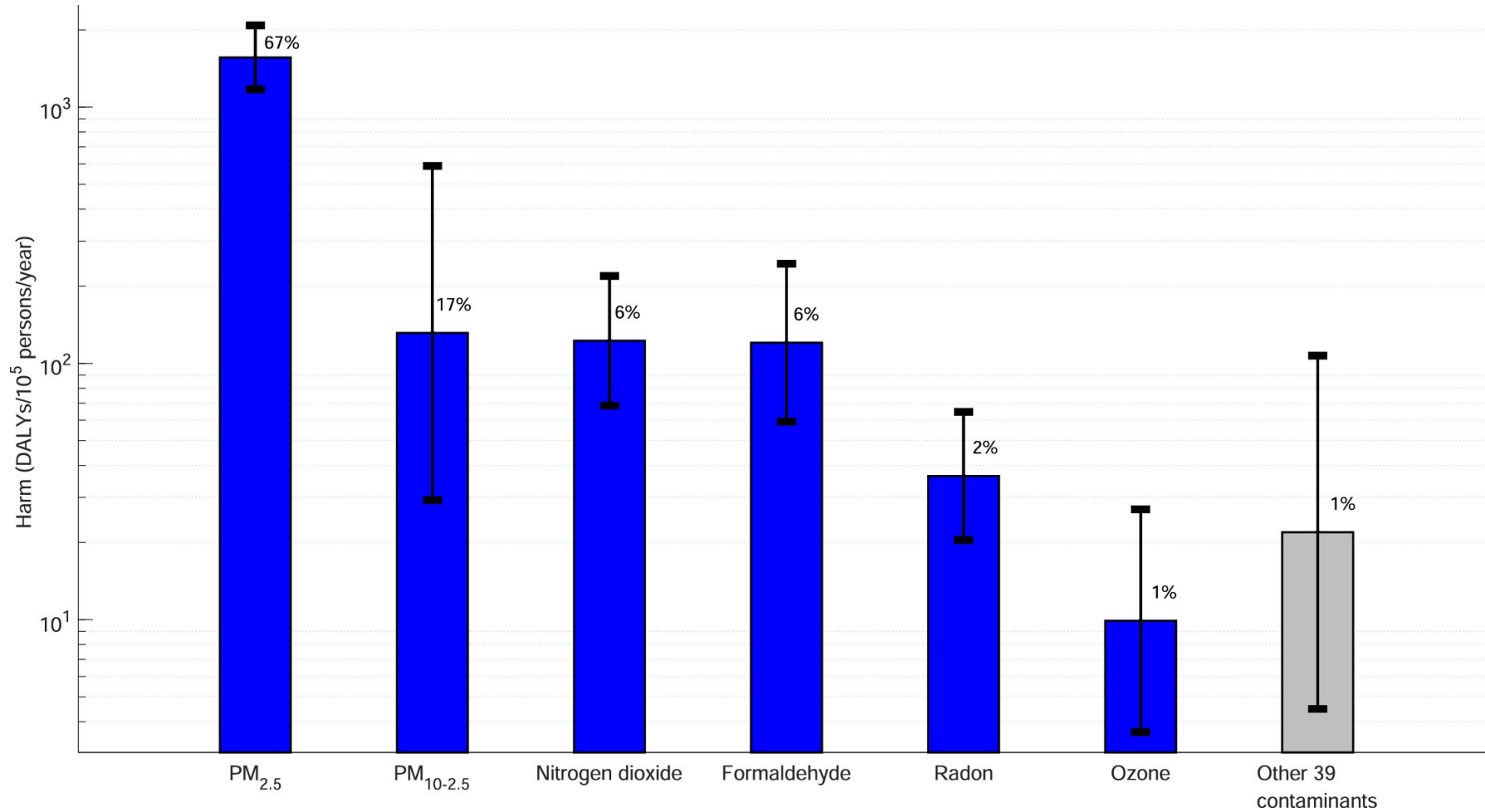
data, such as risk estimates, the population attributable fraction, or disease incidence rates, whereas a toxicology-based approach is derived from toxicological data, such as the median effective dose (ED50). It is important to note that AP-HRAs are epidemiology-based, while LCIA can use EFs



<https://doi.org/10.1021/acs.est.3c07374>

Environ. Sci. Technol. 2024, 58, 242–257

Six contaminants (2 are PM) responsible for 99% of harm – particles pose greatest risk



Morantes, et al. now extended to offices

- Same methodology as in prior residential work
- Somewhat different outcome because of differences in contaminant profiles
- Particles are still the most harmful
- Top four cause > 99% of harm
- ASHRAE SSPC 62.1 is considering relevance to IAQP

Journal Pre-proof

Harm from indoor air contaminants in offices

Gioberti Morantes, Irene Lara-Ibeas, Constanza Molina, Max H. Sherman, Francesco Babich, Benjamin Jones

PII: S0360-1323(25)00841-8

DOI: <https://doi.org/10.1016/j.buildenv.2025.113365>

Reference: BAE 113365

To appear in: *Building and Environment*

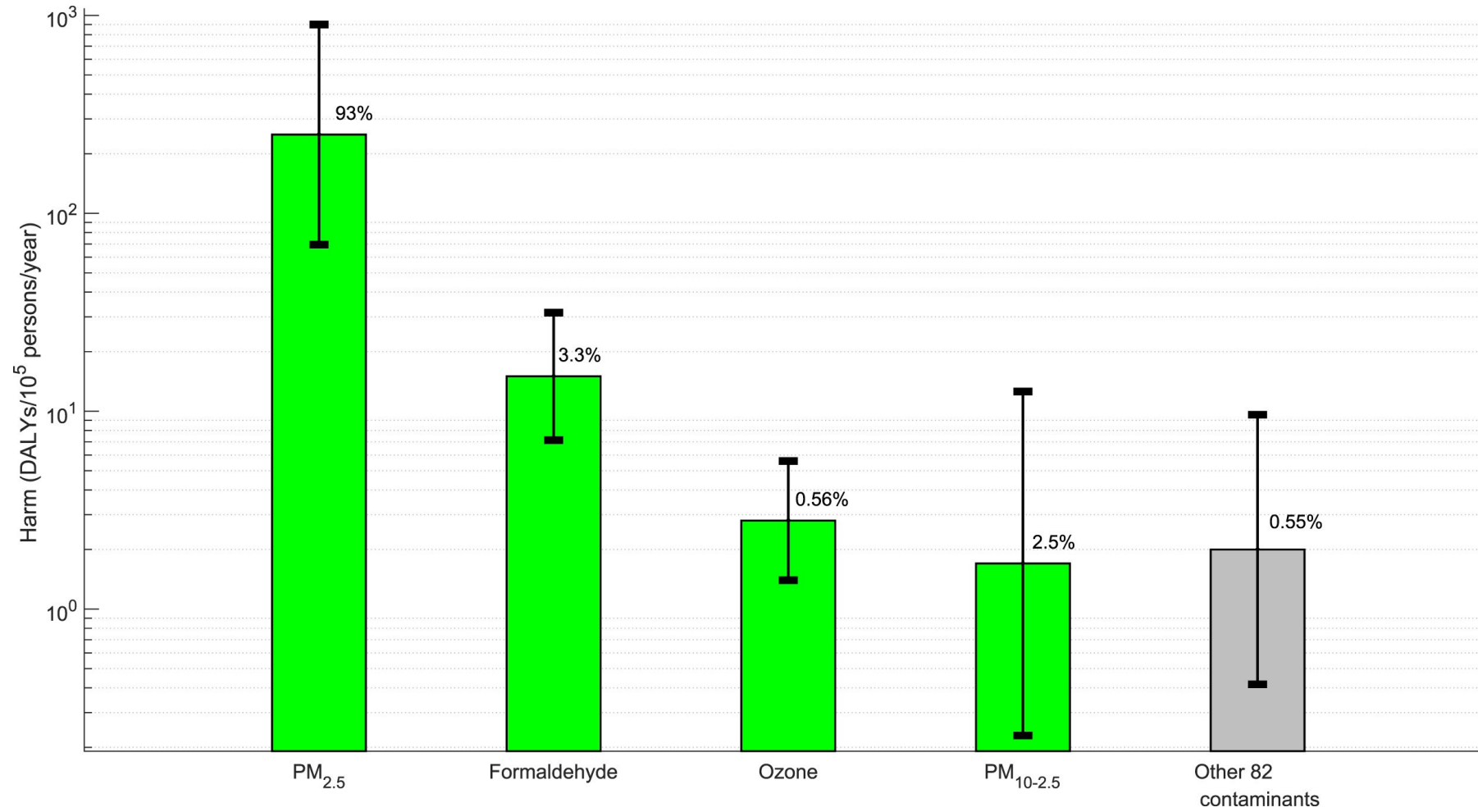
Received date: 4 April 2025

Revised date: 27 June 2025

Accepted date: 2 July 2025

Please cite this article as: G. Morantes, I. Lara-Ibeas, C. Molina et al., Harm from indoor air contaminants in offices, *Building and Environment* (2025), doi: <https://doi.org/10.1016/j.buildenv.2025.113365>.



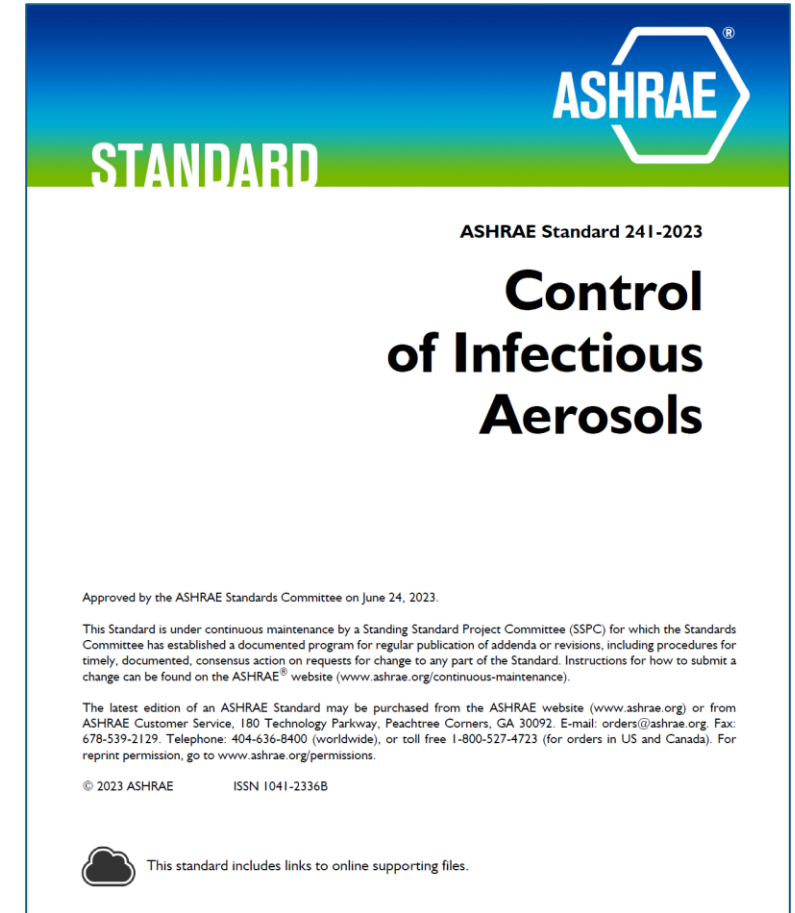


DALY may not be the answer to everything, but has a role to play

- Trade-offs can be tricky
- Calculation of some DALY is not very precise
- Work so far has trimmed the list of contaminants of serious concern
- Someone still needs to draw the line to define acceptability
- Most promising – suggests performance based control may be practical

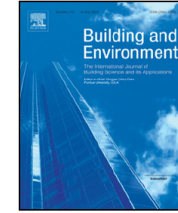
New developments – resilience in standards and guidelines: infectious aerosols

- Addresses risk of airborne infection transmission in all facility types
- Applies during periods of elevated risk (Infection Risk Management Mode, IRMM)
- General IAQ standards are prerequisites (e.g., ASHRAE 62.1, 62.2, 170)
- Specifies equivalent clean airflow requirements per person (ECA_i)
- Level playing field for air cleaners
- Based on population-level risk assessment, documented in an open publication



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journal homepage: www.elsevier.com/locate/buildenv

Risk modeling for ASHRAE Standard 241-2023 — Control of infectious aerosols

Benjamin Jones^a, Christopher Iddon^b, Marwa Zaatari^c, Pawel Wargocki^d,
Richard Bruns^e

Table 1

Input parameters common to all occupancy categories.

	Parameter	Distribution	Values	Source
Constants	Viability fraction remaining after exhalation, RD		1.0	[22]
	Exposure duration, D (h)		1.0	
	Community infection rate, (%)	Healthcare	3.0	
		All other	1.0	[28]
	Probability of infection, $P(I)$ (%)		0.10	
Variables	Respiratory particle evaporation factor, E	Beta	$\alpha = 5.0, \beta = 2.0$ min = 2.0, max = 5.0	[15]
	Genomic viral load ^a , GVL_i (\log_{10} RNA copies ml^{-1})	Normal	$\mu = 7.0, \sigma = 1.4$	[29]
	Viable fraction, VF	Beta	$\alpha = 5.0, \beta = 2.0$ min = 10^{-4} , max = 10^{-2}	[19]
	Respiratory tract absorption fraction, RTD	Uniform	min = 0.43, max = 0.65	[30]
	Dose constant, DK	Uniform	min = 5.0, max = 15	[19]
	Biological decay rate, λ (h^{-1})	Log-normal	GM = 0.52, GSD = 1.9	[31]
	Surface deposition rate, γ (h^{-1})	Uniform	min = 0.42, max = 0.61	[32]

μ , mean; σ , standard deviation; GM, geometric mean;

GSD, geometric standard deviation; α and β are shape parameters.

^a GVL_i is converted into RNA copies per m^3 by multiplying by 10^6 .

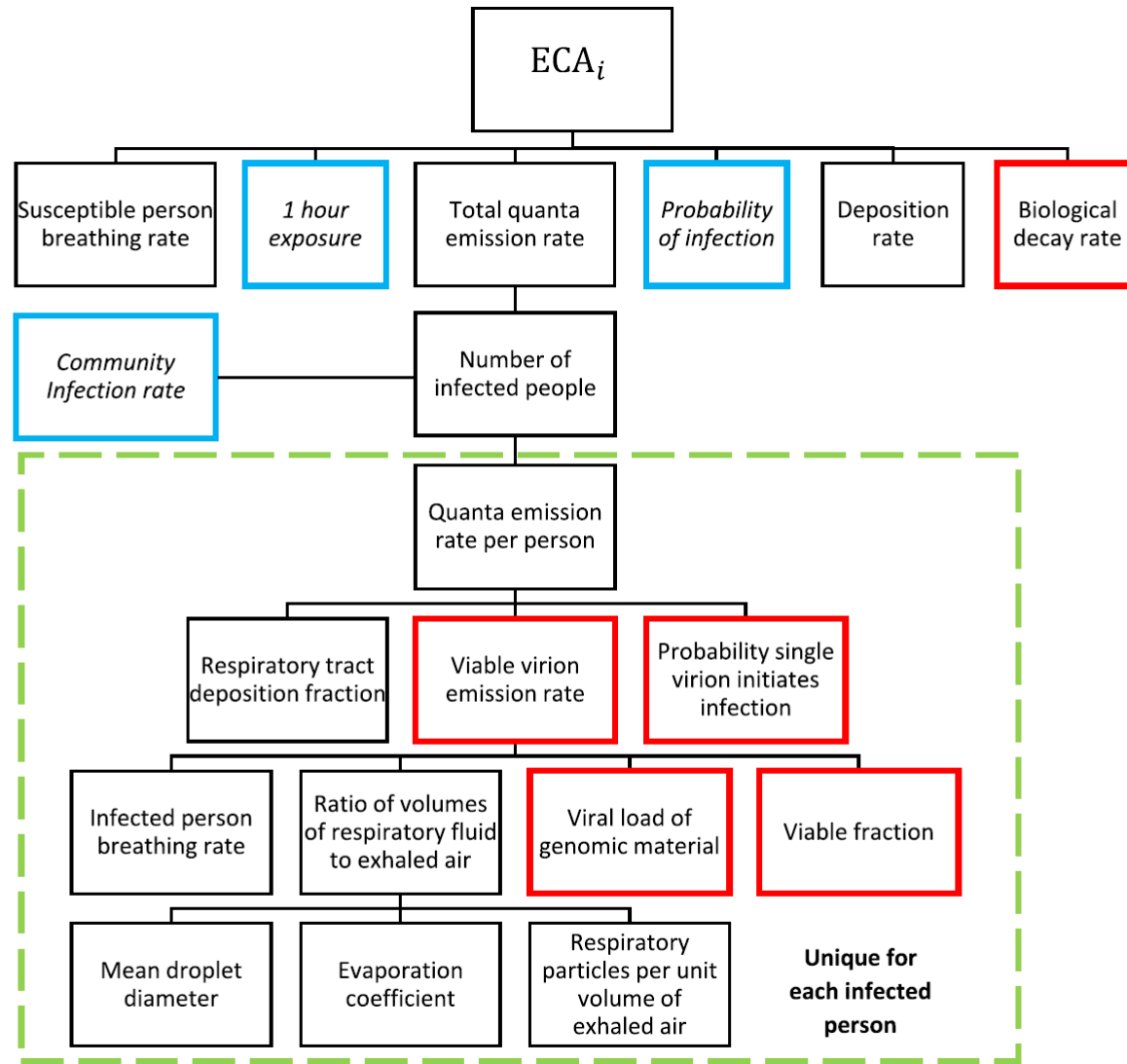


Fig. 1. A model of the relationships between infection risk probability and pathogen removal rate. Blue: deterministic input; Red: biological; Green: unique inputs for each infected person.

Required ECA depends on space type, number of people and activity

- Occupancy categories
 - Correctional facilities
 - Commercial/retail
 - Educational facilities
 - Industrial
 - Health-care
 - Public assembly/sports & entertainment
 - Residential
- 25 space types – office, classroom, food and beverage, etc.
- ECAi range 20-90 cfm/pers (10-40 L/s-pers) values doubled if there is loud vocalization

$$V_{ECAi} = ECAi \times P_{Z, IRMM}$$

or



Design
occupancy



IRMM
occupancy

Table 5-1 – Minimum Equivalent Clean Airflow per Person in Breathing Zone in IRMM

Occupancy Category	ECAi	
	cfm/person	L/s/person
Correctional Facilities		
Cell	30	15
Dayroom	40	20
Commercial/Retail		
Food and beverage facilities	60	30
Gym	80	40
Office	30	15
Retail	40	20
Transportation waiting	60	30
Educational Facilities		
Classroom	40	20
Lecture hall	50	25
Industrial		
Manufacturing	50	25
Sorting, packing, light assembly	20	10
Warehouse	20	10

Occupancy Category	ECAi	
	cfm/person	L/s/person
Health Care		
Exam room	40	20
Group treatment area	70	35
Patient room	70	35
Resident room	50	25
Waiting room	90	45
Public Assembly/Sports and Entertainment		
Auditorium	50	25
Place of religious worship	50	25
Museum	60	30
Convention	60	30
Spectator area	50	25
Lobbies	50	25
Residential		
Common space	50	25
Dwelling unit	30	15

Comparing standard 62.1 outdoor air, CDC recommendations, and ECAi

- ECAi rates are much higher than 62.1 OA rates...but closer after effect of filters is added
- Constant risk ECAi values give very different ACH values for different space types
- CDC recommends 5 eACH all the time
- ECAi has units of flow rate per person because personal risk of infection scales with ECA per person

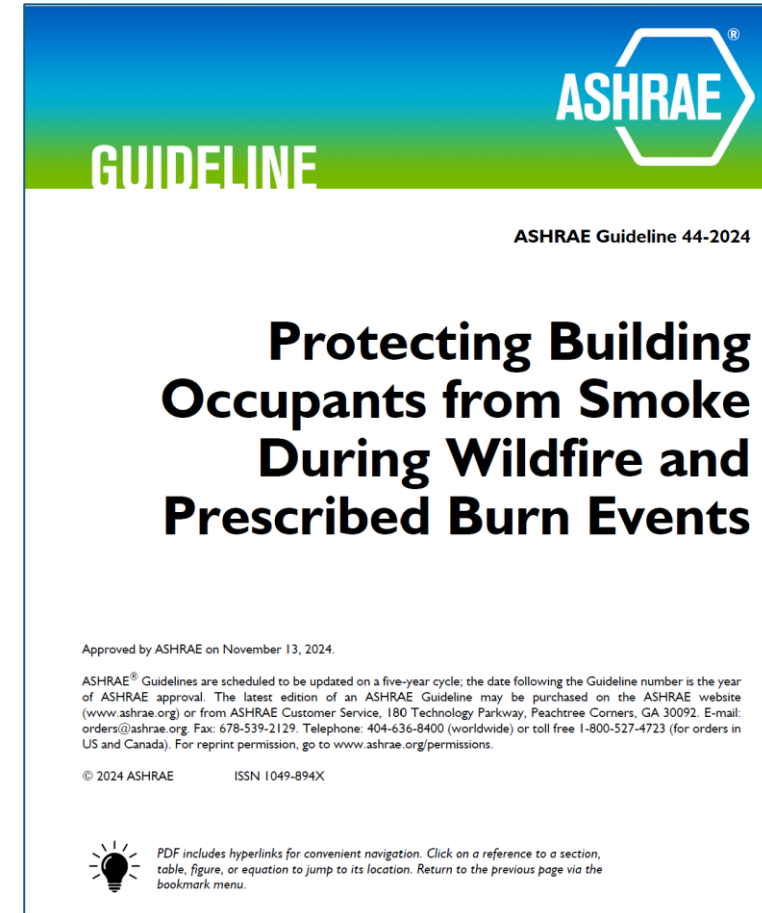
ANSI/ASHRAE Standard 62.1 VRP inputs

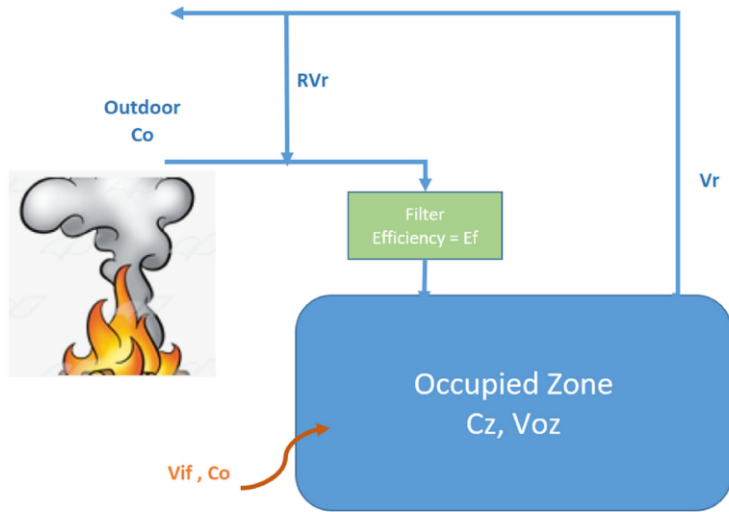
	R_p [cfm/pers]	R_A [cfm/ft ²]	Occupant Density [#/1000 ft ²]
Office	5	0.06	5
Classroom	10	0.12	35
Restaurant	7.5	0.18	70

	ASHRAE 62.1 Default [cfm/pers]	ASHRAE 241 ECAi [cfm/pers]	ASHRAE 241 ACH with 8' ceiling
Office	17	30	1.1
Classroom	13	40	10.5
Restaurant	10	60	31.5

New developments – resilience in standards and guidelines: wildfire smoke

- ASHRAE Guideline 44-2024
 - Guidance, not code-intended
 - Commercial, institutional, health care, multi-unit residential
 - Can use for prescriptive or performance-based design
 - Focuses on PM control with filters and pressurization
 - Addresses operation through development of a Smoke Readiness Plan





Schematic for single-zone design equation.

5.4 Design Calculations and Processes

5.4.1 Removal Need Calculation. The design calculations related to smoke protection (required flow rate and filtration efficiencies) are versions of the conservation of mass of contaminants into the building, which can be presented with the following equation for a given zone:

$$C_z = \frac{V_{if}C_o + V_{oz}(1 - E_f)C_o}{V_{oz} + F_rRV_rE_f} \quad (1)$$

where

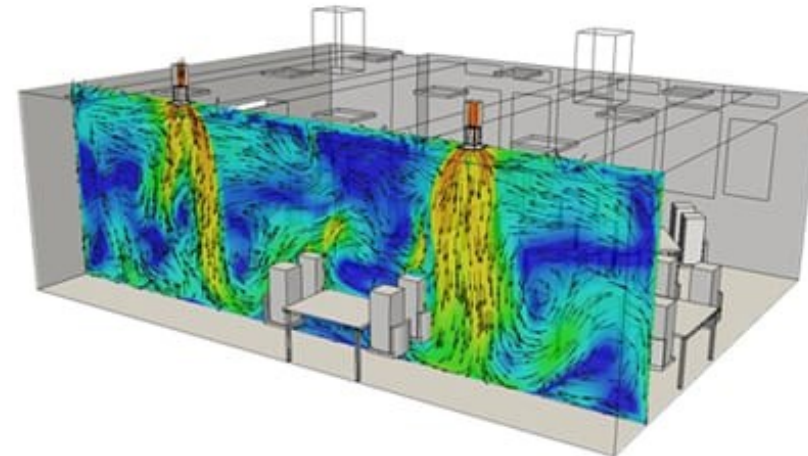
- C_z = indoor contaminant concentration in the zone, $\mu\text{g}/\text{m}^3$
- V_{if} = infiltration flow rate to the building, m^3/h (cfm)
- C_o = concentration of contaminants (PM2.5) in the outdoor air, $\mu\text{g}/\text{m}^3$
- V_{oz} = zone outdoor airflow, m^3/h (cfm)
- E_f = filter removal efficiency
- F_r = design flow reduction factor (=1 if the system is constant flow)
- R = recirculation flow factor (=1 if system is 100% recirculating)
- V_r = recirculating or return airflow, m^3/h (cfm)

One more layer of complexity – air distribution

- All ventilation standards assume “perfect mixing”
- Some adjust with factors like ventilation effectiveness
- Effectiveness depends on the application
- In reality, details of air distribution matter
- They are hard to address prescriptively and expensive to address by testing.



Well-mixed space



Mixing ventilation

Air cleaners are finally getting the attention they need – performance and safety

- Covid-driven air cleaner market revealed...
 - Most performance claims were unsupported by strong evidence
 - Reporting of performance tests was highly misleading
 - Safety testing for anything but ozone production
- Positive outcome
 - Updated and new performance test standards (e.g., ASHRAE 185.3)
 - Research on emissions from all air cleaner types
 - Byproduct test standard is under development (ASTM WK81750, New Test Method for Chemical Assessment of Air Cleaning Technologies)

ENVIRONMENTAL Science & Technology
pubs.acs.org/est Article

Quantification of Byproduct Formation from Portable Air Cleaners Using a Proposed Standard Test Method


Michael F. Link,*[‡] Raleigh Robertson, Megan S. Clafin, and Dustin Poppendieck*[‡]

Cite This: *Environ. Sci. Technol.* 2024, 58, 7916–7923 [Read Online](#)

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ABSTRACT: In response to the COVID-19 pandemic, air cleaning technologies were promoted as useful tools for disinfecting public spaces and combating airborne pathogen transmission. However, no standard method exists to assess the potentially harmful byproduct formation from air cleaners. Through a consensus standard development process, a draft standard test method to assess portable air cleaner performance was developed, and a suite of air cleaners employing seven different technologies was tested. The test method quantifies not only the removal efficiency of a challenge chemical suite and ultrafine particulate matter but also byproduct formation. Clean air delivery rates (CADRs) are used to quantify the chemical and particle removal efficiencies, and an emission rate framework is used to quantify the formation of formaldehyde, ozone, and other volatile organic compounds. We find that the tested photocatalytic oxidation and germicidal ultraviolet light (GUV) technologies produced the highest levels of aldehyde byproducts having emission rates of 202 and 243 $\mu\text{g h}^{-1}$, respectively. Additionally, GUV using two different wavelengths, 222 and 254 nm, both produced ultrafine particulate matter.

KEYWORDS: air cleaners, indoor air chemistry, standards, VOCs



INTRODUCTION

In response to the heightened awareness of indoor air quality caused by the COVID-19 pandemic, there has been an increase in the use of portable air cleaning technologies in public and residential spaces. Portable air cleaners have the potential to mitigate airborne pathogen transmission by removing infectious aerosols from the air. Air cleaners are also advertised to improve indoor air quality by removing particulate matter with some also advertising removal of volatile organic compounds (VOCs) or odors. Recent research has raised questions about the effectiveness of air cleaners, suggesting that some could be a source of VOCs, oxidants, and particulate matter that could potentially present health hazards to building occupants.^{1,2} In particular, air cleaners that use additive technologies may be of concern (e.g., ultraviolet light, oxidant generators, etc.), because they can oxidize chemicals in the air to form potentially harmful gaseous or particulate matter byproducts.

Air cleaners can impact indoor air chemistry in two ways: (1) by removing VOCs, trace gases, and particulate matter and (2) by contributing to the formation of harmful byproducts.³ Notable standard tests for air cleaner particulate matter removal (e.g., American Home Appliance Manufacturer (AHAM)/American National Standards Institute (ANSI) AC-1-2020), chemical removal (e.g., National Research Council Canada (NRCC) NRCC-S4013), and byproduct formation [e.g., Underwriters Laboratories (UL) 2998 “zero ozone” certification] exist, but no comprehensive standard that addresses all of these aspects of air cleaner performance is available. Additionally, gas-phase byproducts that are potentially of concern^{4–6} and particulate matter formation are not considered by existing test methods.

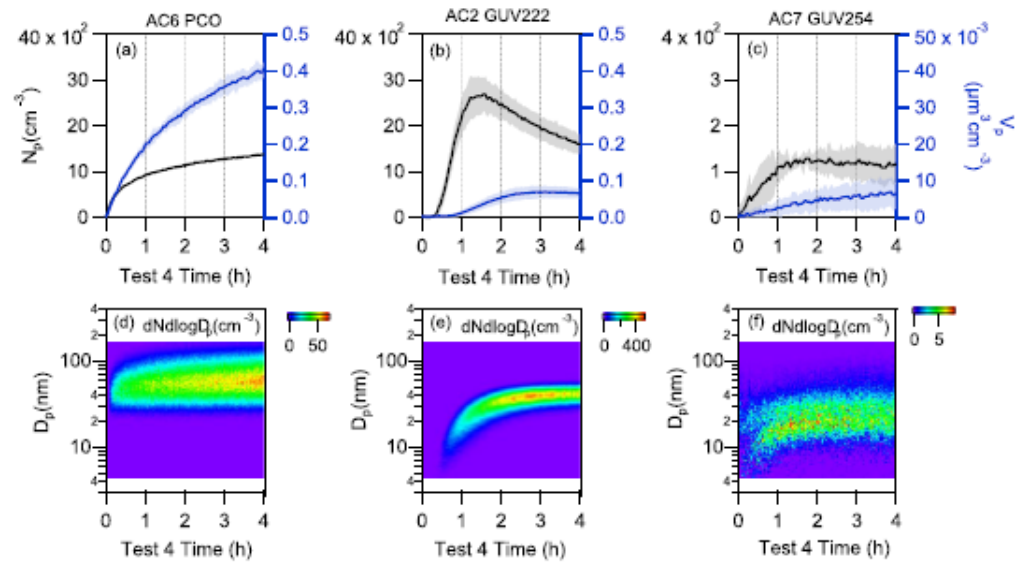
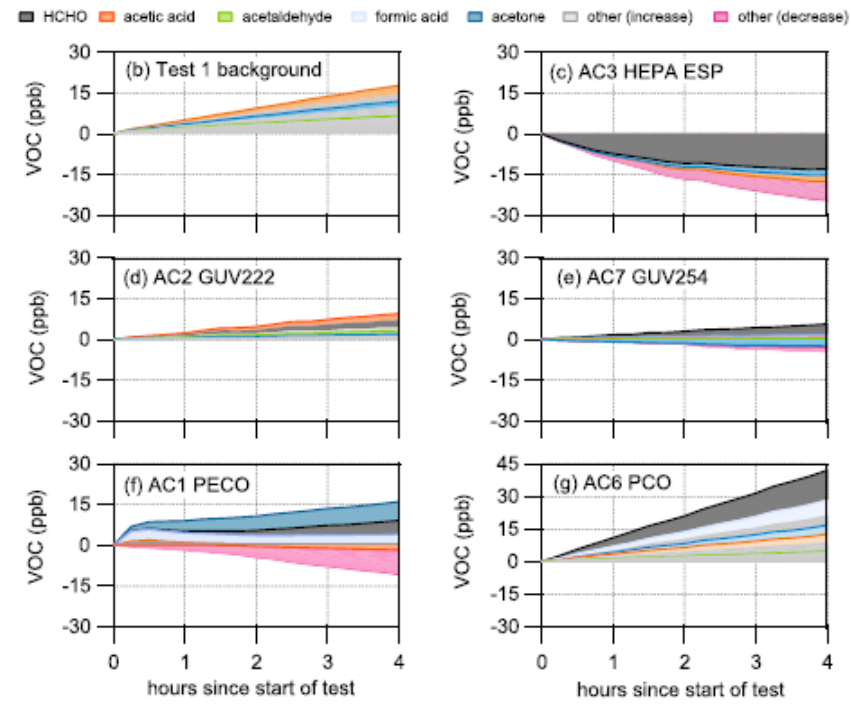
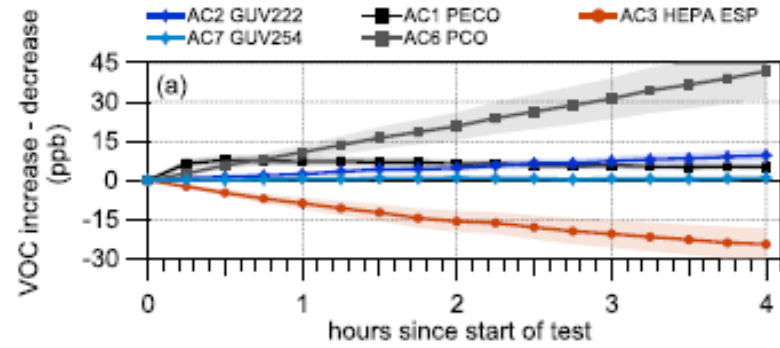
We facilitated an ASTM International working group consisting of academics, industry representatives, and testing laboratory representatives to develop a standard test method to evaluate the removal efficiency for VOCs, trace gases, and ultrafine particulate matter (UFP, particle diameter < 100 nm). Here, we present the results of applying our draft test method to ten different air cleaners that used seven different technologies. Most air cleaners incorporated more than one technology. We found that photocatalytic oxidation and ultraviolet light technologies produced byproducts. We calculate emission rates, as a standard method to report byproduct formation, and apply the emission rate calculation to VOC byproducts using targeted and nontargeted analysis.

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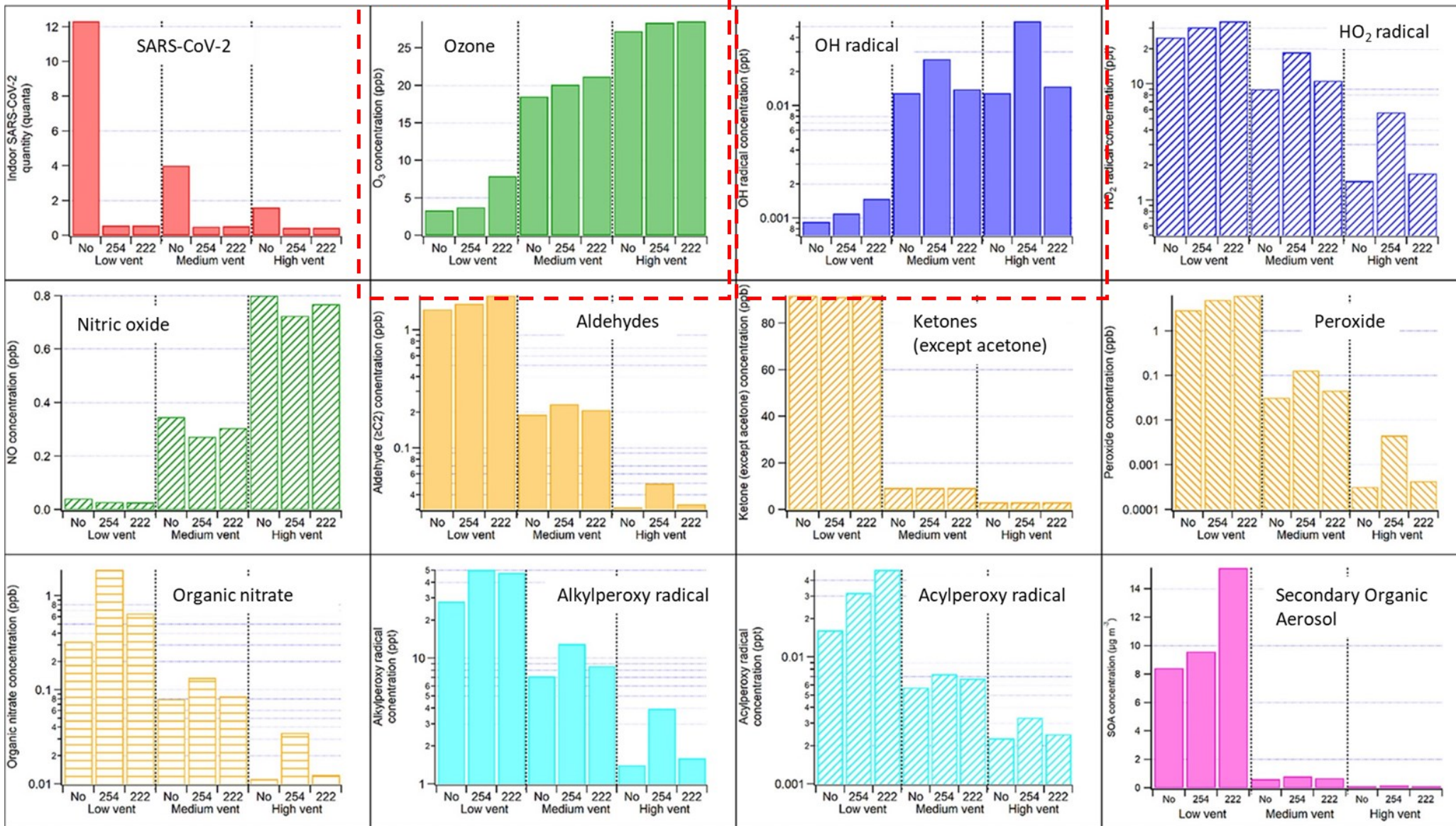
<https://pubs.acs.org/doi/10.1021>

Link, et al. (2024)
<https://doi.org/10.1021/acs.est.3c09331>
 Environ. Sci. Technol. 2024, 58, 7916–7923



Modeling of byproduct formation – 222 nm and 254 nm GUV, variable outdoor air rates

Outdoor airflow rates
 -low 0.3 ACH
 -medium 3 ACH
 -high 9 ACH



Peng, et al. 2023. doi.org/10.1021/acs.estlett.2c00599

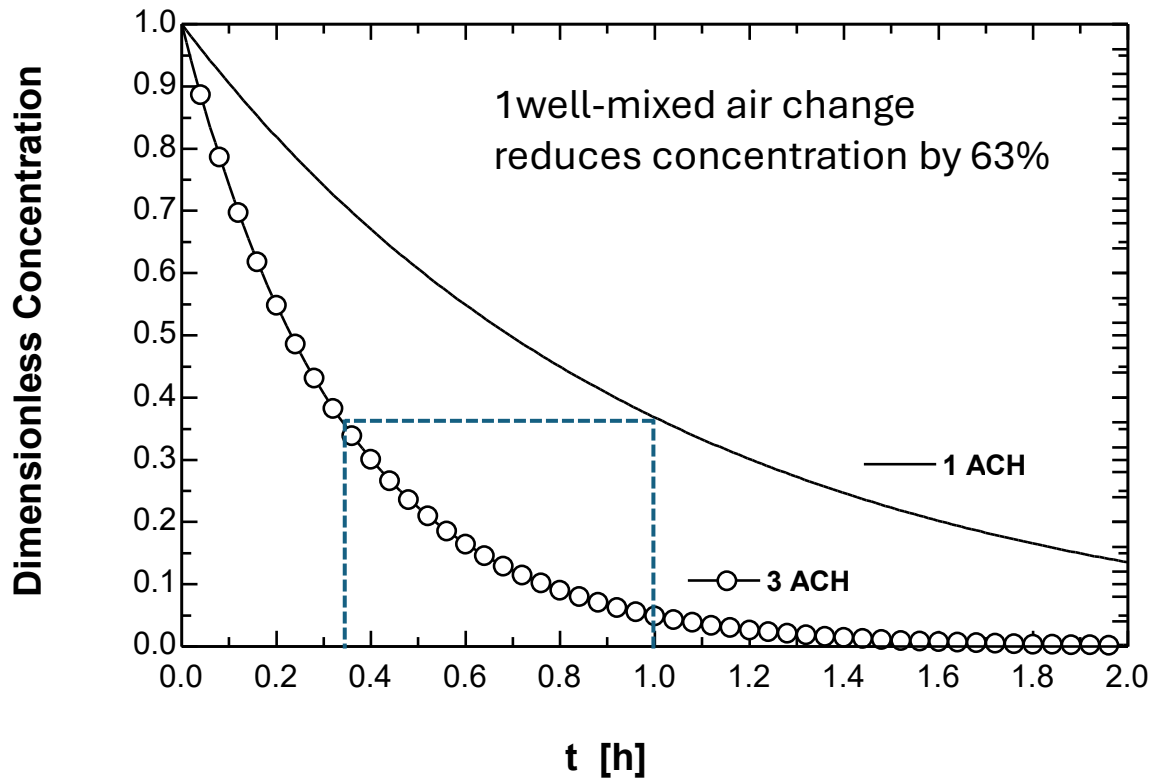
Do ventilation units matter?

- Air change rates (usually ACH)
 - Flow rate measured in room volumes per unit time – not *actual* replacement
 - Used for healthcare, labs, animal facilities
 - Expanded use during covid-19 pandemic
 - Cannot directly determine contaminant concentration from ACH
 - Useful for estimating clearance time, room air distribution
- Absolute flow rates (cfm, L/s...) per unit of something
 - Per person or per unit of floor area
 - Used in residential and non-residential standards
 - Needed for calculating concentration

$$\frac{c_{ss} - c(t)}{c_{ss} - c(0)} = \exp\left(-\frac{Q}{V}t\right)$$

$$C_{ss} = C_o + \frac{S}{Q}$$

$$\exp(-ACR \times t)$$



- C_{ss} = Steady state concentration of a contaminant
- C_o = Concentration of contaminant in ventilation air
- S = Source strength (emission rate of a contaminant)
- Q = Flow rate of uncontaminated ventilation air (cfm, etc.)
- ACR = Air change rate (ACH)

ASHRAE sponsored research on evidence for air change rates in standards (1833-RP, 2023)

- 15 years after publication of Standard 170
- “The only robust evidence is that ventilation can be used to control thermal comfort and therefore minimize distraction and fatigue among caregivers.”
- “Unfortunately, a single optimal air change rate was not identified for any healthcare space.”
- “(G)iven the observed pace of change for the HVAC industry,...air change rate’s days are numbered, but it is likely a large number.

ASHRAE Research Project Report
1833-RP

Literature Review for Evidence of the Basis for Specified Air Change Rates (ACR) for Cleanrooms, Laboratories, laboratory animal facilities, and health care facilities with medium to high ACR

Approval: May 2023


Contractor: Affiliated Engineers, Inc.

Principal Investigator: Roger Lautz
Authors: Ehsan Mousavi, Fred Betz, Arup Bhattacharya, and Author Affiliations, Clemson University

Sponsoring Committee: MTG.ACR

Co-Sponsoring Committee: N/A

Co-Sponsoring Organizations: N/A

 Shaping Tomorrow's
Built Environment Today

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What about carbon dioxide?

- ASHRAE Position Document
 - The history CO₂ concentrations in relation to building ventilation and IAQ
 - Health and cognitive impacts of exposure to CO₂
 - Existing standards and regulations for indoor CO₂ concentrations
 - CO₂ as an indicator of IAQ and ventilation
 - Use of CO₂ as a tracer gas for estimating ventilation rates
 - Increases in outdoor CO₂ concentrations
 - Air cleaning directed at CO₂ removal alone
 - CO₂ as an indicator of the risk of airborne disease transmission



Shaping Tomorrow's Global
Built Environment Today

ASHRAE Position Document on INDOOR CARBON DIOXIDE

Approved by the ASHRAE Board of Directors February 12, 2025

Expires February 12, 2028

ASHRAE is a global professional society of over 55,000 members, committed to serve humanity by advancing the arts and sciences of heating, ventilation, air conditioning, refrigeration and their allied fields (HVAC&R). ASHRAE position documents are approved by the Board of Directors and express the views of the Society on specific issues. These documents provide objective, authoritative background information to persons interested in issues within ASHRAE's expertise, particularly in areas where such information will be helpful in drafting sound public policy. The documents also clarify ASHRAE's position for its members and building professionals.

Indoor Carbon Dioxide is a Public Interest Issue

Indoor carbon dioxide (CO₂) has been considered in the context of building ventilation and indoor air quality (IAQ) for centuries. Historically, these discussions have focused on the use of CO₂ to evaluate ventilation rates, how CO₂ concentrations relate to occupant perceptions of IAQ, and the use of CO₂ as a general indicator of IAQ. While these topics have been studied for decades, incorrect application and misinterpretation of CO₂ concentration as an indicator of IAQ and ventilation is common in the HVAC industry, research community, and the public. Despite many efforts to address these concerns in standards, guidance documents, technical publications, and conference presentations, significant misunderstanding of the application and meaning of indoor CO₂ remains.

Research and discussions over the past decade have considered the impacts of pure CO₂ on humans, in particular its adverse effects on cognitive performance, at commonly observed indoor concentrations. Indoor CO₂ monitoring has also been promoted as a ventilation indicator in the context of managing the risks of airborne disease transmission. Additionally, concerns have long existed regarding the accuracy of indoor CO₂ concentration measurements, which are now more common due to the availability and more widespread application of less expensive sensors. Given all of the above issues, as well as increasing calls to monitor CO₂ in buildings, ASHRAE recognizes the need to clarify the use of indoor CO₂ measurements as a tool to monitor and help improve IAQ and building ventilation.

Why ASHRAE Takes Positions on Indoor Carbon Dioxide

ASHRAE consensus standards, design guides, and other resources provide the technical foundation for international building practices and codes that support the essential need to provide indoor environments that support occupant health, comfort, and productivity in a cost-effective and energy-efficient manner. The design, construction, and operation of buildings' systems can support

ASHRAE positions, paraphrased

- Indoor CO₂ concentration is not an overall indicator of IAQ but can be helpful if you know what you're doing
- For the purpose of evaluating ventilation rates, indoor-outdoor CO₂ is a tracer gas and is accurate only if inputs are accurate and test assumptions are valid
- There is evidence of effects of CO₂ at typical indoor concentrations on health, well-being, learning, sleep, and work performance, but it is mixed
- In theory, there is a connection between CO₂ concentration and airborne infection risk, but in practice, it's hard to apply
- Sensor characteristics and placement are critical for monitoring and control

ASHRAE Standard 62.1 now supports CO₂ Based Demand Control

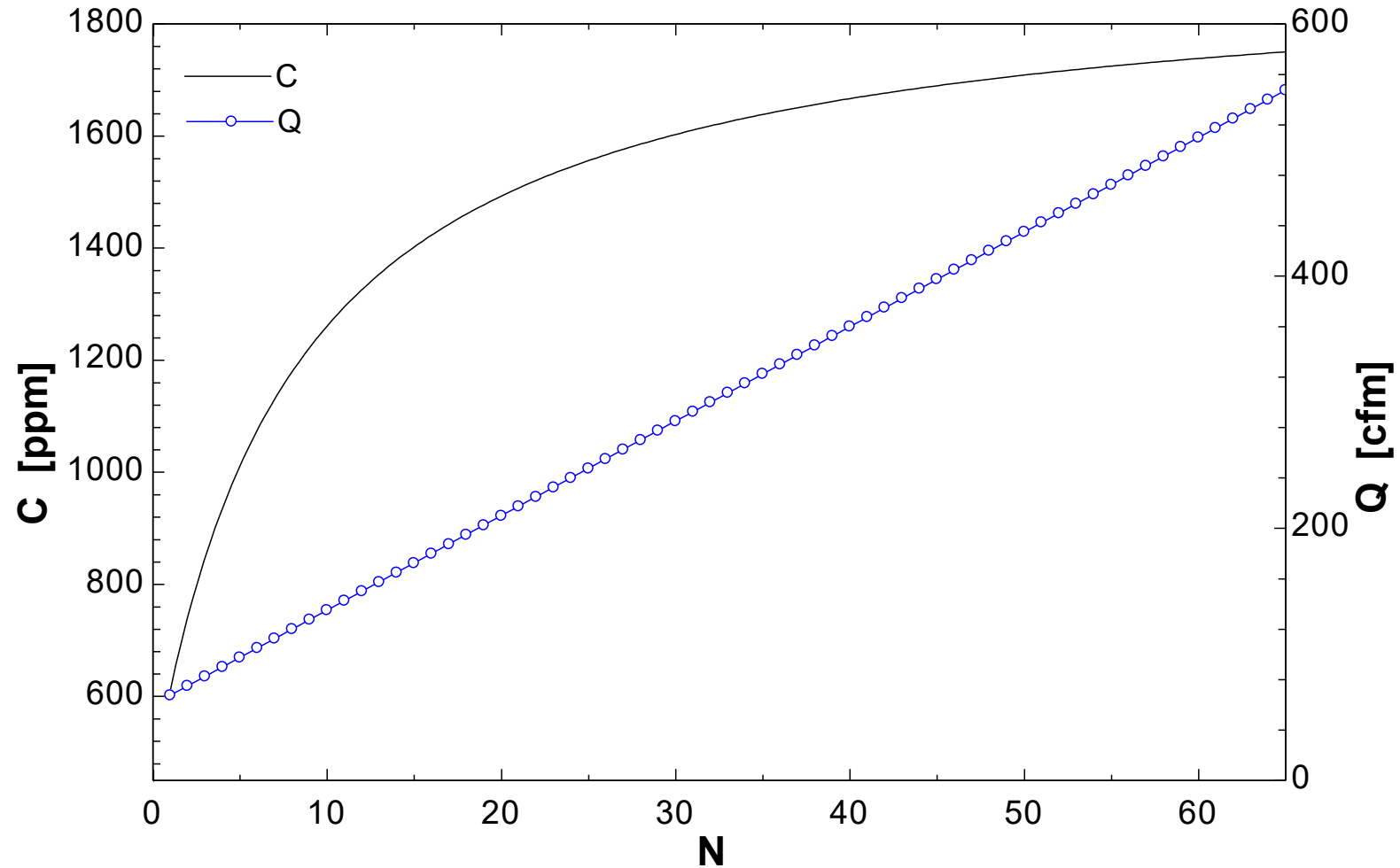
(but I still think it's a bad idea a lot of the time)

Table 6-1 Minimum Ventilation Rates in Breathing Zone (Continued)

Occupancy Category	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Default Values			<u>Maximum CO₂ above Ambient, $\Delta C_{6.1}$</u>
	cfm/person	L/s·person	cfm/ft ²	L/s·m ²	Occupant Density		Air Class	
					#/1000 ft ² or #/100 m ²	OS (6.2.6.1.4)		
Cafeteria/fast-food dining	7.5	3.8	0.18	0.9	100	2		<u>900</u>
Kitchen (cooking)	7.5	3.8	0.12	0.6	20	2		<u>NA</u>
Restaurant dining rooms	7.5	3.8	0.18	0.9	70	2		<u>1500</u>
General								
Break rooms	5	2.5	0.06	0.3	25	1	✓	<u>1500</u>
Coffee stations	5	2.5	0.06	0.3	20	1	✓	<u>1200</u>
Conference/meeting	5	2.5	0.06	0.3	50	1	✓	<u>1500</u>
Corridors	—	—	0.06	0.3	—	1	✓	<u>NA</u>
Occupiable storage rooms for liquids or gels	5	2.5	0.12	0.6	2	2		<u>NA</u>

CO₂ Concentration for Steady State 62.1 Compliance

Single-Zone, 1000 ft² Lecture Classroom, 65 Sedentary Adults, 500 ppm Ambient



At full occupancy, 8.4 cfm/pers. Minimum OA 60 cfm

Wrap-up

- Prescriptive outdoor air supply remains the dominant ventilation control for IAQ
- Objectives of ventilation standards have not changed much in the past 50 years
- There is some evidence behind some outdoor air requirements but not others
- There is great interest in improving IAQ, but more outdoor air is not the way to do it

More wrapping up...

- Promising trends
 - Standards and guidelines for extreme events
 - Equivalent clean air approach
 - Performance approach based on quantified harm or benefit/sensor technology to support it
 - Evidence that a small (manageable) number of contaminants must be controlled – and PM is #1
 - Potential for air cleaners to carry more of the burden – less OA may be fine in some cases
 - Improvements in air cleaner testing

Still wrapping up...

- Needs/concerns
 - Potential cost and complexity of performance standards
 - Some important knowledge gaps
 - Air distribution
 - Modeling of infection risk
 - Air cleaner performance and safety
 - Need to harmonize standards
 - Need for appropriate level of regulation/enforcement, including post-occupancy

Thank You!

Bill Bahnfleth
wbahnfleth@psu.edu

