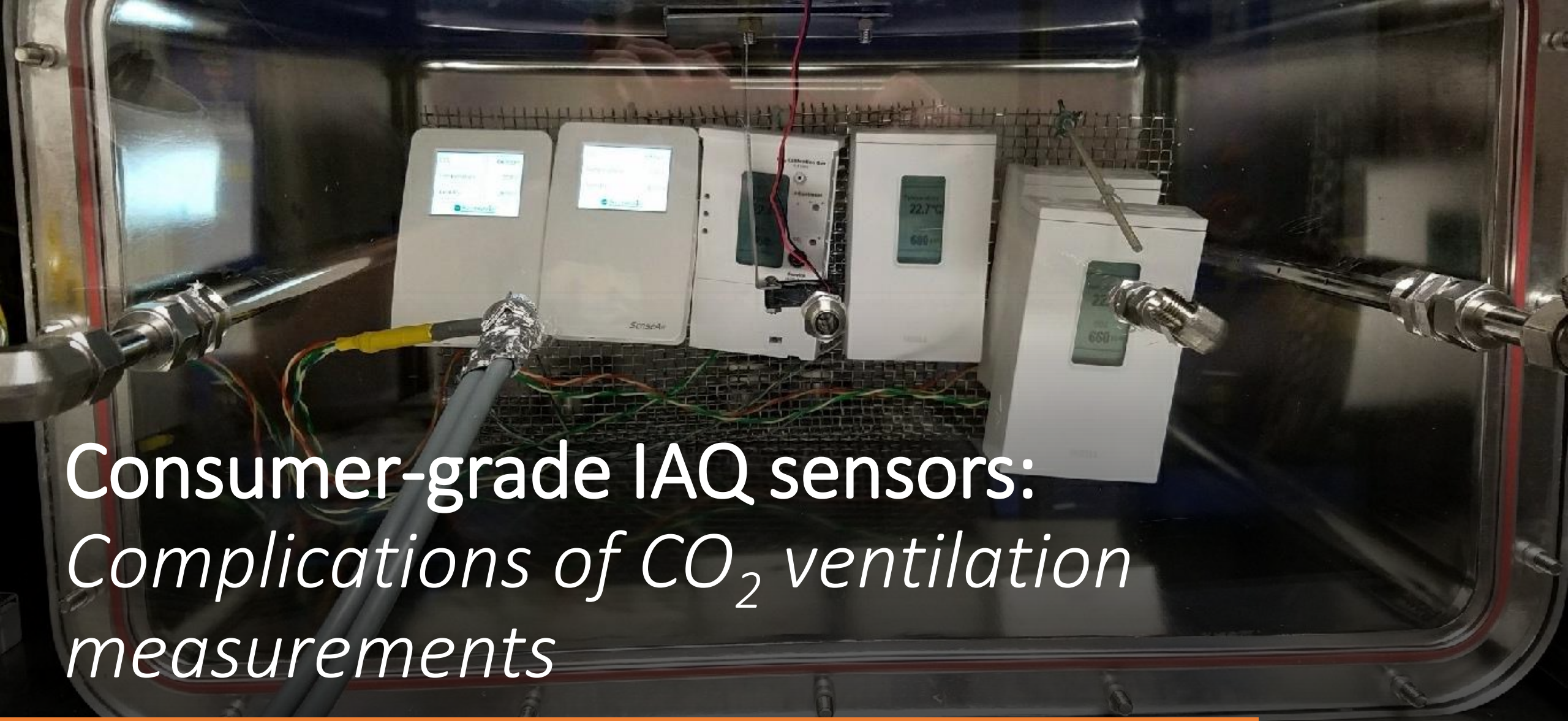


Consumer-grade IAQ sensors: *Complications of CO_2 ventilation measurements*

Dustin Poppendieck, National Institute of Standards and Technology

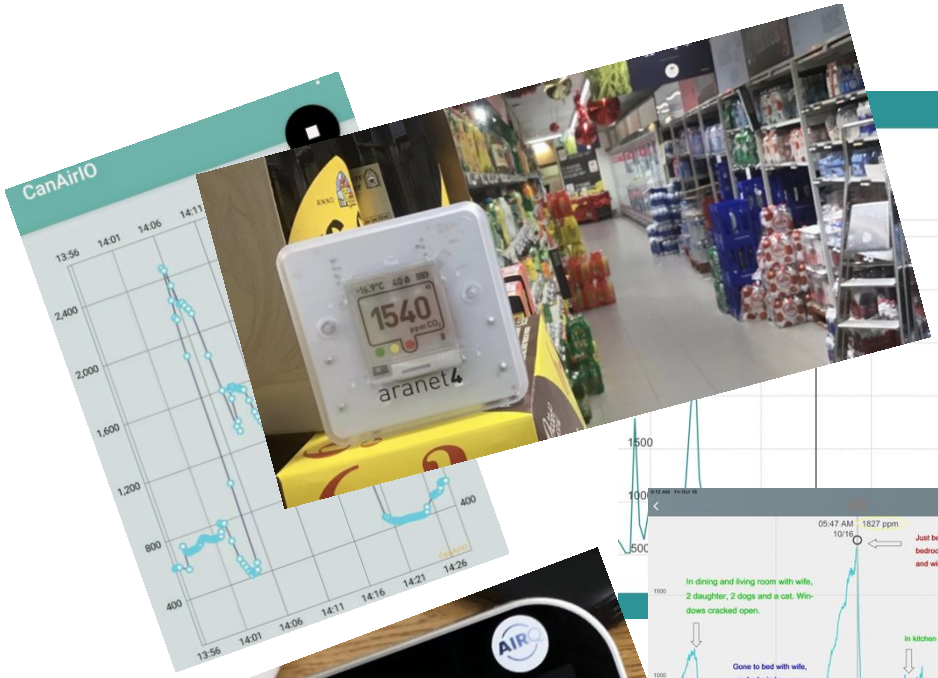
Disclaimer

- *Certain commercial equipment, instruments, websites, or materials are identified in this paper. 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 materials or equipment identified are necessarily the best available for the purpose.*

Educational Tools

- Ownership
- Action
  - Source removal
  - Ventilation
  - Filtration

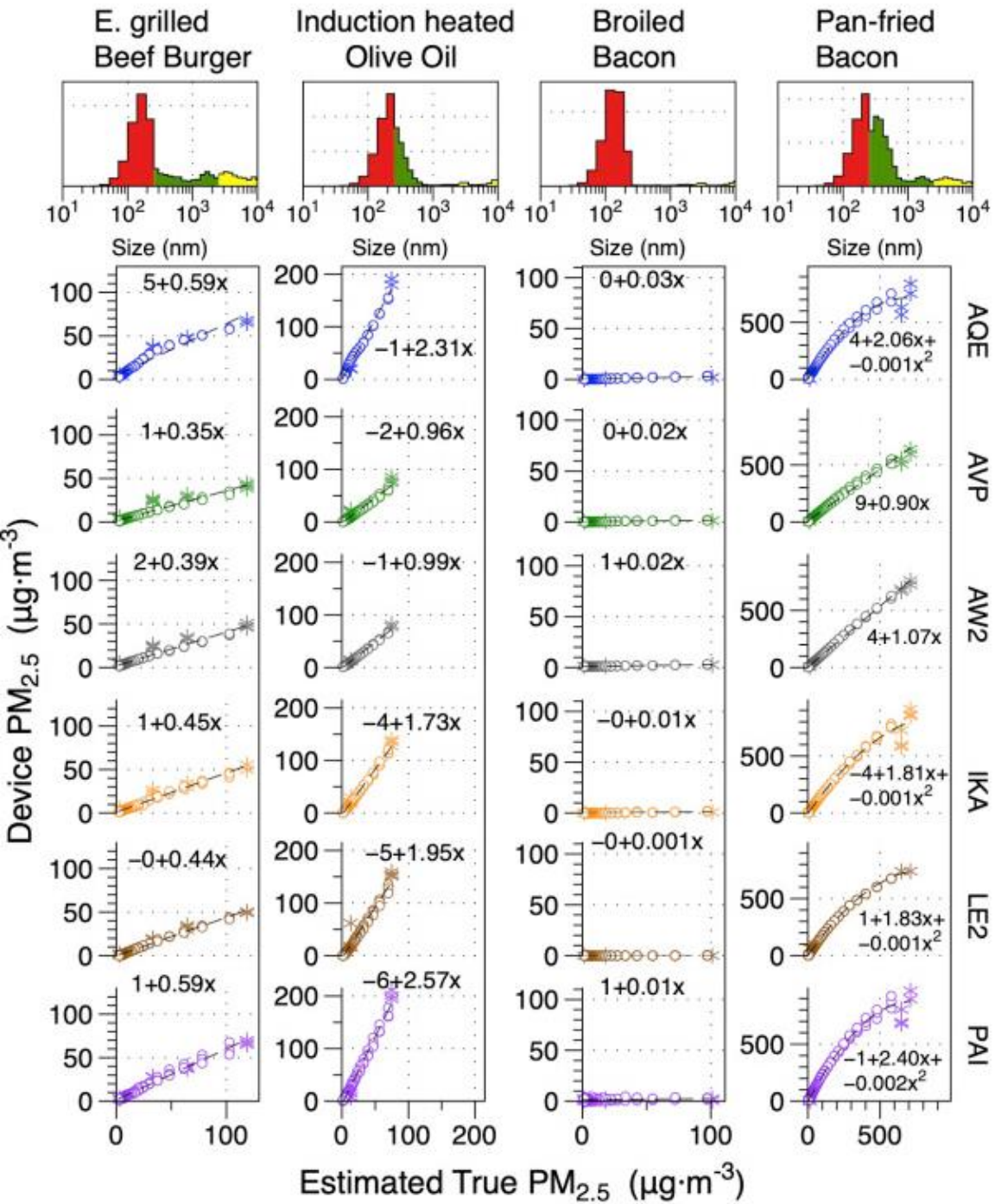
Educational Tools



https://twitter.com/search?q=CO2&src=ty
https://twitter.com/mdc_martinus/status/13[illegible]2667496632328/photo/1
https://twitter.com/corinne_depagne/status/1359530352809807874/photo/1
https://twitter.com/MsWinkel/status/1362401750766870529/photo/1
https://twitter.com/COVID_Airborne/status/1362825292461539332
https://twitter.com/maracarrion6/status/1362717214160396304/photo/1
https://twitter.com/citlanx/status/1352734920645373952/photo/1
https://twitter.com/CO2Guerrillas/status/1352731133385957378/photo/1

What does it all mean?

- Health values
  - Time Weighted/Instantaneous
- Accuracy/Precision
- Ventilation



ELSEVIER

Building and Environment

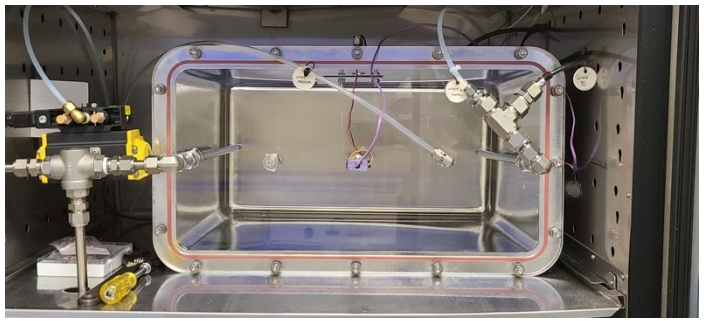
Volume 171, 15 March 2020, 106654

Performance of low-cost indoor air quality monitors for $PM_{2.5}$ and PM_{10} from residential sources

Zhiqiang Wang [a], William W. Delp [b], Brett C. Singer [b]

Test Method for Evaluating $PM_{2.5}$ Monitors

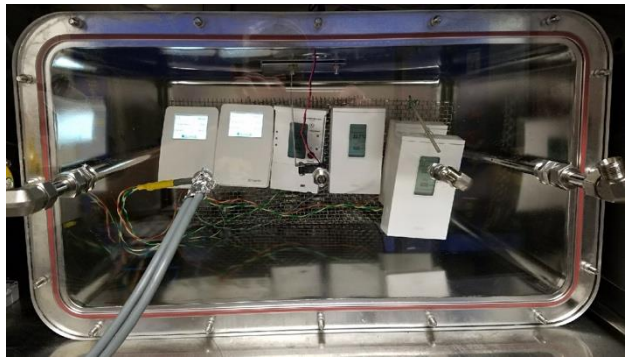
- Class III FEM Reference Monitor
  - 20 nm to 20 μm
  - Gravimetrically calibrated
- Challenge $PM_{2.5}$
  - Sodium chloride (1.5 μm to 1.8 μm)
  - Polystyrene latex spheres (1 μm)
- Chamber system
  - Steady state values



- Process
  - Five step concentration ramp
    - 10 μg m^{-3} to 300 μg m^{-3}
    - Inorganic then organic
  - RH and Temp variation
    - 40 % to 80 %
    - 20 °C and 30 °C
  - Interferent testing
    - Arizona Test Dust (PM_{10})
      - 10 μg m^{-3} to 150 μg m^{-3}
  - Temperature cycling
    - 10 °C to 50 °C 143 times
  - Repeating concentration ramp

Test Method for Evaluating CO_2 Monitors

- Reference Monitor
  - 0 ppm_v to 10,000 ppm_v
  - Calibrated to certified cylinder
  - Drying system
- Chamber system
  - Steady state values



- Process
  - Five step concentration ramp
    - 450 ppm_v to 5,000 ppm_v
  - RH and Temp variation
    - 40 % to 80 %
    - 20 °C and 50 °C
  - Interferent testing
    - Relative humidity 20 % to 90 %
  - Temperature cycling
    - 10 °C to 50 °C 143 times
  - Repeating concentration ramp

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.

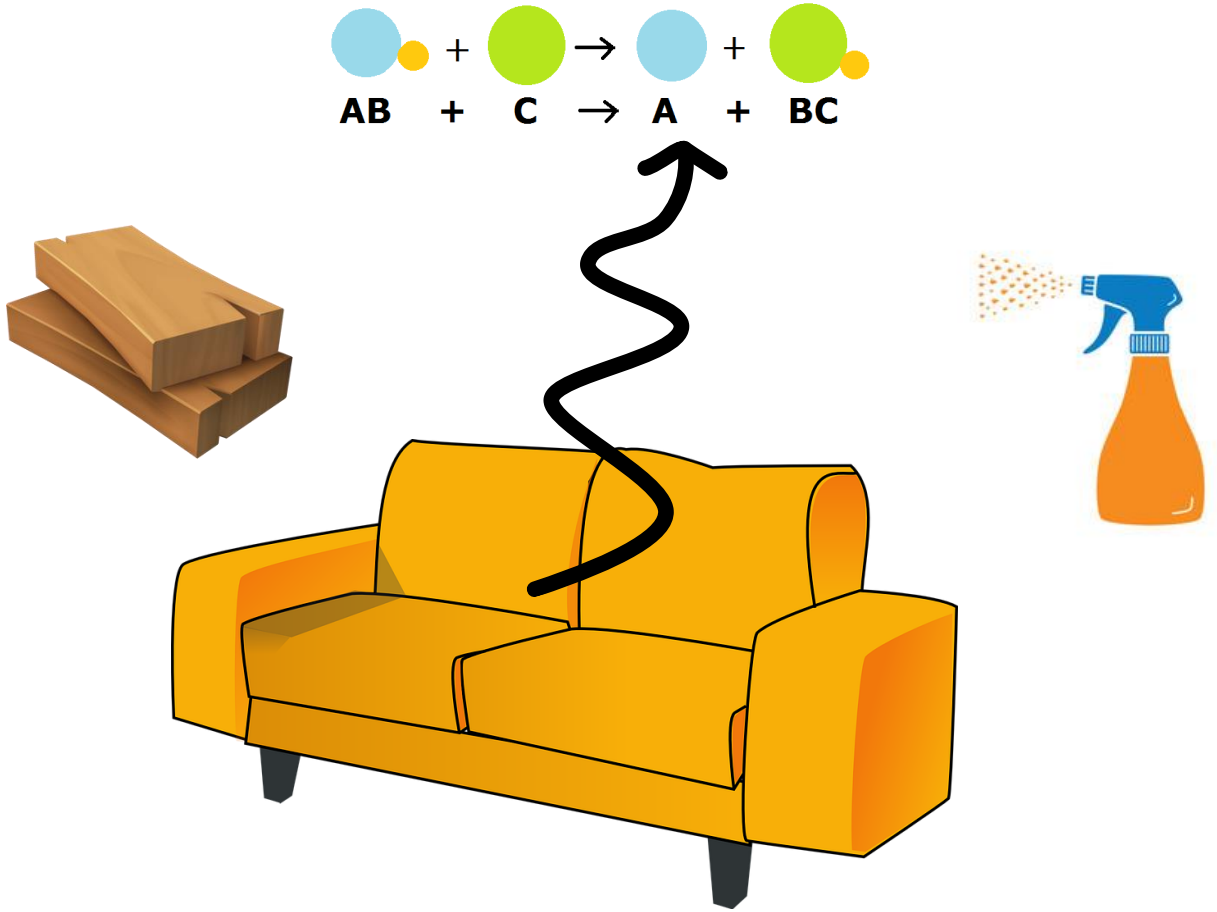
So that will be it then, right?

- Just data. Need accreditation organizations.
- Re-zeroing algorithms for CO_2
- Long term drift?
  - 1 year plus?

Using CO_2 as a Ventilation Clue

The story of 10 Complications

Using CO_2 as a Ventilation Clue



Complication #1

Using CO_2 as a Ventilation Clue

LÍMITE DE CO_2 COMO INDICADOR INDIRECTO DE RIESGO DE INFECCIÓN

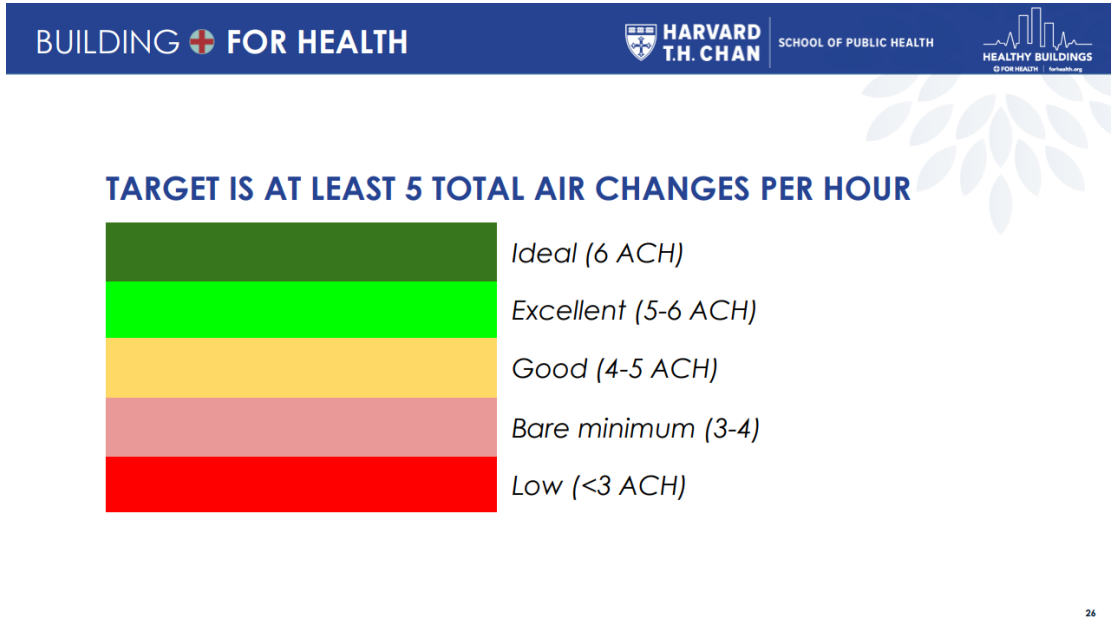
El riesgo de infección (aerosoles) es proporcional a la concentración de CO_2:

- Se evalúa mediante la **diferencia** de CO_2 entre **interior y exterior** (ΔCO_2).
- Si ΔCO_2 **>0**, ya existe **riesgo**.

NIVELES DE CO_2 ($CO_{2,ext}$ ≈ 420 ppm)	ΔCO_2 int-ext	% del aire inhalado	Si se instala filtro HEPA	
≥ 1000 ppm	600 ppm	1,47%	límite	Límite de la **OMS**
≥ 900 ppm	500 ppm	1,21%	atención	Límite del **RITE** (IDA 2)
≥ 800 ppm	400 ppm	0,96%	admisible	-
≥ 700 ppm	300 ppm	0,71%	adecuado	-
< 700 ppm	300 ppm	0,71%	adecuado	*Harvard/Guías IDAEA-CSIC-LIFTEC*
< 550 ppm	150 ppm	0,33%	adecuado	Pasillos y ZZCC (espacios "aliviadero")

@MA_Campano

https://drive.google.com/file/d/1jFavucO98vMz5_LpKtnDXBfDZvWlMLcL/view



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

Using CO_2 as a Ventilation Clue

800 ppm CO_2

38,000 ppm CO_2

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

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

$$Rebreathed\ Fraction = \frac{(800\ ppm_v - 420\ ppm_v)}{38{,}000\ ppm_v}$$

$$Rebreathed\ Fraction = 1.0\ \%$$

$$C_{average} = 2{,}000\ ppm_v => 4.2\%$$

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.

Using CO_2 as a Ventilation Clue

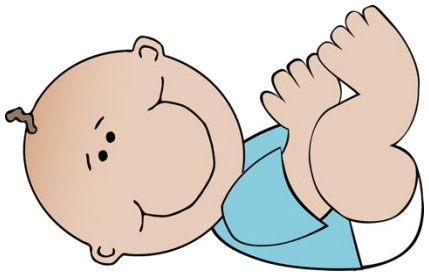
INDOOR AIR
International Journal of Indoor Environment and Health

ORIGINAL ARTICLE | Open Access

Carbon dioxide generation rates for building occupants

A. Persily, L. de Jonge

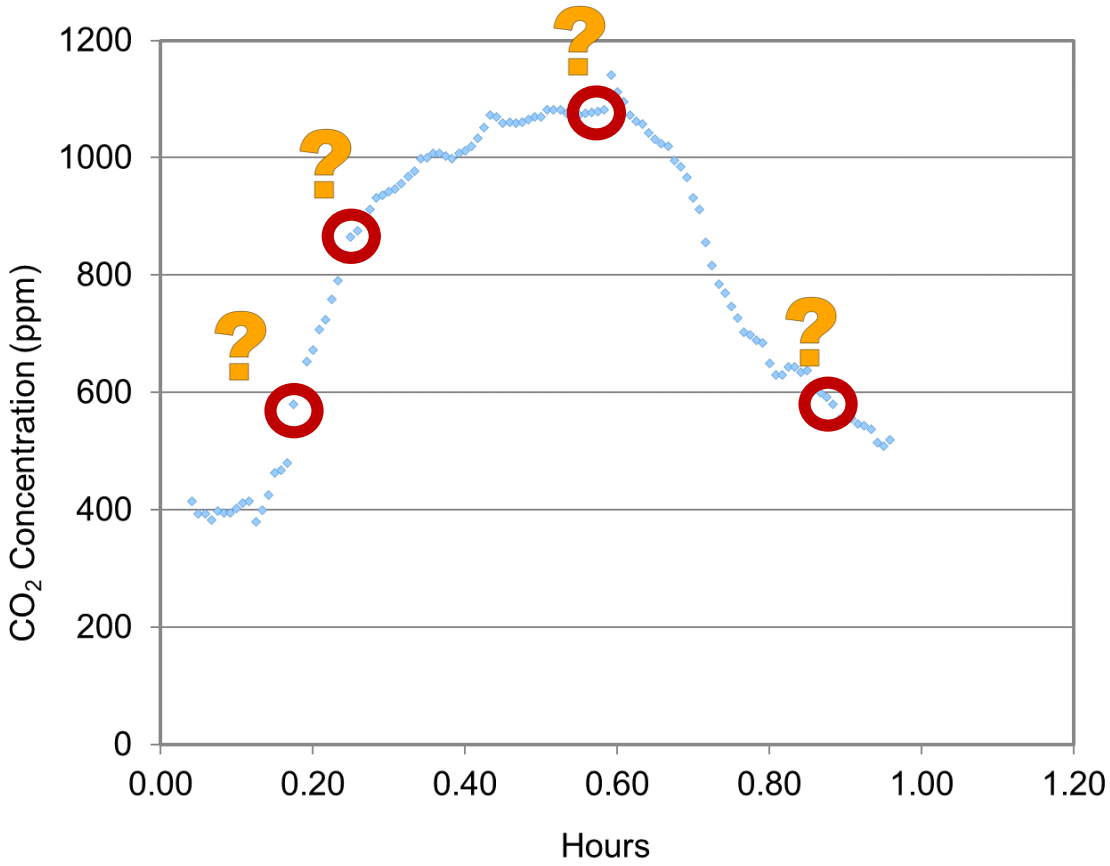
First published: 20 March 2017 | https://doi.org/10.1111/ina.12383 | Citations: 90



Complication #2

Using CO_2 as a Ventilation Clue

650 ppm



Complication #3

Data from student lab at Humboldt State University

Using CO_2 as a Ventilation Clue

Complication #4

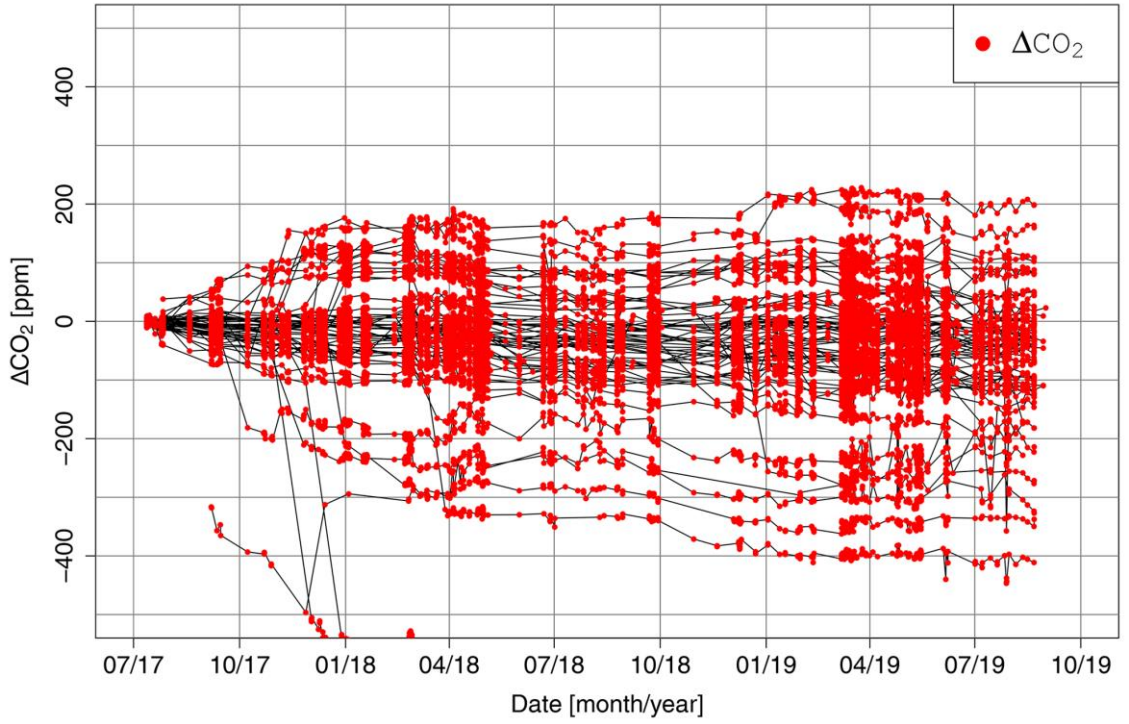
Using CO_2 as a Ventilation Clue

Atmos. Meas. Tech., 13, 3815–3834, 2020
https://doi.org/10.5194/amt-13-3815-2020

Atmospheric Measurement Techniques
Open Access
EGU

Integration and calibration of non-dispersive infrared (NDIR) CO_2 low-cost sensors and their operation in a sensor network covering Switzerland

Michael Müller[1], Peter Graf[1], Jonas Meyer[2], Anastasia Pentina[3], Dominik Brunner[1], Fernando Perez-Cruz[3], Christoph Hüglin[1], and Lukas Emmenegger[1]



Complication #5

Using CO_2 as a Ventilation Clue

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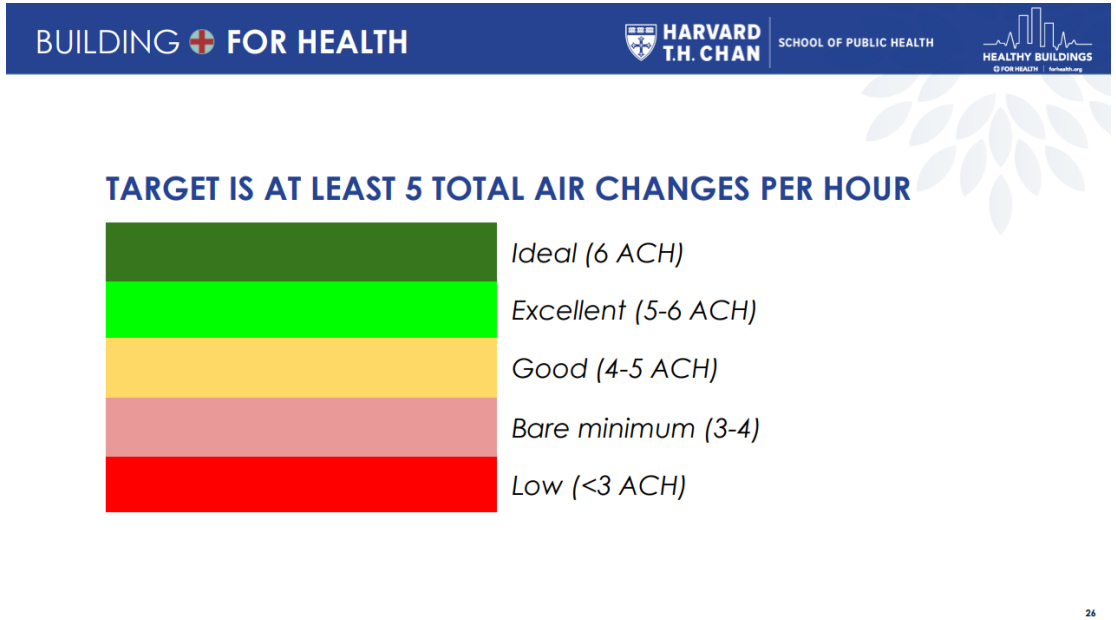
@MA_Campano

https://drive.google.com/file/d/1jFavucO98vMz5_LpKtnDXBfDZvWlMLcL/view



BUILDING FOR HEALTH | HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH | HEALTHY BUILDINGS

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)*

26

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

Using CO_2 as a Ventilation Clue

Space	Occupancy	Ventilation Rate ASHRAE 62.1 (L/s/person)	Outdoor Air Change rate (h^{-1})	Steady State or Mean Peak CO_2 Concentration ppm_v	Reference
Ideal Classroom Meeting Standards (5- to 8-year-olds)	24 students 1 instructor	**7.4**	**~2.6**[a]	828[b]	 INDOOR AIR 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
10 Actual California Classrooms	N/A	2.6 – 7.1	N/A	1,140 - 2,380	 INDOOR AIR 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

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

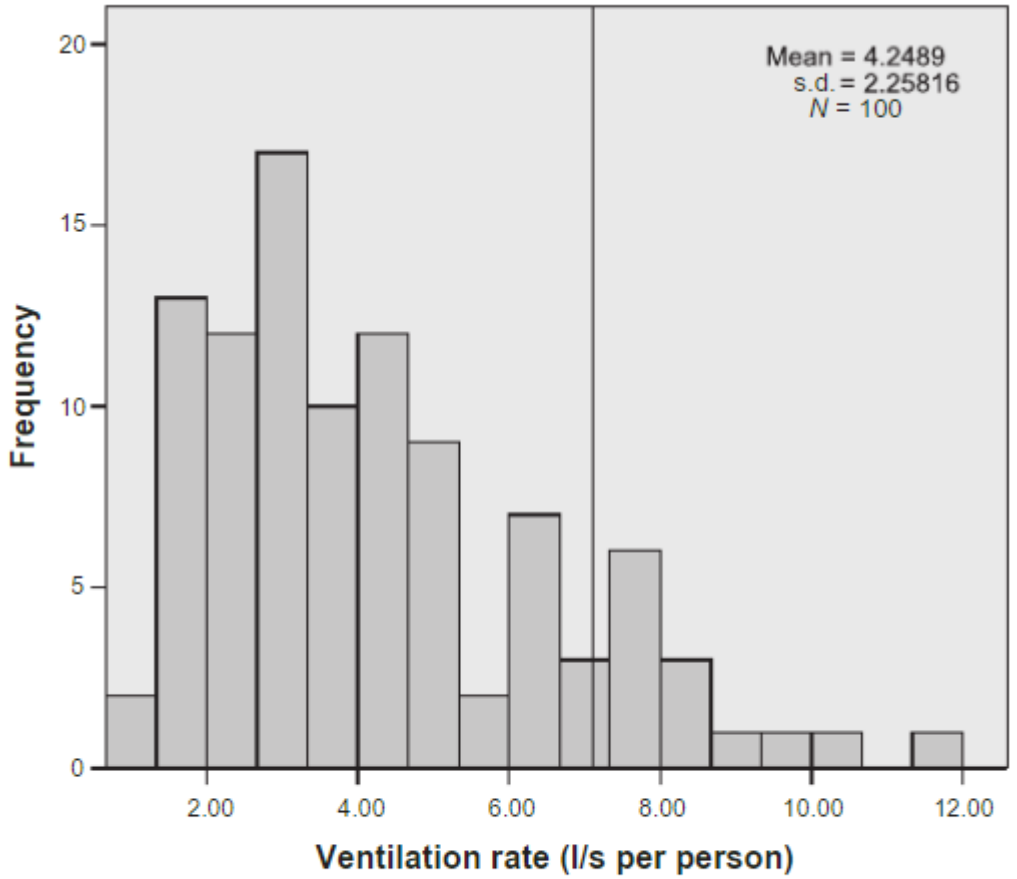


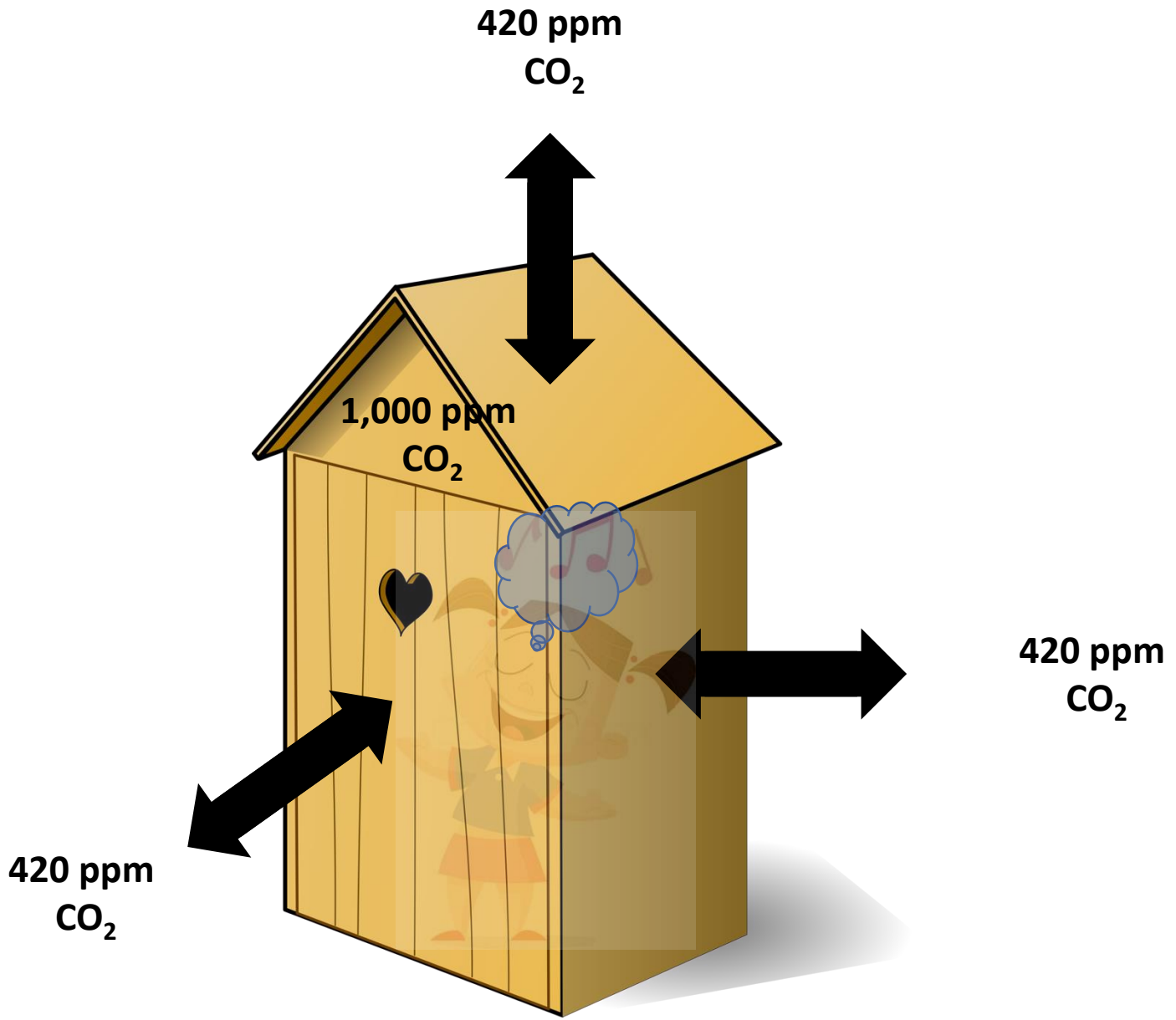
Fig. 1 Ventilation rate distribution (vertical line corresponds to ASHRAE recommended minimum)

Using CO_2 as a Ventilation Clue

Mass Balance

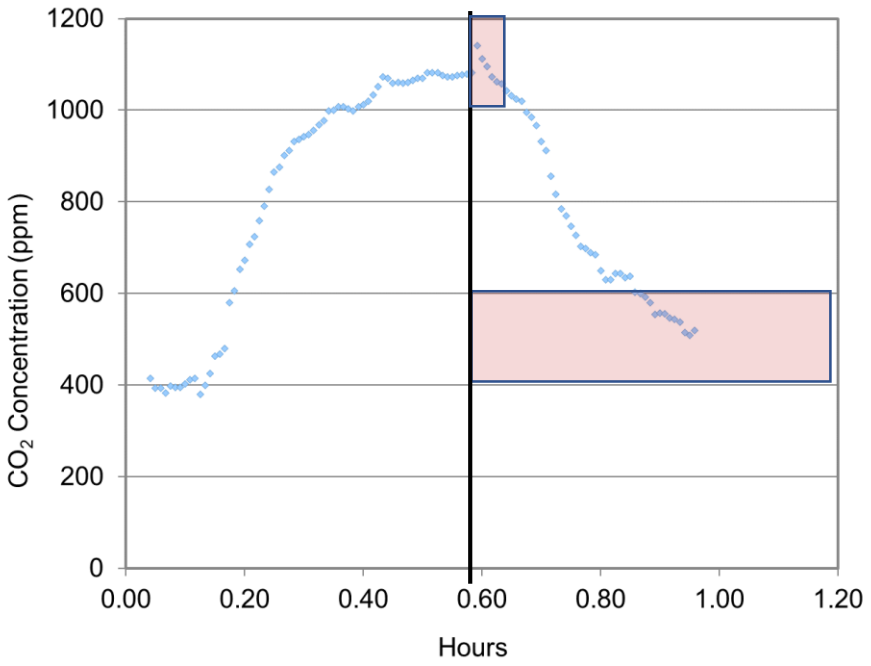
CO_2 in room = (CO_2 In) - (CO_2 Out)

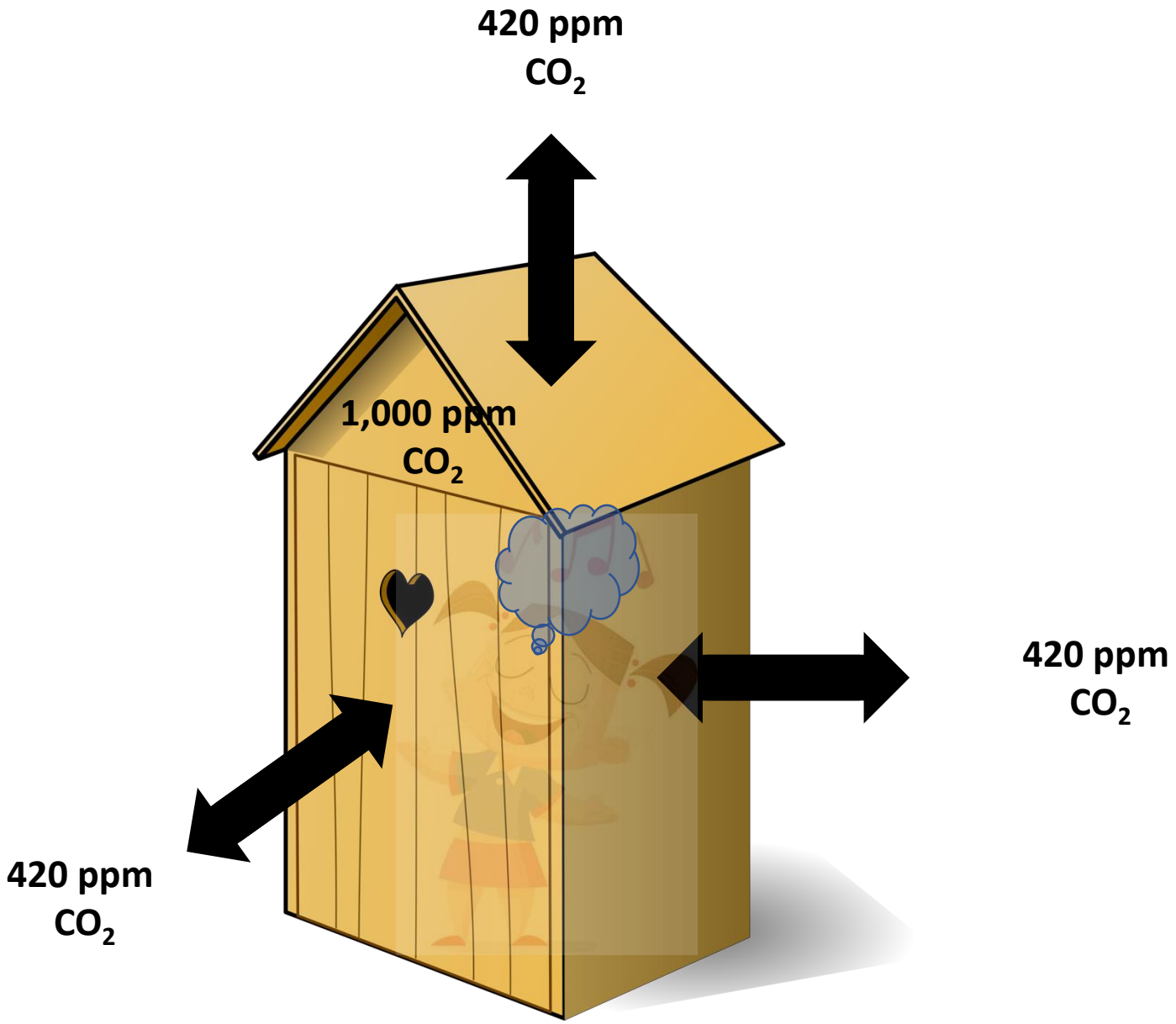
Assumes well-mixed room



Using CO_2 as a Ventilation Clue

Using CO_2 as a Ventilation Clue

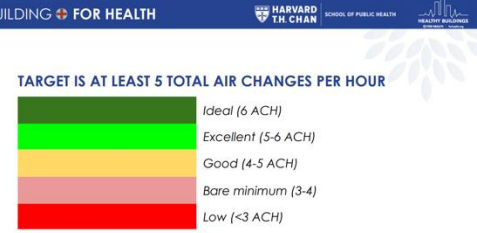




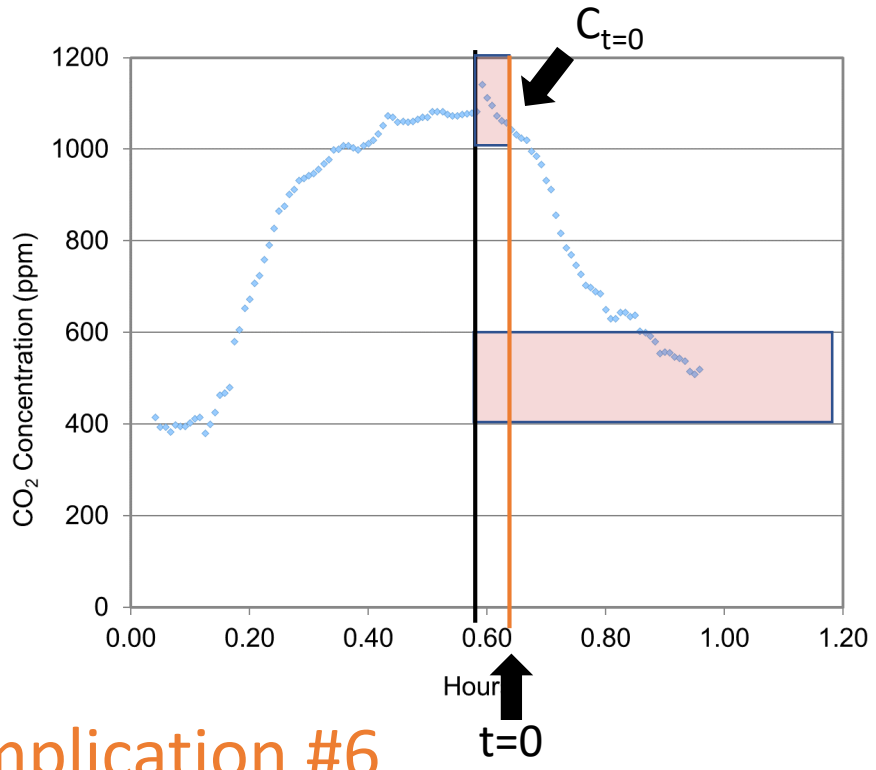
Data from student lab at Humboldt State University

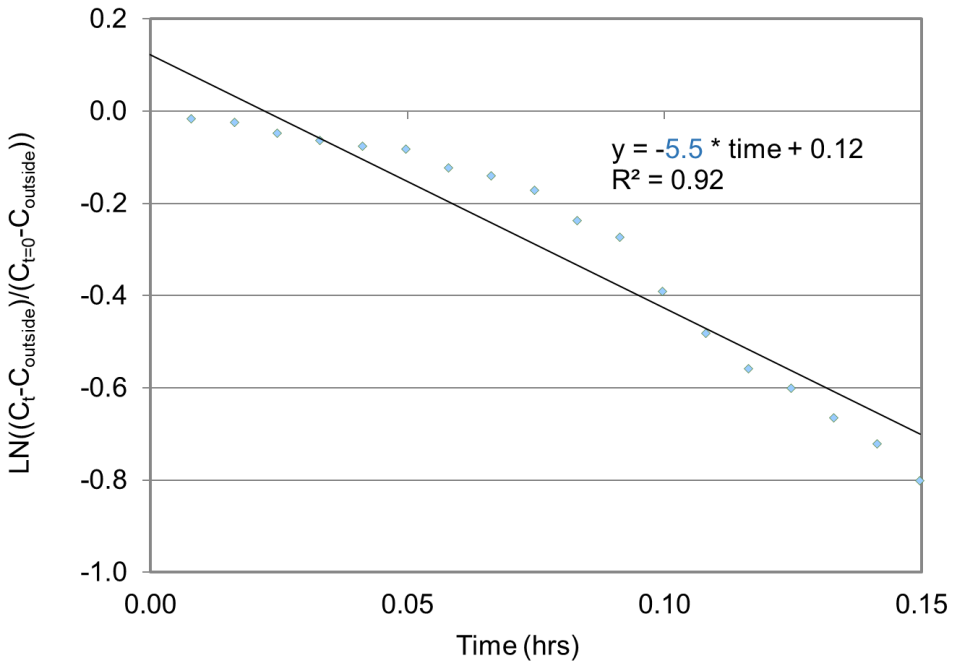
Using CO_2 as a Ventilation Clue

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



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

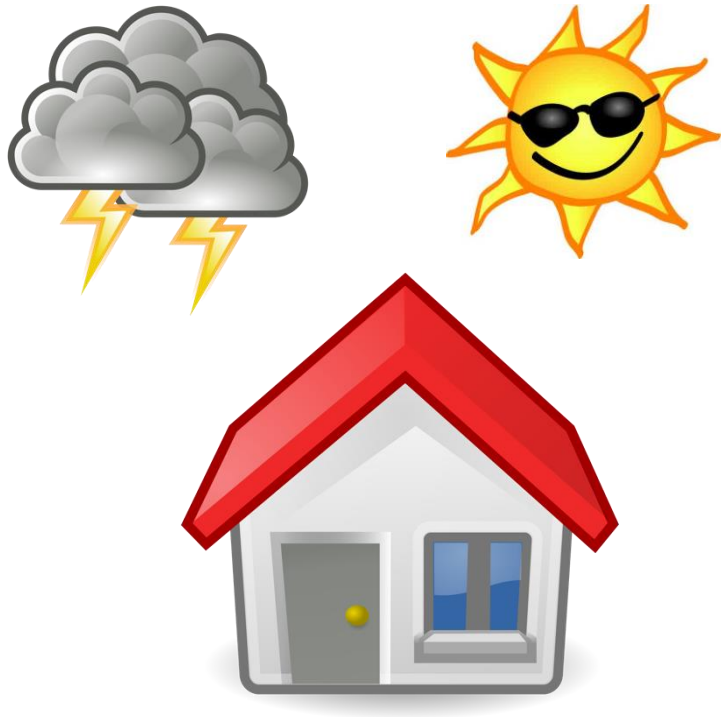




Complication #6

Data from student lab at Humboldt State University

Using CO_2 as a Ventilation Clue



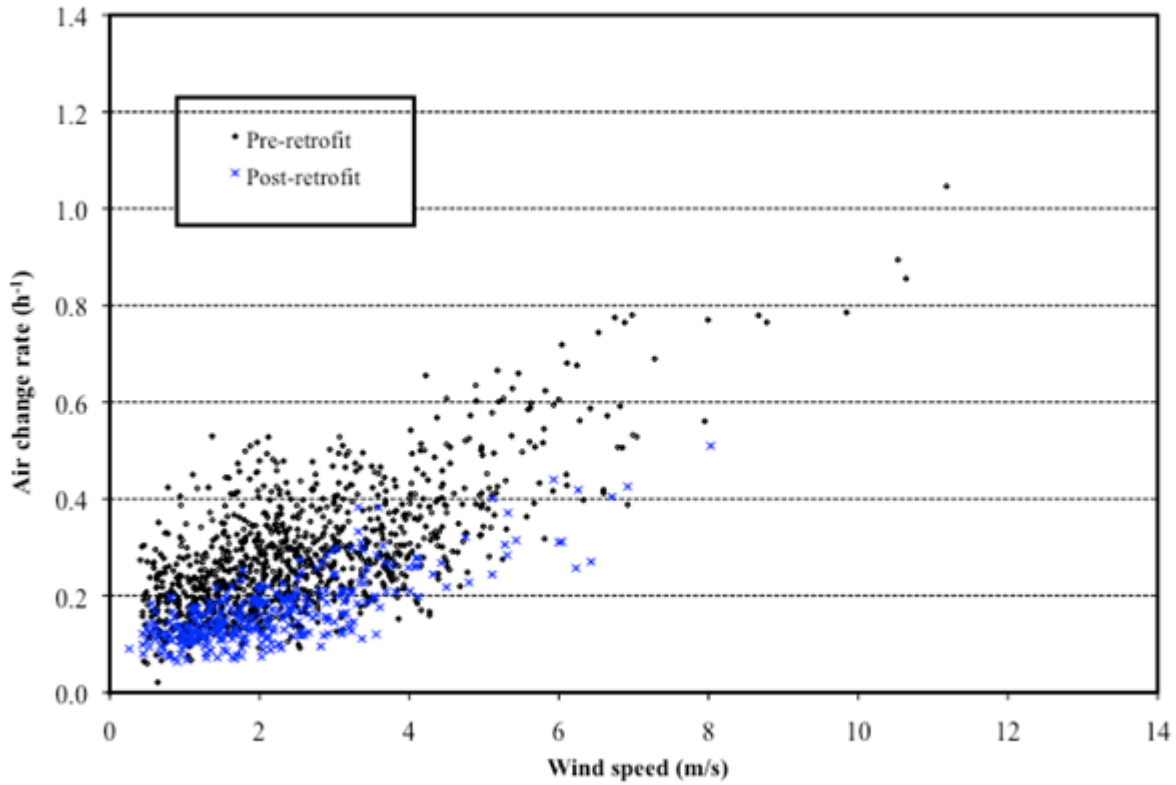
ELSEVIER

Energy and Buildings

Volume 43, Issue 11, November 2011, Pages 3059-3067

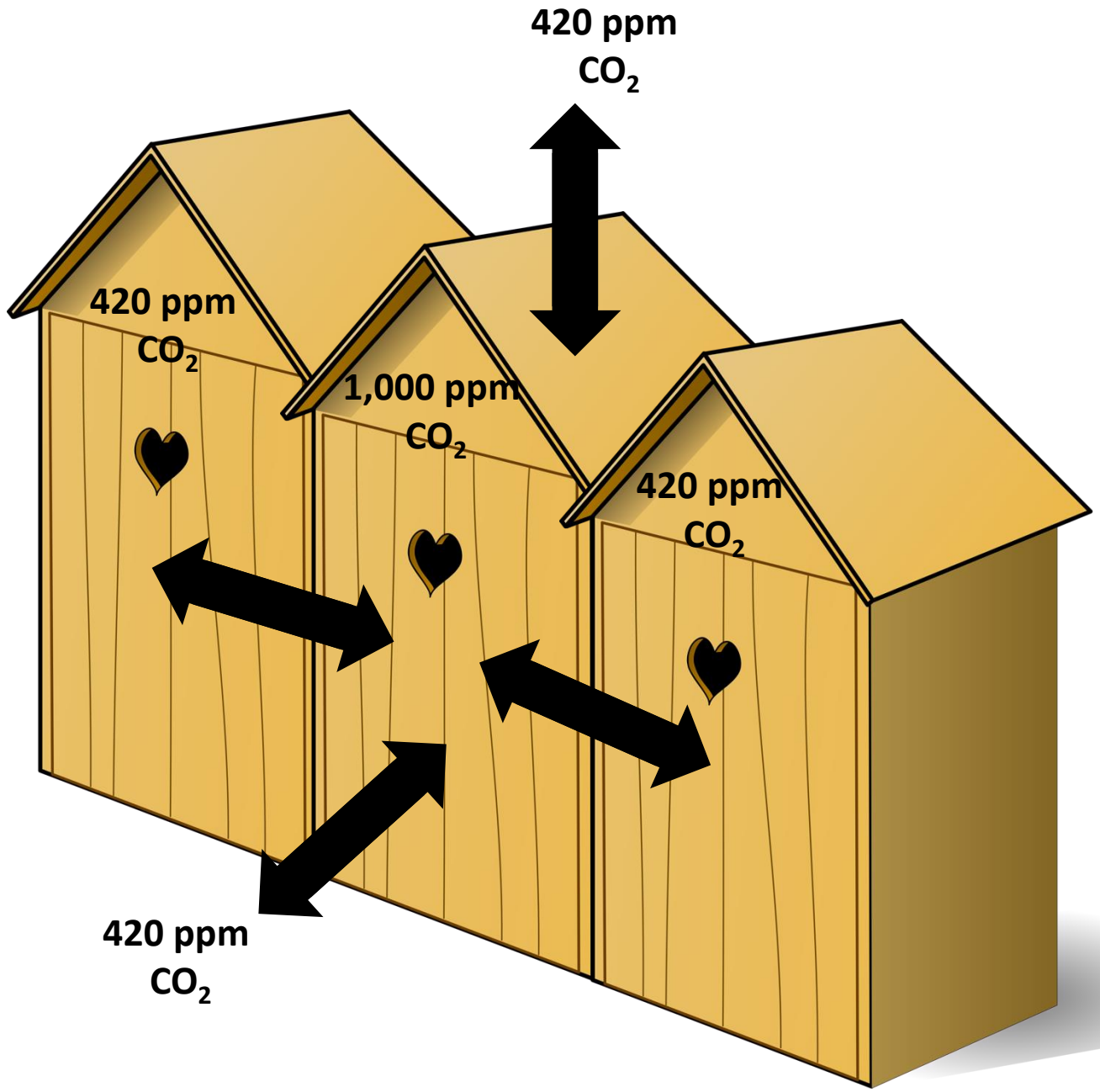
Impacts of airtightening retrofits on ventilation rates and energy consumption in a manufactured home

Steven Nabinger, Andrew Persily



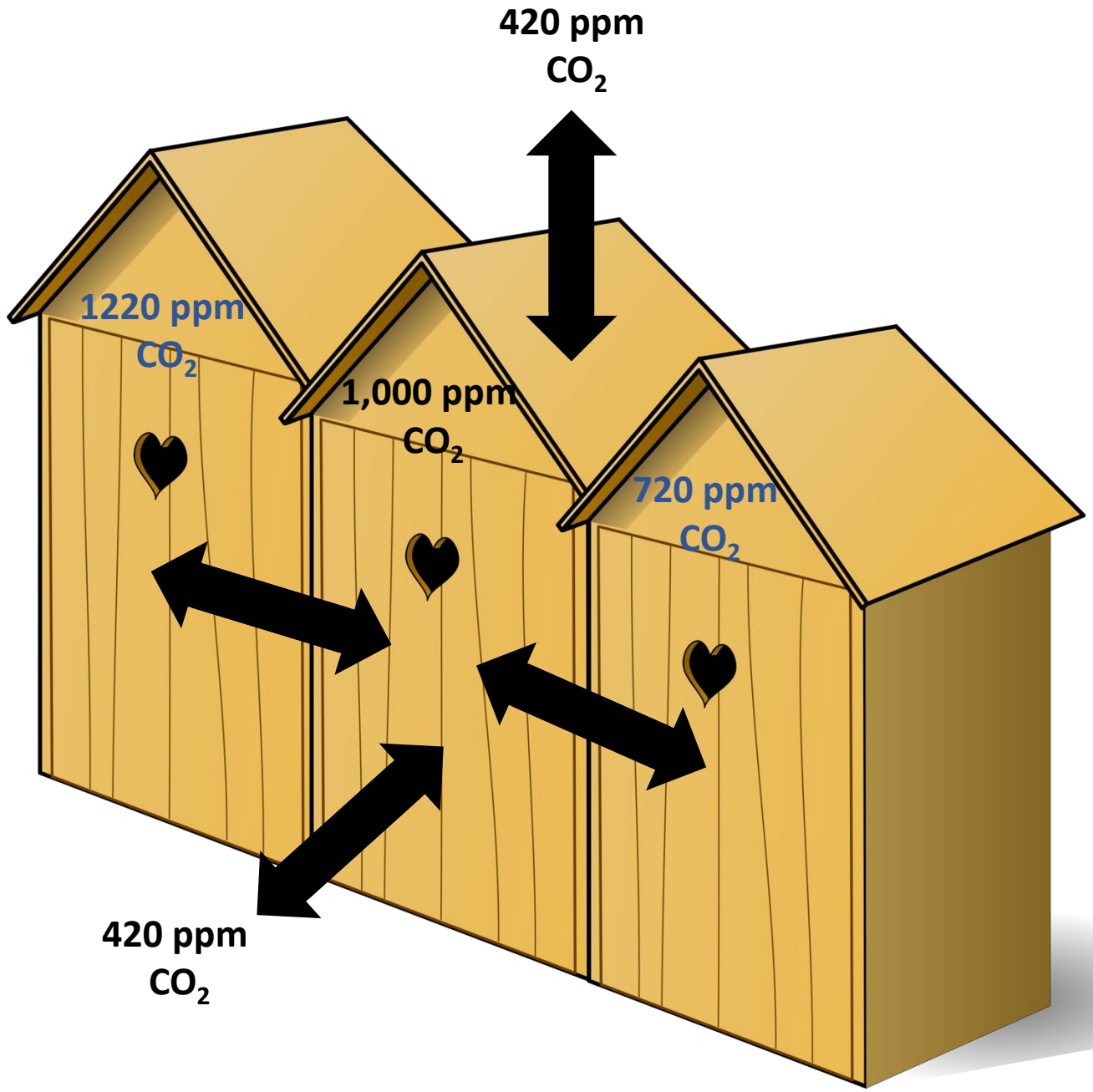
Complication #7

Using CO_2 as a Ventilation Clue



Complication #8

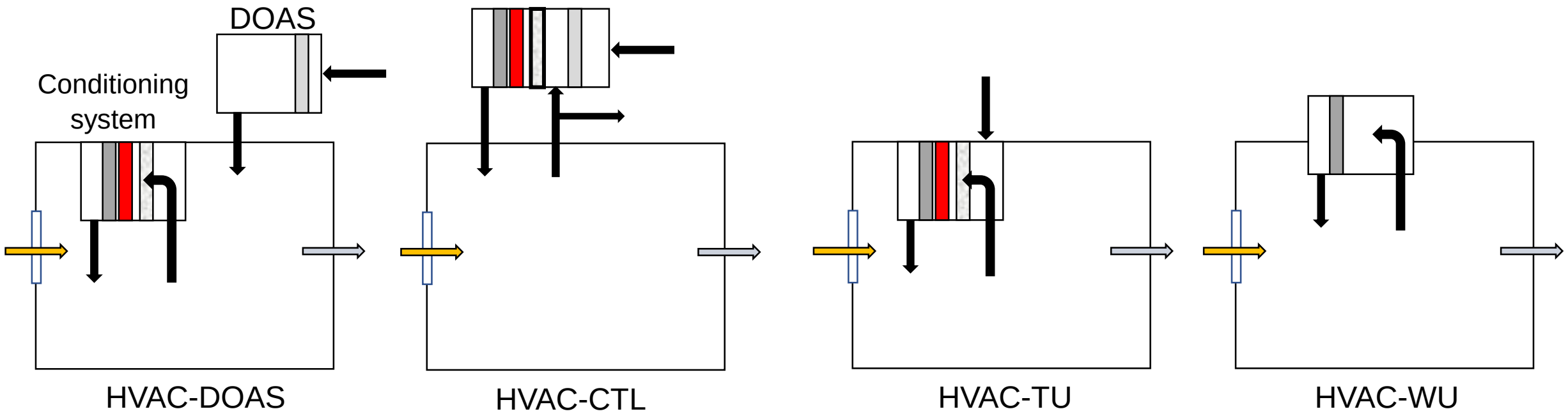
Using CO_2 as a Ventilation Clue



Complication #8

Using CO_2 as a Ventilation Clue

https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=930986



Cooling/Heating coils

OA filter

MERV 6 to 13 filter

Complication #9

Infiltration

Air leaving zone through leakage

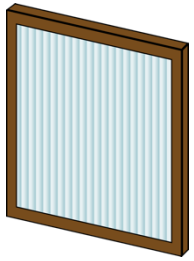
Using CO_2 as a Ventilation Clue

Effective Air Change Rate Estimation for Particle Removal

=

CO_2 Measurement

+



Portable HEPA Filter

+

HVAC MERV 13 Filter

https://www.tsi.com/products/ventilation-test-instruments/alnor/alnor-capture-hoods/alnor-balometer-capture-hood-ebt731/

Complication #10

Conclusion

Ventilation and Consumer Grade Cost Sensors:

It's complicated