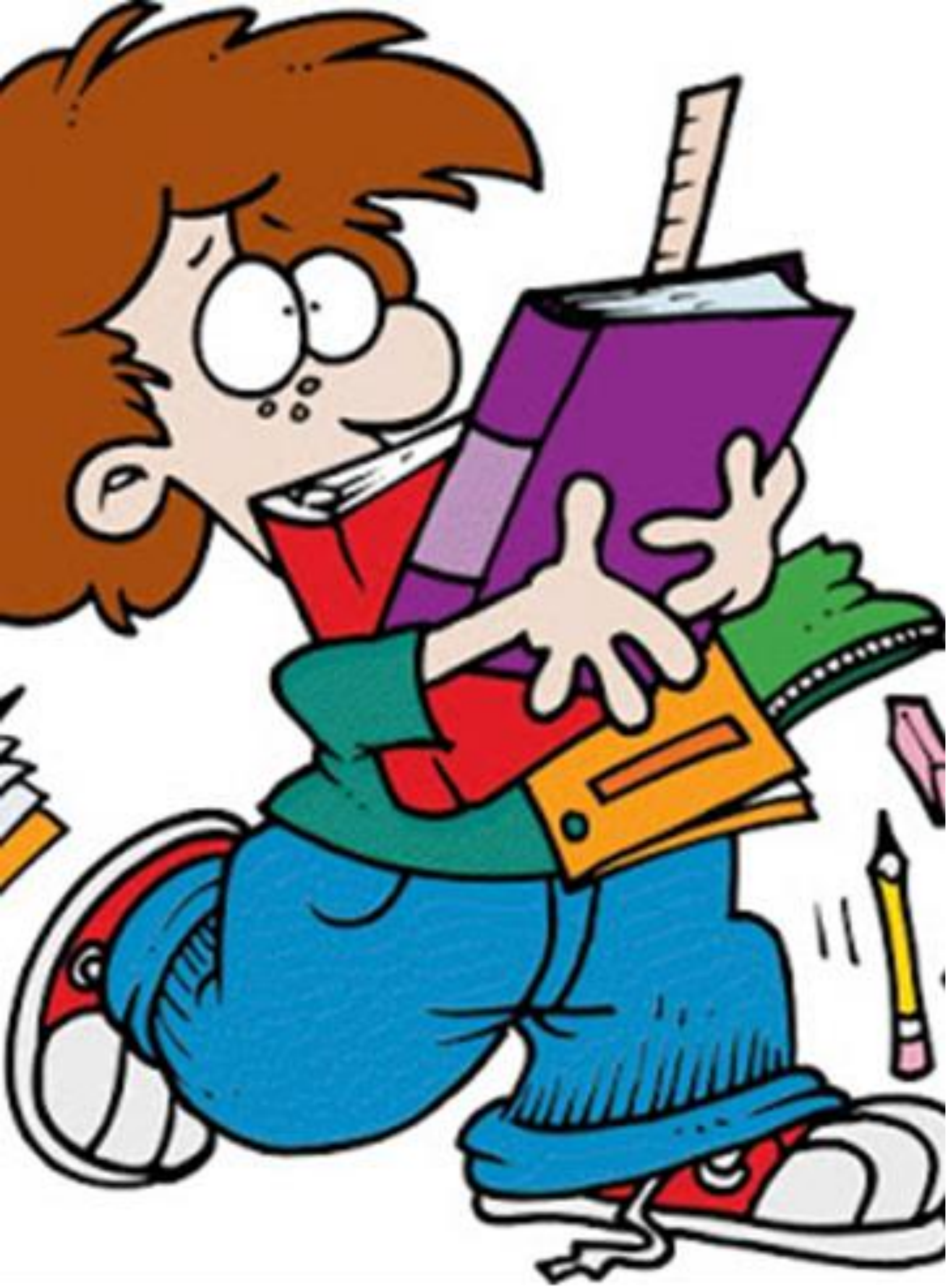


Using CO_2 as a Ventilation Clue

Dustin Poppendieck, PhD
National Institute of Standards and Technology

Disclaimer

- *Certain guidance is identified in this presentation. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the method identified is necessarily the best available for the purpose.*

Goal: Find Poorly (and fix) Ventilated Classrooms

Transmission of SARS-CoV-2 from inhalation of virus in the air farther than six feet from an infectious source can occur

With increasing distance from the source, the role of inhalation likewise increases. Although infections through inhalation at distances greater than six feet from an infectious source are less likely than at closer distances, the phenomenon has been repeatedly documented under certain preventable circumstances.[10-21] These transmission events have involved the presence of an infectious person exhaling virus indoors for an extended time (more than 15 minutes and in some cases hours) leading to virus concentrations in the air space sufficient to transmit infections to people more than 6 feet away, and in some cases to people who have passed through that space soon after the infectious person left. Per published reports, factors that increase the risk of SARS-CoV-2 infection under these circumstances include:

- Enclosed spaces with inadequate ventilation or air handling within which the concentration of exhaled respiratory fluids, especially very fine droplets and aerosol particles, can build-up in the air space.

https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/sars-cov-2-transmission.html

Using CO_2 as a Ventilation Clue

INDOOR AIR
International Journal of Indoor Environment and Health

Full Access

Association between substandard classroom ventilation rates and students' academic achievement

U. Haverinen-Shaughnessy, D. J. Moschandreas, R. J. Shaughnessy

First published: 24 August 2010 | https://doi.org/10.1111/j.1600-0668.2010.00686.x | Citations: 133

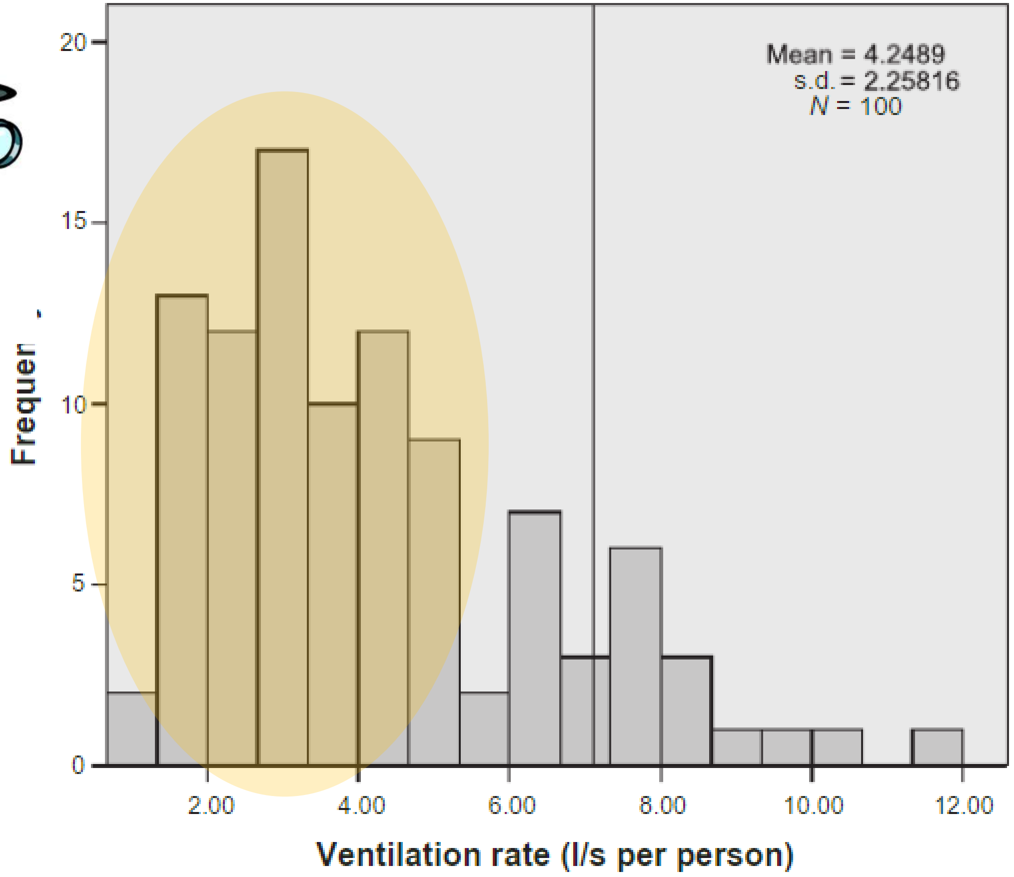


Fig. 1 Ventilation rate distribution (vertical line corresponds to ASHRAE recommended minimum)

Where does CO_2 come from?

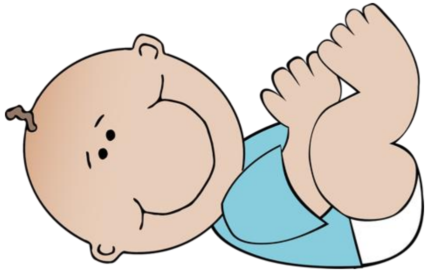

INDOOR AIR
International Journal of Indoor Environment and Health

ORIGINAL ARTICLE | Open Access

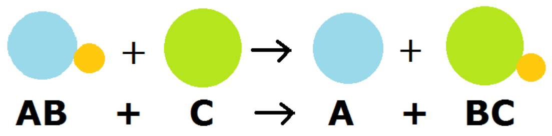
Carbon dioxide generation rates for building occupants

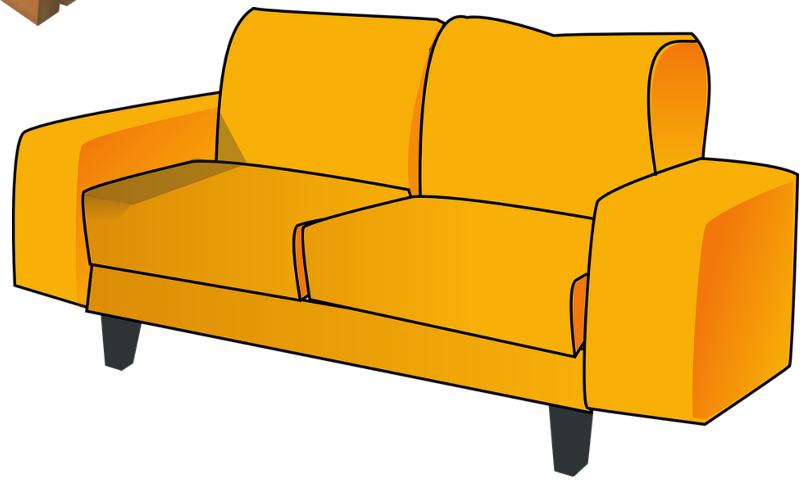
A. Persily, L. de Jonge

First published: 20 March 2017 | https://doi.org/10.1111/ina.12383 | Citations: 90



Are we measuring Indoor Air Quality?





$CO_2 \neq$ IAQ

Consumer Grade CO_2 Monitors

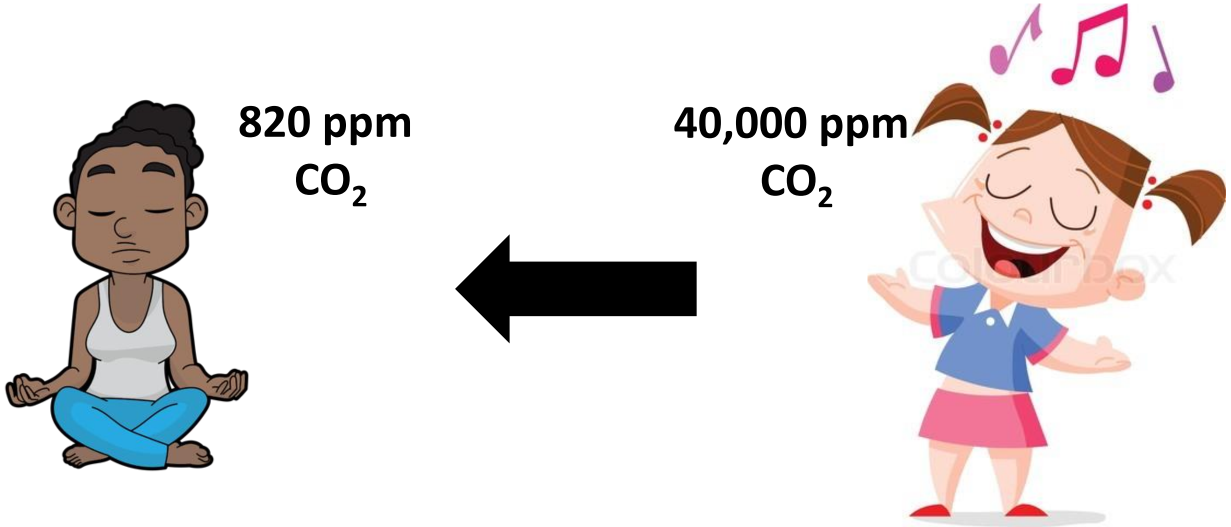
- Non-Dispersive Infrared (NDIR) monitors are calibrated to other chemicals (not CO_2), accuracy is questionable
- NDIR monitors accurate to 50 ppm or ± 2% of reading
  - A reading of 900 ppm_v could be 850 ppm_v or 950 ppm_v
  - Response is typically linear
- Auto-calibrating algorithms used by CO_2 monitors
  - Must be exposed to air without CO_2 source once a week for ~6 hours

No Other CO_2 Sources

What can we do with CO_2 readings from a classroom?

- Relative risk
  - **Rebreathed Fraction**
- Ventilation Assessment
  - Maximum Daily Concentration
  - Air Change Rate

Rebreathed Fraction



INDOOR AIR
International Journal of Indoor Environment and Health

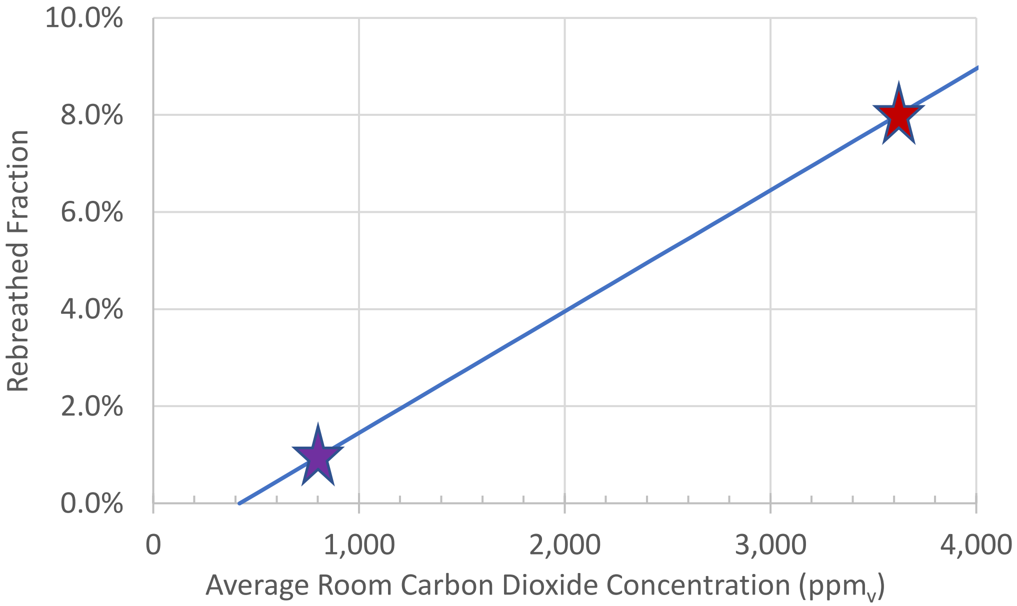
Full Access

Risk of indoor airborne infection transmission estimated from carbon dioxide concentration

S. N. Rudnick, D. K. Milton

First published: 24 October 2003 | https://doi.org/10.1034/j.1600-0668.2003.00189.x | Citations: 143

$$Rebreathed\ Fraction = \frac{(C_{average\ indoor} - C_{outside})}{C_{breath}}$$



Consumer-grade sensors report concentrations in ppm_v. SI units are $\mu g\ m^{-3}$. 1000 ppm_v CO_2 = 929 μg CO_2 m^{-3} at 25 °C and 1 atm.

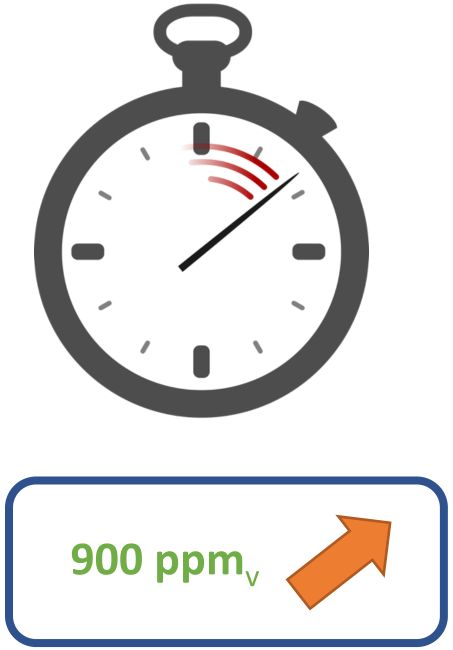
What can we do with CO_2 readings from a classroom?

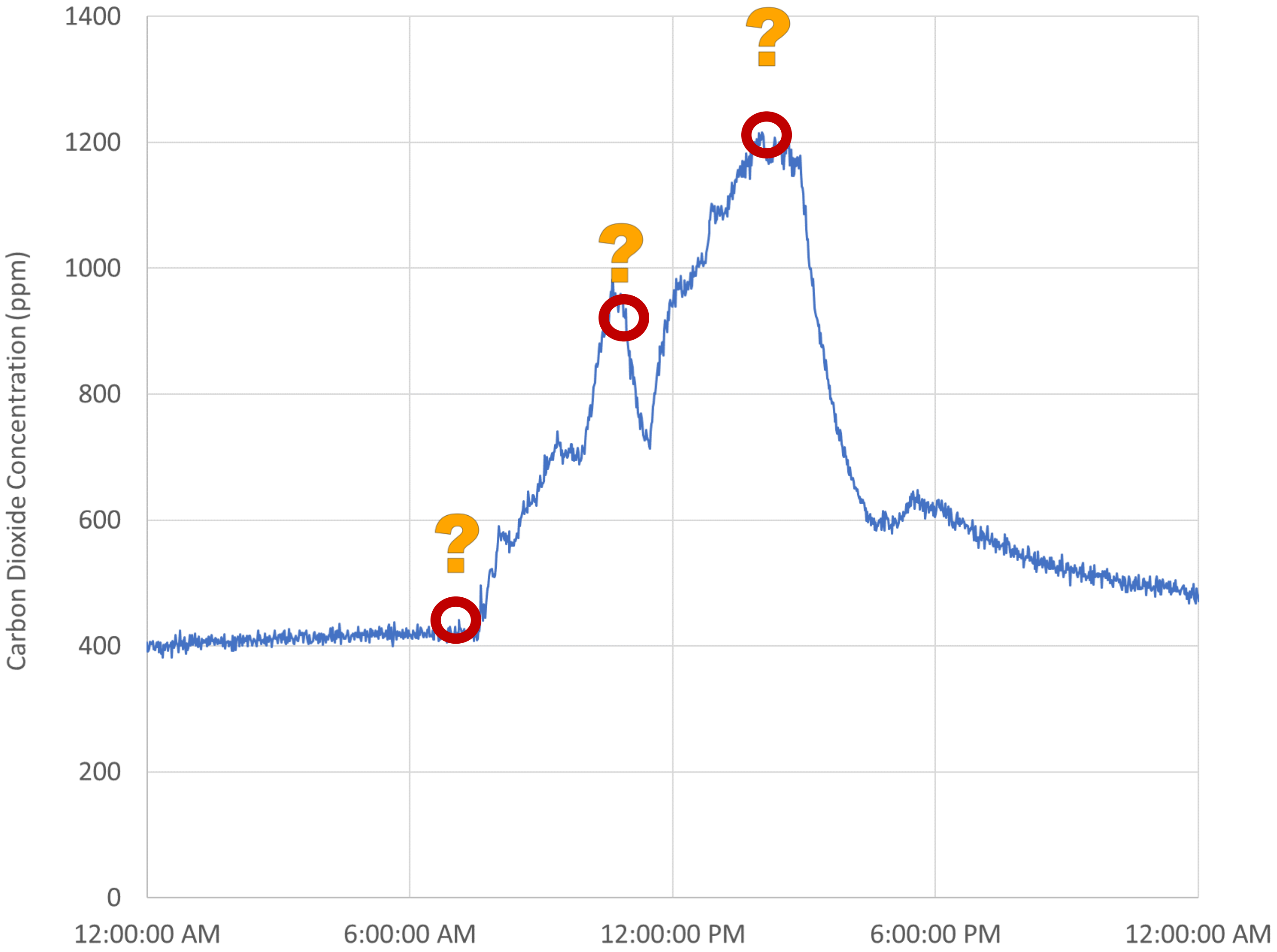
- Relative risk
  - Rebreathed Fraction
- Ventilation Assessment
  - **Maximum Daily Concentration**
    - **Normal OCCUPANCY!**
  - Air Change Rate
    - Unoccupied!

Daily CO_2 measurements

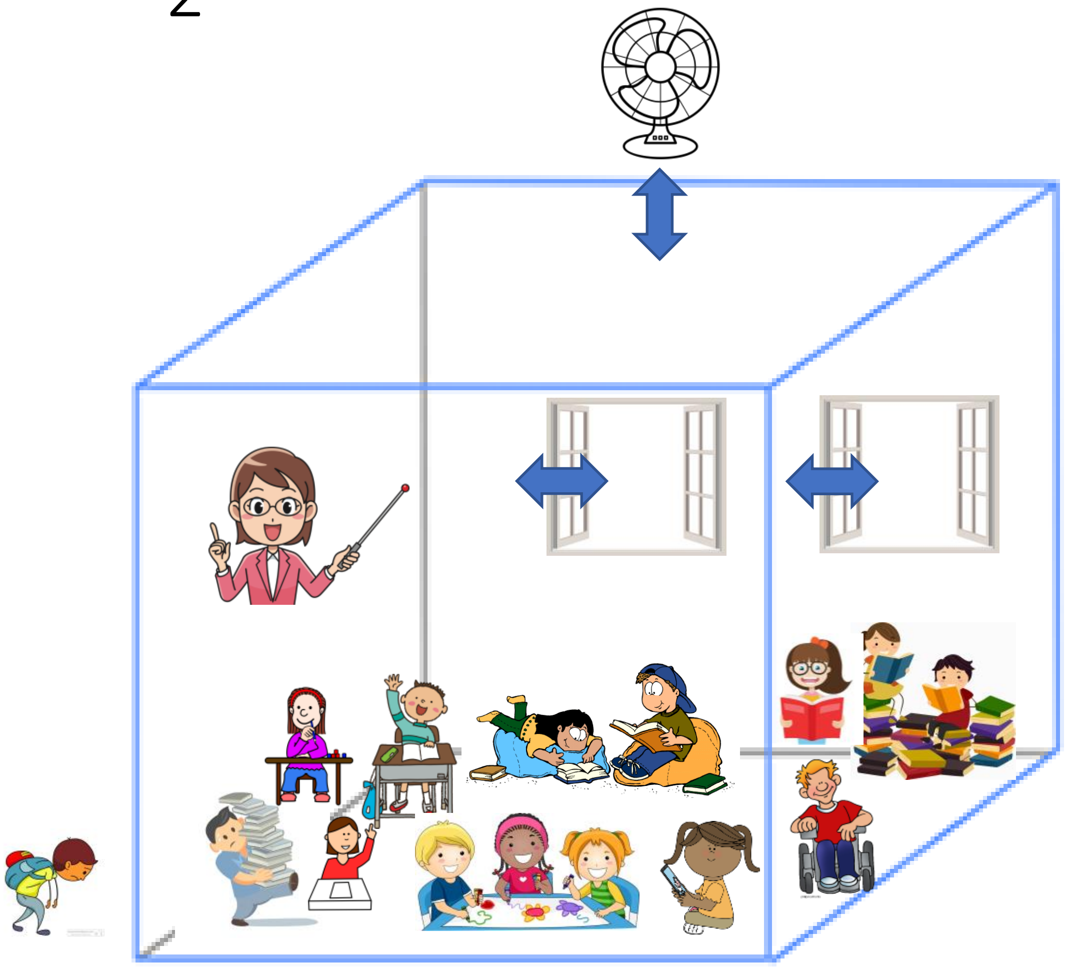
- Outside
  - Measure outside at beginning and end of day
  - Values should be 400 ppm_v to 500 ppm_v, if not use indoor-outdoor concentration difference.
- Occupied Space
  - No other CO_2 sources
  - No CO_2 removal equipment
- Location
  - Near center of room
  - No breathing on it
  - Not directly beneath ventilation vents/open windows
- Log data for full day per room
  - At minimum the last hour room is fully occupied in a day
- Measure more than one day/weather event/season

Example Classroom CO_2 Data



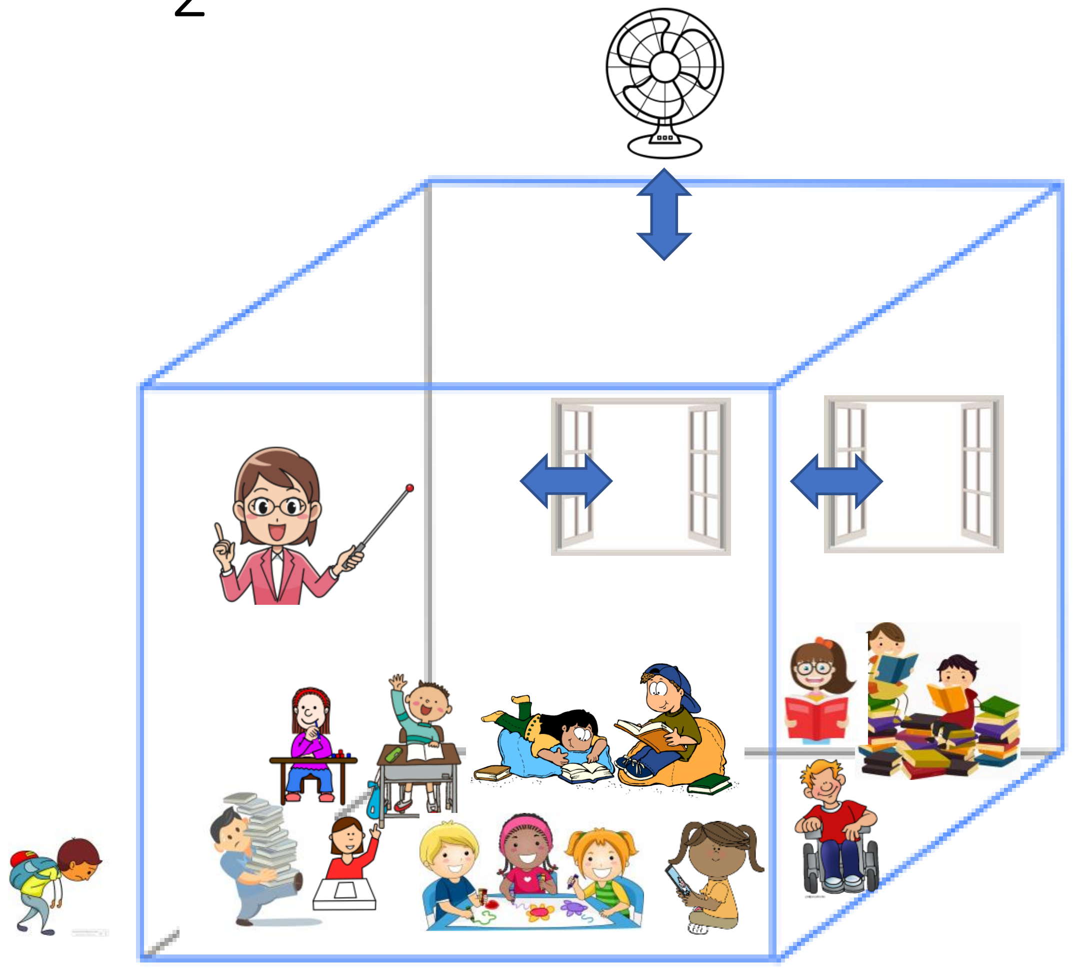


What can we do with occupied classroom CO_2 data?



- CO_2 concentration in room is a function of:
  - Size of room
  - Ventilation rate
  - Students/teachers
    - Number
    - Sex
    - Age
    - Weight
    - Activity level

What can we do with occupied classroom CO_2 data?



- Assumptions
  - Parameters assumed to be constant
    - Not always true. Reasonable approximation for elementary schools
    - High maximum daily readings can indicate problem ventilation spaces even if not constant
  - All air entering room is at outside CO_2 concentrations (not adjacent rooms)
    - True for portable classrooms
    - Not true for classrooms in buildings, which will underpredict/overpredict classroom CO_2 concentrations.

What can we do with occupied classroom CO_2 data?

Primary Ventilation per Person: 7.4 sL/s

Alternate Ventilation per Person: 5 sL/s

Initial Indoor CO2 Concentration: 420 ppm

Outdoor CO2 Concentration: 420 ppm

Ceiling Height: 3 m

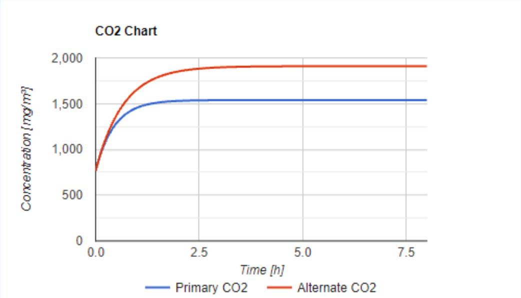
Occupant Density: 25 #/100 m²

Time to Metric: 6 h

Occupants

Number of Occupants	Sex	Mass (kg)	Age Group	Activity Level (met)
1	F	70	30 to 59	2.5
12	M	23	3 to 9	1.5
12	F	23	3 to 9	1.5

	Primary	Alternate
Time to steady state (h):	1.4	2.0
CO2 concentration at steady state (mg/m³):	1,540	1,910
CO2 concentration at time to metric (mg/m³):	1,540	1,910
CO2 concentration at 1 hour (mg/m³):	1,456	1,655



Save Report Back to Inputs

https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/

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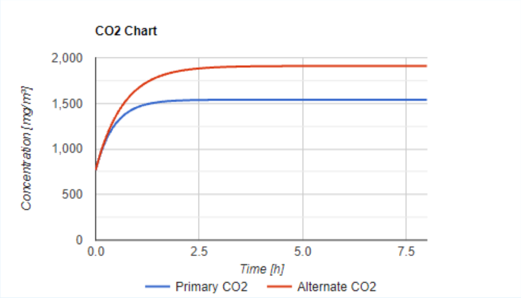

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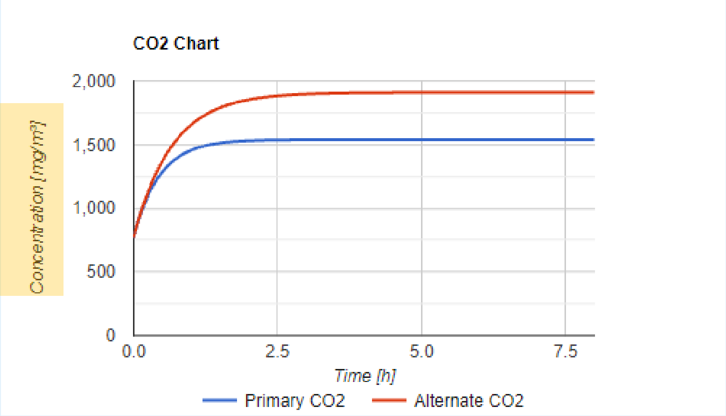
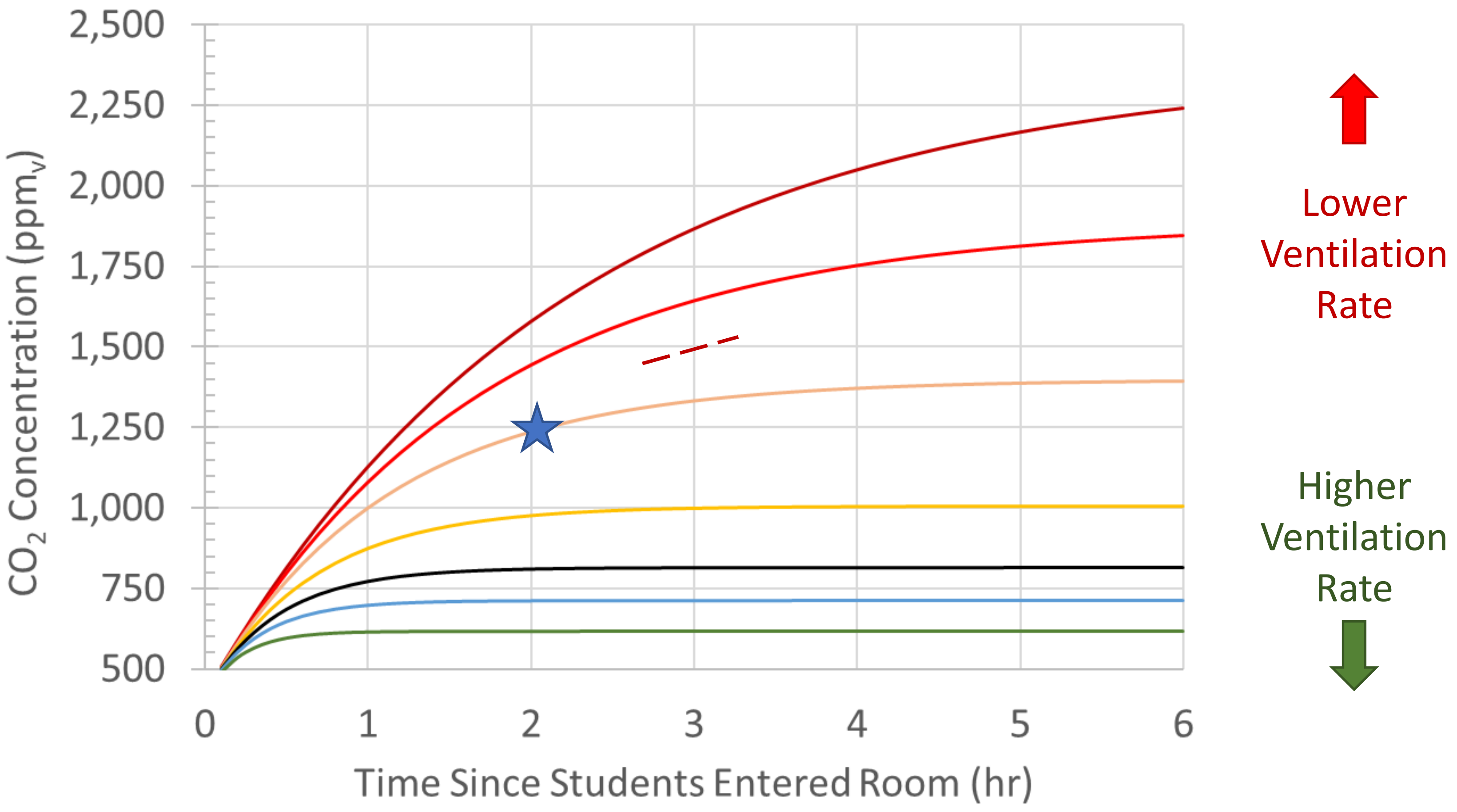


Save Report Back to Inputs

For CO_2 at 25 °C and 1 atm:
1 mg m^{-3} = 0.53 ppm_v

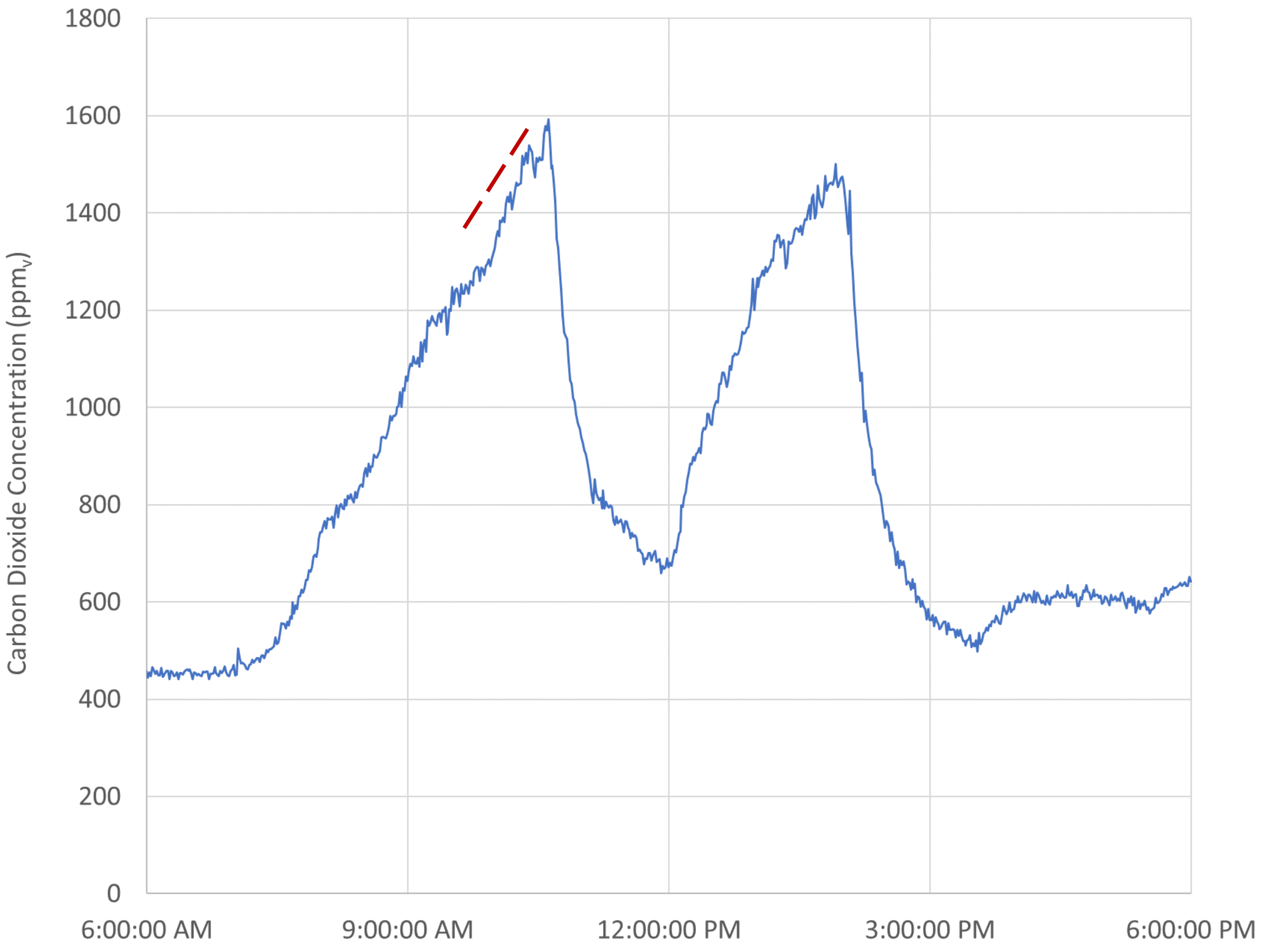
https://pages.nist.gov/CONTAM-apps/webapps/CO2Tool/#/

What can we do with occupied classroom CO_2 data?



*1-70kg Teacher @ 2.5 met, 24-23 kg Students @ 1.5 met

What can we do with occupied classroom CO_2 data?



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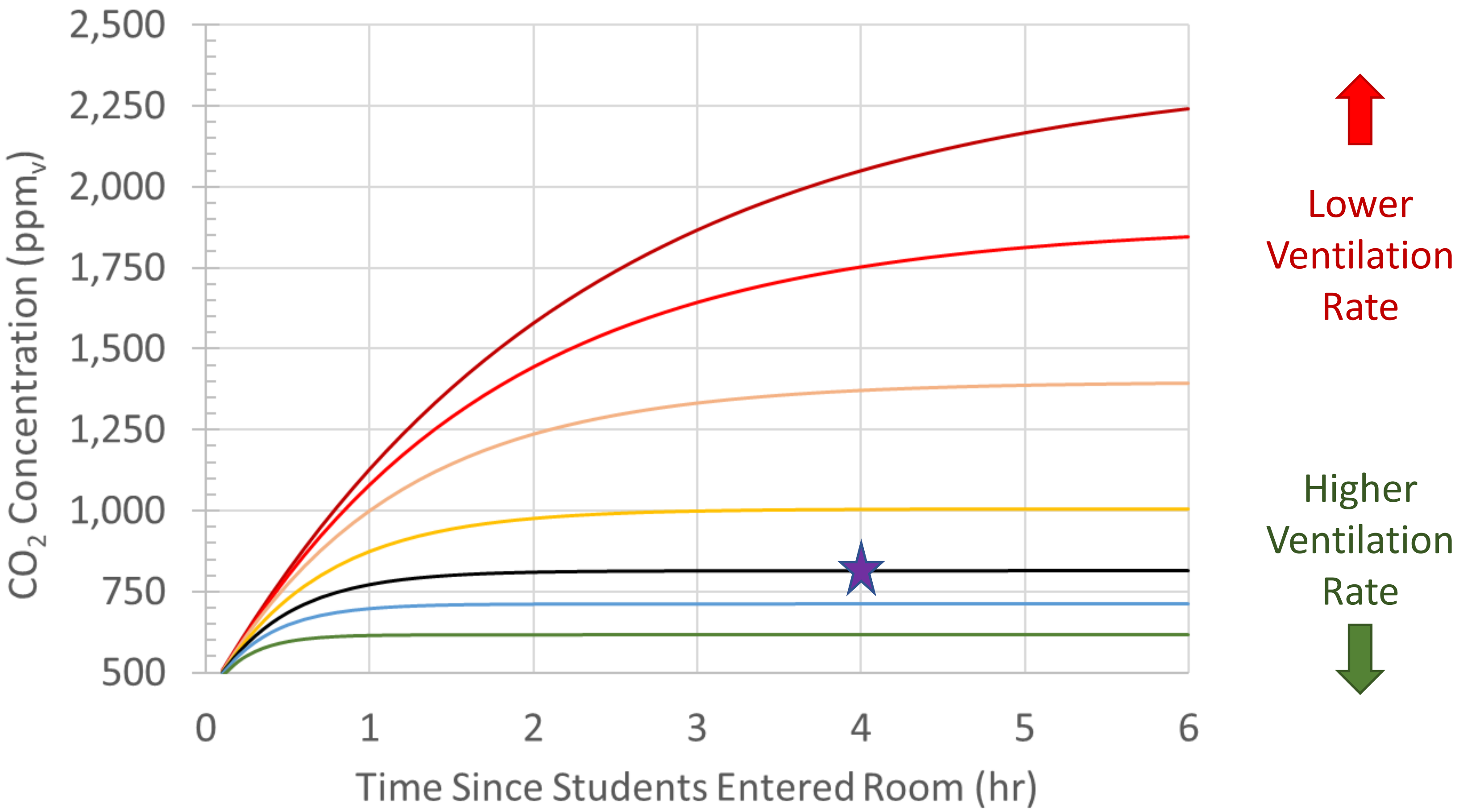

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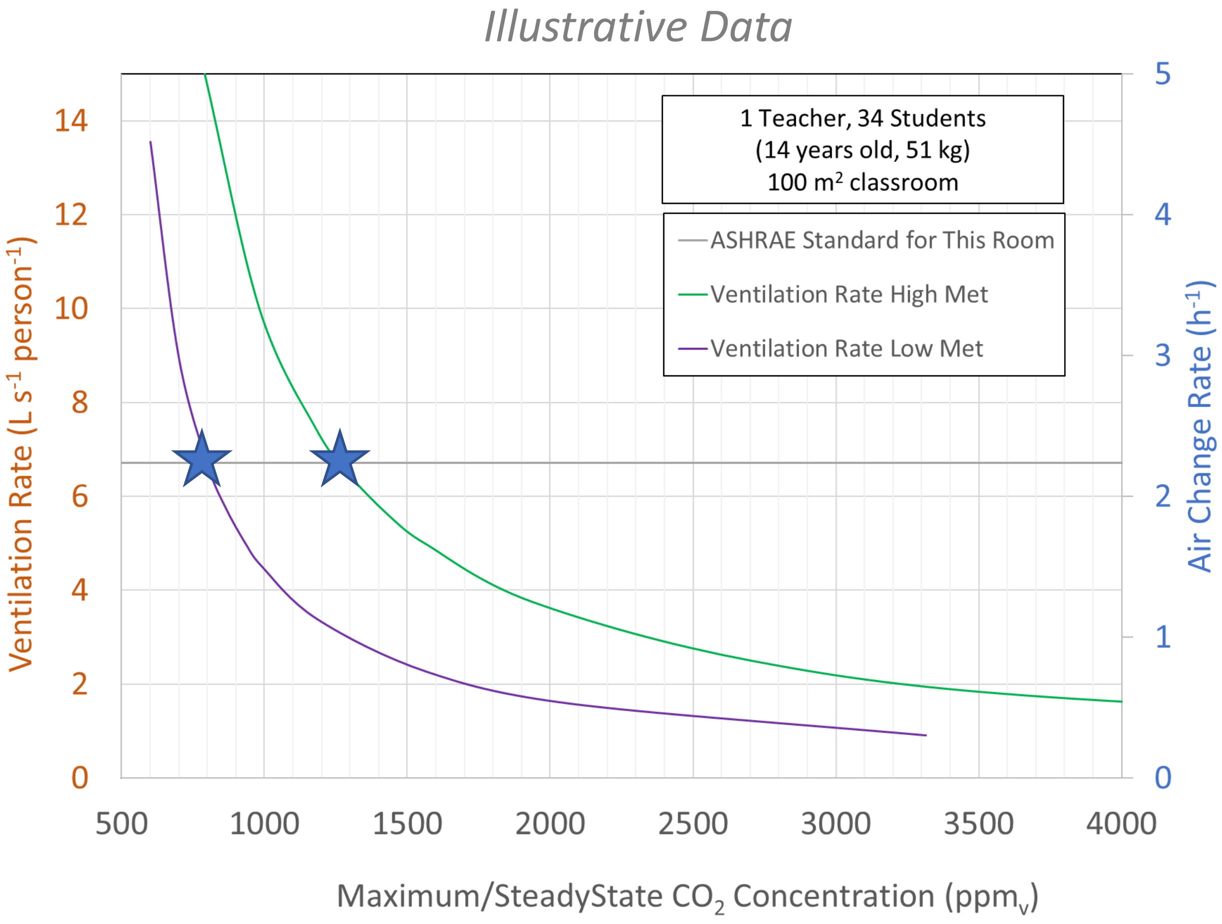
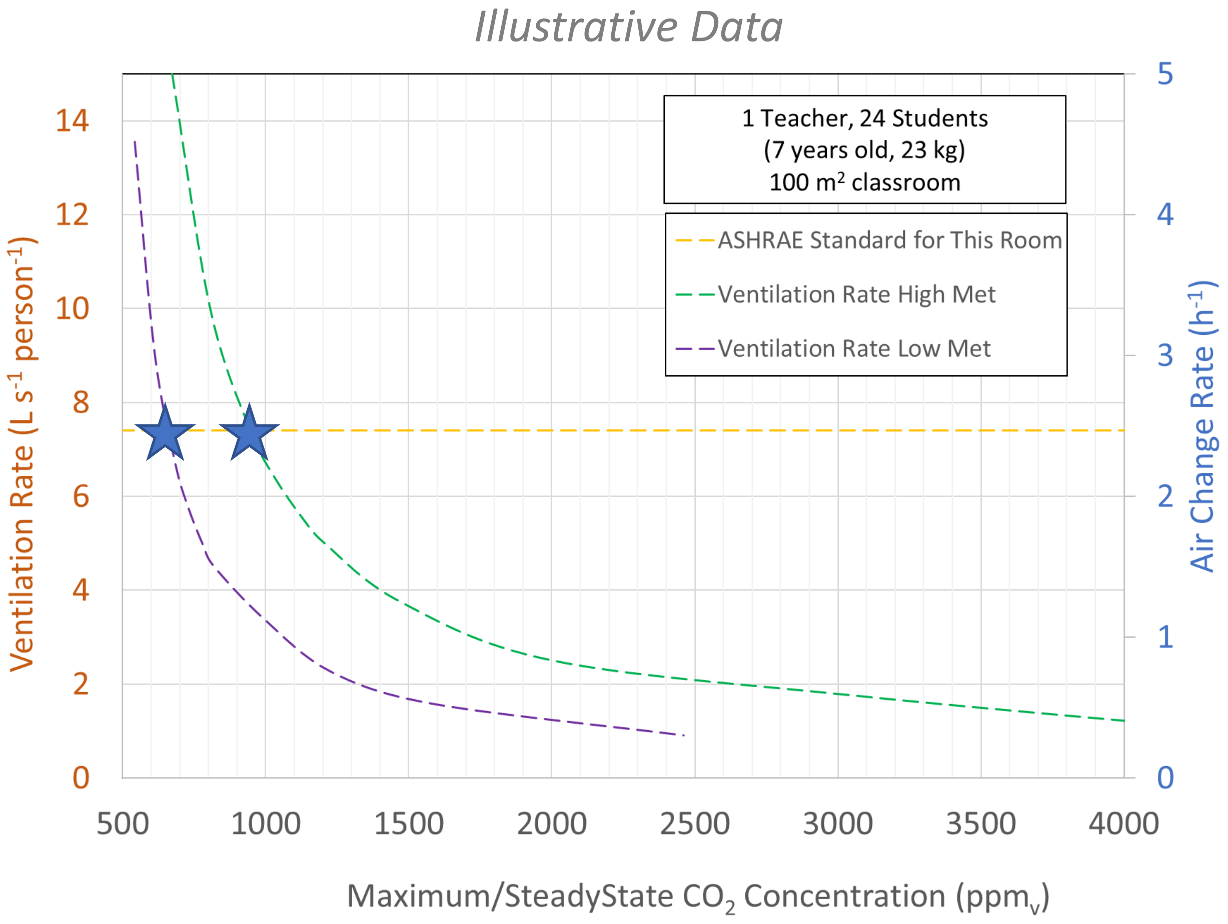


*High = Teacher @ 3 met, Students @ 2 met
Low = Teacher @ 2 met, Students @ 1 met

What can we do with occupied classroom CO_2 data?



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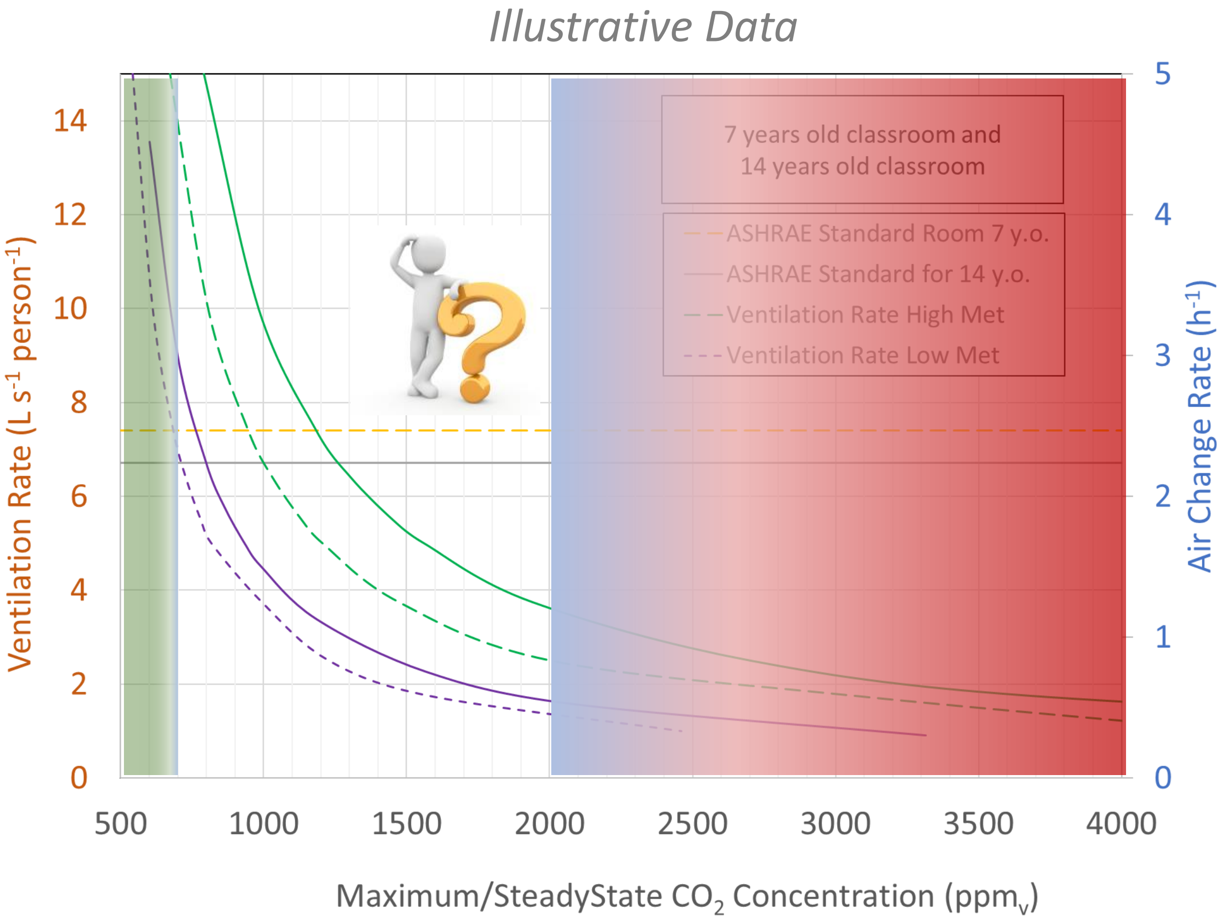


*High = Teacher 3 met, Students 2 met
Low = Teacher 2 met, Students 1 met

CO_2 under Normal Ventilation

Space	Occupancy	Ventilation Rate (L/s/person)	Outdoor Air Change Rate (h^{-1})	Steady State or Mean Peak CO_2 Concentration ppm_v	Reference
Idealized Classroom Meeting ASHRAE Standards (5- to 8-year-olds)	24 students 1 instructor	7.4	~2.6[a]	**970[b]**	INDOOR AIR 2020 The 16th Conference of the International Society of Indoor Air Quality & Climate ONLINE | From November 1, 2020 Paper ID ABS-0446 **Development and Application of an Indoor Carbon Dioxide Metric** Andrew Persily*, Brian Polidoro National Institute of Standards and Technology, Gaithersburg, USA
Idealized Classroom Meeting ASHRAE Standards (>9 year-olds)	34 students 1 instructor	6.7	N/A	**1320[b]**	INDOOR AIR 2020 The 16th Conference of the International Society of Indoor Air Quality & Climate ONLINE | From November 1, 2020 Paper ID ABS-0446 **Development and Application of an Indoor Carbon Dioxide Metric** Andrew Persily*, Brian Polidoro National Institute of Standards and Technology, Gaithersburg, USA
10 Actual California Classrooms	N/A	2.6 – 7.1	N/A	1,140 - 2,380	INDOOR AIR International Journal of Indoor Environment and Health Original Article | Free Access Association of classroom ventilation with reduced illness absence: a prospective study in California elementary schools M. J. Mendell, E. A. Eliseeva, M. M. Davies, M. Spears, A. Lobscheid, W. J. Fisk, M. G. Apte First published: 19 March 2013 | https://doi.org/10.1111/ina.12042 | Citations: 99

Consumer-grade sensors report concentrations in ppm_v. SI units are $\mu g\ m^{-3}$. 1000 ppm_v CO_2 = 929 μg CO_2 m^{-3} at 25 °C and 1 atm.

[a]Classroom volume values from Ng et. al. 2020 https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=930986

[b]Assuming outdoors 420 ppm_v

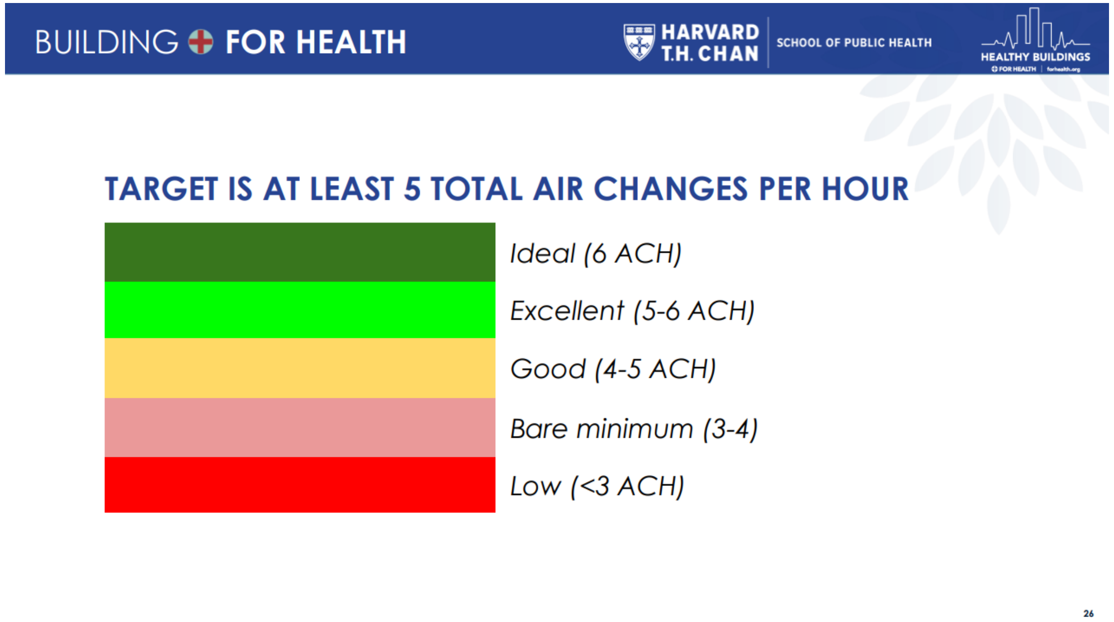
Pandemic Ventilation Guidelines

Ventilation

It is of utmost importance that building ventilation is managed in accordance with the recommendations. As the virus is spread through aerosols, ventilation plays a crucial role in reducing the infection risk. It allows for indoor air renewal of classrooms and reduces the presence of these aerosols, which may be contaminated with COVID-19 by an infected person present in the room.

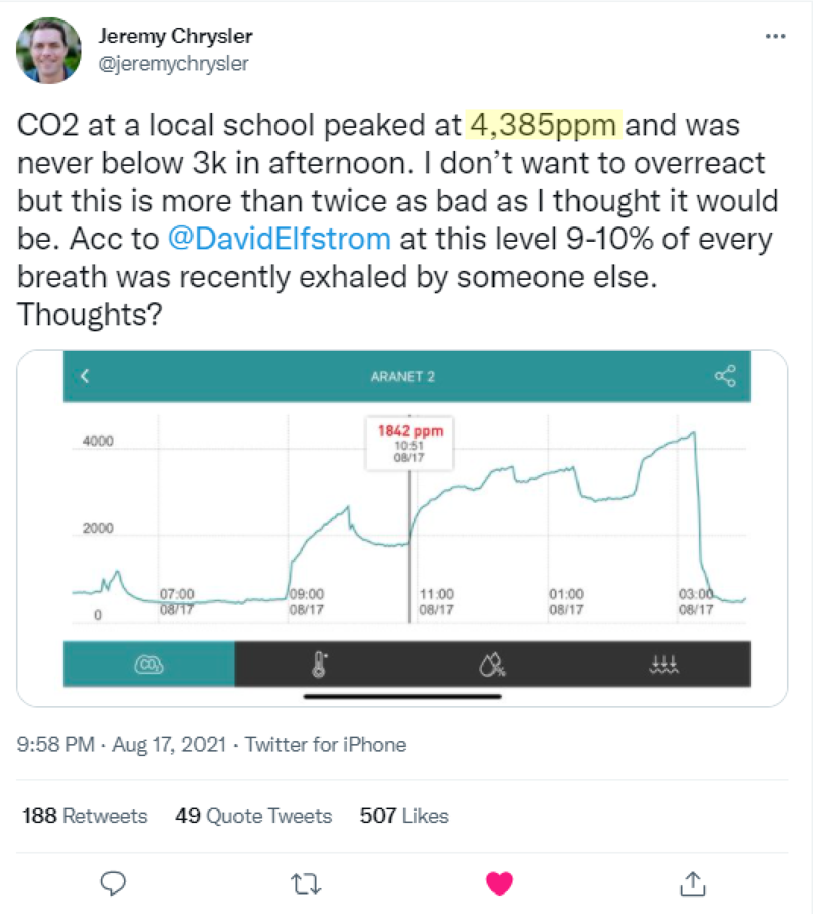
The CO_2 content of the air should, ideally, not exceed **900 ppm** and under no circumstances should it exceed the standard of **1200 ppm**. To achieve this objective, key actions must be taken. These actions are described in the document "Practical recommendations for monitoring ventilation and air quality in COVID-19" prepared by the Ventilation Task Force of the COVID-19 Commissariat.

https://www.info-coronavirus.be/en/ventilation/



https://schools.forhealth.org/wp-content/uploads/sites/19/2020/08/Harvard-Healthy-Buildings-program-How-to-assess-classroom-ventilation-08-28-2020.pdf

We found a poorly ventilated classroom, now what?



https://twitter.com/jeremychrysler/status/1427812197657366535

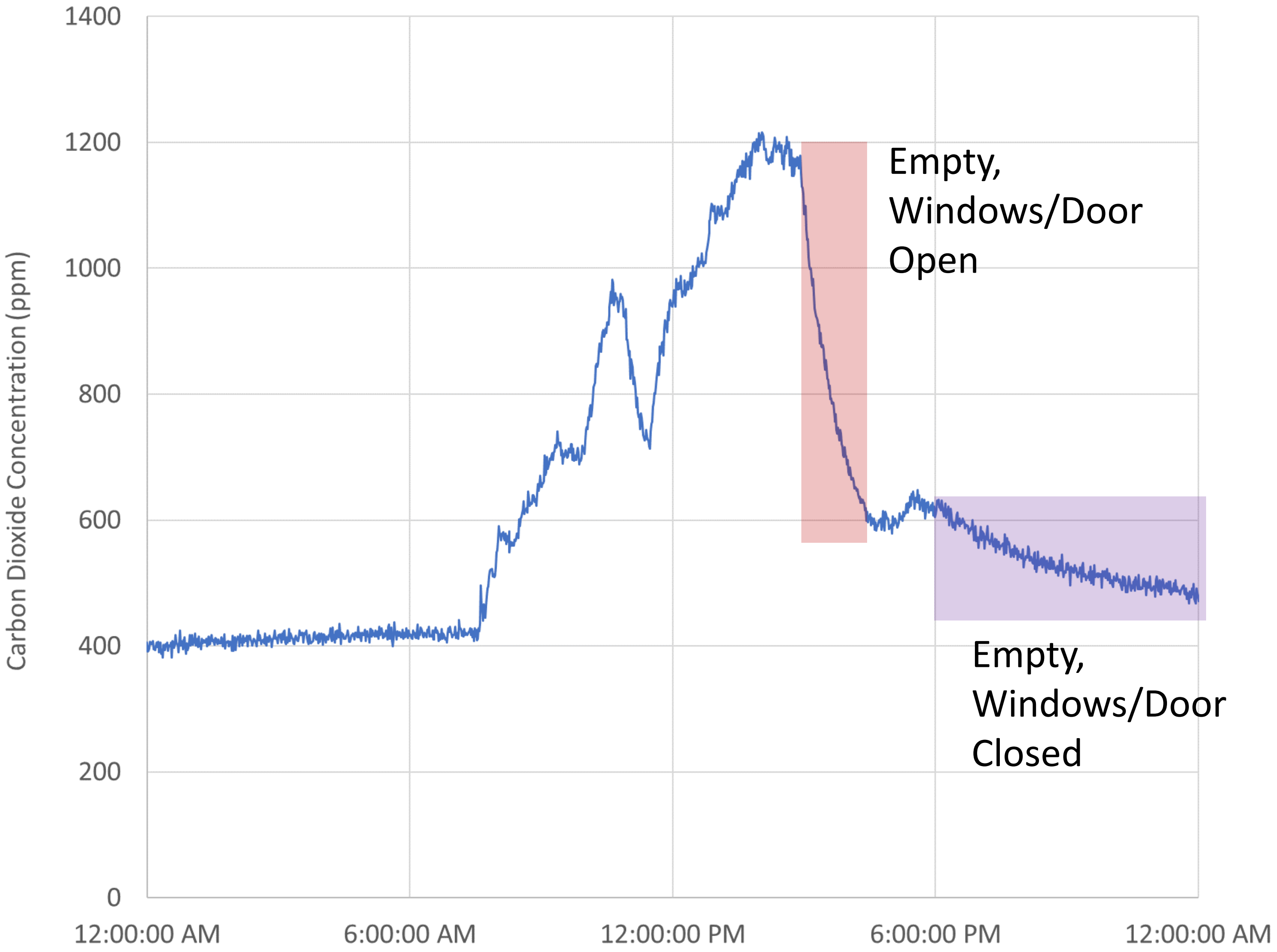
- Check Equipment:
  - Faulty damper, fan, sensor
- Check Room Use:
  - Room is not being used as designed (e.g. 35 students instead of 20)
- Search:
  - Other CO_2 sources?

What can we do with CO_2 readings from a classroom?

- Relative risk
  - Rebreathed Fraction
- Ventilation Assessment
  - Maximum Daily Concentration
    - Normal OCCUPANCY!
  - **Air Change Rate Estimate**
    - **Unoccupied!**

Example Classroom CO_2 Data

1200 ppm_v



Fun Math & Curve Fit =>
CO_2 Decay Rate = **ESTIMATED** Air Change Rate

$$\frac{\partial C}{\partial t} = \lambda C_o - \lambda C + \frac{E}{V}$$

U Substitution

$$\frac{\partial C}{\lambda C_o - \lambda C + \frac{E}{V}} = \partial t \qquad u = -\lambda C_o + \lambda C - \frac{E}{V}$$

$$\int \frac{\partial u}{\lambda(-u)} = \int \partial t \Rightarrow \int \frac{\partial u}{u} = -\lambda \int \partial t \qquad \partial u = \lambda \partial C$$

$$\ln(u) = -\lambda t \qquad \frac{\partial u}{\lambda} = \partial C$$

$$\ln\left(\lambda C - \lambda C_o - \frac{E}{V}\right)\Big|_{C_{t=0}}^{C} = -\lambda t\Big|_0^t$$

$$\ln\left(\frac{\lambda C - \lambda C_o - \frac{E}{V}}{\lambda C_{t=0} - \lambda C_o - \frac{E}{V}}\right) = -\lambda t$$

$$\frac{\lambda C - \lambda C_o - \frac{E}{V}}{\lambda C_{t=0} - \lambda C_o - \frac{E}{V}} = e^{-\lambda t}$$

$$\lambda C - \lambda C_o - \frac{E}{V} = \left(\lambda C_{t=0} - \lambda C_o - \frac{E}{V}\right) e^{-\lambda t}$$

$$\lambda C = \left(\lambda C_{t=0} - \lambda C_o - \frac{E}{V}\right) e^{-\lambda t} + \lambda C_o + \frac{E}{V}$$

$$C = \left(C_{t=0} - C_o - \frac{E}{\lambda V}\right) e^{-\lambda t} + C_o + \frac{E}{\lambda V}$$

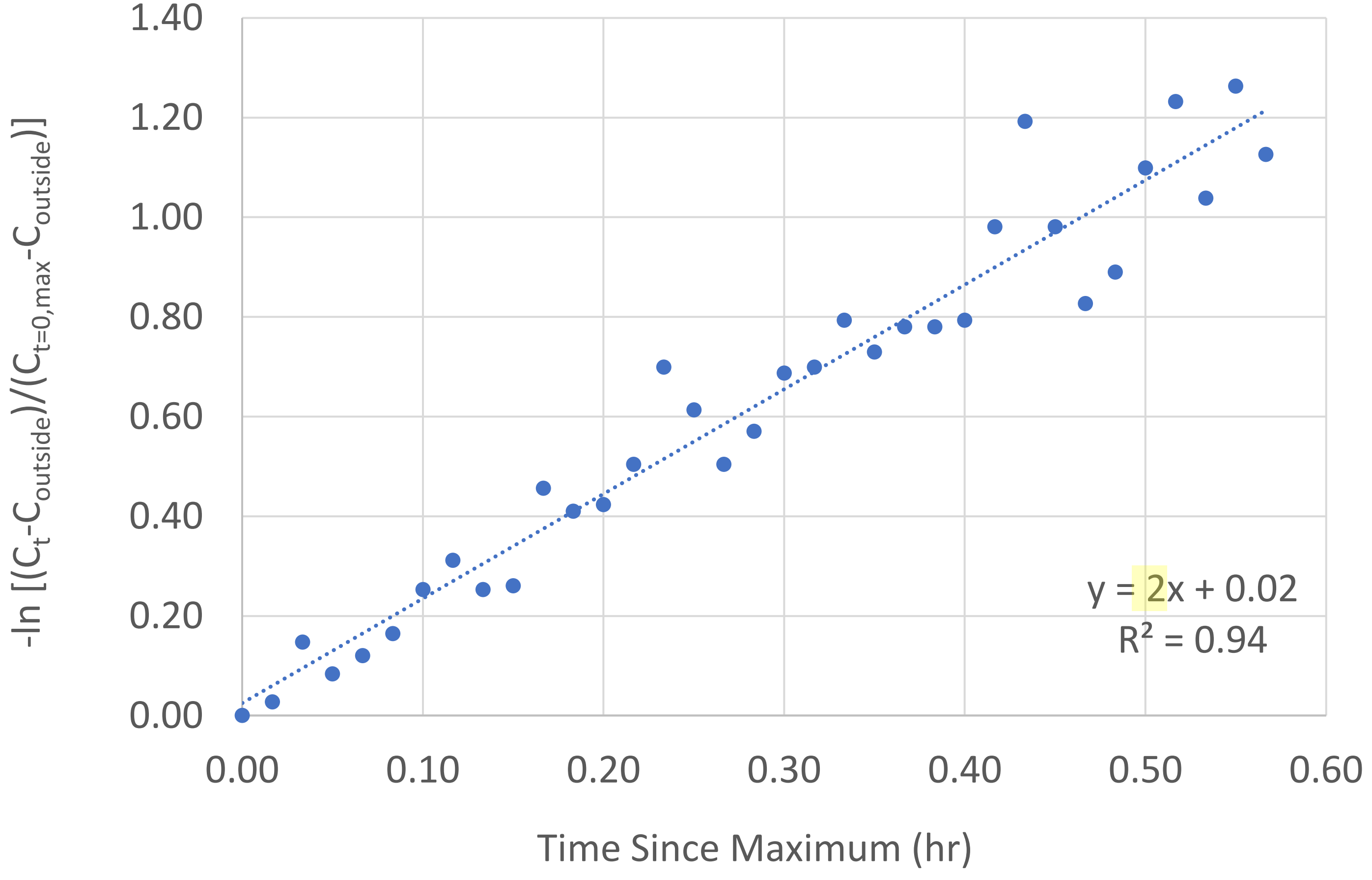
$$C = C_{t=0} e^{-\lambda t} + \left(-C_o - \frac{E}{\lambda V}\right) e^{-\lambda t} + C_o + \frac{E}{\lambda V}$$

$$C = C_{t=0} e^{-\lambda t} + \left(C_o - C_o e^{-\lambda t} + \frac{E}{\lambda V} - \frac{E}{\lambda V} e^{-\lambda t}\right)$$

$$C = C_{t=0} e^{-\lambda t} + C_o\left(1 - e^{-\lambda t}\right) + \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right)$$

$$C = C_{t=0} e^{-\lambda t} + \left(C_o + \frac{E}{\lambda V}\right)\left(1 - e^{-\lambda t}\right)$$

$$-Ln\left[\frac{(C_t - C_{outside})}{(C_{t=0,max} - C_{outside})}\right] \text{ vs. t}$$



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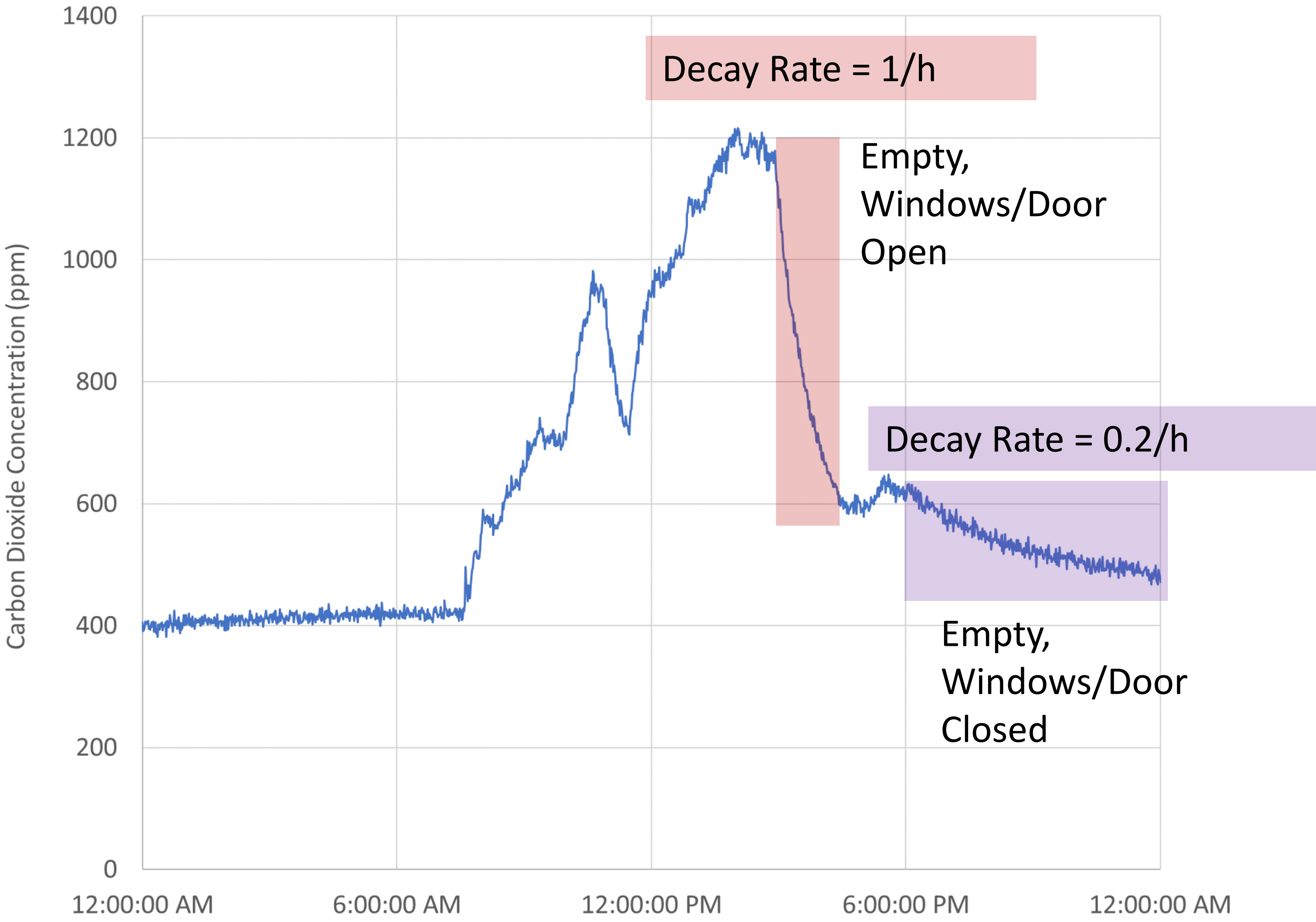
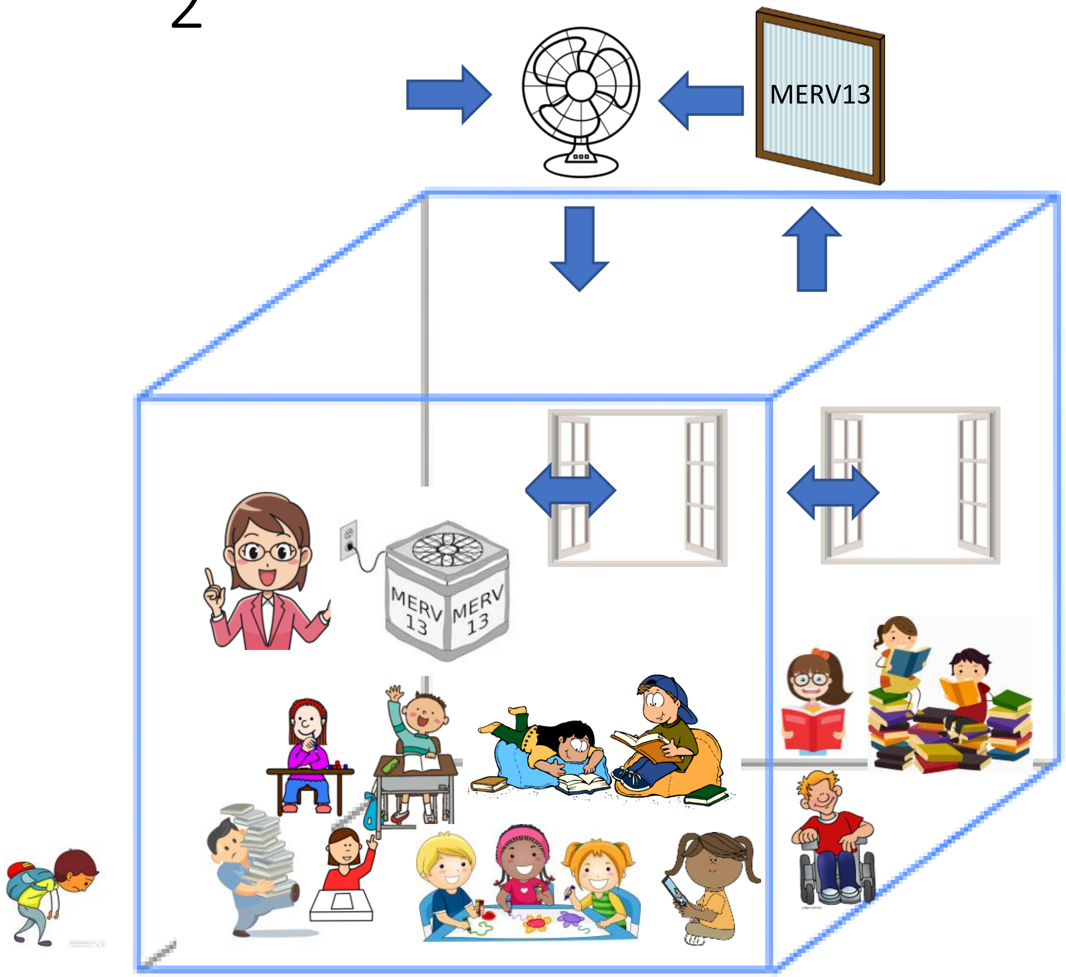
$$C = C_{t=0}e^{-\lambda t} + \left(C_o + \frac{E}{\lambda V}\right)\left(1 - e^{-\lambda t}\right)$$

- The curve fit will introduce uncertainty.
- Air change rates can change by up to a factor of 2-10 depending on the weather and building operation
- CO_2 decay rates assumes all air entering the space comes from outside, rather than hallways/other classrooms.
- This method assumes the entire building has a uniform concentration and all sources are out of the building during the decay phase. This is likely not true in schools/classrooms.
- Some systems may change ventilation when they sense the occupant thermal load has left the room
- High air change rates do not guarantee healthy indoor air

Example Classroom CO_2 Data



What can we do with occupied classroom CO_2 data?



- Effective particle decay rate in classroom (1/h)
- Sometimes called:
  - Effective air change rate (eACH) for particles

Ventilation

+ Portable Air Filtration

+ HVAC Filtration

---

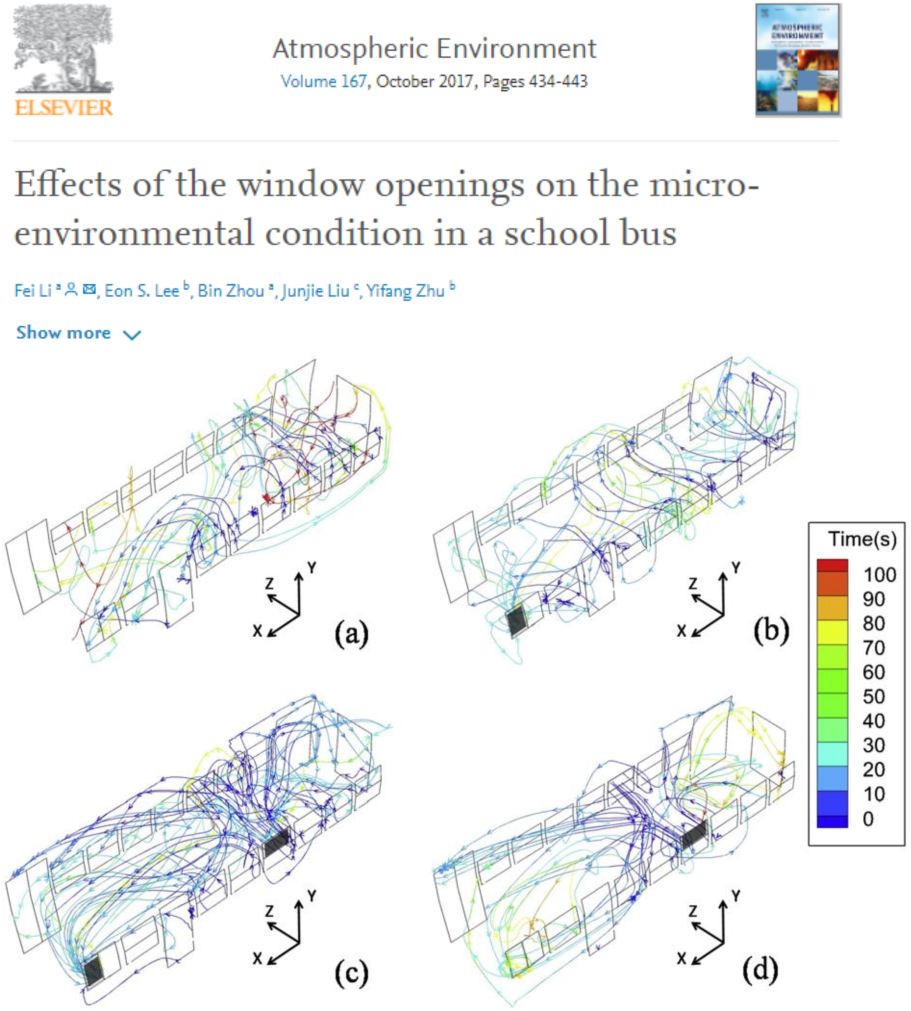
eACH

What can we do with occupied classroom CO_2 data?

- Effective particle decay rate in classroom (1/h)
- Sometimes called:
  - Effective air change rate (eACH) for particles

Ventilation	$a\left(\frac{(L)}{(S)(Person)}\right)\left(\frac{1}{Volume\ (m^3)}\right)(\#People)\left(\frac{m^3}{1000L}\right)\left(\frac{3600s}{h}\right) = x\frac{1}{h}$
+ Portable Air Filtration	$b\left(\frac{(CADR)ft^3}{min}\right)\left(\frac{1}{Volume\ (ft^3)}\right)\left(\frac{60\ min}{h}\right) = \mathrm{y}\frac{1}{h}$
+ HVAC Filtration	$c\left(\frac{ft^3}{min}\right)\left(\frac{1}{Volume\ (ft^3)}\right)\left(\frac{60\ min}{h}\right) = \mathrm{z}\frac{1}{h}$
eACH	$= \mathrm{x}\frac{1}{h} + \mathrm{y}\frac{1}{h} + \mathrm{z}\frac{1}{h}$

Don’t forget the buses!


ELSEVIER
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Effects of the window openings on the micro-environmental condition in a school bus

Fei Li [a], Eon S. Lee [b], Bin Zhou [a], Junjie Liu [c], Yifang Zhu [b]

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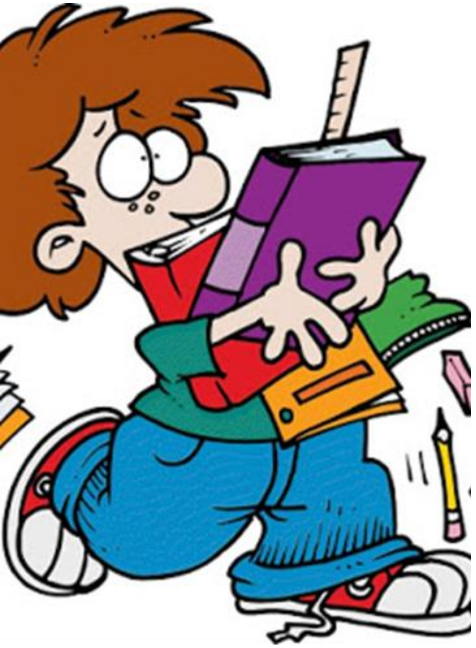
- “At minimum fully open the front two windows and the second to last two windows.”

Bottom Lines of CO_2 Concentration Measurements in Classrooms:



- Varies with
  - Occupants
  - Time and season
- Actionable data
  - High values:
    - Implement remedial actions with building operators
  - Low values:
    - Not a guarantee the space is safe
    - Continue to monitor and inspect
- Can build trust between occupants and building operators
- Ancillary benefits of higher classroom ventilation










Thank you

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