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Abstract

On March 11, 2020, the World Health Organization declared the novel coronavirus (COVID-19) outbreak a global pandemic. As noted by ASHRAE and the Centers for Disease Control and Prevention (CDC), engineering and other controls should be part of a broader, layered risk reduction strategy that includes hand washing, surface cleaning, social distancing, and reduced occupant density (ASHRAE 2020; CDC 2021). To date, many recommendations for operating buildings during and re-opening them post-pandemic have been based upon limited data. Much of the public discussion of re-opening buildings has focused on commercial and institutional buildings in the U.S., but there are almost 20 times more residences in the U.S. than there are commercial buildings. Major questions exist regarding the development of recommendations targeting residences. It is critical to answer these questions because dwellings can be a major source of virus transmission. To help people understand options to use ventilation and filtration in their homes effectively, the authors used the Fate and Transport of Indoor Microbiological Aerosols (FaTIMA) tool to evaluate the effects of ventilation and filtration strategies on particle exposure in homes of various sizes, with different ventilation systems, and with a potentially contagious visitor in the home for various durations. For the home sizes and ventilation systems studied, the 297 CADR portable air cleaner was most effective for reducing particle exposure compared to the other mitigation measures simulated (average 45 % reduction in exposure).

Keywords

Aerosols, exposure, filtration, pandemic, particles, ventilation, virus.

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ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

On March 11, 2020, the World Health Organization declared the novel coronavirus (COVID-19) outbreak a global pandemic. As noted by ASHRAE and the Centers for Disease Control and Prevention (CDC), engineering and other mitigation measures should be part of a broader, layered risk reduction strategy that includes hand washing, surface cleaning, social distancing, and reduced occupant density (ASHRAE 2020; CDC 2021).

Even with such a layered approach, a better understanding of airborne exposure to infectious aerosols as impacted by these controls is needed. To date, many recommendations for operating buildings during and re-opening them post-pandemic have been based upon limited data and analysis. Much of the discussion of re-opening buildings has focused on commercial and institutional buildings in the U.S., but there are almost 20 times more residences in the U.S. than there are commercial buildings. Major questions exist regarding the development of recommendations targeting residences. It is critical to answer these questions because dwellings can be a major source of virus transmission (Bi et al., 2021). This report summarizes a study on reducing exposure in homes using the Fate and Transport of Indoor Microbiological Aerosols (FaTIMA) tool developed by the National Institute of Standards and Technology (NIST). The exposure to 1.0 µm particles in three homes of varying sizes was evaluated. The small home was 93 m^2 (1 000 ft^2), the medium home was 163 m^2 (1 750 ft^2), and the large home was 232 m^2 (2 500 ft^2). All homes were assumed to be single story with 2.7 m (9 ft) ceilings. A potentially contagious visitor entered the home and emitted particles for either 30 min, 120 min or 240 min.

In addition to these parameters, the simulated home either had a central heating, ventilating, and air-conditioning (HVAC) system or a zone-level system. Examples of central HVAC systems include heat pumps and air conditioner-furnace systems. Examples of zone-level systems include window air-conditioners, electric baseboard heaters, and split-unit systems. The following measures were evaluated for their ability to control the occupant exposure. The central HVAC system was simulated with and without mechanical outdoor air (OA) ventilation. The particle filter in the central HVAC system was varied in the simulations whereas the zone-level system had no filter. In the cases with mechanical OA, a fan that supplied an additional 94.4 $L \cdot s^{-1}$ (200 cfm) of outdoor air was also simulated. Other parameters that were varied in the simulations for the central HVAC systems included: fan on/continuous or fan auto/intermittent, the level of filtration as denoted by minimum efficiency reporting values of MERV 6 and MERV 13. The effects of an open window were simulated only for the systems without mechanical OA. The use of a portable air cleaner (PAC) was also investigated in the simulated homes for both central and zone-level HVAC systems. These mitigation measures were evaluated for the period during which the infected visitor was in the home and for an additional 60 min after the visitor left.

After comparing particle exposure in a set of base cases for all home sizes and HVAC systems, it was found that a portable air cleaner (PAC) with a clean air delivery rate (CADR) of 297 was most effective at reducing particle exposure with an average reduction rate of 45 %. Supplementing mechanical OA with an additional 94.4 $L \cdot s^{-1}$ (200 cfm) of OA led to an average exposure reduction of 35 % and operating the HVAC system recirculation fan continuously rather than intermittently reduced particle exposure by an average of 23 %. The MERV 13 filter reduced exposure by an average of 24 % compared with a MERV 6 filter. When comparing the performance of the MERV 13 filter to a PAC with a CADR of 99, the more effective option was dependent on the size of the home: the MERV 13 filter was more effective in the large home and the 99 CADR PAC was more effective in the small home. The 99 CADR PAC was more effective in the medium home when the visit duration was only 30 min; otherwise, the MERV 13 filter was more effective.

The results of this analysis may be useful in the selection of exposure reduction measures in residential buildings. All the results presented herein are also available using the NIST tool, Virus Particle Exposure in Residences (ViPER) that is available for free at the following web address: https://www.nist.gov/services-resources/software/viper-virus-particle-exposure-residences.

Additional information on ViPER can be found here: https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2211.pdf.

The results presented in this report for the small home were used by CDC to develop their Interactive Ventilation Tool (https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html).

1. INTRODUCTION

On March 11, 2020, the World Health Organization (WHO) declared the novel coronavirus (COVID-19) outbreak a global pandemic (WHO 2020). The guidance on protecting oneself at home provided by ASHRAE (ASHRAE 2020) and the Centers for Disease Control and Prevention (CDC) (CDC 2021) include increasing the outdoor air (OA) ventilation rate, using portable air cleaners (PAC), and using high efficiency media filters while maintaining thermal comfort.

Even with such a layered approach, a better understanding of airborne exposure to infectious aerosols as impacted by these controls is needed. To date, many recommendations for operating buildings during and re-opening them post-pandemic have been based upon limited data and analysis. Major questions exist regarding the development of recommendations targeting residences. It is critical to answer these questions because dwellings can be a major source of virus transmission (Bi et al., 2021). The objective of this analysis was to compare the relative change in exposure to particles of a single size (1.0 μm) in a home due to changes in the operation of the heating, ventilating, and air-conditioning (HVAC) system and the implementation of non-HVAC measures or controls (e.g., opening a window or using a PAC). Simulations were performed under the assumption that a potentially contagious visitor entered the home and emitted particles for a period of 30 minutes, 120 minutes, or 240 minutes. The models used in this analysis were generated using FaTIMA, a free, online tool that allows for the analysis of the fate and transport of microbiological aerosols while accounting for ventilation, filtration, deposition, and deactivation mechanisms (Dols et al., 2020). The FaTIMA-generated CONTAM project files (.prj) were then modified using the graphical user interface of CONTAM prior to simulation. This was done to simulate intermittent fan operation which was not possible using the version of FaTIMA available at the time these analyses were performed. The generated project files were then parameterized using the CONTAM Factorial Tool to vary the input parameters of interest, and the full set of simulations was run using the CONTAM simulation engine, ContamX.

This report describes the 1 296 simulations defined by varying the following parameters:

- Home/Zone size (small, medium, large) 3
- Visit duration (30 min, 60 min, 240 min) $\times 3 = 9$
- Fan operating schedule (intermittent, continuous) $\times 2 = 18$
- Mechanical OA ventilation rate (none, low, high, window) $\times 4 = 72$
- Particle filtration efficiency (none, MERV 6, MERV 13) $\times 3 = 216$
- PAC operation (none, low speed, high speed) $\times 3 = 648$
- Additional runtime of fans and PACs (none, 60 minutes) $\times 2 = 1\,296$

Even though 1 296 simulations were run by combining all possible variations of the parameters as outlined above, 333 of these simulations were redundant (for example, when there is no particle filter present, the fan operating intermittently or continuously will produce the same result). A breakdown of the 963 unique simulations for the HVAC systems and their HVAC-related measures are shown in **Table 1**.

This analysis examined the impact of the mitigation measures in reducing airborne exposure to particles of a single size (1.0 μm). The analysis did not explore the effects of masking, the impacts of technologies such as ultraviolet germicidal irradiation (UVGI) or photocatalytic oxidation (PCO), or non-airborne routes of exposure.

The report is organized as follows. The modeling tool FaTIMA is described in Sec. 0. The homes and HVAC system types simulated are described in Sec. 3. The FaTIMA inputs for the base cases (zone geometry, infiltration, ventilation system, filters, etc.) are presented in Sec. 4. Methods used to model mitigation measures (fan operation, windows, additional mechanical OA, filtration level, PAC, and additional runtime) are described in Sec. 5. How integrated exposure was used to calculate a metric to compare results is described in Sec. 6.

Table 1. Outline of simulation parameters by HVAC system.

HVAC TYPE	HOME SIZE	VISIT DURATION	FAN OPERATION	OA VENT LEVELS	FILTRATION	PAC OPERATION SPEED	ADDTL RUNTIME	UNIQUE SIMULATIONS
Central system with mechanical OA	Small, Medium, Large (3)	30 min, 120 min, 240 min (×3)	Intermittent, Continuous (×2)	Low, High (×2)	MERV 6, MERV 13 (×2)	None, Low, High (×3)	No, Yes (×2)	432
Central system without mechanical OA	Small, Medium, Large (3)	30 min, 120 min, 240 min (×3)	Intermittent, Continuous (×2)	None, Window (×2)	MERV 6, MERV 13 (×2)	None, Low, High (×3)	No, Yes (×2)	432
Zone-level system	Small, Medium, Large (3)	30 min, 120 min, 240 min (×3)	N/A	None, Window (×2)	None (×1)	None, Low, High (×3)	No, Yes (×2) (-9) †	99
							TOTAL	963

† The additional 60-minute runtime does not apply to the zone-level system base cases because there is no particle filtration. Since there are nine zone-level base cases (three visit durations for three homes sizes), this results in 9 fewer unique simulations.

As shown in **Table 1**, all three visit durations were simulated for all three home sizes. Not every HVAC system type was simulated with all levels for each mitigation measure. For example, fan operation was simulated as both intermittent and continuous (Sec. 5.1) for both central systems, but not for the zone-level system that only recirculated air with no filter or other particle removal. Varying this mitigation measure within this system would not affect particle concentration.

The OA vent (ventilation) levels were defined as follows: none (only infiltration, Sec. 3.2); low (mechanical OA, Sec. 3.2); window (infiltration plus an open window, Sec. 5.2.1); and high (mechanical OA plus extra ventilation, Sec. 5.2.2). The central HVAC system with mechanical OA had two options for "OA Vent" (low, high) since it was assumed a window would not be open while the HVAC system was on. The central HVAC system without mechanical OA had two options for "OA Vent" (none, window) since extra mechanical ventilation was not provided to homes without mechanical OA. The zone-level HVAC system had two options for “OA Vent” (none, window).

The zone-level HVAC system had only one option for filtration efficiency (none) since this HVAC system did not have a recirculation filter. All levels (none, low, high) of the PAC were simulated for each home size and visitor duration. The additional runtime of 60 min was simulated for all relevant cases. For the zone-level system bases cases, the additional 60-minute runtime was not simulated because it would not affect results since there is no particle filtration.

A subset of the results is discussed in detail (Sec. 7), but all results are presented at the end of the report (Appendix 1 - SIMULATION IE VALUES). All CONTAM project files used in this analysis are available for download on the NIST Multizone Modeling Website at the following web address: https://datapub.nist.gov/od/id/mds2-2548. The results presented in this report were used by the CDC to develop their Interactive Ventilation Tool (https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/interactive-ventilation-tool.html), specifically the results for the small, 93 m^2 (1 000 ft^2) home included in this analysis. The CDC webpage presents the exposure results for a single occupant present in the home while someone visited the home for 240 min, including the exposure of the occupant at the time the visitor left and 60 min after the visitor left, during which time the mitigation measure of interest was assumed to continue running.

Sec. 8 summarizes the results. Sec. 9 discusses the ViPER webtool, which is an interactive tool developed to display the results of this study to a user. Sec. 10 discusses future work.

Note that the predicted impact of the mitigation measures in this analysis will be different for other homes, occupancies, HVAC systems, environmental conditions, and other input parameters. Nevertheless, the results of this analysis could help residents understand options to reduce their exposure to particles generated by a potentially contagious visitor to their home. This analysis does not define levels of exposure considered to be safe or healthy, nor consider the impacts of these mitigation measures as part of a broader risk reduction strategy that might be pursued by a resident.

2. MODELING TOOL – FaTIMA

The simulations in this analysis varied the input parameters available in the web-based software tool, FaTIMA (Fate and Transport of Indoor Microbiological Aerosols). FaTIMA implements a model of a single zone with a uniform concentration that can be served by a mechanical ventilation system and incorporates particle source(s) and removal mechanisms. The mechanical ventilation system model in FaTIMA allows specification of the supply, return, and OA intake fraction to represent either a positive, negative, or balanced ventilation system. An exhaust fan can also be included independently of the mechanical ventilation system; however, the exhaust feature was not utilized in this analysis. Particle sources are provided to enable a combination of continuous (e.g., breathing-related emissions) or intermittent (e.g., coughing-related emissions). Particle removal mechanisms include filters within the ventilation system, a PAC, surface deposition, and virus deactivation (Dols et al., 2020).

Inputs to FaTIMA include zone dimensions (volume and surface areas of walls, floor, and ceiling), infiltration rate, HVAC airflow rates (supply, return, and OA intake), dedicated exhaust fan flow rate, PAC specifications (filter efficiency and fan flow rate which are used to determine the CADR), particle characteristics (size, density, and deactivation rate), particle source emission rate and schedule, surface deposition velocities, and occupancy schedule of exposed occupant. Numerical and graphical outputs presenting the fate of indoor particles include airborne particle concentration, surface loading, filter loading, and occupant exposure. Examples of the input screen and graphical outputs are shown in **Figure 1**.

FaTIMA is a simplified, web-based front end to CONTAM (Dols and Polidoro 2020), which is a multizone indoor air quality and ventilation analysis program developed to estimate interzone airflows, contaminant concentrations, and occupant exposure in buildings. For all of the analyses described below, FaTIMA was used to develop base cases for each home size, which were subsequently modified using CONTAM.

(a)

(b)

(c)

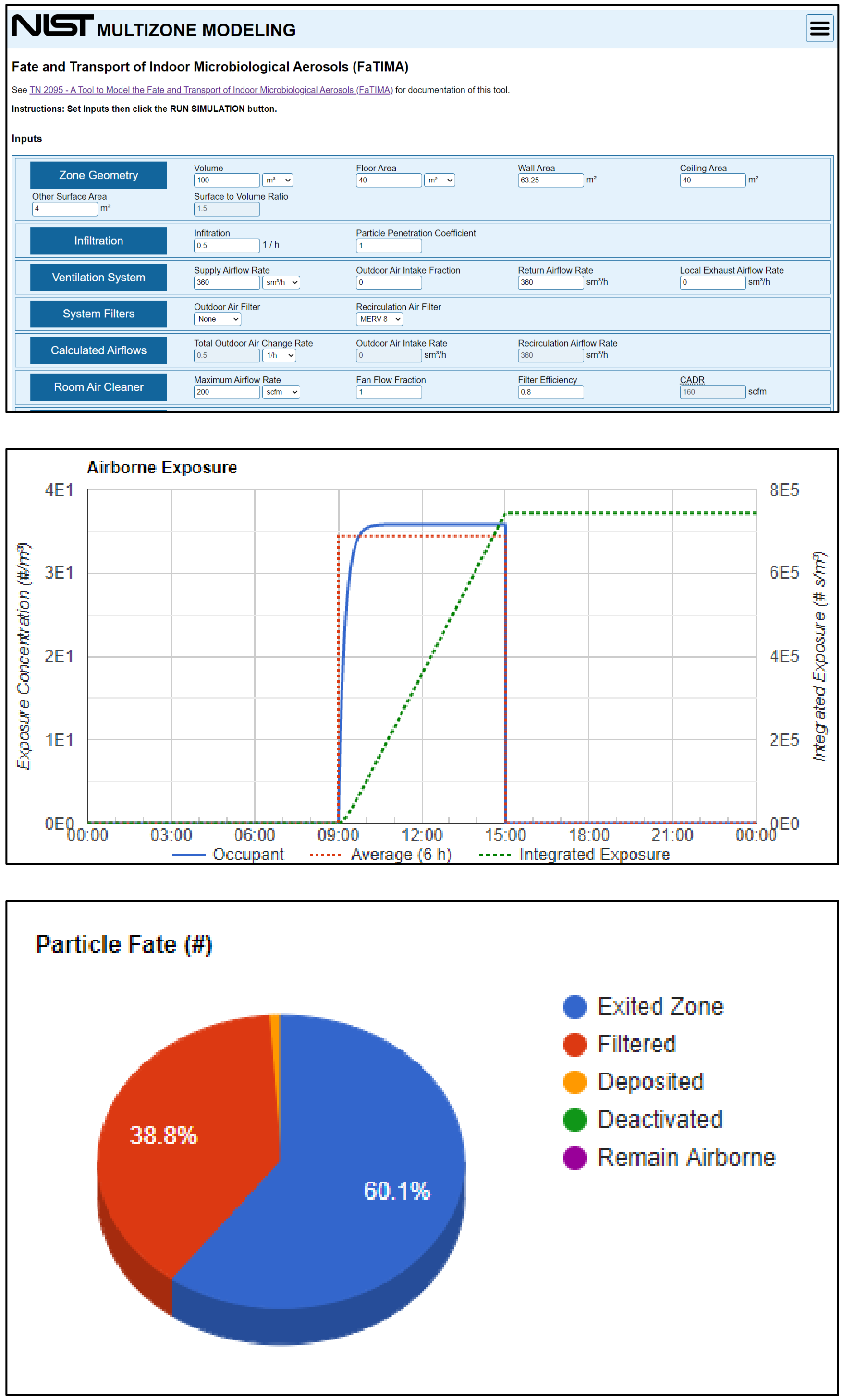


Figure 1. FaTIMA input and output screens: (**a**) portion of the input screen; (**b**) output showing time series of occupant exposure, average hourly exposure, and integrated exposure; and (**c**) output showing the fate of particles.

3. METHODOLOGY

This section describes the characteristics of the homes simulated in Sec. 3.1 and the HVAC system types in Sec. 3.2.

3.1. Homes

Simulations were performed for three homes:

- Small home: 93 m^2 (1 000 ft^2)
- Medium home: 163 m^2 (1 750 ft^2)
- Large home: 232 m^2 (2 500 ft^2)

These home sizes were based on data from the American Housing Survey AHS (2017), where the small home was the low-end of the 25th percentile of home sizes reported, the medium home was the median of the 50th percentile of homes sizes, and the large home was the upper-end of the 75th percentile of home sizes. All homes were assumed to be single story with 2.7 m (9 ft) ceilings with a square footprint. Also, each home was modeled as a single zone. To study room-to-room variations and other details, CONTAM needs to be used instead of FaTIMA.

3.2. HVAC Systems

The simulated homes either had a central HVAC system or a zone-level system. Examples of central HVAC systems include forced air heating and cooling (air conditioner, furnace, or heat pump) systems. Examples of zone-level systems include window air-conditioners, electric baseboard heaters, and split-unit systems. The central HVAC system was simulated with and without mechanical OA ventilation. The zone-level system had no mechanical OA ventilation but only recirculated air. The recirculation filter in the central HVAC system was able to be adjusted, whereas the zone-level system had no filter.

The supply airflow rate for each home was based on floor area: 2.54 $L\cdot s^{-1}m^{-2}$ (0.50 $cfm\cdot ft^{-2}$, where “cfm” is a commonly used acronym in the industry for cubic feet per minute). For the homes with mechanical OA, the total OA ventilation requirement ($Q_{tot,62.2}$) in ASHRAE 62.2-2019 (ASHRAE 2019) was used and calculated from Eq. (1):

$$Q_{tot,62.2}\ (L\cdot s^{-1}) = 0.15A + 3.5(N_{br}+1) \tag{1}$$

where A is the floor area (m^2) and N_{br} is the number of bedrooms. **Table 2** lists $Q_{tot,62.2}$ for the three simulated homes. N_{br} is only used to determine $Q_{tot,62.2}$. As mentioned earlier, the simulations were performed assuming the homes were single zone.

Table 2. Size and number of bedrooms for simulated homes, total OA ventilation requirement, and assumed infiltration rate.

HOME SIZE	FLOOR AREA (A) m^2 (ft^2)	VOLUME (V) m^3 (ft^3)	# OF BEDROOMS (N_{br})	$Q_{tot,62.2}$ $L{\cdot}s^{-1}$ (cfm)	$Q_{inf,62.2}$ $L{\cdot}s^{-1}$ (cfm)
Small	93 (1000)	255 (9000)	2	24.4 (51.8)	16.3 (34.5)
Medium	163 (1750)	446 (15750)	3	38.4 (81.3)	25.6 (54.2)
Large	232 (2500)	637 (22500)	4	52.3 (110.9)	34.9 (73.9)

ASHRAE 62.2-2019 allows for an infiltration credit ($Q_{inf,62.2}$) to be applied to determine the size of the fan required, which must be able to provide $Q_{tot,62.2}$ minus $Q_{inf,62.2}$. The infiltration credit cannot be greater than two-thirds of $Q_{tot,62.2}$, and the value of $Q_{inf,62.2}$ used in this analysis as listed in Table 2 is equal to this maximum value.

The schematic for the central HVAC system type with mechanical OA is shown in **Figure 2a**. The schematic for the central HVAC system type without mechanical OA is shown in **Figure 2b**. The base filtration level of the central HVAC systems incorporated a MERV 6 filter (ASHRAE 2017).The schematic for the zone-level system is shown in **Figure 2c**. The zone-level system had no mechanical OA and no filter. Details of the infiltration and window airflows will be presented in Sec. 4.2 and Sec. 4.3, respectively.

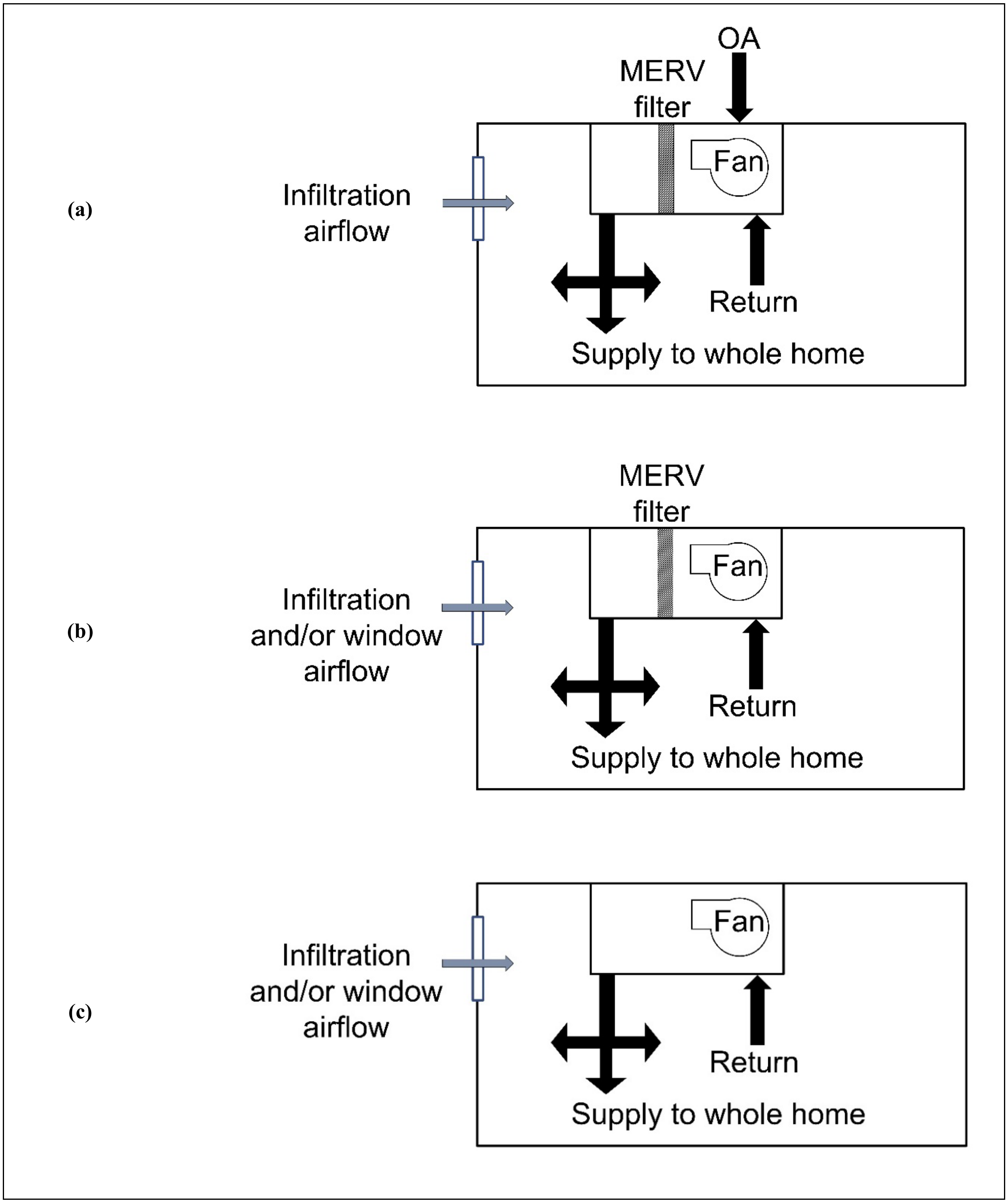


Figure 2. Schematics of a home with **(a)** central HVAC system with mechanical OA, (**b**) central HVAC system without mechanical OA, and **(c)** zone-level system.

4. BASE CASES

This section provides a description of the simulation inputs and how they were implemented in FaTIMA for the base cases. Sections 4.1 to 4.10 follow the order in which inputs are presented in the FaTIMA interface. Sec. 4.11 discusses assumptions made in the simulation cases that were not covered in Sec. 4.1 to Sec. 4.10.

4.1. Zone Geometry

The `Zone Geometry` section of FaTIMA includes fields for `Volume, Floor Area, Wall Area, Ceiling Area`, and `Other Surface Area`. The assumed volume and floor area of each space were defined in Sec. 3.2 and repeated in **Table 3**. The `Wall Area` for each space type was calculated using the assumption of a square footprint and 2.7 m (9 ft) ceilings. The `Wall Area` does not include interior walls. The `Ceiling Area` was assumed to be equal to the `Floor Area`. It was assumed that no other surfaces were present, so the `Other Surface Area` was set to zero. The zone geometry inputs for the space types are listed in **Table 3**.

Table 3. `Zone Geometry` inputs.

HOME SIZE	FLOOR AREA (A) m^2 (ft^2)	VOLUME (V) m^3 (ft^3)	WALL AREA m^2 (ft^2)	CEILING AREA m^2 (ft^2)
Small	93 (1000)	255 (9000)	106 (1138)	93 (1000)
Medium	163 (1750)	446 (15750)	140 (1506)	163 (1750)
Large	232 (2500)	637 (22500)	167 (1800)	232 (2500)

4.2. Infiltration

The `Infiltration` section of FaTIMA has fields for `Infiltration` and `Particle Penetration Coefficient`. `Particle Penetration Coefficient` is the fraction of particles in the OA that will penetrate the building envelope through infiltration (0 = 0 % of particles in the OA penetrate the building envelope through infiltration, 1.0 = 100 % of particles in the OA penetrate the building envelope through infiltration). See Dols et al., (2020) for more information. In this analysis, the `Particle Penetration Coefficient` is set to 1.0 even though it was assumed there were no infectious aerosols in the outdoor air (0 infectious aerosols in the OA × 100 % = 0 infectious particles in the OA penetrate the building envelope through infiltration).

The `Infiltration` input accounted for infiltration as well as any mechanically provided OA. **Table 4** lists the values for the `Infiltration` input depending on the home size and HVAC system type.

Table 4. Infiltration inputs for the base case.

HOME SIZE, HVAC SYSTEM TYPE	Infiltration INPUT† ($L \cdot s^{-1}$)	(cfm)	(h^{-1})
Small Home			
Central system with mechanical OA	24.4	51.8	0.35
Central system without OA	16.3	34.5	0.23
Zone-level system	16.3	34.5	0.23
Medium Home			
Central system with mechanical OA	38.4	81.3	0.31
Central system without OA	25.6	54.2	0.21
Zone-level system	25.6	54.2	0.21
Large Home			
Central system with mechanical OA	52.3	110.9	0.30
Central system without OA	34.9	73.9	0.20
Zone-level system	34.9	73.9	0.20

† The `Infiltration` input in FaTIMA was used to account for infiltration as well as OA intake of central systems with mechanical OA.

The impacts of weather on infiltration are not accounted for in FaTIMA. To do so, users can export the .prj file and simulate it in CONTAM with a weather file.

4.3. Ventilation System

The `Ventilation System` section of FaTIMA has fields for `Supply Airflow Rate`, `Return Airflow Rate` and `Outdoor Air Intake Fraction` (OAF). For the base case, the `Local Exhaust Airflow Rate` was input as zero. The OAF was also set to zero because mechanical OA was incorporated into the `Infiltration` input (See Sec. 4.2).
In the version of FaTIMA used for this analysis, the `Ventilation System` flows could only be held constant for the 24 h simulation. To alter its operation, the CONTAM project file generated by FaTIMA was modified and run using the CONTAM simulation engine. Constant Values Files (.cvf) were used to define the operating schedules. See the CONTAM user manual for more details (Dols and Polidoro 2020).

The base fan operation schedule for both the central HVAC systems, i.e., with and without mechanically provided OA ventilation, was an intermittent schedule. This was done to represent the on/off cycling of the heating and cooling systems in response to thermostat setpoints. An analysis on 7000 homes reported that residential heating and cooling systems operated for less than 20 % of the year (Harriman et al., 2019). Therefore, the intermittent schedule was defined such that the fan was on for the first three minutes of every fifteen-minute interval that the fan was operating. For those cases which included fans, they only operated during the period of the visit or for an additional runtime period as addressed in Sec. 5.5.

The `Ventilation System` values for each home size for the central HVAC system type are listed in **Table 5**. The `Supply Airflow Rate` was equal to the `Return Airflow Rate` in this analysis.

Table 5. `Ventilation System` inputs for the base cases.

HOME SIZE	SUPPLY / RETURN AIRFLOW RATE, $L{\cdot}s^{-1}$ (cfm)
Small	236 (500)
Medium	413 (875)
Large	590 (1 250)

4.4. System Filters

The filter models utilized by FaTIMA were based on the work of Kowalski et al., (1999), who developed models based on MERV ratings of filters as shown in **Figure 3**. The `System Filters` section of FaTIMA has dropdown menus for `Outdoor Air Filter` and `Recirculation Air Filter`. For this analysis, no `Outdoor Air Filter` was used because it was assumed that no infectious aerosols entered from outdoors. For the homes with a central HVAC system, the `Recirculation Air Filter` field of FaTIMA was set to MERV 6 in the base case. For the homes with zone-level systems, it was set to 'None' in the base case (and for all subsequent cases utilizing the zone-level system). From **Figure 3**, at 1 µm, the filtration efficiency for a MERV 6 filter is approximately 0.16

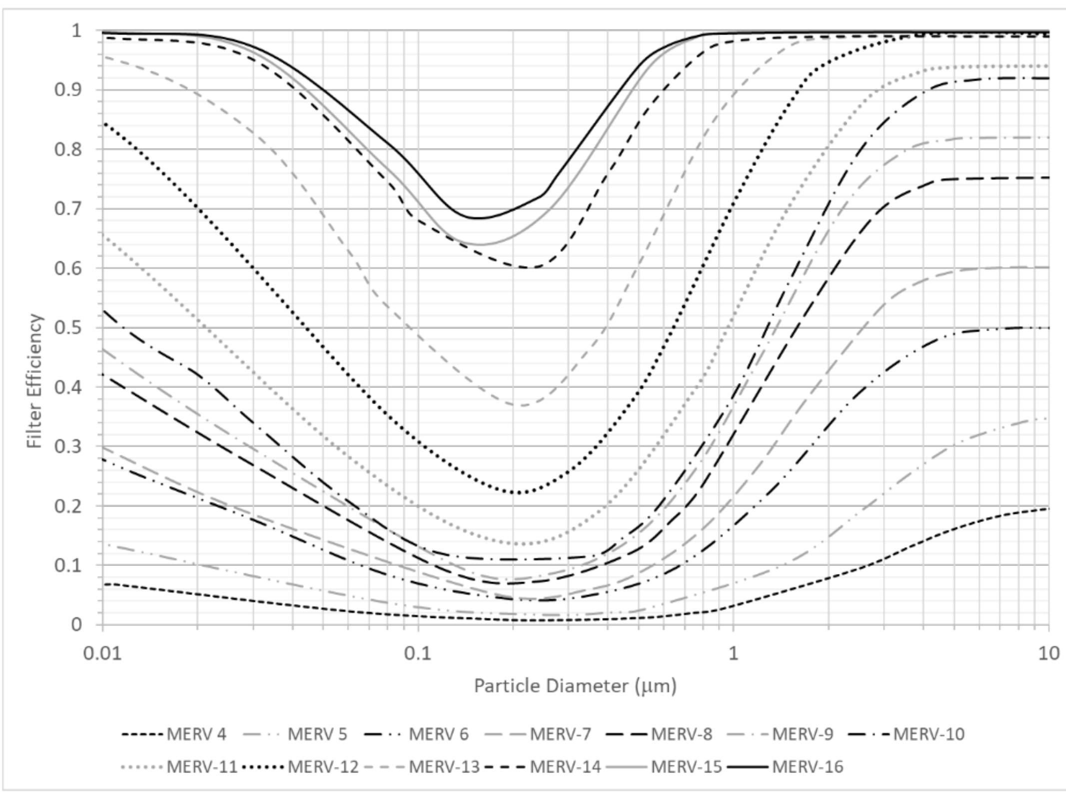


Figure 3. Filter efficiency curves for different MERV ratings based on Kowalski et al. (1999).

4.5. Room Air Cleaner

The `Room Air Cleaner` section of FaTIMA has fields for `Maximum Airflow Rate`, `Fan Flow Fraction`, and `Filter Efficiency`. In this analysis, the room air cleaner is referred to as a PAC (portable air cleaner). The base cases did not include a PAC and the `Fan Flow Fraction` was therefore set to zero.

4.6. Particle Properties

The `Particle Properties` section of FaTIMA has fields for `Name, Diameter, Density,` and `Half-Life` (if `Particle Deactivation` is selected as 'On'). The `Diameter` was entered as 1.0 µm, and the `Density` was entered as 1.0 $g \cdot cm^{-3}$. The `Particle Deactivation` was set to 'Off'.

While SARS-CoV-2 (the virus that causes COVID) itself is smaller than 1 µm (approximately 0.1 µm in diameter), it is typically carried by respiratory aerosols that consist mainly of water, salts, and proteins. According to Liu et al., (2020), the peak concentrations of SARS-CoV-2 occur in aerosols in two size ranges. One range is between: 0.25 µm to 1.0 µm and the other is larger than 2.5 µm. The particle concentration and exposure data in this analysis were simulated using 1.0 µm particles, representing a typical respiratory aerosol that could contain SARS-CoV-2 based on the findings in Liu et al., (2020) and because the version of FaTIMA available at the time of this analysis could only account for a single particle size in any given simulation. These simulations also did not distinguish between aerosols that do and do not contain virus particles.

4.7. Continuous Source

The `Continuous Source` section of FaTIMA has fields for `Generation Rate` and `Generation Time Period Start/End` if the `Source` is selected as 'On'. For this analysis, the `Continuous Source` was set to 'On' and was assumed to represent a single contagious occupant continuously emitting particles for specified intervals depending on visit duration. For the purposes of this analysis, the `Generation Rate` was input as 500 particles per minute ($\# \cdot min^{-1}$), which could be considered a representative value for breathing and talking (Wilson et al., 2021). This generation rate does not assume that all these particles contain virus or that any specific concentration of particles are infectious. This particle generation rate does not consider differences in breathing rates between adults and children, or between different people or activities. Although the literature does identify particle generation rates related to viruses in human exhaled breath (Duguid 1946; Leconte et al., 2011; Milton et al., 2013), the particle generation rate in this analysis is not critical because all reported results of these simulations were normalized as presented in Sec. 6.

Three visit durations were simulated: 30 minutes, 120 minutes, and 240 minutes. For all home sizes and visit durations, the `Generation Time Period Start Time` was set to 00:00. The `End Time` was respectively set to 00:30, 02:00, and 04:00 depending on the visit duration. The `Burst Source` feature of FaTIMA (e.g., coughing) was not used for this analysis.

4.8. Particle Deposition Velocities

The `Particle Deposition Velocities` section of FaTIMA has fields for `Floor, Walls, Ceiling`, and `Other Surface`. Particle size-dependent deposition rates are a function of the friction velocity (u*) as reviewed in Dols et al., (2020). The assumed deposition velocities (floor, walls, and ceiling) were the default values in FaTIMA: 3.71e-3 $cm \cdot s^{-1}$, 3.26e-3 $cm \cdot s^{-1}$ and 4.33e-8 $cm \cdot s^{-1}$, respectively.

The `Effective Deposition Rate` for each home size, listed in **Table 6**, was calculated based on the combination of all deposition velocities and surface areas (Dols et al., 2020). The rates were given in h^{-1} and were almost an order of magnitude lower than the total outdoor ventilation rates modeled. Thus, in this analysis, the deposition was not likely to be a dominant removal mechanism. The deposition onto `Other Surfaces` (e.g., desks and shelves) was set to zero. Deposition onto ductwork surfaces was also not considered as it was not possible with the version of FaTIMA available at the time these analyses were performed.

Table 6. Particle deposition rates used in this analysis.

HOME SIZE	EFFECTIVE DEPOSITION RATE (h^{-1})
Small	0.053
Medium	0.052
Large	0.051

4.9. Initial Concentrations

The `Initial Concentrations` section of FaTIMA has fields for `Outdoor Air` and `Zone Air` concentrations. The initial concentration of the particle was assumed to be zero for both the outdoor air and inside the home.

4.10. Occupant Exposure

The `Occupant Exposure` section of FaTIMA has fields for `Occupancy Type` and `Occupancy Time Period`. For this analysis, the `Occupancy Type` was set to `Constant` because, for all home sizes and visit durations, the resident was present during the entire simulation. Thus, the `Occupancy Time Period Start Time` was set to 00:00 and the `End Time` was set to 24:00. While the occupant was present for the duration of the simulation, the exposure for all cases was analyzed between 00:00 and 01:30 for the 30 min visit, 00:00 and 03:00 for the 120 min visit, and 00:00 and 05:00 for the 240 min visit.

4.11. Other Simulation Assumptions

FaTIMA assumes that the indoor temperature is held constant at 20 °C (68 °F) for the entire simulation. Also, weather data are not used with FaTIMA. To account for weather effects on infiltration and ventilation system operation, the user can download the CONTAM project file associated with the user inputs and simulate those impacts in CONTAM.

5. EXPOSURE MITIGATION MEASURES

Six exposure mitigation measures were simulated for each home size and HVAC system type, as summarized in **Table 7**. A detailed discussion of each mitigation measure is presented in Sec. 5.1 to Sec. 5.5. These mitigation measures were active for the duration of the visit for each case: 30 min, 120 min, or 240 min.

FaTIMA outputs several metrics of exposure. For this analysis, the `Integrated Exposure` (IE) ($\#\cdot s\cdot m^{-3}$) (Sec. 6) was used. The IE of each case was then normalized by that of a base case to yield a normalized integrated exposure (NIE) as described in Sec. 6.

The fan operation of the zone-level system is marked as not applicable (N/A) because the system had no filter and did not provide OA to the home. Thus, the zone-level system operating constantly or intermittently would result in the same particle concentration and occupant exposure.

Table 7. Mitigation options implemented by HVAC system type (includes base case operation).

HVAC TYPE	FAN OPERATION	WINDOW	ADDED OA	FILTRATION	PAC OPERATION SPEED	ADDTL RUNTIME
Central system with mechanical OA	Intermittent, Continuous	No	No, Yes	MERV 6, MERV 13	None, Low Speed, High Speed	No, Yes
Central system without mechanical OA	Intermittent, Continuous	No, Yes	No	MERV 6, MERV 13	None, Low Speed, High Speed	No, Yes
Zone-level system	N/A	No, Yes	No	None	None, Low Speed, High Speed	No, Yes

5.1. Fan Operation

For the homes with a central HVAC system, it was assumed that the fan operation could be switched from “intermittent” in the base case (“Fan Int” cases) to “continuous” (“Fan Cont” cases). Increasing the fan operation time allowed more indoor air to pass through the recirculation filter.

5.2. OA Vent Level

There were four OA vent levels simulated, though each level was not simulated with all HVAC system types (Sec. 3.2). The level “none” (infiltration only) and “low” (ASHRAE 62.2-2019 requirement) were described in Sec. 3.2. The remaining levels “window” (Sec. 5.2.1) and “high” (Sec. 5.2.2) will be described in this section.

5.2.1. Window OA

OA ventilation via windows was simulated in FaTIMA using the `Infiltration` input as described in Sec. 4.2. This section describes how airflow rates attributed to window opening were determined for the purposes of this analysis. Window airflow calculations are described below but were not used in the simulations. Instead, a simplified approach was used to estimate window airflow rates, i.e., doubling the infiltration value for each home size. Windows were only opened during the period of the visit or for an additional runtime period as addressed in Sec. 5.5.

Irving and Clements-Croome (2005) provided methods for calculating the buoyancy- and wind-driven airflow through an opening such as a window. For single-sided, single vent, buoyancy-driven flow, Irving and Clements-Croome (2005) estimated the airflow rate ($q_{\text{opening,buoyancy}}$) as follows:

$$q_{\text{opening,bouyancy}}\ (\mathrm{m \cdot s^{-1}}) = \frac{A_{\text{opening}} \times C_{\mathrm{d}}}{\sqrt{\frac{(T_i+273)}{\Delta T g h}}} \tag{2}$$

where A_{opening} is the area of the opening (m^2), C_{d} is the discharge coefficient, T_{i} is the indoor temperature (°C), ΔT is the indoor-outdoor temperature difference (K), g is the gravitational force per unit mass (9.8 m·s^{-2}), and h is the height of the opening (m). The value of C_{d} is typically 0.25 so that value was used in this analysis.

For single-sided, single vent, wind-driven flow, Irving and Clements-Croome (2005) estimated the airflow rate ($q_{\text{opening,wind}}$) as follows:

$$q_{\text{opening,wind}}\ (\mathrm{m \cdot s^{-1}}) = A_{\text{opening}} \times C \times U \tag{3}$$

where C depends on the geometry of the opening, the position at which the reference wind speed is measured, and the flow field around the building. Reported values range from 0.01 to 0.05. In this analysis, a value of 0.03 was used for C. U is the wind speed (m·s^{-1}).

The airflow through a 70 cm wide × 35 cm tall (27.5 in × 13.8 in) opening for three cities representing a variety of climates in the US (Chicago IL, Atlanta GA, and Baltimore MD) was calculated. Design cooling and heating temperatures are provided for heating and cooling seasons, thus the $q_{\text{opening,bouyancy}}$ was calculated for both (**Table 8**). An average wind speed by city is provided and thus only one $q_{\text{opening,wind}}$ value is calculated (**Table 9**). The total airflow through the opening was determined as the sum of the buoyancy- and wind-driven airflows (**Table 10**).

Table 8. Summary of window airflow calculations (single-sided, single vent, buoyancy-driven flow).

	$q_{\text{opening,buoyancy}}$, h^{-1}					
	CHICAGO, IL		**ATLANTA, GA**		**BALTIMORE, MD**	
HOME SIZE	**HEATING**	**COOLING**	**HEATING**	**COOLING**	**HEATING**	**COOLING**
Small	0.7	0.0	0.6	0.4	0.7	0.4
Medium	0.3	0.2	0.3	0.2	0.3	0.2
Large	0.3	0.1	0.3	0.1	0.3	0.1

Table 9. Summary of window airflow calculations (single-sided, single vent, wind-driven flow).

HOME SIZE	$q_{\mathrm{opening,wind}}$, h^{-1} CHICAGO, IL	ATLANTA, GA	BALTIMORE, MD
Small	0.6	0.5	0.5
Medium	0.3	0.3	0.3
Large	0.2	0.2	0.2

Table 10. Summary of window airflow calculations (single-sided, single vent, total flow).

	$q_{\mathrm{opening,total}}$, h^{-1}					
	CHICAGO, IL		ATLANTA, GA		BALTIMORE, MD	
HOME SIZE	HEATING	COOLING	HEATING	COOLING	HEATING	COOLING
Small	1.3	0.6	1.1	0.9	1.1	0.8
Medium	0.7	0.5	0.6	0.5	0.6	0.5
Large	0.5	0.4	0.5	0.3	0.4	0.3

For design cooling and heating conditions, the average calculated total airflow through a single-sided, single-vent for the three home sizes was 0.6 ± 0.3 h^{-1}. Note that this value was determined using design conditions, meaning high temperatures in the summer and colder temperatures in the winter. Note also that airflow through an open window would not be expected to remain constant as was assumed in these simulations.

Given the uncertainty in window location, the environment surrounding a home, the size of the window opening, how much a resident might open their window (opening height and frequency), weather, and other factors, rather than using the calculated values just described, this analysis assumed that a window opening would provide double the infiltration rate (**Table 11**). The range of assumed window opening airflow was between 0.39 h^{-1} and 0.46 h^{-1} depending on the home size, which was within the range of calculated single-sided, single vent flow in **Table 11**.

Table 11. Window inputs by home size for the central system without mechanical OA and zone-level HVAC system types.

	Infiltration INPUT WITH WINDOW OA CASES		
HOME SIZE	(L·s^{-1})	(cfm)	(h^{-1})
Small	32.6	69.0	0.46
Medium	51.2	108.5	0.41
Large	69.8	147.9	0.39

5.2.2. High OA or Added Mechanical OA

Only the homes with a central HVAC system and mechanical OA had the option to supply an additional 94.4 L·s^{-1} (200 cfm) of OA ("AddedOA" cases). This additional airflow is listed in **Table 12** and was incorporated into the `Infiltration` input. However, such an intervention might result in reduced indoor air quality because no filter was modeled with this intervention and the outdoor air may contain elevated levels of contaminants such as particulate matter.

Table 12. Additional mechanical OA inputs by home size for the central HVAC system with mechanical OA.

HOME SIZE	Infiltration INPUT WITH ADDED OA ($L{\cdot}s^{-1}$)	(cfm)	(h^{-1})
Small	118.8	251.8	1.68
Medium	132.8	281.3	1.07
Large	146.7	310.9	0.83

5.3. Filtration

Enhanced filtration in the central HVAC systems was simulated as MERV 13. From **Figure 3**, at 1 µm, the filtration efficiency for a MERV 13 filter is approximately 0.90. The filtration was varied under the `Recirculation Air Filter` section in FaTIMA (See Sec. 4.4).

5.4. Portable Air Cleaner (PAC)

PACs were implemented in all three homes regardless of HVAC system type. PACs are rated according to their CADR as described in ANSI/AHAM Standard AC-1 (AHAM 2006). The CADR is determined by the airflow rate through the air cleaner (in units of cubic feet of air per minute or cfm) multiplied by the removal efficiency associated with three different types of particles: smoke 0.09 µm to 1.0 µm, dust 0.5 µm to 3 µm and pollen 5 µm to 11 µm. The CADR rating for smoke was used in this analysis.

It was assumed that the simulated PAC contained a high-efficiency particulate air (HEPA) filter with a filter efficiency of 99 % for 1 µm particles. At low speed, the maximum airflow rate of 47 $L{\cdot}s^{-1}$ (100 cfm) and filter efficiency of 0.99 resulted in a CADR of 99 cfm (“PAC Low” cases). At high speed, the maximum airflow rate of 142 $L{\cdot}s^{-1}$ (300 cfm) and filter efficiency of 0.99 resulted in a CADR of 297 cfm (“PAC High” cases). The Maximum Airflow Rate of the Room Air Cleaner section in FaTIMA (see Sec. 4.5) was set to these values and the Fan Flow Fraction was set to 1.0. PACs only operated during the period of the visit or for an additional runtime period as addressed in Sec. 5.5.

Table 13 converts the PAC CADR flow rates to air changes per hour (h^{-1}) by dividing the maximum flow in $L{\cdot}s^{-1}$ by the home’s volume. The PAC delivers a higher air change in the small home because it has the smallest volume of the home sizes simulated.

Table 13. Summary of air changes per hour (h^{-1}) delivered by simulated PAC.

HOME SIZE	PAC LOW - 99 CADR	PAC HIGH - 297 CADR
Small home	0.7	2.0
Medium home	0.4	1.1
Large home	0.3	0.8

5.5. Additional Runtime

This parameter means that if a mitigation measure (HVAC fan operation, window opening, additional mechanical OA, and/or PAC) was activated, it would be active for the duration of the visit as well as 60 min after the visitor left (“Addtl Runtime” cases). For these cases, the exposure was analyzed between 00:00 and 01:30 for the 30 min visit, 00:00 and 03:00 for the 120 min visit, and 00:00 and 05:00 for the 240 min visit.

6. METRICS FOR COMPARING EXPOSURE

The `Integrated Exposure`, highlighted in **Figure 4**, was calculated by FaTIMA using trapezoidal integration to perform a summation of the product of the airborne particle concentration and the simulation time step over the user-defined occupancy interval.

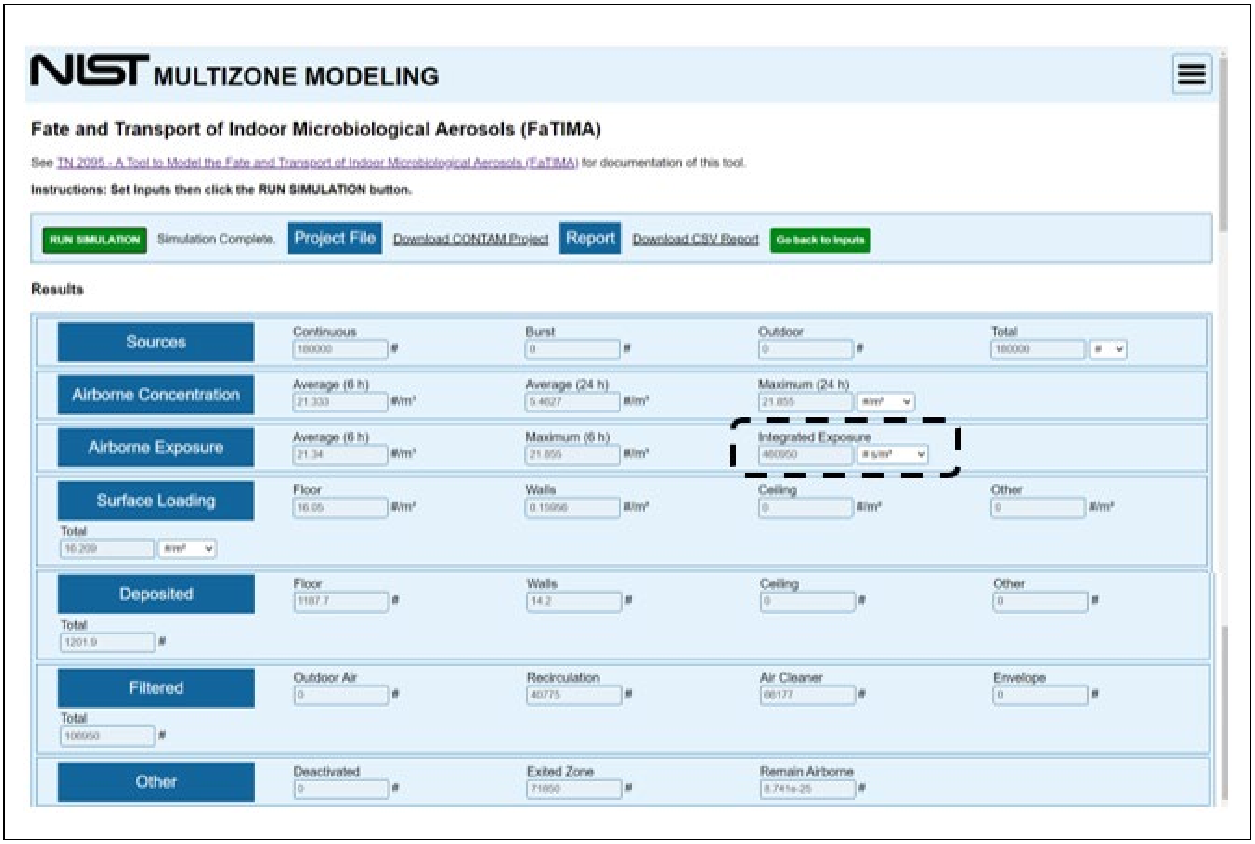


Figure 4. Screenshot of FaTIMA numerical outputs.

Since the goal of this analysis was to evaluate the relative reduction in particle exposure, a Normalized Integrated Exposure (NIE) was used. The term "NIE" was used to represent simulation results normalized to the results of a corresponding base case, i.e., a case with no mitigation measures. with respect to home size and HVAC system type.

7. RESULTS

In Sec. 7.1, comparisons made between the base cases are discussed for the three home sizes. Detailed data are presented in Sec. 7.2 for the small home, Sec. 7.3 for the medium home, and Sec. 7.4 for the large home for the mitigation measures applied individually. The results are then presented for combined mitigation measures in Sec. 7.5.

7.1. Base Cases

Table 14, **Table 15**, and **Table 16** show the NIE for the three home sizes by HVAC system type and visit duration. When comparing base cases, the NIE was normalized by the IE of the zone-level system with the 240 min visit duration. The NIE values were lower for shorter duration visits of the contagious visitor regardless of the home size or HVAC system type. For the 30 min visitor, there was a maximum 4 % difference in exposure among the HVAC system types. For the 120 min visitor, there was a maximum 15 % difference in exposure among the HVAC system types. For the 240 min visitor, there was a maximum 23 % difference in exposure among the HVAC system types.

The zone-level HVAC system had the highest NIE values of the three HVAC systems because these systems had no additional OA ventilation beyond that provided by infiltration and had no filtration. For the 30 min visit, the NIE of all HVAC system types were the same within two significant digits for the small home and the central system without mechanical OA and zone-level system were the same within two significant digits for the medium and large homes. The central HVAC system with mechanical OA had the lowest NIE values because it was the only system with both mechanical OA and filtration in the HVAC system.

Table 14. NIE one hour after the respective visit duration normalized to small home base case with a 240 min visit and zone-level system.

SMALL HOME VISIT DURATION	CENTRAL SYSTEM WITH MECHANICAL OA	CENTRAL SYSTEM WITHOUT MECHANICAL OA	ZONE-LEVEL SYSTEM
30 min	0.07	0.07	0.07
120 min	0.33	0.36	0.39
240 min	0.77	0.87	**1.00**

Table 15. NIE one hour after the respective visit duration normalized to medium home base case with a 240 min visit and zone-level system.

MEDIUM HOME VISIT DURATION	CENTRAL SYSTEM WITH MECHANICAL OA	CENTRAL SYSTEM WITHOUT MECHANICAL OA	ZONE-LEVEL SYSTEM
30 min	0.06	0.07	0.07
120 min	0.33	0.35	0.38
240 min	0.77	0.87	**1.00**

Table 16. NIE one hour after the respective visit duration normalized to large home base case with a 240 min visit and zone-level system.

LARGE HOME VISIT DURATION	CENTRAL SYSTEM WITH MECHANICAL OA	CENTRAL SYSTEM WITHOUT MECHANICAL OA	ZONE-LEVEL SYSTEM
30 min	0.06	0.07	0.07
120 min	0.33	0.35	0.38
240 min	0.78	0.87	**1.00**

7.2. Small home with mitigation measures applied individually

Figure 5 to **Figure 7** show the results for the small home with the 30 min, 120 min, and 240 min visit durations and the available mitigation measures described in Sec. 5 applied individually, without and with the extra 60 min of additional runtime. In this discussion, the NIE was normalized by the IE of the respective system and visit duration with no mitigation measures.

On average, the AddedOA cases resulted in the lowest NIE values (average of 0.55) across all visit durations. The next lowest NIE values were for all PAC cases with an average NIE = 0.57. The average NIE values for both the MERV 13 cases and the Fan Cont cases was 0.77, and for the Window cases was 0.86. In the cases simulated, the window mitigation measure was the least effective in reducing exposure, on average.

When the additional 60 min runtime was implemented, the NIE values were further reduced (**Figure 5b**, **Figure 6b**, and **Figure 7b**). The average NIE with additional runtime for the AddedOA cases was 0.44, for all PAC cases was 0.46, for the MERV 13 cases was 0.67, for the Fan Cont cases was 0.72, and for the Window cases was 0.82 across all HVAC system types and visit durations.

As the visit duration increased, the effectiveness of a mitigation measure increased as evidenced by lower NIE values shown for longer visit durations. For example, in the 30 min case, the continuous fan operation reduced the NIE to an average of 0.90. However, in the 120 min case, the continuous fan operation reduced the NIE to an average of 0.76. In the 240 min case, the continuous fan operation reduced the NIE to an average of 0.67. This trend was observed for all mitigation measures.

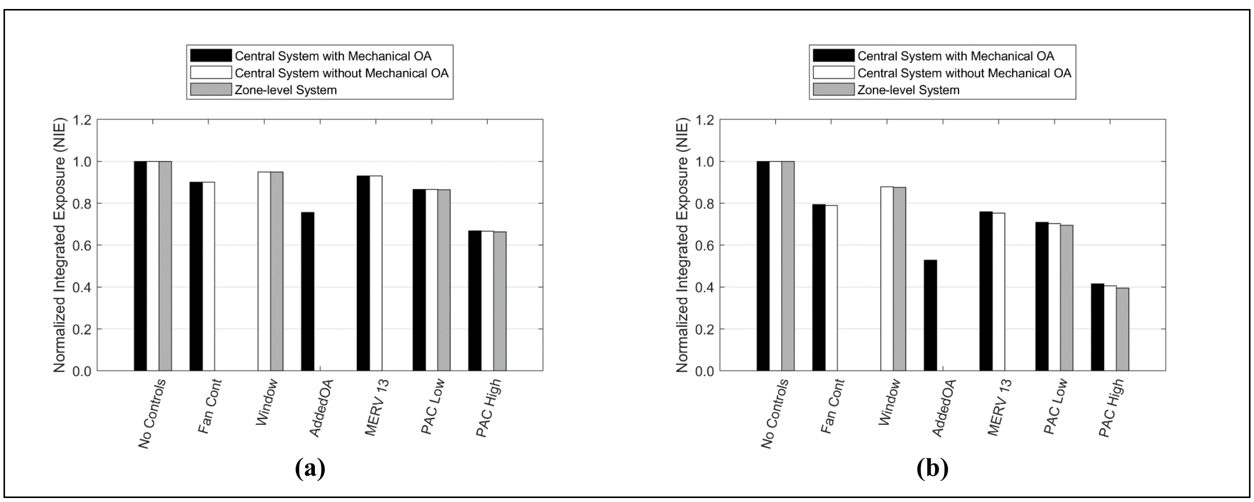


Figure 5. NIE results for small home (a) without and (b) with additional runtime of mitigation measures and 30 min visitor (mitigation measures applied individually).

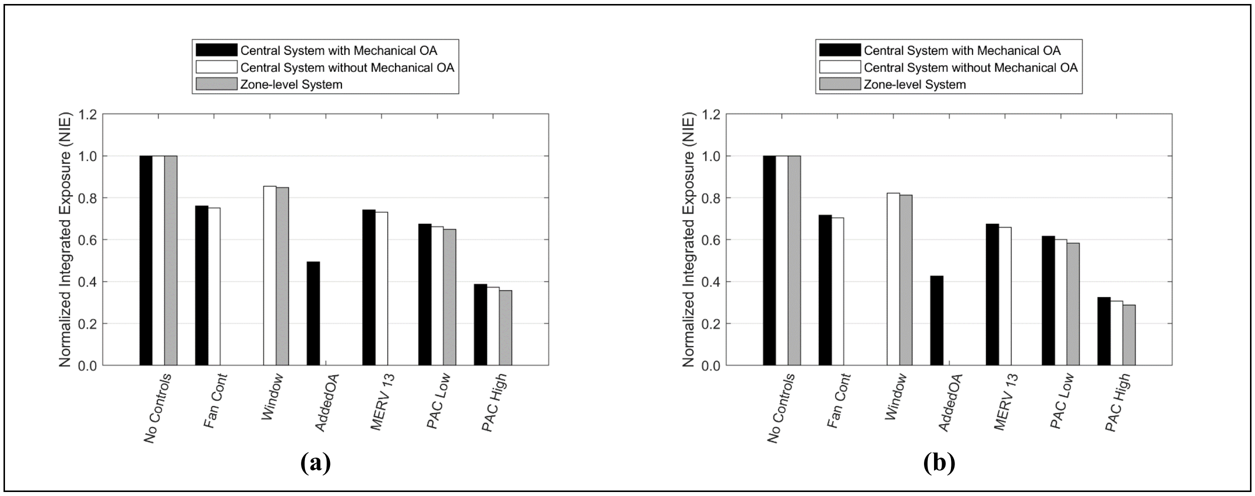


Figure 6. NIE results for small home (A) without and (b) with additional runtime of mitigation measures and 120 min visitor (mitigation measures applied individually).

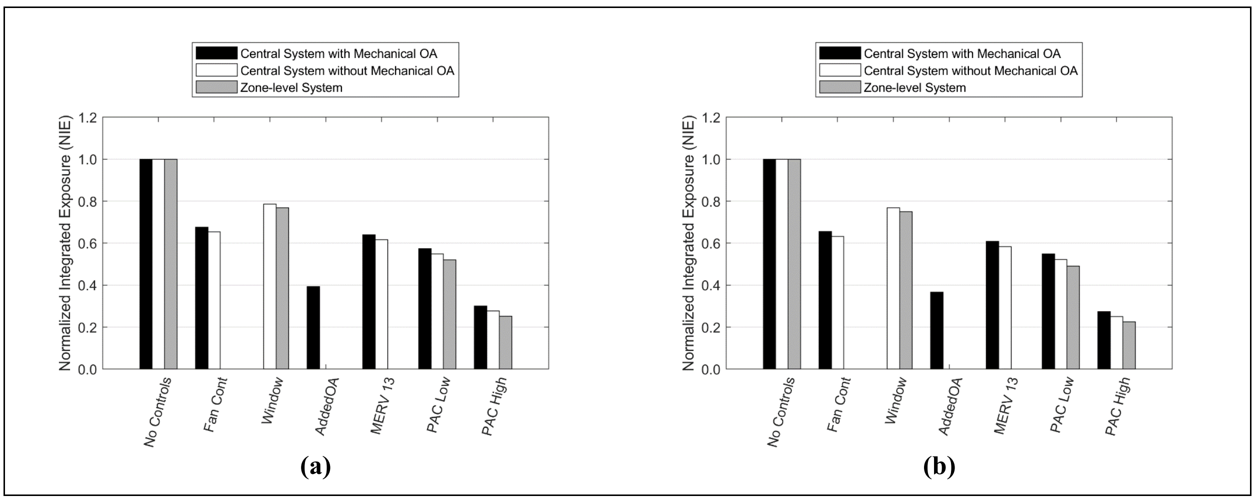


Figure 7. NIE results for small home (a) without and (b) with additional runtime of mitigation measures and 240 min visitor (mitigation measures applied individually).

7.3. Medium home with mitigation measures applied individually

Figure 8 to **Figure 10** show the results for the medium home with the 30 min, 120 min, and 240 min visit durations and the available mitigation measures described in Sec. 5 applied individually, without and with the extra 60 min of additional runtime. In this discussion, the NIE was normalized by the IE of the respective system and visit duration with no mitigation measures.

On average, the AddedOA cases resulted in the lowest NIE values (average of 0.67) across all visit durations. The next lowest NIE values were for all PAC cases with an average NIE = 0.68. The average NIE for the MERV 13 cases was 0.76, for the Fan Cont cases was 0.77, and for the Window cases was 0.87. In the cases simulated, the window mitigation measure was the least effective in reducing exposure, on average.

When the additional 60 min runtime was implemented, the NIE values were further reduced (**Figure 8b**, **Figure 9b**, and **Figure 10b**). The average NIE with additional runtime for the AddedOA cases was 0.58, for all PAC cases was 0.60, for the MERV 13 cases was 0.67, for the Fan Cont cases was 0.71, and for the Window cases was 0.83 across all HVAC system types and visit durations.

As the visit duration increased, the effectiveness of a mitigation measure increased as evidenced by lower NIE values shown for the longer visit durations. For example, in the 30 min case, the continuous fan operation reduced the NIE to an average of 0.90. However, in the 120 min case, the continuous fan operation reduced the NIE to an average of 0.75. In the 240 min case, the continuous fan operation reduced the NIE to an average of 0.66. This trend was observed for all mitigation measures.

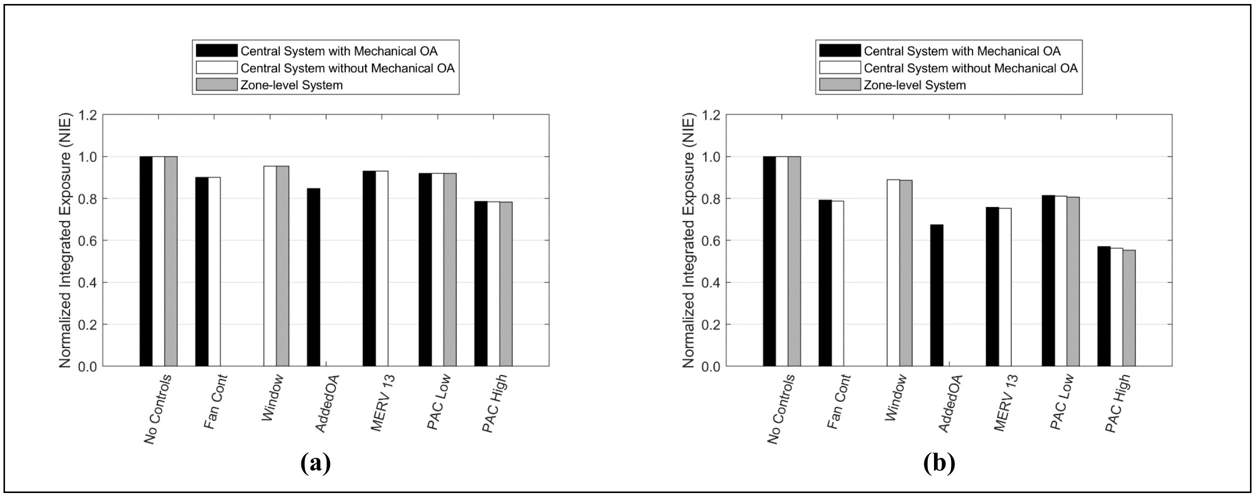


Figure 8. NIE results for medium home (a) without and (b) with additional runtime of mitigation measures and 30 min visitor (mitigation measures applied individually).

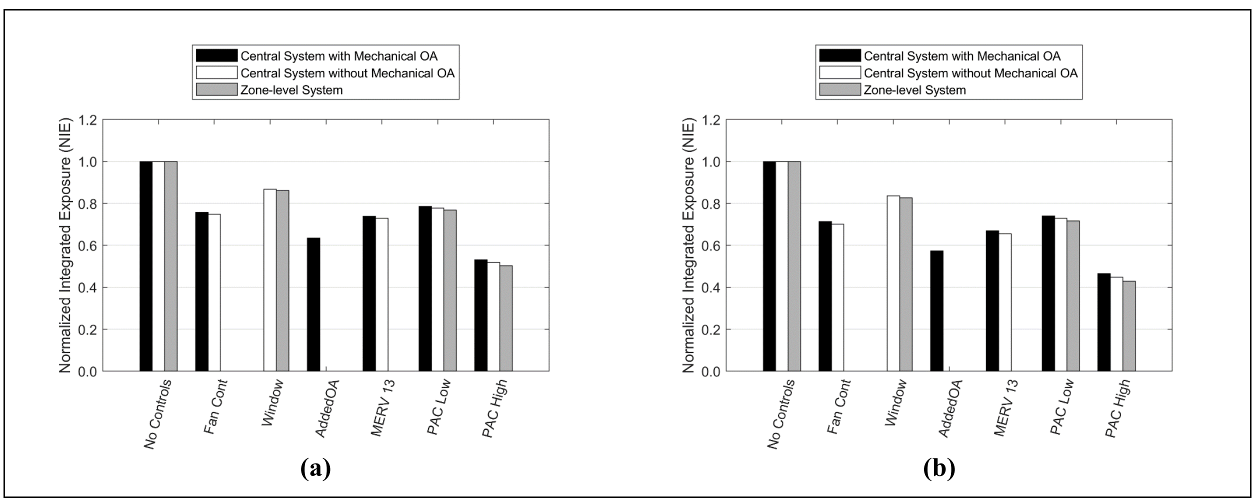


Figure 9. NIE results for medium home (a) without and (b) with additional runtime of mitigation measures and 120 min visitor (mitigation measures applied individually).

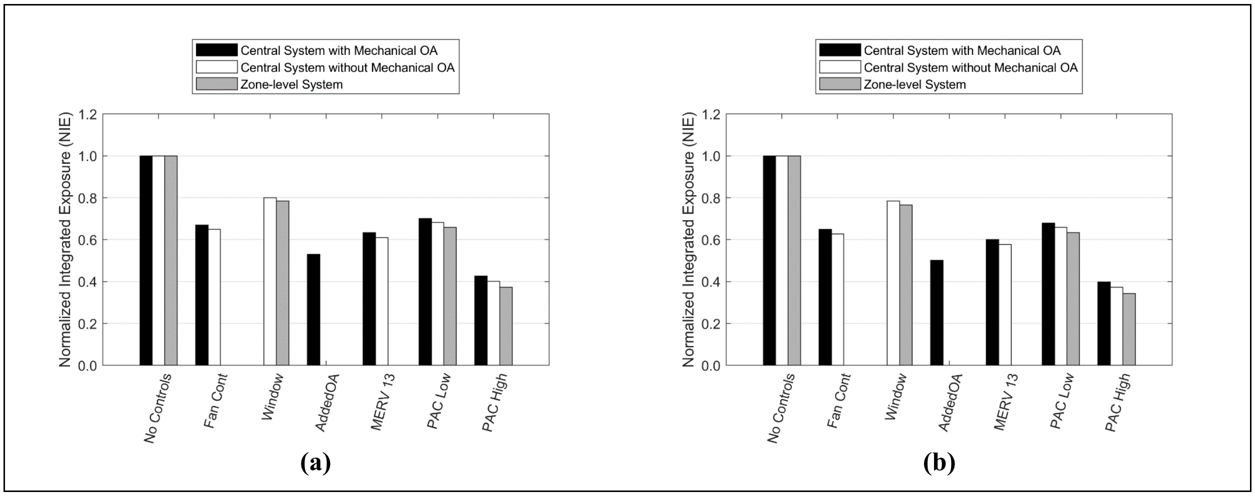


Figure 10. NIE results for medium home (a) without and (b) with additional runtime of mitigation measures and 240 min visitor (mitigation measures applied individually).

7.4. Large home with mitigation measures applied individually

Figure 11 to **Figure 13** show the results for the large home with the 30 min, 120 min, and 240 min visit durations and the available mitigation measures described in Sec. 5 applied individually, without and with the extra 60 min of additional runtime. In this discussion, the NIE was normalized by the IE of the respective system and visit duration with no mitigation measures.

On average, the AddedOA cases resulted in the lowest NIE values (average of 0.74) across all visit durations. The next lowest NIE values were for the PAC cases with an average NIE = 0.75. The average NIE for the MERV 13 cases was 0.76, for the Fan Cont cases was 0.77, and for the Window cases was 0.87. In the cases simulated, the window mitigation measure was the least effective in reducing exposure, on average.

When the additional 60 min runtime was implemented, the NIE values were further reduced (**Figure 11b**, **Figure 12b**, and **Figure 13b**). The average NIE with additional runtime for the AddedOA cases was 0.67, for all PAC cases was 0.68, for the MERV 13 cases was 0.67, for the Fan Cont cases was 0.71, and for the Window cases was 0.84 across all HVAC system types and visit durations.

As the visit duration increased, the effectiveness of a mitigation measure increased as evidenced by lower NIE values shown for longer visit durations. For example, in the 30 min case, the continuous fan operation reduced the NIE to an average of 0.90. However, in the 120 min case, the continuous fan operation reduced the NIE to an average of 0.75. In the 240 min case, the continuous fan operation reduced the NIE to an average of 0.66. This trend was observed for all mitigation measures.

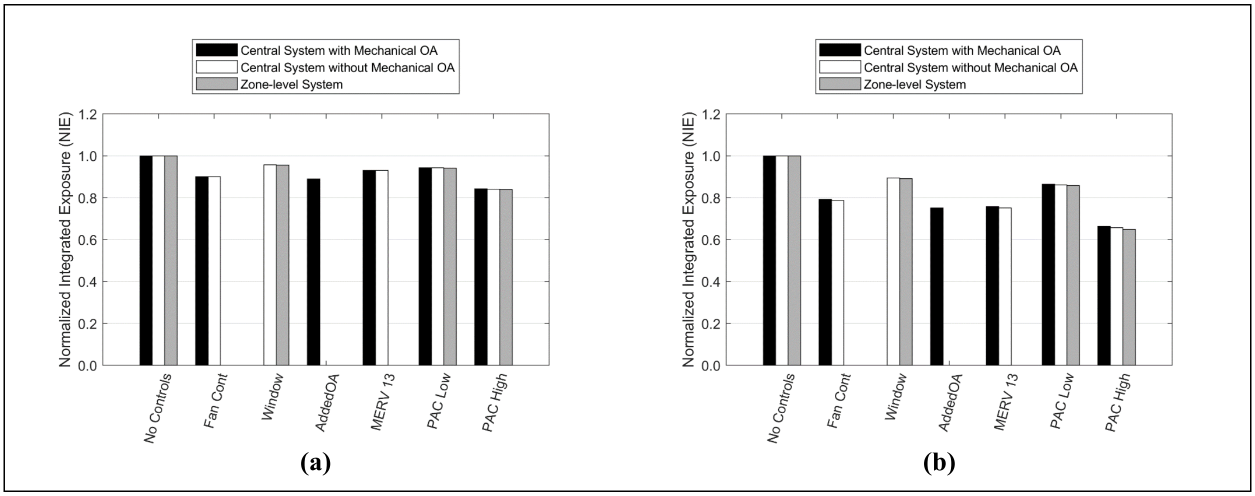


Figure 11. NIE results for large home (a) without and (b) with additional runtime of mitigation measures and 30 min visitor (mitigation measures applied individually).

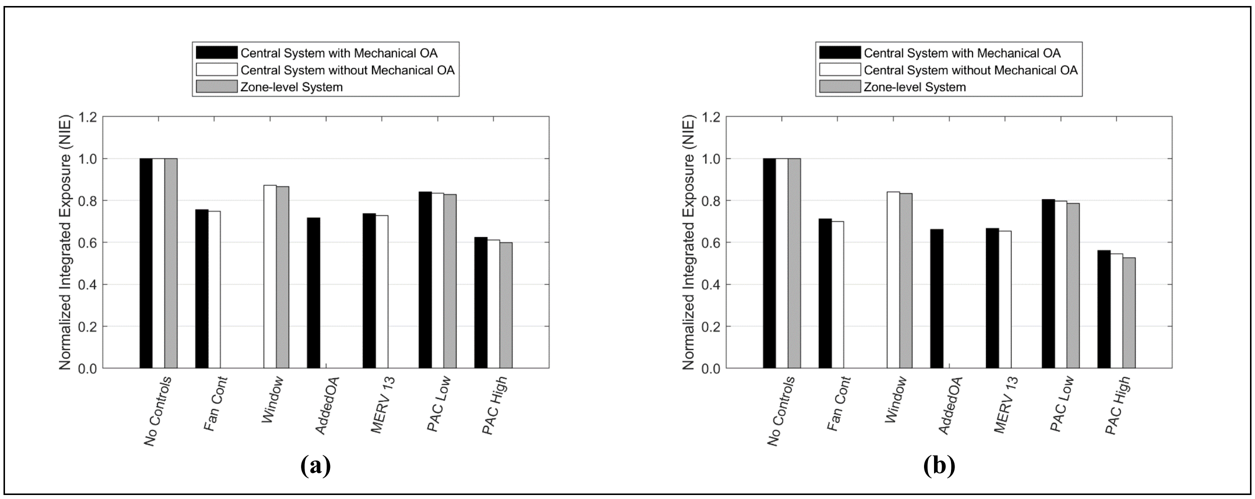


Figure 12. NIE results for large home (a) without and (b) with additional runtime of mitigation measures and 120 min visitor (mitigation measures applied individually).

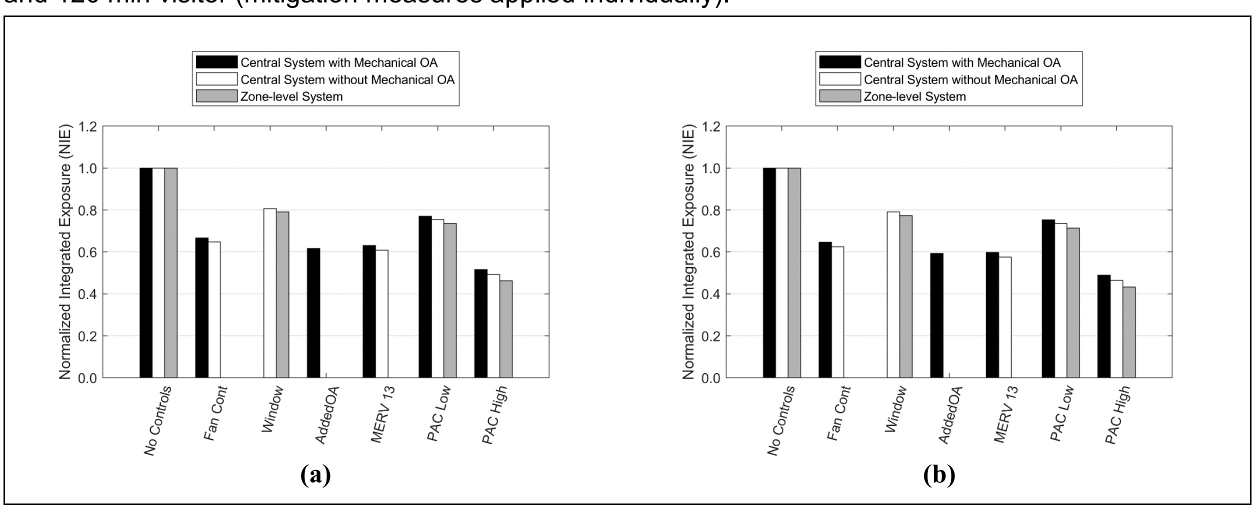


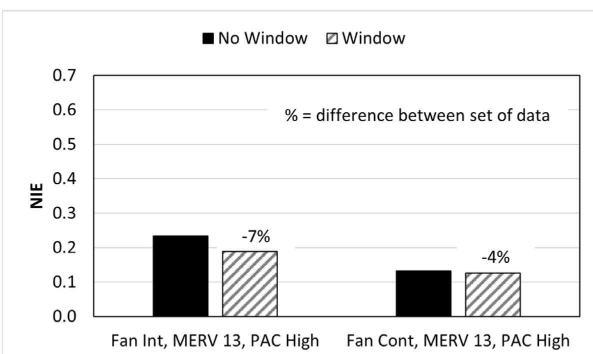
Figure 13. NIE results for large home (a) without and (b) with additional runtime of mitigation measures and 240 min visitor (mitigation measures applied individually).

7.5. Results with combined mitigation measures

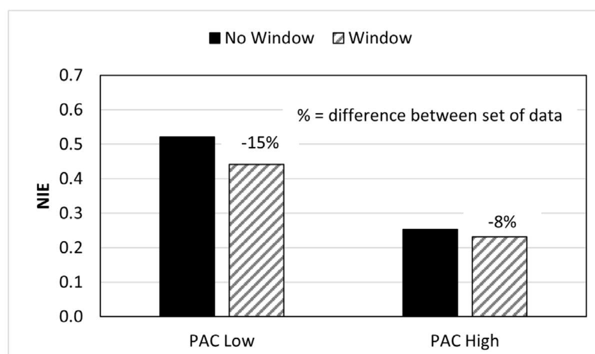
The subset of results for combined mitigation measures are only discussed in detail for the small home, 240 min visit duration. For the results discussed, the reductions in NIE were within 7 % for all the home sizes if the results from the PAC were excluded. This is because the same size PAC was not as effective in the large home as it was in the small home. For the performance of mitigation measures for every home and visit duration, the user can reference Appendix 1 - SIMULATION IE VALUES or use ViPER (Sec. 9).

In this discussion, the NIE was normalized by the IE of the respective system and 240 min visit duration with no mitigation measures (NIE=1.0 not shown on graphs below for clarity). Of the combinations of mitigation measures to be presented, PAC High in combination with other mitigation measures reduced NIE the most. Of the cases presented, the average reduction was 48 %. Of the mitigation measure combinations to be presented, window opening in combination with other mitigation measures did not reduce the NIE as much as other mitigation measures. Of the cases presented, the average reduction was 8.5 %. Keep in mind these averages are only for the combinations presented for the small home and 240 min visit duration.

The central system without mechanical OA and zone-level system had the option to include open windows. **Figure 14** shows that the combination of open windows with other mitigation measures (e.g., Fan Int/Cont, MERV 13, and/or PAC) reduced NIE between 4 % and 15 % in the small home. Window OA reduced NIE more for the zone-level system (in combination with a PAC), which was not surprising since the zone-level system had no base mechanical OA and no recirculation filter.



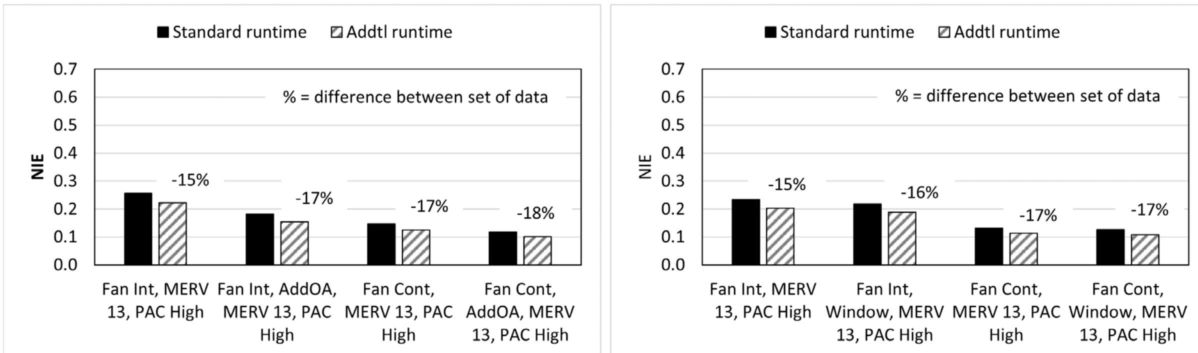
(a) Central system without mechanical OA



(b) Zone-level system

Figure 14. Reductions in NIE due to combination of Window OA with other mitigation measures for small home.

Addtl Runtime was simulated for all HVAC system types. The combination of Addtl Runtime with either Window OA or PAC High for the zone-level system was discussed in Sec. 7.2 so it will not be repeated. **Figure 15** shows that the combination of Addtl Runtime with other mitigation measures (e.g., Fan Int/Cont, MERV 13 filter, AddedOA, PAC High) reduced NIE between 15 % and 18 % in the small home for the central HVAC systems.



(a) Central system with mechanical OA **(b)** Central system without mechanical OA

Figure 15. Reductions in NIE due to combination of Addtl Runtime with other mitigation measures for small home.

Only the central system with mechanical OA had the option to include AddedOA. **Figure 16** shows that AddedOA combined with Fan Int reduced NIE by 29 %. The reduction was smaller (19 %) in combination with Fan Cont. This was not surprising since constant fan operation resulted in lower NIE than intermittent fan operation.

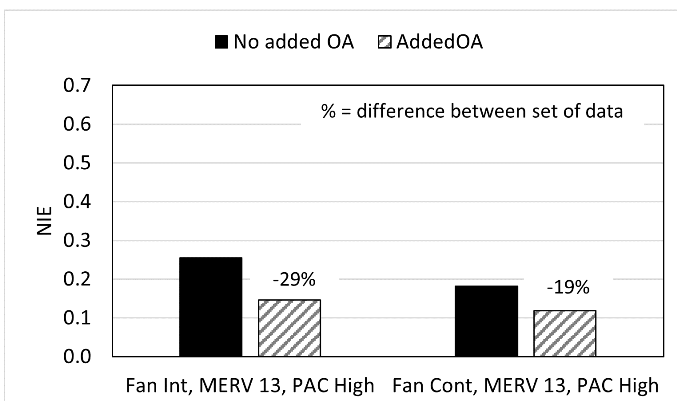
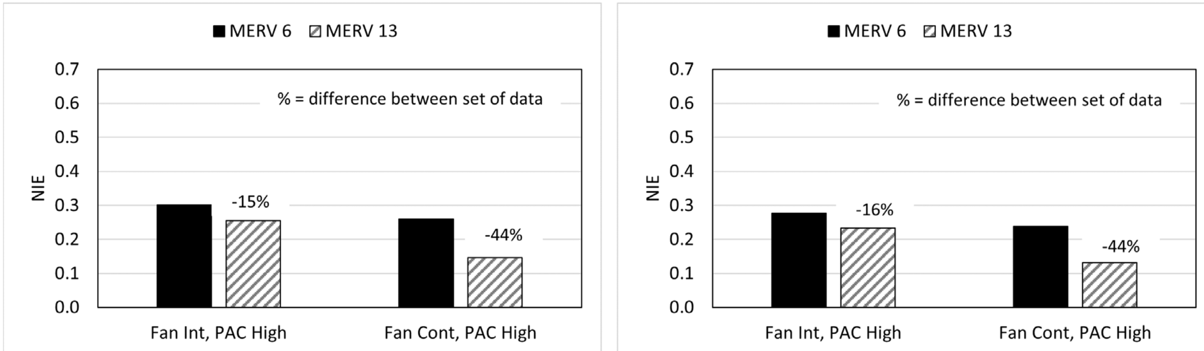


Figure 16. Reductions in NIE due to due to combination of AddedOA with other mitigation measures for small home with central system with mechanical OA.

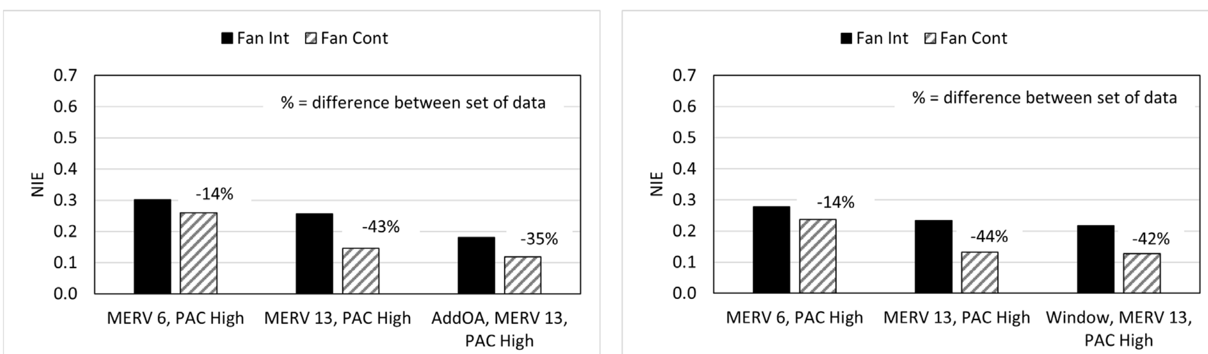
The central systems had the option to enhance the filter from MERV 6 to MERV 13. **Figure 17** shows that MERV 13 in combination with other mitigation measures (e.g., Fan Int/Cont, PAC High) reduced NIE between 15 % and 44 % in the small house. MERV 13 filtration reduced NIE more in combination with Fan Cont, which was not surprising. Continuous fan operation would allow more air to pass through the filter thereby increasing the filtration effect.



(a) Central system with mechanical OA **(b)** Central system without mechanical OA

Figure 17. Reductions in NIE due to combination of MERV 13 with other mitigation measures for small home.

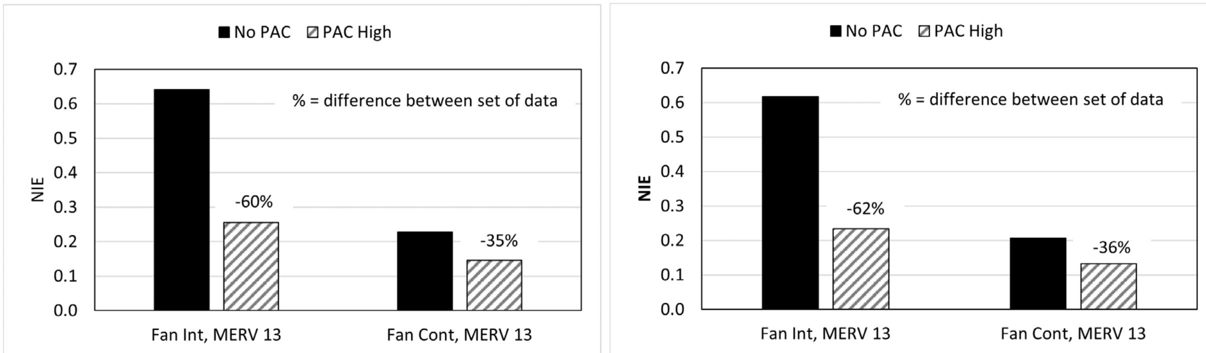
The central systems had the option to change fan operation from intermittent to continuous. **Figure 18** shows that the combination of Fan Cont with other mitigation measures (e.g., PAC High, MERV 13, AddedOA) reduced NIE between 14 % and 44 % in the small home. Continuous fan operation reduced NIE more for the central system without OA on average (33 % versus 30 %), which was not surprising since this system had no base OA.



(a) Central system with mechanical OA **(b)** Central system without mechanical OA

Figure 18. Reductions in NIE due to combination of Fan Cont with other mitigation measures for small home.

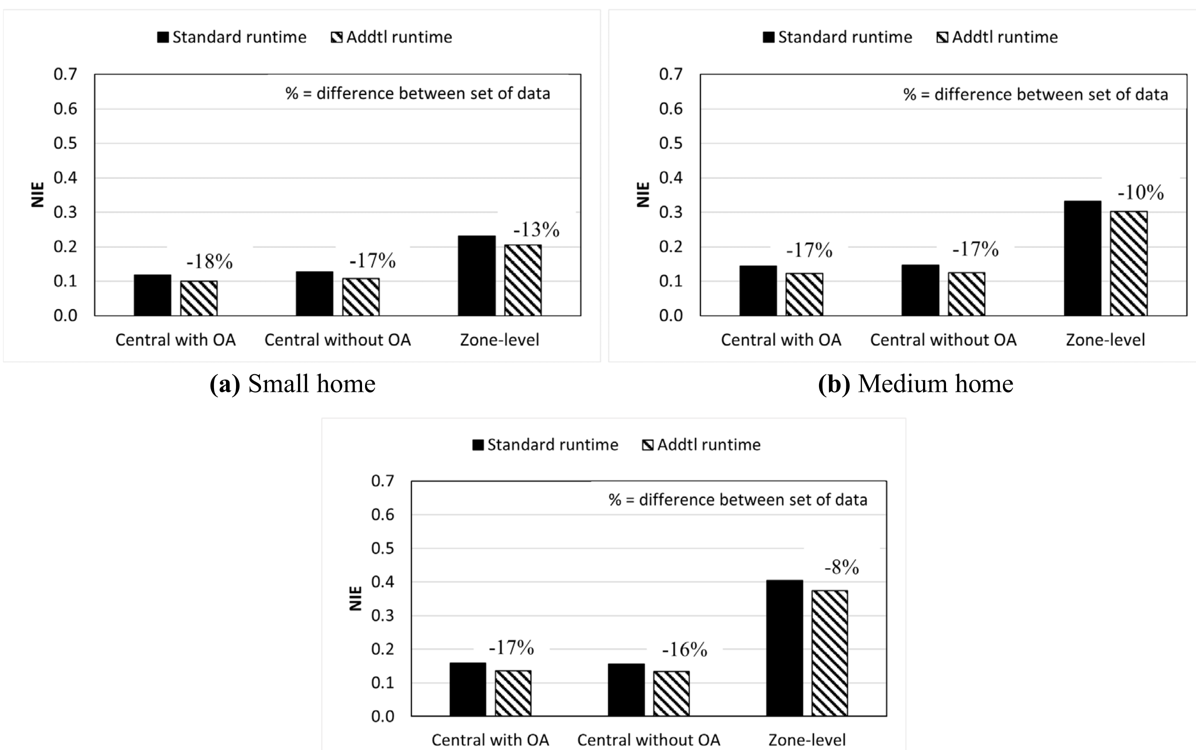
The PAC was simulated for all HVAC system types. The combination of PAC High with Window OA was shown in **Figure 14** so it will not be repeated. **Figure 19** shows that the combination of PAC High with other mitigation measures (e.g., Fan Int/Cont, MERV 13 filter) reduced NIE between 35 % and 62 % in the small home for the central systems. PAC High reduced NIE more in combination with Fan Int, which was not surprising because Fan Int resulted in higher particle concentration compared to Fan Cont.



(a) Central system with mechanical OA **(b)** Central system without mechanical OA

Figure 19. Reductions in NIE due to combination of PAC High with other mitigation measures for small home.

Combining all available mitigation measures, which will vary by HVAC system type, **Figure 20** shows the NIE for all three homes. For the central systems, the NIE was reduced between 16 % and 17 % when including additional runtime. For the zone-level system in the small home, the reduction was smaller after all available mitigation measures were combined with additional runtime (8 % to 13 %). Keep in mind as well that operating the zone-level system in the small home resulted in the highest base IE as discussed in Sec. 7.1.



(a) Small home **(b)** Medium home

(c) Large home

Figure 20. Reductions in NIE due to all available mitigation measures for all homes and for all HVAC system types.

8. RESULTS SUMMARY

A summary of the 1296 simulations performed in this analysis is presented in **Figure 21** as a carpet plot. The carpet plot shows the $NIE_{Simulation\ case}$, which is defined as the particle exposure for each simulation case normalized against the maximum value of all simulation cases:

$$NIE_{Simulation\ Case} = IE_{Simulation\ Case}/IE_{Maximum\ IE\ of\ All\ Cases} \tag{7}$$

The parameters listed on the left of **Figure 21** are:

- Zone (home) size: small, medium, large
- Visit (duration): 30 min, 120 min, 240 min
- Fan Ops (fan operation): Int = intermittent, Con=continuous
- Add Run (additional runtime): N = none, Y=yes for 60 min post-visit

The parameters listed on the top are:

- PAC (portable air cleaner): None, medium (99 CADR), high (297 CADR)
- Filter: None, MERV 6, MERV 13
- Ventilation (OA):
  - N=none/infiltration only,
  - L=low/ASHRAE 62.2-2019 compliant,
  - W=window,
  - H=high/ASHRAE 62.2-2019 compliant with additional mechanical OA (only applicable to central HVAC systems or columns with MERV 6 or MERV 13 filtration)

Figure 21 shows the $NIE_{Simulation\ Case}$ results at the 05:00 (5 hour) timestep for all 1 296 simulations. In general, the small home had higher IE than the other homes because of its smaller volume. The shorter visit duration decreased IE compared with the longer visit durations – shortening the visit duration of a contagious visitor greatly reduces exposure to the particles they emit. The IE decreased as fans were operated longer, filter efficiencies increased, and PACs were operated at higher speeds.

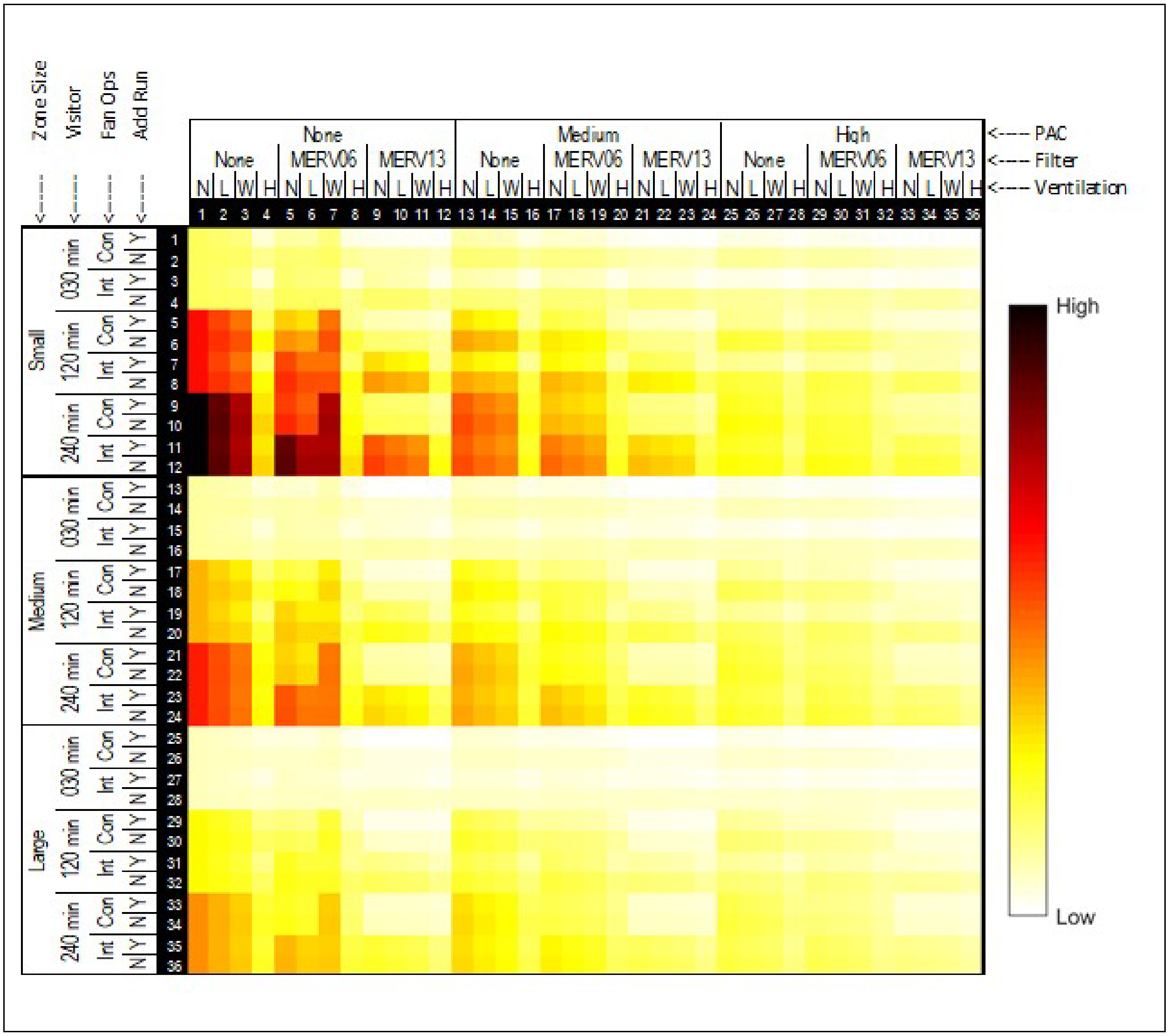


Figure 21. Carpet plot showing the NIE$_{\text{Simulation Case}}$ results at the 05:00 timestep for all 1 296 simulations.

9. ViPER WEBTOOL

The results in this analysis were used as a database for a new webtool, Virus Particle Exposure in Residences (ViPER), that may be useful to homeowners or tenants in the selection of mitigation measures in residential buildings. This tool is specifically designed for use in a residential environment by homeowners and tenants that may not be familiar with the best ways to operate their home's systems in order to reduce infectious aerosols. ViPER's user interface can be seen in **Figure 22**, which is designed to simplify analysis by providing users with a predetermined set of parameters, allowing them to make selections based on their home, then providing a result of "increase", "decrease", or "no change" in either particle concentration or integrated exposure. Users can evaluate multiple "Comparison Cases" to a "Base Case" that best represents their home.

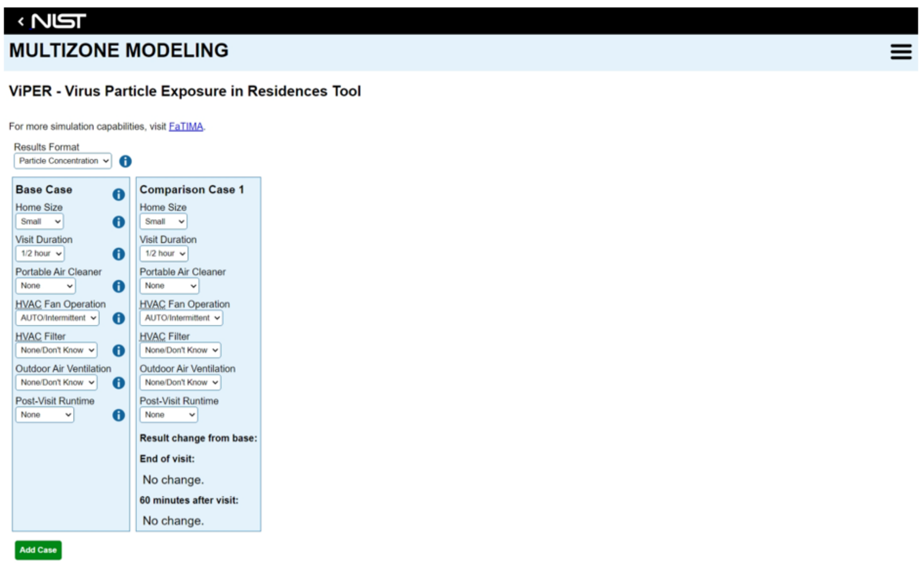


Figure 22. The "Home Screen" of ViPER's user interface.

ViPER is available for free here: https://www.nist.gov/services-resources/software/viper-virus-particle-exposure-residences.

Additional information in the form of a user guide for ViPER can be found here: https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2211.pdf.

10. FUTURE WORK

The simulations performed in this analysis were based on the single zone model implemented in the web-based tool, FaTIMA. The work described in this analysis could be expanded in several ways.

Future work could involve multizone simulations using CONTAM to include bedrooms and other indoor spaces. By using a multizone model, the locations and timing of both the exposed occupant and visitor could be varied and the exposure of multiple occupants could be considered. The mitigation measures implemented in this work could be modified and expanded as well. Another option could be to vary the infiltration rates by climate and building envelope airtightness for an entire year.

Alternative building types or indoor environments where people may gather could also be included in future work. Some such buildings or environments may include multifamily buildings, restaurants, healthcare facilities, and cruise ships. Different particle sizes as well as particle distributions could also be investigated.

11. CONCLUSION

Guidance for reducing exposure to potentially infectious aerosols includes increasing ventilation, increasing filtration, and using PACs. This analysis compared the relative increase or decrease in particle exposure in homes of varying sizes as a result of changes to the HVAC system operation and the inclusion of non-HVAC mitigation measures (e.g., opening a window, using a portable air cleaner (PAC)) using FaTIMA. Particle exposure was evaluated in three sizes of homes with two different types of HVAC systems: central system and zone-level systems. With no mitigation measures, it was found that the largest home with a central HVAC system had the lowest exposure and the smallest home with a zone-level HVAC system had the highest exposure.

For all home sizes and HVAC systems, the portable air cleaner (297 CADR) was the most effective mitigation measure for reducing exposure. Operating the HVAC system continuously rather than intermittently reduced particle exposure, but not as much as an additional fan that supplied 94.4 $L \cdot s^{-1}$ (200 cfm) of outdoor air. A MERV 13 filter was more effective at reducing particle exposure than a MERV 6 filter, but less effective than a portable air cleaner operating at 297 CADR. When comparing the MERV13 filter to a portable air cleaner operating at 99 CADR, the more effective option is dependent on the size of the home; the MERV 13 filter is more effective in a large home and the 99 CADR portable air cleaner is more effective in a small home. Continuing to implement any active mitigation measure for an additional 60 mins resulted in further reductions in particle exposure. While not a mitigation measure, shortening the visit duration of a potentially contagious visitor was demonstrated to be one of the most effective strategies in reducing exposure to the particles they emit. These results assume all mitigation measures were performing as described in this report, i.e., no deviations in actual performance were considered. Note also that the estimated exposure reductions would be different for different assumptions for the model inputs. As noted by ASHRAE and the Centers for Disease Control and Prevention (CDC), engineering and other mitigation measures should be part of a larger, layered risk reduction strategy that includes hand washing, surface cleaning, social distancing, and reduced occupant density (ASHRAE 2020; CDC 2021). This analysis does not define levels of exposure considered to be safe or healthy, nor consider the impacts of these mitigation measures as part of a broader risk reduction strategy that might be pursued by a resident.

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Appendix 1. SIMULATION IE VALUES

This appendix contains the Integrated Exposure (IE) ($\#\cdot s\cdot m^{-3}$) values one hour after the respective visit duration for the 963 unique simulations. These results are presented in the following 9 tables (**Table A1** through **Table A9**), which group IE values according to home size and heating, ventilating, and air-conditioning (HVAC) system type. **Table A1** presents the IE values for the small home with a central system with mechanical OA. **Table A2** presents the IE values for the medium home with a central system with mechanical OA. **Table A3** presents the IE values for the large home with a central system with mechanical OA. **Table A4** presents the IE values for the small home with a central system without mechanical OA. **Table A5** presents the IE values for the medium home with a central system without mechanical OA. **Table A6** presents the IE values for the large home with a central system without mechanical OA. **Table A7** presents the IE values for the small home with a zone-level system. **Table A8** presents the IE values for the medium home with a zone-level system. **Table A9** presents the IE values for the large home with a zone-level system.

Table A1. Summary of the small home with a central system with mechanical OA. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION	ADDITIONAL RUNTIME: NONE			ADDITIONAL RUNTIME: 60 MINUTES		
				Visit Duration (min)			Visit Duration (min)		
				30	120	240	30	120	240
None	Low	MERV 6	Continuous	1.01e-10	4.31e-10	8.94e-10	8.08e-11	3.87e-10	8.43e-10
			Intermittent	1.12e-10	5.67e-10	1.32e-09	1.02e-10	5.39e-10	1.28e-09
		MERV 13	Continuous	6.33e-11	1.69e-10	3.00e-10	3.22e-11	1.31e-10	2.62e-10
			Intermittent	1.04e-10	4.21e-10	8.46e-10	7.73e-11	3.63e-10	7.82e-10
	High	MERV 6	Continuous	7.70e-11	2.36e-10	4.31e-10	4.57e-11	1.90e-10	3.85e-10
			Intermittent	8.44e-11	2.80e-10	5.21e-10	5.38e-11	2.30e-10	4.70e-10
		MERV 13	Continuous	5.14e-11	1.25e-10	2.19e-10	2.34e-11	9.40e-11	1.88e-10
			Intermittent	7.95e-11	2.34e-10	4.22e-10	4.42e-11	1.84e-10	3.71e-10
Low Speed	Low	MERV 6	Continuous	8.77e-11	3.09e-10	5.86e-10	5.94e-11	2.59e-10	5.35e-10
			Intermittent	9.67e-11	3.82e-10	7.59e-10	7.22e-11	3.32e-10	7.05e-10
		MERV 13	Continuous	5.69e-11	1.44e-10	2.54e-10	2.72e-11	1.10e-10	2.19e-10
			Intermittent	9.06e-11	3.04e-10	5.66e-10	5.72e-11	2.48e-10	5.08e-10
	High	MERV 6	Continuous	6.83e-11	1.91e-10	3.42e-10	3.67e-11	1.50e-10	3.01e-10
			Intermittent	7.45e-11	2.19e-10	3.96e-10	4.21e-11	1.74e-10	3.51e-10
		MERV 13	Continuous	4.68e-11	1.11e-10	1.93e-10	2.06e-11	8.25e-11	1.65e-10
			Intermittent	7.05e-11	1.90e-10	3.36e-10	3.57e-11	1.45e-10	2.92e-10
High Speed	Low	MERV 6	Continuous	6.85e-11	1.91e-10	3.43e-10	3.68e-11	1.50e-10	3.02e-10
			Intermittent	7.46e-11	2.20e-10	3.98e-10	4.23e-11	1.75e-10	3.52e-10
		MERV 13	Continuous	4.69e-11	1.11e-10	1.94e-10	2.07e-11	8.27e-11	1.65e-10
			Intermittent	7.06e-11	1.91e-10	3.38e-10	3.58e-11	1.46e-10	2.93e-10
	High	MERV 6	Continuous	5.50e-11	1.37e-10	2.41e-10	2.59e-11	1.04e-10	2.08e-10
			Intermittent	5.94e-11	1.52e-10	2.68e-10	2.87e-11	1.16e-10	2.31e-10
		MERV 13	Continuous	3.95e-11	9.01e-11	1.56e-10	1.66e-11	6.63e-11	1.33e-10
			Intermittent	5.67e-11	1.37e-10	2.39e-10	2.54e-11	1.02e-10	2.04e-10

Table A2. Summary of the medium home with a central system with mechanical OA. IE (#·s·m-3) values one hour after the respective visit duration.

				ADDITIONAL RUNTIME: NONE			ADDITIONAL RUNTIME: 60 MINUTES		
				Visit Duration (min)			Visit Duration (min)		
PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION	30	120	240	30	120	240
None	Low	MERV 6	Continuous	5.84e-11	2.53e-10	5.27e-10	4.70e-11	2.27e-10	4.97e-10
			Intermittent	6.49e-11	3.34e-10	7.87e-10	5.93e-11	3.18e-10	7.65e-10
		MERV 13	Continuous	3.67e-11	9.77e-11	1.73e-10	1.86e-11	7.54e-11	1.51e-10
			Intermittent	6.04e-11	2.46e-10	4.98e-10	4.50e-11	2.13e-10	4.60e-10
	High	MERV 6	Continuous	4.99e-11	1.72e-10	3.24e-10	3.30e-11	1.43e-10	2.95e-10
			Intermittent	5.50e-11	2.12e-10	4.17e-10	4.00e-11	1.82e-10	3.84e-10
		MERV 13	Continuous	3.25e-11	8.13e-11	1.43e-10	1.53e-11	6.16e-11	1.23e-10
			Intermittent	5.16e-11	1.70e-10	3.14e-10	3.18e-11	1.37e-10	2.80e-10
Low Speed	Low	MERV 6	Continuous	5.40e-11	2.06e-10	4.04e-10	3.92e-11	1.77e-10	3.73e-10
			Intermittent	5.97e-11	2.62e-10	5.52e-10	4.84e-11	2.36e-10	5.20e-10
		MERV 13	Continuous	3.45e-11	8.88e-11	1.57e-10	1.68e-11	6.79e-11	1.36e-10
			Intermittent	5.58e-11	2.02e-10	3.87e-10	3.76e-11	1.68e-10	3.51e-10
	High	MERV 6	Continuous	4.64e-11	1.47e-10	2.71e-10	2.84e-11	1.20e-10	2.43e-10
			Intermittent	5.09e-11	1.77e-10	3.34e-10	3.38e-11	1.47e-10	3.03e-10
		MERV 13	Continuous	3.06e-11	7.50e-11	1.32e-10	1.41e-11	5.65e-11	1.13e-10
			Intermittent	4.79e-11	1.46e-10	2.65e-10	2.75e-11	1.15e-10	2.34e-10
High Speed	Low	MERV 6	Continuous	4.64e-11	1.48e-10	2.72e-10	2.85e-11	1.20e-10	2.44e-10
			Intermittent	5.10e-11	1.78e-10	3.36e-10	3.39e-11	1.48e-10	3.05e-10
		MERV 13	Continuous	3.07e-11	7.52e-11	1.32e-10	1.41e-11	5.66e-11	1.13e-10
			Intermittent	4.79e-11	1.46e-10	2.65e-10	2.75e-11	1.16e-10	2.34e-10
	High	MERV 6	Continuous	4.03e-11	1.14e-10	2.04e-10	2.19e-11	8.94e-11	1.80e-10
			Intermittent	4.40e-11	1.32e-10	2.39e-10	2.52e-11	1.05e-10	2.11e-10
		MERV 13	Continuous	2.75e-11	6.50e-11	1.13e-10	1.21e-11	4.84e-11	9.68e-11
			Intermittent	4.16e-11	1.13e-10	2.01e-10	2.13e-11	8.67e-11	1.74e-10

Table A3. Summary of the large home with a central system with mechanical OA. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION	ADDITIONAL RUNTIME: NONE			ADDITIONAL RUNTIME: 60 MINUTES		
				Visit Duration (min)			Visit Duration (min)		
				30	120	240	30	120	240
None	Low	MERV 6	Continuous	4.12e-11	1.79e-10	3.74e-10	3.32e-11	1.60e-10	3.52e-10
			Intermittent	4.57e-11	2.36e-10	5.60e-10	4.19e-11	2.25e-10	5.45e-10
		MERV 13	Continuous	2.59e-11	6.88e-11	1.22e-10	1.31e-11	5.30e-11	1.06e-10
			Intermittent	4.26e-11	1.74e-10	3.53e-10	3.17e-11	1.50e-10	3.26e-10
	High	MERV 6	Continuous	3.68e-11	1.35e-10	2.60e-10	2.57e-11	1.14e-10	2.38e-10
			Intermittent	4.07e-11	1.69e-10	3.46e-10	3.15e-11	1.49e-10	3.23e-10
		MERV 13	Continuous	2.37e-11	6.02e-11	1.06e-10	1.14e-11	4.58e-11	9.17e-11
			Intermittent	3.80e-11	1.33e-10	2.50e-10	2.47e-11	1.09e-10	2.25e-10
Low Speed	Low	MERV 6	Continuous	3.89e-11	1.54e-10	3.07e-10	2.91e-11	1.34e-10	2.85e-10
			Intermittent	4.31e-11	1.99e-10	4.31e-10	3.62e-11	1.81e-10	4.10e-10
		MERV 13	Continuous	2.47e-11	6.43e-11	1.14e-10	1.22e-11	4.92e-11	9.85e-11
			Intermittent	4.02e-11	1.51e-10	2.94e-10	2.79e-11	1.27e-10	2.67e-10
	High	MERV 6	Continuous	3.49e-11	1.20e-10	2.25e-10	2.29e-11	9.92e-11	2.04e-10
			Intermittent	3.85e-11	1.47e-10	2.88e-10	2.77e-11	1.26e-10	2.65e-10
		MERV 13	Continuous	2.27e-11	5.67e-11	9.97e-11	1.07e-11	4.29e-11	8.59e-11
			Intermittent	3.61e-11	1.18e-10	2.18e-10	2.21e-11	9.49e-11	1.94e-10
High Speed	Low	MERV 6	Continuous	3.50e-11	1.20e-10	2.25e-10	2.30e-11	9.95e-11	2.04e-10
			Intermittent	3.85e-11	1.47e-10	2.89e-10	2.78e-11	1.26e-10	2.66e-10
		MERV 13	Continuous	2.27e-11	5.68e-11	9.98e-11	1.07e-11	4.30e-11	8.60e-11
			Intermittent	3.61e-11	1.18e-10	2.18e-10	2.21e-11	9.51e-11	1.95e-10
	High	MERV 6	Continuous	3.15e-11	9.69e-11	1.77e-10	1.86e-11	7.79e-11	1.58e-10
			Intermittent	3.46e-11	1.15e-10	2.15e-10	2.20e-11	9.46e-11	1.94e-10
		MERV 13	Continuous	2.10e-11	5.08e-11	8.89e-11	9.49e-12	3.81e-11	7.62e-11
			Intermittent	3.25e-11	9.61e-11	1.73e-10	1.81e-11	7.51e-11	1.52e-10

Table A4. Summary of the small home with a central system without mechanical OA. IE (#·s·m-3) values one hour after the respective visit duration.

				ADDITIONAL RUNTIME: NONE			ADDITIONAL RUNTIME: 60 MINUTES		
				Visit Duration (min)			Visit Duration (min)		
PAC	**VENTILATION**	**HVAC FILTER**	**HVAC FAN OPERATION**	30	120	240	30	120	240
None	None	MERV 6	Continuous	1.03e-10	4.61e-10	9.80e-10	8.57e-11	4.20e-10	9.31e-10
			Intermittent	1.14e-10	6.14e-10	1.50e-09	1.09e-10	5.96e-10	1.47e-09
		MERV 13	Continuous	6.46e-11	1.74e-10	3.10e-10	3.33e-11	1.35e-10	2.71e-10
			Intermittent	1.06e-10	4.49e-10	9.24e-10	8.19e-11	3.93e-10	8.59e-10
	Window	MERV 6	Continuous	9.81e-11	4.04e-10	8.20e-10	7.63e-11	3.58e-10	7.68e-10
			Intermittent	1.09e-10	5.25e-10	1.18e-09	9.54e-11	4.90e-10	1.13e-09
		MERV 13	Continuous	6.21e-11	1.64e-10	2.91e-10	3.13e-11	1.26e-10	2.53e-10
			Intermittent	1.01e-10	3.95e-10	7.80e-10	7.31e-11	3.37e-10	7.17e-10
Low Speed	None	MERV 6	Continuous	8.98e-11	3.25e-10	6.24e-10	6.25e-11	2.76e-10	5.72e-10
			Intermittent	9.91e-11	4.06e-10	8.23e-10	7.63e-11	3.58e-10	7.68e-10
		MERV 13	Continuous	5.79e-11	1.48e-10	2.61e-10	2.80e-11	1.13e-10	2.26e-10
			Intermittent	9.27e-11	3.20e-10	6.01e-10	6.01e-11	2.63e-10	5.42e-10
	Window	MERV 6	Continuous	8.57e-11	2.93e-10	5.52e-10	5.66e-11	2.45e-10	5.02e-10
			Intermittent	9.44e-11	3.60e-10	7.05e-10	6.84e-11	3.10e-10	6.50e-10
		MERV 13	Continuous	5.59e-11	1.40e-10	2.47e-10	2.65e-11	1.07e-10	2.13e-10
			Intermittent	8.85e-11	2.89e-10	5.35e-10	5.46e-11	2.34e-10	4.78e-10
High Speed	None	MERV 6	Continuous	6.99e-11	1.98e-10	3.56e-10	3.81e-11	1.56e-10	3.14e-10
			Intermittent	7.62e-11	2.29e-10	4.15e-10	4.40e-11	1.83e-10	3.69e-10
		MERV 13	Continuous	4.76e-11	1.13e-10	1.98e-10	2.11e-11	8.45e-11	1.69e-10
			Intermittent	7.21e-11	1.97e-10	3.50e-10	3.71e-11	1.51e-10	3.04e-10
	Window	MERV 6	Continuous	6.71e-11	1.85e-10	3.31e-10	3.55e-11	1.45e-10	2.91e-10
			Intermittent	7.31e-11	2.12e-10	3.82e-10	4.07e-11	1.67e-10	3.37e-10
		MERV 13	Continuous	4.61e-11	1.09e-10	1.90e-10	2.02e-11	8.10e-11	1.62e-10
			Intermittent	6.92e-11	1.84e-10	3.26e-10	3.46e-11	1.41e-10	2.82e-10

Table A5. Summary of the medium home with a central system without mechanical OA. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION	ADDITIONAL RUNTIME: NONE Visit Duration (min) 30	120	240	ADDITIONAL RUNTIME: 60 MINUTES Visit Duration (min) 30	120	240
None	None	MERV 6	Continuous	5.98e-11	2.69e-10	5.74e-10	4.96e-11	2.44e-10	5.44e-10
			Intermittent	6.64e-11	3.59e-10	8.83e-10	6.30e-11	3.48e-10	8.68e-10
		MERV 13	Continuous	3.74e-11	1.00e-10	1.79e-10	1.92e-11	7.77e-11	1.56e-10
			Intermittent	6.17e-11	2.62e-10	5.40e-10	4.74e-11	2.29e-10	5.01e-10
	Window	MERV 6	Continuous	5.72e-11	2.38e-10	4.87e-10	4.47e-11	2.11e-10	4.56e-10
			Intermittent	6.34e-11	3.11e-10	7.07e-10	5.60e-11	2.91e-10	6.81e-10
		MERV 13	Continuous	3.61e-11	9.51e-11	1.69e-10	1.81e-11	7.32e-11	1.47e-10
			Intermittent	5.91e-11	2.33e-10	4.62e-10	4.27e-11	1.99e-10	4.24e-10
Low Speed	None	MERV 6	Continuous	5.51e-11	2.17e-10	4.32e-10	4.11e-11	1.89e-10	4.00e-10
			Intermittent	6.10e-11	2.79e-10	6.02e-10	5.11e-11	2.54e-10	5.72e-10
		MERV 13	Continuous	3.51e-11	9.11e-11	1.61e-10	1.73e-11	6.98e-11	1.40e-10
			Intermittent	5.70e-11	2.13e-10	4.12e-10	3.94e-11	1.79e-10	3.75e-10
	Window	MERV 6	Continuous	5.28e-11	1.96e-10	3.79e-10	3.73e-11	1.67e-10	3.48e-10
			Intermittent	5.84e-11	2.47e-10	5.08e-10	4.59e-11	2.19e-10	4.76e-10
		MERV 13	Continuous	3.39e-11	8.67e-11	1.53e-10	1.64e-11	6.61e-11	1.32e-10
			Intermittent	5.46e-11	1.92e-10	3.64e-10	3.59e-11	1.58e-10	3.29e-10
High Speed	None	MERV 6	Continuous	4.74e-11	1.54e-10	2.85e-10	2.96e-11	1.26e-10	2.57e-10
			Intermittent	5.21e-11	1.86e-10	3.55e-10	3.55e-11	1.56e-10	3.24e-10
		MERV 13	Continuous	3.12e-11	7.68e-11	1.35e-10	1.44e-11	5.79e-11	1.16e-10
			Intermittent	4.89e-11	1.52e-10	2.77e-10	2.86e-11	1.21e-10	2.46e-10
	Window	MERV 6	Continuous	4.55e-11	1.42e-10	2.61e-10	2.74e-11	1.15e-10	2.33e-10
			Intermittent	5.00e-11	1.70e-10	3.18e-10	3.25e-11	1.40e-10	2.88e-10
		MERV 13	Continuous	3.02e-11	7.36e-11	1.29e-10	1.38e-11	5.53e-11	1.11e-10
			Intermittent	4.70e-11	1.41e-10	2.54e-10	2.65e-11	1.11e-10	2.24e-10

Table A6. Summary of the large home with a central system without mechanical OA. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION	ADDITIONAL RUNTIME: NONE Visit Duration (min)			ADDITIONAL RUNTIME: 60 MINUTES Visit Duration (min)		
				30	120	240	30	120	240
None	None	MERV 6	Continuous	4.21e-11	1.90e-10	4.05e-10	3.49e-11	1.72e-10	3.85e-10
			Intermittent	4.67e-11	2.53e-10	6.26e-10	4.43e-11	2.46e-10	6.15e-10
		MERV 13	Continuous	2.63e-11	7.06e-11	1.26e-10	1.34e-11	5.46e-11	1.09e-10
			Intermittent	4.35e-11	1.85e-10	3.81e-10	3.33e-11	1.61e-10	3.54e-10
	Window	MERV 6	Continuous	4.03e-11	1.69e-10	3.46e-10	3.16e-11	1.50e-10	3.24e-10
			Intermittent	4.47e-11	2.21e-10	5.05e-10	3.96e-11	2.07e-10	4.87e-10
		MERV 13	Continuous	2.54e-11	6.70e-11	1.19e-10	1.27e-11	5.15e-11	1.03e-10
			Intermittent	4.17e-11	1.65e-10	3.28e-10	3.02e-11	1.41e-10	3.01e-10
Low Speed	None	MERV 6	Continuous	3.98e-11	1.63e-10	3.29e-10	3.05e-11	1.43e-10	3.07e-10
			Intermittent	4.41e-11	2.12e-10	4.73e-10	3.82e-11	1.96e-10	4.53e-10
		MERV 13	Continuous	2.52e-11	6.59e-11	1.17e-10	1.25e-11	5.05e-11	1.01e-10
			Intermittent	4.11e-11	1.59e-10	3.13e-10	2.92e-11	1.35e-10	2.87e-10
	Window	MERV 6	Continuous	3.81e-11	1.47e-10	2.88e-10	2.78e-11	1.26e-10	2.66e-10
			Intermittent	4.22e-11	1.87e-10	3.96e-10	3.44e-11	1.68e-10	3.74e-10
		MERV 13	Continuous	2.44e-11	6.27e-11	1.11e-10	1.19e-11	4.79e-11	9.59e-11
			Intermittent	3.94e-11	1.44e-10	2.76e-10	2.67e-11	1.20e-10	2.50e-10
High Speed	None	MERV 6	Continuous	3.57e-11	1.25e-10	2.37e-10	2.40e-11	1.05e-10	2.16e-10
			Intermittent	3.93e-11	1.55e-10	3.08e-10	2.91e-11	1.34e-10	2.86e-10
		MERV 13	Continuous	2.31e-11	5.81e-11	1.02e-10	1.09e-11	4.40e-11	8.81e-11
			Intermittent	3.68e-11	1.23e-10	2.29e-10	2.31e-11	9.99e-11	2.05e-10
	Window	MERV 6	Continuous	3.43e-11	1.15e-10	2.15e-10	2.21e-11	9.47e-11	1.94e-10
			Intermittent	3.77e-11	1.40e-10	2.72e-10	2.66e-11	1.19e-10	2.49e-10
		MERV 13	Continuous	2.24e-11	5.56e-11	9.76e-11	1.04e-11	4.20e-11	8.40e-11
			Intermittent	3.54e-11	1.13e-10	2.08e-10	2.13e-11	9.07e-11	1.85e-10

Table A7. Summary of the small home with a zone-level system. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION †	ADDITIONAL RUNTIME: NONE Visit Duration (min) 30	120	240	ADDITIONAL RUNTIME: 60 MINUTES Visit Duration (min) 30	120	240
None	None	None	Continuous/Intermittent	1.16e-10	6.65e-10	1.72e-09	††	††	††
	Window			1.11e-10	5.65e-10	1.32e-09	1.02e-10	5.41e-10	1.29e-09
Low Speed	None			1.01e-10	4.32e-10	8.97e-10	8.10e-11	3.88e-10	8.46e-10
	Window			9.59e-11	3.81e-10	7.59e-10	7.23e-11	3.33e-10	7.07e-10
High Speed	None			7.72e-11	2.37e-10	4.34e-10	4.59e-11	1.92e-10	3.88e-10
	Window			7.40e-11	2.19e-10	3.97e-10	4.24e-11	1.75e-10	3.53e-10

† The zone-level system has one option for HVAC Fan Operation, either continuous or intermittent, because the fan runtime would not affect the concentration of particles in the air since the system had no filter.

†† The additional 60-minute runtime will not affect the concentration of particles in the air when there is no PAC, ventilation, or filter.

Table A8. Summary of the medium home with a zone-level system. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION †	ADDITIONAL RUNTIME: NONE Visit Duration (min) 30	120	240	ADDITIONAL RUNTIME: 60 MINUTES Visit Duration (min) 30	120	240
None	None	None	Continuous/Intermittent	6.75e-11	3.89e-10	1.02e-09	††	††	††
	Window			6.44e-11	3.35e-10	7.98e-10	5.98e-11	3.22e-10	7.79e-10
Low Speed	None			6.20e-11	2.99e-10	6.70e-10	5.44e-11	2.79e-10	6.44e-10
	Window			5.93e-11	2.63e-10	5.57e-10	4.87e-11	2.38e-10	5.27e-10
High Speed	None			5.29e-11	1.96e-10	3.79e-10	3.74e-11	1.67e-10	3.48e-10
	Window			5.07e-11	1.78e-10	3.38e-10	3.41e-11	1.49e-10	3.07e-10

† The zone-level system has one option for HVAC Fan Operation, either continuous or intermittent, because the fan runtime would not affect the concentration of particles in the air since the system had no filter.

†† The additional 60-minute runtime will not affect the concentration of particles in the air when there is no PAC, ventilation, or filter.

Table A9. Summary of the large home with a zone-level system. IE (#·s·m-3) values one hour after the respective visit duration.

PAC	VENTILATION	HVAC FILTER	HVAC FAN OPERATION †	ADDITIONAL RUNTIME: NONE Visit Duration (min) 30	120	240	ADDITIONAL RUNTIME: 60 MINUTES Visit Duration (min) 30	120	240
None	None	None	Continuous/Intermittent	4.75e-11	2.75e-10	7.22e-10	††	††	††
	Window			4.55e-11	2.38e-10	5.71e-10	4.24e-11	2.29e-10	5.58e-10
Low Speed	None			4.48e-11	2.28e-10	5.31e-10	4.08e-11	2.16e-10	5.16e-10
	Window			4.29e-11	2.00e-10	4.38e-10	3.66e-11	1.84e-10	4.18e-10
High Speed	None			3.99e-11	1.65e-10	3.35e-10	3.09e-11	1.45e-10	3.12e-10
	Window			3.83e-11	1.48e-10	2.92e-10	2.81e-11	1.28e-10	2.70e-10

† The zone-level system has one option for HVAC Fan Operation, either continuous or intermittent, because the fan runtime would not affect the concentration of particles in the air since the system had no filter.

†† The additional 60-minute runtime will not affect the concentration of particles in the air when there is no PAC, ventilation, or filter.