Ventilation and Filtration to Reduce Long-Range Airborne Transmission of COVID-19 and Other Respiratory Infections: Considerations for Reopened Schools

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Indoor Air Quality Section
Environmental Health Laboratory Branch
Center for Healthy Communities
California Department of Public Health

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Introduction

The Centers for Disease Control and Prevention (CDC) has included ventilation in the multiple layered strategies to reduce exposures to SARS-CoV-2.[1] In recognition of the importance of proper ventilation in indoor environments to reduce the spread of COVID-19, the California Department of Public Health (CDPH), together with the Office of Statewide Health Planning and Development (OSHPD) and the California Division of Occupational Safety and Health (Cal/OSHA), has recently issued *Interim Guidance for Ventilation, Filtration, and Air Quality in Indoor Environments* for non-healthcare organizations in general, including schools.[2]

This document on ventilation and filtration is intended to supplement the above State interim ventilation guidance by providing a road map, with simple flow charts, focused on the practical steps that schools can take to assess and improve classroom ventilation and air filtration. Appendix A lists the units of measure, acronyms, and abbreviations used in this guide. Because many other information resources are now available on best practices in schools during the COVID pandemic, this guide refers to such resources whenever appropriate for details on specific measures or actions.

The primary audience for this document on ventilation and filtration includes school facility managers (operations and maintenance) and testing personnel or IAQ/industrial hygiene consultants that schools hire to check the ventilation system. Persons with an interest in the safe reopening of schools as well as improving IAQ in the long term (e.g., school district officials, teachers, parents, and students) may also use this document for an overview on checking school ventilation and air filtration to protect against infectious agents and other airborne hazards.

Ventilation and Filtration Considerations

Schools vary widely in the design, complexity, flexibility, and age of their HVAC equipment, systems, and controls. Schools also include a variety of space types with different VR design requirements (e.g., classrooms, cafeterias, and multi-use assembly areas). For each occupiable space, it is always important to first:

- Determine the floor area (in m^2 or ft^2), the maximum number of occupants, and the occupancy schedule.
- Check if the space is naturally ventilated with openable windows only or has a mechanical ventilation system.

Naturally ventilated spaces

If a space has no mechanical ventilation (i.e., it relies solely on openable windows and doors for outdoor air), employers must follow Cal/OSHA's COVID-19 Emergency Temporary Standard (ETS) and evaluate how to maximize ventilation (fully opening all windows and openings) with outdoor air.[3] To do this, schools can use use the following flow chart (**Figure 1**) to check the space. Additionally, Appendix B provides a Do-it-yourself (DIY) inspection checklist to determine the *area of openable windows* in classrooms.

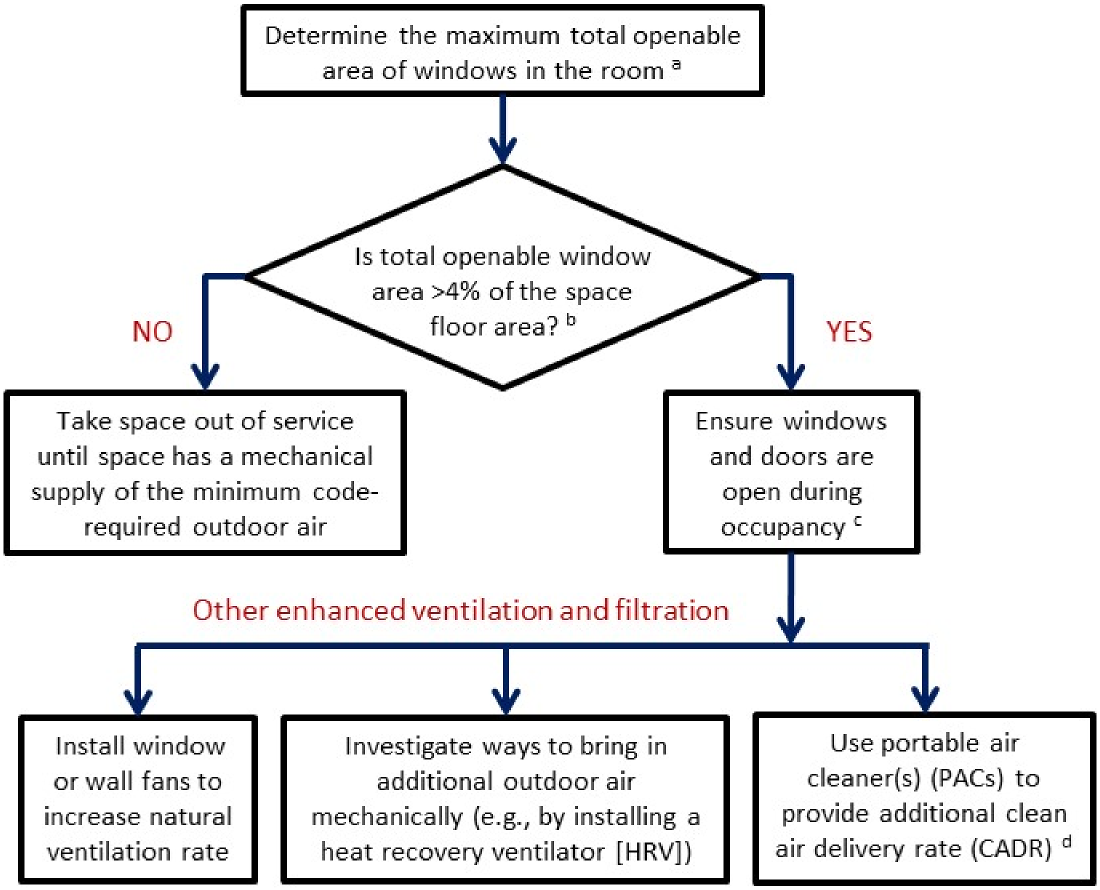


Figure 1. Flow chart for checking spaces without mechanical ventilation.

[a] See Appendix B for a DIY inspection checklist to determine the area of openable windows.

[b] The California Building Standards Code (Title 24)—in both Part 4 of the California Mechanical Code (CMC) and Part 6 of the California Energy Code (CEC)—requires that buildings with no mechanical supply of outdoor air have windows with a total openable area of at least 4 percent of the floor area.[4,5]

[c] When weather conditions allow, opening windows and doors can provide fresh outdoor air. Ensure that windows are fully open. See Appendix C for background information on VRs for naturally ventilated classrooms.

[d] Schools can refer to the SF DPH web page FAQs: Portable Air Cleaners for detailed instructions on how to properly size and select PACs.[6]

Mechanically ventilated spaces

If the space is mechanically ventilated, employers must comply with Cal/OSHA's ETS to maximize the quantity of outside air provided to the extent feasible and can use the following flow chart (**Figure 2**) to check the space. (Note: even with mechanical ventilation, windows and doors should be opened to provide additional outdoor air ventilation.)

In addition to Figure 2, several Appendices are relevant to mechanical ventilation systems. Appendix C provides background information on common types of ventilation and filtration in schools and minimum VR requirements. Appendix D provides a simplified, DIY checklist for operation inspection of classroom HVAC systems. Appendix E describes how to use carbon dioxide (CO_2) decay to measure outdoor air VR. For more complete HVAC checklists and operation guidance, schools are encouraged to read the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) guideline on *Reopening Schools and Universities* [7] and the California Coalition for Adequate School Housing (CASH) Maintenance Network's guidebook on *Healthy Schools: Cleaning, Disinfecting, Healthy Air Quality, Scheduling and Social Distancing*.[8]

Several guidance documents recommend a target minimum VR of 6 air changes per hour (ACH) in non-healthcare environments to reduce the spread of airborne SARS-CoV-2.[6,9] The metric "ACH" is considered preferable to airflow rate (e.g., in cubic feet per minute, cfm) to describe VRs used to control indoor air contaminants, because it scales with room volume (i.e., larger rooms need more airflow rates). ACH can be calculated from airflow rate and room volume, using the following equation:

$$\text{ACH} = \text{airflow rate } (\text{m}^3/\text{h})/\text{room volume } (\text{m}^3) \quad \text{(using International System of Units [SI] units), or} \qquad (1a)$$

$$\text{ACH} = \text{airflow rate (cfm)} \times 60/\text{room volume } (\text{ft}^3) \quad \text{(using English units)} \qquad (1b)$$

The minimum ventilation requirement of 6 ACH can be traced to the 1970 Centers for Disease Control and Prevention (CDC) recommendations for infection control *Isolation Techniques for use in Hospitals.*[10] *Current recommendations* are to provide at least 6 ACH in existing healthcare facilities and 12 ACH in new ones and those undergoing renovation.[11] In addition, if it is not possible to exhaust air from a room directly to the outside, the air may be returned to the air-handling system or adjacent spaces if all air is directed through high-efficiency particulate air (HEPA) filters. Although devised for healthcare settings, these ventilation recommendations can provide a good reference for other workplaces and public spaces where persons with aerosol transmissible infections, such as SARS-CoV-2, may be present.

In addition to outdoor air ventilation, the removal of airborne virus-containing particles from indoor air by HVAC system filters and PACs can be included in calculation of the above-mentioned minimum ACH. However, because the HVAC filters used in general building environments are not true HEPA filters, they only remove a portion of airborne viruses. The total ACH for SARS-CoV-2 removal, $\text{ACH}_{\text{Total}}$, including the combination of outdoor air ventilation, HVAC system filtration, and PAC rates, can be calculated using Equation (2).

$$\text{ACH}_{\text{Total}} = \text{ACH}_{\text{OA}} + \text{ACH}_{\text{HVAC-Filtration}} + \text{ACH}_{\text{PAC}} \qquad (2)$$

where:

ACH_{OA} = outdoor air VR
$\text{ACH}_{\text{HVAC-Filtration}}$ = SARS-CoV-2 removal rate by HVAC system filtration

ACH_{PAC} = SARS-CoV-2 removal rate by PAC.

This calculation function has been implemented as an output spreadsheet in the Interactive Model of CDPH IAQ's modeling paper (Appendix 3).[12] See Appendix F for an example calculation. A more user-friendly online tool based on similar methodology is available on the Harvard T.H. Chan School of Public Health's (HSPH) web page COVID-19 TOOLS.[13]

Opening windows and doors can further increase outdoor air ventilation for classrooms with mechanical ventilation. See Appendix B for how to determine the area of openable windows in classrooms.

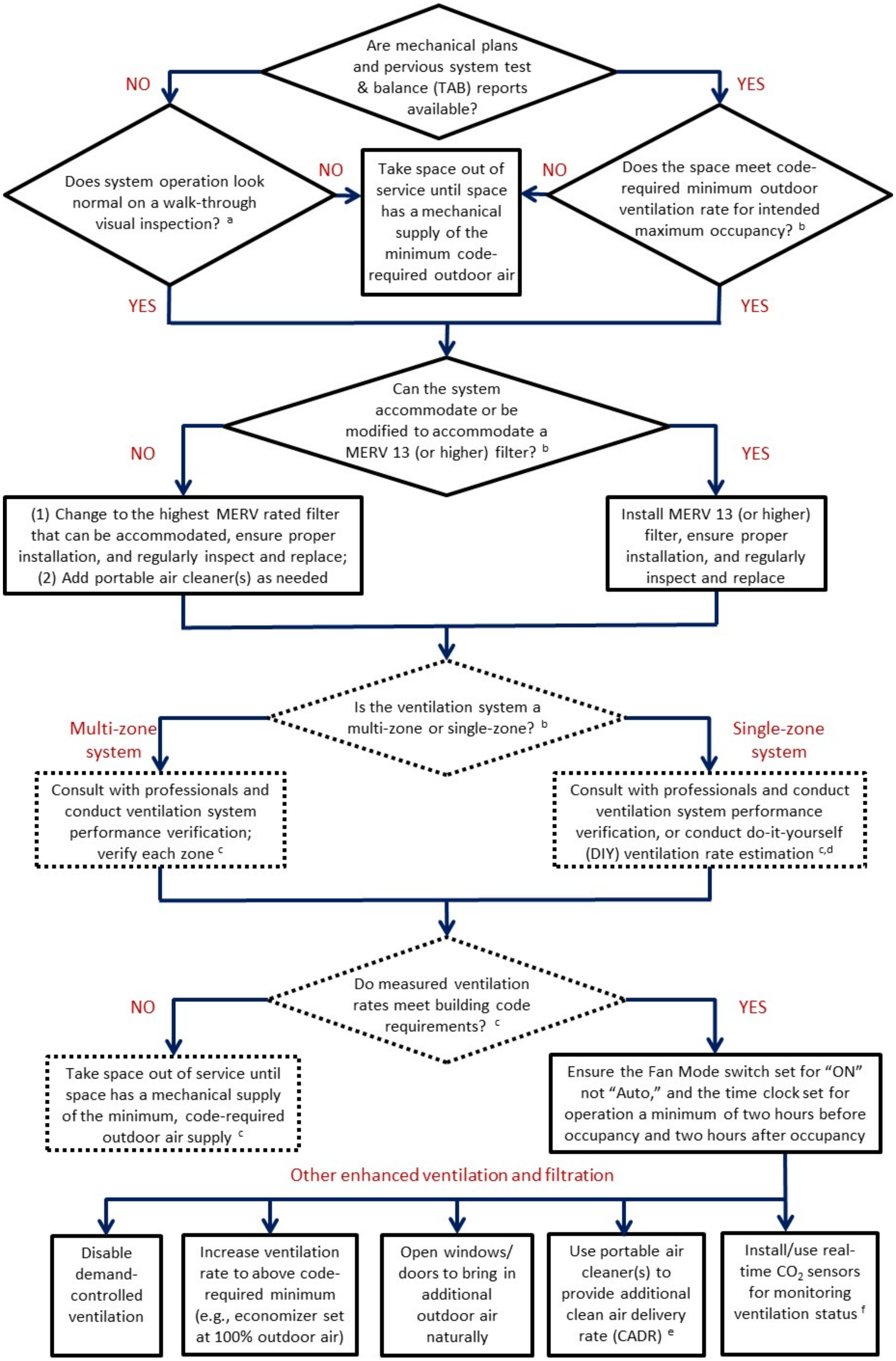


Figure 2. Flow chart for checking spaces with mechanical ventilation.

[a] See Appendix D for a DIY checklist for initial operation inspection of classroom HVAC systems; see the Environmental Protection Agency (EPA)'s web page Indoor Air Quality Tools for Schools Action Kit for a more complete ventilation checklist.[14]

[b] See Appendix C for background information on common types of ventilation and filtration in schools and minimum VR requirements.

[c] Unless otherwise required, VR measurement and verification are optional as they may not be feasible prior to school reopening.

[d] DIY VR measurement can be done using a CO_2 decay method (Appendix E), a steady-state CO_2 method, or a balometer; see the Harvard T.H. Chan School of Public Health's (HSPH) web page 5 Step Guide to Checking Ventilation Rates in Classrooms for detailed instructions.[9]

[e] Schools can refer to the SF DPH web page FAQs: Portable Air Cleaners for detailed instructions on how to properly size and select PACs.[6]

[f] Real-time CO_2 monitoring can be helpful to determine the outdoor air ventilation status in classrooms, especially in more densely occupied classrooms; see HSPH web page COVID-19 TOOLS for a maximum classroom CO_2 concentration calculator.[13] It should be noted that the measurement of CO_2 levels does not reflect the additional air cleaning benefit from the use of filters (or portable air cleaners). It is possible to exceed target CO_2 concentrations and still be meeting targets for clean air through filtration.

Appendix A. List of Units of Measure, Acronyms, and Abbreviations of Measure

Symbol	Name
cfm	cubic foot per minute
ft^2	square foot
ft^3	cubic foot
H	hour
In	inch
L	Liter
lb	pound
lbs	pounds
L/s-occupant	liter per second per occupant
m/s	meter per second
m^2	square meter
m^3	cubic meter
min	minute
ppm	part per million

Acronym	Group or program
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Cal/OSHA	California Division of Occupational Safety and Health
CASH	California Coalition for Adequate School Housing Maintenance Network
CCR	California Code of Regulations
CDC	Centers for Disease Control and Prevention
CDPH	California Department of Public Health
CEC	California Energy Code
CMC	California Mechanical Code
EPA	Environmental Protection Agency
HSPH	Harvard T.H. Chan School of Public Health
IAQS	Indoor Air Quality Section
LEED	Leadership in Energy and Environmental Design
OSHPD	Office of Statewide Health Planning and Development
SF DPH	San Francisco Department of Public Health

Abbreviation	Meaning
ACH [a]	air changes per hour (also called air change rate)
CADR [b]	clean air delivery rate
CO_2	carbon dioxide
COVID-19	the disease caused by SARS-CoV-2; CO stands for coronavirus, VI for virus, D for disease, and -19 for the year 2019[15]
DCV	demand control ventilation
DIY	do-it-yourself
DOAS	dedicated outdoor air system
ERV	energy recovery ventilator
ETS	Cal/OSHA's COVID-19 Emergency Temporary Standard
FCU	fan coil unit
HEPA	high-efficiency particulate air
HRV	heat recovery ventilator
HVAC	heating, ventilation, and air-conditioning
IAQ	indoor air quality
MERV [c]	minimum efficiency reporting value
PAC	portable air cleaner
RTU	rooftop unit
SARS	severe acute respiratory syndrome due to SARS-CoV or SARS-CoV-1
SARS-CoV-2	severe acute respiratory syndrome due to SARS-CoV-2, the virus that causes COVID-19; previously referred to as the "2019 novel coronavirus" or "2019-nCoV"
SI	international system of units of measure
Title 24	California Building Standards Code
VAV	variable air volume
VR	ventilation rate

[a] **ACH** is a calculated value that allows ventilation standards, guidelines, and comparisons to be made for rooms that have different dimensions or different ventilation systems. It is

considered preferable to airflow rate to describe VRs used to control indoor air contaminants, because it scales with room volume (i.e., larger rooms need more ventilation).

[b] **CADR** measures an air cleaner's effectiveness based on room space and the volume of clean air delivered per minute. Commercially available portable air cleaners often have three CADR ratings certified by the Association of Home Appliance Manufacturers (AHAM).[16] For COVID-19 purposes, use of the CADR rating for “tobacco smoke” (i.e., for particles in the 0.09–1 µm size range) is preferred because research has demonstrated that a significant number of SARS-CoV-2-containing particles could be <0.5 µm.[17] The CADR rating for “tobacco smoke” is typically less than or equal to the CADR for “dust” (i.e., 0.5–3 µm particles.

[c] **MERV** is a measurement and reporting scale to rate the performance of HVAC filters for removing particles in the 0.3–10 µm size range, based on an ASHRAE test standard.[18] MERV values range from 1–16. Higher MERV ratings correspond to a greater percentage of particles captured on each pass through a filter, especially for smaller sized particles (i.e., 0.3–1 µm). For COVID-19 purposes, MERV 13 is the recommended minimum; MERV 14 is preferred.[7]

Appendix B. DIY Inspection for Area of Openable Windows in Classrooms

Purpose: To determine if classrooms windows have operable openings that meet the code-required, minimum openable area (i.e., 4 percent of the room floor area if there is no mechanical ventilation).

Note:

- Title 24 requires that classrooms have windows with a total openable area of at least 4 percent of the floor area or a mechanical ventilation system with an outdoor air VR of at least 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater. Therefore, this inspection should be conducted in classrooms without mechanical ventilation systems, i.e., those that rely solely on openable windows for ventilation. This inspection may also be conducted in classrooms that have mechanical ventilation, as opening windows can further increase outdoor air ventilation.
- Openable windows can provide a substantial amount of outdoor air depending on how much and often the windows are opened and weather conditions (e.g., wind speed and outdoor air temperature). However, if the window opening is restricted—they cannot be opened at all, openable but the opening is limited (e.g., windows open only partially because of mechanical limiters or because they are stuck), or the windows are obstructed by furniture (e.g., bookshelves, cabinets, or shelving)—then the amount of outdoor air entering a classroom through the windows may be restricted.
- Other alternative ways of providing clean air should be considered when opening windows poses safety risks or other health harzards (e.g., wildfire smoke).
- In this section, we assume that English rather than SI units are employed.

The following is guidance for completing the attached DIY Classroom Openable Area Inspection Datasheet (window datasheet).

What You Need:

- Tape measure or laser distance meter
- Clipboard and the window datasheet

Blank and example window datasheets follow this section and also are available as Excel spread sheets (in both SI and English units).

Procedure for Determining the Area of Openable Windows

1) Measure classroom floor area.

Measure in feet the width and length of the classroom, multiply to determine the floor area, and record on the window datasheet.

Note: If the classroom has an adjacent area, separated by a wall, with permanently unobstructed openings (i.e., no doors), the classroom and adjacent space may be considered one room for purposes of calculating the window open area provided that openings between the rooms have a total area of not less than 8 percent of the adjacent space floor area or 25 ft^2, whichever is greater.[4]

2) Determine if windows are obstructed.

For each window, record whether the windows are obstructed or unobstructed. For example, windows that have an object (e.g., furniture, bookcase, etc.) that is within 3 ft of the window opening and covers any portion of the window opening as determined by line of sight from any occupiable location in the space may be considered obstructed.

3) Calculate the openable window area for each unobstructed window.

For each unobstructed window, open the window to its maximum openable area and record the type of window (e.g., slider, casement, or awning), the opening dimensions, and the maximum openable area (ft^2).

See below for calculation methods for the types of windows commonly found in classrooms.

<u>Sliding windows</u> For windows with vertical sliders (e.g., single- or double-hung windows) and windows with horizontal sliders, measure and record the opening width and height of the opening in inches. Multiply the width by the height and divide by 144, which converts square inches to square feet.

<u>Awning windows</u> For awning windows, which have a section that tilts out along a horizontal hinge, measure and record the window opening width and the swing-open distance, then calculate the openable area as for sliding windows. The swing-open distance is defined as the perpendicular distance from the awning window to the edge of the opening opposite the hinge. Examples of swing-open distances (i.e., the dark line with two end arrows) at different window opening levels are shown in **Figure 3**. Note that the amount that a window opens determines where the measurement should be taken.

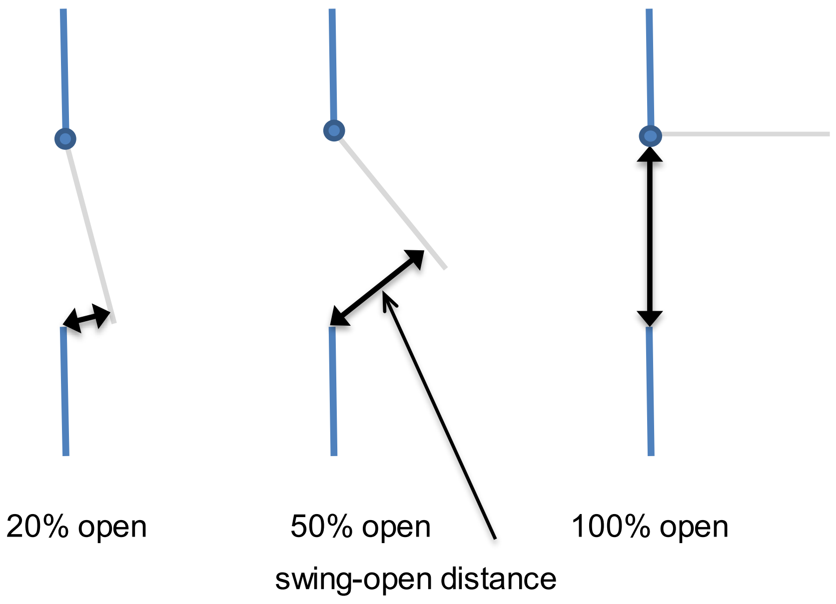


Figure 3. Swing-open distance measurement for casement and awning windows.

<u>Casement windows</u> For casement windows, which have a section that tilts out along a vertical hinge, measure and record the window opening width and the swing-open distance, then calculate the openable area as for sliding windows. The swing-open distance is defined and measured similarly as for awning windows but using the perpendicular distance from the casement window to the edge of the opening opposite the hinge.

4) Calculate the total openable window area.

Sum the openable area from each unobstructed window and record the total openable window area. Divide this total area by the floor area, multiply by 100, and record the total openable window area as a percentage of the floor area.

> Note: If the total area is less than the code-required 4 percent, windows need to be repaired or upgraded to achieve at least the required minimum (e.g., remove obstructions, adjust limiters on window openings, and free stuck windows) or a mechanical supply of at least the code-required minimum outdoor air needs to be provided.

5) Sign and date the window datasheet.

Window Openable Area Inspection Datasheet

Classroom Name: _

Floor Area (ft^2): _____________

Window Maximum Openable Area

Window number	Window obstructed (Yes/No)	Width or swing-open distance (in)	Height or swing-open distance (in)	Openable area (ft^2)
1				
2				
3				
4				
5				
6				
7				
8				

Total openable area for unobstructed windows (ft^2) ___________________

Total openable area (ft^2) as a percentage of floor area (ft^2) _____________________

Does the classroom have a total openable window area of at least 4 percent of the floor area?

☐ Yes—No further action required; open windows fully whenever possible to increase outdoor air ventilation.

☐ NO—Make necessary window repairs or install a mechanical supply of outdoor air if none present.

> **Note:** Title 24 requires that classrooms have windows with a total openable area of at least 4 percent of the floor area or a mechanical ventilation system with an outdoor air VR of at least 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater.

Inspector’s name: _________________________

Date: ___________________

Window Openable Area Inspection Datasheet (EXAMPLE)

Classroom Name: Room 101

Floor Area (ft^2): 960

Window Maximum Openable Area

Window number	Window obstructed (Yes/No)	Width or swing-open distance (in)	Height or swing-open distance (in)	Openable area (ft^2)
1	N	36	34	8.50
2	N	36	33	8.25
3	N	36	32	8.00
4	N	36	33	8.25
5	N	36	34	8.50
6	N	36	34	8.50
7				
8				

Total openable area for unobstructed windows (ft^2) 50

Total openable area (ft^2) as a percentage of floor area (ft^2) 5.2%

Does the classroom have a total openable window area of at least 4 percent of the floor area?

☑ Yes—No further action required; open windows fully whenever possible to increase outdoor air ventilation.

☐ NO—Make necessary window repairs or install a mechanical supply of outdoor air if none present.

> **Note:** Title 24 requires that buildings with no mechanical supply of outdoor air have windows with a total openable area of at least 4 percent of the floor area or a mechanical ventilation system with an outdoor air VR of at least 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater.

Inspector's name: Luis Martinez

Date: February 10, 2021

Appendix C. Common Ventilation and Filtration Equipment in California Schools and Code-required Minimum VR

This appendix is intended to provide basic background information on common ventilation and filtration equipment and minimum VR requirements in California schools. For details on how to select and operate each type of system, readers should refer to ASHRAE guideline on *Reopening Schools and Universities*[7] and also Cal/OSHA's COVID-19 Emergency Temporary Standard [3] for MERV 13 filter requirements.

Mechanical Ventilation Equipment

The California Code of Regulations (CCR) Title 8 section 5142 requires mechanical ventilation equipment to operate continuously when employees are present.[19] Setting mechanical ventilation equipment to only operate when heating or cooling (sometimes referred to as "auto mode") is prohibited.

Mechanically ventilated classrooms use either "multi-zone" or "single-zone" systems. Multi-zone systems are centralized, relatively large air-handling units that serve multiple classrooms with a remote fan and compressor. In single-zone systems, HVAC units are often either packaged rooftop units (RTUs) or wall-mounted units serving only one or a few classrooms. Wall-mounted units—such as unit ventilators with integrated outdoor air ventilation and filtration, heat pumps with dedicated outdoor air system (DOAS), or fan coil units (FCUs) with DOAS—are used more often in relocatable classrooms. For example, HVAC systems in these classrooms, per a 2004 California study, were typically packaged wall units with teacher-controlled in-room thermostats.[20] A 2020 study of California schools with retrofitted HVAC equipment also reported that relocatable classrooms predominately used wall-mounted, single-package, HVAC systems, while permanent classrooms generally had RTUs.[21] It should be noted that some classrooms have units that only heat or cool the air within a space, with no outdoor air intake (e.g., split systems or FCUs without DOAS). These classrooms do not provide mechanical outdoor air ventilation and rely entirely on openable windows for natural ventilation. Such systems should be discouraged because they are in violation of CCR Title 8 section 5142, which requires outdoor air supply in all mechanically driven HVAC systems.

For all types of HVAC equipment, a fixed position ventilator/damper is the basic control for the mechanical ventilation system, where the position of the outdoor air damper or the size of the opening is fixed so as to provide the indoor space with (at least) the minimum outdoor air VR specified in the design code. Additional features for optimizing both energy efficiency and indoor air quality (IAQ) are often available, either as standard or optional upgrades depending on the product brand and model. Such features include variable air volume (VAV) systems, airside economizers, energy or heat recovery ventilators (ERVs or HRVs), and demand control ventilation (DCV) systems. These are explained further below.

- Variable air volume (VAV) systems: Traditionally, single-zone VAV systems have been used for large, densely occupied zones that have variable cooling loads. However, due to increased focus on energy efficiency, a single-zone VAV currently is used more often in K–12 classrooms, and also is offered in smaller equipment, such as packaged RTUs or direct expansion split systems, fan-coils, classroom unit ventilators, and water-source heat pumps.[22] In contrast with a constant supply airflow rate delivered by a conventional constant air volume system, the supply airflow rate delivered by a VAV system can adjust to demand. With VAV systems, steps need to be taken to ensure that the amount of outdoor air is not reduced below applicable standards when supply air is reduced during part-load conditions.

- Economizer: Economizers use outdoor air to provide free cooling. An airside economizer is now a typical feature in unit ventilators and RTUs. With an economizer, the outdoor air damper can open fully and deliver up to 100 percent outdoor air under favorable weather conditions.
- Energy Recovery Ventilators (ERVs) and Heat Recovery Ventilators (HRVs): An ERV transfers heat and moisture between exhausted room air and incoming outdoor air, thereby reducing the energy required to condition the incoming air. An HRV transfers heat only. An ERV or HRV option is commonly offered in wall-mount units.
- Demand control ventilation (DCV) systems: DCV, using CO_2 sensing, varies the outdoor air supply in response to the indoor CO_2 concentration, to ensure that the maximum concentration remains below a set threshold, generally 1000–1200 ppm. A DCV system always incorporates a minimum outside air setting to dilute building-emitted contaminants during low-occupancy periods. Classroom CO_2 level can be displayed on a monitor (i.e., readily visible to teachers) or directly transmitted to the school's facility energy management system. Both RTU and wall-mount unit manufacturers offer DCV as an add-on feature.

Limited data is available on the prevalence of various ventilation system types in California schools or on trends in changes over the years. Chan et al. recently conducted a survey in 104 mechanically ventilated California classrooms and reported the frequency of occurrence for different types of ventilation equipment, including four commonly used technology types (**Table 1**).[21]

Table 1. Common ventilation equipment found in 104 mechanically ventilated California classrooms with single-zone systems

Technology type	Number (percentage)
ERVs [a]	5 (4.8%)
Fixed position ventilators	19 (18%)
DCVs [b]	25 (24%)
Economizers [c]	74 (71%)

[a] ERVs were all in wall-mount units and not RTUs (although adding an ERV to an RTU is possible).

[b] DCVs were all installed in RTUs

[c] Economizers were common in both RTUs and wall-mount units.

Another factor that may influence the operation of HVAC systems is system noise. Research has found that this is often the most significant source of classroom noise, and cooling system type usually determines the level of overall mechanical noise.[23] Because relocatable classrooms typically have packaged wall units with fans (and sometimes also a compressor) attached outside to one end of the classroom, they can transmit unacceptable ventilation noise and vibration that results in teachers turning off the ventilation system. For example, a 2004 California classroom study found that 60 percent of teachers in relocatable classrooms turned off the mechanical ventilation at times because of the noise (thus providing no outside air, which is a violation of CCR Title 8 section 5142), whereas this occurred less often in traditional classrooms.[20] Some manufacturers of packaged wall units for relocatable classrooms have improved the design of systems manufactured after 2005 to reduce transmission of noise and vibration. The ANSI/Acoustical Society of America [ASA] classroom acoustic standard recommends that the A-weighted sound level measured in an unoccupied classroom with ventilation (mechanical) systems on should not exceed 35 dB(A).[24]

Code-required Minimum VR

For a mechanically ventilated space, Title 24—in both Part 4 of the California Mechanical Code (CMC) and Part 6 of the California Energy Code (CEC)—lists code-required minimum outdoor air VRs for a total of 14 space types in educational facilities. [4,5] However, the two code requirements sometimes differ. For example, the CEC-required outdoor air VRs for classrooms (ages 5–8 and 9 and older) are 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater. These values are 3 percent higher than the CMC-required rates for classrooms of ages 5–8 and 12 percent higher for classrooms of age 9 and older, using the default occupancies specified in the CMC code. To ensure the recommended minimum 3-ft physical distance between students and a minimum 6-ft physical distancing from employees during the COVID-19 pandemic, actual occupant density may be less than the default value specified in the CMC code. Although VR per occupant is a better indicator of ventilation condition in terms of reducing airborne viral transmission, it should be noted that reducing classroom occupancy does not mean that the code-specified minimum outdoor VR can always be proportionally reduced. This is because the specified minimum is also influenced by floor area (to dilute pollutants of concern emitted from building materials, furniture, and indoor products), and this does not change with reduced occupancy.

HVAC Filters

HVAC filters are available in a variety of Minimum Efficiency Reporting Value (MERV) ratings (i.e., MERV 1 through MERV 16), dimensions (e.g., differing lengths, widths, and 1-, 2-, 4-, 6-, or 12-inch depths), media types (e.g., fiberglass or synthetic media), and design configurations (e.g., panel, pleat, mini-pleat, or bag). In terms of reducing indoor airborne particle concentrations, high-efficiency filters (either installed in a centralized HVAC system to treat recirculated air or included in PACs) can be considered to provide “equivalent” outdoor air ventilation. While outdoor air ventilation equally dilutes the concentration of all gases and all sizes of airborne particles, the “equivalent” clean air provided by filtration for airborne viruses depends on the particle removal efficiency of the filter for the size distribution of the virus-containing particles. It is therefore important to optimize the combination of ventilation and filtration to achieve the desired overall system performance.

During the pandemic, many people have asked about the type of HVAC filtration used in California schools, for those with mechanical ventilation systems. Almost no peer-reviewed information is available on the frequency of use of various MERV filter grades and filter rack depths in California schools. MERV 8 filters in 1- and 2-inch deep filter frames appear to be the most common for classrooms with small RTUs, unit ventilators, heat pumps, and FCUs, while MERV 13 filters appear to be found more frequently in school buildings with larger air handling units and packaged air conditioners. If a school building has been Leadership in Energy and Environmental Design (LEED) or Collaborative for High Performance Schools (CHPS) certified, the filters should already be MERV 13. In California, Title 24-2019 Energy Efficiency Standards now require a MERV 13 or higher filter for schools with mechanical ventilation systems.[5] CASH school reopening guidance also recommend at least a MERV 13 filter,[8] as does ASHRAE guidance if higher efficiency filters do not adversely impact system operation.[7] The Cal/OSHA ETS also requires employers to evaluate how to use the highest level of filtration efficiency compatible with their existing ventilation system.[3] A MERV 13 filter or better will comply with the ETS.

Upgrading to MERV 13 can be relatively inexpensive compared to increasing outdoor air VR to well above the code-required minimum, depending on the current filter rack depth. If the existing filters and filter racks are 2 inch or deeper, replacing a MERV 8 with a MERV 13 filter in most systems will not cause a significant reduction of the supply airflow rate. Many commercially available MERV 13 filters of 2-inches or deeper have pressure drops only slightly higher (i.e., ≤0.1 inches water gauge or ≤25 pascals) than those of MERV 8 filters at air speeds of 300–500 feet per minute (1.5–2.5 m/s). Such a slight increase of pressure drop typically will not cause a significant reduction in the supply airflow rate. The fan performance curve (i.e., design static pressure vs. flow rate) can be checked as needed to verify that there is no significant airflow reduction due to a filter upgrade. However, if the existing filters and filter racks are only 1-inch deep, finding a true 1-inch MERV 13 filter with a low pressure drop can be difficult. This is because commercially available 1-inch MERV 13 filters often use electrostatically charged media, which may lose efficiency quickly after installation. Still, upgrading to a MERV 13 filter may be feasible if a 1-inch rack can be modified to accept a 2-inch filter.

The filter change-out frequency can vary from system to system. It also may vary due to seasonal and atmospheric considerations (e.g., during pollen or wildfire season). As a general rule, it should be established based on one of the following criteria: [25,26]

- The specific or allowable pressure drop (e.g., reaching a pressure drop across the filter that causes the supply air flow rate to drop by 20%)
- Filter manufacturers' recommended final pressure drop

- Values demonstrated by experience (e.g., every three months)
- Values determined by life cycle cost analysis.

Installing a pressure gauge on filter units can assist in determining change frequency. Measuring the pressure drop across a filter provides a quantitative measure of the filter resistance that can be used to determine when to change filters.

> Note: When considering filtration devices, it is best to select only those with MERV (or for PACs, CADR) ratings. Some other types of air cleaning devices, although commercially available and marketed as effective and safe for indoor use in response to the COVID-19 outbreak, have unproven efficacy, and some (i.e., ozone generators and ionization devices) may even produce harmful pollutants.[27]

VRs from Opening Windows for Naturally Ventilated Classrooms

There are two driving forces for natural ventilation: wind pressure and stack (or buoyancy) pressure due to indoor-outdoor air temperature difference. Therefore, the amount of outdoor air entering through windows varies with time and location, depending on the outdoor wind speed and the indoor-outdoor temperature difference. For spaces with standard window and room geometry, if the opening area and height, wind speed, and indoor and outdoor temperature difference are known, the natural VR can be roughly estimated using simplified equations (see Natural Ventilation for Infection Control in Health-Care Settings).[28] As for the actual operational conditions of windows and VRs in naturally ventilated classrooms, currently available information is limited, and more research is needed.

Appendix D. Initial DIY Operation Inspection for Classroom HVAC Systems

Purpose: To determine if HVAC systems are operable and are delivering outdoor and appropriately filtered air to a classroom.

> Caution: This inspection <u>does not</u> ensure that the desired <u>quantity</u> of outdoor air is being delivered to a space. To determine the quantity of delivered outdoor air, HVAC airflow rate measurements (see ASHRAE[7] and HSPH[9] recommendations) or a CO_2 decay test is required (see <u>Appendix E</u>).

The following is guidance for completing the following DIY checklist to assess important aspects of HVAC operation.

What You Need:

- Airflow indicator (e.g., a flexible piece of ribbon or tissue paper)
- Clipboard and the Classroom HVAC System Operation Inspection Checklist.

1) Inspect overall system operation

Identify the HVAC system that serves a classroom

For many classrooms the HVAC system that serves the space will be obvious if there is a dedicated system such as a wall-mounted unit ventilator. For classrooms with a rooftop unit (RTU), the RTU on the roof that is closest to the space is likely the system that serves the space. To confirm that a specific RTU serves a space, turn it on and off while observing if air is coming out of the supply air diffusers.

> Note: Attaching an airflow indicator to a supply air diffuser provides "at a glance" feedback that the HVAC system is operating. The RTU fan typically can be turned on and off at the room thermostat using the fan mode switch "Auto/On." Record the name and location of the HVAC system on the checklist.

Determine if outdoor air is entering the HVAC outdoor air intake

With the HVAC system operating, use an airflow indicator to determine if air is entering the outdoor air intake, and record on the checklist. Typically, the outdoor air intake is in a section of the HVAC system upstream of the filters and often has a sheet metal canopy to protect it from rain. **Figure 4** shows the outdoor air inlet for a typical rooftop HVAC system. If no air is entering, a mechanical contractor will need to inspect and repair the system.

Figure 4. Outdoor air inlet for a typical rooftop HVAC system.

Determine if supply air is coming out of each of the supply air diffusers of the HVAC system

With the HVAC system operating, use an airflow indicator to determine if air is entering from each of the supply air diffuser and record on the checklist. Typically, an RTU has ceiling “supply air” diffusers (often with deflection blades) as well as “return air” inlets (with perforated plates). **Figure 5** shows an airflow indicator to determine that air is being delivered from a supply air diffuser.

If air is not visibly entering a classroom from each of the supply air diffusers, a mechanical contractor will need to inspect and repair the system.

> Note: Seeing that air visibly enters a room simply shows that the system is operating but does not ensure that the desired amount of outdoor air is being supplied (see Appendices D and E).

Figure 5. Checking that air is entering the room from a ceiling supply air diffuser with an airflow indicator.

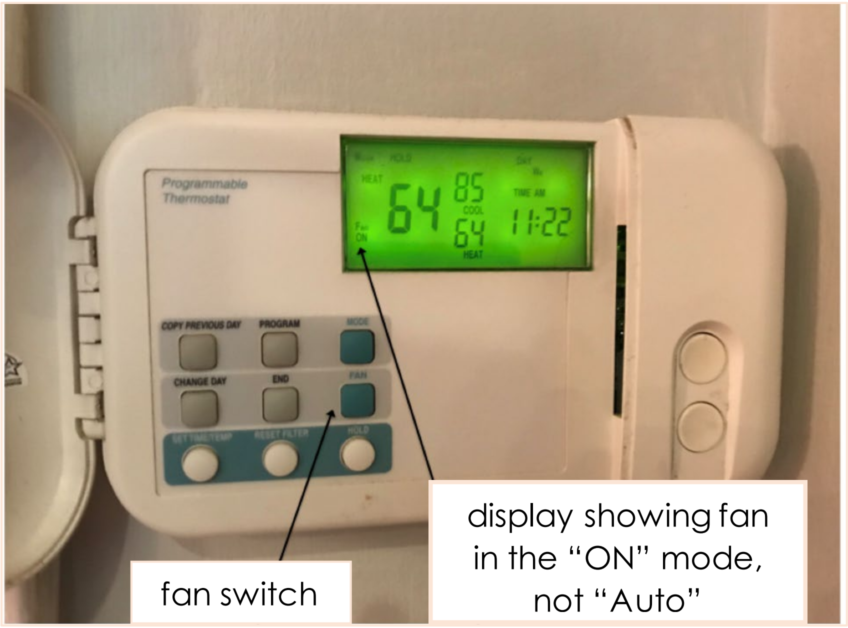
2) Inspect the HVAC filters

Determine the filter's Minimum Efficiency Reporting Value (MERV) rating and filter condition, and record on the checklist as follows:

- With the HVAC system off, locate and open the filter slot (typically a 1–4-inch deep slot with a removable cover). Remove the filter and record the MERV rating on the checklist. If the MERV rating is not labelled, record the manufacturer and model number and look up the MERV rating online. The recommended minimum efficiency is MERV 13. If the filter slot is ≥2 inches deep, a MERV 13 filter with a low air pressure drop can be installed in most HVAC systems.
- Determine if the filters are installed in the filter rack without significant air bypass around the edges. Replace any missing or damaged filters and seal any gaps in the filter rack, e.g., with a sheet metal spacer.
- Replace the filters if they are visibly overloaded with particulate matter (dust). Checking filters at least every three months is recommended. See Appendix C for more information on how to establish a proper filter change out frequency.

3) Inspect the HVAC fan controls

Single-zone HVAC systems often have a Fan Mode switch integrated with the wall thermostat. The Fan Mode switch can be set for "Auto" or "On." When the switch is set for "Auto," the HVAC fan only operates when the thermostat calls for heating or cooling. To ensure continuous operation of the fan and thus delivery of outdoor and filtered air, ensure that the switch is set for "On" and record on the checklist. Figure 6 shows a thermostat with the fan mode switch set to "On". The fan controls for larger, multi-zone HVAC systems most often are integrated with the Building Automation System, and not located on the wall.



display showing fan in the “ON” mode, not “Auto”

fan switch

Figure 6. Thermostat with the fan mode switch set to “On.”

4) Inspect the HVAC time clock

Single-zone HVAC systems often have a time clock integrated with a wall thermostat that starts and stops them at programmed times. HVAC time clocks for larger, multi-zone HVAC systems most often are integrated with the Building Energy Management System. The time clock should start HVAC operation two hours before and after students, teachers, and custodial staff initially enter and finally leave the room.

Record the normal occupancy start and stop times along with the HVAC time clock start and stop times on the checklist.

5) Sign and date the checklist

Classroom HVAC System Initial Operation Inspection Checklist

Classroom Name: ______________________________

System Operation

Identify HVAC system serving the space. System ID and Location: ______________

Turn system on and determine each of the following:

Yes No

☐ ☐ Outdoor air is entering the HVAC outdoor air intake

☐ ☐ Supply air is coming out each of the HVAC supply air diffusers

Air Filtration—Determine each of the following:

☐ What is the filter MERV rating: ______ (targeting MERV 13 or higher)

☐ ☐ Filters are installed in filter rack without significant air bypass

☐ ☐ Filters are not overloaded with particulate matter (dust)

Fan Control—HVAC system thermostat has the Fan Mode switch set for “ON” not “AUTO”

☐ ☐ Fan Mode switch is set for “ON”

Time Clock

Normal Occupancy Start Time: ________ HVAC Start Time: ________

Normal Occupancy Stop Time: ________ HVAC Stop Time: ________

☐ Time clock is set to start system two hours before occupancy and to stop system two hours after occupancy (including time needed to clean room).

Note: If a box is checked “NO,” conduct necessary repairs before occupancy.

Inspector’s name: ________________________

Date: __________________

Appendix E. Using CO_2 Decay to Estimate VR—Method Description and Test Procedure

Increasingly, California classrooms are equipped with CO_2 monitoring devices (i.e., display only or also with datalogging capability), due to the increased availability and improved performance of low-cost sensors. This has made real-time, classroom CO_2 measurement more feasible.

There are several ways to estimate VRs using measured indoor CO_2 concentration (occupant generated or from a CO_2 source) and measured (or assumed) outdoor concentration.[29-31] The steady-state method (CO_2 rise to a steady, unchanging concentration) and the concentration decay method (rate of CO_2 decline) are most commonly used. Both methods assume that the measured CO_2 concentration represents the room average (i.e., the room air is well mixed, and the CO_2 concentration is similar throughout). The CO_2 decay method (outlined below) estimates VR more accurately than the steady-state method, because the later depends on assumed occupant CO_2 generation rate (which varies substantially by occupant age, gender, weight, and metabolic activity).[32]

When using exhaled breath as the source, CO_2 decline can be measured over a period of time (e.g., 30 min) after occupants leave (e.g., at the end of school day), and the outdoor air change rate (ACH) can be calculated directly.(HSPH 2020) This rate can then be multiplied by the room air volume to calculate the outdoor airflow rate (cfm or m^3/h). Knowing the airflow rate, maximum occupancy, and floor area, the VR per occupant (cfm or L/s-occupant) and per floor area (cfm/ft^2 or L/s-m^2) can be determined, see following procedure in the section below "Procedure for Measuring Classroom Outdoor Air VR Using a CO_2 Decay Test". Alternatively, in unoccupied rooms, CO_2 gas can be released (e.g., from a compressed gas cylinder or dry ice) to purposely generate a high initial concentration (e.g., 2000 ppm), and the same measurement and calculation procedure can then be applied.

If a classroom remains occupied (e.g., by a teacher or custodian), the outdoor ACH estimated from CO_2 decay will be less than the true ACH because the method assumes no indoor CO_2 sources. Such deviation due to continued occupancy is influenced mainly by the measurement period, the initial CO_2 concentration, and the actual ACH, and to a lesser extent, by the outdoor CO_2 concentration. For example, in a typical classroom defined in the CDPH IAQS modeling paper (i.e., 27 occupants, 89.3 m^2 floor area, 3 m ceiling, and code-required minimum 2.54 ACH outdoor air),[12] with an initial CO_2 concentration of 1500 ppm and one occupant remaining, the estimated VR will be only ~5 percent lower than the true VR if the final concentration is measured at 30 min. In general, even if an occupant remains, the estimated VR is still a sufficient and conservative approximation of the true ACH.

Procedure for Measuring Classroom Outdoor Air VR Using a CO_2 Decay Test

Purpose: To determine the delivery of outdoor air from a ventilation system.

Caution: This procedure provides a measurement of the outdoor air VR in a single classroom with a single mechanical ventilation system. Spaces with multi-zone HVAC systems that serve more than one classroom require a different test method.

What You Need:

- CO_2 meter
- Cylinder of CO_2 (e.g., a 20-lb aluminum cylinder) or a cooler with dry ice pellets; approximately 1–2 lbs of CO_2 are required for each classroom test.
- Box fan and extension cord
- Tape measure or laser distance meter
- Clipboard, pen, calculator, watch
- Classroom CO_2 Decay Ventilation Measurement Datasheet.

Blank and example CO_2 datasheets follow this section and also are available as excel spread sheets (in both SI and English units).

How to Measure CO_2 Concentration Decay

1. Indoors, close all windows and doors.
2. Determine the maximum classroom occupancy (number of persons), measure and record the room dimensions, and calculate and record the floor area and air volume. If the ceiling is sloped, use the average ceiling height to calculate air volume.
3. Outdoors, turn on the CO_2 meter, place it out of direct sunlight, let equilibrate for 5 min, and record time and the initial outdoor concentration ($C_{\text{outdoor initial}}$).
4. Indoors, place the CO_2 meter in the center of the room and let equilibrate for 5 min.
5. Place the CO_2 source at one end of the room with the box fan positioned behind the tank or cooler blowing air to the opposite side of the room. Turn the box fan on at high speed.
6. Slowly open the CO_2 tank valve until you hear that gas is flowing. Or, if using dry ice, open the cooler lid. Do <u>not</u> touch dry ice with bare hands, to avoid the risk of burns.
7. When the room CO_2 concentration reaches approximately 2000 ppm, close the tank valve or cooler lid, remove from the room, and leave the box fan running.
8. Record the initial indoor CO_2 concentration ($C_{\text{indoor initial}}$) and time ($T_{\text{initial}}$), then leave the room.
9. After 30 min have elapsed, return to the room and record the final concentration ($C_{\text{indoor final}}$) and time (T_{final}).
    - Note: If the CO_2 concentration is not recorded at 30 min (e.g., 1 or 2 min before or after 30 min have elapsed), the ACH can still be calculated, just enter the time and use the actual number of minutes that elapsed since the initial concentration measurement.
10. Outdoors, place the CO_2 meter out of direct sunlight, let equilibrate for 5 min, and record time and the final outdoor concentration ($C_{\text{outdoor final}}$).
11. Calculate and record the average outdoor CO_2 concentration ($C_{\text{outdoor average}}$): sum the initial and final concentrations and divide by two.

  - Note: If occupant-generated CO_2 is used to establish the initial CO_2 concentration, eliminate Steps 5–7 and apply the rest of procedure. To reduce estimation uncertainty, an initial indoor CO_2 concentration >1000 ppm or a shorter measurement end time (e.g., 15 min) is recommended.

How to Calculate the Outdoor Air VR

- Calculate and record the elapsed time (min) between the initial and final indoor concentration measurements.
  - $T_{\text{elapsed}} = T_{\text{final}} - T_{\text{initial}}$
- Calculate and record the initial and final indoor concentrations after subtracting background outdoor concentration ($C_{\text{corrected initial}}$ and $C_{\text{corrected final}}$).
  - $C_{\text{corrected initial}} = C_{\text{indoor initial}} - C_{\text{outdoor average}}$
  - $C_{\text{corrected final}} = C_{\text{indoor final}} - C_{\text{outdoor average}}$
- If the elapsed time is 30 min, use the look-up table below in “CO_2 Ventilation Test Look-Up Table” to estimate outdoor ACH from the concentration ratio ($C_{\text{corrected final}}$) / ($C_{\text{corrected initial}}$). Otherwise, calculate and record the outdoor ACH.
  - $\text{ACH} = \text{Ln}\,(C_{\text{corrected initial}} / C_{\text{corrected final}}) / (T_{\text{elapsed}} / 60)$
- Calculate and record the outdoor airflow rate (cfm).
  - $\text{cfm} = \text{ACH} \times \text{room air volume (ft}^3) / 60$
- Calculate and record the outdoor air flow rate per occupant (cfm/occupant):
  - cfm/occupant = cfm / maximum number of persons
- Calculate and record the outdoor air flow rate per room floor area (cfm/ft^2):
  - $\text{cfm/ft}^2 = \text{cfm / room floor area (ft}^2)$.

Note:

- For mechanically ventilated classrooms (including classrooms for both ages 5–8 and 9 and older), the California code-required minimum outdoor air VRs are 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater.
- If the outdoor CO_2 concentration cannot be measured, assume an outdoor concentration of 400 ppm. This assumption results in a sufficient but conservative estimation of VR (i.e., a calculated VR that is 10–20 percent lower than the true VR), because actual outdoor CO_2 concentrations are usually higher than 400 ppm.[33]

CO_2 Ventilation Test Look-Up Table

Use this table to estimate the outdoor ACH from the ratio of final/initial concentrations.

Note:

- For this table, $C_{\text{indoor final}}$ must be measured at 30 min following $C_{\text{indoor initial}}$. If not, use the following equation.
  - ○ $ACH = Ln (C_{\text{corrected initial}} / C_{\text{corrected final}}) / ((T_{\text{final}} – T_{\text{initial}}) / 60)$
- If the measured concentration ratio is in between two values of this table, use the average of the corresponding two ACH values.

$(C_{\text{corrected final}})/ (C_{\text{corrected initial}})$	Outdoor air ACH	$(C_{\text{corrected final}})/ (C_{\text{corrected initial}})$	Outdoor air ACH
0.88	0.3	0.48	1.5
0.86	0.3	0.46	1.6
0.84	0.3	0.44	1.6
0.82	0.4	0.42	1.7
0.80	0.4	0.40	1.8
0.78	0.5	0.38	1.9
0.76	0.5	0.36	2.0
0.74	0.6	0.34	2.2
0.72	0.7	0.32	2.3
0.70	0.7	0.30	2.4
0.68	0.8	0.28	2.5
0.66	0.8	0.26	2.7
0.64	0.9	0.24	2.9
0.62	1.0	0.22	3.0
0.60	1.0	0.20	3.2
0.58	1.1	0.18	3.4
0.56	1.2	0.16	3.7
0.54	1.2	0.14	3.9
0.52	1.3	0.12	4.2
0.50	1.4	0.10	4.6

(continued)

Classroom CO_2 Decay Ventilation Measurement Datasheet

Classroom Name:

Floor Area (ft^2): __

Ceiling Height (ft): __________

Volume (ft^3): __________

Maximum Number of Occupants: __________

Location		Time	CO_2 Concentration (ppm)
Outdoor	$C_{outdoor\ initial}$	_______	__________
	$C_{outdoor\ final}$	_______	__________
		Indoor $C_{indoor\ initial}$	
	$C_{indoor\ final}$	_______	__________
$C_{outdoor\ average}$			__________
$C_{corrected\ initial}$ ($C_{indoor\ initial}$ − $C_{outdoor\ average}$)			__________
$C_{corrected\ final}$ ($C_{indoor\ final}$ − $C_{outdoor\ average}$)			__________
Concentration Ratio ($C_{corrected\ final}$) / ($C_{corrected\ initial}$)			__________

$T_{initial}$ – T_{final} (elapsed minutes) _______

ACH: (ACH = Ln ($C_{corrected\ initial}$ / $C_{corrected\ final}$) / ($T_{elapsed}$ / 60)) ____________________

cfm: (cfm = ACH × room air volume (ft^3) / 60) __________

cfm/occupant: (cfm/occupant = cfm / maximum number of persons) ________________________

cfm/ft^2: (cfm/ft^2 = cfm / room floor area (ft^2)) ________________

Does the classroom meet the California code-required minimum outdoor air VR?

☐ Yes—No further action required.

☐ NO—Make necessary ventilation system checks and repair equipment as required to achieve minimum outdoor air VR.

> **Note:** For mechanically ventilated classrooms, the California code-required minimum outdoor air VRs are 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater.

Inspector's name: __________________________

Date: ___________________

Classroom CO_2 Decay Ventilation Measurement Datasheet (EXAMPLE)

Classroom Name: Room 101
Floor Area (ft^2): 960
Ceiling Height (ft): 9
Volume (ft^3): 8640
Maximum Number of Occupants: 27

Location		Time	CO_2 Concentration (ppm)
Outdoor	$C_{\text{outdoor initial}}$	10.14	443
	$C_{\text{outdoor final}}$	11:23	449
Indoor	$C_{\text{indoor initial}}$	10:37	1063
	$C_{\text{indoor final}}$	11:07	546
$C_{\text{outdoor average}}$			441
$C_{\text{corrected initial}}$ ($C_{\text{indoor initial}} - C_{\text{outdoor average}}$)			622
$C_{\text{corrected final}}$ ($C_{\text{indoor final}} - C_{\text{outdoor average}}$)			105
Concentration Ratio ($C_{\text{corrected final}}$) / ($C_{\text{corrected initial}}$)			0.17

$T_{\text{initial}} - T_{\text{final}}$ (elapsed minutes) 30

ACH: (ACH = Ln ($C_{\text{corrected initial}} / C_{\text{corrected final}}$) / ($T_{\text{elapsed}}$ / 60)) =

Ln (622 / 105) / (30 / 60) = 3.6

cfm: (cfm = ACH × room air volume (ft^3) / 60) =

3.6 × 8640 / 60 = 512

cfm/occupant: (cfm/occupant = cfm / maximum number of persons) =

512 / 27 = 19

cfm/ft^2: (cfm/ft^2 = cfm / room floor area (ft^2)) = 512 / 960 = 0.53

Does the classroom meet the California code-required minimum outdoor air VR?

☑ Yes—No further action required.

☐ NO—Make necessary ventilation system checks and repair equipment as required to achieve minimum outdoor air VR.

> **Note:** For mechanically ventilated classrooms, the California code-required minimum outdoor air VRs are 15 cfm/occupant or 0.15 cfm/ft^2, whichever is greater.

Inspector's name: Marvin Wong

Date: March 12, 2021

Appendix F. Example Calculation of Total ACH for Removing Virus-containing Particles

The following is an example calculation for a typical classroom defined in CDPH IAQ's modeling paper (i.e., with 27 occupants, floor area of 89.3 m^2, and ceiling height of 3 m).[12] Appendix 3 in this paper has an interactive spreadsheet that calculates ACH_{Total}, from ACH_{OA}, $ACH_{HVAC\text{-}Filtration}$, and ACH_{PAC}.

For the defined reference case (i.e., with the code-required minimum outdoor air VR, a MERV 8 filter, 6 ACH of supply air, and no PACs),[12] the calculated total ACH for removing virus-containing particles is 4.14 ACH (under the given model assumptions and limitations):

ACH_{OA} = 2.54 ACH (outdoor ventilation airflow rate = 27 occupants × 7 L/s-occupant or 15 cfm/occupant = 680 m^3/h or 405 cfm)

$ACH_{HVAC\text{-}Filtration}$ = 1.60 ACH (MERV 8 removal of SARS-CoV-2 particles)

ACH_{PAC} = 0 ACH

$ACH_{Total} = 2.54 + 1.60 + 0 = 4.14$ ACH

Thus, to achieve a minimum ACH_{Total} of 6 ACH for this classroom scenario, an additional 1.86 ACH, or 498 m^3/h (i.e., 1.86 ACH × 89.3 m^2 × 3 m) or 293 cfm, is required. This additional removal of airborne particles can be provided by increasing the outdoor ventilation airflow rate, improving the HVAC air filtration rate, or adding PACs with total Clean Air Delivery Rates (CADRs) for "tobacco smoke" ≥ 498 m^3/h (or 293 cfm).

Acknowledgements

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