Simulation of Controls for Reducing Aerosol Exposure in Educational Spaces using FaTIMA

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Replaces previous versions

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Outline

- Study objective
- FaTIMA (**F**ate **a**nd **T**ransport of **I**ndoor **M**icrobiological **A**erosols)
- Educational spaces simulated
- Simulation parameters
- Results
- Summary
- Next steps

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Study Objective

To evaluate the relative reduction in aerosol exposure in education spaces as a result of changes to the operation of heating, cooling and ventilation (HVAC) systems and inclusion of non-HVAC controls (e.g., wearing of face coverings) using FaTIMA

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Disclaimers

- This study characterizes the relative reduction in aerosol exposure (of individuals with face coverings) due to controls studied
- This study provides data that can help decision makers select changes to HVAC operation that may reduce aerosol exposure
- This study is for a single zone with uniform aerosol concentration and for single contagious occupant
- This study does not define a level of exposure that is safe or healthy
- Controls presented should be part of a larger risk reduction strategy

FaTIMA

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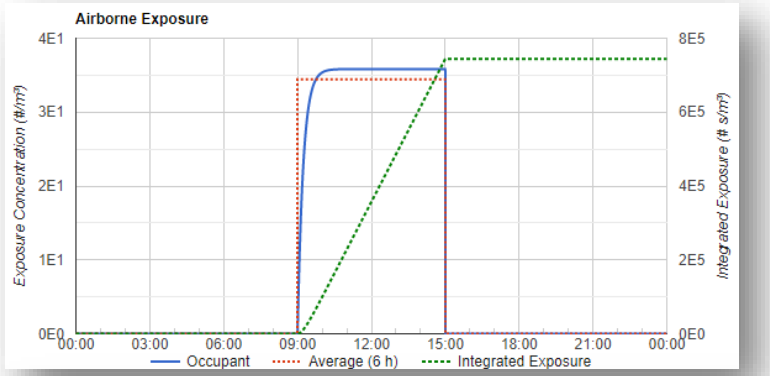
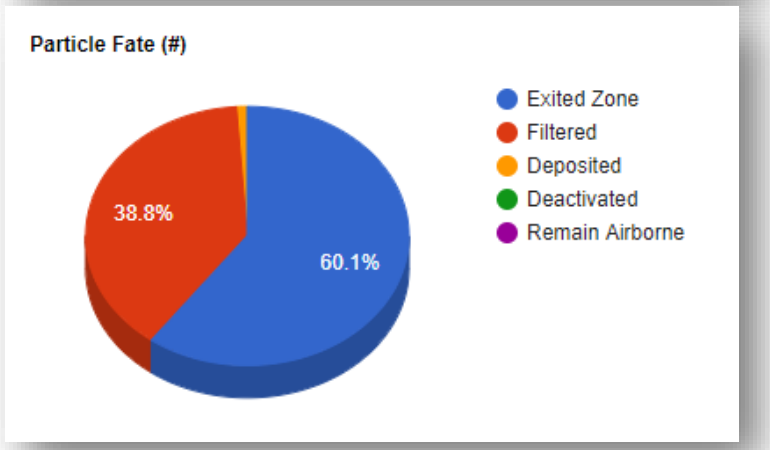
- **FaTIMA: F**ate **a**nd **T**ransport of **I**ndoor **M**icrobiological **A**erosols [Ref 1]
- https://pages.nist.gov/CONTAM-apps/webapps/FaTIMA/
- Free online tool for evaluating aerosol exposure
  - Single-zone with uniform aerosol concentration
  - 24 h simulation





Inputs
• Room dimensions • Infiltration rate • HVAC airflow rates • Portable air cleaner specs • Aerosol characteristics • Deactivation rate • Sources • Surface deposition rates • Occupied time

Outputs
• Airborne aerosol concentration • Surface loading • Aerosols on filter • Occupant exposure • Numerical and graphical

FaTIMA web interface

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NIST MULTIZONE MODELING

Fate and Transport of Indoor Microbiological Aerosols (FaTIMA)

See TN 2095 - A Tool to Model the Fate and Transport of Indoor Microbiological Aerosols (FaTIMA) for documentation of this tool.

Instructions: Set Inputs then click the RUN SIMULATION button.

Inputs

Zone Geometry	Volume: 191 m³	Floor Area: 74 m²	Wall Area: 89 m²	Ceiling Area: 74 m²	Other Surface Area: 0 m²	Surface to Volume Ratio: 1.2
Infiltration	Infiltration: 0.3 1 / h	Particle Penetration Coefficient: 1				
Ventilation System	Supply Airflow Rate: 413 sL/s	Outdoor Air Intake Fraction: 0.3	Return Airflow Rate: 371 sL/s	Local Exhaust Airflow Rate: 0 sL/s		
System Filters	Outdoor Air Filter: None	Recirculation Air Filter: MERV 8				
Calculated Airflows	Total Outdoor Air Change Rate: 2.6353 1/h	Outdoor Air Intake Rate: 123.9 sL/s	Recirculation Airflow Rate: 289.1 sL/s			
Room Air Cleaner	Maximum Airflow Rate: 94.39 sL/s	Fan Flow Fraction: 0	Filter Efficiency: 0.8	CADR: 0 sL/s		
Particle Properties	Name: IV1	Diameter: 1 µm	Density: 1 g/cm³	Particle Deactivation: Off	Half-life: 1.1 h	Decay Rate: 0.63014 1/h
Continuous Source	Source: On	Generation Rate: 500 #/min	Generation Time Period: Start 09:00 / End 15:00			
Burst Source	Source	Burst Type	Amount per Burst	Generation Time Period	Burst Interval	

FaTIMA results

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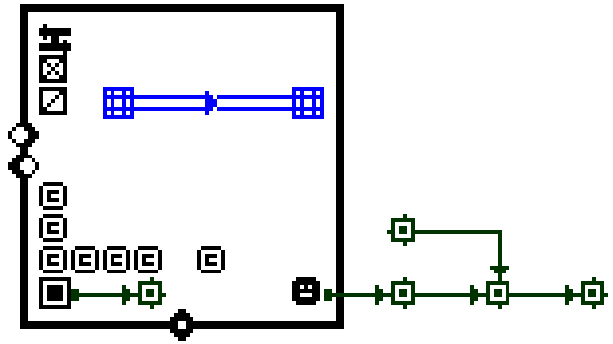
RUN SIMULATION | Simulation Complete. | Project File | Download CONTAM Project | Report | Download CSV Report | Go back to Inputs

Results

Sources	Continuous: 180000 #	Burst: 0 #	Outdoor: 0 #	Total: 180000 #	
Airborne Concentration	Average (6 h): 34.439 #/m³	Average (24 h): 8.9546 #/m³	Maximum (24 h): 35.825 #/m³		
Airborne Exposure	Average (6 h): 34.45 #/m³	Maximum (6 h): 35.825 #/m³	Integrated Exposure: 744130 # s/m³		
Surface Loading	Floor: 26.31 #/m²	Walls: 0.26156 #/m²	Ceiling: 0 #/m²	Other: 0 #/m²	Total: 26.572 #/m²
Deposited	Floor: 1946.1 #	Walls: 23.281 #	Ceiling: 0 #	Other: 0 #	Total: 1969.4 #
Filtered	Outdoor Air: 0 #	Recirculation: 69844 #	Air Cleaner: 0 #	Envelope: 0 #	Total: 69844 #
Other	Deactivated: 0 #	Exited Zone: 108190 #	Remain Airborne: 7.1272e-14 #		

FaTIMA results

RUN SIMULATION | Simulation Complete. | Project File | Download CONTAM Project | Report | Download CSV Report | Go back to Inputs



CONTAM Project

Air handler
- User sets OA (fraction of supply)
- Exhaust rate calculated using supply, return, and OA rates set by user

Supply for air handler

Return for air handler

C Defines burst (cough) source, constant (breathing) source, sinks (for deposition), or deactivation

Zone characteristics (area, volume)

Controls for outputting 15-min zone concentration, integrated zone concentration, integrated exposure

Portable air cleaner (supply, return, and fan with filter)

Standalone exhaust fan, infiltration set by user

FaTIMA results

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CSV: "inputs" portion

Inputs

Zone Geometry

Zone Volu	Floor Area	Wall Area	Ceiling Ar	Other Sur	Surface Volume Ratio
191	74	89	74	0	1.2

Infiltration

Infiltratic	Penetration Factor
0.3	1

Ventilation System

Supply Ai	Outdoor A	Return Ai	Local Exhaust Airflow Rate (sL/s)
413	0.3	371	0

System Filters

Outdoor A	Recirculation Air Filter
None	MERV 8

Calculated Airflows

Total Out	Outdoor A	Recirculation Airflow Rate (sL/s)
2.6353	123.9	289.1

Room Air Cleaner

Maximum	Fan Flow	Filter Effi	CADR (sL/s)
94.39	0	0.8	0

Particle Properties

Name	Diameter	Density (g	Particle D	Half-life	Decay Rate (1/h)
IV1	1	1	Off	1.1	0.63014

Continuous Source

Source	Generatic	Generatic	Generation Time Period (End)
On	500	9:00	15:00

Burst Source

Source	Burst Typ	Amount p	Generatic	Generatic	Burst Interval (min)
Off	Intermitte	45	0:01	24:00:00	10

Particle Deposition Velocities

Floor (cm	Wall (cm/	Ceiling (c	Other Sur	Effective Deposition Rate (1/h)
0.0034	3.38E-05	0	0	0.047989

Initial Concentrations

Outdoor A	Zone Air (#/m³)
0	0

Occupant Exposure

Occupanc	Occupanc	Occupanc	Intermitte	Intermittent Occupancy Duration (min)
9:00	15:00	Constant	60	10

CSV: "results" portion

Results

Sources

Continuo	Burst (#)	Outdoor (	Total (#)
180000	0	0	180000

Airborne Concentration

Average (	Average (	Maximum (24 h) (#/m³)
34.439	8.9546	35.825

Airborne Exposure

Average (	Maximum	Integrated Exposure (# s/m³)
34.45	35.825	744130

Surface Loading

Floor (#/n	Wall (#/n	Ceiling (#	Other (#/n	Total (#/m²)
26.31	0.26156	0	0	26.572

Deposited

Floor (#)	Walls (#)	Ceiling (#	Other (#)	Total (#)
1946.1	23.281	0	0	1969.4

Filtered

Outdoor A	Recircula	AirCleane	Envelope	Total (#)
0	69844	0	0	69844

Other

Deactivat	Exited Zo	Remining in Zone (#)
0	108190	7.13E-14

Same as what's on web interface

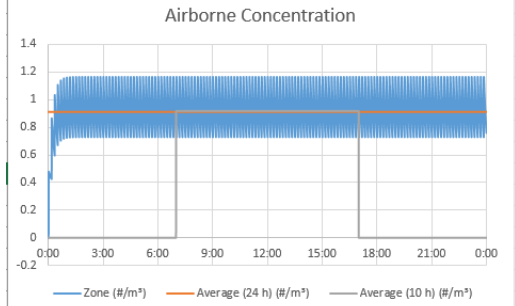
Time series of airborne exposure and surface loading

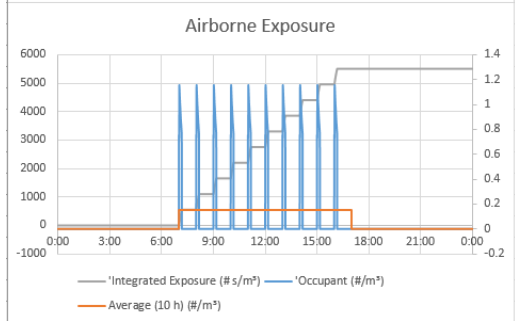
Airborne Concentration				Airborne Exposure				Surface Loading					
Time	Zone (#/n	Average (	Average (6 h) (#/m³)	Time	'Occupant	Average (	'Integrated Exposur	Time	Total (#/n	Floor (#/n	Wall (#/n	Ceiling (#	Other (#/m²)
0:00:00	0	8.95462	0	0:00:00	0	0	0	0:00:00	0	0	0	0	0
0:00:15	0	8.95462	0	0:00:15	0	0	0	0:00:15	0	0	0	0	0
0:00:30	0	8.95462	0	0:00:30	0	0	0	0:00:30	0	0	0	0	0
0:00:45	0	8.95462	0	0:00:45	0	0	0	0:00:45	0	0	0	0	0
0:01:00	0	8.95462	0	0:01:00	0	0	0	0:01:00	0	0	0	0	0
0:01:15	0	8.95462	0	0:01:15	0	0	0	0:01:15	0	0	0	0	0
0:01:30	0	8.95462	0	0:01:30	0	0	0	0:01:30	0	0	0	0	0
0:01:45	0	8.95462	0	0:01:45	0	0	0	0:01:45	0	0	0	0	0
0:02:00	0	8.95462	0	0:02:00	0	0	0	0:02:00	0	0	0	0	0

FaTIMA results

Paste fatima.csv file here

Template for NIST FaTIMA single zone aerosol exposure tool.



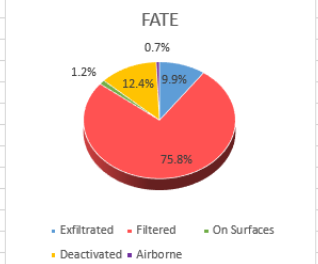


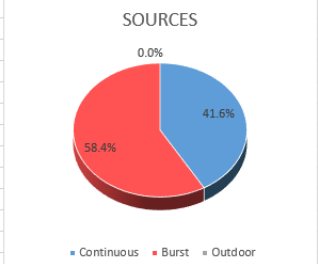
FATE		
Qbal	50	
	(#)	
Exfiltrated	1.09E+03	9.9%
Filtered	8.41E+03	75.8%
On Surfaces	1.33E+02	1.2%
Deactivated	1.38E+03	12.4%
Airborne	7.59E+01	0.7%
TOTAL	1.11E+04	

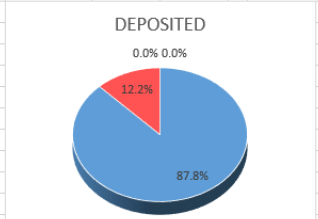
SOURCES	(#)	
Continuous	4.61E+03	41.6%
Burst	6.48E+03	58.4%
Outdoor	0.00E+00	0.0%
	1.11E+04	

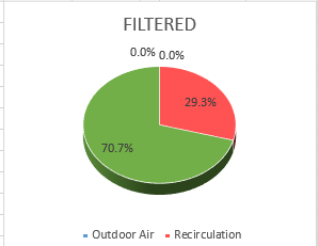
DEPOSITED	(#)	
Floor	1.17E+02	87.8%
Walls	1.62E+01	12.2%
Ceiling	1.36E-03	0.0%
Other	0.00E+00	0.0%
	1.331E+02	

FILTERED	(#)	
Outdoor Air	0.00E+00	0.0%
Recirculatior	2.46E+03	29.3%
Air Cleaner	5.95E+03	70.7%
Envelope	0.00E+00	0.0%
	8.41E+03	









Paste fatima.csv file here.

Inputs		
Zone Geometry		
	Zone Volume (m³)	
	100	
Infiltration		
	Infiltration 1/h	
	0.5	
Ventilation System		
	Supply Airflow Rate (sm³/h)	
	360	
System Filters		
	Outdoor Air Filter	
	None	
Calculated Airflows		
	Total Outdoor Air Change Rate (1/h	
	0.5	
Room Air Cleaner		
	Maximum Airflow Rate (scfm)	
	200	
Particle Properties		
	Name	
	IV1	
Continuous Source		
	Source	
	On	
Burst Source		
	Source	
	On	
Particle Deposition Velocities		
	Floor (cm/s)	
	0.00371	
Initial Concentrations		
	Outdoor Air (#/m³)	
	0	

Downloadable results template

Study

Educational spaces simulated

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Required outdoor air (OA)

ASHRAE 62.1-2019	L/s·person	L/s·m²	cfm/person	cfm/ft²	Default occupancy (#/100 m² or #/1000 ft²)
Classroom (ages 5-8)	5	0.6	10	0.12	25
Classroom (ages 9+)	5	0.6	10	0.12	35
Lecture hall	3.8	0.3	7.5	0.06	65

Note:
Total OA required = per·person rate x #ppl + per·area rate x Area

Supply rates[Ref 2]

	L/s·m²	cfm/ft²
Classroom (ages 5-8)	5.60	1.12
Classroom (ages 9+)	7.05	1.41
Lecture hall	7.05	1.41

Space information

Size	Dimensions (m)	Dimensions (ft)	Occupancy	Assumption/Source
Classroom (ages 5-8)	8.6 x 8.6 x 2.6	28 x 28 x 8.5	18	California Specification 01350 [Ref 3]
Classroom (ages 9+)	12.2 x 7.3 x 2.6	40 x 24 x 8.5	31	Portable classroom [Ref 4]
Lecture hall	18.9 x 18.9 x 5.2	62 x 62 x 17	232	Area = 4 x classroom (ages 5-8) Height = 2 x classroom (ages 5-8)

Simulated spaces

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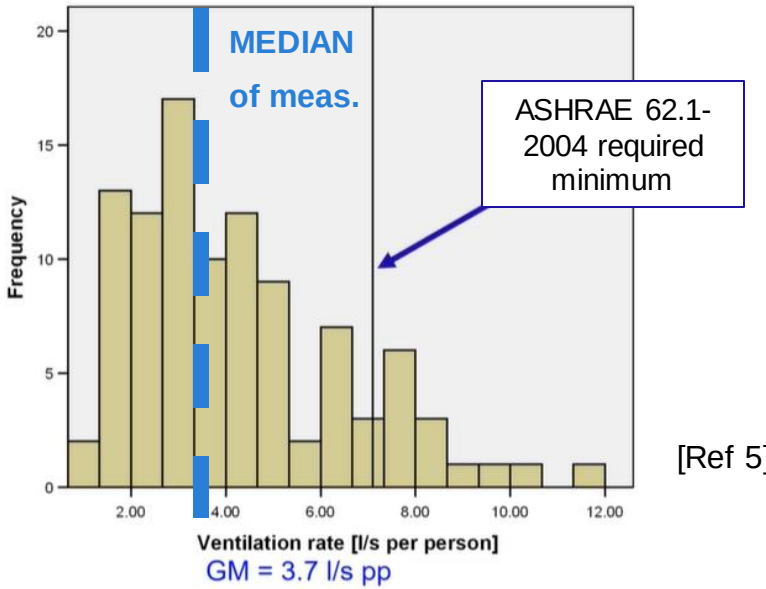
Space Type (occupant ages)	Floor area, m^2 (ft^2)	Volume, m^3 (ft^3)	Full occupancy	Total outdoor air ventilation rate			Supply airflow rate		
				L/s·p	cfm/p	h^{-1}	L/s·m^2	cfm/ft^2	h^{-1}
Classroom (5-8)	74 (793)	191 (6,739)	18	7.4	15.2	2.6	5.60	1.12	7.8
Portable classroom (9+)	89 (960)	231 (8,158)	31	6.7	13.7	3.3	7.05	1.41	9.8
Lecture hall	357 (3,841)	1,848 (65,270)	232	4.3	8.5	1.9	7.05	1.41	4.9

Notes:

- Zone Air Distribution Effectiveness E_z = 1 used to calculate outdoor air ventilation rate in ASHRAE Standard 62.1-2019
- As a reference, measured rates below:



[Ref 5]

Ventilation rate distributions in school classrooms; 94% below minimum recommended

Aerosol simulation parameters

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- Size: 1 μm
- Density: 1 g/cm^3 (water)
- No virus inactivation
- Deposition velocities

Space Type (occupant ages)	Air change rate (h^{-1}) (supply)	Deposition velocity (cm/s) [Ref 1]			Total deposition rate (h^{-1})
		Floors	Walls	Ceiling	
Classroom (5-8)	7.8	3.40E-03	3.38E-05	0	0.048
Portable classroom (9+)	9.8		1.13E-03	1.75E-04	0.067
Lecture hall	4.9		3.38E-06	0	0.024

- Continuous source
  - Contagious person emitting 500 particles/min
- All results will be normalized

Exposure calculations

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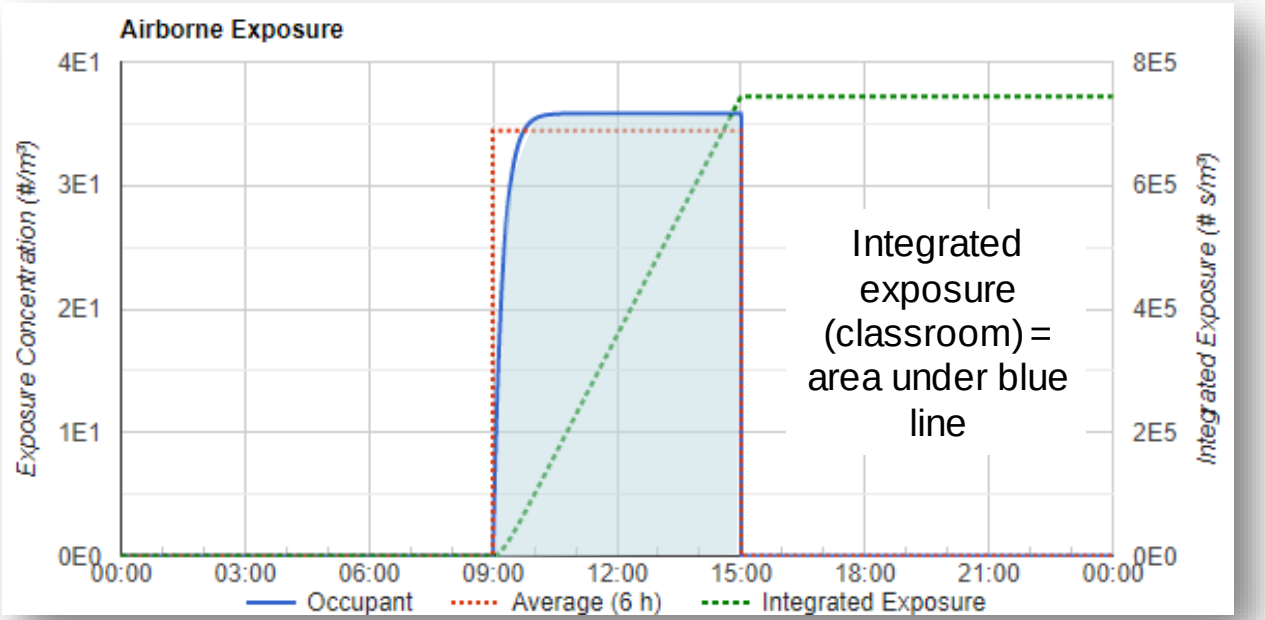
- Integrated exposure evaluated for:
  - Classrooms: 9 am to 3 pm
  - Lecture hall:
    - 9 am to 3 pm (a contagious person in each 1 h class)
    - Integrated exposure evaluated from 2 pm to 3 pm (last class of the day)



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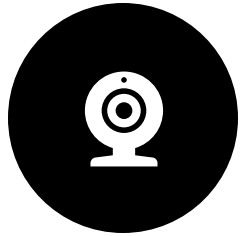
Simulated aerosol controls

FACE COVERINGS

OUTDOOR AIR (OA)



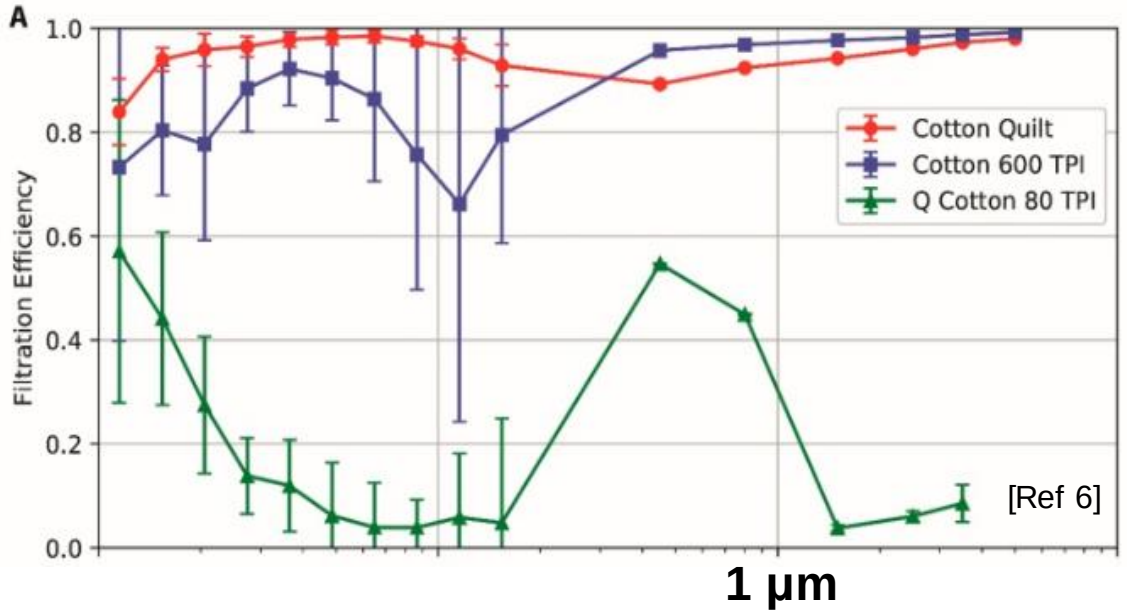
PORTABLE AIR CLEANER (PAC)

FILTER/ MERV RATING

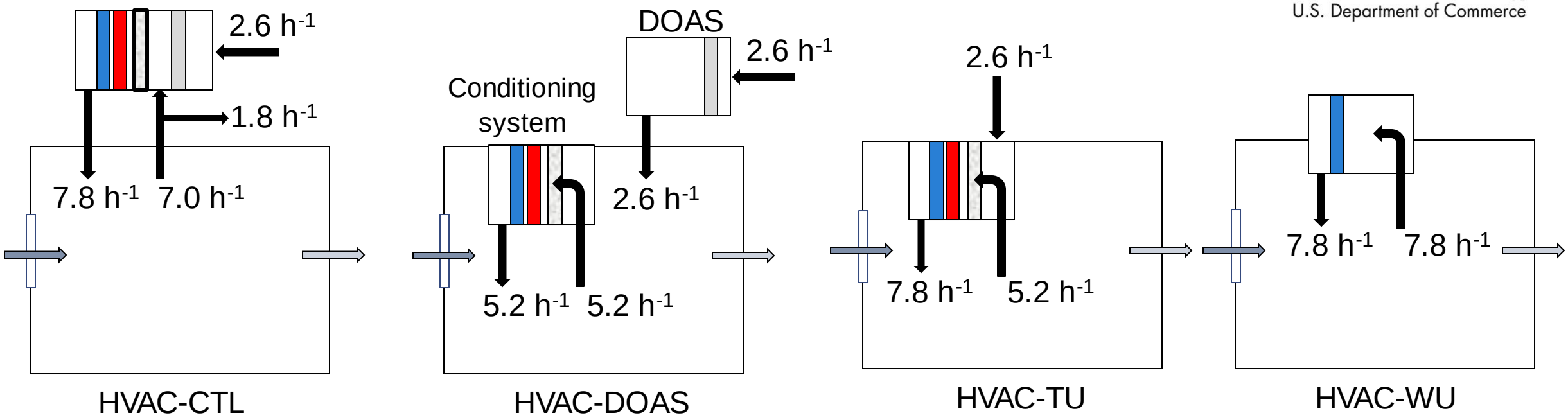
EXHAUST FAN

Simulation of face coverings

- Assuming homemade cotton masks (80 threads per inch, TPI) filter efficiency:
  - Filter efficiency at 1 μm: 30 % [Ref 6]
- Assume perfect fit in simulations



Simulated HVAC system types – classroom (5-8) values



Cooling/Heating coils

OA filter (rating N/A for this study)

MERV 6 filter

MERV 8 filter

Simulation of HVAC operation (OA & filter)

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- For each space, four HVAC systems simulated:
  - CTL: central systems (e.g., roof top units, central multizone, variable air volume (VAV))
  - DOAS: dedicated outdoor air system (assume separate unit handling room-level conditioning)
  - TU: terminal units (e.g., fan coil units, unit ventilators) with no supplementary HVAC
  - WU: window units (e.g., room air conditioners)

HVAC system	Mechanical OA (h^{-1})			Can OA be varied?	Assumed infiltration (h^{-1})	Recirculation filtration level	Can filter be upgraded?
	Class (5-8)	Class (9+)	Lecture hall				
HVAC-CTL	2.6	3.3	1.9	Y	0.30 [Ref 7]	MERV 8	Y
HVAC-DOAS	2.6	3.3	1.9	N		MERV 6	N
HVAC-TU	2.6	3.3	1.9	N		MERV 6	Y
HVAC-WU	0	0	0	N		None	N

Notes:
1. HVAC-CTL: MERV 8 filters per ASHRAE 62.1-2019
2. MERV 6 filters for terminal units per manufacturer specifications

More about filters

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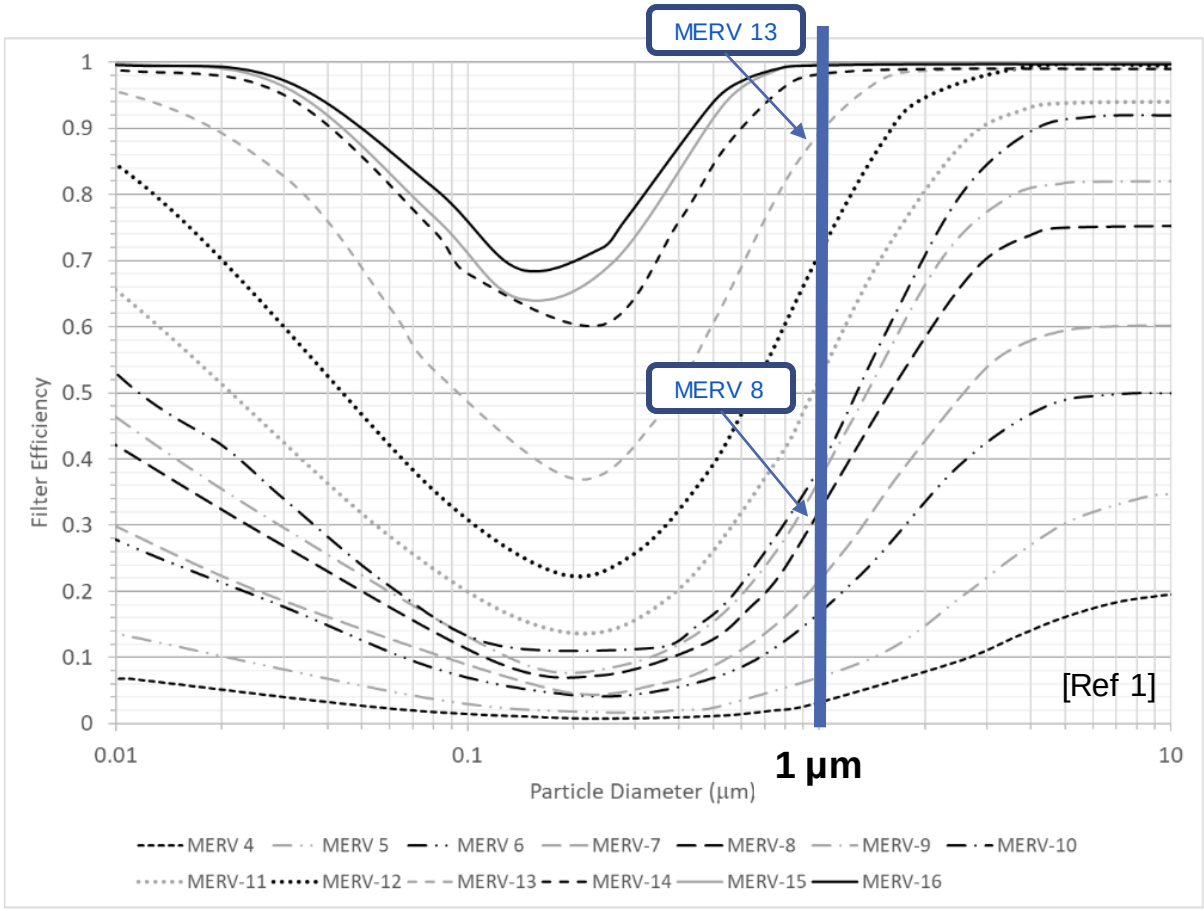
- Filters can be rated using MERV (minimum efficiency reporting value) rating system [Ref 8]
  - Depends on particle/aerosol diameter
  - Filter efficiency for 1 µm varies from 0.01 to 0.99 as MERV rating increases
- Most HVAC-related guidance recommends minimum MERV 13 which are 90 % effective at removing 1 µm aerosols [Ref 9]
- Performance curves for new, perfectly installed filters



Simulation of PACs

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- Portable air cleaner (PAC)
  - CADR [Ref 10]: clean air delivery rate = airflow (cfm) x efficiency of particle removal of 3 test particles (i.e., smoke 0.09 µm -1.0 µm, dust 0.5 µm -3 µm and 5 µm -11 µm pollen) per ANSI/AHAM Standard AC-1
  - Convert CADR to h^{-1}

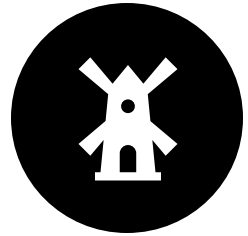
$$h^{-1} = \frac{CADR \times 60}{(area \times height)\ ft^3}$$

  - PACs: typically 50 CADR to 400 CADR
- Simulation assumptions
  - Filter efficiency 0.99 (HEPA filter)
  - Operated at highest speed setting
  - For classroom and portable classroom: units that deliver between 1 h^{-1} and 6 h^{-1}
  - For lecture hall, no single available PAC able to deliver 1 h^{-1} so simulated multiples of 400 CADR

Space Type (occupant ages)	Area, m^2 (ft^2)	Equivalent air changes (h^{-1}) achieved with CADR listed						
		150	250	300	350	400	2x400	3x400
Classroom (5-8)	74 (793)	1.3	2.2	2.7	3.1	3.6	7.1	10.7
Portable classroom (9+)	89 (960)	1.1	1.8	2.2	2.6	2.9	5.9	8.8
Lecture hall	357 (3,841)	0.1	0.2	0.3	0.3	0.4	0.7	1.1

Note: classrooms ceiling height = 2.6 m (8.5 ft), lecture hall ceiling height = 5.2 m (17 ft).

Simulation of exhaust fan



- Exhaust fans simulated for TU and WU systems
- Simulation assumptions
  - For classroom and portable classroom: airflow from 1 h^{-1} to 6 h^{-1}
  - For lecture hall, no single available PAC able to deliver 1 h^{-1} so simulated multiples of 400 cfm
- Makeup air for exhaust fans typically from adjacent spaces (corridor, other classroom) and through building envelope
  - Can lead to IAQ issues: cross-contamination, moisture → mold

Sensitivity analysis

	Base assumption	Uncertainty
Face coverings	30 % filtration efficiency	20 % less effective for fit
Infiltration	0.30 h^{-1}	0.1 h^{-1} and 1.0 h^{-1}
OA (HVAC-TU)	62.1-2019 rate	20 % less for performance issues
Filter	MERV 13: 90 % filtration efficiency at 1 μm	10 % less for improper installation, age, etc.
PACs	99 % effective at max setting	33 % capacity when operated at <max setting
Exhaust fan	100 % effective	10 % less for improper installation

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Results
across systems

No controls – all space types

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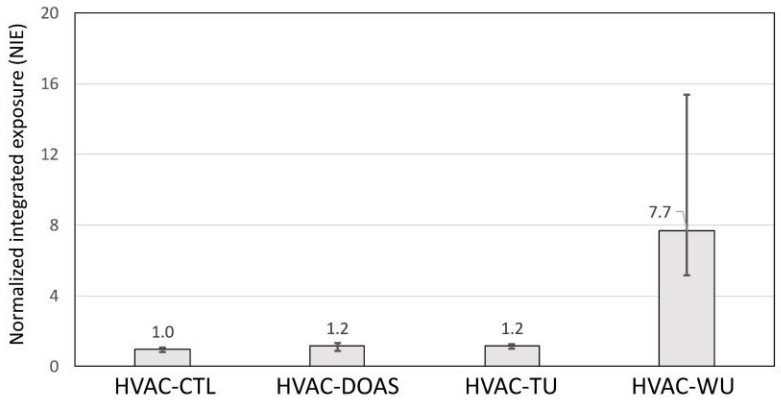
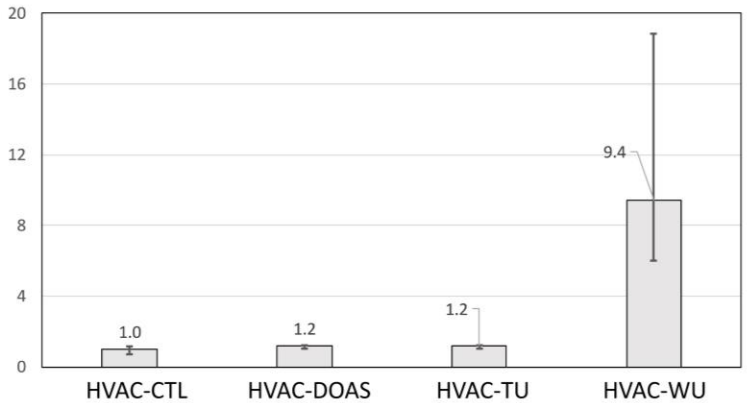
- Integrated exposure normalized (NIE) to HVAC-DOAS with:
  - One person contagious
  - No face covering
  - 6 h day (classrooms 5-8 and 9+) or 1 h day (last class of the day, lecture)
- Error bars account for simulation results using infiltration rates that are higher/lower than base
  - HVAC-WU system has largest error bar due to having no mechanical OA as its base
- HVAC-WU systems have highest NIE

$DOAS_{oa}, CTL_{oa}, TU_{oa}$ = 2.6 h^{-1} WU_{oa}=0.0 h^{-1}



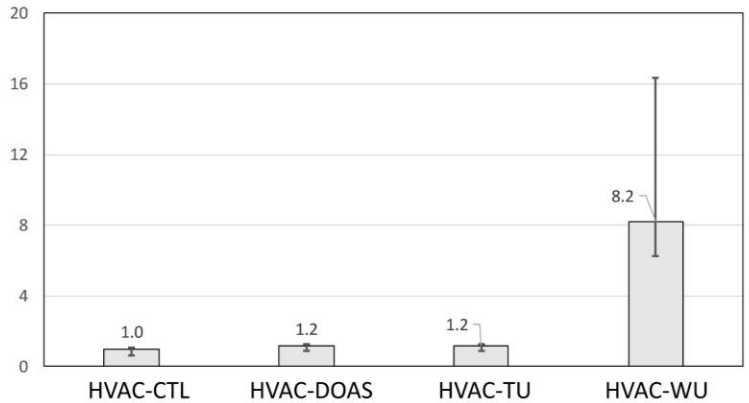
Classroom (5-8)

$DOAS_{oa}, CTL_{oa}, TU_{oa}$ = 3.3 h^{-1} WU_{oa}=0.0 h^{-1}



Portable classroom (9+)

$DOAS_{oa}, CTL_{oa}, TU_{oa}$ = 1.9 h^{-1} WU_{oa}=0.0 h^{-1}



Lecture hall

NIE ventilating at half of OA requirement

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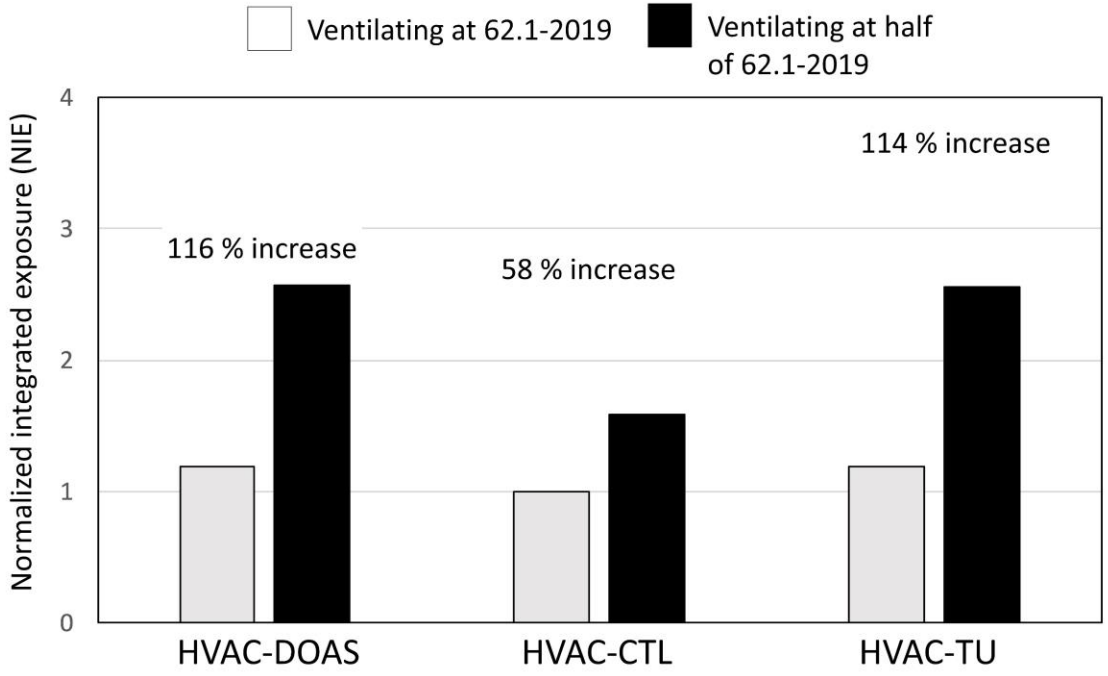
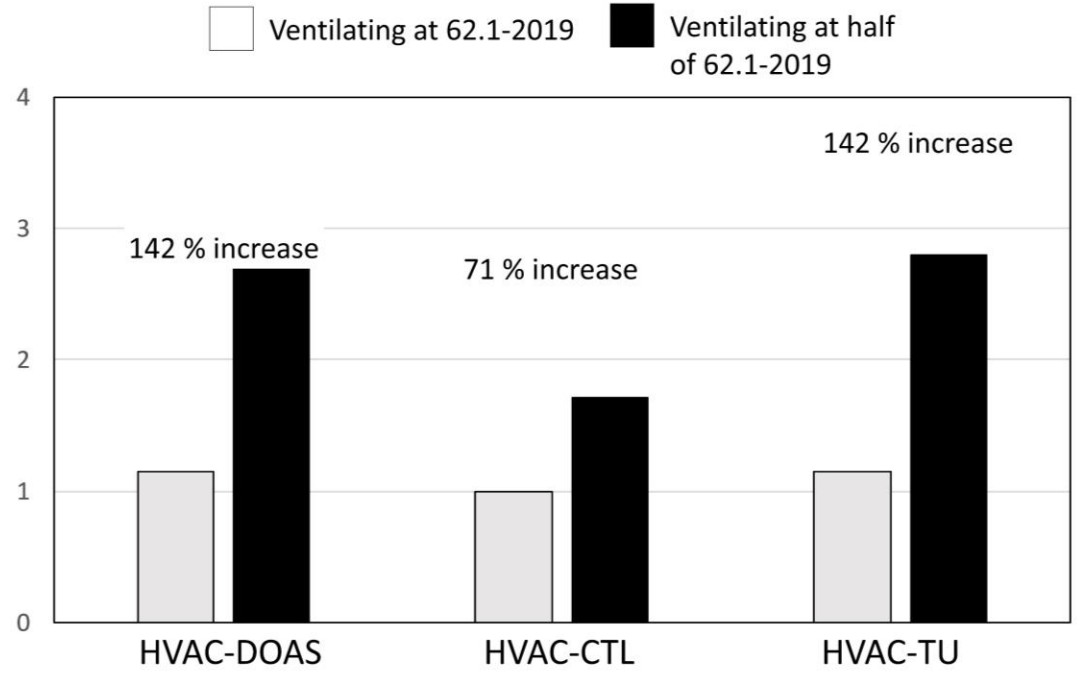
- Increases in NIE similar in classrooms (5-8, 9+)



Classroom (5-8)



Lecture hall

Combined face coverings + PAC (300 CADR) – all spaces

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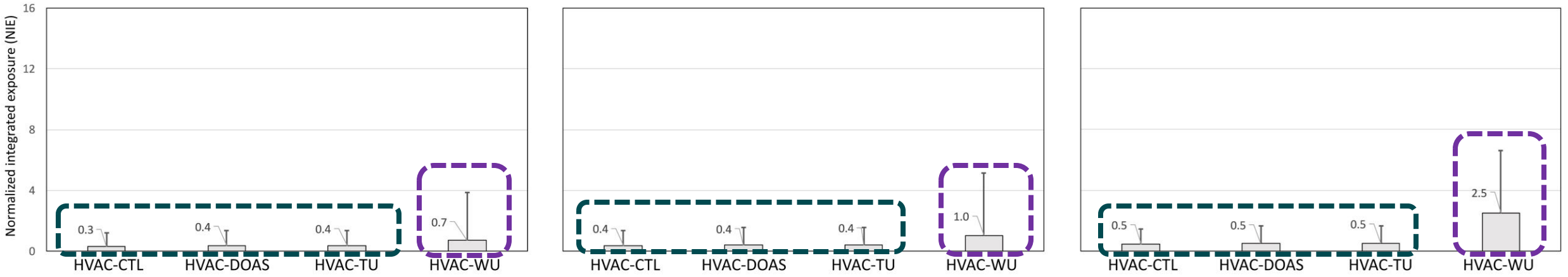
- Normalized to HVAC-DOAS (no control)
- Error bars account for combined uncertainty[a] in reduced effectiveness of face coverings fit plus 300 CADR PAC operated at 33 % capacity
- Higher NIE for lecture hall with HVAC-WU system because 300 CADR not as effective in larger lecture hall

Avg 64 % reduction in NIE for HVAC-DOAS, CTL, and TU systems (all spaces)

Avg 83 % reduction in NIE for HVAC-WU systems (all spaces)



Classroom (5-8)

Portable classroom (9+)

Lecture hall

a. "Combined uncertainty" refers to propagation of error in this presentation.

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Results
by system type

HVAC-DOAS with controls – all spaces

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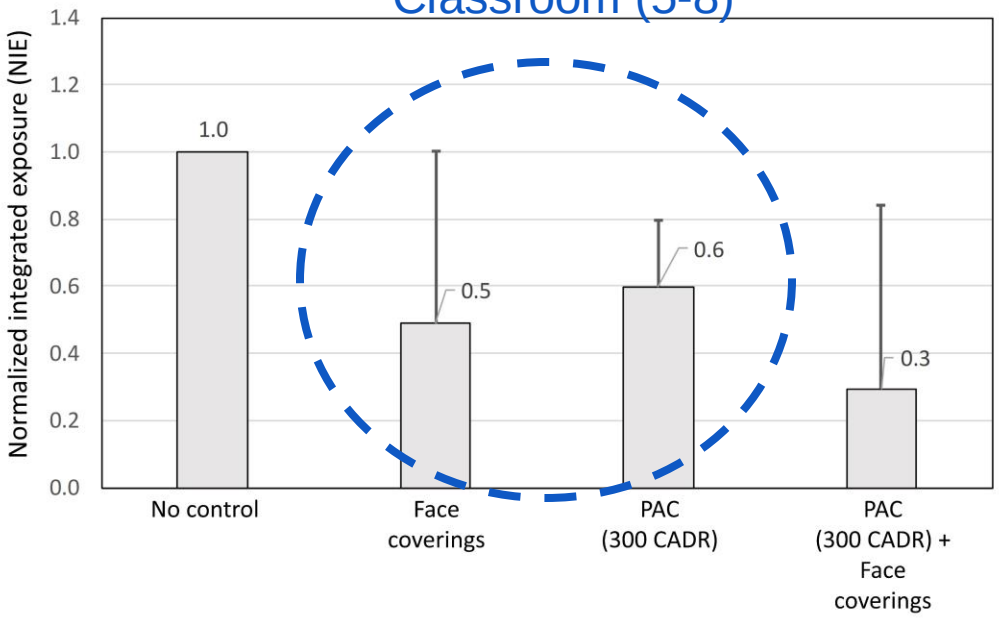
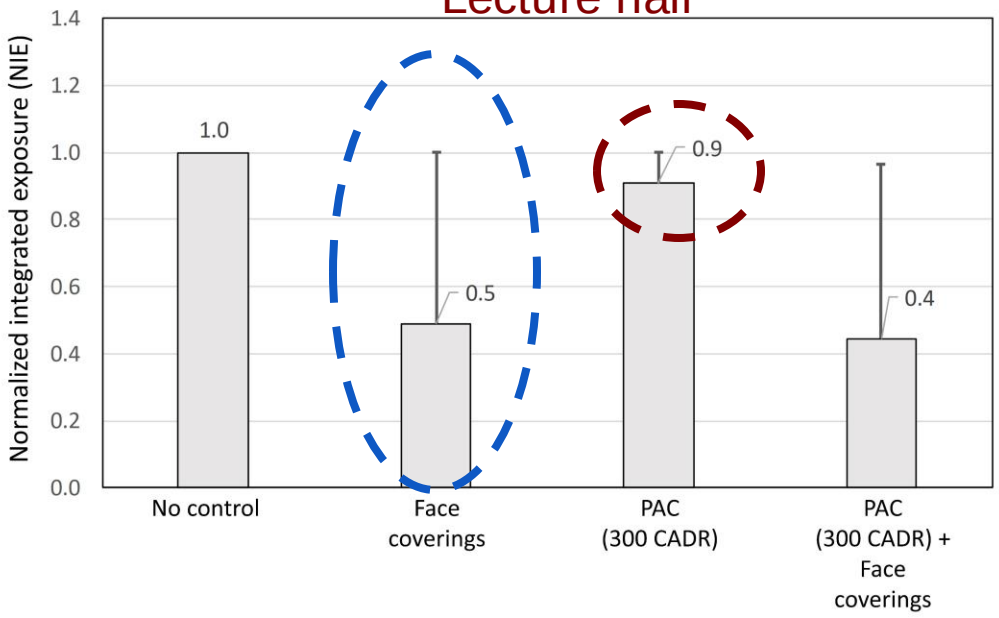
- For no controls, error bars account for lower and higher infiltration
- Results similar in both classrooms
- Face coverings or PAC (300 CADR) alone reduce NIE to 0.5 and 0.6, respectively in classrooms
- NIE for PAC alone in lecture hall greater than in classrooms because of larger space volume
  - In addition, NIE for PAC alone was 0.9

Classroom (5-8)



Lecture hall



HVAC-DOAS: varying PAC with face coverings – classrooms

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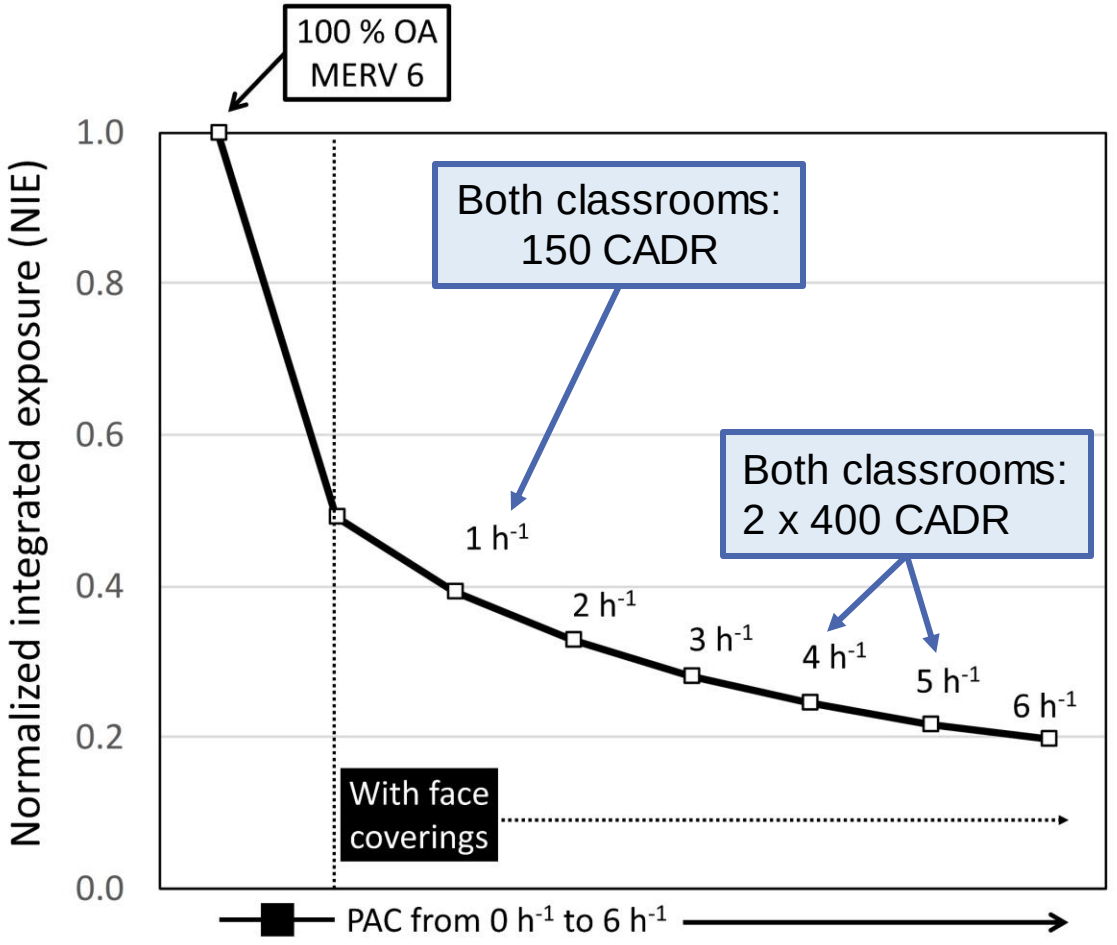
- Similar for both classrooms (5-8, 9+)
- 50 % reduction in NIE at 2 h^{-1}
  - Classroom (5-8): 250 CADR
  - Classroom (9+): 300 CADR



HVAC-DOAS: varying PAC with face covering– lecture hall

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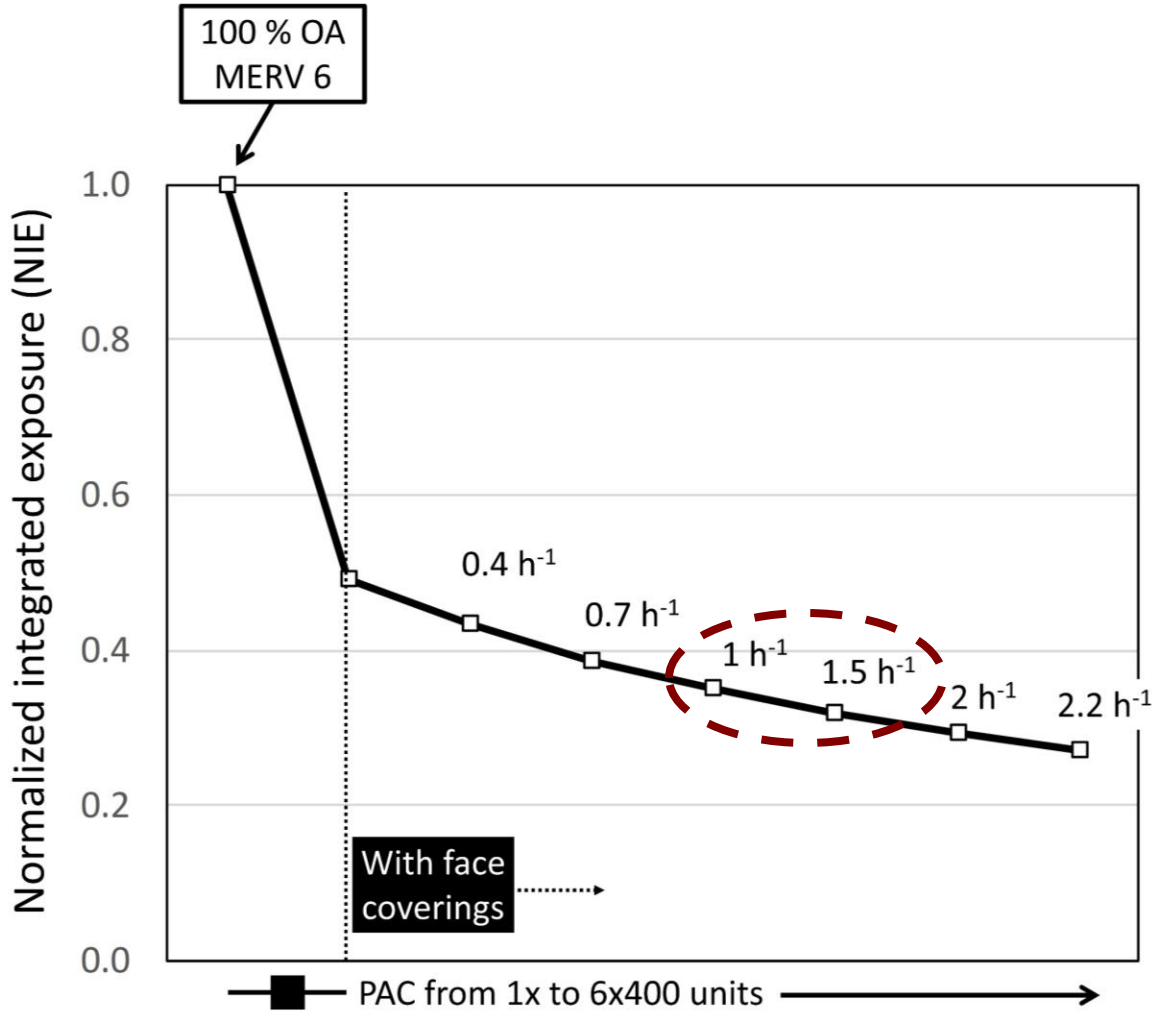
- 50 % reduction in NIE between 1 h^{-1} (3x400 CADR) and 1.5 h^{-1} (4x400 CADR)



HVAC-CTL with controls – classrooms

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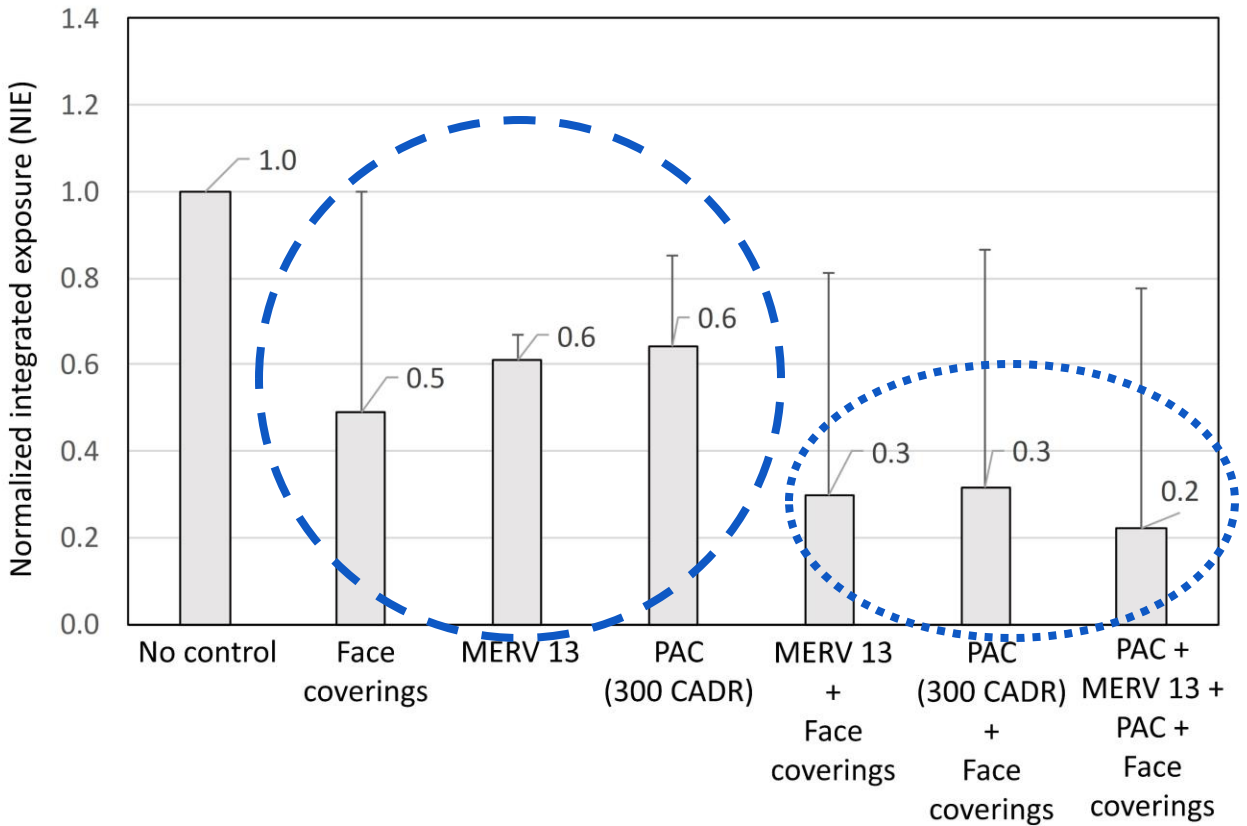
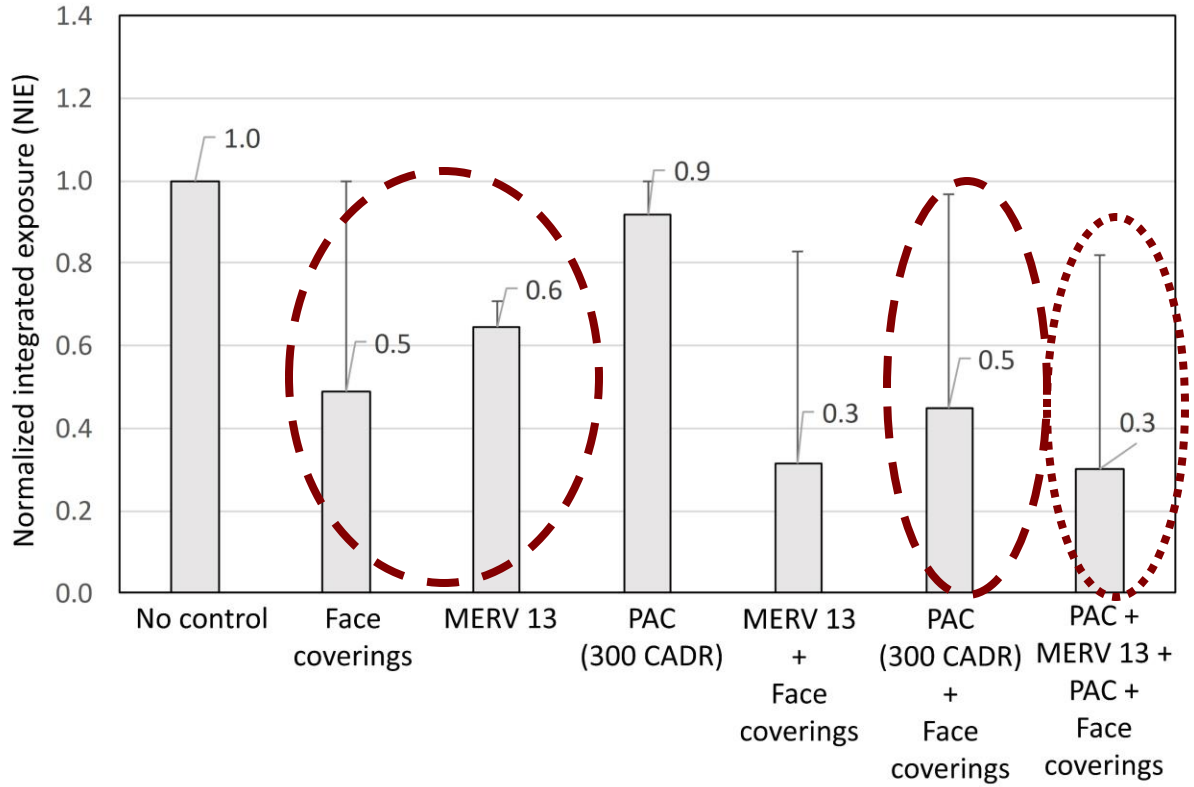
- Results similar in both classrooms
- Error bars account for uncertainty in effectiveness of filter, face coverings and/or PAC
- Face coverings, MERV-13 and PAC (300 CADR) reduced NIE to 0.5, 0.5 and 0.6, respectively
- Combined face coverings with MERV-13 (or PAC) had lower NIE compared with individual controls



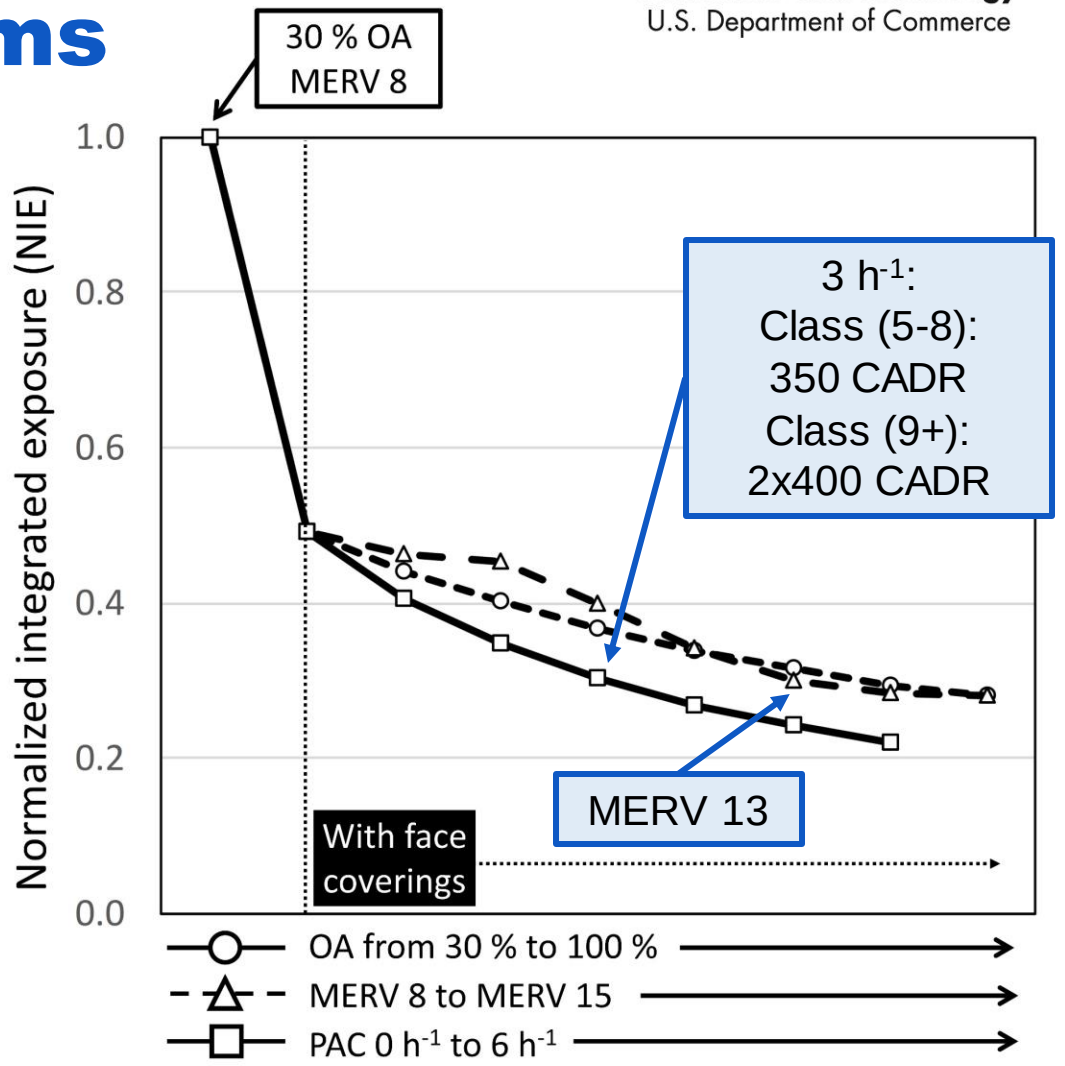
HVAC-CTL with controls – lecture hall

- Error bars account for uncertainty in effectiveness of filter, face coverings and/or PAC
- Face coverings, MERV-13 and PAC + face coverings reduced NIE to 0.5, 0.6, and 0.5 respectively
- Face coverings with MERV-13 (or PAC) had lower NIE compared with individual controls
- PAC (300 CADR) not as effective in lecture hall compared with classrooms because of larger volume



HVAC-CTL: varying controls with face coverings – classrooms

- Similar for both classrooms (5-8, 9+)
- 70 % reduction in NIE at MERV 13
  - Equivalent controls: 90 % OA or 3 h^{-1} PACs
- OA and MERV lines crossover at 70 % OA and MERV 12
- PAC may be more effective than other controls (OA, filtration) as capacity increases beyond 1 h^{-1}
  - Assumes good fit of face coverings and PAC operated at max setting



HVAC-CTL: varying controls with face coverings – lecture hall

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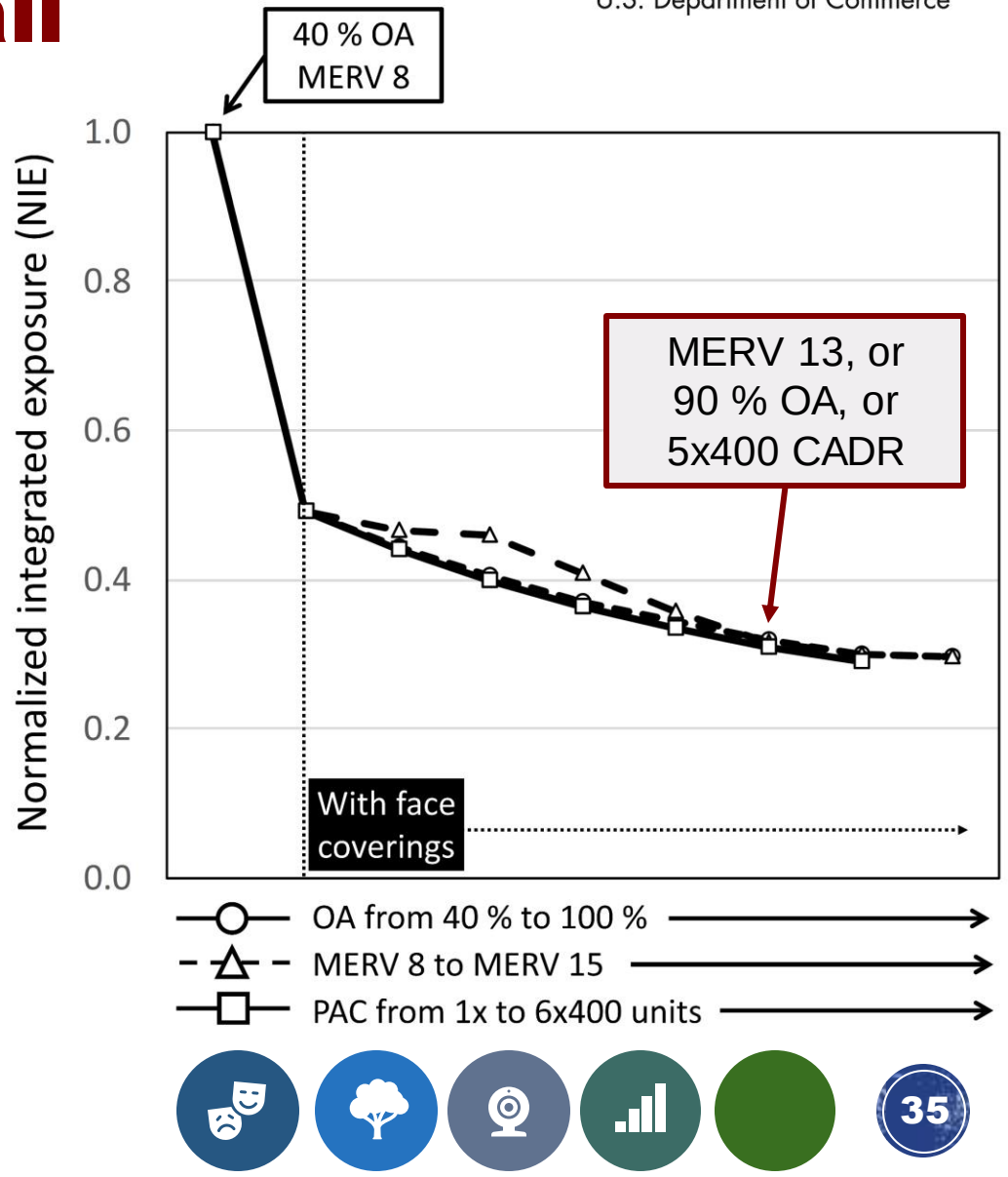
- 68 % reduction in NIE at MERV-13
  - Equivalent controls: 90 % OA or 5x400 CADR (1.8 h^{-1})
- Each additional 400 CADR unit (~0.3 h^{-1}) resulted in similar NIE as each 10 % increase in OA (~0.5 h^{-1})



HVAC-TU with controls – classrooms

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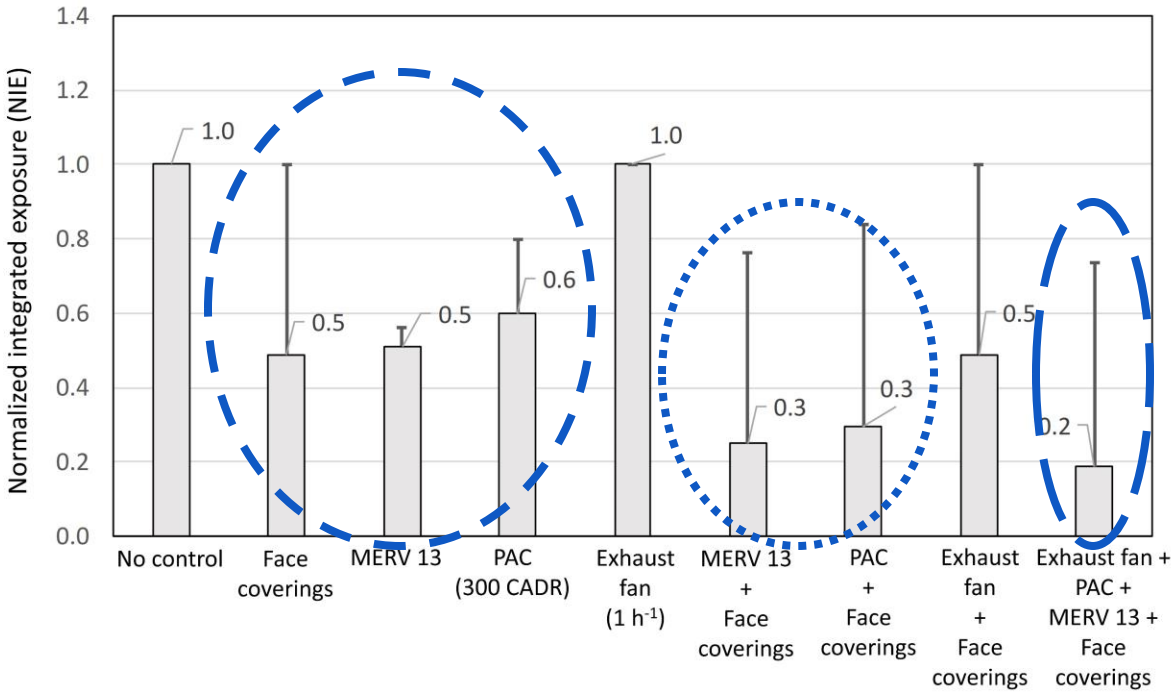
- Results similar in both classrooms
- Error bars account for uncertainty in effectiveness of face covering, filter, PAC and/or exhaust fan
  - Use of exhaust fan resulted in exposure similar to high infiltration rate
- Face coverings, MERV-13 and PAC (300 CADR) reduced NIE to 0.5, 0.5 and 0.6, respectively
- Combined face coverings with MERV 13 (or 300 CADR) reduced NIE to 0.3
- Combined face coverings with MERV 13 (or 300 CADR) and exhaust fan reduced NIE to 0.2



HVAC-TU with controls – lecture hall

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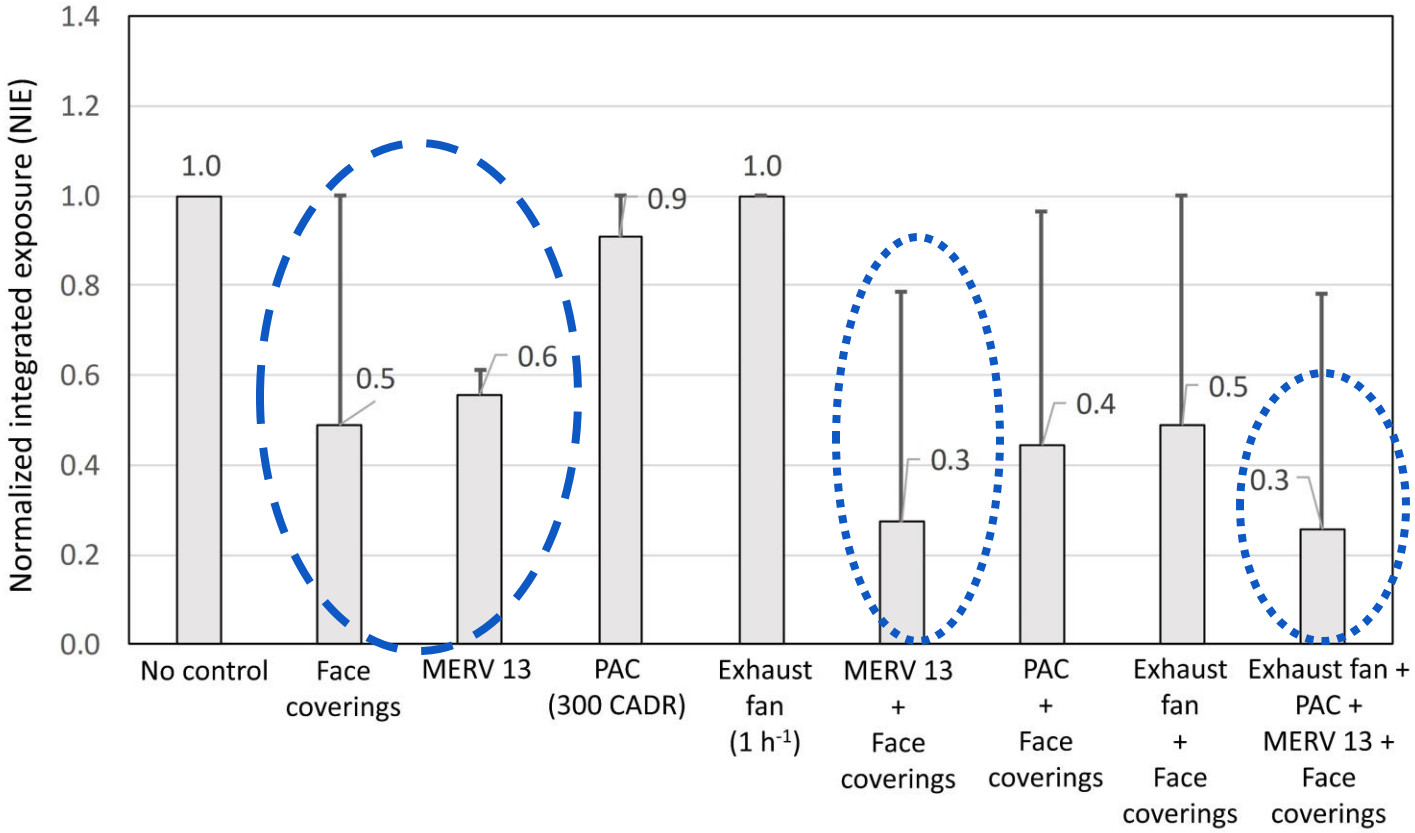
- Error bars account for uncertainty in effectiveness of face coverings, filter, PAC and/or exhau
  - Use of exhaust fan resulted in exposure similar to natural ventilation approaches
- Face coverings, MERV 13 and PAC (300 CADR) reduced NIE to 0.5 and 0.6, respectively
- Combined face coverings with MERV 13 had lower NIE compared with individual controls
  - Combined face coverings with MERV 13 and exhaust fan had same NIE (0.3) because exhaust fan (1 h^{-1}) not large enough to overcome HVAC pressurization



HVAC-TU: varying controls with face coverings – classrooms

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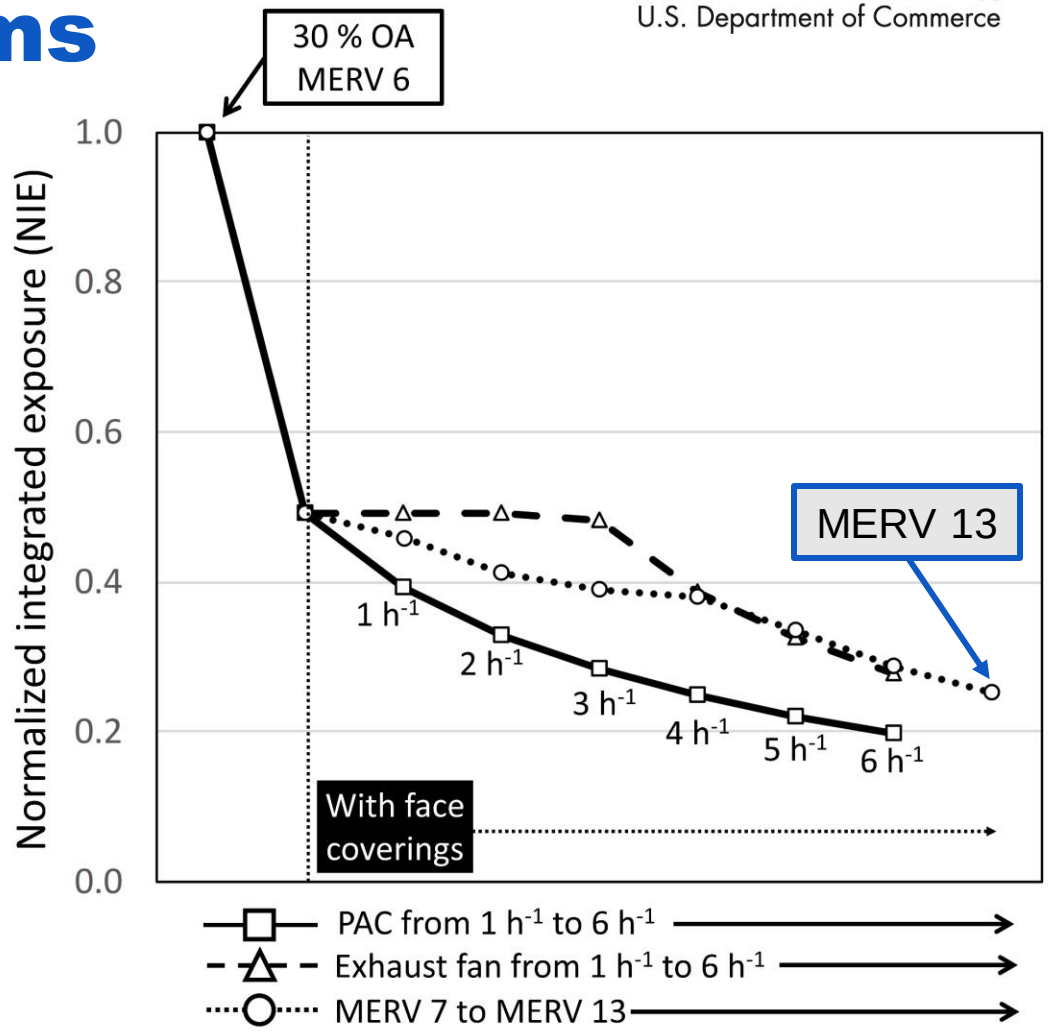
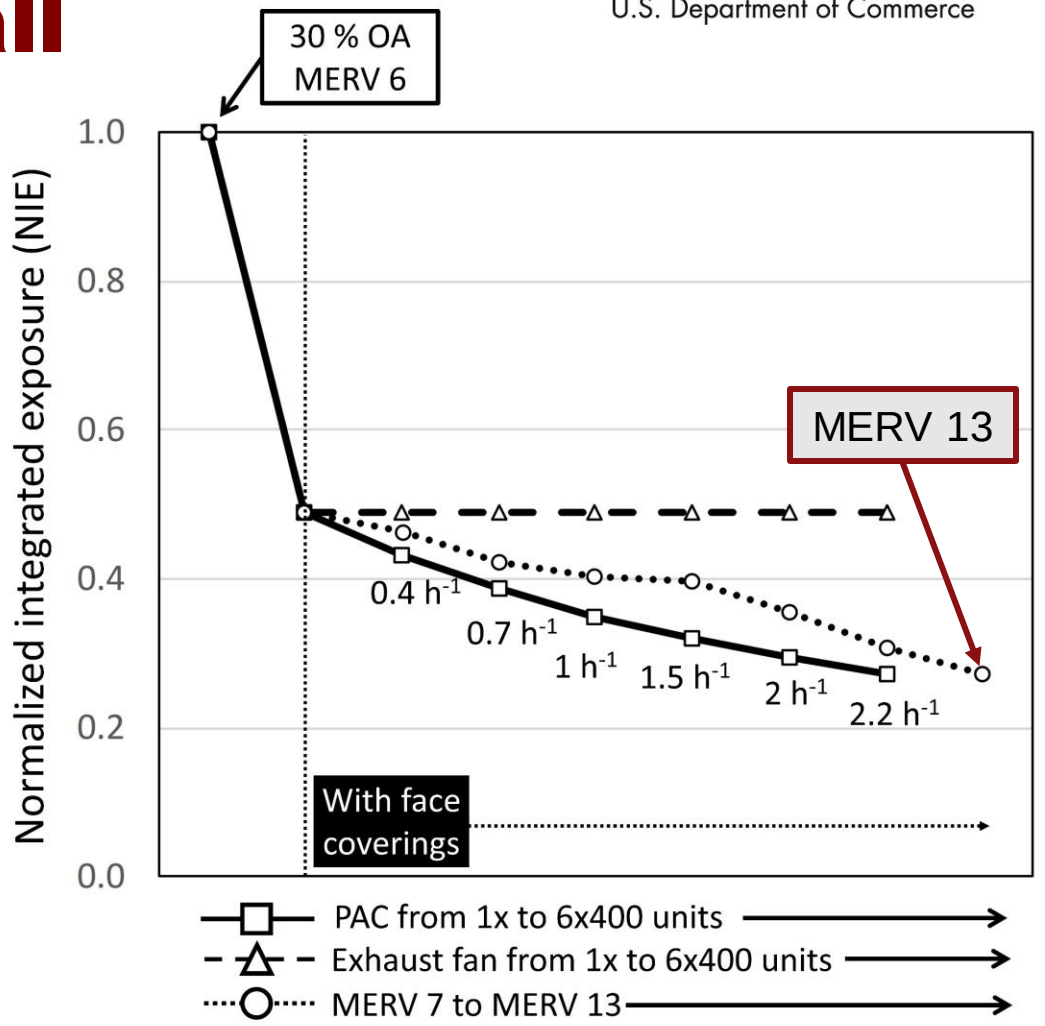
- Similar for both classrooms (5-8, 9+)
- PAC reduced NIE by more than Exhaust Fan with same capacity
  - Exhaust fan (1 h^{-1} to 3 h^{-1}) had similar NIE to no exhaust fan
- 75 % reduction in NIE at MERV 13
  - Equivalent controls: 4 h^{-1} PACs (450 CADR in classroom (ages 5 to 8) or 500 CADR in classroom (ages 9+)



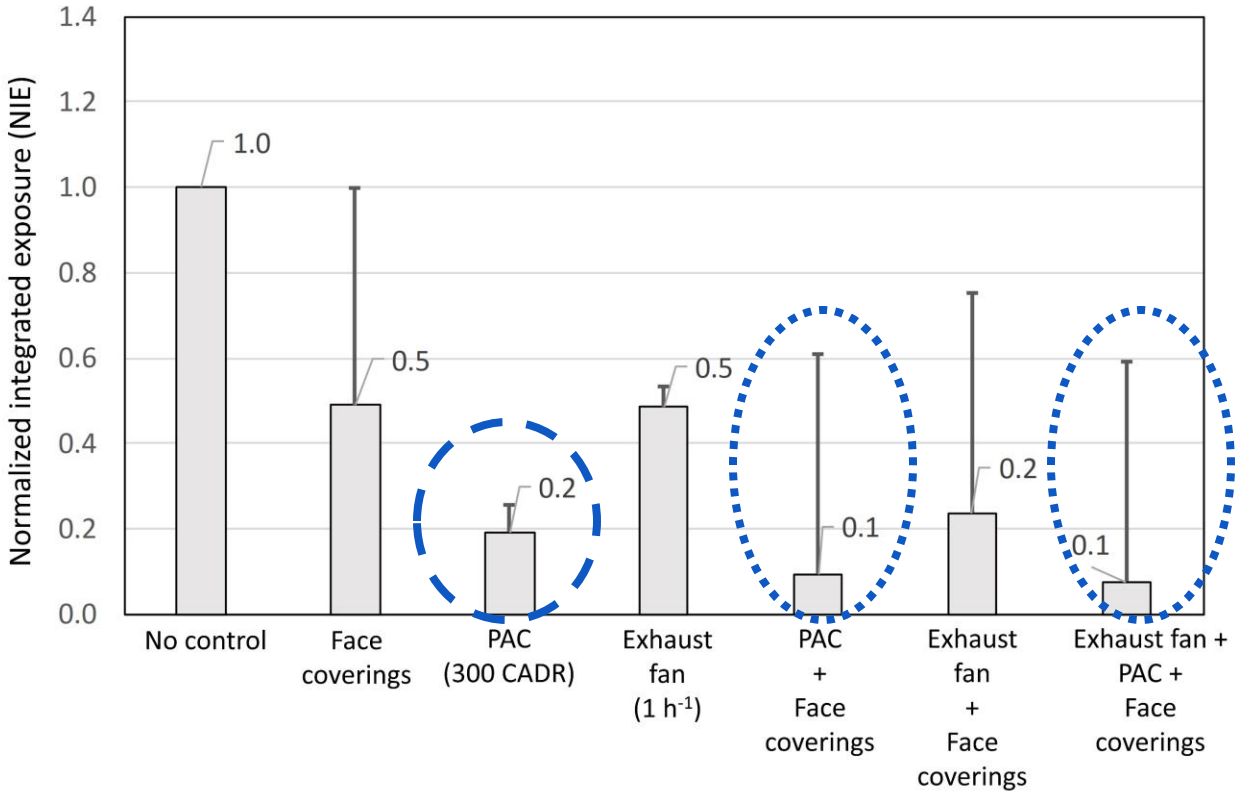
HVAC-TU: varying controls with face coverings – lecture hall

- Exhaust fan with face coverings did not reduce NIE compared with face coverings alone
- 73 % reduction in NIE at MERV 13
  - Equivalent controls: 6x400 CADR (2.2 h^{-1})



HVAC-WU with controls - classroom

- Similar for both classrooms (5-8, 9+)
- Error bars account for uncertainty in effectiveness of face coverings, PAC and/or exhaust fan
- PAC (300 CADR) alone reduced NIE to 0.2
- Combined face coverings with PAC (300 CADR) reduced NIE to 0.1
  - Combined face coverings with PAC and exhaust fan reduced NIE to 0.85



HVAC-WU with controls – lecture hall

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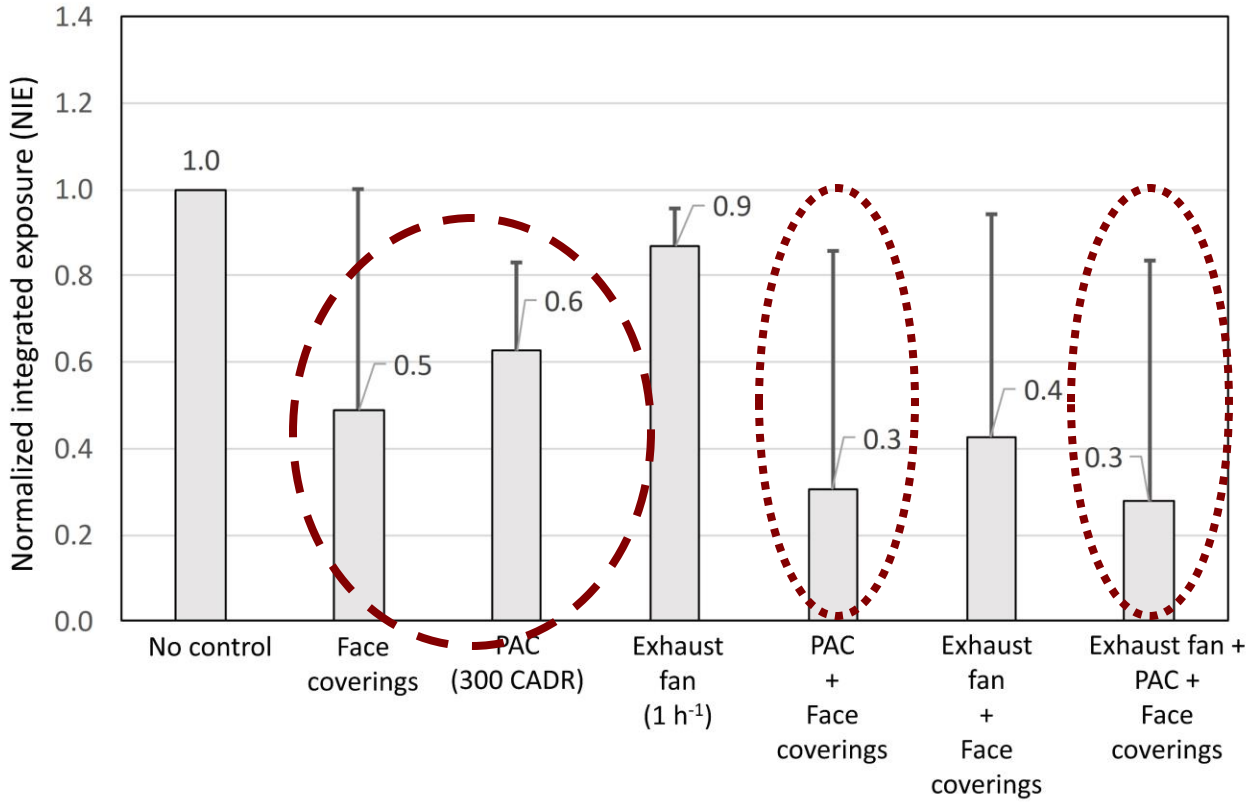
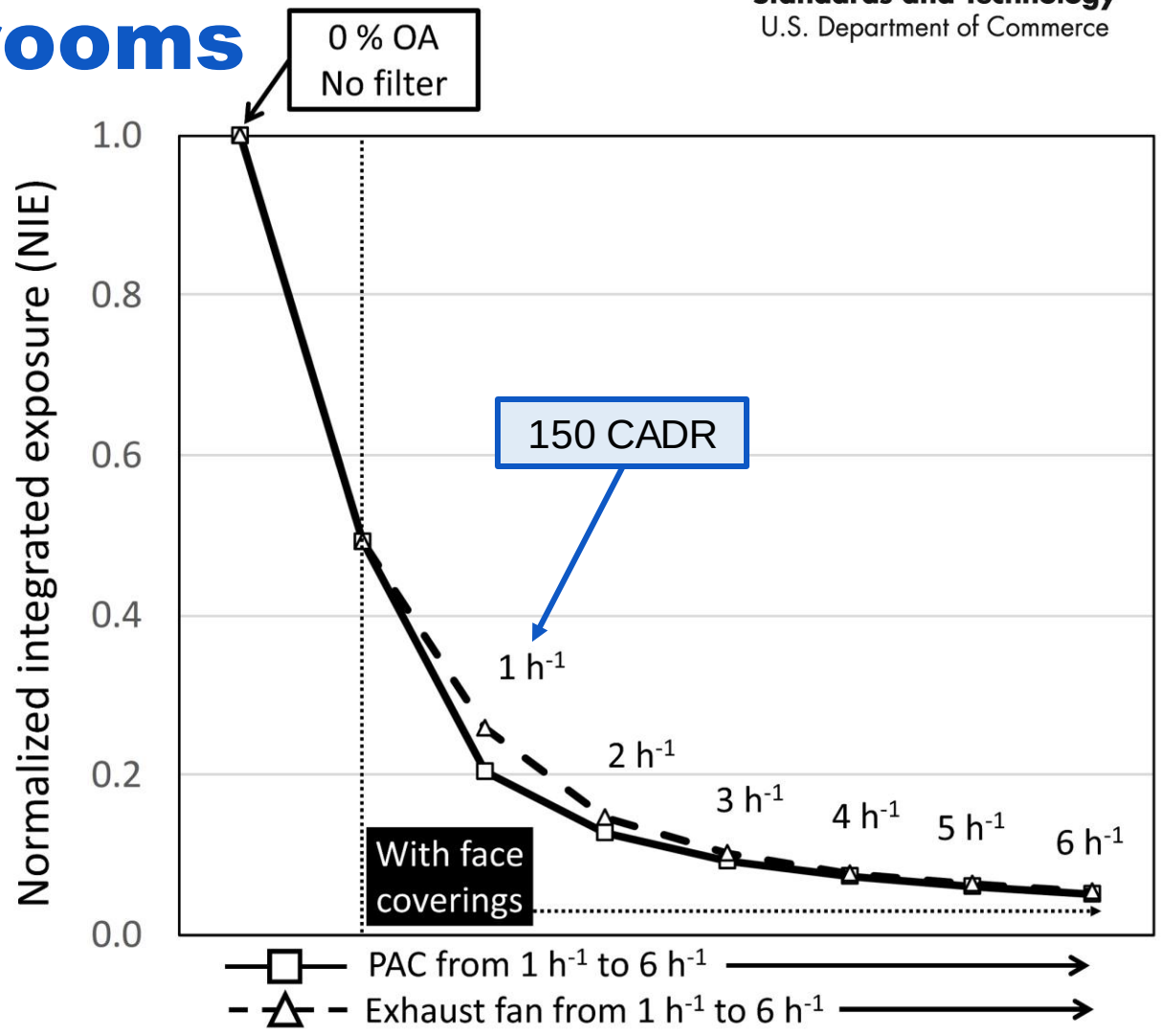
- Error bars account for uncertainty in effectiveness of face covering, PAC and/or exhaust fan
- Face coverings and PAC (300 CADR) reduced NIE to 0.5 and 0.6, respectively
- Combined face coverings with PAC (300 CADR) reduced NIE to 0.3
  - Combined face coverings with PAC and exhaust fan reduced NIE to 0.28



HVAC-WU: varying controls with face coverings – classrooms

- Similar for both classrooms (5-8, 9+)
- PAC and exhaust fan reduced NIE by similar amounts over range of capacities
- 81 % reduction in NIE at 150 CADR
  - 90 % reduction with 300 CADR
- Note: HVAC-WU system (no controls) started with 9x exposure of HVAC-DOAS (avg both classrooms)



HVAC-WU: varying controls with face coverings – lecture hall

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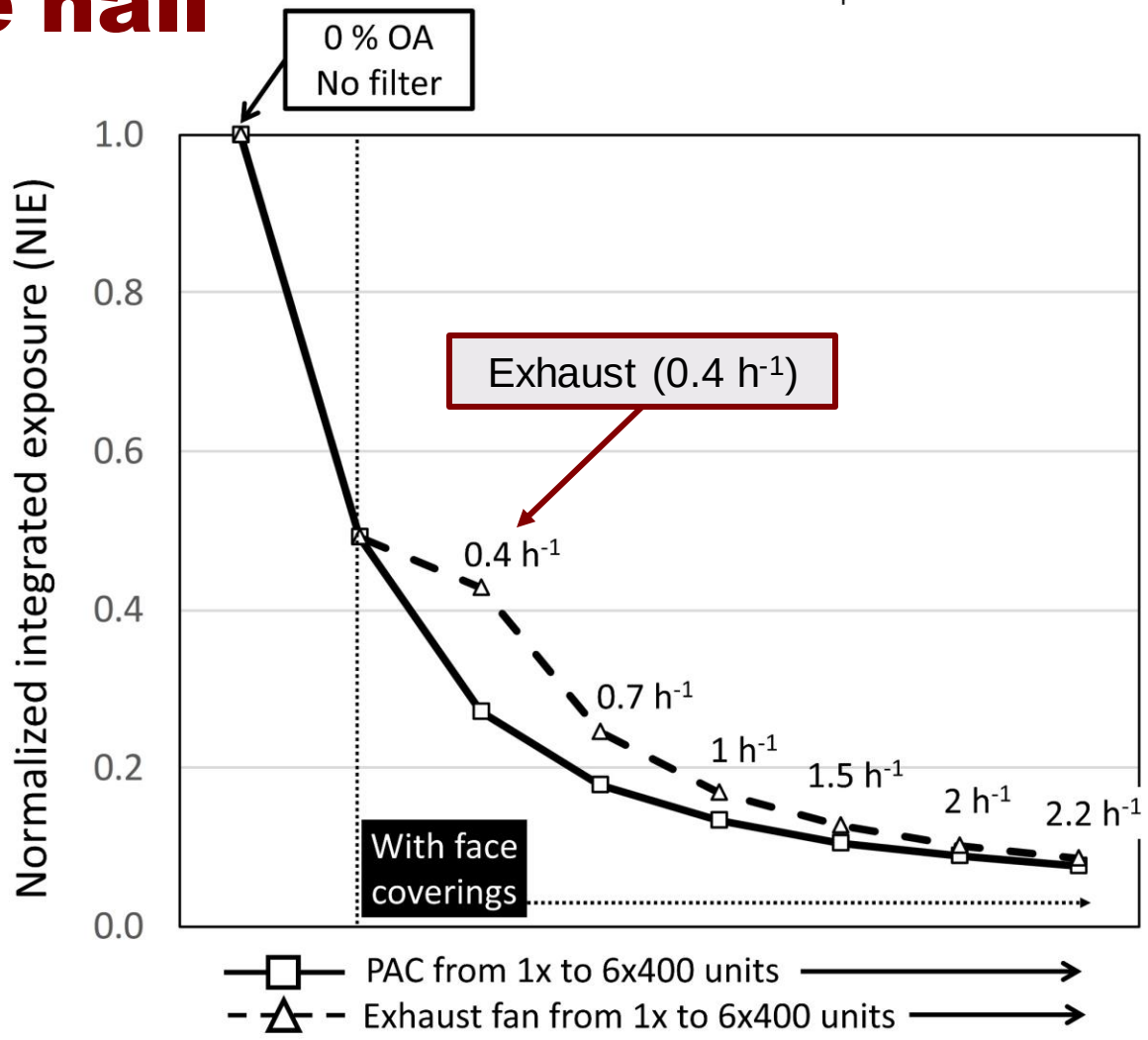
- PAC reduced NIE slightly more than exhaust fan
  - Exhaust fan (0.4 h^{-1}) with face coverings did not significantly reduce NIE compared with face coverings alone
- 50 % reduction in NIE with face coverings alone
- Note: HVAC-WU system (no controls) started with 8x exposure of HVAC-DOAS system



Summary:

Integrated exposure with no controls

Integrated exposure with no controls

- HVAC-WU system starts out with highest exposure
- Values are not a direct metric of infection risk

Classroom (5-8)

System – base operation	OA (h^{-1})	Infiltration (h^{-1})	Integrated exposure (#•s/m3) w/ no controls
HVAC-DOAS	2.6	0.30	855,000
HVAC-CTL	2.6		717,000
HVAC-TU	2.6		855,000
HVAC-WU	0.0		5,519,000

Portable classroom (9+)

System – base operation	OA (h^{-1})	Infiltration (h^{-1})	Integrated exposure (#•s/m3) w/ no controls
HVAC-DOAS	3.3	0.30	574,000
HVAC-CTL	3.3		486,000
HVAC-TU	3.3		574,000
HVAC-WU	0.0		4,571,000

Lecture hall

System – base operation	OA (h^{-1})	Infiltration (h^{-1})	Integrated exposure (#•s/m3) w/ no controls
HVAC-DOAS	1.9	0.30	21,000
HVAC-CTL	1.9		18,000
HVAC-TU	1.9		21,000
HVAC-WU	0.0		151,000

Summary:

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Effects of controls by HVAC system and space

Comparing controls across HVAC systems - classrooms

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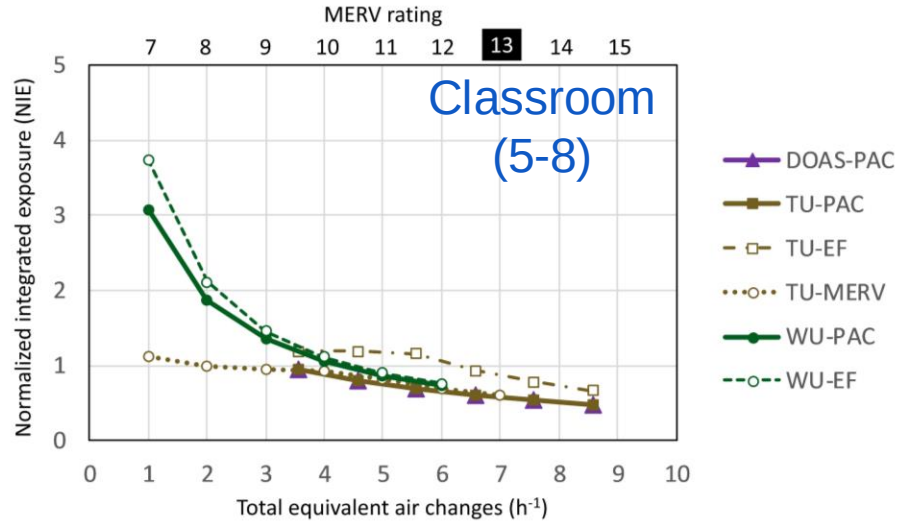
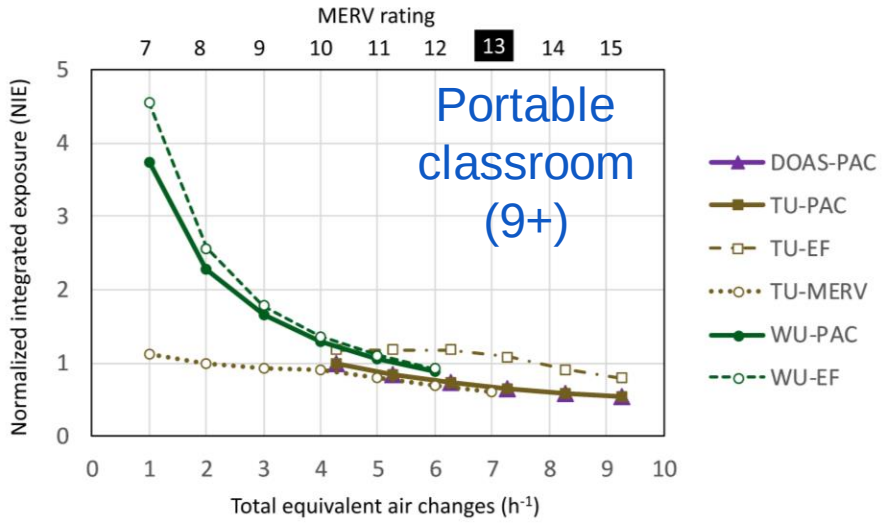
- All results with face coverings
- To achieve NIE = 1 (same IE as HVAC-CTL):
  - HVAC-DOAS: PAC (150 CADR)
  - HVAC-TU:
    - PAC (150 CADR) or
    - Exhaust fan (4 h^{-1}) or
    - MERV 8 filter
  - HVAC-WU:
    - Classroom (5-8):
      - PAC (2x400 CADR) or
      - Exhaust fan (5 h^{-1})
    - Classroom (9+):
      - PAC (3x400 CADR) or
      - Exhaust fan (6 h^{-1})





Comparing controls across HVAC systems – lecture hall

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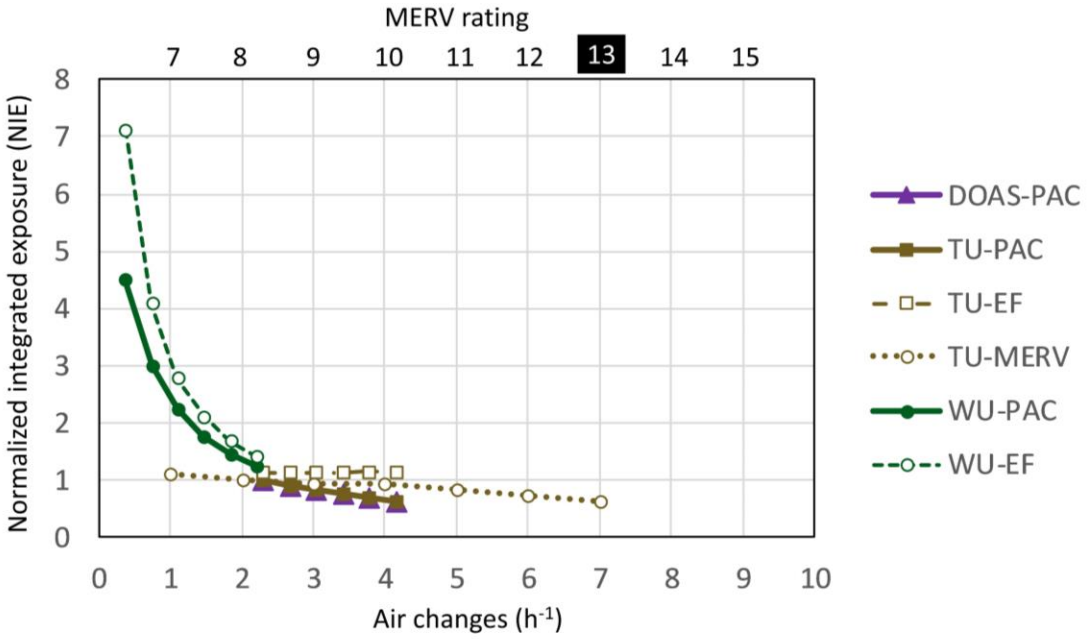
- All results with face coverings
- To achieve NIE = 1 (same IE as HVAC-CTL):
  - HVAC-DOAS: PAC (1x400 CADR)
  - HVAC-TU:
    - PAC (1x400 CADR) or
    - MERV 8 filter
  - HVAC-WU:
    - Not achievable with 6xPACs or exhaust fans



Summary:

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Comparing controls across and within HVAC systems

Summary: comparing within each HVAC system – classrooms

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Average NIE across classrooms (5-8, 9+)			No face coverings			With face coverings			
System	No controls	Face coverings alone	PAC (300 CADR)	MERV 13	Exhaust fan (1 h^{-1})	PAC (300 CADR)	MERV 13	Exhaust fan (1 h^{-1})	All combined
HVAC-Central	1.0	0.5	0.7	0.6	N/A	0.3	0.3	N/A	0.2
HVAC-DOAS	1.0	0.5	0.6	N/A	N/A	0.3	N/A	N/A	N/A
HVAC-Terminal Unit	1.0	0.5	0.6	0.5	1.0	0.3	0.2	0.5	0.2
HVAC-Window Unit	1.0	0.5	0.2	N/A	0.5	0.1	N/A	0.2	0.1

- Dark cells indicate controls with lowest NIE
- Assumes controls are performing “perfectly”
- These values are not a direct metric of infection risk

Summary: comparing within each HVAC system – lecture hall

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Average NIE lecture hall			No face coverings			With face coverings			
System	No controls	Face coverings alone	PAC (300 CADR)	MERV 13	Exhaust fan (1 h^{-1})	PAC (300 CADR)	MERV 13	Exhaust fan (1 h^{-1})	All combined
HVAC-Central	1.0	0.5	0.9	0.6	N/A	0.5	0.3	N/A	0.3
HVAC-DOAS	1.0	0.5	0.9	N/A	N/A	0.4	N/A	N/A	N/A
HVAC-Terminal Unit	1.0	0.5	0.9	0.6	1.0	0.4	0.3	0.5	0.3
HVAC-Window Unit	1.0	0.5	0.6	N/A	0.9	0.3	N/A	0.4	0.3

- Dark cells indicate controls with lowest NIE
- Assumes controls are performing “perfectly”
- These values are not a direct metric of infection risk

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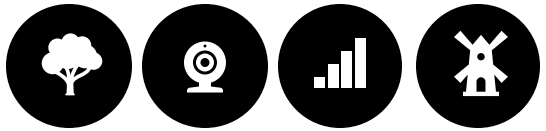
Conclusions

- Effect of controls varies depending on HVAC system type
- Effect of controls depends on how they are implemented
  - Fit of face coverings
  - Portable air cleaner setting
  - Filter fit, sealing or condition
- While the exposure presented here are not a direct metric of infection risk, FaTIMA can be used to identify and compare possible control strategies to reduce exposure

Future work



- Sensitivity analyses
  - Combination of controls
  - Additional controls: UVGI
  - Additional space types (educational and other)
  - Additional HVAC systems
  - Impacts of poor ventilation system performance
- More detailed analyses using CONTAM
  - Multizone
  - Infiltration rates by climate
  - Building envelope airtightness
  - Varying OA and PAC schedules

References

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Other tools

- Harvard-UC Boulder Portable Air Cleaner Calculator for Schools v1 (Joseph Allen and Shelly Miller) https://docs.google.com/spreadsheets/d/1NEhk1IEdbEi_b3wa6gI_zNs8uBJjlSS-86d4b7bW098/edit#gid=1882881703
- COVID-19 Aerosol Transmission Estimator (Jose-Luis Jimenez) https://docs.google.com/spreadsheets/d/16K1OQkLD4BjgBdO8ePj6ytf-RpPMlJ6aXFg3PrIQBbQ/edit#gid=519189277
  - App based on estimator: https://covid-infection-risk.netlify.app
- The SAFEAIRSPACES COVID-19 Aerosol Relative Risk Estimator https://safeairspaces.com/ (Rich Corsi, Kevin Van Den Wymelenberg, Hooman Parhizkar)