



MANAGING HVAC SYSTEMS TO REDUCE INFECTIOUS DISEASE TRANSMISSION

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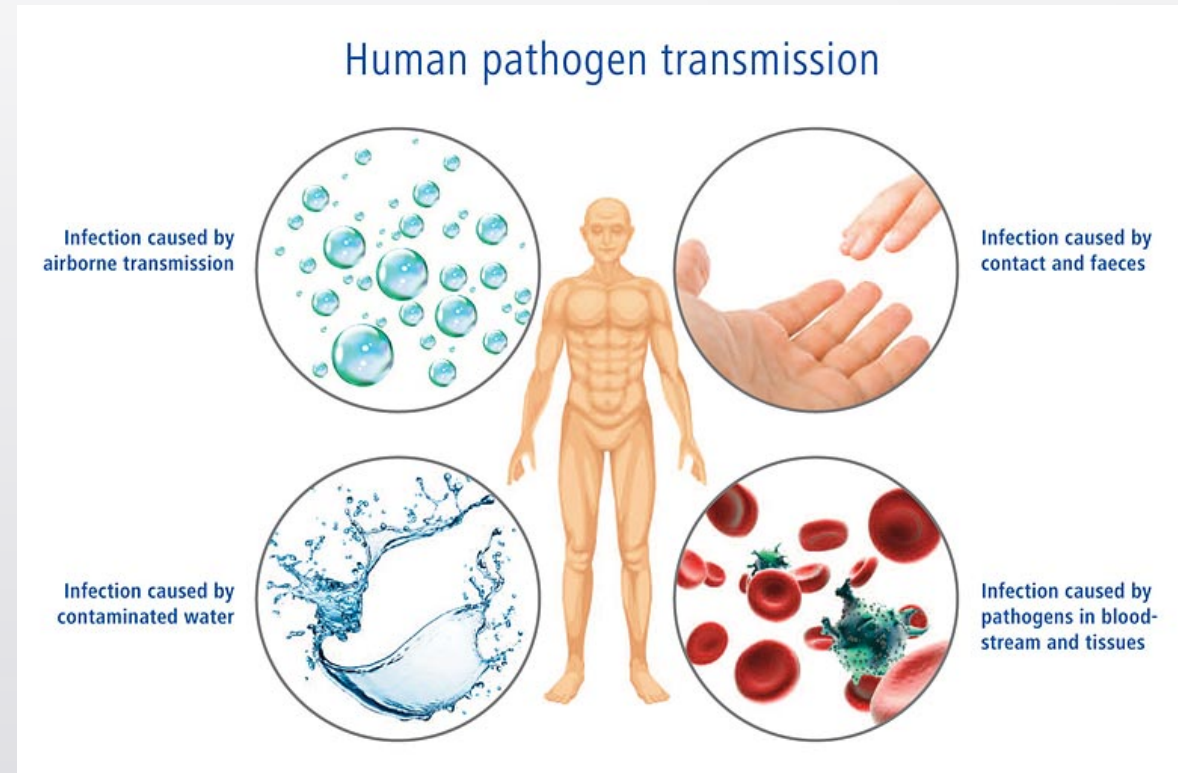
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**ARCHITECTURAL
ENGINEERING**

Infectious Disease Transmission Modes

- Airborne
 - Droplet spray
 - Aerosol
- Fomite – intermediate surface
- Physical contact
- Water/food
- Insect/animal vector

...HVAC mainly impacts aerosol and fomite transmission

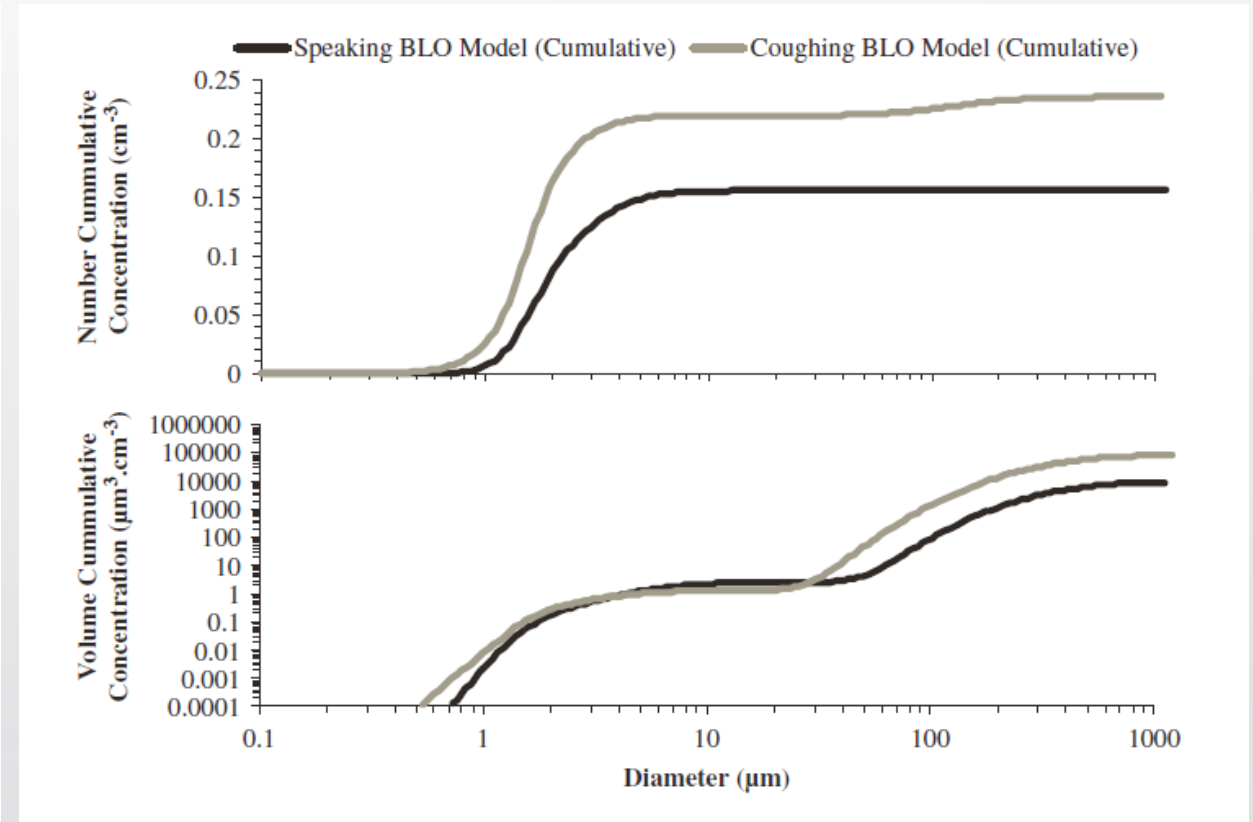
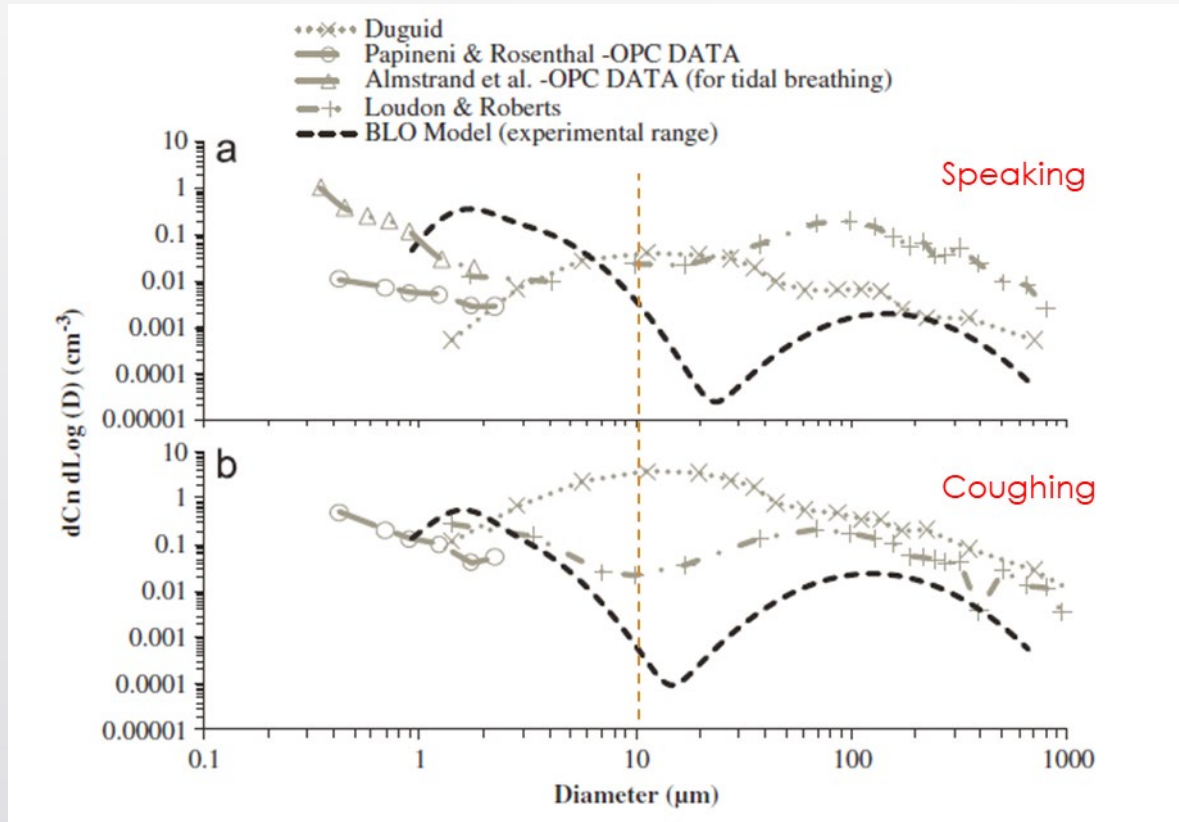


Sources of Infectious Aerosols

- Humans – breathing, talking, singing, coughing, sneezing
- Plumbing – toilet flushing, splashing in sinks
- Medical procedures – dentistry, endotracheal intubation, and others



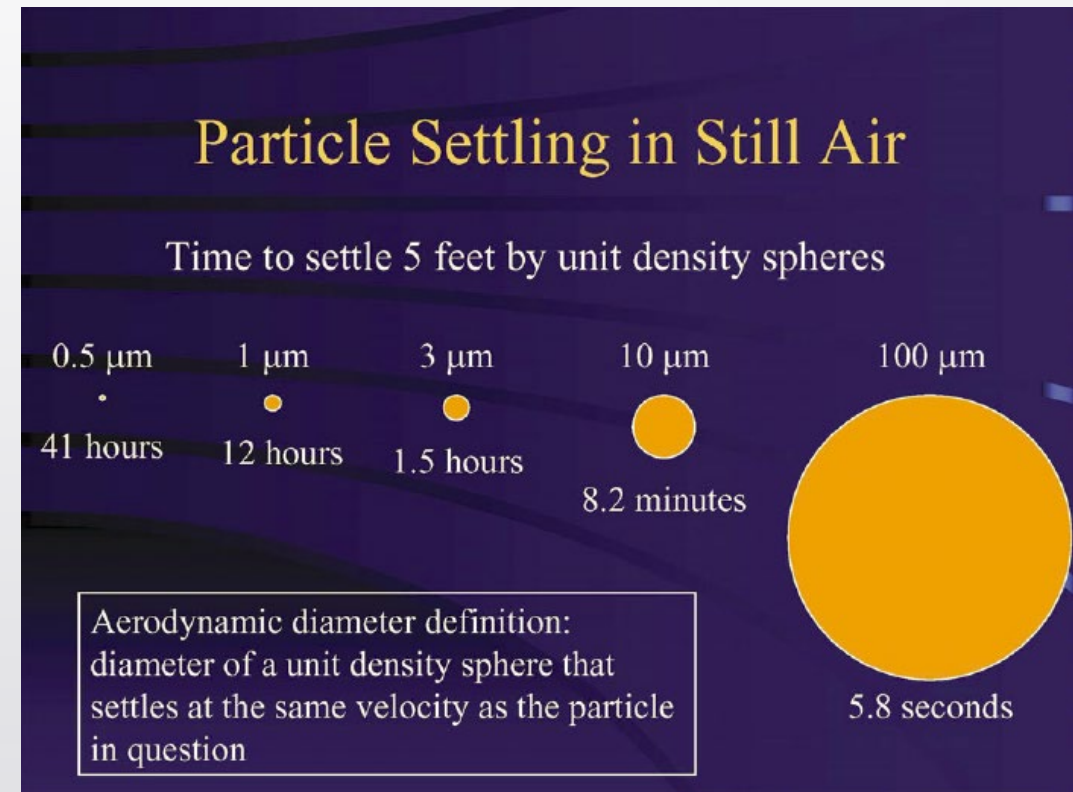
Respiratory Droplet Size and Concentration



Johnson, et al. 2011. Modality of human expired aerosol size distributions. *Journal of Aerosol Science* 42:839-851.

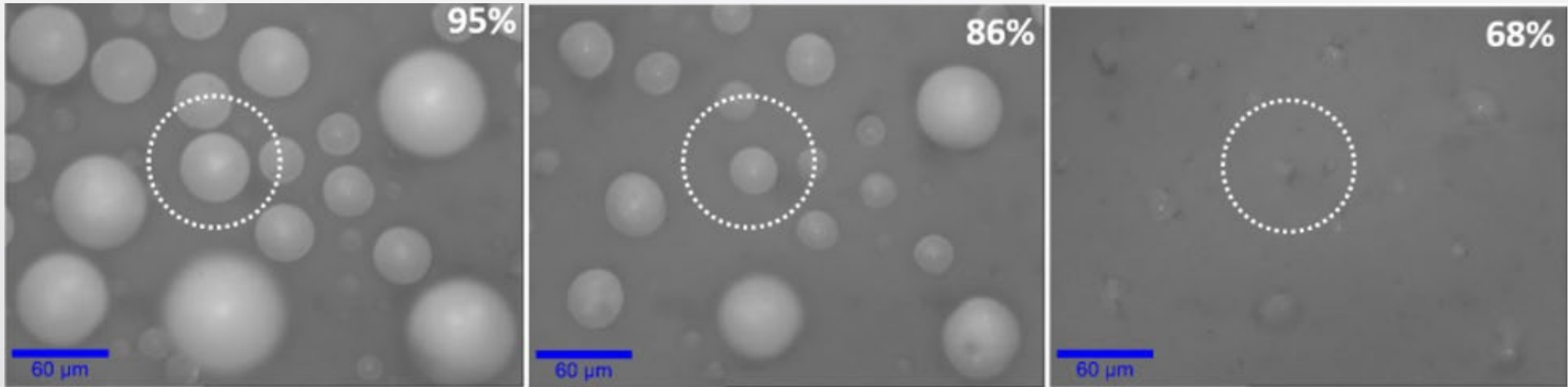
Small droplets become particles that remain in air

- Droplets contain water, proteins, salts...
- Dry to 20 – 40% of initial size
- Viruses non-uniformly distributed by size
- Studies of influenza have found ~90% of viral load in particles $< \sim 5 \mu\text{m}$
(Milton, et al. PLoS Pathog 9(3): e1003205.
doi:10.1371/journal.ppat.1003205)



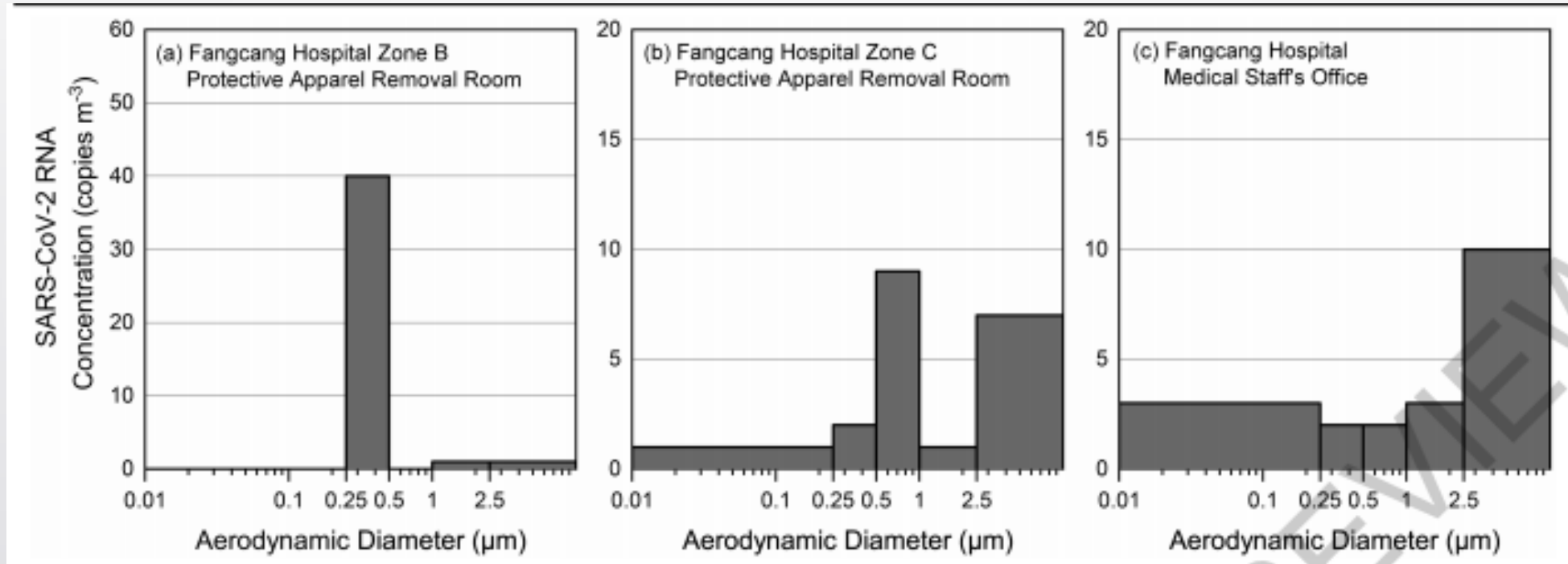
5 ft = 1.52 m

Evaporation of respiratory droplets with variable humidity



Vejerano EP, Marr LC. 2018 Physico-chemical characteristics of evaporating respiratory fluid droplets. J. R. Soc. Interface 15: 20170939.
<http://dx.doi.org/10.1098/rsif.2017.0939>

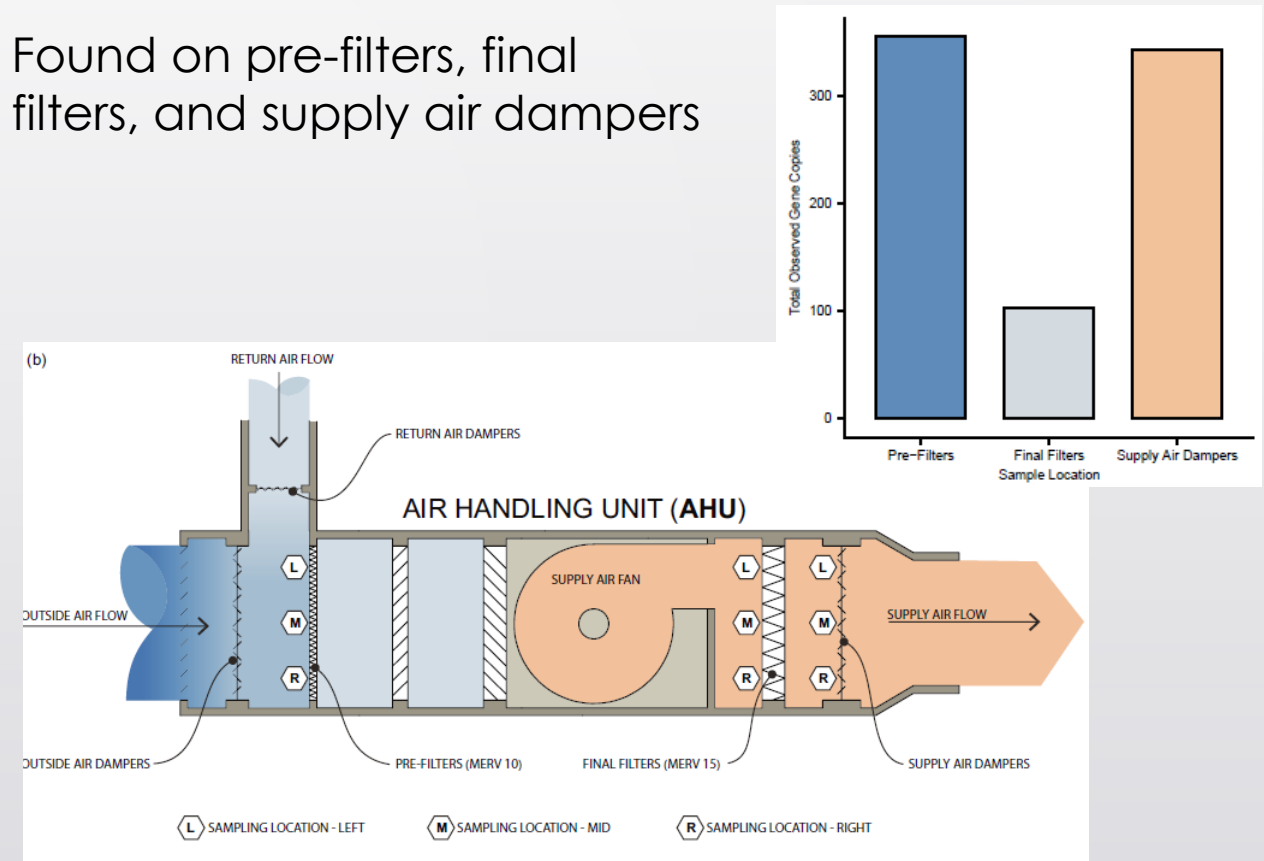
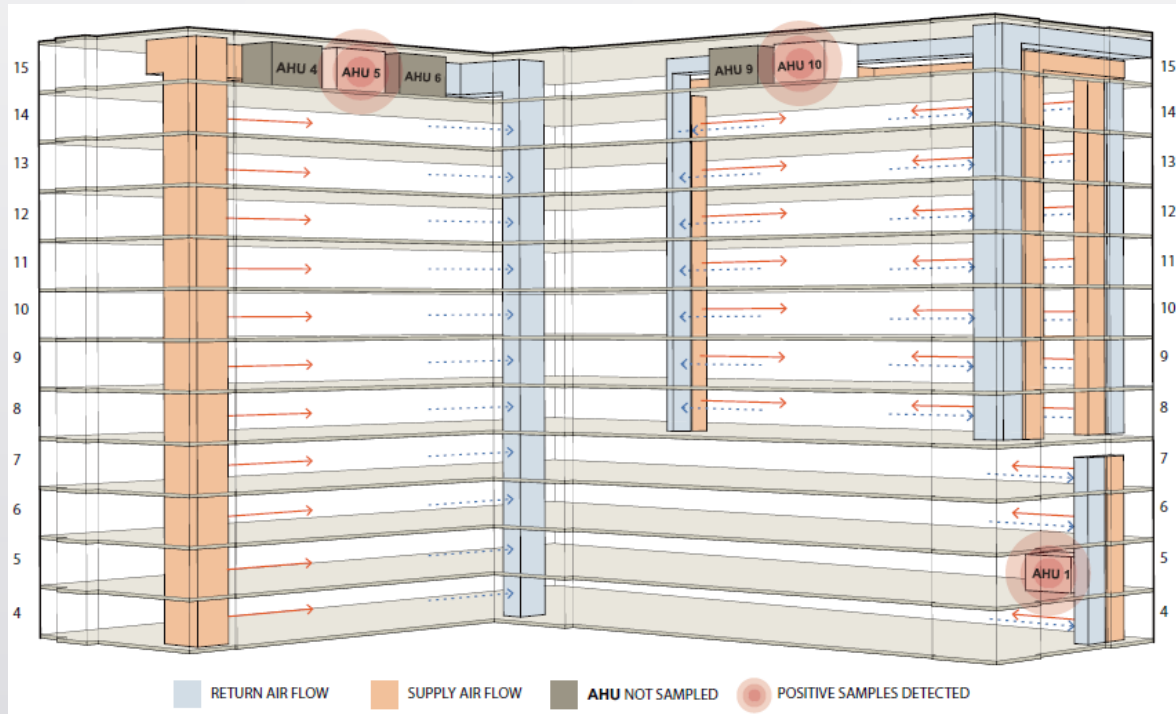
SARS-CoV-2 RNA has been found in aerosols



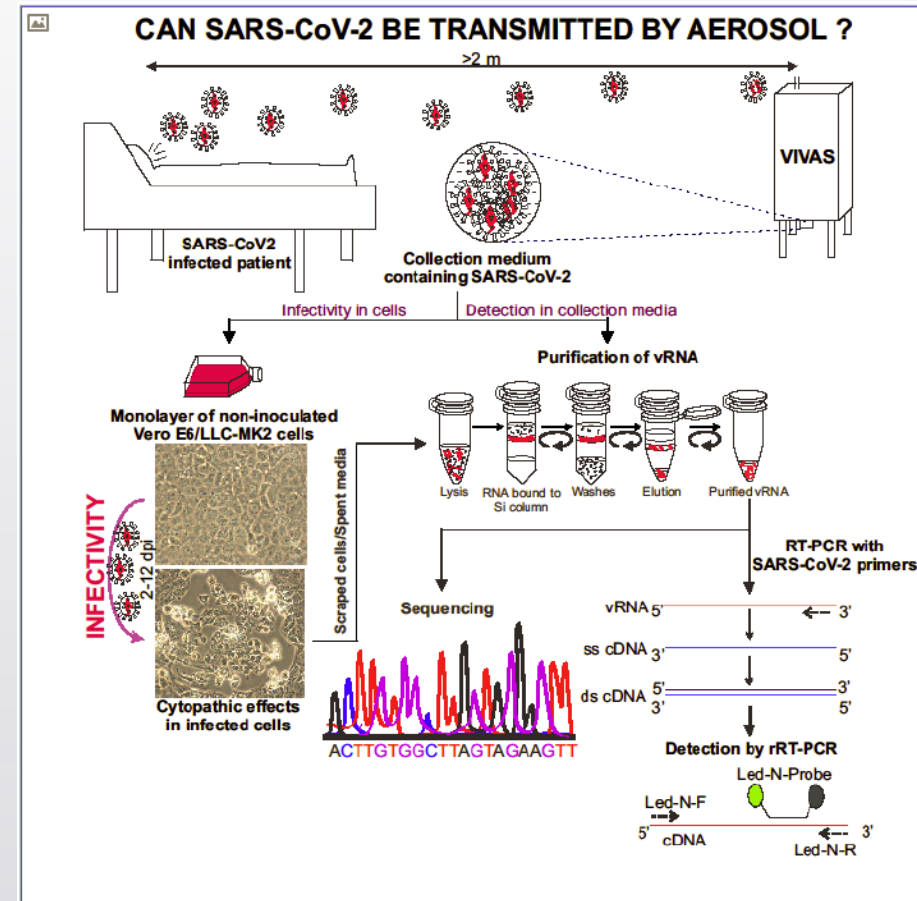
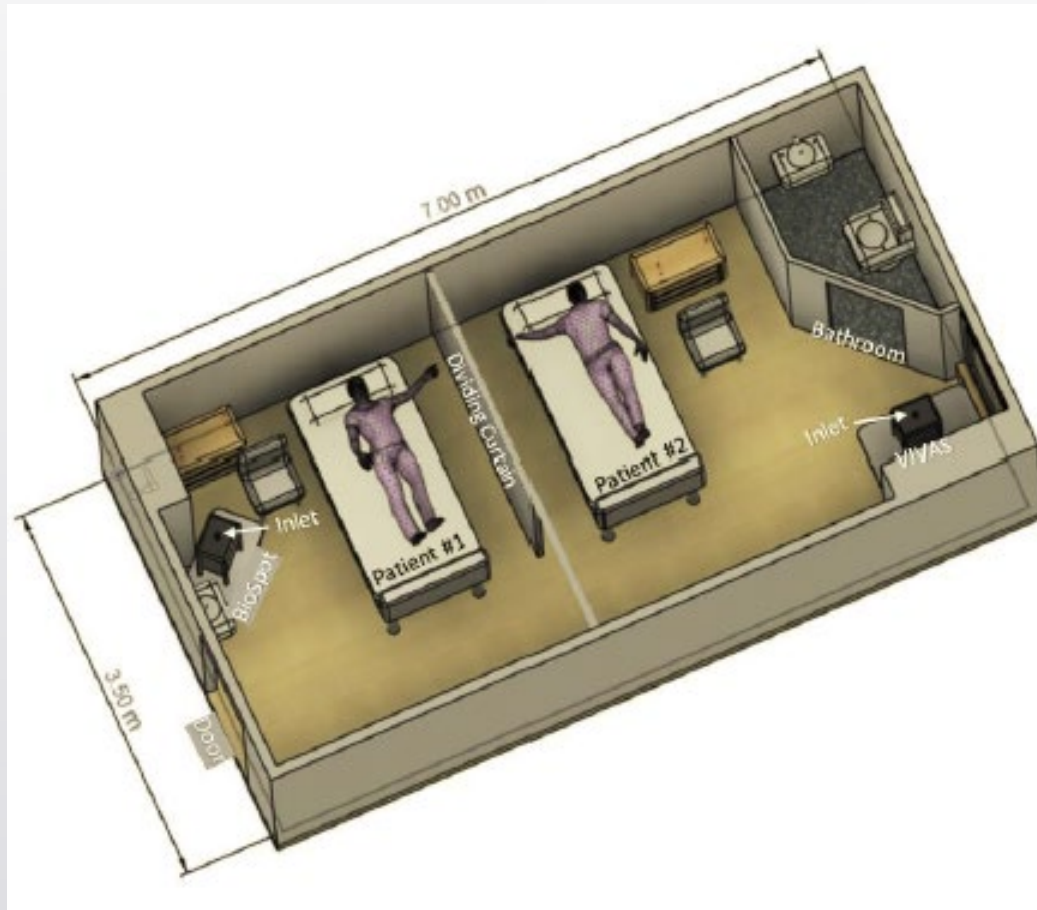
Liu, et al., Nature 40 (2020) <https://doi.org/10.1038/s41586-020-2271-3>

SARS-CoV-2 RNA has been recovered from HVAC systems

Found on pre-filters, final filters, and supply air dampers



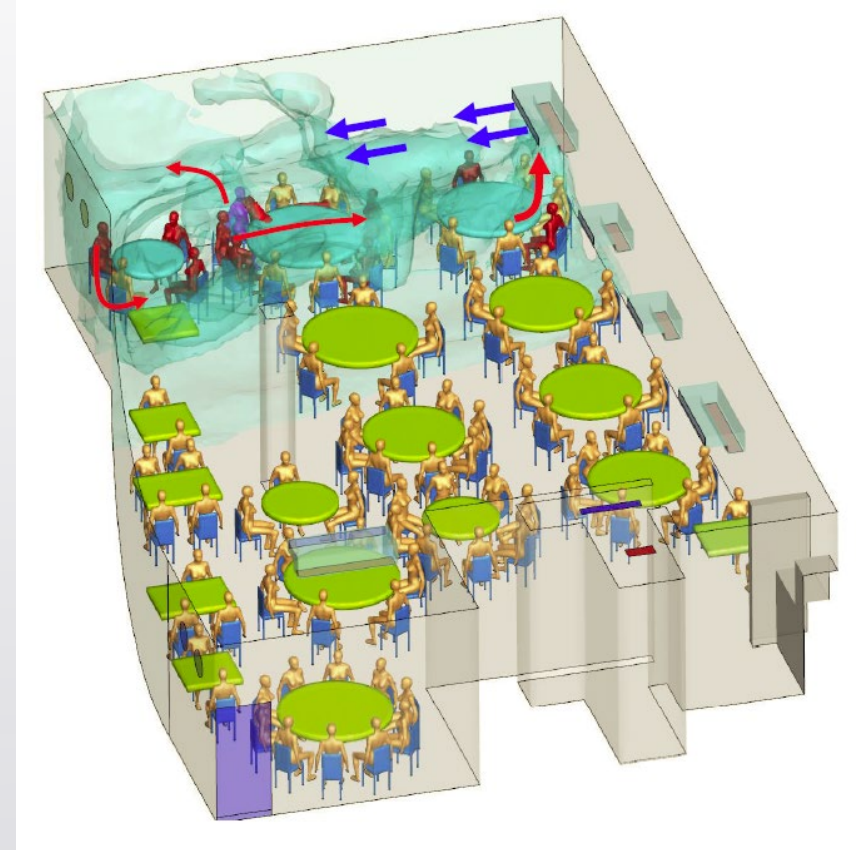
Active SARS-CoV-2 has been found in aerosols



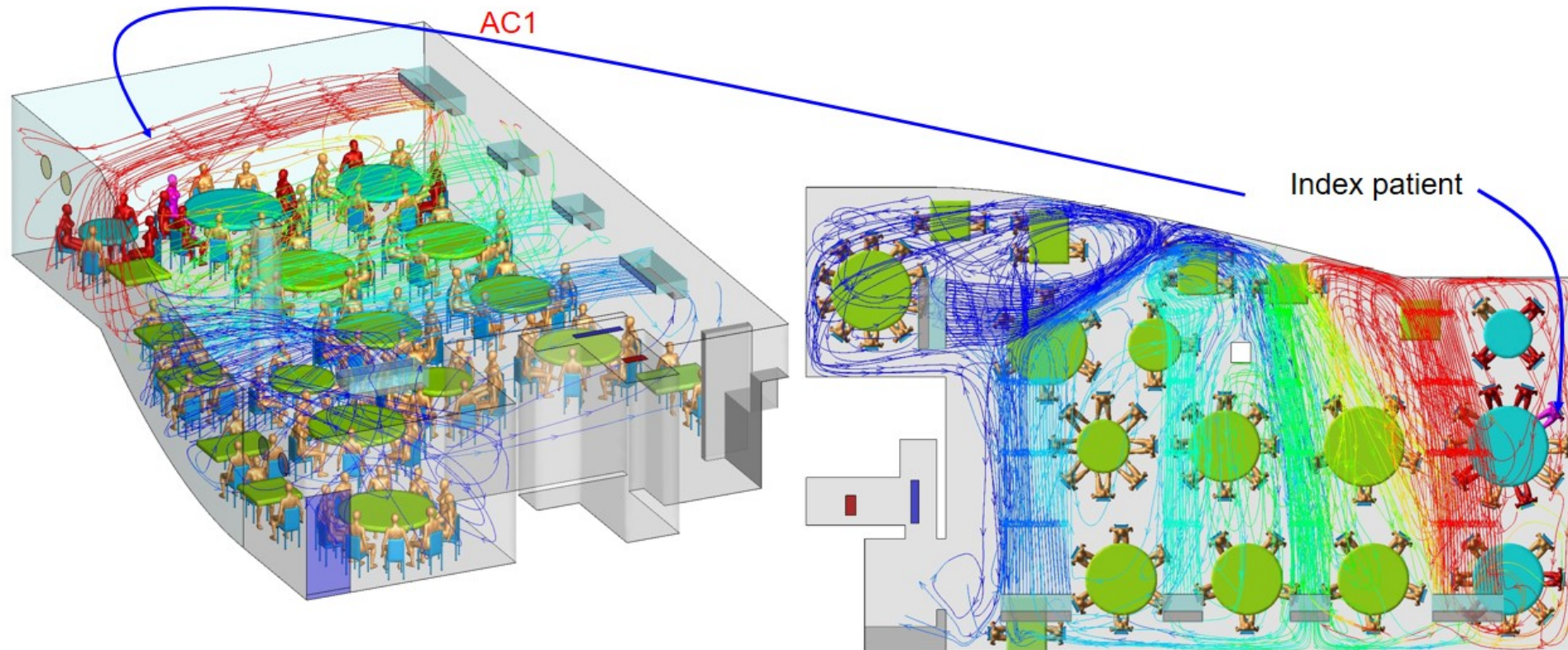
Lednicky, J., et al. 2020 Viable SARS-CoV-2 in the air of a hospital room with COVID-19 Patients. Int. J. of Infectious Diseases. doi.org/10.1016/j.ijid.2020.09.025

Community Spread Incidents Suggest In-Space Airborne Spread

- Guangzhou restaurant
 - Split system air-conditioning – strong in-space recirculation
 - No ventilation air supply
 - Four exhaust fans, none running
 - No close contact observed on video
 - Measured ventilation rate $\sim 0.75 - 1$ L/s per patron
 - *Conclusions:* “aerosol transmission of SARS-CoV-2 due to poor ventilation may explain the community spread of COVID-19. “



The streamlines showed how the ABC recirculation bubble was possibly established.

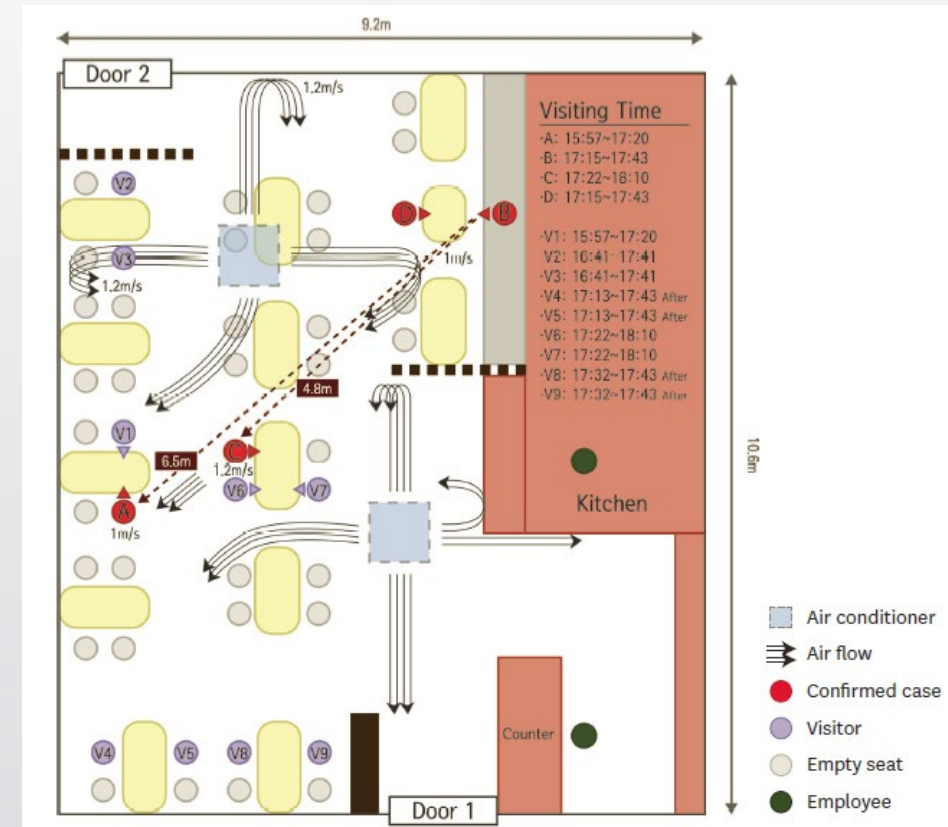


View from top of the restaurant 3F

AC1

Long-distance droplet transmission suggested by Korean restaurant incident

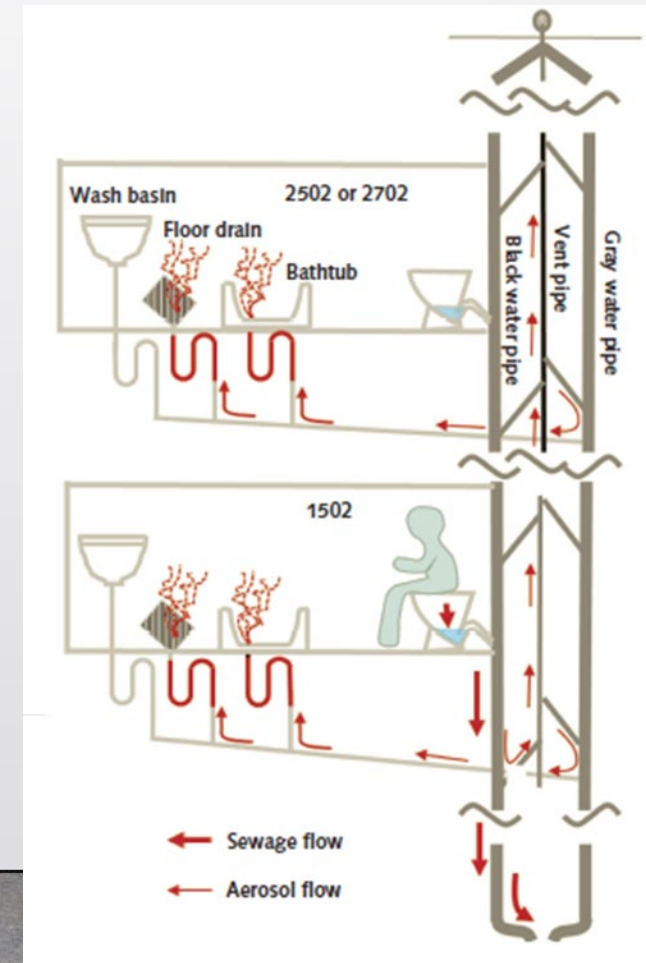
- Infector (B) was only in restaurant for five minutes with infected person (A) and 20 minutes with infected person (C)
- Infections occurred along airflow path created by HVAC with horizontal velocity up to 1.2 m/s
- No close contact observed



Fecal aerosol transmission believed to occur in apartment building

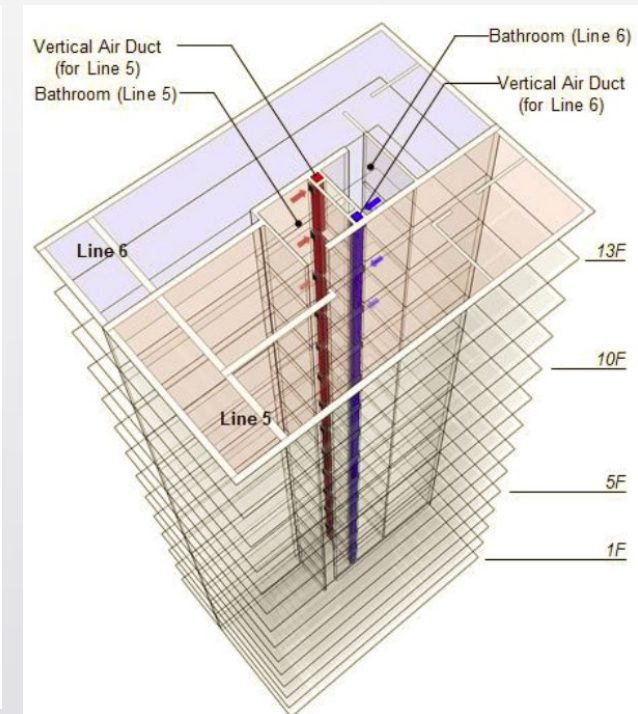
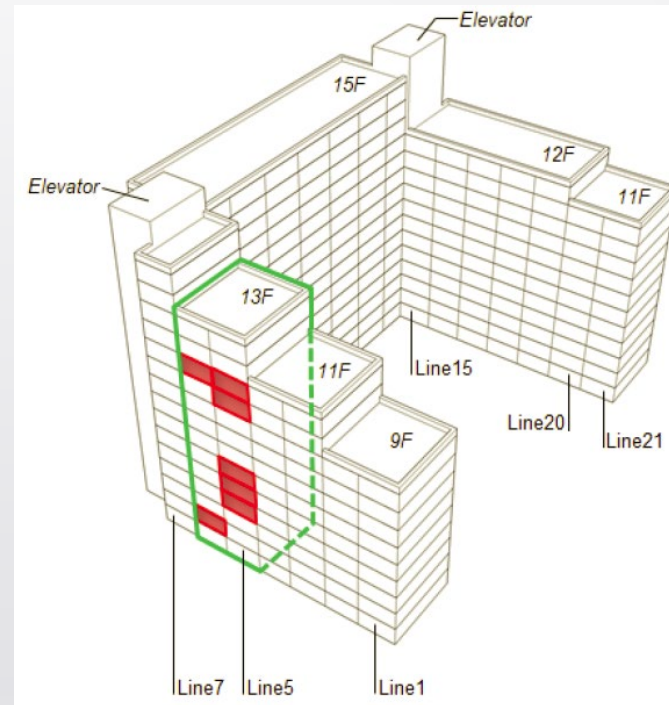
- SARS-CoV-2 has been cultured from feces
- 9 infections in three families
- Apartments vertically aligned and connected to same plumbing stack
- No evidence (sampling) of transmission via elevator or other routes
- Similar to Amoy Garden SARS outbreak

Kang, M., et. al. 2020 Probable evidence of faecal aerosol transmission of SARS-CoV-2 in a High-Rise Building. *Ann Intern Med*. doi:10.7326/M20-0928



Airborne transmission through bathroom ventilation shaft suspected in apartment building

- Apartment building in Seoul, S. Korea
- 10 cases, along two bathroom natural ventilation shafts
- No backdraft damper
- No close contact identified
- Similar to Amoy Gardens SARS outbreak



Hwang, S.E., Chang, J.H., Bumjo, O. and Heo, J., 2020. Possible Aerosol Transmission of COVID-19 Associated with an Outbreak in an Apartment in Seoul, South Korea, 2020. *International Journal of Infectious Diseases*.



Summary – HVAC-related transmission

- Active SARS-CoV-2 has been found in indoor air
- Viral aerosols are captured by return air and can pass through air handling units
- Airborne infection can occur in poorly ventilated spaces
- Strong air currents can cause extended “close-range” transmission
- There is no clear evidence of transmission of COVID-19 from one space to another through HVAC

US CDC and WHO recognize possible indoor airborne transmission of Covid-19

(10/5/2020)

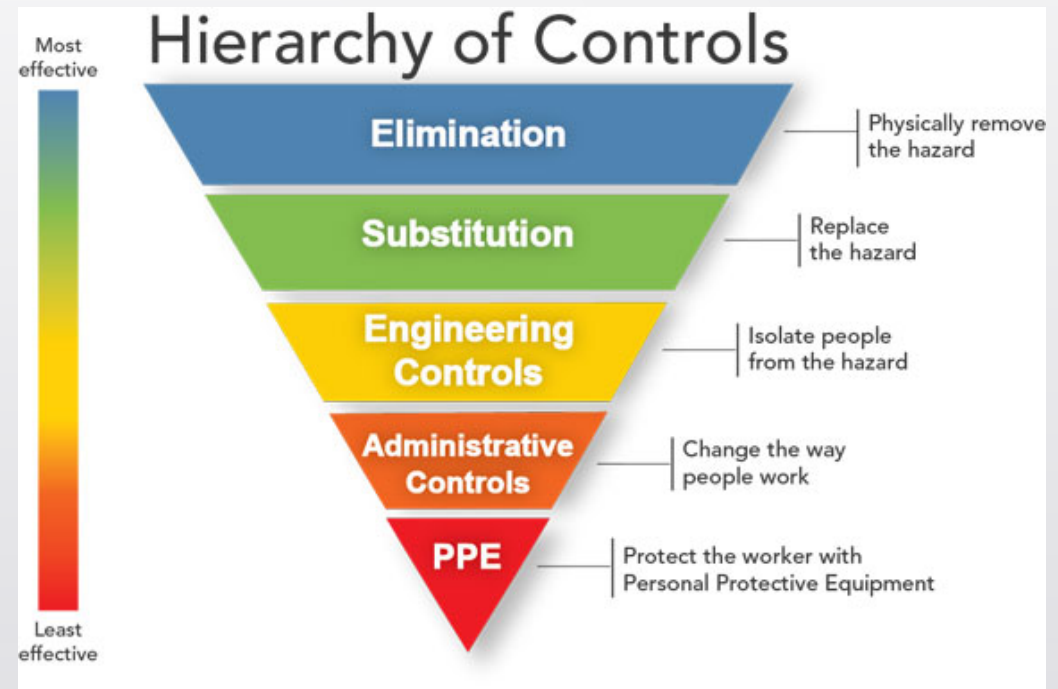
- COVID-19 most commonly spreads during close contact
([cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html](https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html))
- COVID-19 spreads less commonly through contact with contaminated surfaces
([cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html](https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html))
- Airborne transmission of SARS-CoV-2 can occur under special circumstances
([cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html](https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html))
 - Enclosed spaces
 - Prolonged exposure to respiratory particles
 - Inadequate ventilation and air-handling



“Ventilation represents a very important aspect, a very important factor to prevent the virus from spreading indoors.”

Risk Management – HVAC is one layer of an effective mitigation strategy

- Source elimination
 - Testing, contact tracing
- Substitution – NA
- **Engineering controls**
 - **HVAC interventions to control aerosols**
- Administrative controls
 - Rules and procedures
- Personal protective equipment
 - N95 mask – mainly protects wearer
 - Surgical/cloth masks mainly protect others



Quantifying airborne risk – the Wells-Riley model

$$P = 1 - \exp\left(-\frac{Iqpt}{Q}\right)$$

- Steady-state conditions
- Time-dependent risk
- Quanta determined from data
- P = probability of new infections
- I = number of infectors
- q = quanta (infectious dose)
emission rate per infector [1/hr]
- p = pulmonary ventilation rate per
susceptible [m^3/h]
- t = exposure time [hr]
- Q = flow rate of uncontaminated air [m^3/h]

Equivalent clean (outdoor) air flow for other removal factors can be included in Wells-Riley

$$P = 1 - \exp\left[-\frac{ipqt}{Q}\right] = 1 - \exp\left[-\frac{ipqt}{\cancel{V}} / \alpha_{OA}\right] \quad \text{Can express } Q \text{ in air changes, } \alpha_{OA} \text{ if desired}$$

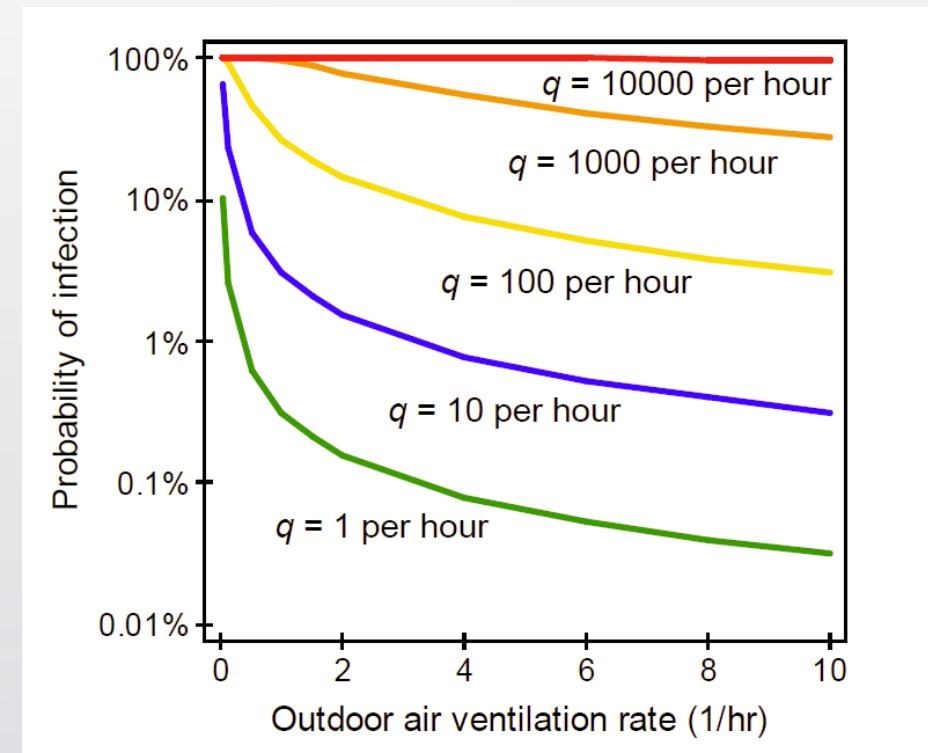
For an air cleaner with CADR = Q_{AC} , $\alpha_{AC} = \frac{Q_{AC}}{\cancel{V}}$

Equivalent ACH = $\alpha_{OA} + \alpha_{AC}$, so $P = 1 - \exp\left[-\frac{ipqt}{\cancel{V}} / (\alpha_v + \alpha_{AC})\right]$

- Can include outdoor air, mechanical filtration, air cleaners, deposition, natural decay if quantifiable
- Applies contaminant by contaminant
- Placement of filter or air cleaner in system matters

Exposure time and air flow are the main independent parameters

- Risk of infection for an average adult susceptible ($p = 0.48 \text{ m}^3/\text{h}$) in a 500 m^2 office for 8 hours with one infected person



Quanta emission rates have been estimated for SARS-CoV-2...but not very accurately

		Resting, oral breathing	Heavy activity, oral breathing	Light activity, speaking	Light activity, singing (or speaking loudly)
ER_q	5th percentile	2.4×10^{-2}	1.6×10^{-1}	3.2×10^{-1}	2.1×10^0
	25th percentile	1.2×10^{-1}	8.2×10^{-1}	1.6×10^0	1.0×10^1
	50th percentile	3.7×10^{-1}	2.5×10^0	5.0×10^0	3.2×10^1
	75th percentile	1.1×10^0	7.7×10^0	1.5×10^1	9.8×10^1
	90th percentile	3.1×10^0	2.1×10^1	4.2×10^1	2.7×10^2
	95th percentile	5.7×10^0	3.8×10^1	7.6×10^1	4.9×10^2
	99th percentile	1.7×10^1	1.2×10^2	2.4×10^2	1.5×10^3

Environment International 145 (2020) 106112

Contents lists available at ScienceDirect

Environment International

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

Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications

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ARTICLE INFO

Handling Editor: Dr. Xavier Querol

Keywords:
 SARS-CoV-2 (COVID-19) assessment
 Virus airborne transmission
 Indoor
 Ventilation
 Coronavirus

ABSTRACT

Airborne transmission is a recognized pathway of contagion; however, it is rarely quantitatively evaluated. The numerous outbreaks that have occurred during the SARS-CoV-2 pandemic are putting a demand on researchers to develop approaches capable of both predicting contagion in closed environments (predictive assessment) and analyzing previous infections (retrospective assessment).

This study presents a novel approach for quantitative assessment of the individual infection risk of susceptible subjects exposed in indoor microenvironments in the presence of an asymptomatic infected SARS-CoV-2 subject. The application of a Monte Carlo method allowed the risk for an exposed healthy subject to be evaluated or, starting from an acceptable risk, the maximum exposure time. We applied the proposed approach to four distinct scenarios for a prospective assessment, highlighting that, in order to guarantee an acceptable risk of 10^{-3} for exposed subjects in naturally ventilated indoor environments, the exposure time could be well below one hour. Such maximum exposure time clearly depends on the viral load emission of the infected subject and on the exposure conditions; thus, longer exposure times were estimated for mechanically ventilated indoor environments and lower viral load emissions. The proposed approach was used for retrospective assessment of documented outbreaks in a restaurant in Guangzhou (China) and at a choir rehearsal in Mount Vernon (USA), showing that, in both cases, the high attack rate values can be justified only assuming the airborne transmission as the main route of contagion. Moreover, we show that such outbreaks are not caused by the rare presence of a superspreader, but can be likely explained by the co-existence of conditions, including emission and exposure parameters, leading to a highly probable event, which can be defined as a "superspreading event".

Engineering Controls

- Ventilation
- Air distribution
- Filtration
- Disinfection
- Temperature and humidity control

Ventilation with Outdoor Air

- Dilutes contaminants, increases exposure time required for exposure to an infectious dose
- Effective, but energy intensive, even with energy recovery
- Minimum required (e.g., ASHRAE 62.1) is a good baseline
- 7-10 L/s-pers $\approx$ 15-20 cfm/pers

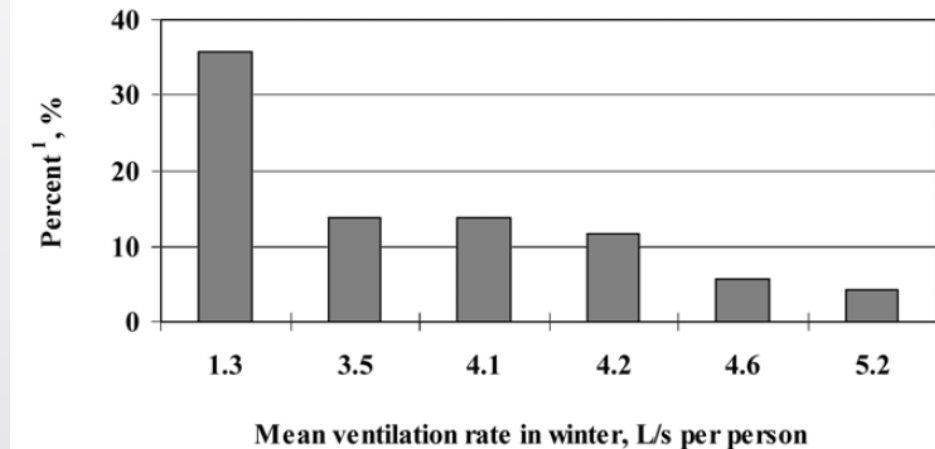


Figure 4. Associations between common cold infection rates and mean ventilation rate in winter in buildings constructed after year 1993. ¹ Proportion of occupants with ≥ 6 common colds in the previous 12 months.

Sun, et al. (2011)

<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3217956/>

How much ventilation is enough?

- Difficult to say for Covid-19 due to limited knowledge of shedding rate and infectious dose
- Superspreading incidents seem to be associated with lower than minimum standard ventilation rates
- *At least up to minimum standard seems like a good starting place*
- *~ 7L/s-pers, 15 cfm/pers*

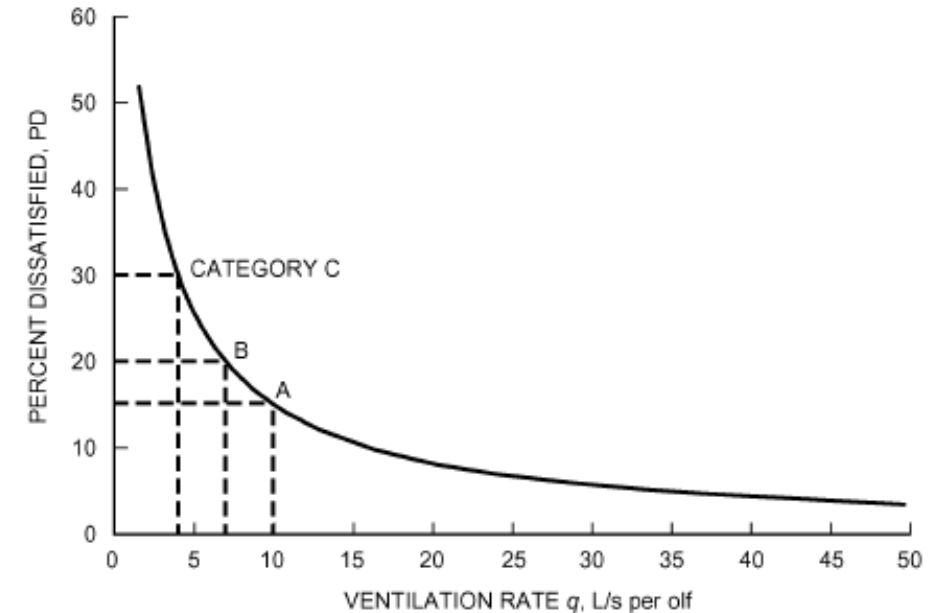
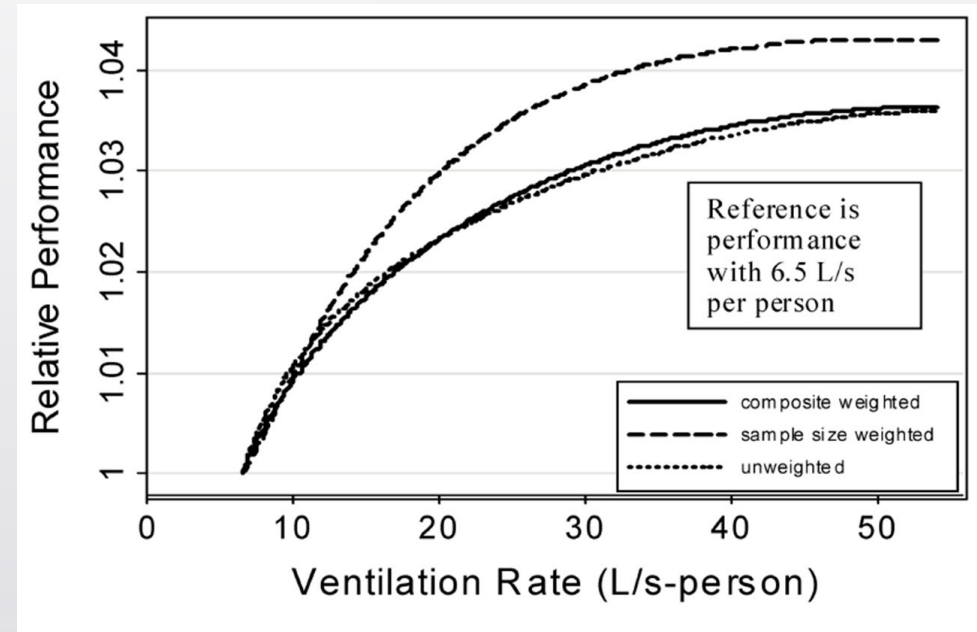
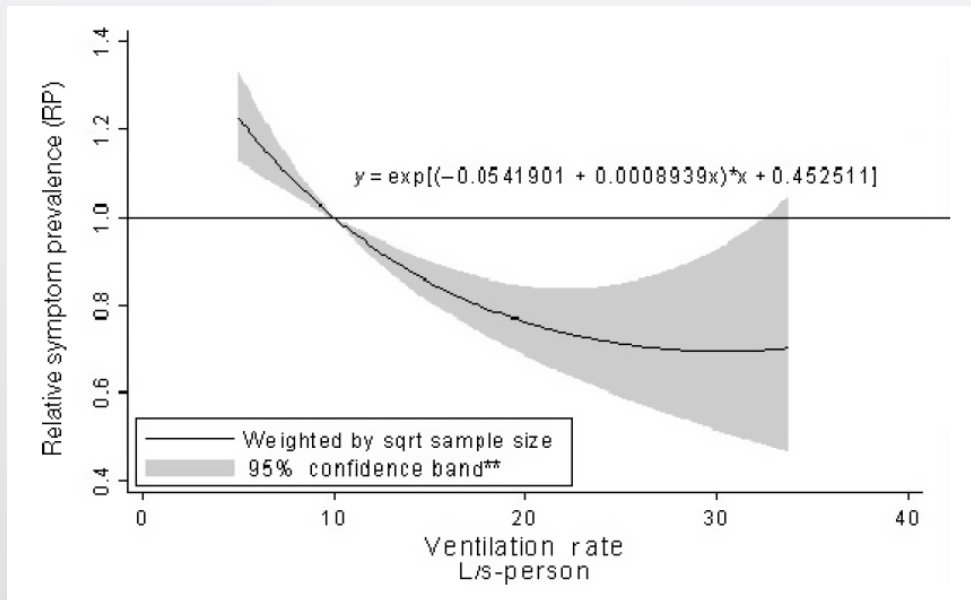


Fig. 5 Percentage of Dissatisfied Persons as a Function of Ventilation Rate per Standard Person (i.e., per Olf)
(CEN 1998)

Many studies point to health and productivity benefits at 2 – 3X current minimums

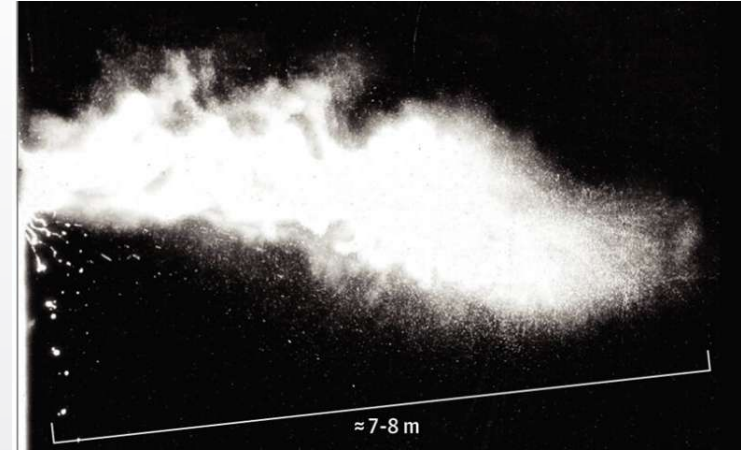


W. Fisk, A Mirer, M. Mendell. 2009. Quantitative relationship of sick building syndrome symptoms with ventilation rates. Indoor Air

Seppänen, O. and W. Fisk. 2006. Some Quantitative Relations between Indoor Environmental Quality and Work Performance or Health. HVAC&R Research.

Air Distribution

- Strong drafts may extend distance travelled by large droplets
- Lower velocity mixing may be preferable to displacement



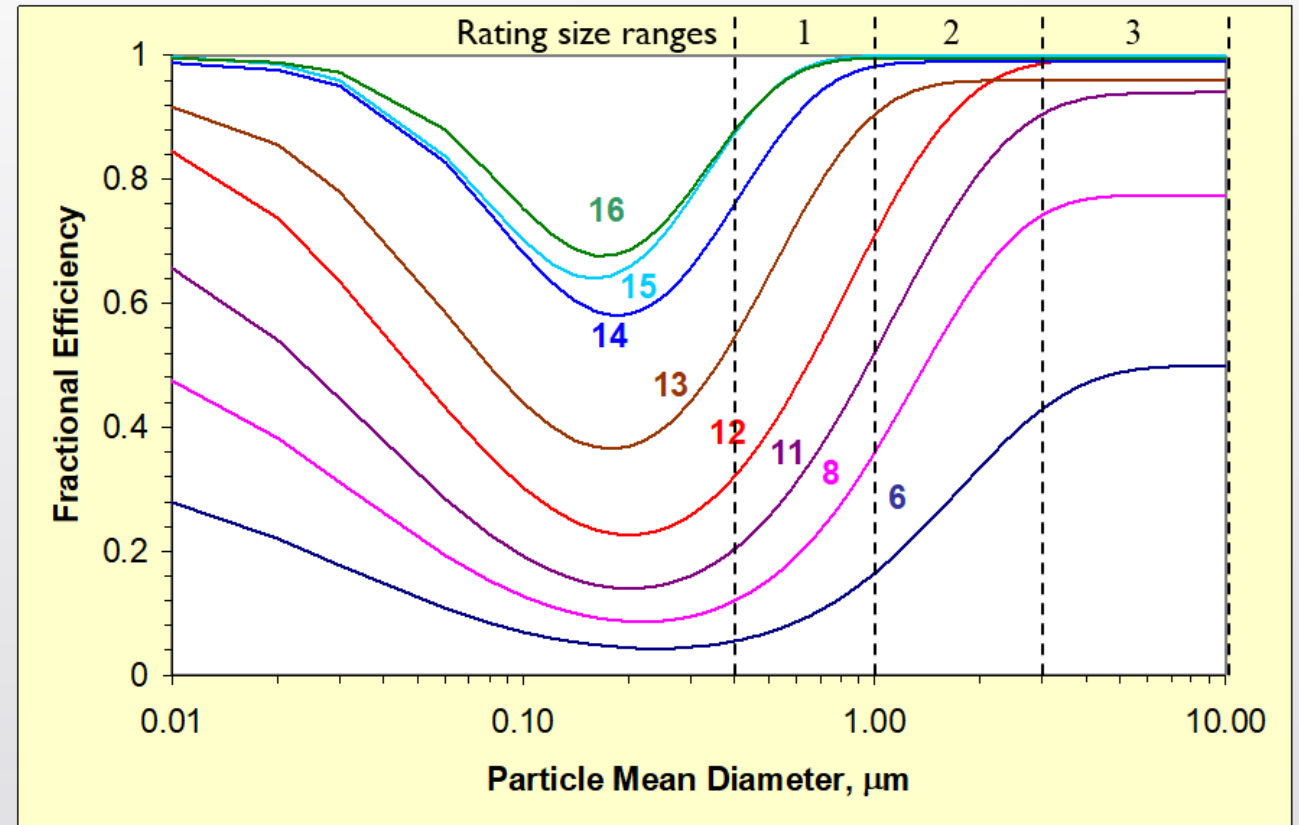
Bourouiba, L. JAMA. 2020;323(18):1837-1838.



Li, Y., P. Nielsen, M. Sandberg. 2011. ASHRAE J. 53(6): 86-88

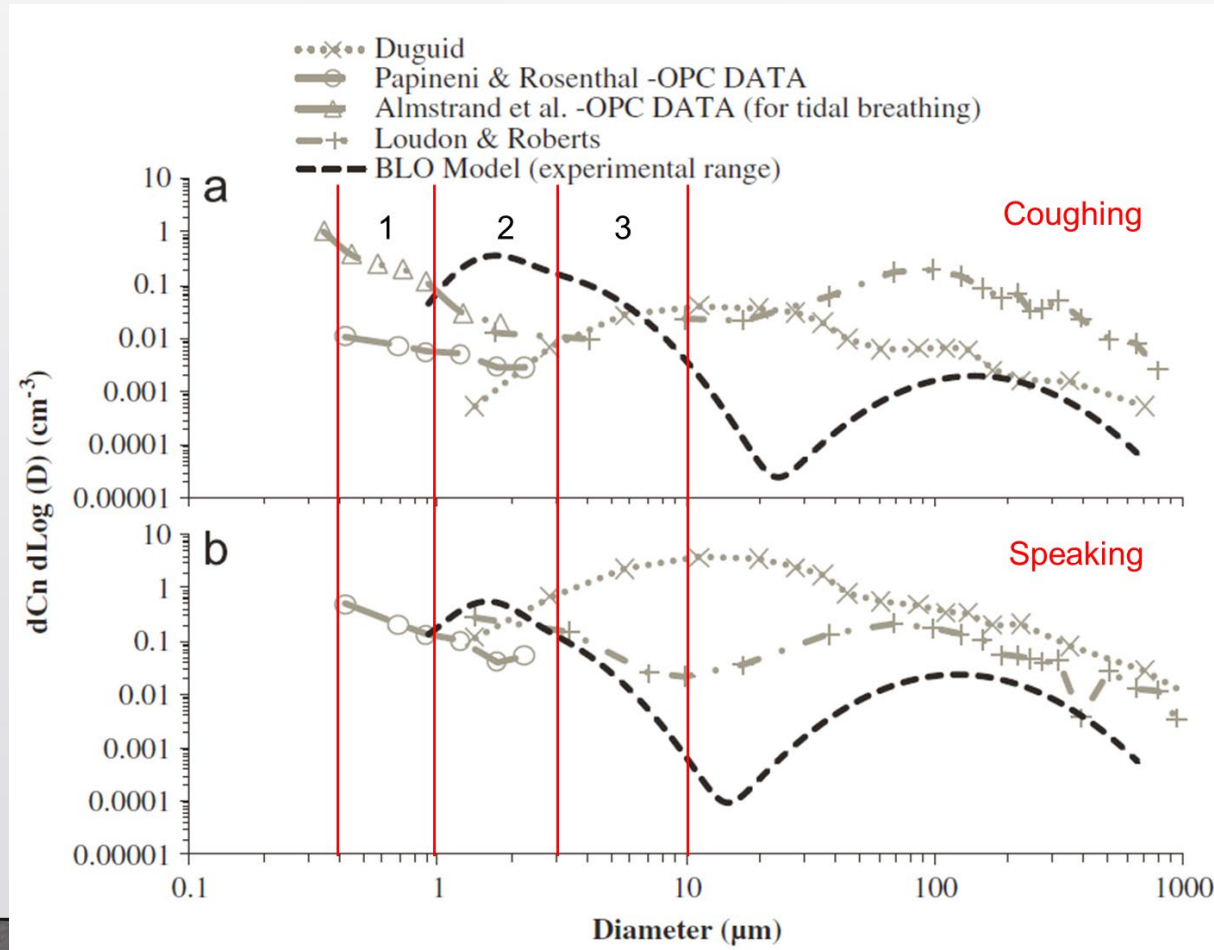
Filtration

- High efficiency filters can remove respiratory aerosols efficiently
- For indoor sources, must have recirculation in space or through central system
- Effective if clean air delivery rate (efficiency $\times$ flow rate) is high enough



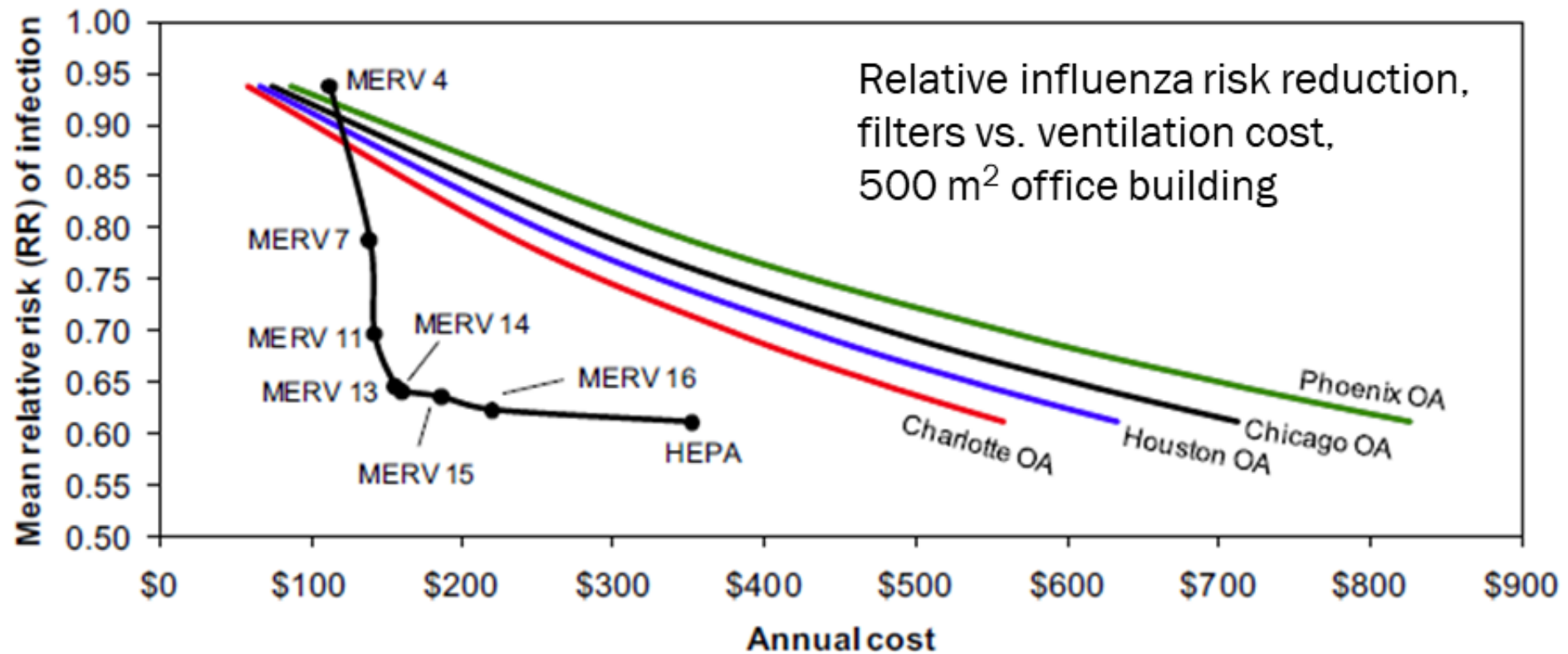
Kowalski, W.J. and Bahnfleth, W.P., 2002. MERV filter models for aerobiological applications. Air Media, Summer, 1.

Respiratory droplets that carry infectious disease pathogens are not captured by minimum standard (MERV 6, 8) filters – use MERV 13



	MERV 6	MERV 8	MERV 13
1 (0.3-1 μm)	N/A	N/A	≥ 50%
2 (1-3 μm)	N/A	≥ 20%	≥ 85%
3 (3-10 μm)	≥ 35%	≥ 70%	≥ 90%

Filtration can be a lower energy way to reduce aerosol/airborne infection risk



Particles that can penetrate the alveolar region of the lungs are not captured by minimum standard filters

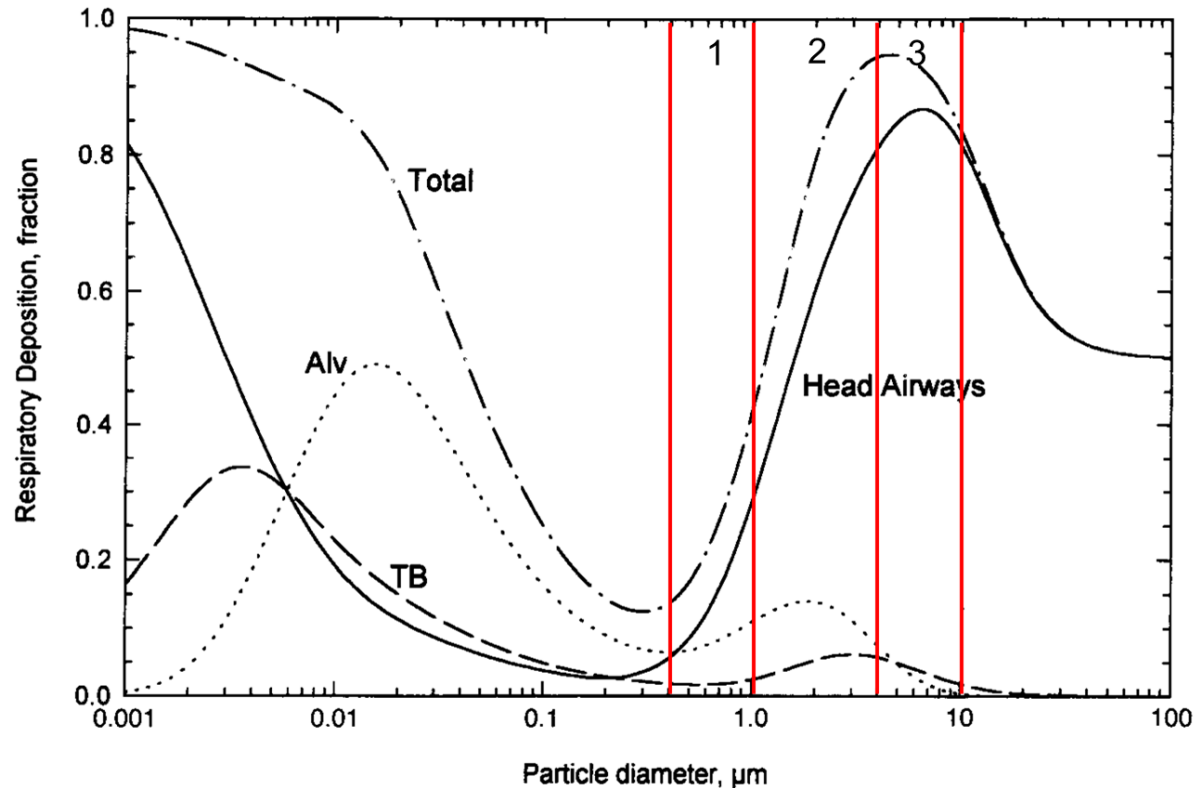
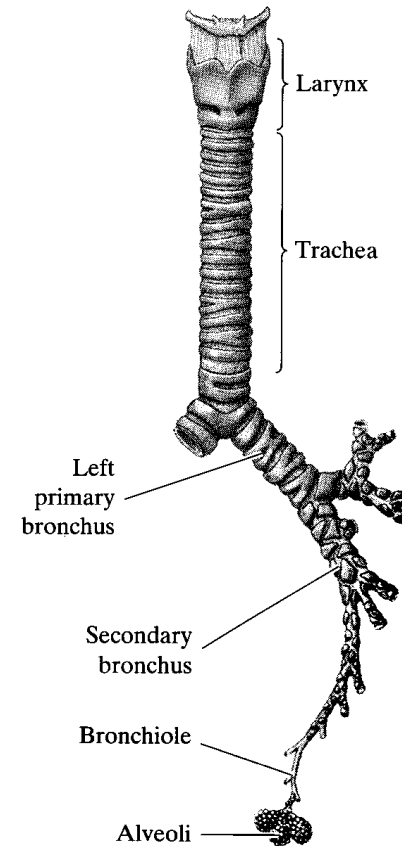
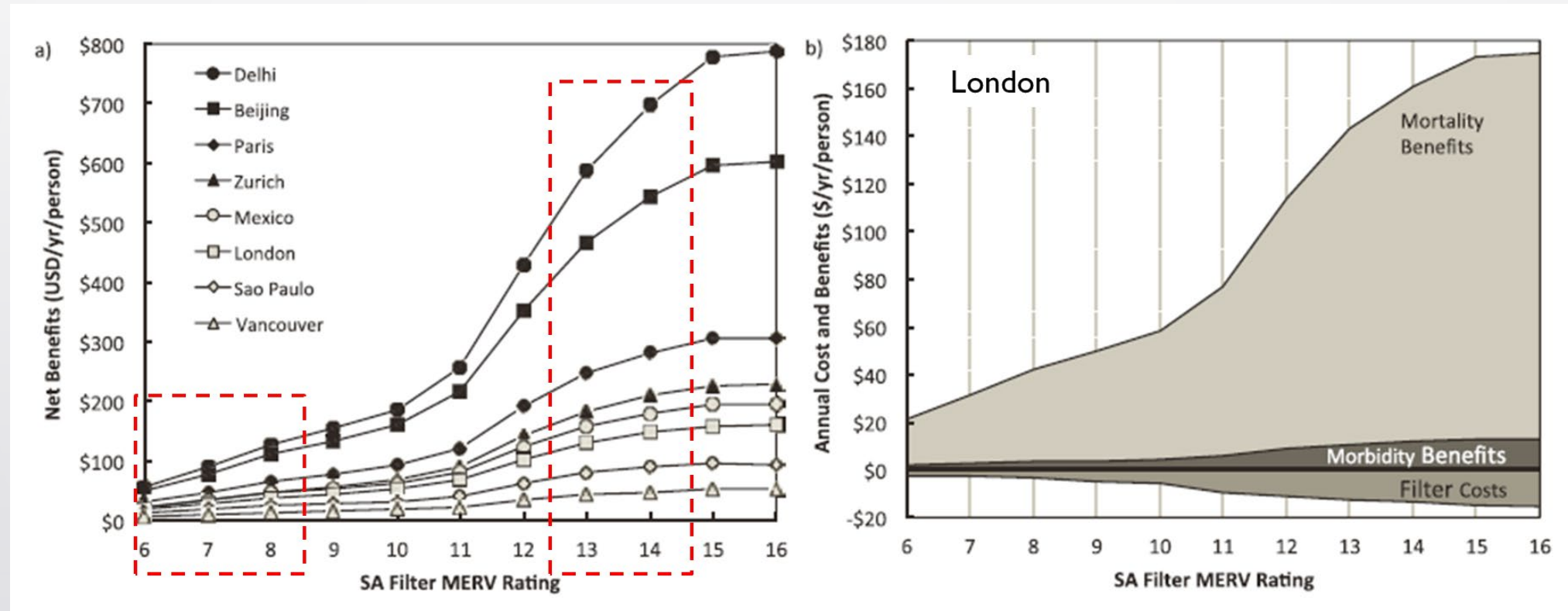


FIGURE 11.3 Predicted total and regional deposition for light exercise (nose breathing) based on ICRP deposition model. Average data for males and females.



Range	MERV 6	MERV 8
1	N/A	N/A
2	N/A	$\geq 20\%$
3	$\geq 35\%$	$\geq 70\%$

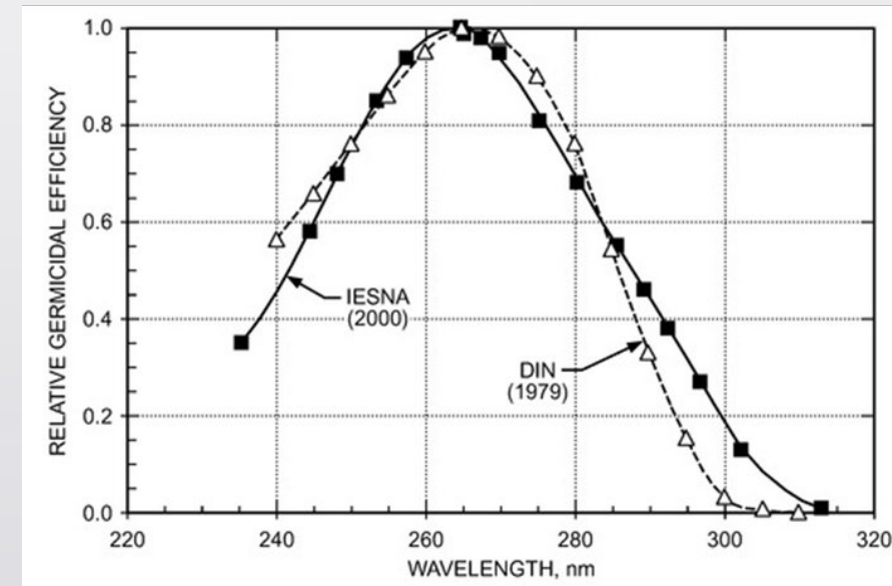
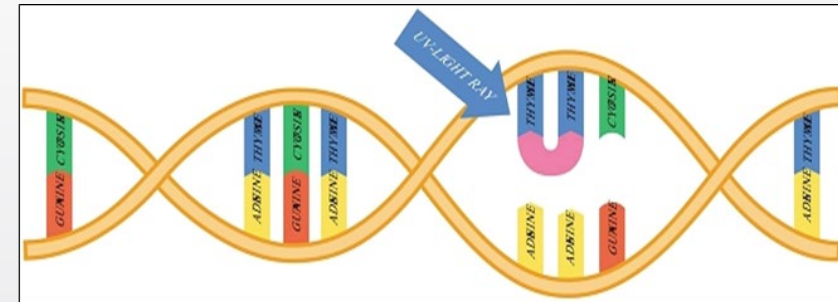
Filtration has benefits other than infection control



(Montgomery, J., C. Reynolds, S. Rogak, S. Green. 2015. Financial Implications of Modifications to Building Filtration Systems. Building and Environment 85:17-28.)

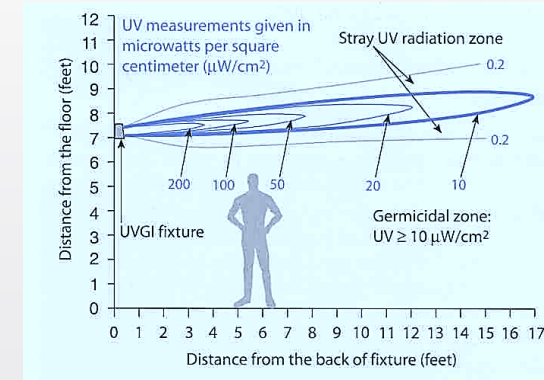
Air disinfection – germicidal UV light

- Ultraviolet light in UVC band
- 265 nm ideal, 254 nm produced by low pressure Hg vapor lamps is standard
- Disrupts microbial DNA/RNA, prevents reproduction
- Exponential dose response
- Coronavirus susceptibility is good



Germicidal UV applications

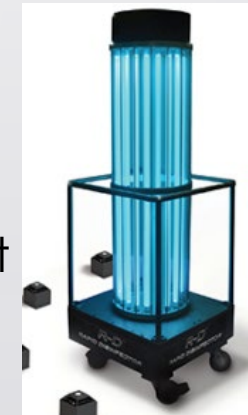
Upper Air
UVGI



In-Duct/Coil
UVGI



Portable
Surface
Treatment
UVGI



Other air cleaners – many types with different evidence of effectiveness and safety

- Electrostatic precipitators
- Thermal filters
- Reactive oxygen species - based
 - Ionization
 - Dry hydrogen peroxide
 - Photocatalytic oxidation
- Key questions
 - What is evidence for effectiveness as applied?
 - Is it safe in application?
 - Direct exposure
 - Byproducts
 - Is it really better than increased filtration efficiency or outdoor air?

System Effects – Combining Ventilation, Filtration, and Air Cleaning

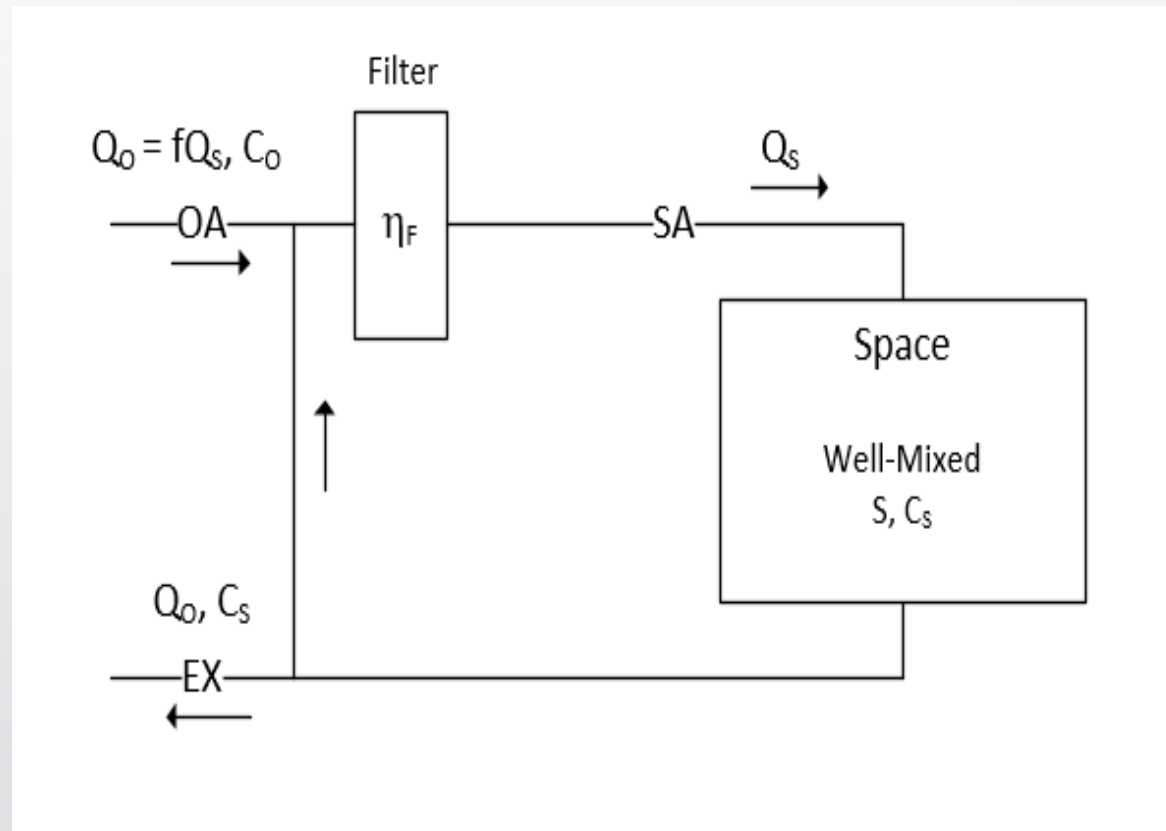
- Combinations of controls can be synergistic
 - MERV rated filter + UV can approach HEPA performance
- Some combinations of controls are mutually exclusive
 - DOAS + central filtration for indoor contaminants
- Some are additive but trade off
 - Ventilation + air cleaning
- Air cleaner effectiveness – describes incremental effect of a control

$$\varepsilon = \frac{C_{uncontrolled} - C_{controlled}}{C_{uncontrolled}}$$

Nazaroff, W. 2000. Effectiveness of Air Cleaning Technologies. *Proc. of Healthy Buildings 2000*.

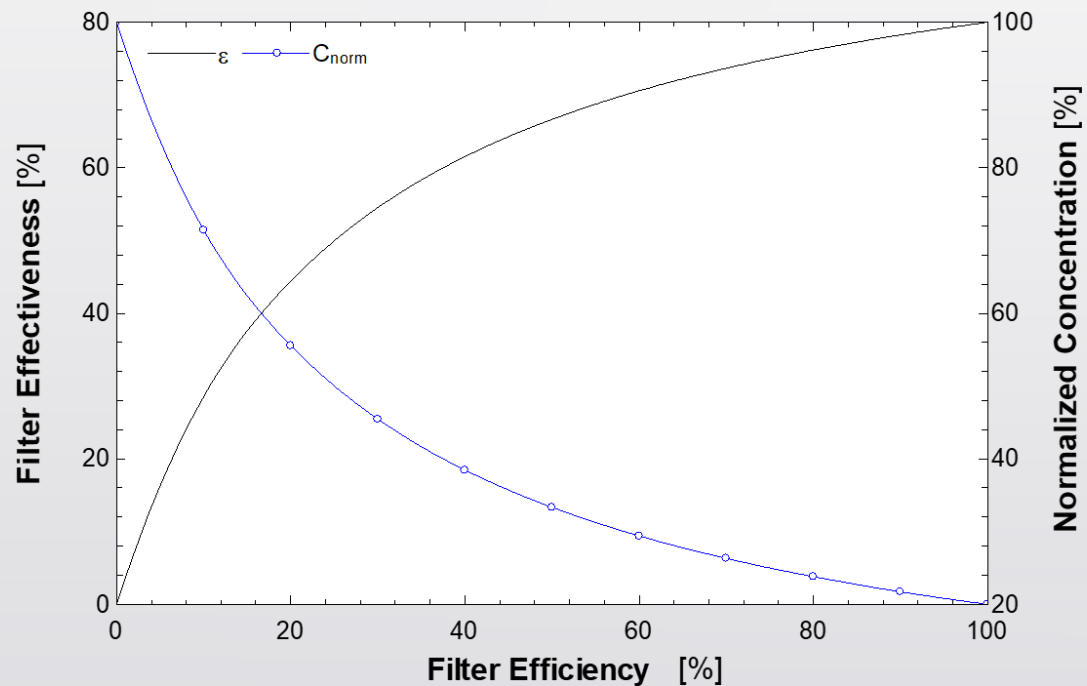
Ventilation/Filtration Trade Off

- Simple example:
Ventilation + Filtration
 - Well-mixed, steady state
 - $Q_s = 100$
 - $S=1$
 - $C_o = 0$
- Scenario 1
 - $\eta_F = \text{variable}$
 - 20% OA
- Scenario 2
 - $\eta_F = 60\%$
 - $f = \text{variable}$

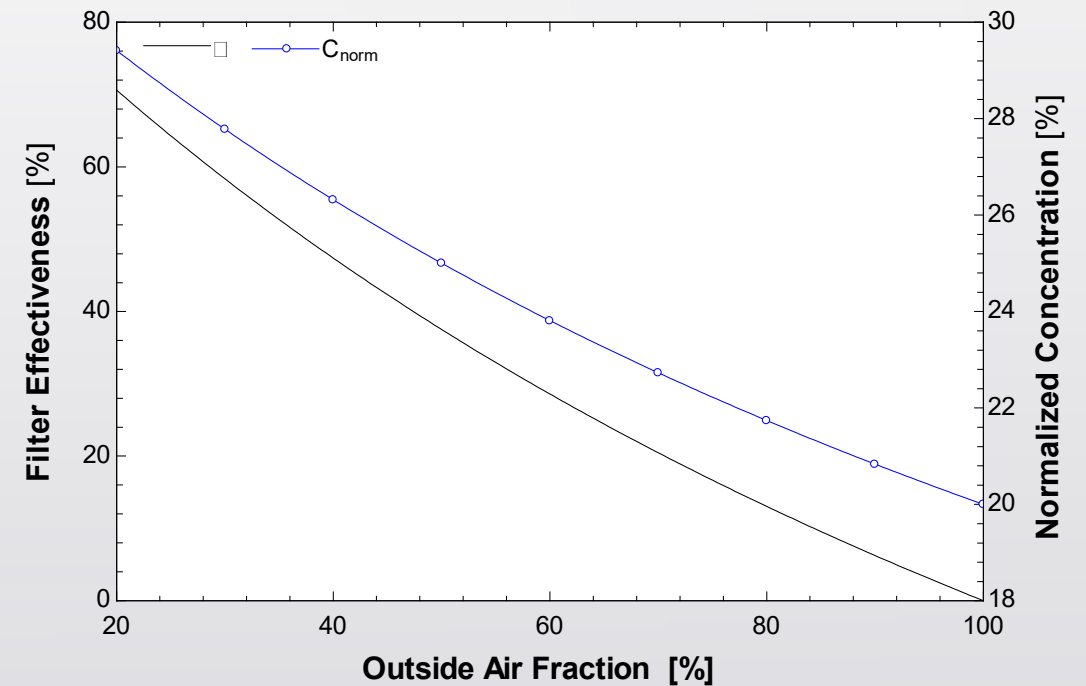


Ventilation/Filtration Trade-Off

20% OA, variable
filter efficiency



60% filter efficiency,
variable OA

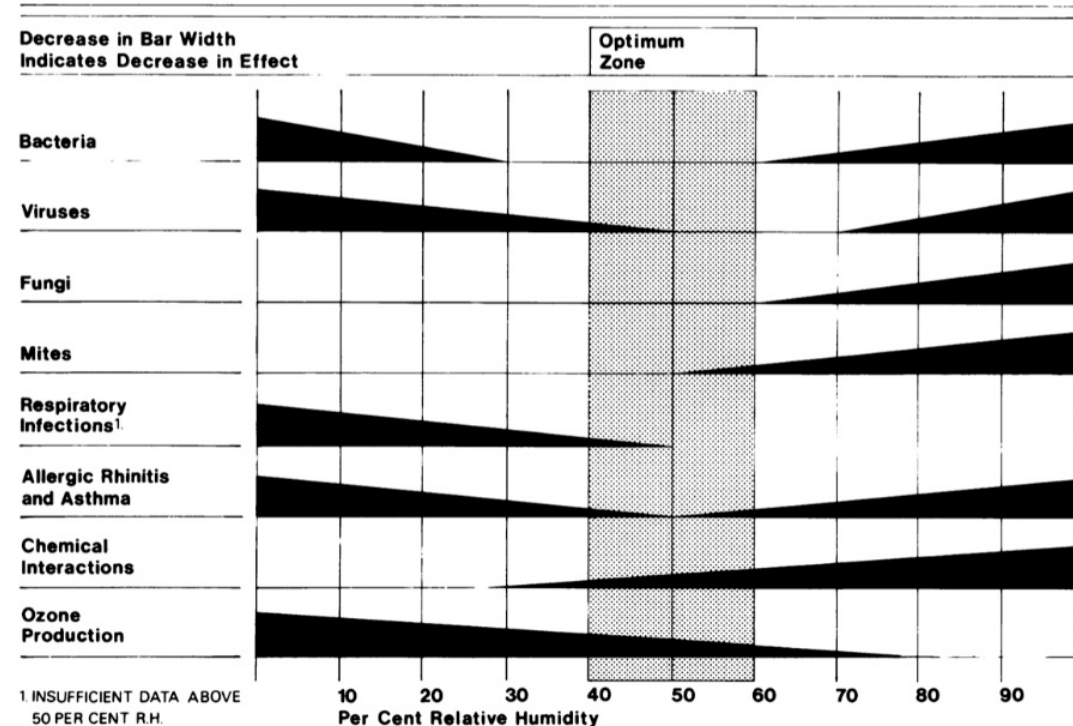


Normalized space concentration is relative to value at 20% OA with no filter

Temperature and Humidity Control

- Faster inactivation of SARS-CoV-2 at higher T and RH
- Limited ability to vary T in comfort zone
- 40-60% RH → lower infection rates in some studies
- Good to do if feasible
- Difficult to humidify many existing buildings safely
- Significance for COVID-19 needs further investigation

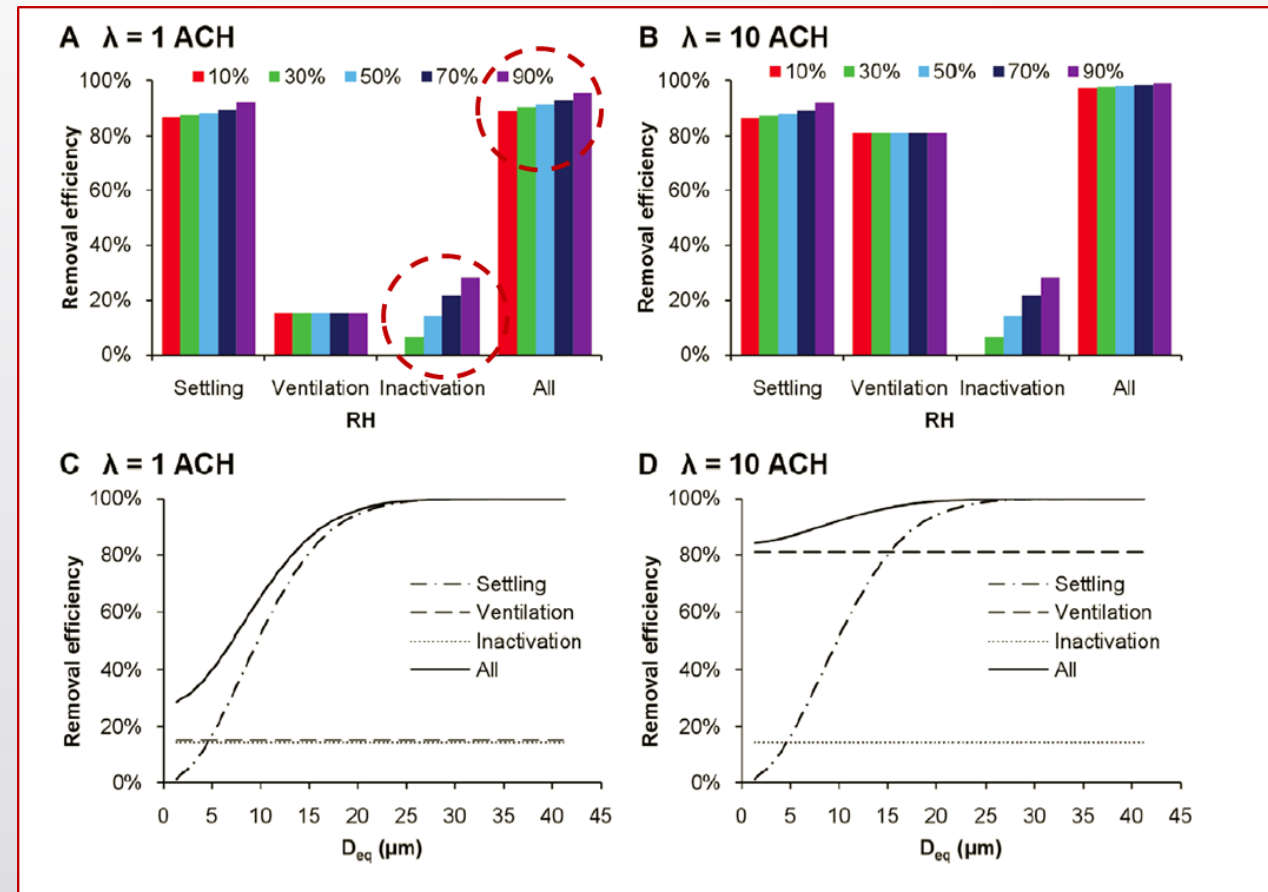
Arundel AV, Sterling EM et al. *Indirect Health Effects of Relative Humidity in Indoor Environments*, Environmental Health Perspectives Vol 65, 351-61, 1986.



Optimum relative humidity range for minimizing adverse health effects.

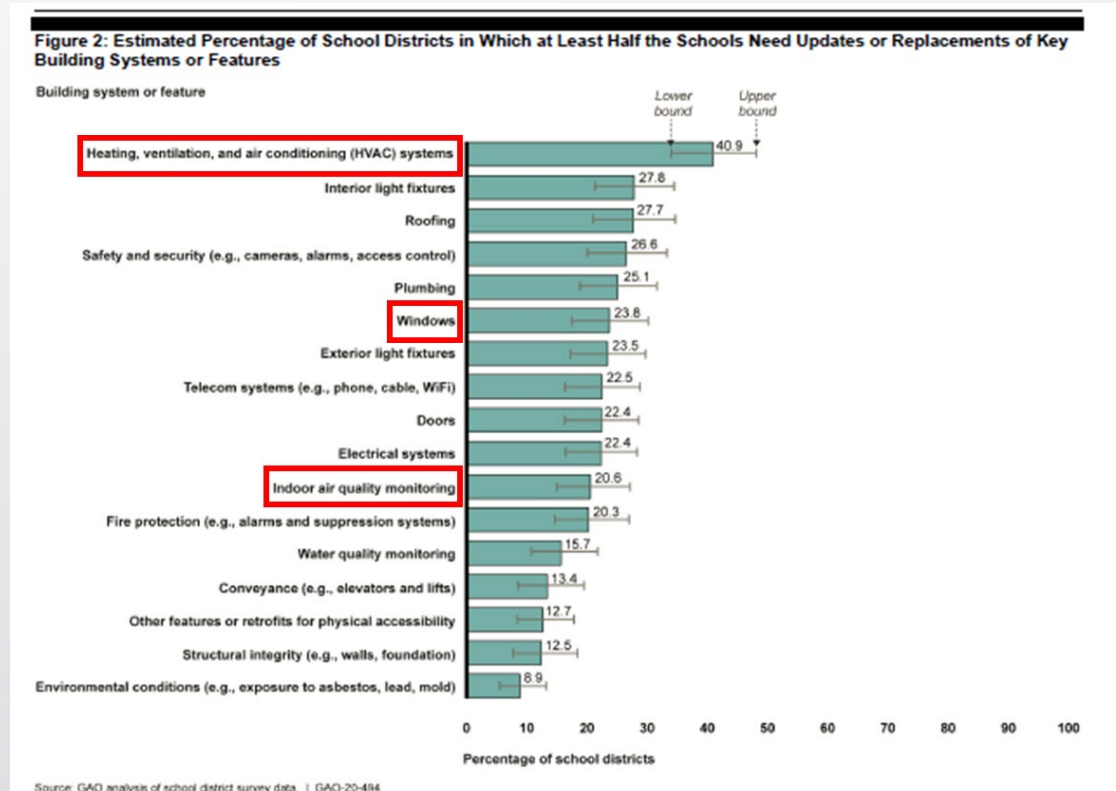
Temperature and Humidity Control

- Humidity has a large impact on rate of inactivation
- Settling is affected by humidity, but not much
- If ventilation and filtration are at recommended levels, impact of RH on exposure is secondary
- Not clear – effect of RH on susceptibility

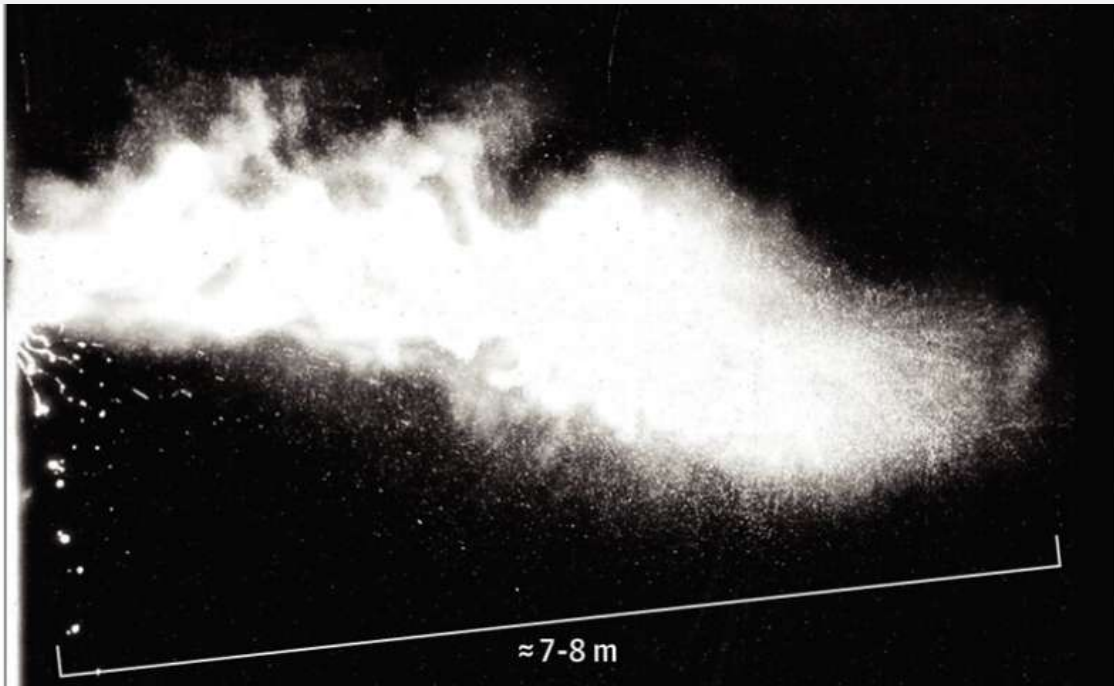


Commissioning is an important part of ensuring effective risk mitigation

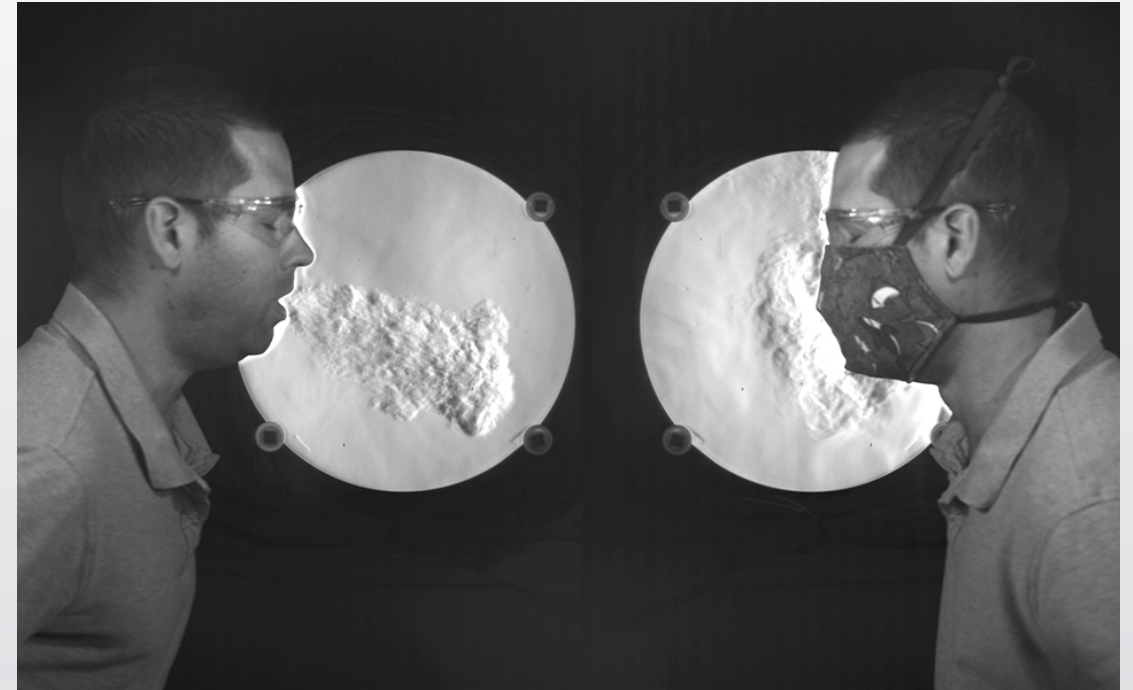
- Deferred maintenance is widespread
- Problems
 - Inadequate ventilation
 - Controls that don't work
 - Energy waste



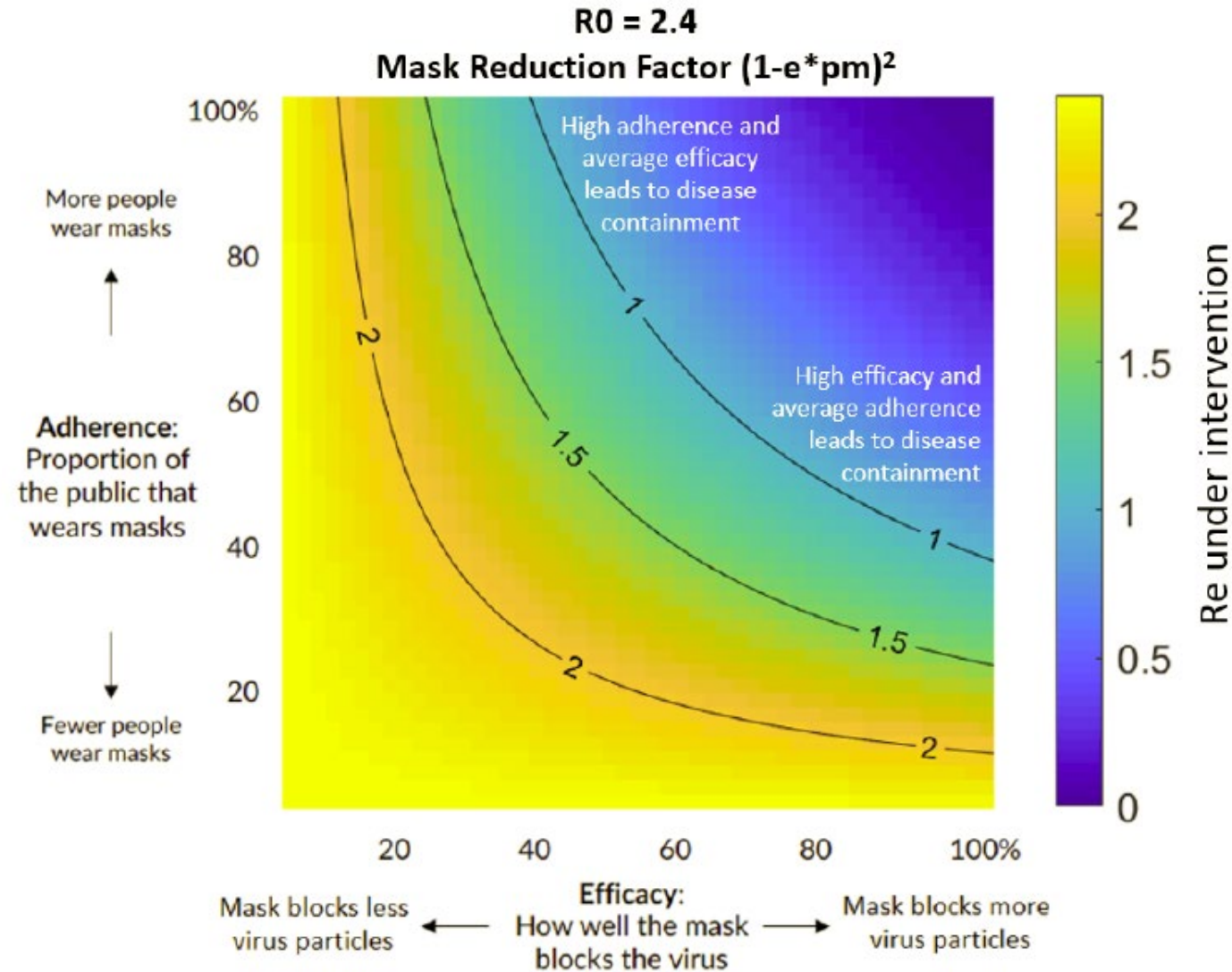
During an epidemic, mask use plays an important part in controlling airborne transmission



Bourouiba, L. JAMA. 2020;323(18):1837-1838.
doi:10.1001/jama.2020.4756



Credit: M. Staymates/N. Hanacek/NIST
<https://www.nist.gov/blogs/taking-measure/my-stay-home-lab-shows-how-face-coverings-can-slow-spread-disease>





Core Recommendations for HVAC

- Follow public health guidance – masks, distancing, hygiene...
- Ventilation, Filtration, Air Cleaning
 - Provide at least code minimum outdoor air
 - Use MERV 13 or better filters for recirculated air
 - Consider supplementing ventilation and filtration with air cleaner demonstrated to be effective and safe
 - Combine controls to achieve risk targets while minimizing energy penalties
- HVAC System Operation
 - Maintain temperature and humidity set points
 - Maintain design clean air supply during occupied periods
 - When necessary, flush between occupancy periods at least 3 eACH
 - Limit re-entry of contaminants to acceptable levels
- Commission systems to verify operation as designed

Summary

- HVAC systems reduce risk of aerosol/airborne transmission by reducing airborne concentration – one part of a layered risk management program
- Multiple engineering controls are available
- Ventilation and filtration are fundamental
- Air cleaners have great promise, but many are of unproven effectiveness and safety
- Equivalent air exchange rate approach provides a path to optimized solutions

ASHRAE Epidemic Task Force

- Formed in March 2020 by direction of ASHRAE BOD to Environmental Health Committee
- Scope
 - Short term guidance
 - Re-opening/2nd wave guidance
 - Future directions
 - Research
 - Standards
 - Education
- 26 members
 - 22 volunteers
 - 4 ASHRAE staff
- Functions as a steering committee
- 15 teams with over 150 members
- Activities
 - Guidance
 - Q&A
 - Meetings and presentations
 - Educational programs

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Frequently Asked Questions and Glossary of Terms

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There's one data center for every 100 people in the United States and thousands of facilities worldwide

AND ASHRAE Standard 90.4-2019 - Energy Standard for Data Centers



ashrae.org/904

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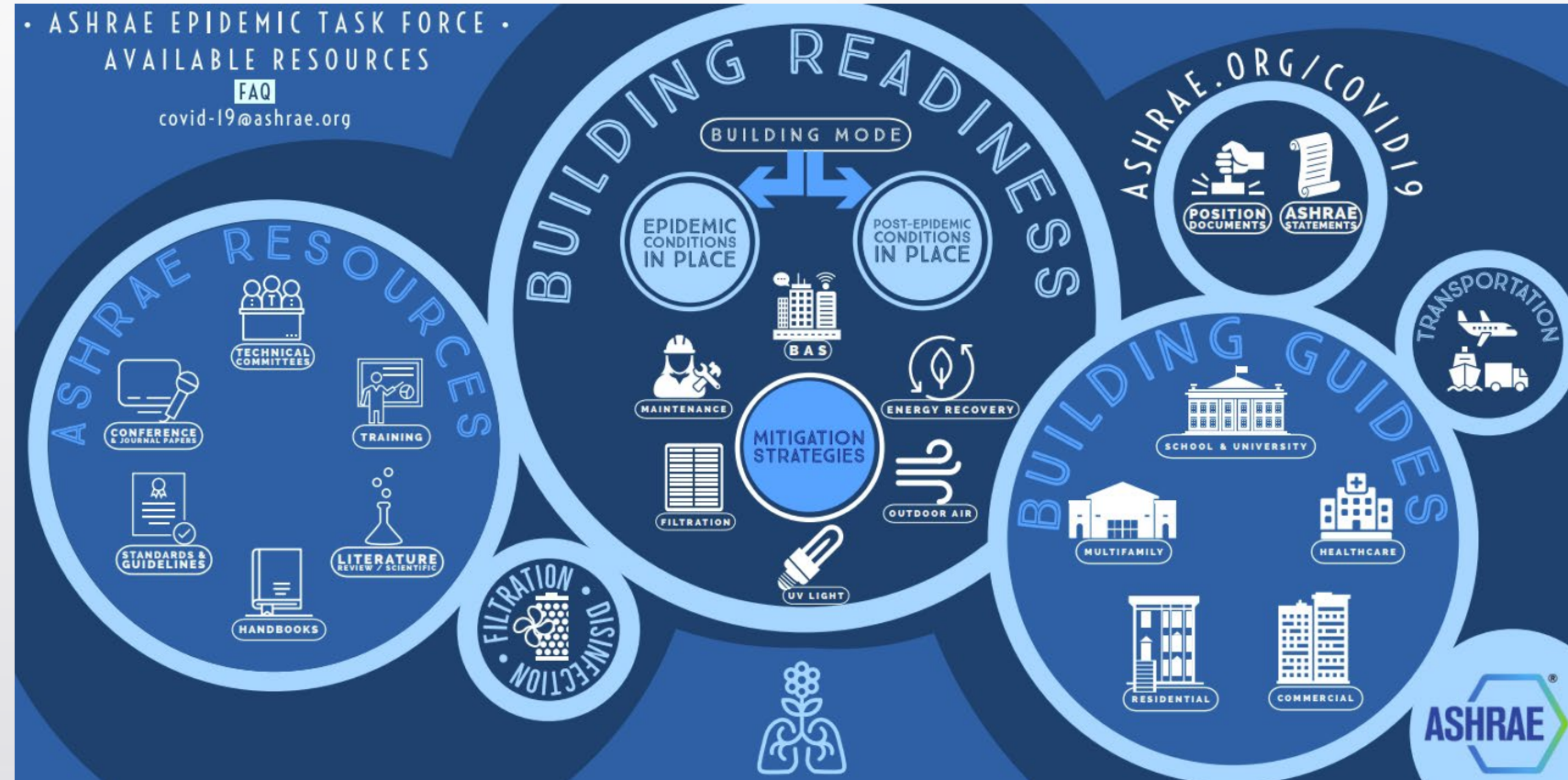
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This page is updated as new information becomes available.

Thank You!

Bill Bahnfleth

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