

SCHOOLS



HEALTHY BUILDINGS
FOR HEALTH



HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH

How School Buildings Influence
Student Health, Thinking and
Performance



5-step guide to checking ventilation rates in classrooms

Joseph Allen, Jack Spengler, Emily Jones, Jose Cedeno-Laurent
Harvard Healthy Buildings program | www.ForHealth.org

October, 2020



5 Step Guide to Measuring Ventilation Rates in Classrooms

1. Measure the Classroom Dimensions
2. Perform Preliminary Audio and Visual Checks
3. Measure or Estimate Outdoor Air Ventilation Rate (using one of four methods)
4. Compare Results to Targets
5. If Needed, Consider Supplemental Air cleaning Strategies to Meet Targets

The examples at the end of this guide show how to follow these steps to meet ventilation targets in different scenarios.



HEALTHY BUILDINGS
FOR HEALTH



HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH

Step 0

What You'll Need



Materials Needed

- ☐ Tape measure/ laser measure
- ☐ Paper or cardboard and tape to cover unit ventilator or diffusers
- ☐ Additional materials listed below depending on which option is selected to accomplish Step 3

For Step 3, Option A or B (Measuring outdoor air ventilation with a balometer)

- ☐ Balometer* with appropriately shaped hoods for your school's systems (e.g. https://tsi.com/products/ventilation-test-instruments/alnor/alnor-capture-hoods/alnor-balometer-capture-hood-ebi731/?gclid=Cj0KCQjwhlP6BRCMARIsALu9LfkRMQl0LE9GDZvDC49MUbEbuomuj7B18MJR7XQKgB-PPQ1IDsA5DnlaAt0yEALw_wcB)

For Step 3, Option C or D (Estimating outdoor air ventilation from CO₂ concentration)

- ☐ Carbon dioxide monitor*, ** (e.g. CO2meter.com, www.getawair.com, Onsetcomp.com, <https://aranet.com>)

For Step 3, Option C (Estimating outdoor air ventilation from CO₂ concentration)

- ☐ Cooler to transport dry ice
- ☐ Dry ice (~10 pounds will work for approx. five 1000 ft² classrooms)
- ☐ At least two fans per room to enhance mixing

Carbon dioxide (CO₂) is often used as an indirect measure of ventilation. When a building is occupied, the CO₂ concentrations indoors are elevated by CO₂ exhaled by occupants. When occupants leave and no other CO₂ sources are present (e.g. people, combustion sources, etc.), the rate of decay of the CO₂ concentration can be used to estimate how fast air from outdoors (at approximately 400 ppm CO₂) replaces the indoor volume of air.

In the absence of occupants, dry ice (the solid form of carbon dioxide) can be used to cause the concentration of CO₂ in indoor air to increase. Be careful when handling dry ice, since its low temperature (-109°F) can cause burns. Do not touch dry ice with bare hands. Do not let CO₂ concentrations indoors exceed the occupational exposure limit of 5,000 parts per million (ppm).

**Note: These recommendations are not endorsements of any particular brand or product. They are intended to assist users of this guide while choosing the equipment needed to perform the suggested measurements. There are several alternative suppliers of reliable equipment.*

***Note: Carbon dioxide sensors have become better and less expensive in the recent years. For the uses described here, it is useful to have a sensor that can give back the raw data to the users. It is also useful to have a sensor with a display that shows realtime CO₂ levels and a sensor that reports measurements at least once a minute.*

Step 1

Measure the Classroom Dimensions



Step 1. Measure the Classroom

Goal: Obtain the volume of space.

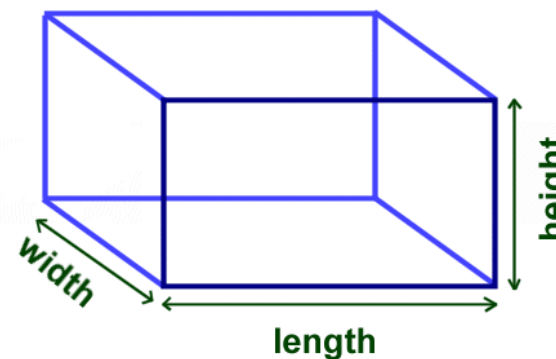
How to:

Measure the room length and width, and ceiling height, to estimate volume in cubic feet, using the formula:

$$\text{length} \times \text{width} \times \text{height}$$

Notes:

- For spaces with intricate geometries, use square footage of architectural plans and multiply by the floor-to-ceiling height.
- If the room has a tapered ceiling, first estimate the area of the wall and multiply by the length of the room.
- If the space has many built-ins (e.g. fireplace) try to account for the dead volume, as well as volume occupied by furniture. It could be that functional volume is ~80% of the total volume of the space.
- Count number of windows, measure their dimension and their openable area.



Step 2

Perform Preliminary Audio and Visual Checks



Step 2. Perform Audio and Visual Checks

Goal: Make sure the system is on and understand the direction of airflow.

How to:

- 1. Audio test:** Listen for sound coming out of the ventilator units and supply/exhaust fans.
- 2. Visual test:** Use a piece of light tissue, or a puff cloud tracer, to see if air is being supplied (puff cloud or tissue flows away from fan) or air is being exhausted (puff cloud or tissue gets sucked in the fan grille).

“Tissue Test”



Notes:

- Some systems, such as AC units, can have both supply and exhaust fans; in this case, you want to identify which area of the unit diffuser performs each function.
- One might check to see if air is entering or leaving the room by using a tissue to indicate direction of air flow under a door or with the door slightly ajar. This check indicates whether the room is typically 'positively' pressurized relative to the adjacent areas (i.e. tissue is sucked toward door) or 'negatively' pressurized relative to the adjacent areas (i.e. tissue floats away from door).

Step 3

Measure or Estimate Outdoor Air Ventilation Rate



Select the option for measuring or estimating classroom ventilation based on your scenario and type of system

	Classroom Scenario	Type of Ventilation System	Materials Needed
Option A	Occupied or unoccupied	Unit ventilator	balometer
Option B	Occupied or unoccupied	Central air system	balometer
Option C	Unoccupied	Any	CO ₂ monitor & dry ice
Option D	Occupied	Any	CO ₂ monitor

Step 3, Option A

Measure Outdoor Air Ventilation Rate

Materials: Balometer

Classroom Scenario: Occupied or unoccupied

Ventilation Type: Unit ventilator



Step 3, Option A. Determine Outdoor Air Ventilation Rate (Unit Ventilators)

Goal: Measure incoming outdoor air flow via mechanical ventilation through unit ventilators.

How to:

1. Choose a capture hood for the balometer with the closest form factor to cover the air diffusers (i.e. pick a hood that has a shape similar to the air diffuser's shape). In case the capture hood does not cover the entire diffuser, use a piece of cardboard and tape to direct the flow exclusively through the capture hood.
2. Start outside and use the balometer to measure the flow rate (in cubic feet per minute [CFM]) coming into the building through the grille where air is sucked in.
3. Move inside the classroom and use the balometer to measure the flow rate (in CFM) at the air diffusers where air is supplied, or blown into, to the room.





Step 3, Option A. Determine Outdoor Air Ventilation Rate (Unit Ventilators)

4. Calculate the percentage of outdoor air (OA) coming in as the ratio of the first measurement to the second. In cases where some of the air delivered to the classroom is recirculated, the % OA will be *less than* 100%; in cases when all of the air delivered to the classroom comes directly from outdoors, the % OA will be 100%.

% outdoor air =

$$\frac{\text{outdoor air flow coming in, measured outdoors}}{\text{total air flow coming in, measured inside the room}}$$

5. Calculate air exchange rates (ACH) from balometer measurements by dividing the outdoor air flow coming into the room (measured outdoors) by the room volume (length * width * ceiling height).

ACH =

$$\frac{\text{outdoor air flow coming in (ft}^3 \text{ per minute)} * 60 \text{ (minutes per hour)}}{\text{classroom volume (ft}^3 \text{)}}$$

Notes:

- Unit ventilators are one of the most common ventilation systems found in classrooms. These systems can provide a combination of outdoor air and recirculated air into the space.
- In many cases, dampers are not fully open. It is important to verify their position by comparing the flow going into the unit (outdoor diffuser) to the air being supplied indoors (indoor diffuser), as described in Step 4 above.
- To maximize ventilation, and when the weather permits, open the unit ventilator's dampers fully to provide 100% outdoor air.
- Do not place books or other materials over the air flow diffusers.
- Ventilation systems are usually designed to promote air mixing in the central areas of a classroom, which may lead to lower ACH in corners or other peripheral areas.

Step 3, Option B

Measure Outdoor Air Ventilation Rate

Materials: Balometer

Classroom Scenario: Occupied or unoccupied

Ventilation Type: Central air system



Step 3, Option B. Determine Outdoor Air Ventilation Rate (Central Systems)

Goal: Measure incoming outdoor air flow via mechanical ventilation through a central system.

How to:

1. Identify the supply diffusers in the classroom (i.e. grilles where air enters the room) and use the balometer to measure flows, making sure that the capture hood covers the entire area of each diffuser and creates a good seal around the diffuser. In case the capture hood does not cover the entire diffuser, use a piece of cardboard and tape to direct the flow exclusively through the capture hood.
2. Determine the damper position in the central air system by asking the school's facilities team or HVAC maintenance team. The damper position will be between 0% and 100% open.
3. Calculate air exchange rates (ACH) from balometer measurements. For central air systems, the outdoor air flow coming into the classroom is the sum of the supply cfm measurements (indoor diffusers) multiplied by the fraction of outdoor air allowed in by the damper (e.g. multiply by 0.2 if the damper position is 20%).

ACH =

$$\frac{\text{Total measured air flow (ft}^3 \text{ per minute)} * 60 \text{ (minutes per hour)} * \text{fraction outdoor air (based on damper position)}}{\text{classroom volume (ft}^3\text{)}}$$

Step 3, Option C

Estimate Outdoor Air Ventilation Rate

Materials: CO₂ monitor & dry ice
Classroom Scenario: Unoccupied (CO₂ decay method)
Ventilation Type: Any



Step 3, Option C. Determine Outdoor Air Ventilation Rate using the CO₂ Decay Method

Goal: Estimate incoming outdoor air flow in an unoccupied classroom using a CO₂ sensor.

How to:

1. Follow manufacturer instructions to calibrate the CO₂ sensor.
2. Set up the CO₂ sensor to log measurements at least one time per minute. This will help you select the beginning and end of a decay period more precisely.
3. Measure the outdoor CO₂ concentration with the CO₂ sensor for at least five minutes. (Note: you should also measure outdoor CO₂ again after you finish making indoor measurements.) While the background concentration outdoors is approximately 400 ppm, in denser urban areas CO₂ can fluctuate throughout the course of the day due to emissions from combustion sources. Take note of the outdoor concentrations both before and after your indoor measurements, as you will need the average to estimate the ventilation rate.



(continued on next page)



4. Place the CO₂ sensor in the classroom away from the dry ice container location and approximately 3 feet above the floor.
5. Use dry ice to cause the CO₂ concentration to rise in the classroom to approximately 2000 ppm.
 - a. Do not touch dry ice with bare hands. It is very cold and can cause burns.
 - b. Do not allow CO₂ concentrations to exceed the occupational exposure limit of 5000 ppm.
 - c. Reduce airflow from your mechanical systems to speed up the concentration buildup. Ideally, turn off the unit ventilators and exhaust fans (only during this step while the CO₂ concentration builds up). If this is not possible, cover the air diffusers with a piece of paper and tape.
 - d. Place an open container of dry ice in the classroom. For a regular classroom (500-1000 ft²), approximately 10 pounds of dry ice pellets should suffice to raise the CO₂ concentration to 2000 ppm in less than 15 minutes for five tests. Place a fan blowing on the dry ice to assist with sublimation of CO₂. Also, use fans to promote mixing of the dry ice CO₂ in room air to ensure a uniform concentration throughout the room. This is important because you are generating CO₂ from a single point in space, and because it is a heavier, colder gas than the room air.
 - e. Check the concentration of CO₂ on the CO₂ sensor. When it reaches at least 2000 ppm, remove the dry ice or close the dry ice container, return airflow to normal conditions (i.e. undo airflow reductions in 5c), and have all people present in the room leave the room.

(continued on next page)

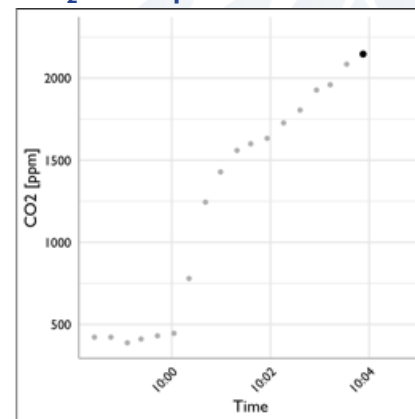




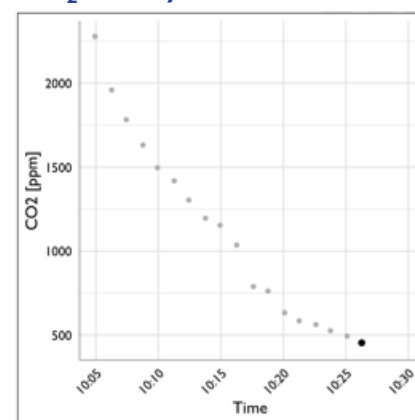
6. Allow the CO₂ concentration in the classroom to decay to a concentration ~ 37% of its original peak concentration above background.
 - a. The CO₂ concentration will begin to decrease when the dry ice is removed from the room and when people leave the room.
 - b. During this period, try to keep ventilation as constant as possible by leaving the mechanical systems setting unchanged, and minimize the number of times and people going in and out of the test room.
 - c. The test may end when the CO₂ level approaches 37% of its original peak concentration above background. For example, if the peak concentration is 2500 ppm and the outdoor concentration is 400 ppm (excess CO₂ = 2500-400 = 2100 ppm), you should aim for 1177 ppm (i.e., [2100 ppm*0.37] + 400 ppm).
7. Repeat steps 5 and 6 to test the following scenarios, if applicable, to understand ventilation in each circumstance:
 - Empty classroom with doors and windows closed and with 'fresh' outside air dampers open for the room unit ventilators (if present).
 - Empty classroom with some doors and/or windows open for supplemental natural ventilation. Can try multiple configurations of open doors and windows. Even with windows open, interior door(s) might need to be open to allow the extra air to flow through the classroom.
 - Test other classrooms to understand the influence of wind flow over and around the building and the effect of window opening.

(continued on next page)

CO₂ Buildup



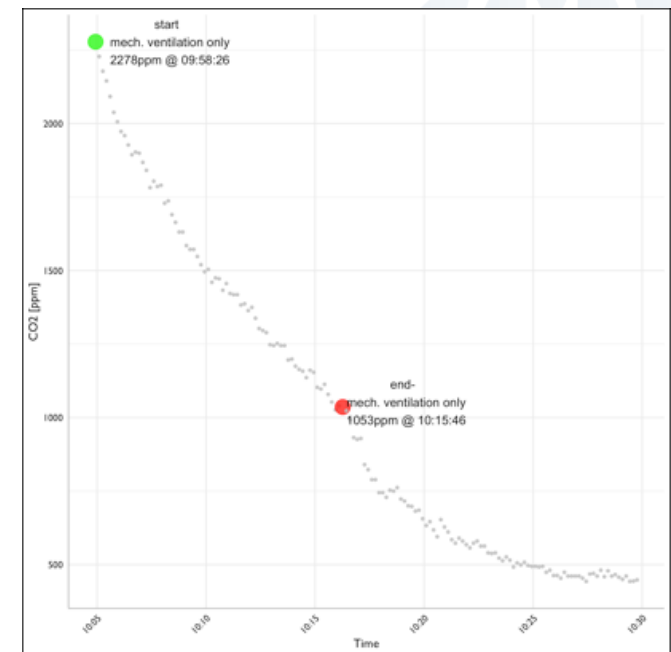
CO₂ Decay





8. Use data from the CO₂ sensor to calculate air changes per hour (ACH) for each test:
- Access the data collected by the CO₂ sensor.
 - Identify the beginning of the decay curve by looking at the data and comparing it with the timing of your testing and mark down the concentration (C_{start}) and the corresponding time (t_{start})- shown with the **green dot** in the graph. Try avoiding periods when the CO₂ concentrations oscillate around the same value, and choose a point that has a clear, consistent concentration decrease.
 - Identify the end of the decay curve by looking at the data and comparing it with the timing of your testing and mark down the concentration (C_{end}) and the corresponding time (t_{end}) - shown with the **red dot** in the graph.
 - Take the average of outdoor concentrations measured with the sensor before and after the indoor tests ($C_{ambient}$).
 - Estimate the decay duration in hours $t_{end}-t_{start}$. For example, a 10-min decay equals $10/60=0.167$ hrs
 - Use the following equation to obtain the air changes per hour (note that all concentrations, C , will be in ppm and all times, t , will be in hours:

$$ACH = \frac{-1 * \ln \left(\frac{C_{end} - C_{ambient}}{C_{start} - C_{ambient}} \right)}{t_{end} - t_{start}}$$





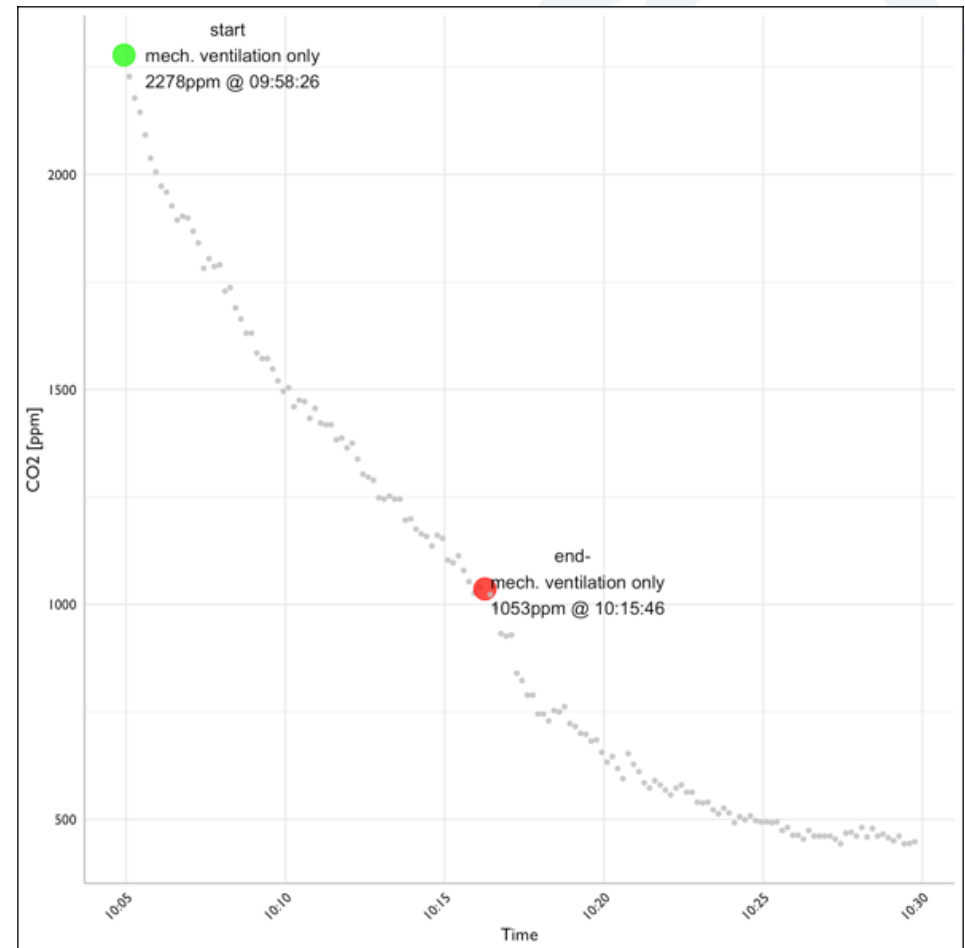
Example – test impact of mechanical ventilation

- Identify the beginning of the decay, $C_{\text{start}} = 2278$ ppm and $t_{\text{start}} = 09:58:26$
- Identify the end of the decay, $C_{\text{end}} = 1053$ ppm and $t_{\text{end}} = 10:15:46$.

(Note that this endpoint was chosen because, in this test, windows were opened after 10:15:46 and we want to know the air changes per hour from only mechanical ventilation.)

- Outdoor concentration $C_{\text{ambient}} = 400$ ppm
- Time difference $t_{\text{end}} - t_{\text{start}}$ is 17 minutes and 20 seconds. In hours that would be $17/60 + 20/3600 = 0.2889$ hours.

$$ACH = \frac{-1 \cdot \ln\left(\frac{1053 - 400}{2278 - 400}\right)}{0.2889} = 3.7 \text{ changes per hour}$$





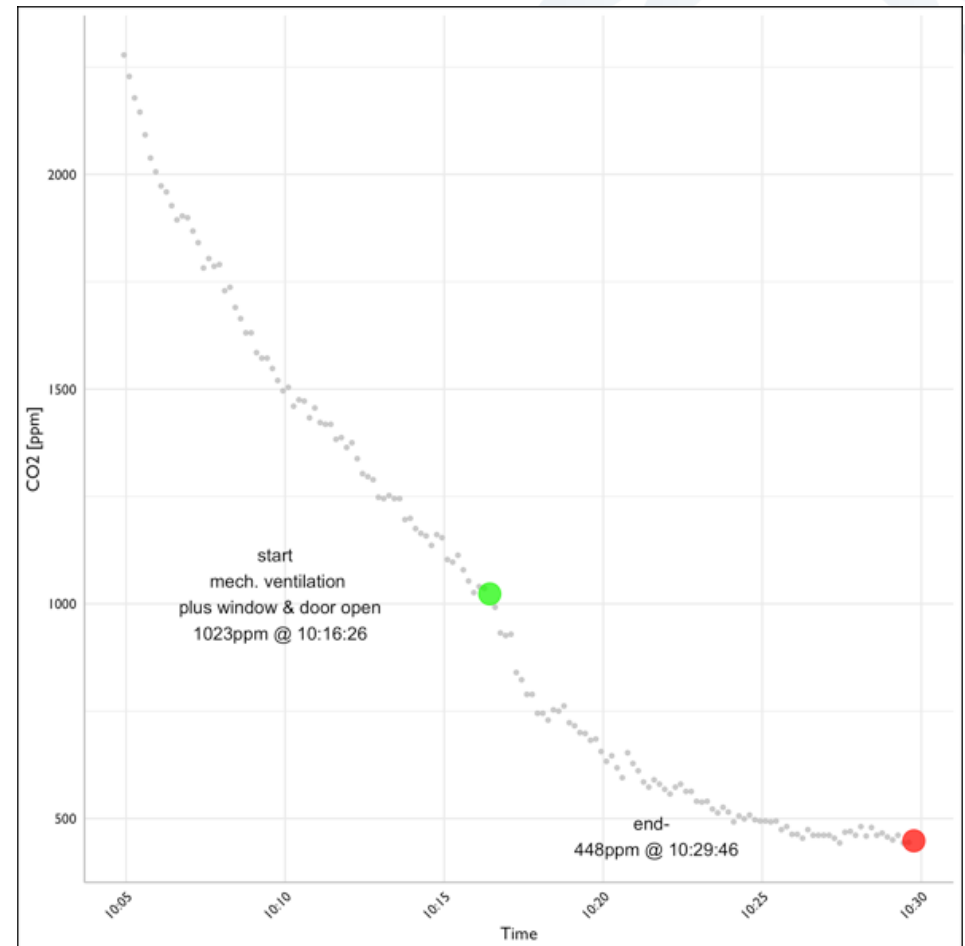
Example – test additional impact of opening windows and doors

- Identify the beginning of the decay, $C_{\text{start}}=1023$ ppm and $t_{\text{start}}=10:16:26$.

(Note that this beginning point was chosen because, in this test, windows and doors were closed before 10:16:26 and we want to know the air changes per hour from mechanical ventilation with windows and doors open.)

- Identify the end of the decay, $C_{\text{end}}=448$ ppm and $t_{\text{end}}=10:29:46$
- Outdoor concentration $C_{\text{ambient}}=400$ ppm
- Time difference $t_{\text{end}}-t_{\text{start}}$ is 13 minutes and 20 seconds. In hours that would be $13/60 + 20/3600 = 0.2222$ hours

$$ACH = \frac{-1 * \ln\left(\frac{448-400}{1023-400}\right)}{0.2222} = 11.5 \text{ changes per hour}$$



Step 3, Option D

Estimate Outdoor Air Ventilation Rate

Materials: CO₂ monitor

Classroom Scenario: Occupied (steady state CO₂ method)

Ventilation Type: Any



Step 3, Option D. Determine Outdoor Air Ventilation Rate using the Steady State CO₂ Method

Goal: Estimate incoming outdoor air flow in an occupied classroom using a CO₂ sensor.

Once the space is occupied, CO₂ sensors in the classroom can be used to approximately know how well-ventilated the space is. For example, a 500 ft², 10-ft ceiling classroom with 15 teenager students, and a ventilation rate of 4 ACH should have a steady state concentration around 800 ppm. That steady state concentration drops to ~700 ppm and ~650 ppm for 5 and 6 ACH, respectively.

How to:

1. Follow manufacturer instructions to calibrate the CO₂ sensor.
2. Set up the CO₂ sensor to log measurements at least 1 time per minute.
3. Measure the outdoor CO₂ concentration with the CO₂ sensor for at least five minutes. While the background concentration outdoors is approximately 400 ppm, in denser urban areas, CO₂ can fluctuate throughout the course of the day due to emissions from combustion sources. Take note of the outdoor concentration as you will need this number to estimate the concentration at steady state.
4. Estimate the CO₂ generation rate by multiplying the number of occupants in the classroom by their rate of CO₂ exhalation (in CFM). The per person CO₂ generation rate is dependent on age, gender, weight, and metabolic activity. For students 6-11 years old, consider an average generation rate of 0.0066 cfm per child, and for teenagers use 0.0087 cfm per teenager. Multiply the corresponding generation rate times the number of kids in the classroom. For teachers (standing and speaking, average age 30-40) use 0.013 cfm.
 - For a classroom with 14 teenage students and one teacher, the CO₂ generation rate is $14 \times 0.0087 \text{ cfm} + 1 \times 0.013 \text{ cfm} = 0.1348 \text{ cfm}$

(continued on next page)



5. Estimate the target volumetric flow of outdoor air. Multiply the volume of the classroom (in cubic feet) times the target air changes per hour and divide by 60 minutes per hour.

- e.g., For a target of 4 ACH in a 5000 ft³ classroom, $5000 \times 4 / 60 = 333$ cfm

6. Estimate the steady state CO₂ concentration using the following formula

$$C_{\text{steady-state}} = \frac{CO_2 \text{ generation rate} + \text{target volumetric flow} * \text{outdoor } CO_2 * 1 * 10^{-6}}{\text{target volumetric flow} * 1 * 10^{-6}}$$

$$\text{Continuing the example above, } C_{\text{steady-state}} = \frac{0.1348 \text{ cfm} + 333 \text{ cfm} * 400 \text{ ppm} * 1 * 10^{-6}}{333 \text{ cfm} * 1 * 10^{-6}} = 804 \text{ ppm CO}_2$$

This method only considers the dilution effect due to outdoor air flow. If part of your air supply is filtered through a MERV 13 or higher efficiency filter, or a portable air cleaner with a HEPA filter, you may use a lower target air exchange rate for this calculation as long as the total air changes per hour of clean air still meets the recommended ACH target. For example, if your mechanical ventilation can provide 3ACH, estimate the steady state concentration at 3 ACH considering that you could add 2 ACH with portable air cleaners to meet the 5 ACH target

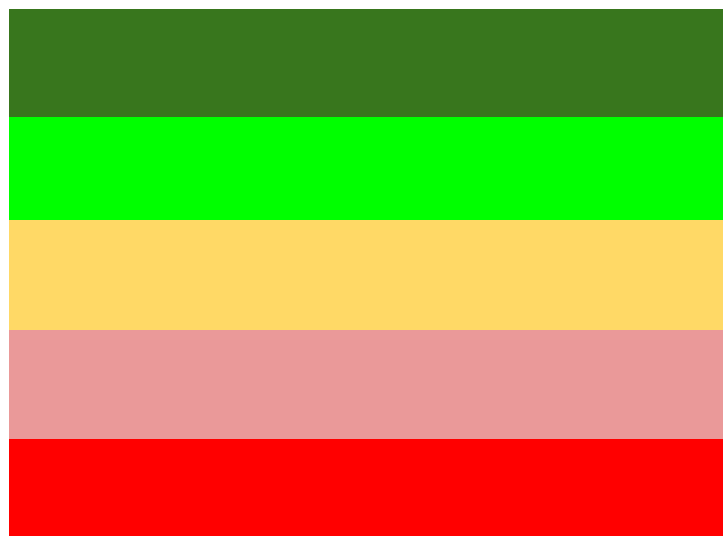
- Now that you've done this calculation, you can use your CO₂ monitor while class is in session to evaluate whether ventilation is adequate. In the example presented here, if the CO₂ sensor read around 800 ppm while the 14 students and 1 teacher were in class, we'd know we were meeting the stated target of 4 ACH of outdoor air ventilation. If we noticed the CO₂ sensor consistently read 1400 ppm while the 14 students and 1 teacher were in class, we'd want to check the ventilation because the increased steady-state CO₂ concentration indicates that the actual ACH is below the stated target of 4 ACH. In this way, CO₂ sensors can be used to determine when ventilation may not be adequate.

Step 4

Compare Results to Target



TARGET IS AT LEAST 5 TOTAL AIR CHANGES PER HOUR



Ideal (6 ACH)

Excellent (5-6 ACH)

Good (4-5 ACH)

Bare minimum (3-4)

Low (<3 ACH)

Step 5

If Needed, Consider Supplemental Air Cleaning Strategies



Strategies to use if the classroom does not meet the target ACH

1. Increase outdoor air
2. Use MERV13 filters (or greater) on recirculated air
3. Add portable air cleaners with HEPA filters to the classroom



1. Increase outdoor air

Natural Ventilation

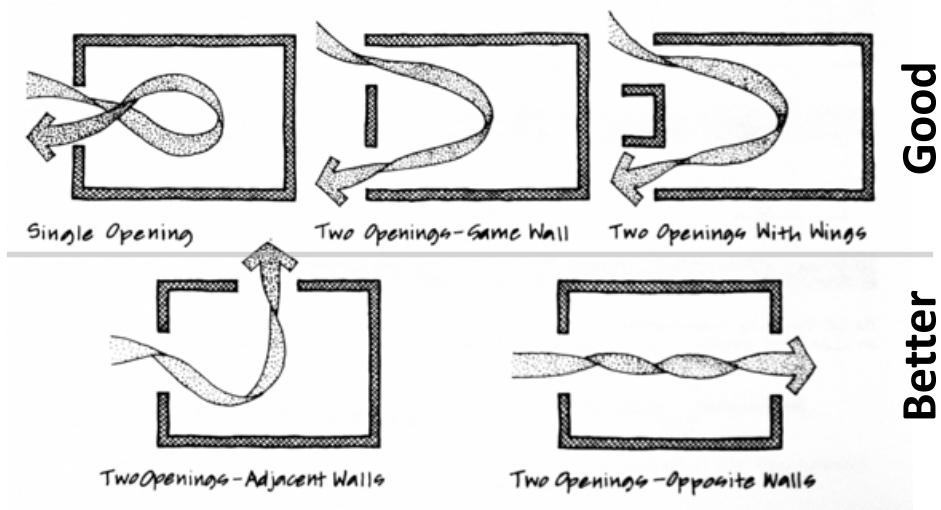
- Open windows and/or doors to increase airflow

Mechanical Ventilation

- Set unit ventilator or central air system to maximum outdoor air ventilation rate that the system can handle based on outdoor temperature conditions

Note:

- Outdoor air gets into the classroom due to a pressure differential, caused by bulk motion (wind), a temperature gradient (buoyancy), or a mechanical system (negative pressure due to an exhaust fan)
- Cross-ventilation is a preferred strategy since it displaces air more effectively in a larger portion of the classroom. Having a functional exhaust fan or opening the door to a hallway can facilitate the flow coming through an open window.
- Performing tests with different window/ door opening configurations might suggest the optimal strategy for a classroom.



Graphic reference unknown. Credits to the author



2. Use MERV13 filters (or greater) on recirculated air

- In a mechanical system, a filter of MERV 13 (or greater) can help remove some particles from air that recirculates through the system and is redistributed into classrooms
- Check with a commissioning agent to determine whether your mechanical system can handle the pressure drop of installing a MERV 13 filter.
- The recirculated flow passing through a higher efficiency filter can be added to the air flow (CFM) in the ventilation calculations to reach the ACH target.
- We recommend assuming 80% capture efficiency for calculations that include a MERV 13 filter.



3. Add portable air cleaners with HEPA filters to the classroom

- If your mechanical systems cannot accommodate a higher efficiency filter, you can use portable air cleaners with HEPA filters.
- To choose a portable air cleaner with the right dimensions for your classroom size and clean air delivery rate to meet the ventilation target, use the Portable Air Cleaner Calculator for Classrooms developed by the Harvard Healthy Buildings team and Shelly Miller at CU Boulder (tinyurl.com/portableaircleanertool)
- The center of the classroom might be the ideal location. If this is not possible, choose a location in which the flow out of the portable air cleaner does not blow directly into the occupants.

Example 1

Central Mechanical Ventilation with MERV 13 Filters



- Step 1.** Room dimensions were measured to be:
Square footage = 700 square feet // Ceiling height = 9.8 feet // Volume = 6,883 cubic feet
(volume = square footage * ceiling height)
- Step 2.** Systems were confirmed to be on via eyes and ears.
- Step 3.** Option B was selected because the school had access to a balometer and had a central ventilation system. The balometer was used to measure the outdoor air ventilation rate from the supply diffusers where air enters the room. The central ventilation system uses 20% outdoor air.
- Measured air flow rate inside the classroom (ie, outdoor air + recirculated air) 760 cfm
 - Percent outdoor air 20%
 - Outdoor air ventilation rate $760 \text{ cfm} * 20\% = 152 \text{ cfm}$
 - Air changes per hour ($152 \text{ cfm} * 60 \text{ minutes/hour} / 6,883 \text{ cubic feet}$) **1.3 ACH**
- Step 4.** The ACH of 1.3 is less than the 5 ACH target.

(continued on next page)



Step 5. Determine which supplemental ventilation or filtration strategy can be pursued.

1. Can outdoor air be increased?
 - through greater % of outdoor air? In this example, no.
 - through opening windows? In this example, no.
2. Can MERV13 filters be installed on the recirculated air? In this example, **YES**.
3. Are portable air cleaners with HEPA filters needed? First determine if MERV13 filters can be used to meet target ACH

Next step will be to determine the impact of MERV 13 filters

Measured air flow rate inside the classroom (ie, outdoor air + recirculated air)	760 cfm
Percent outdoor air	20%
Outdoor air ventilation rate	$760 \text{ cfm} * 20\% = 152 \text{ cfm}$
Recirculated air ventilation rate	$760 \text{ cfm} - 152 \text{ cfm} = 608 \text{ cfm}$
Clean recirculated air rate through MERV 13	$608 \text{ cfm} * 0.8 \text{ efficiency} = 486 \text{ cfm}$
Outdoor air + clean recirculated air through MERV 13 filter	$152 \text{ cfm} + 486 \text{ cfm} = 638 \text{ cfm}$
Air changes per hour ($638 \text{ cfm} * 60 \text{ minutes/hour} / 6,883 \text{ cubic feet}$)	5.6 ACH

This room now meets the 5 ACH target. No further action is needed.

Example 2

Unit Ventilators + Opening Windows



- Step 1.** Room dimensions were measured to be:
Square footage = 1,010 square feet // Ceiling height = 9.5 feet // Volume = 9,595 cubic feet
(volume = square footage * ceiling height)
- Step 2.** Systems were confirmed to be on via eyes and ears.
- Step 3.** Option A was selected because school had access to a balometer and the classroom measured had a unit ventilator. The following balometer measurements were made:
- Measured air flow rate outside the classroom (ie, outdoor air supply to the classroom) 231 cfm
 - Measured air flow rate inside the classroom (ie, outdoor air + recirculated air) 800 cfm
 - Percent outdoor air being delivered into the classroom 29%
 - Air changes per hour (231 cfm * 60 minutes) / 9,595 cubic feet **1.4 ACH**
- Step 4.** The measured ACH of 1.4 is lower than the 5 ACH target. This classroom needs supplemental ventilation and/or filtration.
- Step 5.** Determine which supplemental ventilation or filtration strategy can be pursued.
1. Can outdoor air be increased?
 - through the unit ventilator? In this example, no.
 - through opening windows? In this example, **YES**.
 2. Can MERV13 filters be installed on the recirculated air? In this example, no.
 3. Are portable air cleaners with HEPA filters needed? First determine if opening windows can meet target ACH

(continued on next page)



Next step is to return to Step 3 and evaluate ventilation rate with windows open using the CO₂ decay method (Option C)

Identify the beginning of the decay:

C_{start}=1794ppm and t_{start}=9:16:26

Identify the end of the decay:

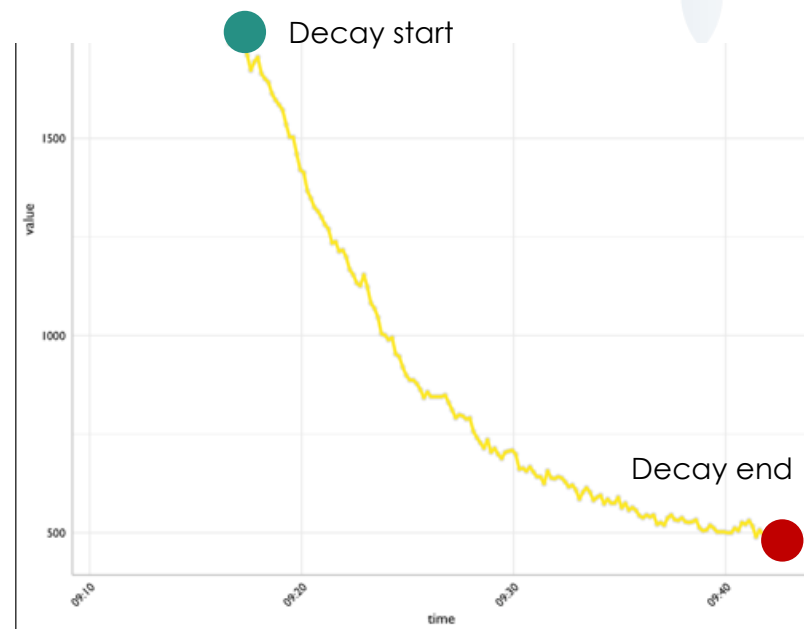
C_{end}=475ppm and t_{end}=9:42:46

Outdoor concentration: C_{ambient}=400 ppm

Time difference: t_{end}-t_{start} is 26 minutes and 20 seconds. In hours that would be 26/60 + 20/3600 = 0.4389 hours

$$ACH = \frac{-1 * \ln\left(\frac{475 \text{ ppm} - 400 \text{ ppm}}{1794 \text{ ppm} - 400 \text{ ppm}}\right)}{0.4389 \text{ hours}} = 6.7 \text{ ACH}$$

6.7 ACH is greater than the 5 ACH target. This classroom with windows open meets the target ventilation. Efforts should still be made to increase the % of outdoor air delivered by the unit ventilators, and install higher grade filters



Example 3

Mechanical Ventilation + Portable Air Cleaner



- Step 1.** Room dimensions were measured to be:
Square footage = 1,010 square feet // Ceiling height = 9.5 feet // Volume = 9,595 cubic feet
(volume = square footage * ceiling height)
- Step 2.** Systems were confirmed to be on via eyes and ears.
- Step 3.** Option A was selected because school had access to a balometer and the classroom measured had a unit ventilator. The following balometer measurements were made:
- Measured air flow rate outside the classroom (ie, outdoor air supply to the classroom) 400 cfm
 - Measured air flow rate inside the classroom (ie, outdoor air + recirculated air) 800 cfm
 - Percent of outdoor air being delivered into the classroom 50%
 - Air changes per hour (400 cfm * 60 minutes) / 9,595 cubic feet **2.5 ACH**
- Step 4.** The measured ACH of 2.5 is lower than the 5 ACH target.
- Step 5.** Determine which supplemental ventilation or filtration strategy can be pursued.
1. Can outdoor air be increased?
 - through the unit ventilator? In this example, no.
 - through opening windows? In this example, no.
 2. Can MERV13 filters be installed on the recirculated air? In this example, no.
 3. Are portable air cleaners with HEPA filters needed? In this example, **YES**.

(continued on next page)



Next step will be to determine the right size of portable air cleaner

Select the appropriate sized portable air cleaner using this tool: <https://tinyurl.com/portableaircleanertool>

- Air changes needed to meet target ACH in this example = $5 - 2.5 = 2.5$ additional ACH needed
- Determine the clean air delivery rate (CADR) needed from the portable air cleaner CADR value required (CADR ratings are listed on most portable air cleaners available for purchase.)
 - $2.5 \text{ ACH needed} * 9,595 \text{ cubic feet} / 60 \text{ minutes} = 400 \text{ cfm}$
- This classroom meets the 5 ACH target if portable air cleaner(s) with HEPA filtration and with a total CADR of 400 cfm are used.**

Tool for selecting an appropriate portable air cleaner can be found here:

<https://tinyurl.com/portableaircleanertool>

Also available at:

<https://schools.forhealth.org/>

Additional Resources for School Reopening

Schools for Health



HEALTHY BUILDINGS

FOR HEALTH



HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH

Additional Resources



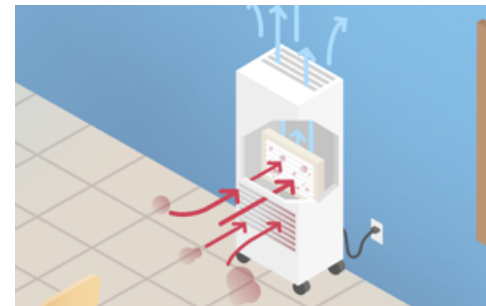
**Risk Reduction
strategies for
reopening
schools**



**When to open
based on
community
spread**



**20 questions
every parent
should ask before
sending kids back
to school**



**Tool for selecting
portable air
cleaners for
classrooms**

All resources available at: <https://schools.forhealth.org/>



Limitations

- Values measured on one day will reflect only the conditions experienced that day, both within and outside the building. Infiltration and flow through windows is highly dependent on outdoor weather conditions, whether the classroom and hallway doors are open, and whether the exhaust system (gravity or mechanical) is working as intended.
- Opening windows and doors is not a permanent solution and should not replace efforts to ensure ventilation systems are working properly.
- Not all areas of the room can be considered well mixed. For example, a mechanical system may more thoroughly mix the central area of a classroom and less thoroughly mix corners or other peripheral areas.
- Our target air changes per hour (ACH) values (Step 4) are based on classroom default densities as expressed in ASHRAE Standard 62.1-2019 (25 students/1000 sq ft for 5- to 8-year-olds). These densities should not be exceeded not only because of an effective reduction of the equivalent ventilation rate per person considered in our calculations, but also because of the risk of droplet transmission if not preserving the recommended physical distancing.
- Limitations of using CO₂ to estimate ventilation (Step 3, Option C or D):
 - For the purpose of infectious disease control, filtering recirculated air with high efficiency filters (MERV 13 or higher) or portable air cleaners with HEPA filters provides additional clean air capable of diluting bioaerosols. Estimating air changes per hour with CO₂ is only capable of approximating the rate of outdoor air supply and DOES NOT account for any benefit due to filtering air. For more details on how to combine the flow from adequately filtered air, please use our portable air cleaner calculator (tinyurl.com/portableaircleanertool).
 - The results are sensitive to errors due to poorly calibrated CO₂ sensors, proper selection of the start and end points of the decay, flows from other spaces within the building, as well as changes in ventilation rate during the measurement due to changes in pressure differentials within the building and in the building envelope.



Disclaimer

- This document is provided for informational and educational purposes only. It is intended to offer guidance regarding questions about best practices regarding assessing ventilation in school classrooms in an effort to reduce the risk of disease transmission, specifically novel coronavirus SARS-CoV-2 and the disease it causes, COVID-19.
- Adherence to any information included in this document will not ensure successful treatment in every situation, and the user should acknowledge that there is no “zero risk” scenario, that each building and situation are unique and some of the guidance contained in the document will not apply to all buildings, or countries outside the United States.
- Furthermore, the document should not be deemed inclusive of all proper methods nor exclusive of other methods reasonably directed to obtaining the same results. The document is in no way intended to override or supersede guidance from government and health organizations, including, without limitation, the Centers for Disease Control and Prevention, the World Health Organization, the United States Government, and or any States.
- The information contained herein reflects the available information at the time the document was created. The user recognizes that details and information are changing daily, and new information and/or the results of future studies may require revisions to the document (and the general guidance contained therein) to reflect new data.
- We do not warrant the accuracy or completeness of the guidance in this document and assume no responsibility for any injury or damage to persons or property arising out of or related to any use of the report or for any errors or omissions.

SCHOOLS



HEALTHY BUILDINGS
FOR HEALTH



HARVARD T.H. CHAN
SCHOOL OF PUBLIC HEALTH

How School Buildings Influence
Student Health, Thinking and
Performance



5-step guide to checking ventilation rates in classrooms

Joseph Allen, Jack Spengler, Emily Jones, Jose Cedeno-Laurent
Harvard Healthy Buildings program | www.ForHealth.org

August, 2020