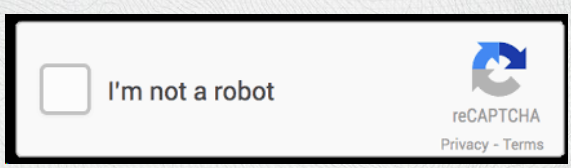
VENTILATION IN THE AGE OF COVID-19 AEROSOL TRANSMISSION: WHICH VENTILATION SYSTEM IS BEST OR IS THERE ONE?

THOUGHTFUL VENTILATION DESIGN TO ADDRESS COVID-19 RISKS

Redefining possible.

Duncan Phillips, Practice Area Leader, Ph.D., P.Eng.



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Best Practice

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Learning Objectives

- To understand how droplets of different sizes move in a ventilated environment.
- To be able to describe different types of air distribution systems in indoor environments.
- To recognize the merits and drawbacks of different air distribution methods.
- To explain how ventilation systems can be simulated and the limitations of those methods.
- To understand how mixing models work and advantages of these over higher order models.

Acknowledgements

We have the privilege of working with a particularly bright group of individuals at RWDI on cool projects for inspired clients.

Speaker

Global Practice Leader for Building Performance, Ventilation & CFD

Worked on all 8 continents on Earth + 1 on Mars

Joined RWDI in 2000

Conduct studies involving detailed physics of air movement

Have been involved in projects with unusual ventilation requirements:

- Protection of art work
- Protection of specialised equipment
- Industrial ventilation
- Operating rooms
- Patient isolation rooms
- cleanrooms

Sit on committees feeding into ASHRAE's ETF

Duncan Phillips
Global Practice Leader,
Building Performance

+1 519 823 1311 x2409
Duncan.Phillips@rwdi.com

Background: What we do

RWDI is a specialty consultant

We work on the design and operation of buildings, infrastructure and industry.

Focused on using science to make the built environment better:

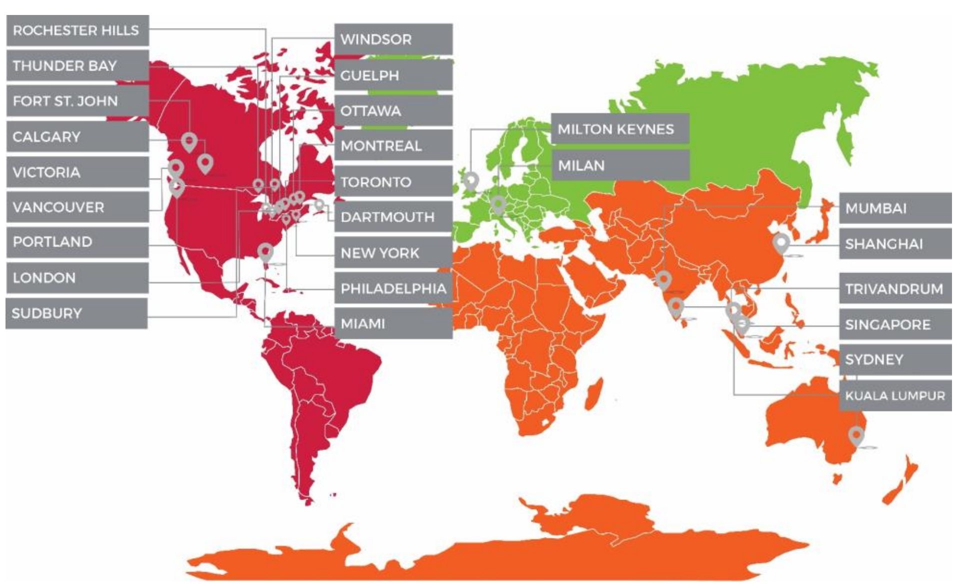
- Safer
- More energy efficient
- Cleaner
- Lower cost

Employ a range of experience, tools and analyses on each project type.

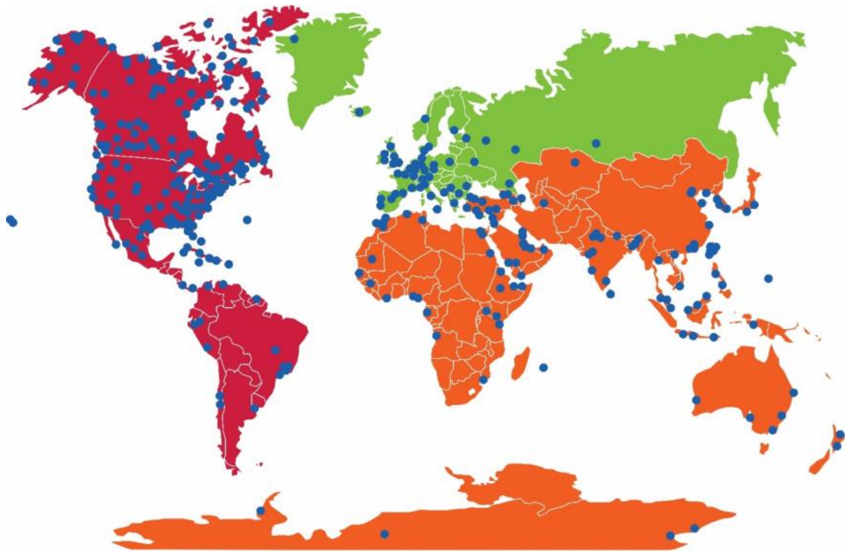
Have worked on all continents on Earth.

People at RWDI want to be the leader in all we do and leverage that for our clients and their projects.

A Global Presence



Global Experience



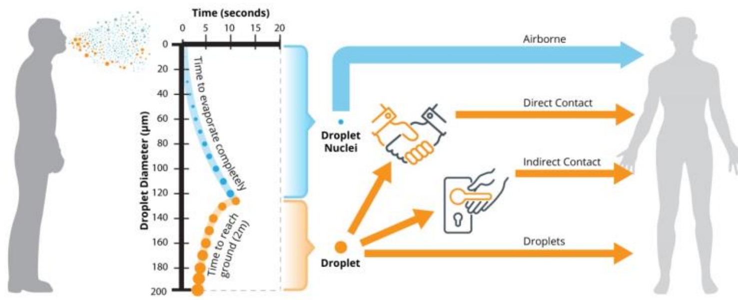
Outline

- Brief background on COVID-19 Transmission
- Background on contaminant control
- Challenges of COVID-19 to ventilation control
- Types of ventilation systems
- Case studies of impact of ventilation systems on virus transmission.
- Discussion of single zone model

COVID-19 Transmission

The relative importance of different transmission routes are still disputed

- COVID-19 is spread through respiratory droplets.
  - No one disputes this
- The dispute is whether the droplets mostly infect another person through direct impact and touching surfaces (indirect) and the importance of airborne transmission.
- Recent CDC and WHO guidance has downplayed Fomite transfer.



Adapted from: Xie, X., Li, Y., Chwang, A. T. Y., Ho, P. L., Seto, W. H. (2007), **How far droplets can move in indoor environments – revisiting the Wells evaporation–falling curve**, *Indoor Air*, 17: 211 – 225.

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How are Viruses Transmitted: It Really Depends on the Virus

SARS-CoV (2002 – 2003 global threat)
- Thought to only be transmitted by ***symptomatic patients***
- Spread through respiratory droplets:
  - Via mucous membranes in mouth, eyes, nose
  - Surface to face transmission via hands
  - SARS-CoV might be spread more broadly through the air

MERS-CoV (2015)
- Not much known about this virus
- Spread via respiratory droplets
- Thought to be transmitted to people caring for ill in close contact.
- Mostly restricted to Arabian Peninsula and Korea.

SARS-CoV2 (2019) – aka COVID-19
- Transmitted through respiratory droplets: coughs, sneezes or talking.
- Enters body via mucous membranes in eyes, nose, mouth through droplets
- Now acknowledged as being transmitted via inhalation.
- Implication it can be transmitted via fecal matter.
- Studies are suggested that COVID-19 may be spread by ***asymptomatic people***

Common Flu
- Transmitted via respiratory droplets
  - By direct contact with infected individuals;
  - By contact with contaminated objects; and
  - by inhalation of virus-laden aerosols.
- Can transmit while ***asymptomatic*** but most contageous 3 – 4 days after illness begins

Polio
- Most people (72%) infected will not have any symptoms
- Those with paralytic symptoms are said to have polio
- Those who recover in their childhood might develop symptoms up to 40 years later.
- Polio enters through the mouth through:
  - Contact with the feces of an infected person; or
  - Droplets from a sneeze or cough of an infected person although this is not as common.
- A person is infectious while ***asymptomatic***.

Tuberculosis
- Spread via respiratory droplets inhaled from person with disease (***symptomatic***). If infected only one isn't contagious.
- ***Not*** transmitted via droplets on hands from surface.

Where are those Mucous Membranes

Sometimes referred to as Mucosa … they produce mucus …

They are membranes that line body cavities and canals that lead to the outside, chiefly the respiratory, digestive, and urogenital tracts.

- https://www.britannica.com/science/mucous-membrane

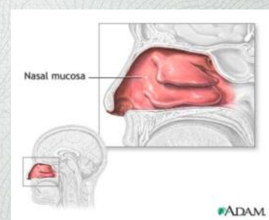
The function of these membranes is to stop pathogens (anything that can cause a disease) and dirt from entering the body and to prevent bodily tissues from becoming dehydrated.

- https://en.wikipedia.org/wiki/Mucous_membrane

We have many mucous membranes.

Relevant ones cited for Covid-19 are:

- The mouth
- The eyes
- The nose



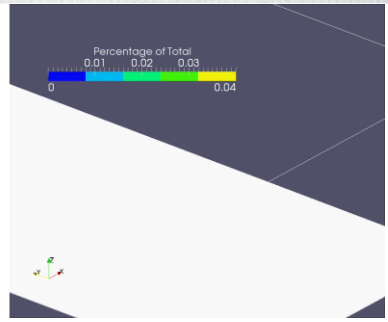
Source: Medlineplus.gov

Dynamics of Droplet Movement

Droplets:
There are Many in the Environment

Cooling Towers

Rain

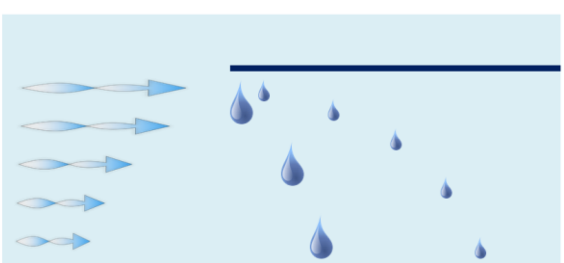


Parks & Playgrounds

Respiratory Droplets

Science of Transport

A droplet's ability to travel in air is driven by its size and density



Terminal Velocity:

$$V = \left(\frac{2\ x\ m\ x\ g}{\rho\ A\ C_d}\right)^{\frac{1}{2}}$$

For Water:

$$V_{H_2O} = \left(\frac{d\ x\ 3270}{0.3\ x\ C_d}\right)^{\frac{1}{2}}$$

D = diameter [m], C_d = drag coeff (0.5)

Note: The value of C_d is very sensitive to the actual velocity and size of the droplet. For large particles it is ~0.5, for 100 μm droplets it is ~10.5.

Science of Transport

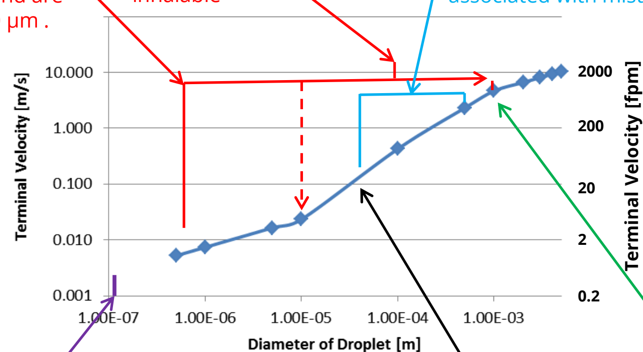
As a droplet gets smaller, it will appear to "float"

~0.6 – 1000 μm are respiratory (out) and are respirable (in) <10 μm .

~<100 μm are inhalable

> 50 - 500 μm are associated with mist

Note: The value of C_d is very sensitive to the actual velocity and size of the droplet. The plot here is an estimate.



A single Covid-19 particle is ~0.12 μm

However other research says Covid-19 is sticky and tends to attached to dust and other particles making it bigger.

> 1000 μm are rain

50 μm smallest particle we can see

Method of Thinking About Droplet Transport

Some of the calculations were a little off in 1934, and they were updated in 2007.

The red line is from the original Wells work.

What is important here is that some droplets will fall out of the air and others will evaporate

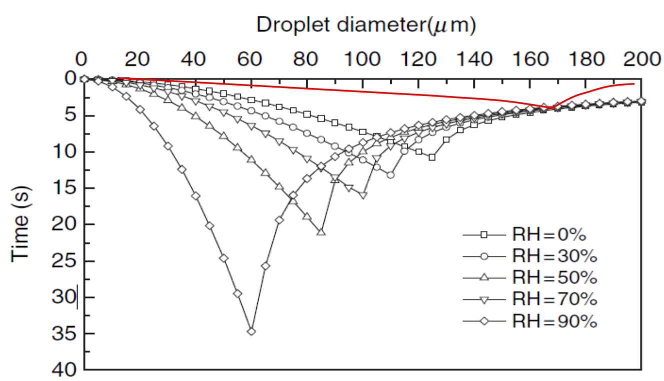


Figure 6 from: Xie, X., Li, Y., Chwang, A. T. Y., Ho, P. L., Seto, W. H. (2007), **How far droplets can move in indoor environments – revisiting the Wells evaporation–falling curve**, *Indoor Air*, 17: 211 – 225.

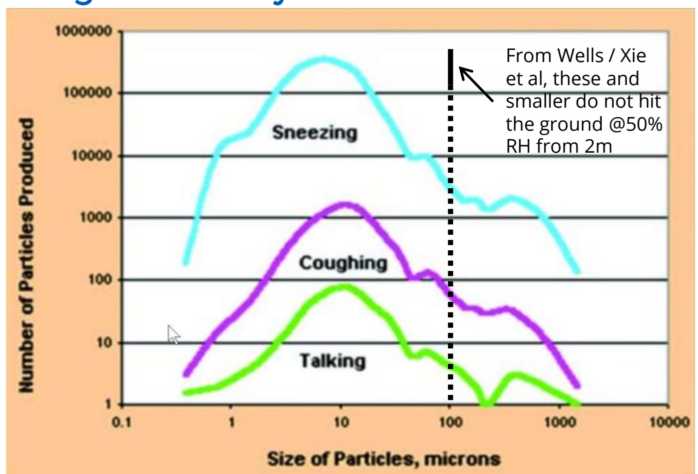
Droplets and Respiratory Events

Data from Duguid is still being used today.

At 50% RH:

- Particles >100 µm drop out 2.0m
- Particles <100µm evaporate

Anything that was in an evaporated droplet is free to float.



From: W. J. Kowalski, William Bahnfleth, (1998), **Airborne Respiratory Diseases and mechanical systems for control of microbes,** *Heating, Piping, Air-Conditioning (HPAC)*, 34-48
Based on Duguid, J. P. **The size and the duration of air-carriage of respiratory droplets and droplet nuclei.** *Journal of Hygiene* 54 (1945): 471-479.

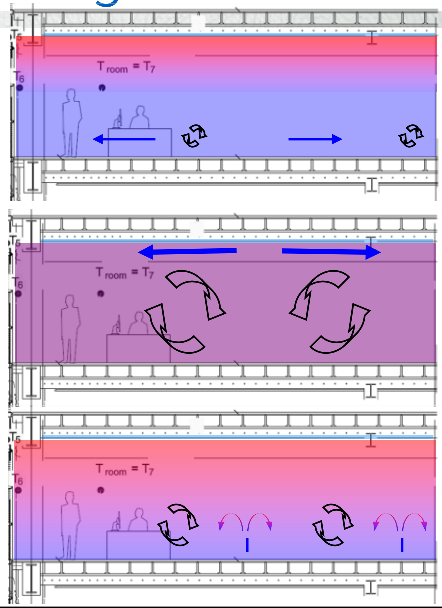
Ventilation Configurations

Air Distribution Configurations

Displacement
- Deliver air low
- Minimize mixing
- Return high
- Characterized by large gradients in vertical direction

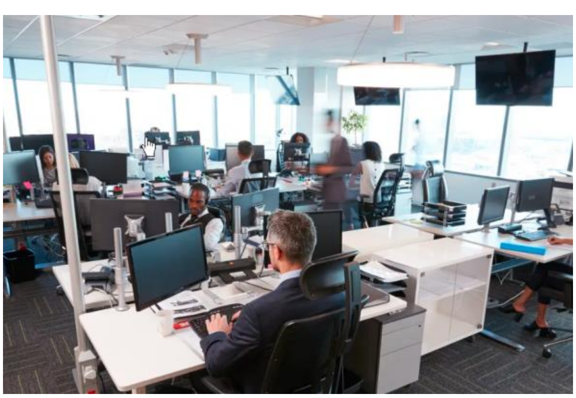
Mixing
- Deliver air high
- Maximize mixing
- Return low or high
- Characterized by uniform conditions

UFAD
- Deliver low
- Mix in occupied space only
- Return high
- Characterized by uniform conditions in occupied space and gradients in upper zone



Droplets can be Released Any- and Everywhere

How do we minimise risk here …. … or here?



Source: BusinessInsider.com

Source: Motorsport.com

In Industrial Ventilation we use Layers of Protection

In sequence of preference:

- Remove the contaminant source completely
- Control the source
- Move people away from the contaminant source
- Provide general ventilation to dilute the contaminant
- Institute operational controls
- Wear PPE

In Industrial Ventilation we use Layers of Protection

If we assign common industrial hygiene practices to COVID-19

There are three general steps to contaminant control

Control / eliminate the source

Remove the occupant from the presence of the source

Provide good general ventilation

.

Most of these are in-room filters and UVGI

To prevent transmission of COVIV-19, there are multiple options

Masks are primarily source control not PPE

Social distancing and reduced occupancy lowers risk of having an infected person in the space and duration they contaminate.

Ventilation systems cannot easily be adapted but systems can be added

The challenge for many buildings is what sort of addition can be made that does not adversely impact control of other contaminants.

- Do we need to?

ASHRAE's Guidance – Similar to REHVA

Different organizations are speaking to the benefits of ventilation systems to assist in controlling COVID-19

Concern that people were turning ventilation system off.

Reports of "HVAC system spreading virus"

Dilution
- Turn up the OA
- Turn off the DCV
- Reduce recirculation
- Maintain 24/7 ventilation

Setting target RH levels
- There is evidence this helps fight infections and increases the mortality of SARS-CoV2.

Filtration
- Minimum of MERV 13, 14 preferred, HEPA better

Purge
- Turn on the system early
- Leave the system running later

CIBSE as a member of REHVA is using that collective guidance.

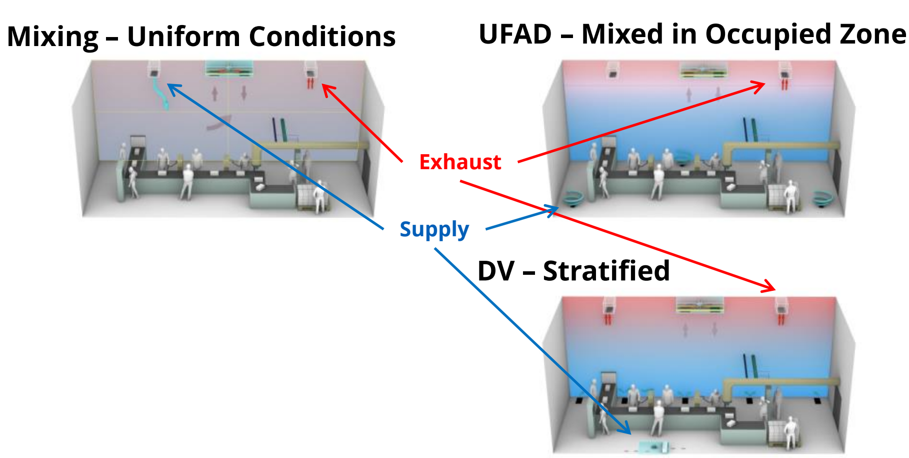
AIRAH is assembling information from a variety of sources for the membership including from ASHRAE, ISHRAE, etc.

Guidance tends to be consistent with ASHRAE but not exact.

None of this addresses room air distribution.

Not all Technologies can Work in All Settings

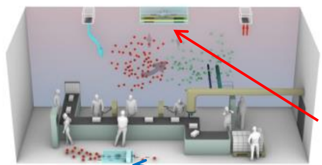
If we consider upper room UVGI and In-room (HEPA) filtration ….



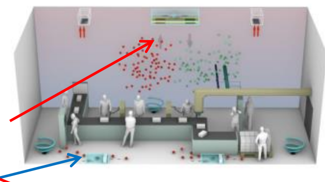
Not all Technologies can Work in All Settings

If we consider upper room UVGI and In-room (HEPA) filtration ....

Mixing



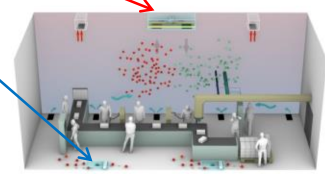
UFAD



Upper room UVGI

In-room filtration

DV



Installation of some devices can disrupt the existing ventilation system and disrupt stratification.

In other circumstances they have no value to the room conditions.

TB Patient Isolation Room

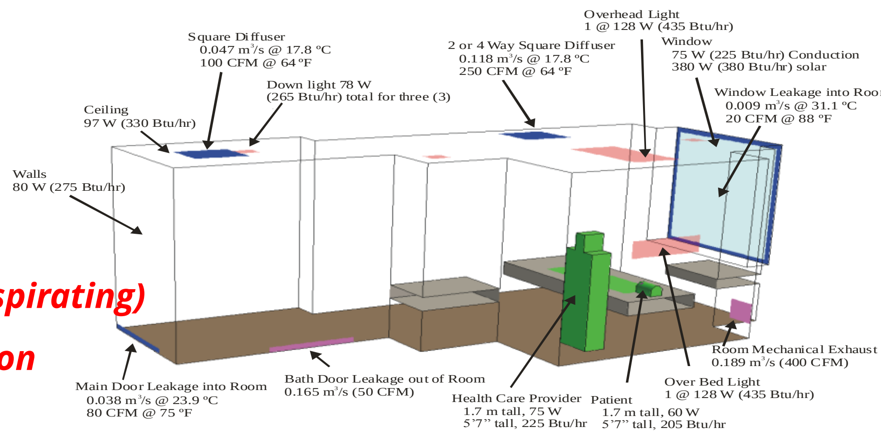
TB Patient Isolation Room

Three diffuser configurations assessed

- "Laminar" diffuser
- Square 4-way
- Square 2-way
- Displacement

Square Four-Way (aspirating)

Diffuser Configuration



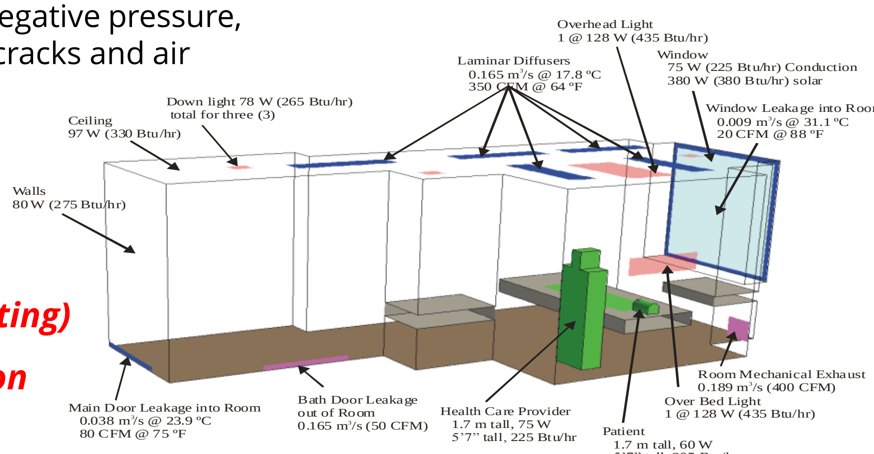
TB Patient Isolation Room

Negative pressure patient isolation room

- Meets criteria for negative pressure, flow through door cracks and air change rates

Laminar (non-aspirating)

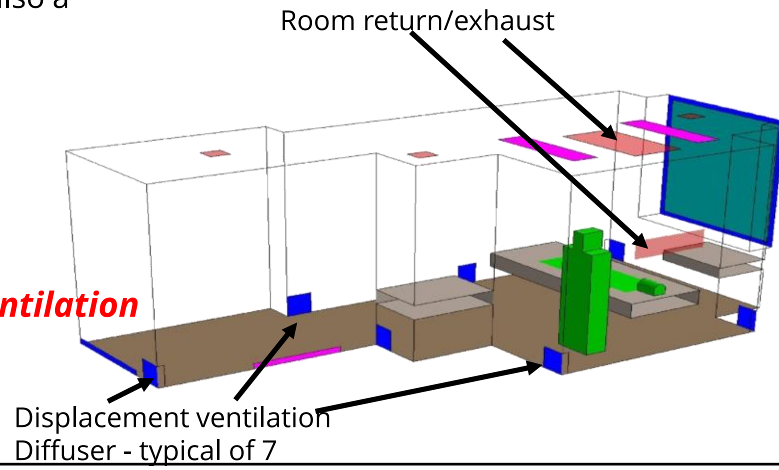
Diffuser Configuration



Displacement Ventilation

- Concerned about the contaminant concentration at the door
- Thermal comfort also a consideration

All Displacement Ventilation Configurations



Age of Air Results

Age of air is a means of assessing:

- How "fresh" the air is within a room
- The well distributed that "fresh" air is

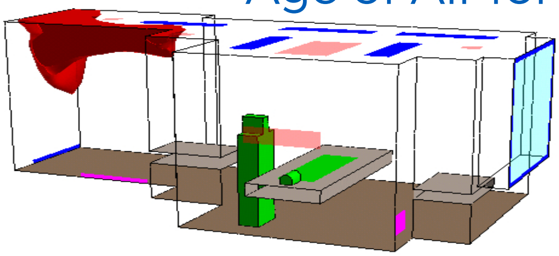
15 ACH were delivered to the room:

- The target minimum is 12 ACH in all locations in the room
- The air must be no more "stale" than 300s

An air change effectiveness (room average):

- 1.0 = perfect mixing ventilation
- 2.0 = displacement ventilation

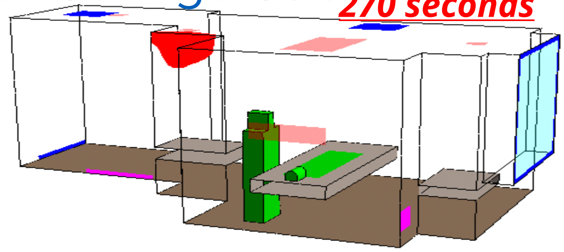
Age of Air for Four Configurations



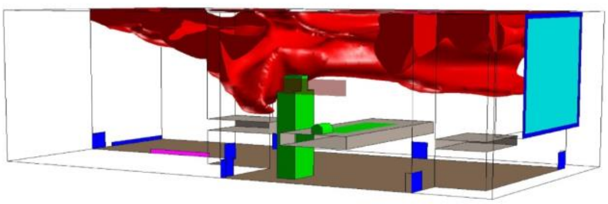
Laminar Diffuser

300 seconds

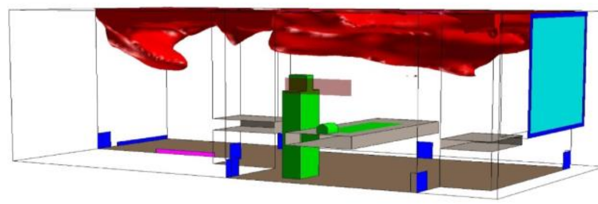
270 seconds



Square 4-Way



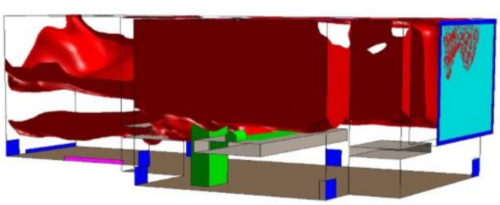
Displacement Ventilation 12 ACH



Displacement Ventilation 15 ACH

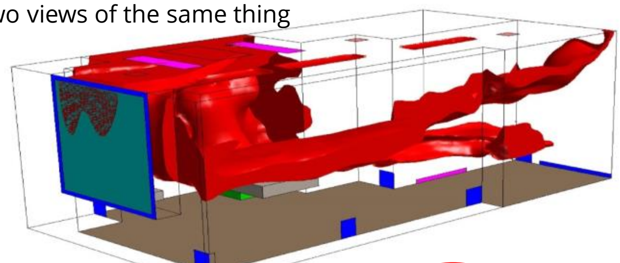
Age of Air – DV

Two views of the same thing

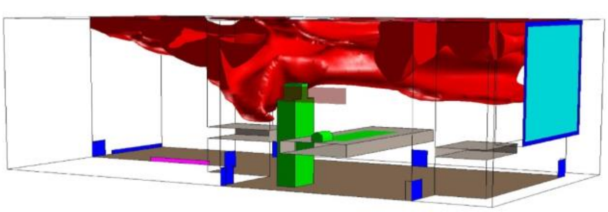


Displacement Ventilation 9 ACH

300 seconds



Displacement Ventilation 9 ACH



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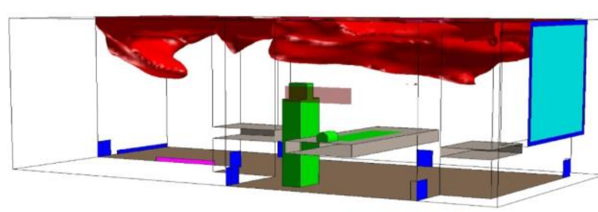


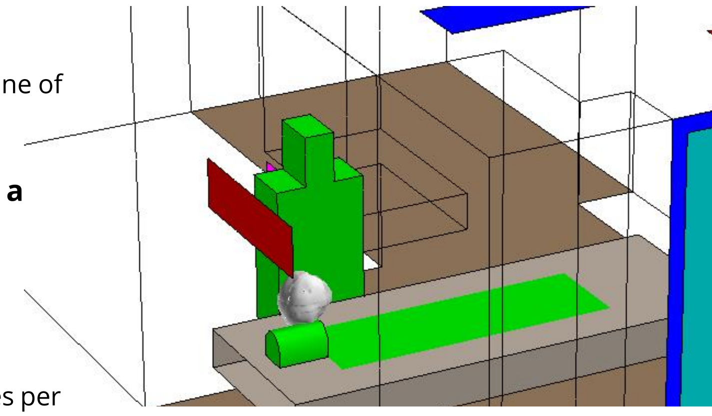
Displacement Ventilation 15 ACH

TB Patient Isolation Room: Modeling a Cough

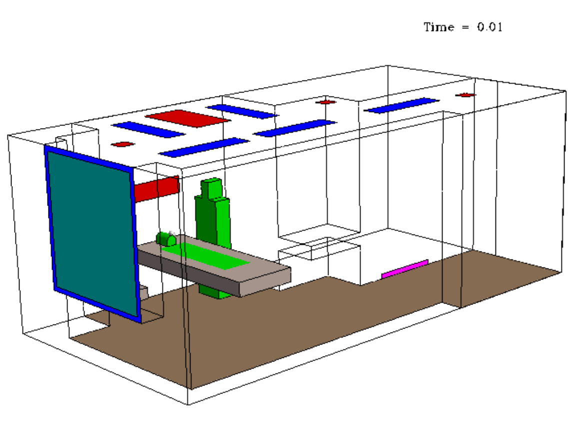
Modeled the release of a cough towards the healthcare worker
- The simulation is representative of one of many different "cough" scenarios

Assumed a release velocity over a short period of time
- Results in a cough volume

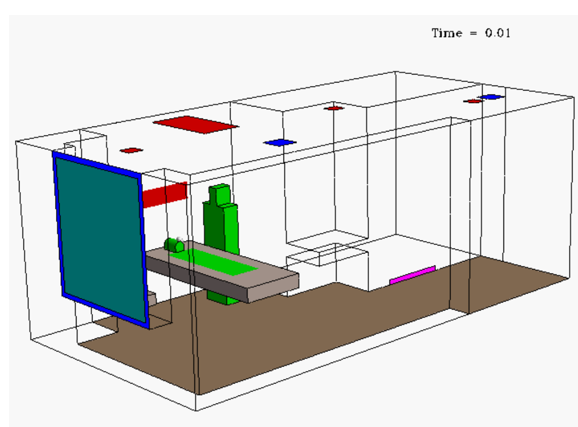
Assumed the cough released a specific number of particles
- Results in a concentration of particles per cough volume



Comparison of Flow Arrangements: Original Cases

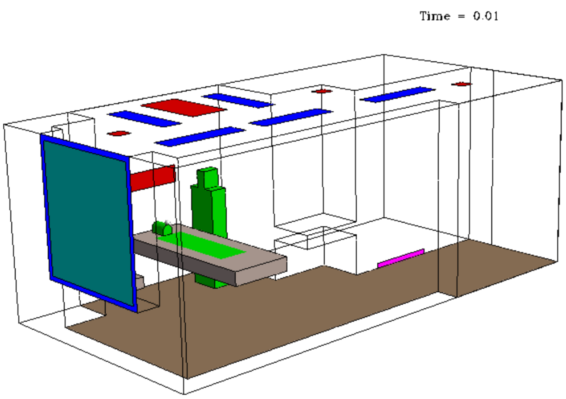


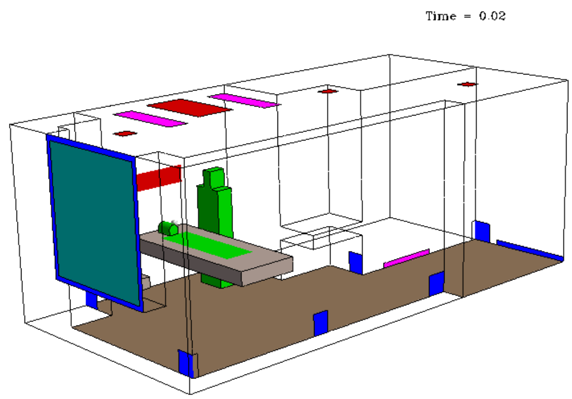
Ceiling Mounted: Laminar Diffusers



4-Way Diffusers

Comparison of Flow Arrangements: 15 ACH for "Laminar" and Displacement

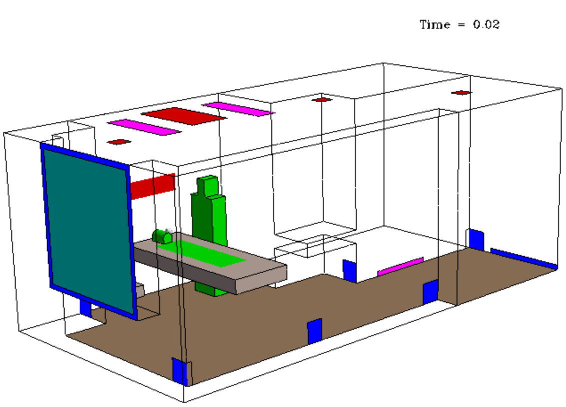


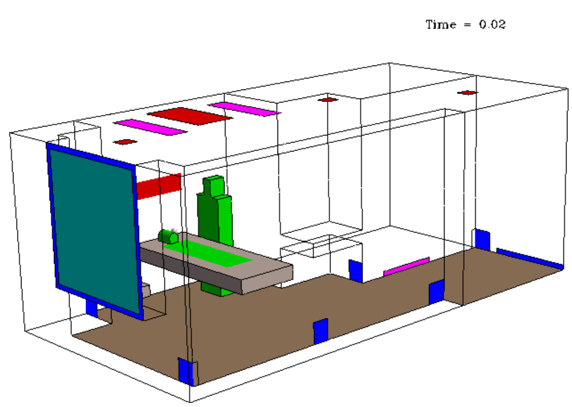


Ceiling Mounted: Laminar Diffusers

Displacement Ventilation

Comparison of Flow Rates: Displacement Ventilation

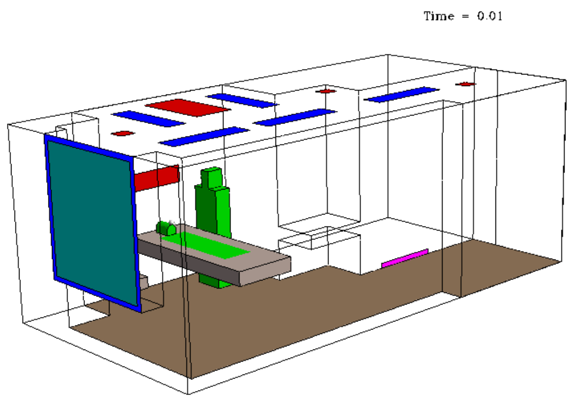




9 ACH

15 ACH

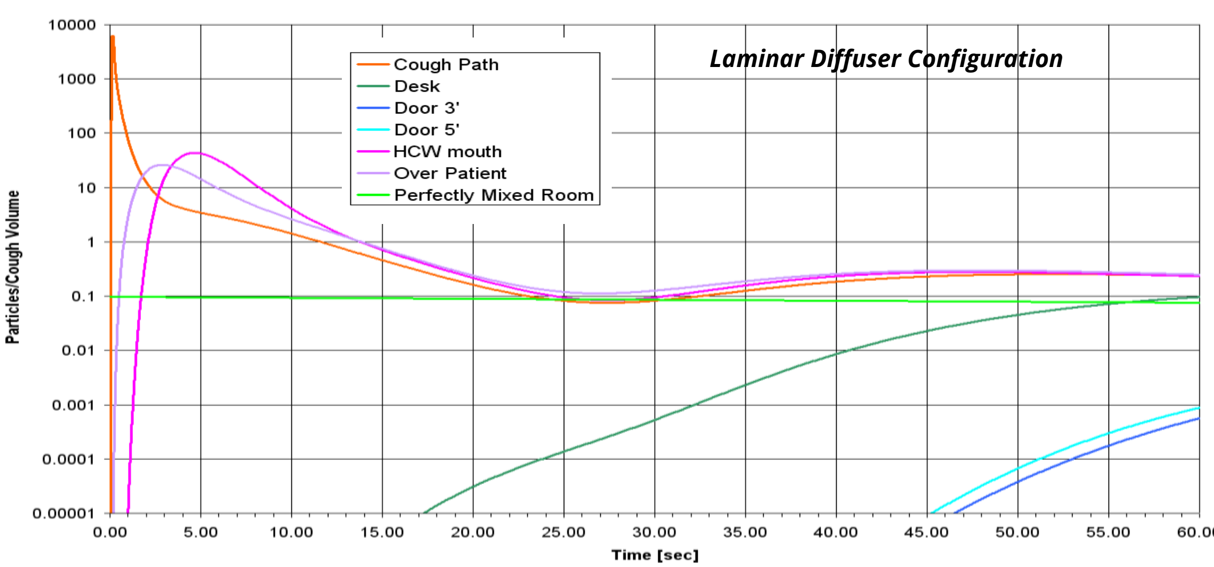
Comparison of Flow Arrangements: Different ACH

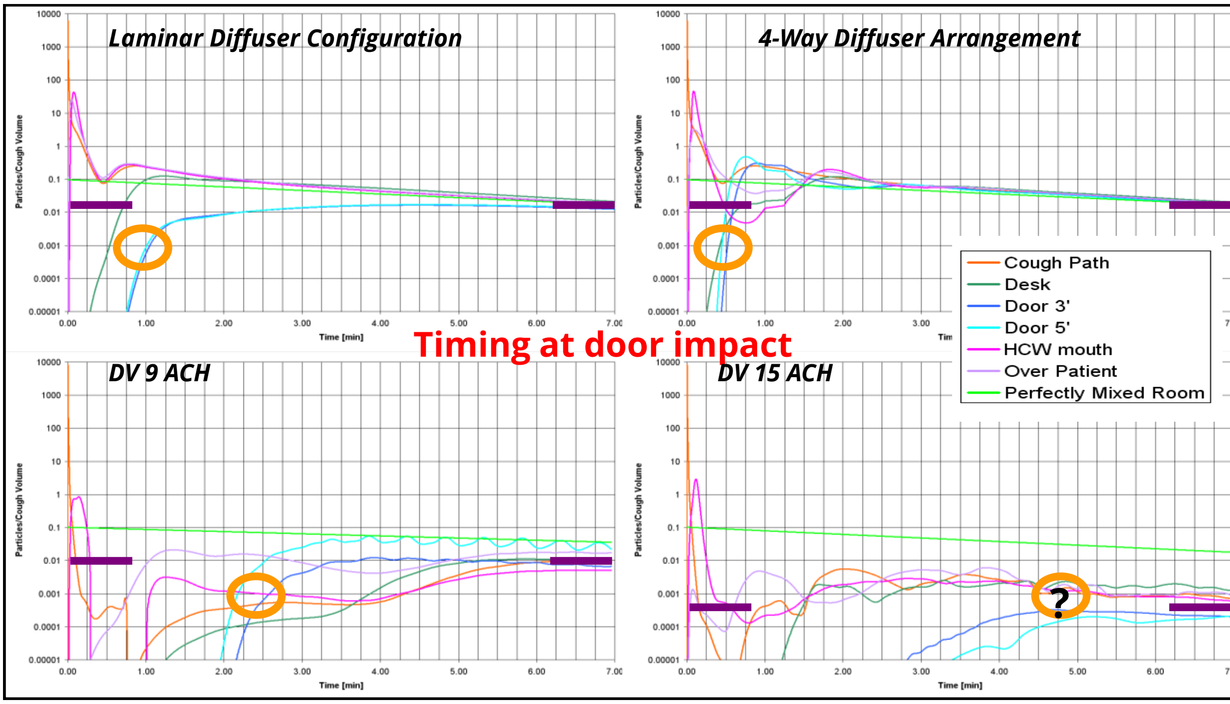


Ceiling Mounted: Laminar Diffusers 15 ACH

Displacement: Ventilation 9 ACH

Transport of Cough Particles Concentration [# particles / cough V]





15 Minute Accumulated Dosage [Units Below] (Low is Better)

	Laminar Diffuser	Square 4-way		Displacement with 9 ACH	Displacement with 15 ACH
Cough Path	1275.80	1275.80		1438.64	1358.38
6" above desk	26.30	22.30		1.62	0.58
3' above floor near door	7.50	26.00		2.27	0.060
5' above floor near door	7.90	27.50		9.32	0.03
At HCW mouth	212.60	182.20		7.97	11.59
1' above patient	155.20	56.10		4.56	0.93
Room average	N / A				
Perfectly Mixed Room	22.90	22.90		36.50	22.90

Dosage = integral of (cough droplets / cough volume) * seconds

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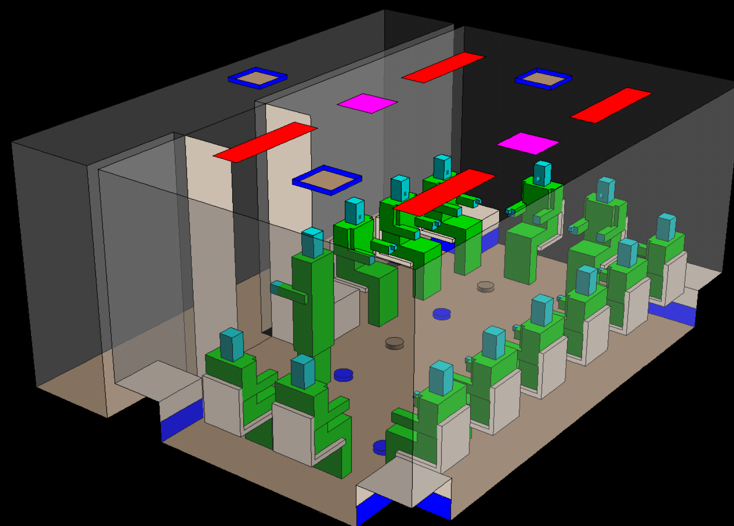
Dosage = integral of (cough droplets / cough volume) * seconds

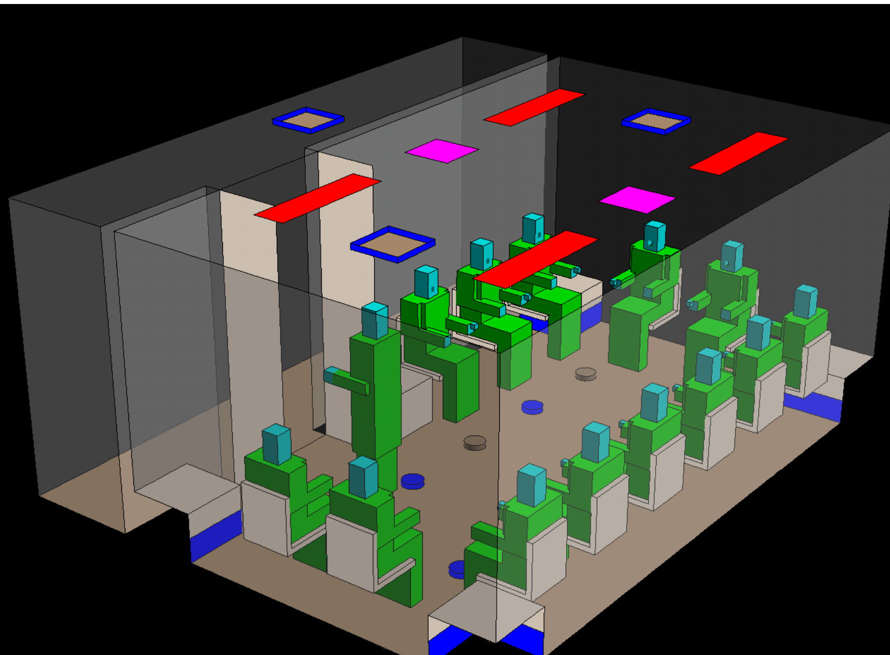
Small Office, Meeting or Waiting Room

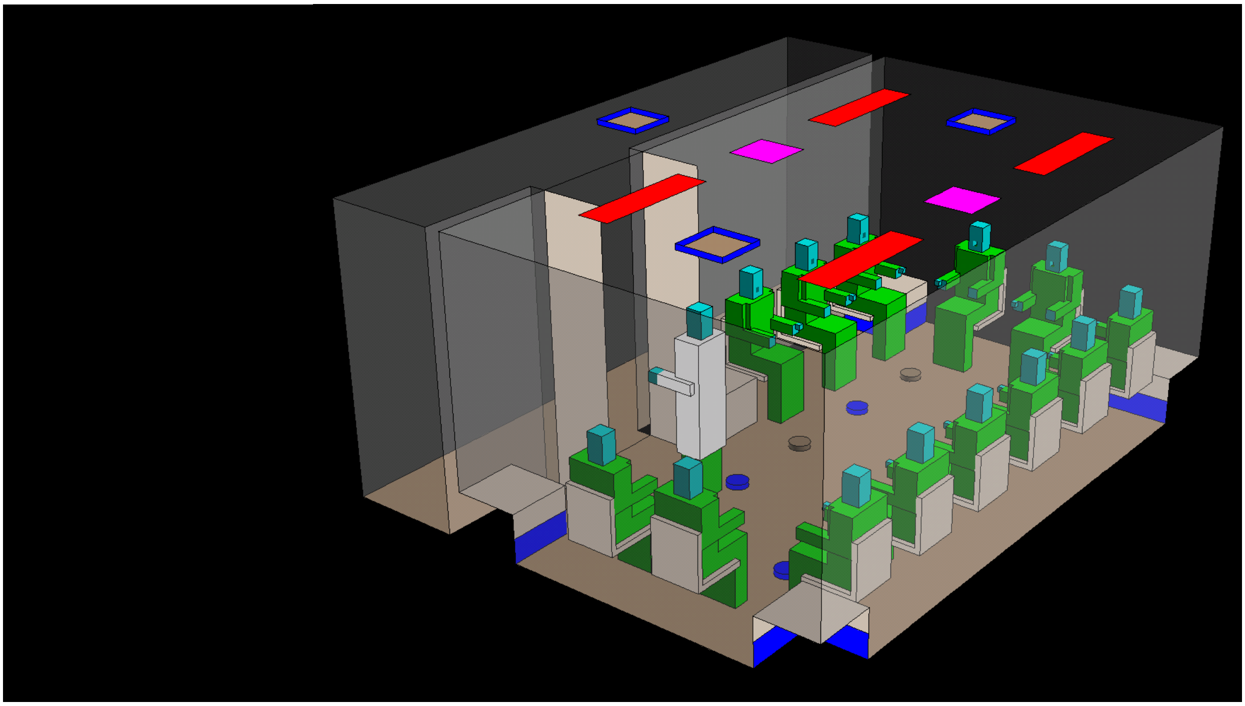
Small Office, Meeting or Waiting Room

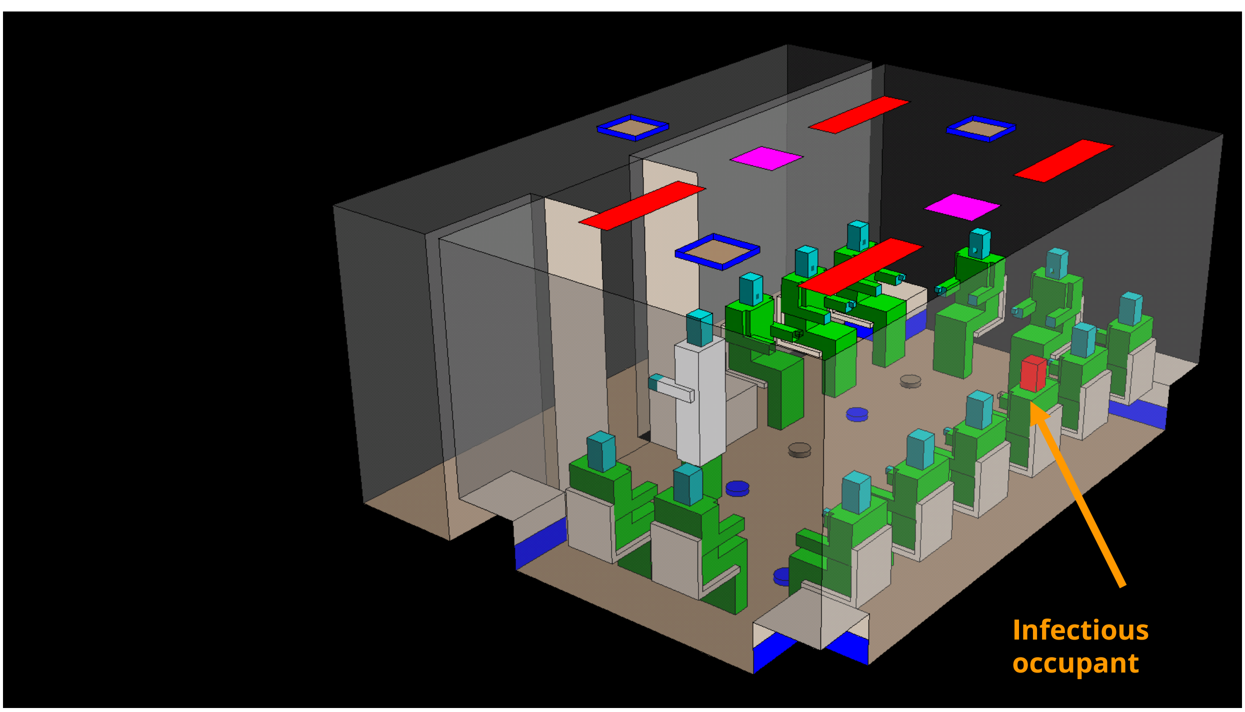
There are many small rooms in our buildings.

Some have high density some have low density.








Infectious
occupant

CFD Simulations

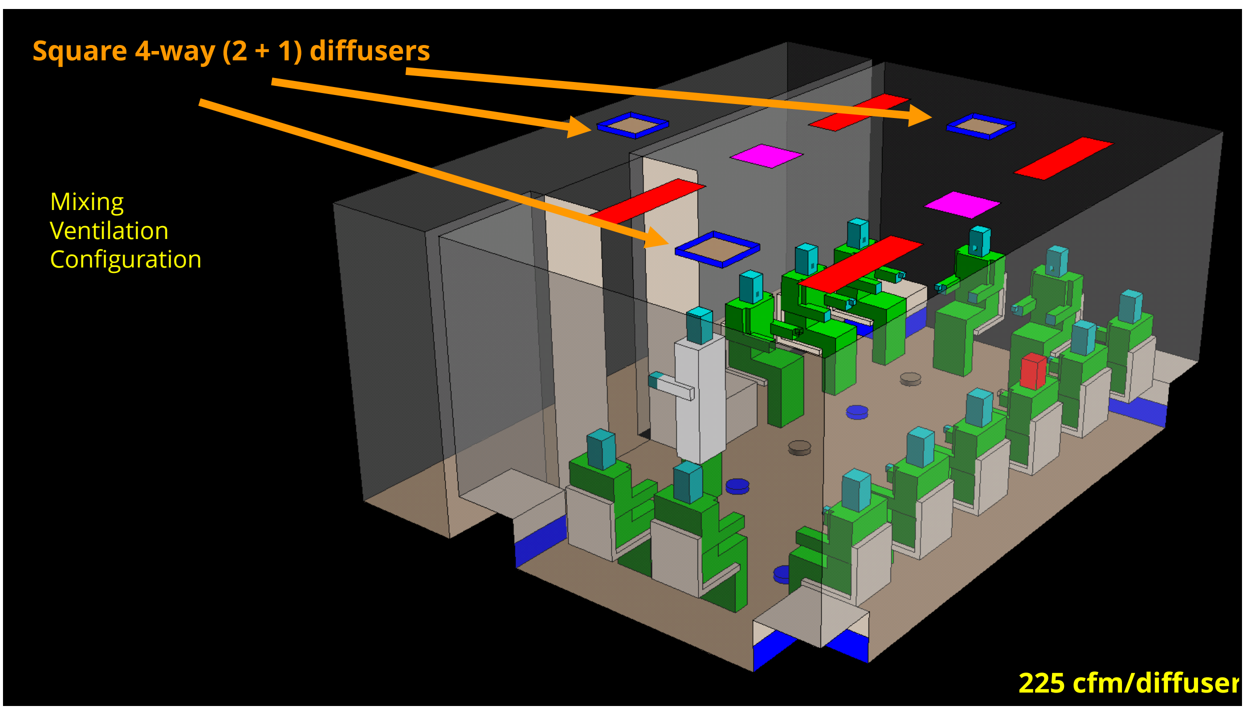
Assume occupants are quiescent

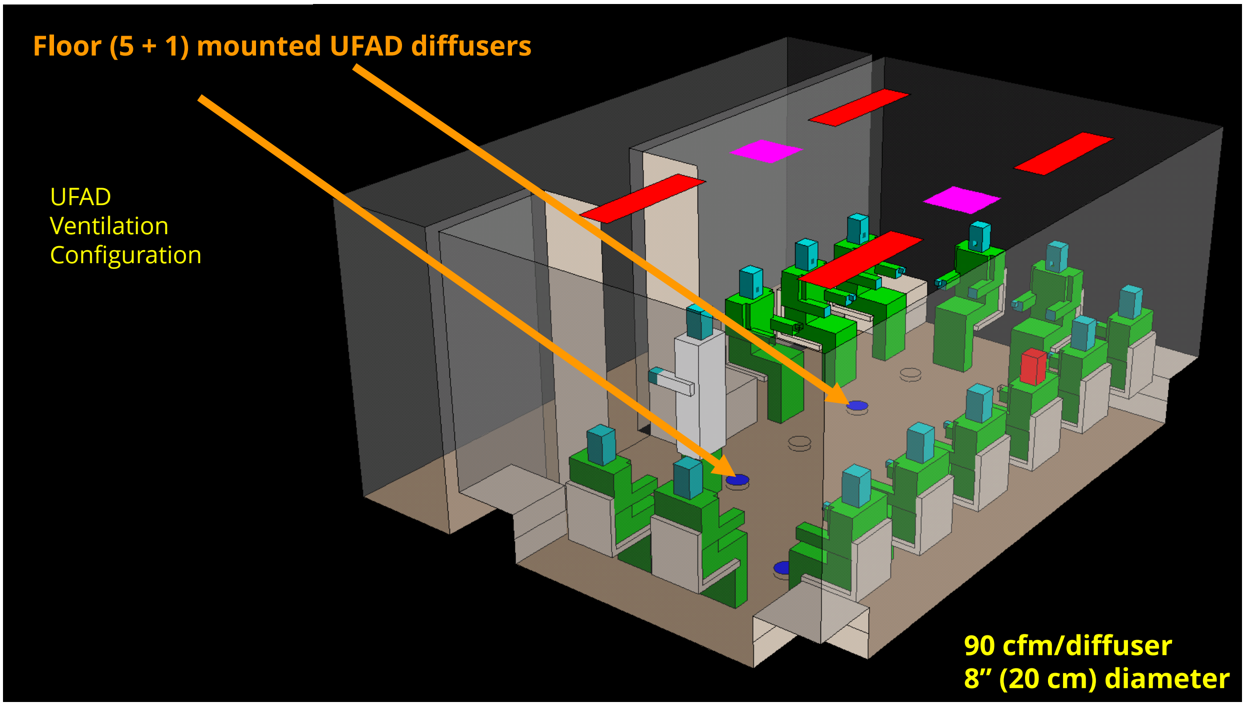
One person is ill with respiratory condition

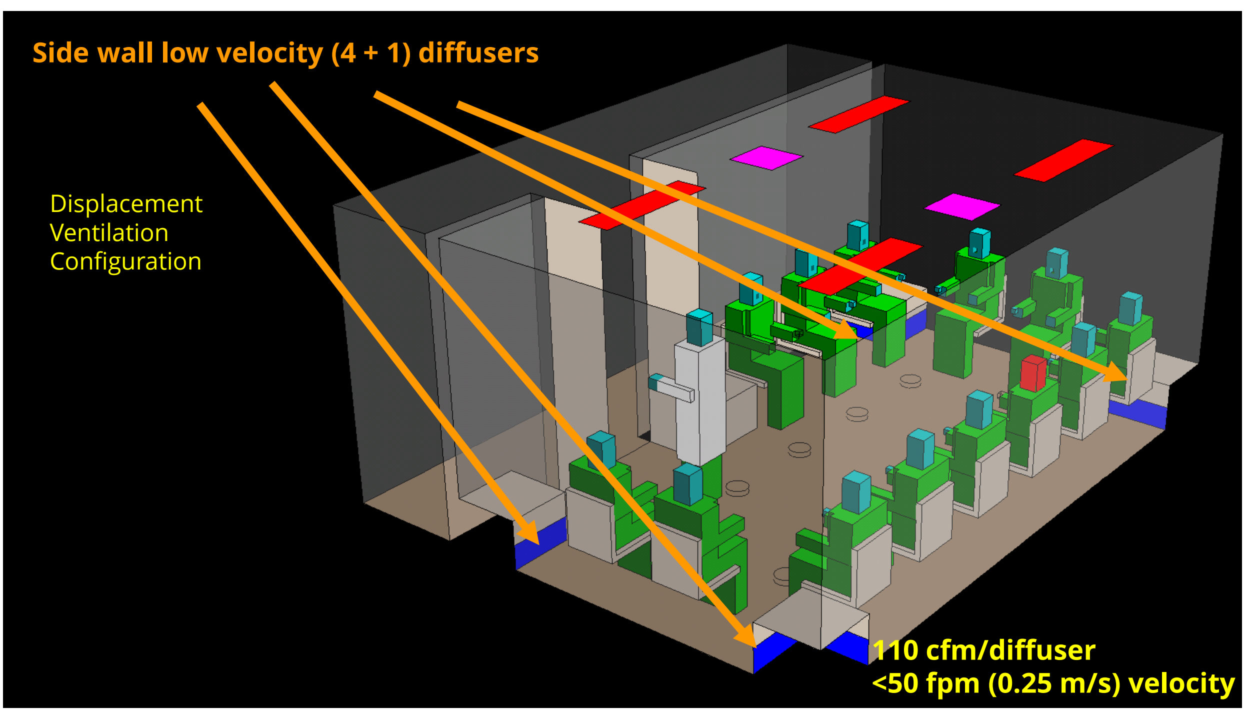
Determine risk of cross-infection for:

- Mixing (overhead)
- Displacement ventilation from corners
- UFAD

Other configurations are possible

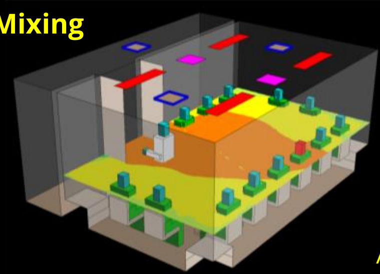



Floor (5 + 1) mounted UFAD diffusers
UFAD
Ventilation
Configuration
90 cfm/diffuser
8" (20 cm) diameter

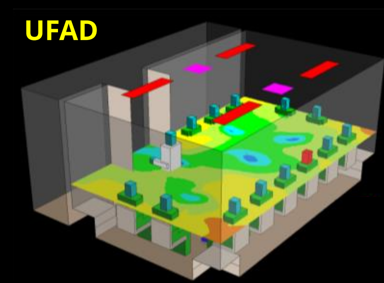

Side wall low velocity (4 + 1) diffusers
Displacement
Ventilation
Configuration
110 cfm/diffuser
<50 fpm (0.25 m/s) velocity

Compare the Different Arrangements for Age of Air

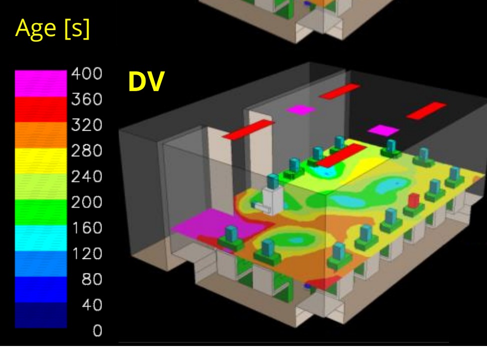
Mixing



UFAD



DV

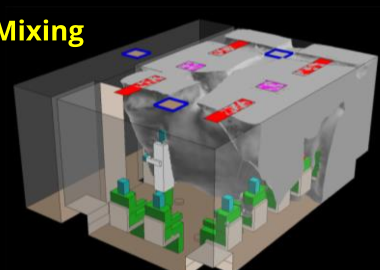


Average Age of Air
V/Q = 300 s
- (12 ACH)

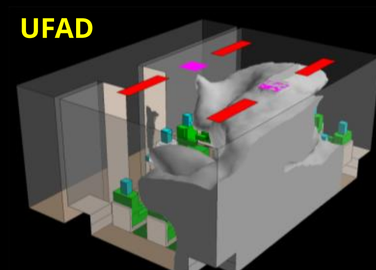
MIXING = 270 s
UFAD = 215 s
DV = 238 s

Compare the Different Arrangements for Dilution at 500

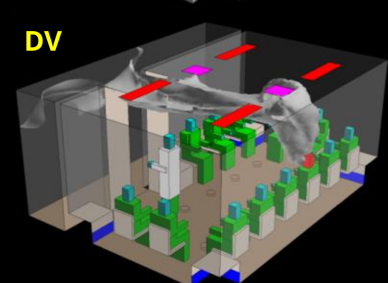
Mixing



UFAD



DV



Average Age of Air
V/Q = 300 s
- (12 ACH)

MIXING = 270 s
UFAD = 215 s
DV = 238 s

MODELING

Need for a rapid tool

There are a number of ways that the various factors can be modeled

Computational fluid dynamics (CFD)

The ventilation flow field can be simulated.

- The adjustable parameters (e.g. flow rates, filtration) turned into boundary conditions
- The options (e.g. number of people) turned into scenarios.
- The concentrations of droplet nuclei turned into a predicted variable.

Most accurate: some of animations are cool!

It would be too slow and is not within the fiscal reach of most building owners.

Need for a rapid tool

There are a number of ways that the various factors can be modeled

Network flow (zonal) modeling

Any space can be subdivided into zones.

- The flows between spaces can be estimated and entered as a boundary condition.
- The concentrations of droplet nuclei turned into a predicted variable.

This is faster than CFD and can be lower cost.

Most of the analysis for COVID-19 needs to happen of single spaces rather than multiple zones in a building.

21/06/16 102

Need for a rapid tool

There are a number of ways that the various factors can be modeled

Continuously stirred tank reactor (CSTR)

As noted before, most of the attention on transmission is within a single space / zone.

- A CSTR model permits us to estimate the concentration a zone very quickly.
- The model can be extended to multi-zones and in the limit becomes a network flow model.

This is much faster than the other methods.

Can be programed to make it easy for non-technical people to setup, run and understand.

21/06/16 103

Other zonal CSTR-like tools

The benefits of the CSTR approach was adopted quickly by many

There are a variety of tools that are available.

A recent webinar from ISIAQ highlighted a dozen of these.

Commonly cited tools are:

- The COVID-19 Aerosol Transmission Estimator: University of Colorado
- Harvard-University of Colorado Boulder Portable Air Cleaner Calculator for Schools: Harvard and UC
- Fate and Transport of Indoor Microbiological Aerosols (FaTIMA): NIST
- Facility Infection Risk Estimator: Developed by a private consultant

There are many others …

There is no ideal tool

Ideally, a tool would be:

- Quick and simple to use;
- Highly precise;
- Not require much data entry;
- Address all transmission physics;
- Show the results of all combinations of mitigation scenarios;

Unfortunately

- Quick and simple …
- Does not line up with precise.
- Information about a space is required!
- Not all transmission physics is known.
- Running combinations of scenarios takes time.

What can be done

Develop simplifications that still allow guidance to be generated …

We don’t know much about transmission …

- How many particles are released through respiratory events by an infected person…
- How much transfers across a space to another person …
- How much lands on, or in, a susceptible person …
- How much is required to infect the second person.

Develop a means to combine these unknowns into a single parameter …

- The is the basis of “quanta”.
- It is a metric that is used to define a viral load that leads to an infection.
- A quantum is defined as dose of droplet nuclei required to cause an infection in 63% of recipients.

Calculate the risk of infection based on the concentration / dosage of quanta.

We can predict concentrations of quanta and extrapolate to risk.

This then permits us to evaluate different scenarios to develop guidance based on revisions to the concentration data.

This is effectively how we use the Wells-Riley Model

21/06/16 106

There are challenges

How does one acknowledge the wide range of ventilated environments.

- Requires that a model has flexibility
- Treating a space as a single zone may:
  - Inadequately credit the space for protection it provides (e.g. displacement); or
  - May suggest more protection than is actually afforded (e.g. short-circuiting)

A single zone model is convenient, but also doesn’t recognize differences in connected spaces:

- Front of house vs. back of house

How does one review and assess the enormous range of options and their combinations

- There are literally 10,000’s of combinations of options. Think for a moment about business trying to evaluate the following:
  - Mask types for employees (N95 or cloth);
  - Increasing ventilation rate through system;
  - Changing system filters – what MERV rating;
  - Providing local HEPA filtration – what CADR?
  - Reducing occupancy;
  - Adding UVGI.

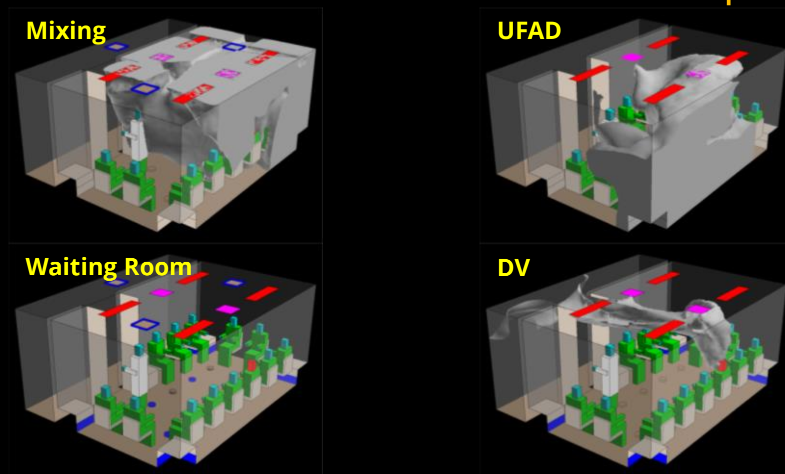
This results in 1000’s of combinations.

Example of different protection provided

In room transport: the air distribution method drives the dispersion

In the waiting / meeting room example here, an ill person coughs.

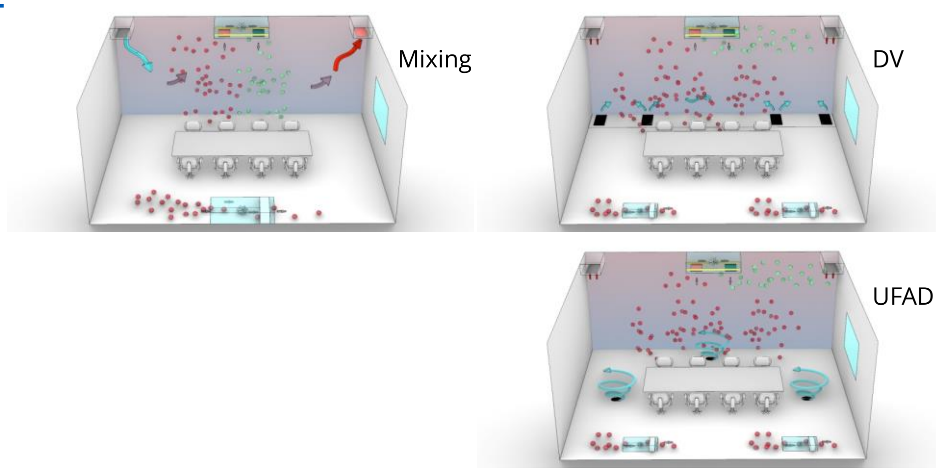
The clouds represent a zone where ~20 particles might be present



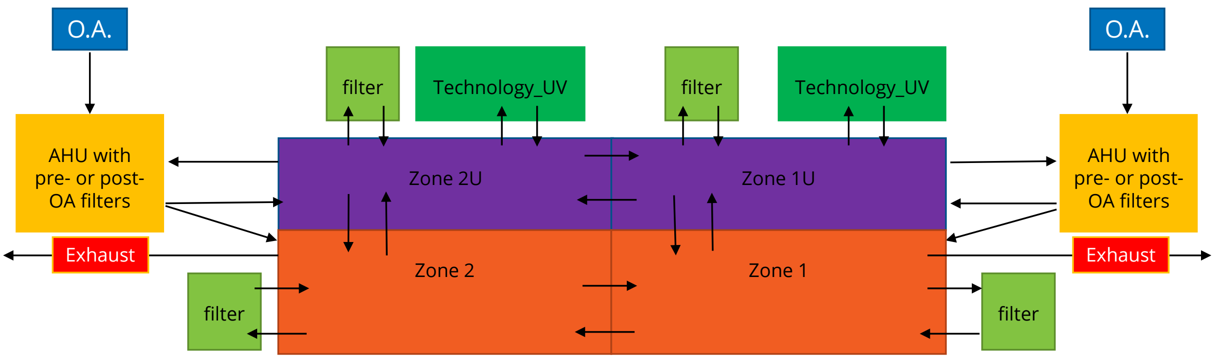
We must be careful with cleaning technology

A single zone model cannot demonstrate how an in-room filter might HURT

If you think about it, a filter with a fan blowing air around a room can destroy a stratification layer



A two-zone model



Example of a Bank

Example

A bank – like environment

Assume every 30 minutes that a vocal customer comes in for 15 minutes.

Divide the space into 2 zones plus ceiling level

- 900 sq ft front of house (FOH) – zone 1
- 450 sq ft back of house (BOH) – zone 2

Total flow of 4.6 ACH with 25% O.A.

Code (ASHRAE 62.1) required amount of O.A.

- Form of DOAS with FOH receiving the O.A.

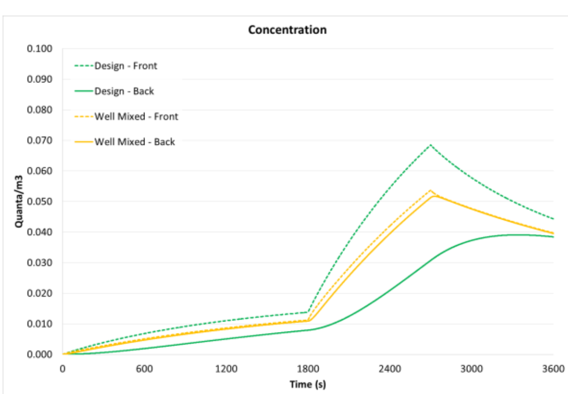
Merv13 in the owners building while code has MERV8.

Bank decides to protect employees and add 240 cfm CADR HEPA to the space (represents 4 ACH for BoH)

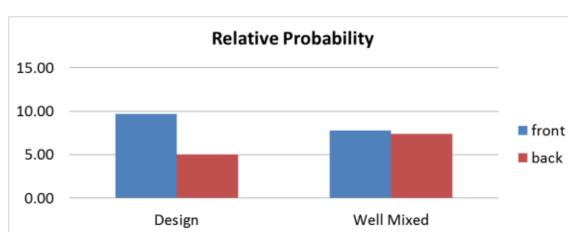
Which is better? BOH or FOH?

The decision on # zones plays a role

Concentration Results

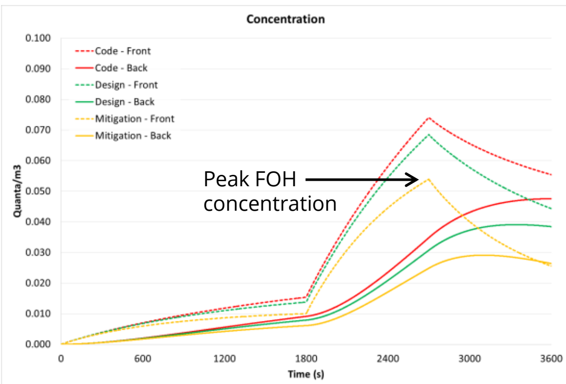


Probability of Infection



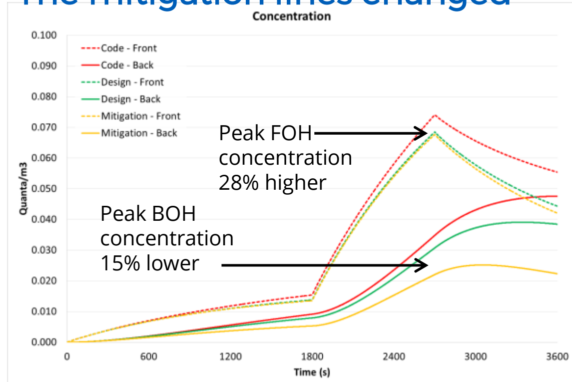
Concentration Results HEPA Location

Use HEPA in the FOH



Use HEPA in the BOH

The mitigation lines changed



The design and code versions have no HEPA – the curves for the mitigation scenarios do.
Moving the filtration to the BoH lowered the concentration there and raised it in the FOH.

The challenge assessing 1000's of Scenarios

The magic of a parallel coordinates plot …

This is an example of a food court in the podium of a building

- ~9000 sq ft = 835 m^2
- ~35% is back of house / kitchen
- Overall airflow rate of 5.7 ACH
- O.A. is 64% (high exhaust)

Issue is to determine what are best mitigation options.

There are lots of mitigation options available.

- Limit occupancy of clients – prevent walkthroughs.
- Install in-room HEPA filtration or UVGI – what level of filter?
- Change the filters on the AHU.
- Increase the O.A. rate.
- Enforce mask wearing and provide masks to employees.

This represents an easy 6000 permutations.

We need to track the employees and the customers differently.

21/06/16 116

Foodcourt Example

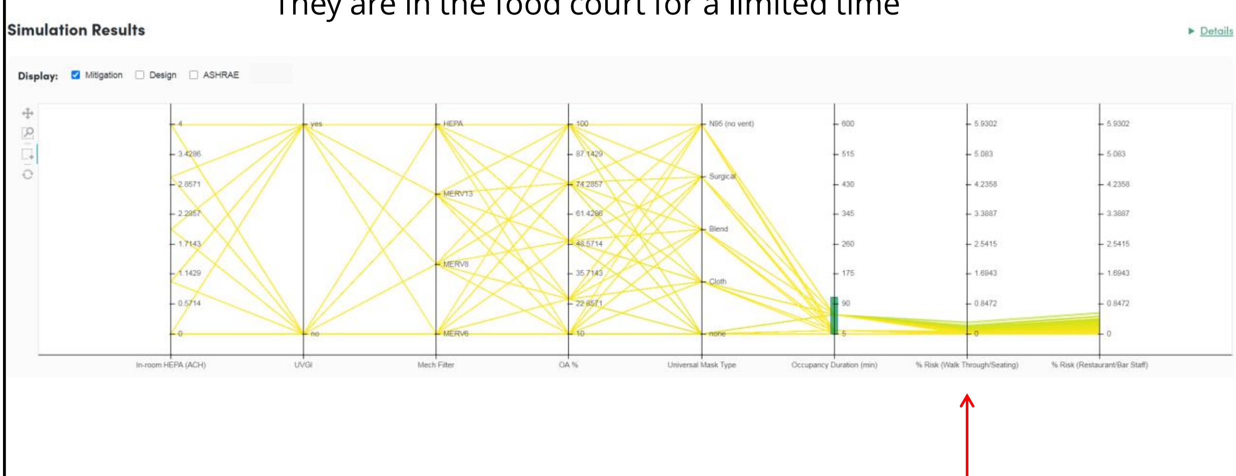
Consider the starting options

Risks for both the customers and employees are estimated

Foodcourt Example

Looking at the customers

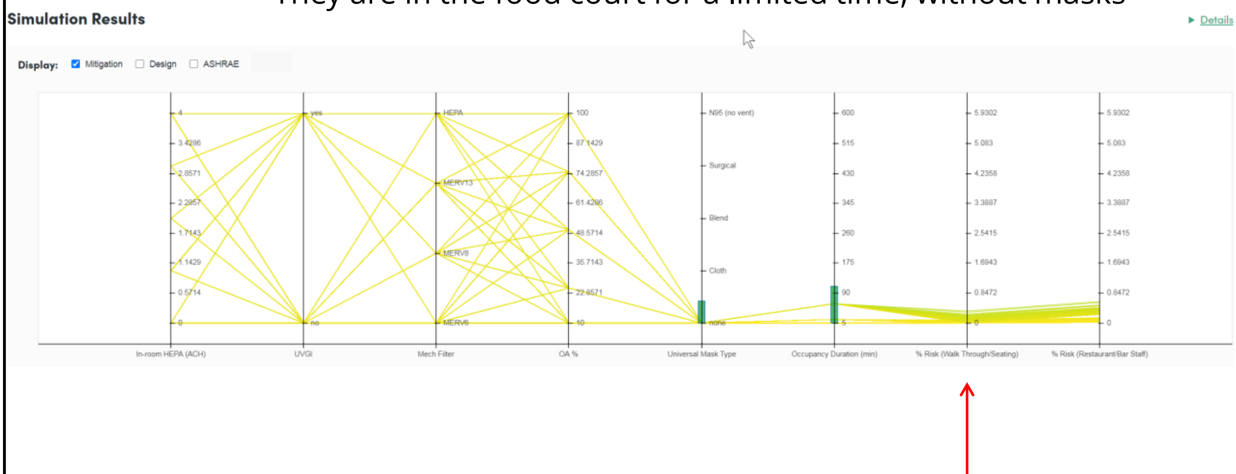
They are in the food court for a limited time



Foodcourt Example

Looking at the customers

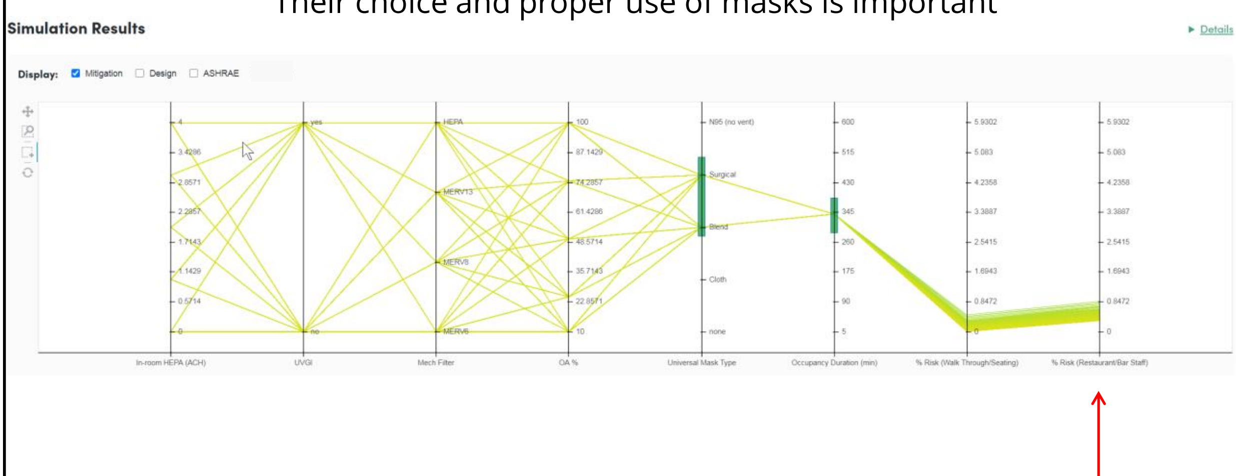
They are in the food court for a limited time, without masks



Foodcourt Example

Consider the employees

Their choice and proper use of masks is important



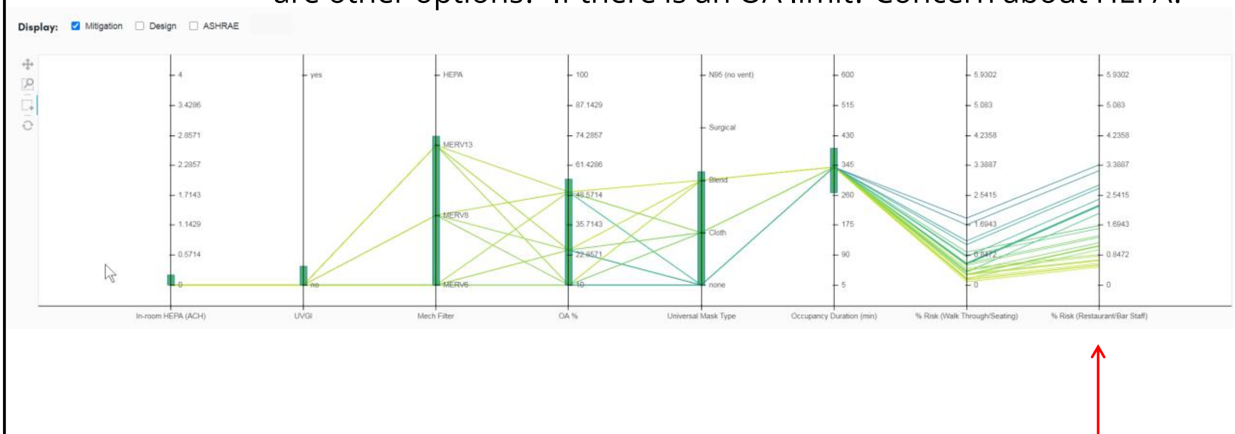
Foodcourt Example

Consider the employees

If masks are not universally used properly by employees, what are other options? If there is an OA limit? Concern about HEPA?

Simulation Results

Details



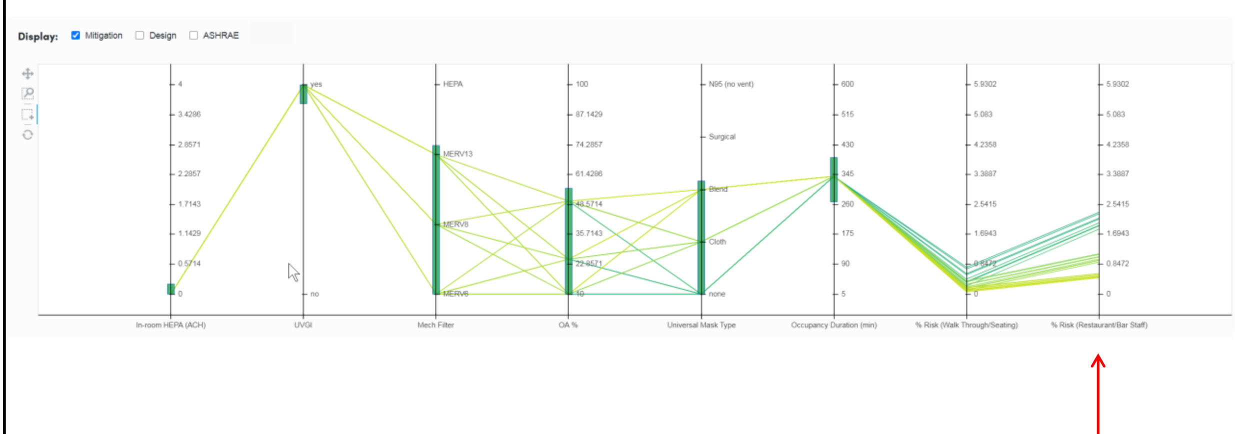
Foodcourt Example

Consider the employees

UVGI becomes important under these circumstances

Simulation Results

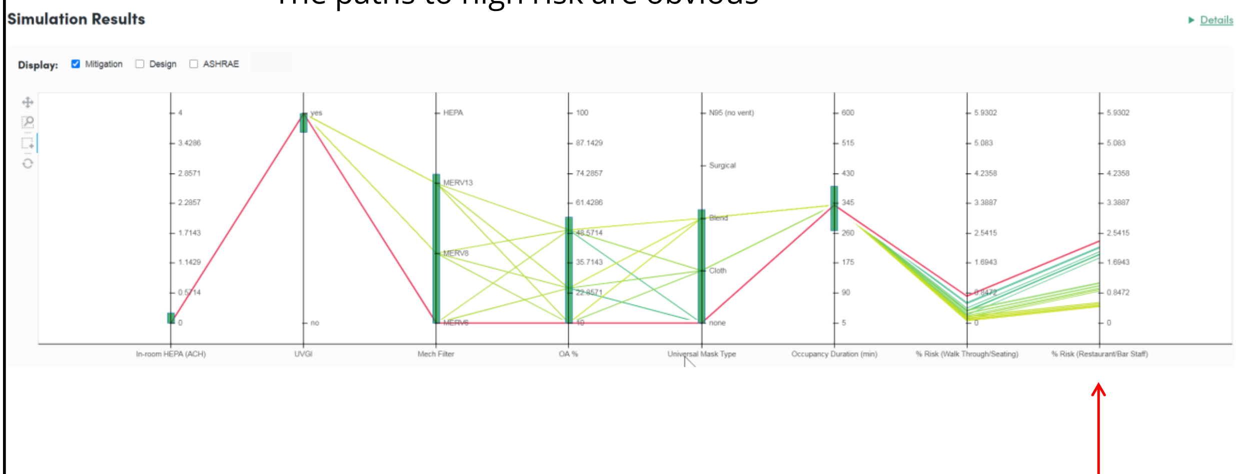
Details



Foodcourt Example

Consider the employees

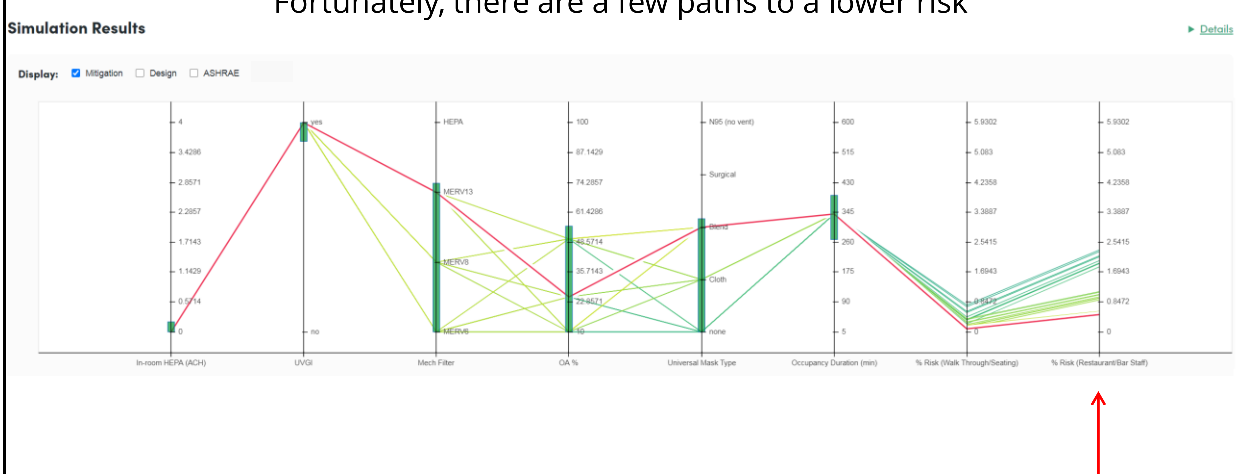
The paths to high risk are obvious



Foodcourt Example

Consider the employees

Fortunately, there are a few paths to a lower risk



Closing

Air flow and contaminant transport are dependent on numerous factors such as number and location of supply and exhaust points, room obstructions, heat sources, and the location of the contaminant release

- Understanding the source and receptors in a room is important

Using ventilation systems to manage both thermal comfort and providing protection from SARS-CoV2 can be achieved simultaneously.

- However, attention to the process and movement of people is important.

As we get back to sharing spaces, the ventilation system can help protect us.

- Will require rethinking how we use the air that we blow into spaces.

Different assessment tools have different strengths

- One should pick the right tool for the job.

What ventilation system is better: displacement or mixing?

- Either and both. A well designed system of either type can work.
- A poorly design system of either type can increase infection risk.

QUESTIONS

Duncan Phillips
Global Practice Leader,
Building Performance

+1 519 823 1311 x2409
Duncan.Phillips@rwdi.com