Improving Indoor Air Quality, Energy Efficiency, and Greenhouse Gas Reductions through Multifamily Unit Compartmentalization

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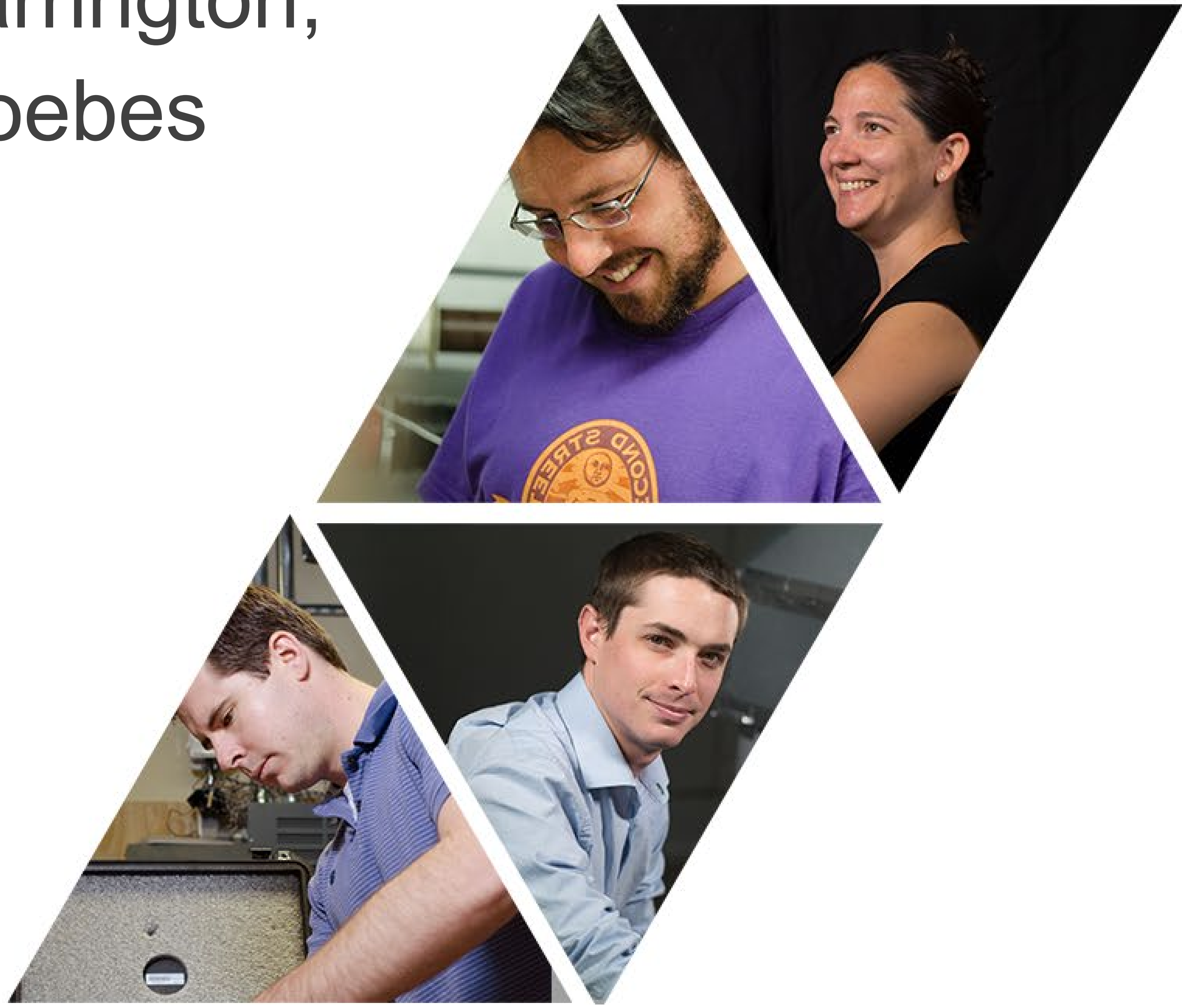
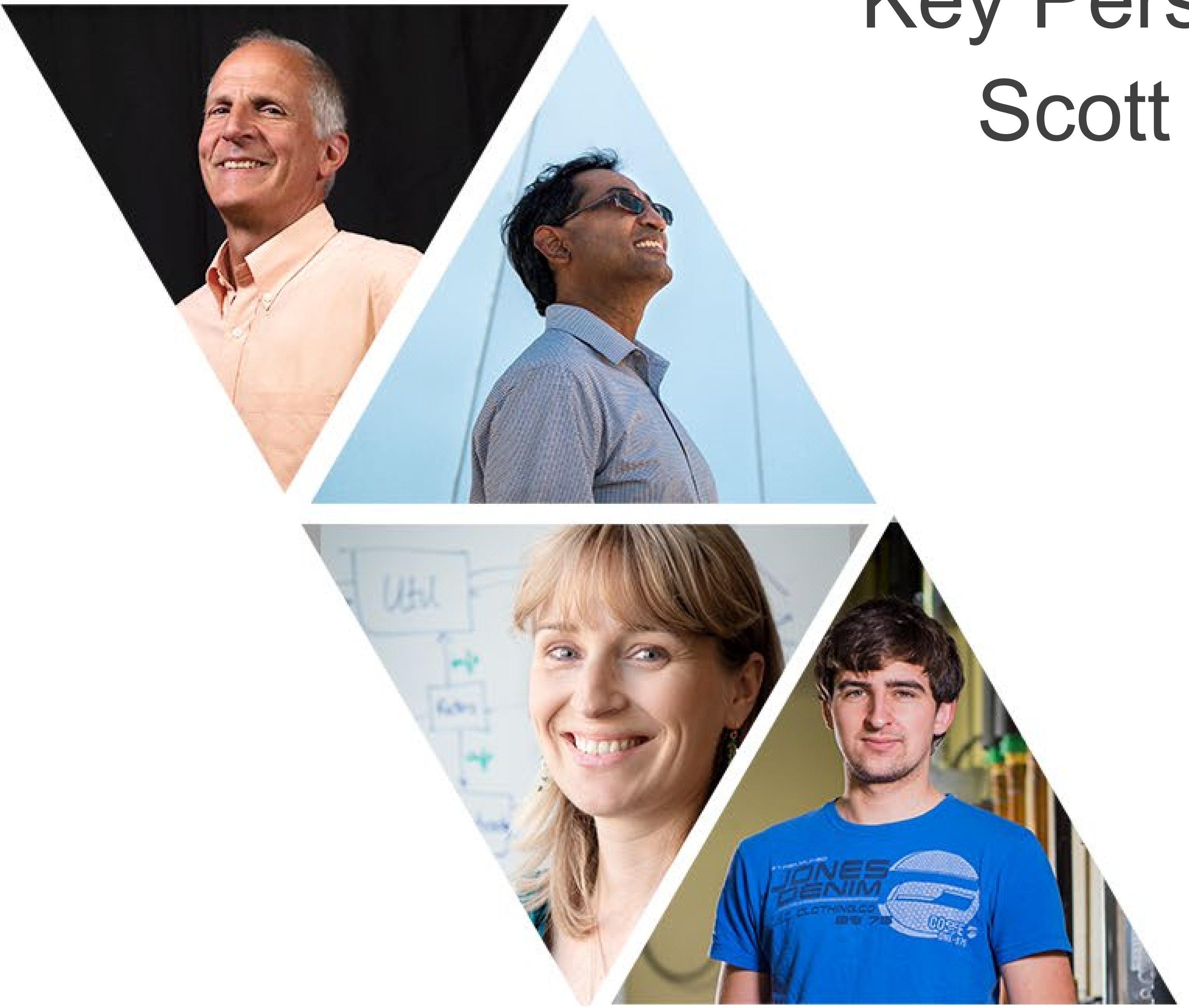
Key Personnel: Curtis Harrington, Scott Adler, Marian Goebes



Final Meeting
April 26th 2023



Background

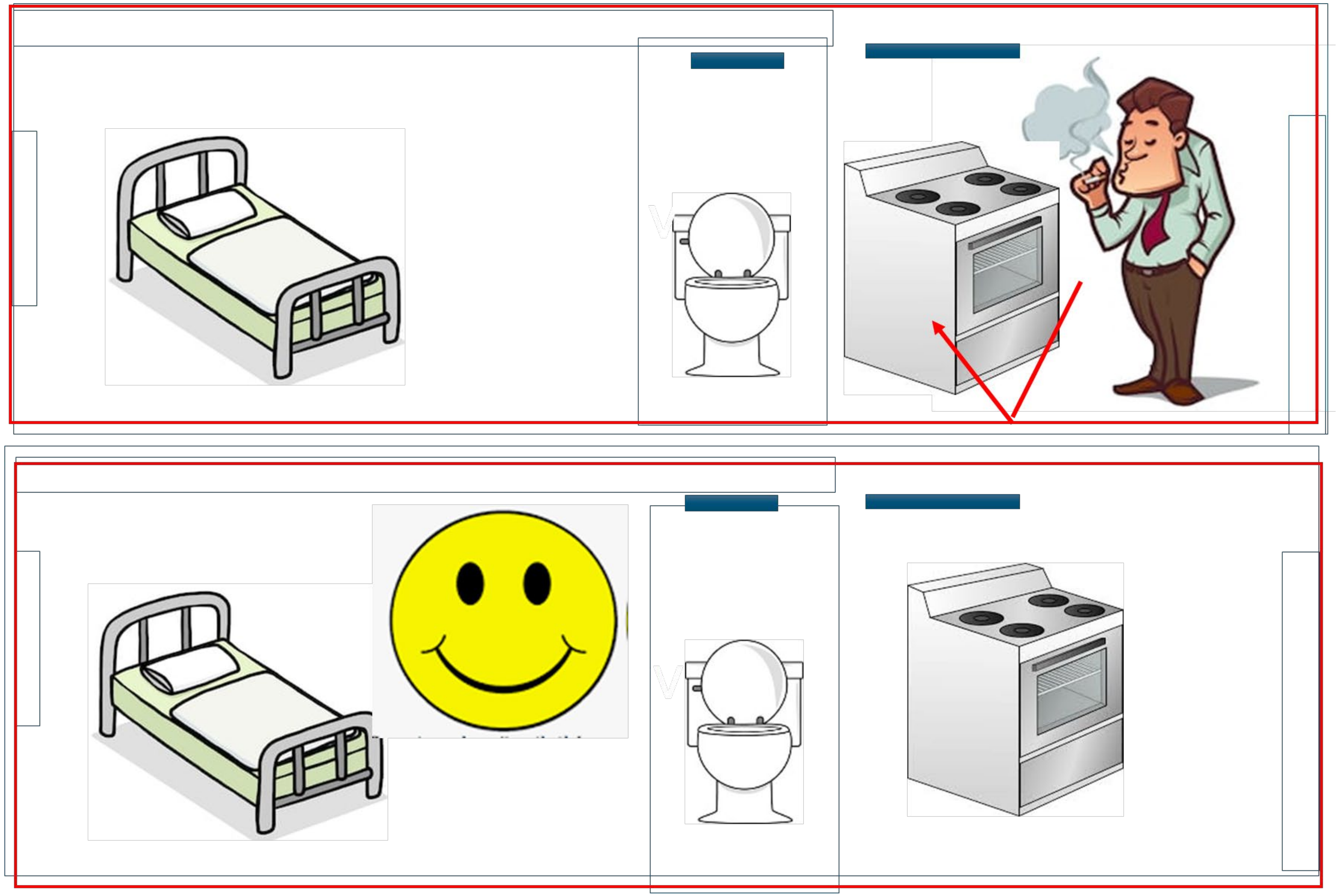
» 2019 Energy Code

- Requires all new multifamily units to either use balanced ventilation **OR** meet a **compartmentalization** requirement (0.3 cfm_{50}/ft^2)

» Compartmentalization

- Sealing each unit from adjacent units, hallways and the exterior
- Should provide significant indoor air quality (IAQ) benefits – reduced pollutants, noise, and odor transfer between units - in addition to saving energy/GHG
- Not standard practice, principally due to a lack of data quantifying IAQ and GHG impacts at different levels of compartmentalization

Compartmentalization



Project Overview

- Overall project goals are:
  - Assess the adequacy and impacts of current California multifamily building standards relative to **ventilation and air tightness**
  - Provide **primary field data and modeling analyses on compartmentalization** requirements and ventilation strategies
  - Investigate impacts of compartmentalization and ventilation strategies on **pollutant transfer, energy use, and GHG emissions**
  - Inform updates to improve future revisions to California's **Title-24 Building Energy Efficiency Standards**

Project Objectives

1. Measure the distribution of **total air leakage** of apartments in the same building
2. Measure the distribution of **mechanical ventilation flow rates** for apartments in the same building
3. Measure **inter-apartment pollutant transfer** between apartments with different levels of air tightness
4. Measure **overall air exchange rates** in apartments with different levels of air tightness
5. **Model air transfer paths, energy usage, and GHG emissions** using different total leakage levels, supply fan flows and exhaust fan flows to test the impact of compartmentalization
6. **Analyze field-test and modeling results** to determine the impacts of compartmentalization on IAQ, energy savings, and GHG reduction

Project Team

- **Western Cooling Efficiency Center (WCEC, UC Davis)**
  - Field Measurements of Leakage and Airflow
  - Compartmentalization Level Attainment
  - Field Measurement Analysis
  - Airflow, IAQ and Energy Modeling
  - Modeling Analysis
  - Overall Project Management
- **Department of Public Health (UC Davis)**
  - IAQ Field Procedures
  - IAQ Data Analysis
- **TRC**
  - Building Recruitment
  - Technical Support

Key Project Findings

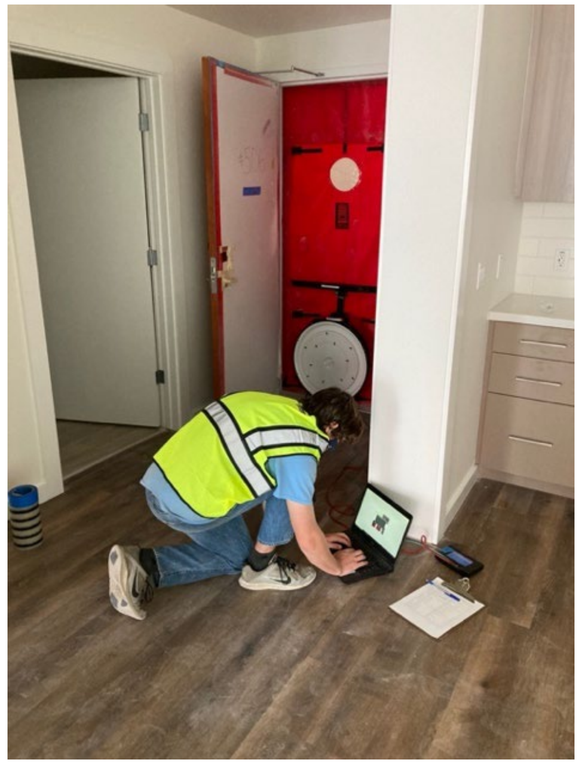
- Building Characterization
  - Measured Unit Leakage Levels were **~50%** lower than code: A tighter standard is achievable
  - Unit leakage and ventilation flow rates vary with a standard deviation of **~10-15%**
- Indoor Air Quality
  - Compartmentalization to stricter leakage targets results in lower gaseous pollutant transfer
  - No observed particulate transfer between units in buildings tested
  - NO_2 in units with gas stoves was higher than the 1-hour NAAQS if the kitchen fan was not used. Units next to a smoker have benzene exposure above the 1×10^{-6} cancer risk level if with the highest leakage level
- Energy Use and Greenhouse Gas Emissions
  - HVAC energy and GHG savings of **4-6%** by going from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2
  - Additional **5-20%** of HVAC energy and GHG savings by going from balanced to single-fan ventilation **OR** **16-26%** by adding heat exchangers to balanced systems (not including pressure losses)
  - EnergyPlus results had to be modified to account for window openings – otherwise simulates San Francisco as a cooling-dominated climate
  - Standard EnergyPlus prototype dramatically overestimates infiltration

Field Testing - Buildings Tested

	Building A	Building B	Building C
Location	Oakland, CA	El Cerrito, CA	San Jose, CA
Rate	Affordable	Market	Affordable
Number of stories	6 (1^{st} floor is parking)	6 (1^{st} floor is parking)	6 (1^{st} floor is parking)
Construction type	Site-built (traditional)	Modular	Site-built (traditional)
Airtightness Target	0.3 cfm_{50}/ft^2	N/A	0.23 cfm_{50}/ft^2 (LEED)
Ventilation System	Balanced with heat recovery as design intent, but exhaust was more than supply	Balanced	Exhaust

Field Testing - Methods

Parameter	# of buildings	Units per building	Methodology
Total unit leakage	3	10-14	Single-zone blower-door test
Mechanical Ventilation flows	3	10-13	Powered flow-capture hood
Inter-unit leakage	2	3-6	Guarded blower-door test
Air change rate	2	2-3	CO_2 decay
Gas and PM transfer	2	2-3	CO_2 and PM elevation




Field Testing – Overall Unit Leakage

Building	Air tightness (cfm_{50}/ft^2)	SD (%)	ACH50	SD (%)	# units
A	0.173	15%	3.88	16%	14
B	0.140	15%	3.20	14%	10
C	0.165	10%	4.26	11%	12

Field Testing – Inter-Unit Leakage

Building	Horizontal Adjacent	Horizontal SD (%)	Vertical Adjacent	Vertical SD (%)
A	12%	3%	7%	N/A
B (Modular)	**0.8%**	1%	8%	2%
C	16%	3%	N/A	N/A

Field Testing – Ventilation System Performance

Building	Supply [cfm]	SD (%)	Exhaust [cfm]	SD (%)	Net Flow [cfm]	Overall ACH	# units
A	52	8%	81	5%	-30	0.7	13
B	53	33%	53	14%	-1	0.6	10
C	114	6%	142	25%	-29	2.4	12

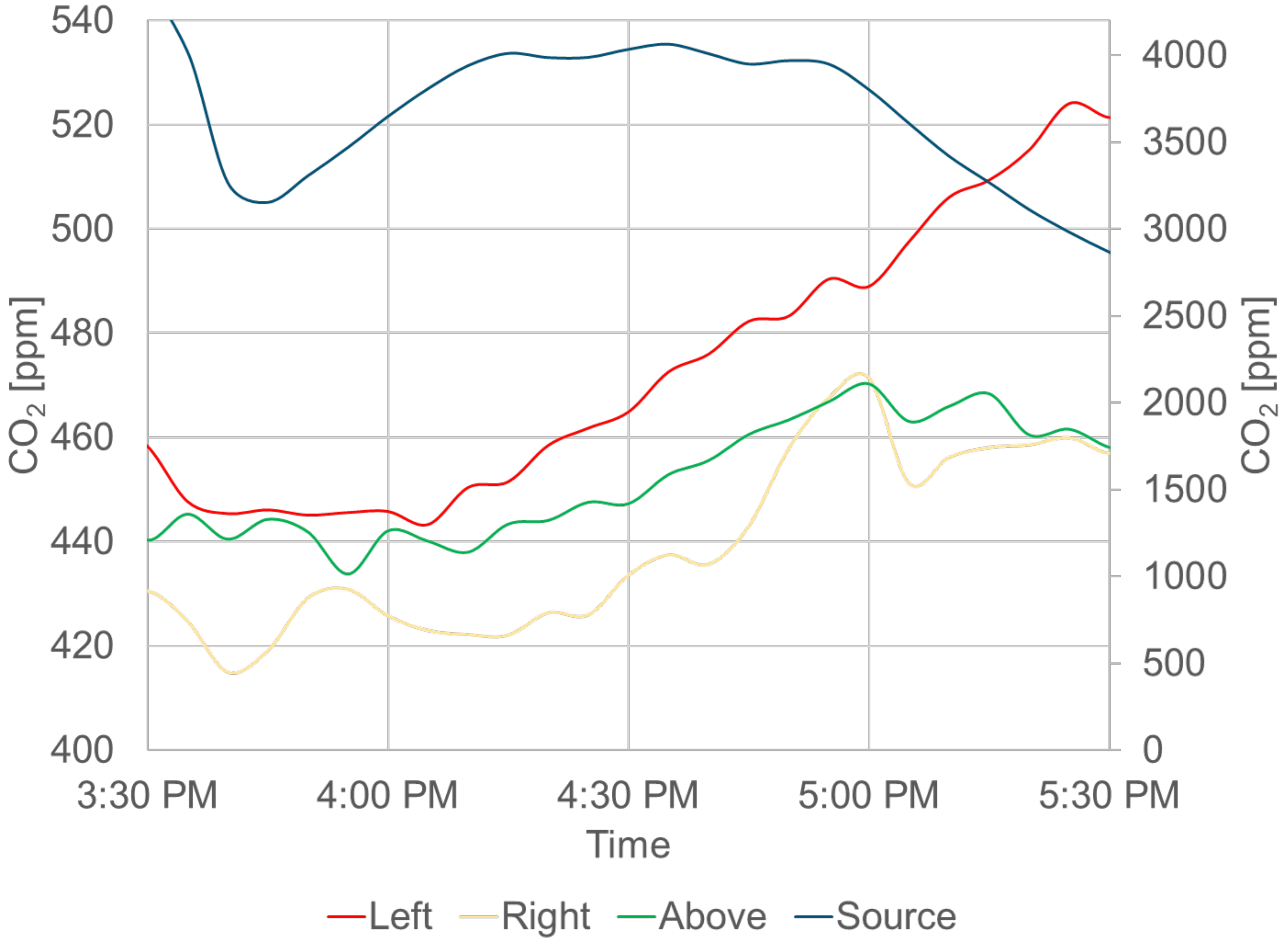
Sealing to Modify Level of Compartmentalization

» Sealing of Selected Units

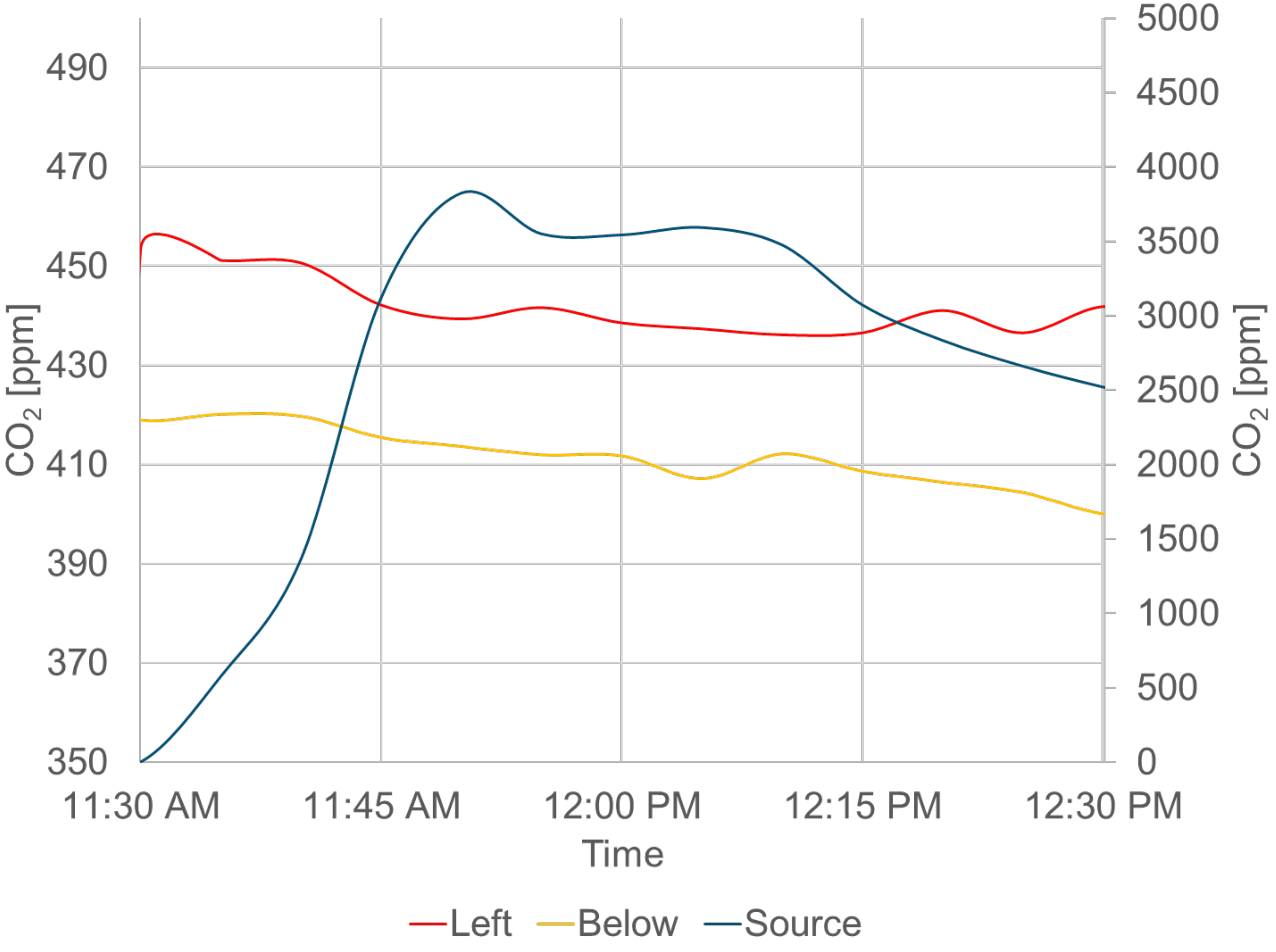
- Aerosol Sealing used to increase compartmentalization of two units in both Building A and Building B
- Sealing process performed at medium point in construction
- Attempted to produce three different levels of tightness in each building, however both buildings were both rather tight at the outset
- Sealing process was purposefully aborted prematurely in all cases to try to achieve target leakage levels (and avoid over-tightening)
  - Ultimately did not achieve enough spread in **final leakage** levels between units due to trying to achieve specific targets at **rough construction**
  - Remainder of construction process, and untouched leaks contributed to lack of variability

Examples of CO_2 Transfer Results

» Building A, sealed unit with kitchen fans on in adjoining units



» Building A, unsealed unit with kitchen fans off in adjoining units



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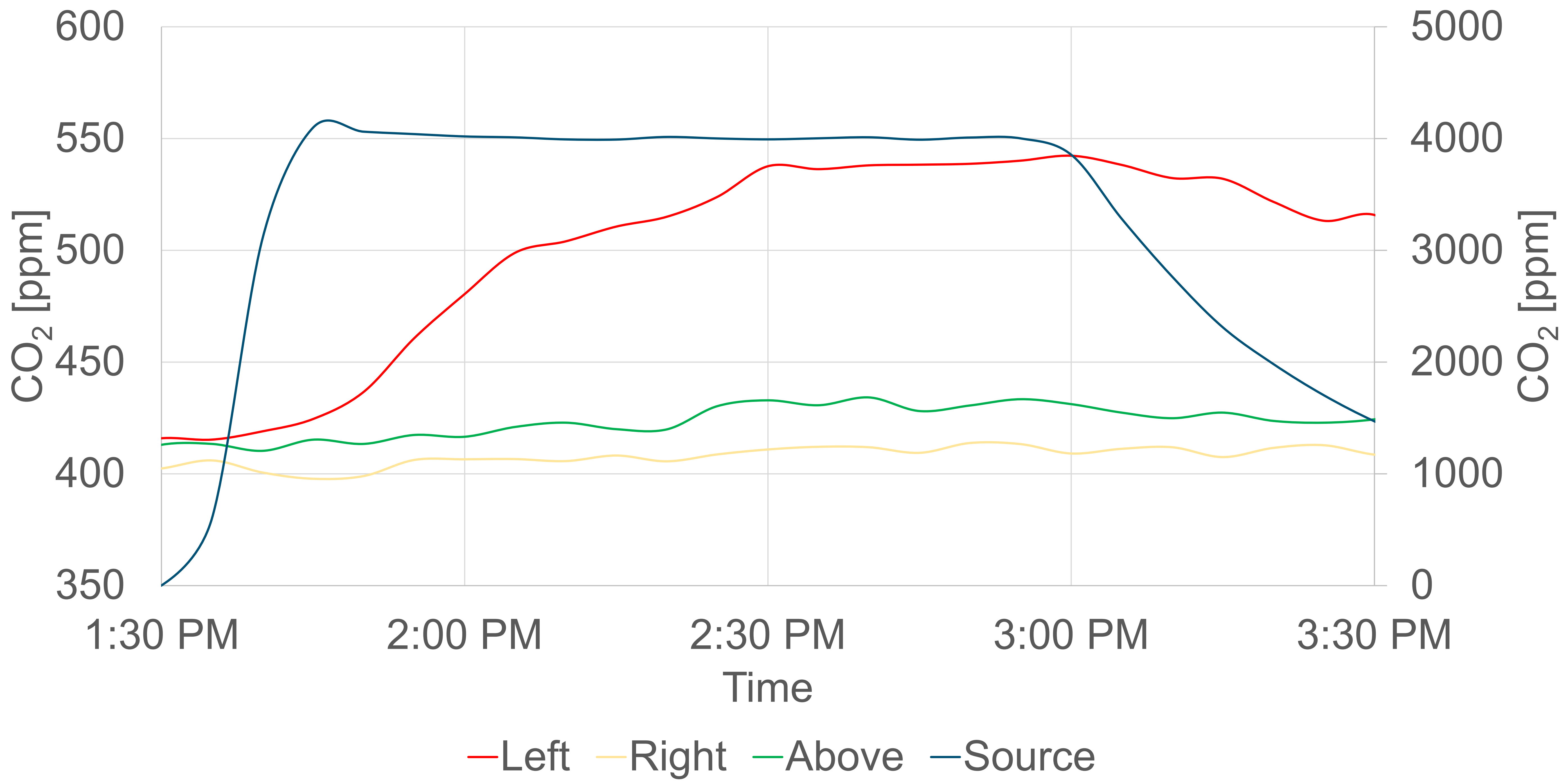
Examples of CO_2 Transfer Results

» Building C, transfers occurred when unit had adjoining bathrooms, but not when they had adjoining living rooms



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Gas Transfer Rates – Building A

Adjacent Kitchen Exhaust Fans **Off**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
409	0.13	-1	0	0%	0	0	0%	NA	0	0%
509	0.15	-3	3	3%	2	0	0%	NA	0	0%
609	0.16	-4	0	0%	3	1	2%	NA	0	0%

Adjacent Kitchen Exhaust Fans **On**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
409	0.13	-10	8	3%	-8	5	2%	NA	6	2%
509	0.15	-2	2	1%	-10	7	2%	NA	2	1%
609	0.16	-14	7	3%	NA*			NA	4	1%

Gas Transfer Rates – Building C

Adjacent Kitchen Exhaust Fans **Off**

		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
531	0.18	-5	0	0%	1	0	0%	NA	0	0%
534	0.12	0	0	0%	NA	0	0%	NA	0	0%

Adjacent Kitchen Exhaust Fans **On**

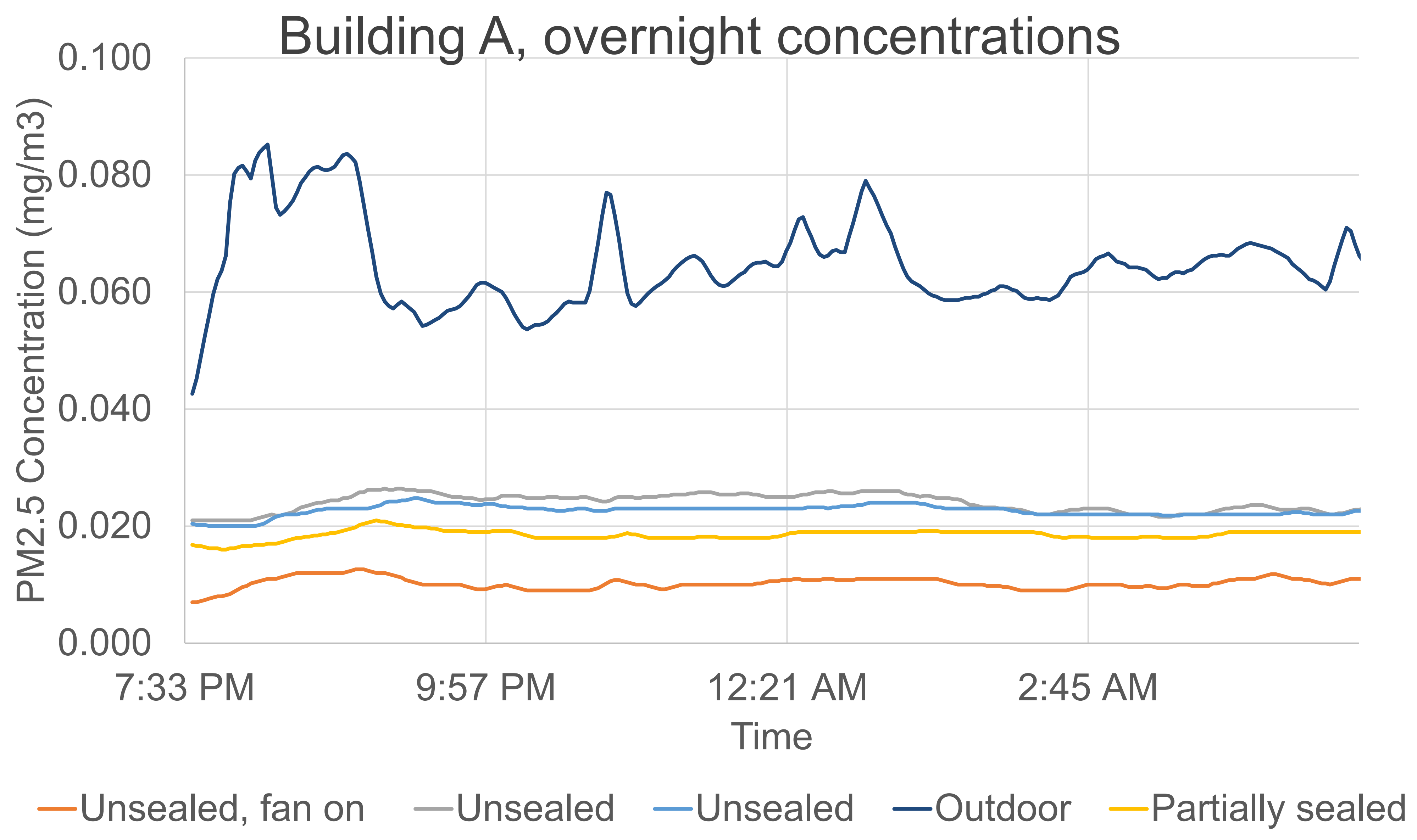
		Left Unit			Right Unit			Above/Below Unit		
Source unit	Total Unit Leakage [cfm_{50}/ft^2]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]	Pressure Difference [Pa]	Inter-unit Air Transfer [cfm]	[%]
531	0.18	-12	4	2%	-7	0	0%	NA	0	0%
534	0.12	-6	3	1%	NA	1	0%	NA	1	0%

IAQ Field-Test Methods

- Overnight I/O ratios calculated using DustTrak (DRX and II) samplers with one located outdoors and multiple samplers placed in different units indoors. In Building A, samplers placed in units with different levels of sealing
- PM transfer experiments conducted simultaneously with CO_2 transfer experiments. PM levels increased through the transfer of cat litter. Levels of PM and CO_2 held at high levels for approximately 1 hour, with levels measured in that unit and adjoining units
- In Building A, experiments done in units with multiple levels of sealing performed with aerosol-based method during construction. In Building C, experiments done in units with naturally varied sealing levels
- Experiments done with and w/o the kitchen fan on in receiving units

Summary of I/O Ratios

Overnight measurements of PM2.5 concentration in four units at Building A and outdoors



I/O ratio at Building A

Collected 5 nights of data but only showed 3 nights' results

Building A	Night 1	Night 2	Night 3
Unsealed	0.43	0.53	0.37
Unsealed	0.37	0.52	0.35
Unsealed , fan on			0.17
Partial Seal	0.35	0.48	0.29
Sealed		0.45	

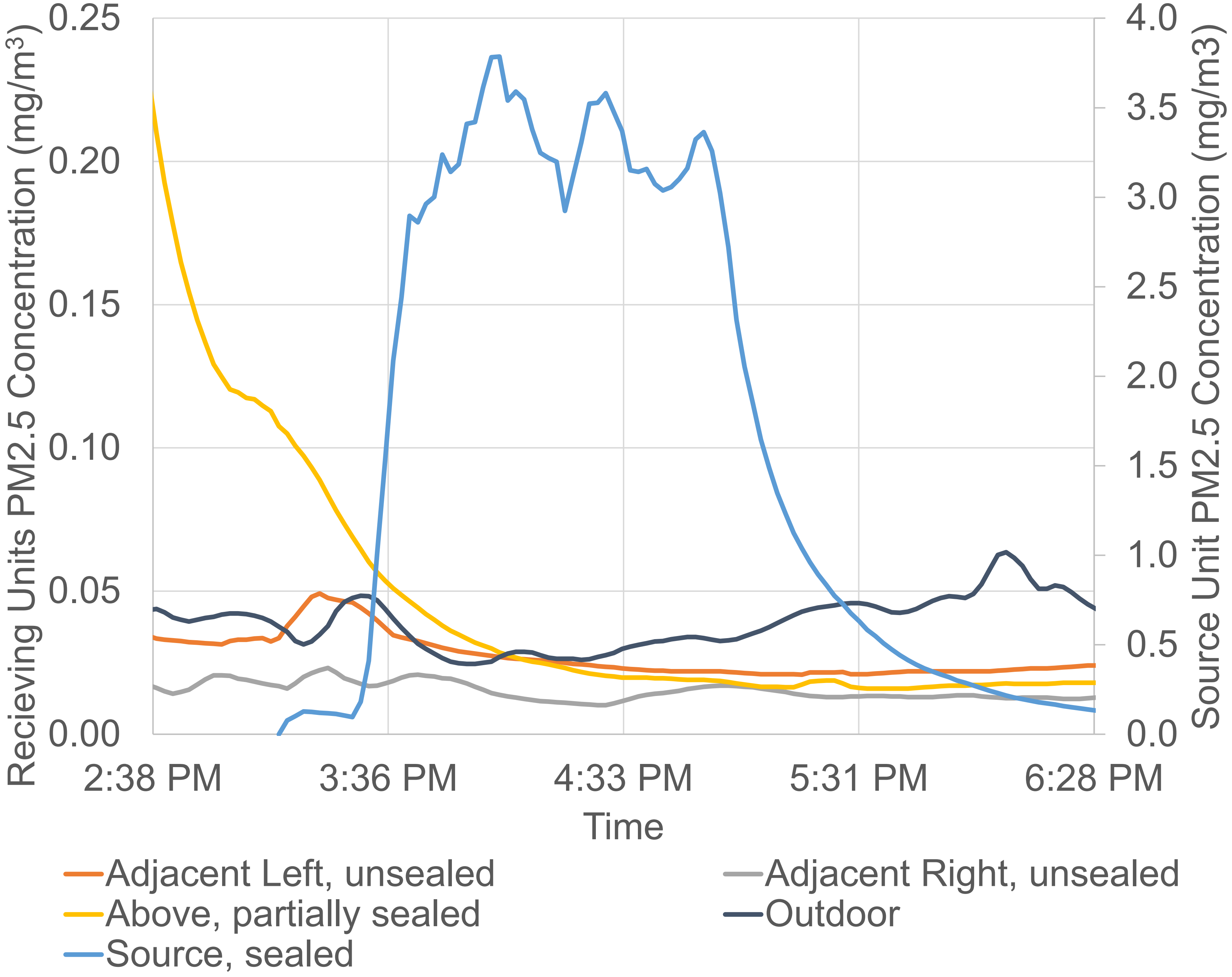
I/O ratio at Building C

Collected 1 night of data in multiple units

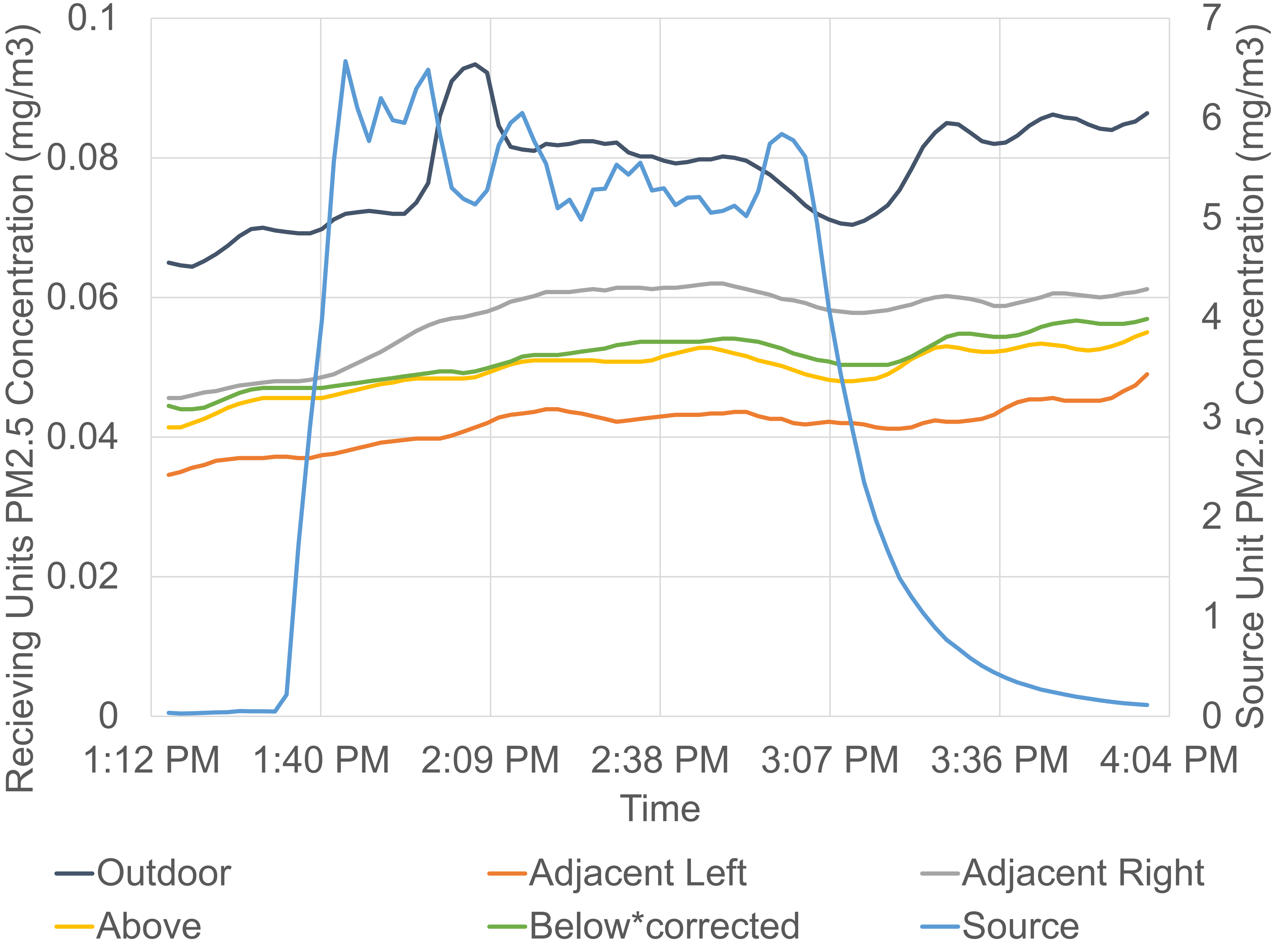
Building C	Night 1
Unit 529	0.70
Unit 533	0.71
Unit 631	0.68
Unit 431	0.69

Examples of PM Transfer Results

» Building A, a sealed unit with kitchen fans on in adjoining units



» Building C, an unsealed unit with kitchen fans on in adjoining units



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Field Testing – Key IAQ Results

- No measurable PM2.5 transfer between units
  - Even with adjacent units depressurized with Kitchen Exhaust Fans
  - **<3%** of air entering the adjacent unit (depressurized with Kitchen Exhaust Fan) was from the pollutant-source unit in all cases
- Indoor/Outdoor PM2.5 Ratios
  - Significantly higher ratio in Building C due to high outdoor airflow through Packaged Terminal Air Conditioning (PTAC) units: **0.7 ± 2%** (**62%** higher than unsealed apartments at Building A)
  - Measurable compartmentalization impact in Building A **(-14%)** for the first level of sealing, and **(-6%)** relative to the sealed unit with additional sealing
  - Large impact of running the HVAC fan continuously in unsealed Building-A units: **-53%**

Modeling with CONTAM and Energy Plus

» Overview

- CASE Prototype Building modeled in **Energy Plus**
- Air flow modeling performed with **CONTAM**
  - Used to analyze IAQ implications of leakage and ventilation options
- CONTAM-calculated outdoor air flowrates used to modify Energy Plus results to analyze marginal energy implications of leakage and ventilation options in **Excel**

CONTAM Modeling – Input Data

- Leakage distribution (airflow paths) based on field testing results
- Mechanical ventilation flow rates based on field testing
- Kitchen exhaust fan schedules from existing literature with flow rates based on field testing
- Pollutant generation rates for nitrogen dioxide (NO_2), formaldehyde (CH_2O), and cigarette smoke (benzene – C_6H_6) from the existing literature
- All parameters assumed to follow distributions based upon either field measurements or other studies' measurements
- Particle generation and transfer were not simulated
  - Did not see noticeable transfer during field testing

CONTAM Modeling - Simulation Configurations:

- Leakage levels: 0.15, 0.3, 0.45 [cfm_{50}/ft^2]
- Ventilation strategies: Exhaust, supply, balanced (min Code rates)
- Climate zones: Four CA zones
- Variability in leakage: 0% (baseline) and 10% (only CZ12)
- Variability in ventilation rates: 0% (baseline) and 15% (only CZ12)
- Total permutations: 26

CONTAM Modeling - Outputs

- **Air Flows**
  - Overall Air Exchange Rate
  - Actual fresh-air ventilation rate [cfm/ft^2] (mech supply air + outdoor air + corridor air)
  - Source of airflows (% coming from: mech supply, outdoors, corridor, and neighbors)
  - Distribution of airflows by apartment type (corner vs. interior units)
  - Distribution of airflows of apartment location (bottom, middle, top floor) – stack effect
- **Pollutant concentrations**
  - Average pollutant concentrations in each apartment (NO_2, CH_2O, and C_6H_6)
  - Maximum hourly pollutant concentrations in each apartment
  - Pollutant transfer between apartments
  - Distribution based on kitchen exhaust fan operation (for people who do and do not use their kitchen range hoods)
  - Distribution based on smoking behavior (smoker, non-smoker living next to a smoker, non-smoker not living next to a smoker)
  - Smells (using NO_2 from cooking as proxy gases)

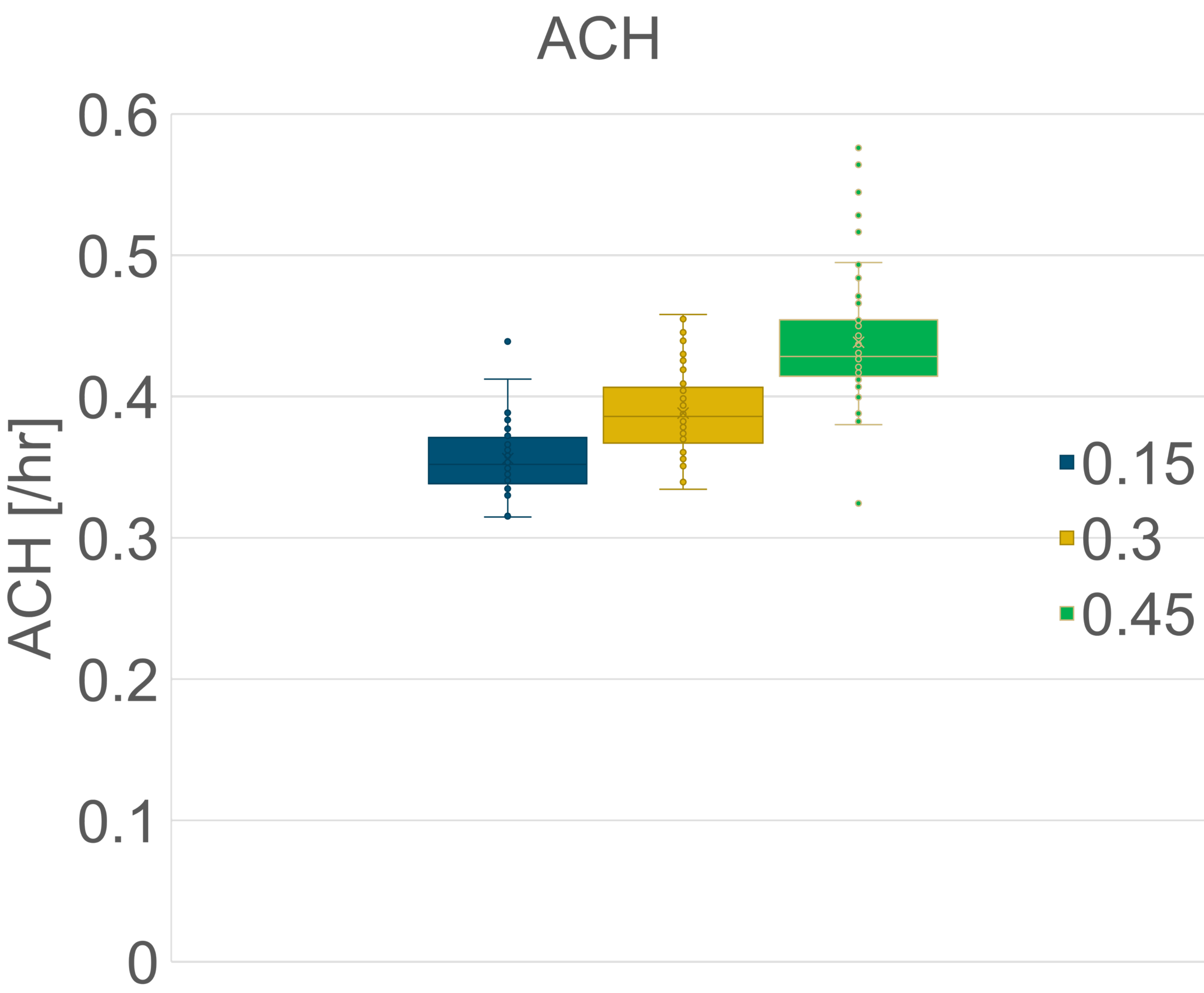
CONTAM Modeling Air Flow Results

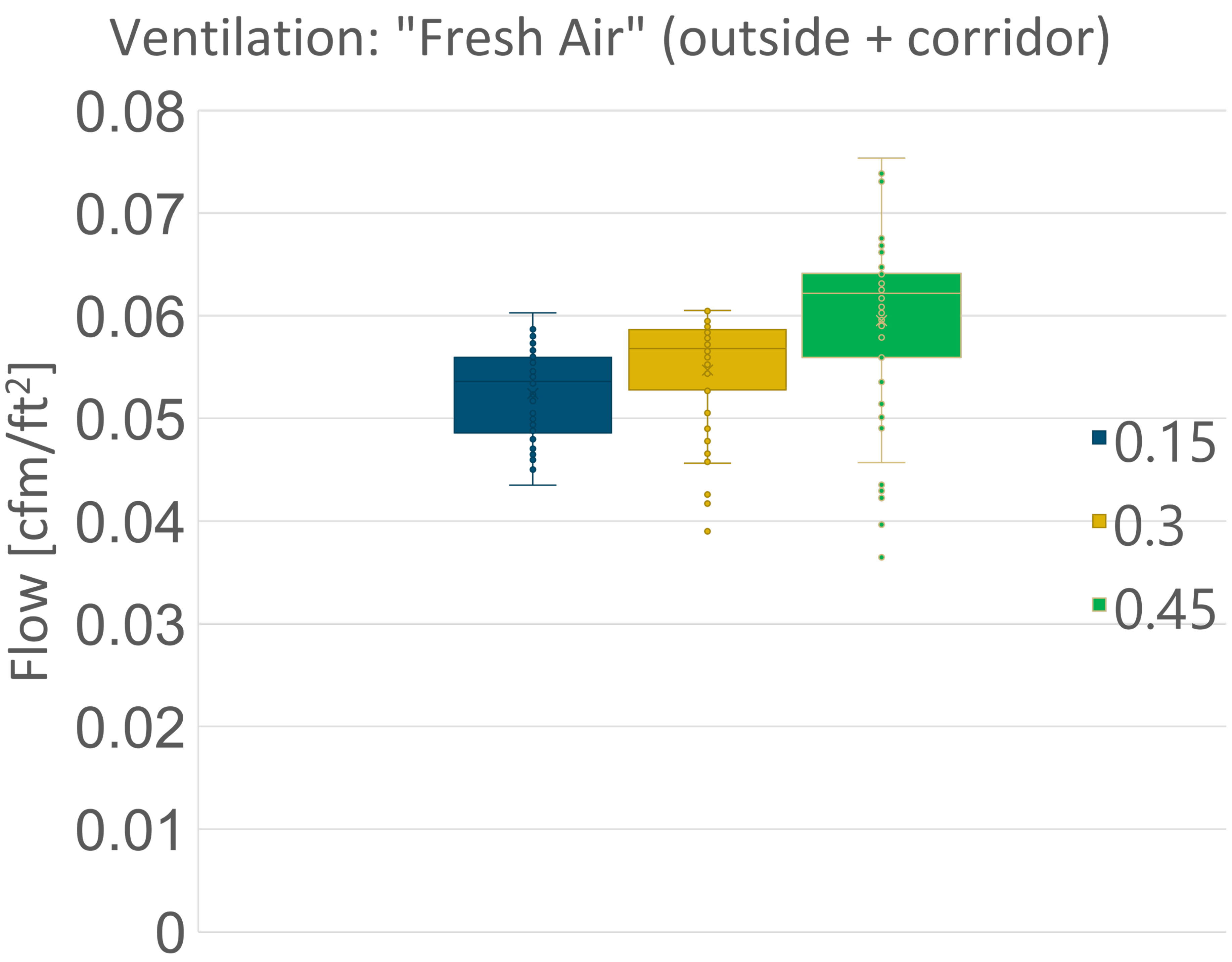
- Average Air Changes per Hour (ACH) increased by **5-15%** when moving from **0.15 to 0.3 cfm_{50}/ft^2** and by **15-30%** when moving from **0.15 to 0.45 cfm_{50}/ft^2**
- Standard Deviation in ACH increased at higher leakage levels
  - This larger variability is not desirable for IAQ or energy use
- "Fresh" outdoor-air ventilation air increased only slightly with increased unit leakage, **0.52, 0.55, 0.6 cfm/ft^2** for leakage levels of **0.15, 0.3, 0.45 cfm_{50}/ft^2**
- Corner units are "over" ventilated, sucking in extra air that they shared with interior units
  - Outdoor ventilation is correlated with exterior surface area
- Energy benefits at tighter leakage levels are climate-zone dependent

CONTAM Modeling Pollutant Results

- Maximum hourly NO_2 concentrations in units with cooking were found to consistently exceed 100 ppb (National Ambient Air Quality Standard for 1-h NO_2) when kitchen exhaust fans were not run
- Formaldehyde levels were found to consistently exceed the concentration resulting in a 1 x 10^{-6} cancer risk in all modeled scenarios, which is consistent with other studies
- Average benzene levels from smoking were found to be just above the concentration resulting in a 1 x 10^{-6} cancer risk in neighboring units for the 0.3 and 0.45 cfm_{50}/ft^2 simulations and just below for the 0.15 cfm_{50}/ft^2 simulation

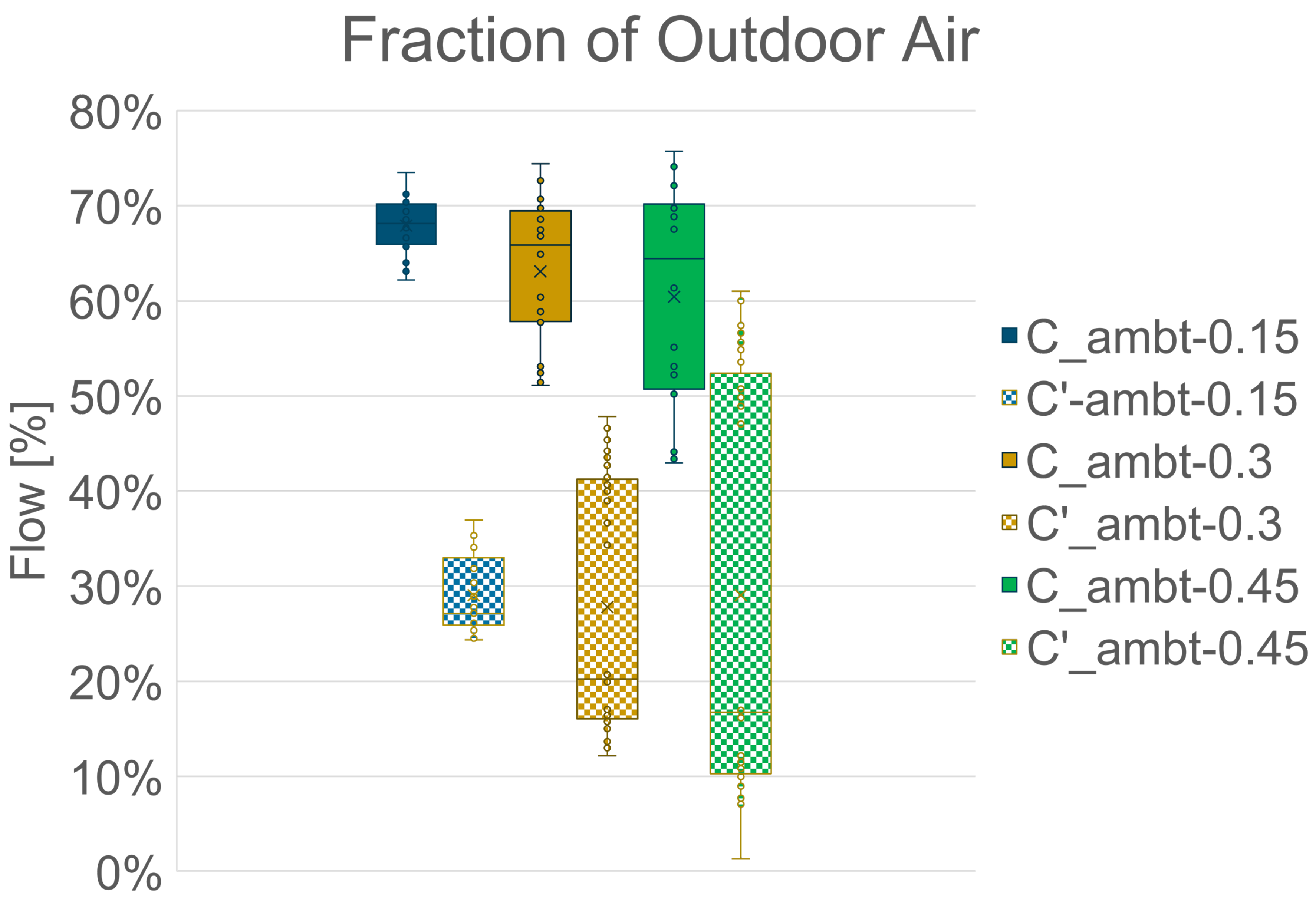
Modeling Results: Leakage Impact on Ventilation

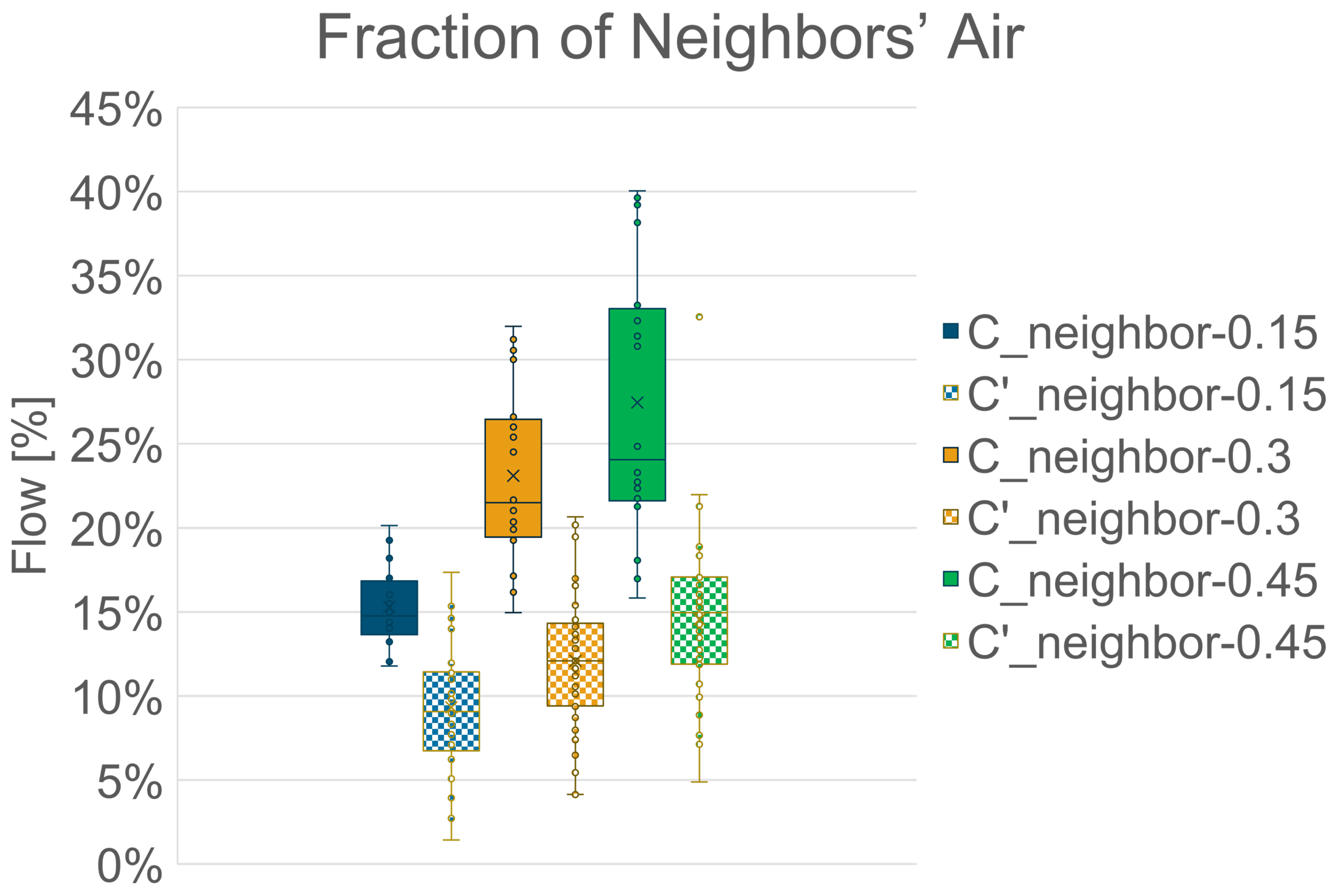




- Leakier buildings have higher overall ACH, and more "fresh" air
- Standard Deviation increases significantly with leakage level, indicating unequal changes among units

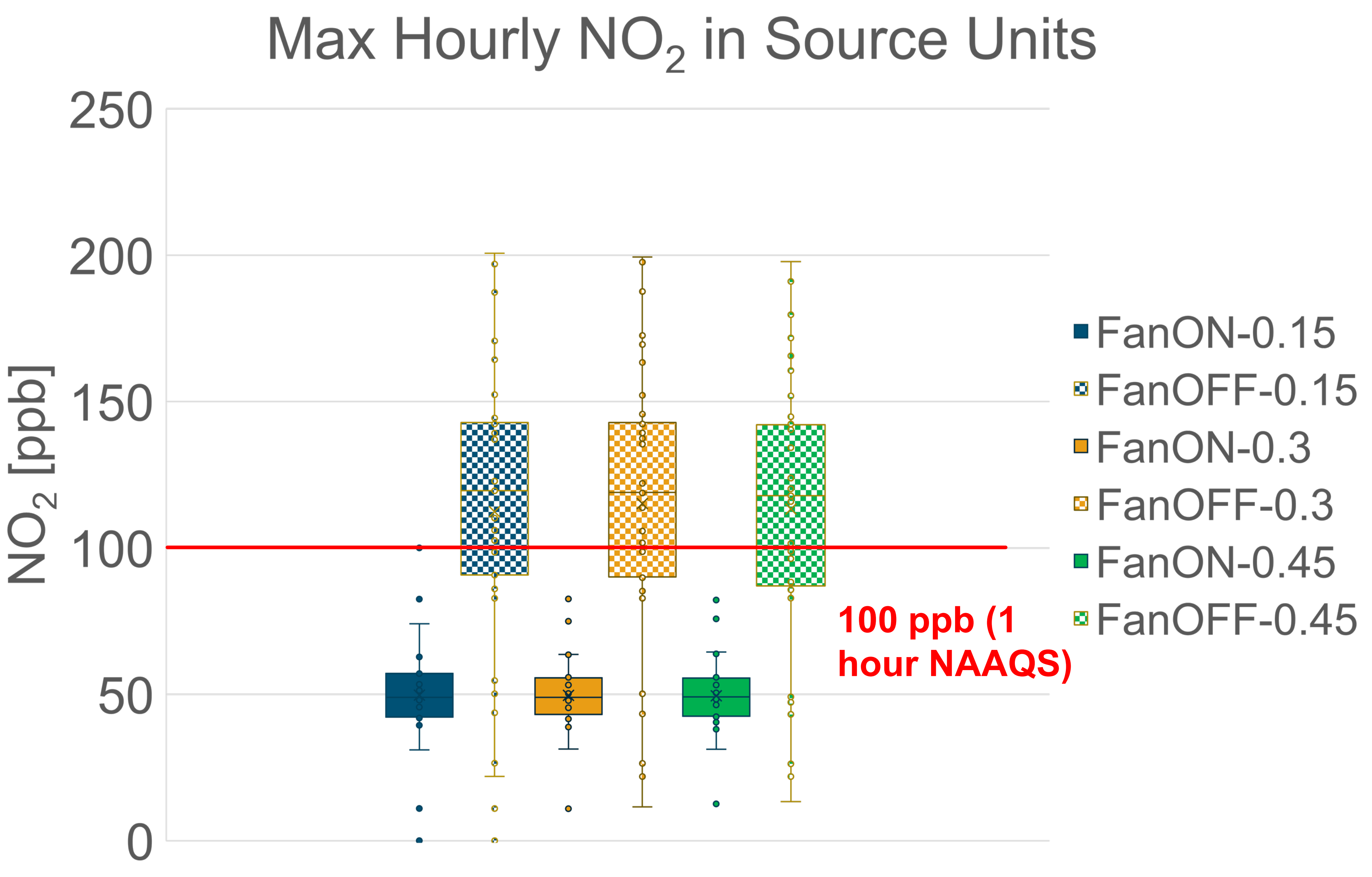
Modeling Results: Leakage Impact on Individual Units

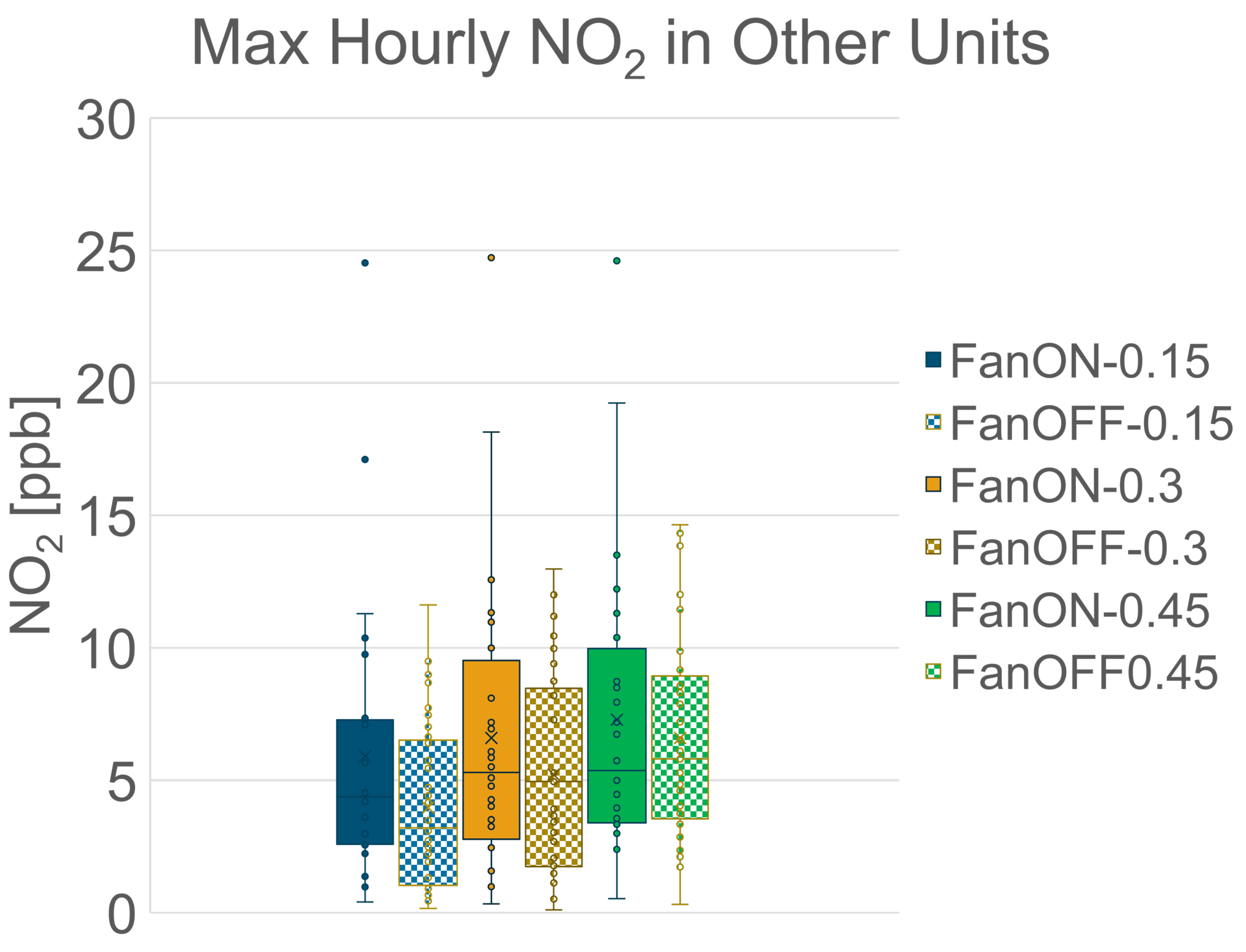




- In "leaky" continuous exhaust buildings, corner units are overventilated, sucking in extra air that they pass on to neighboring units (outdoor flow is proportional to exterior surface area)
- The fraction of "dirty" air flowing into apartments increases in leakier buildings
- C is the corner unit, C' is the middle unit, and more outdoor air flows into corner units

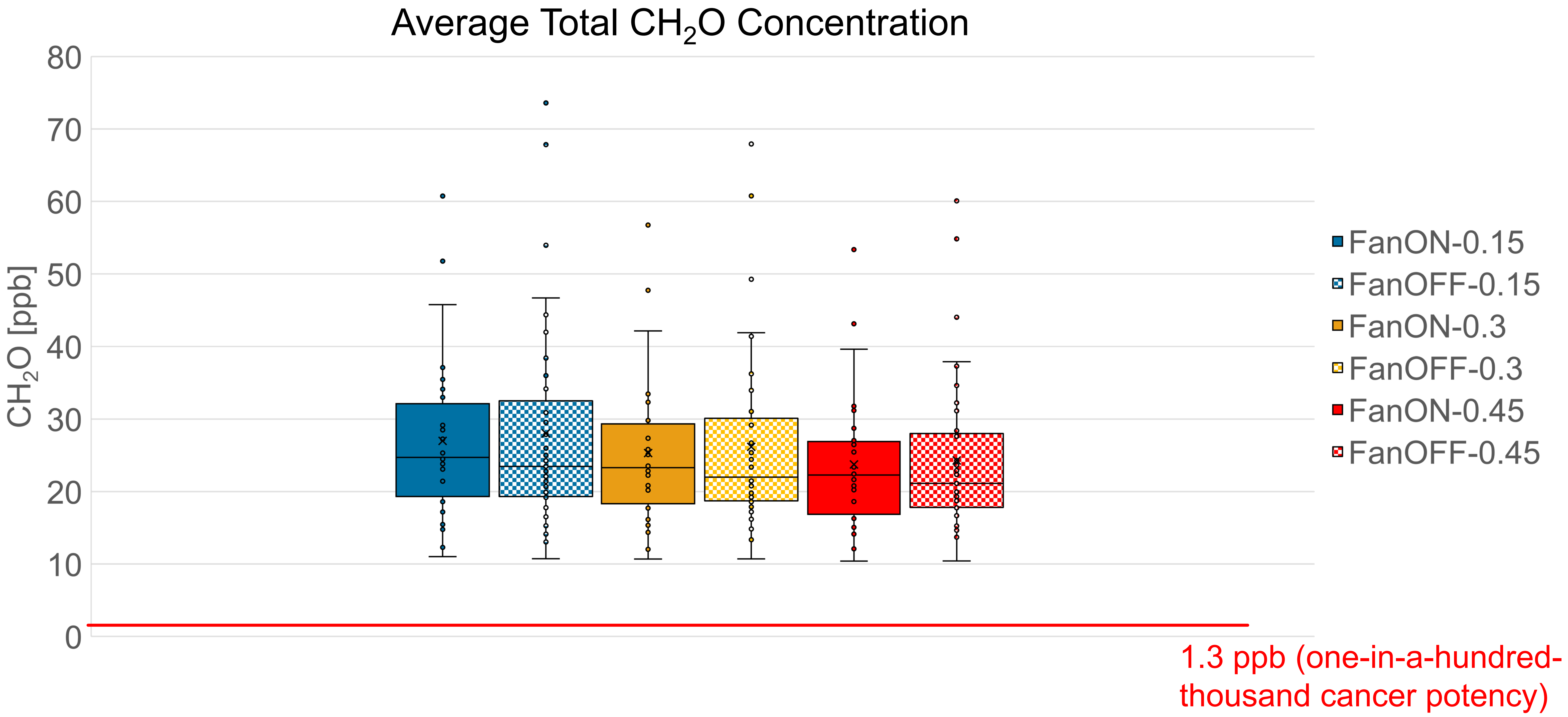
Modeling Results: Leakage Impacts on NO_2





- Units that did not operate their kitchen exhaust fans while cooking had unsafe hourly exposure levels
- Gaseous transfer increased with leakage and fan operation (sucking on other units)

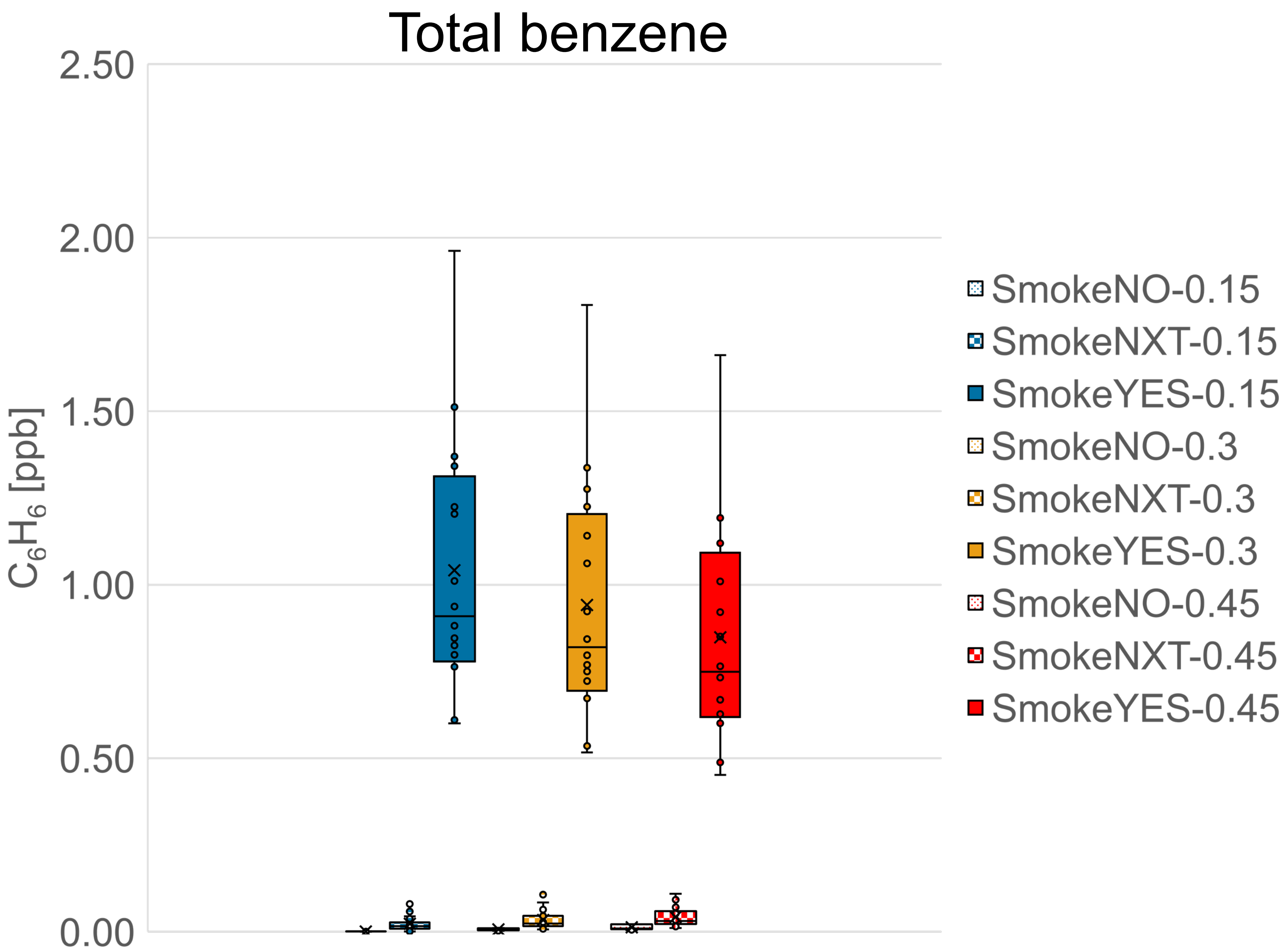
Modeling Results: Leakage Impacts on CH_2O

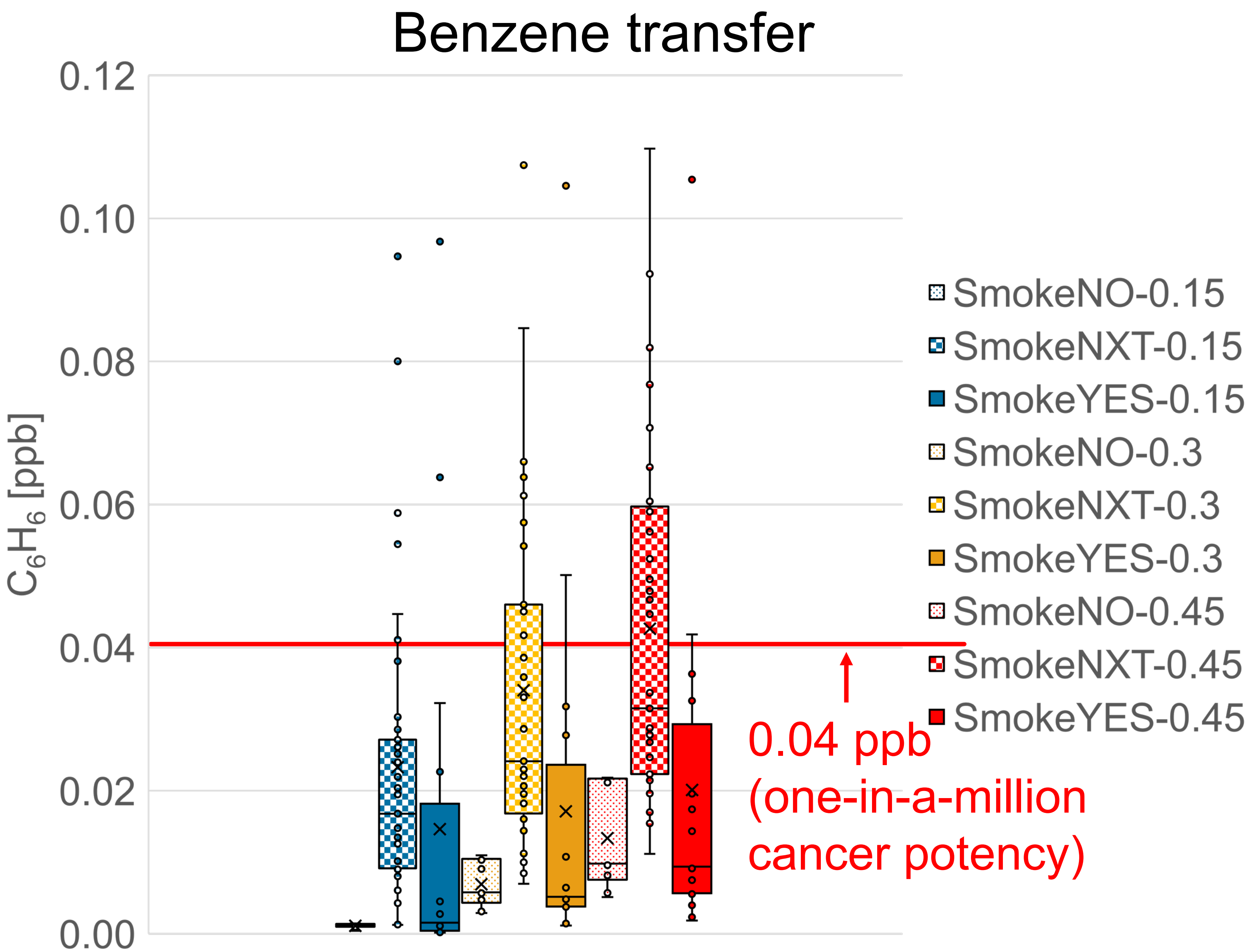


» Formaldehyde levels were “high”, which is consistent with other studies.

» Tighter buildings have higher levels of formaldehyde.

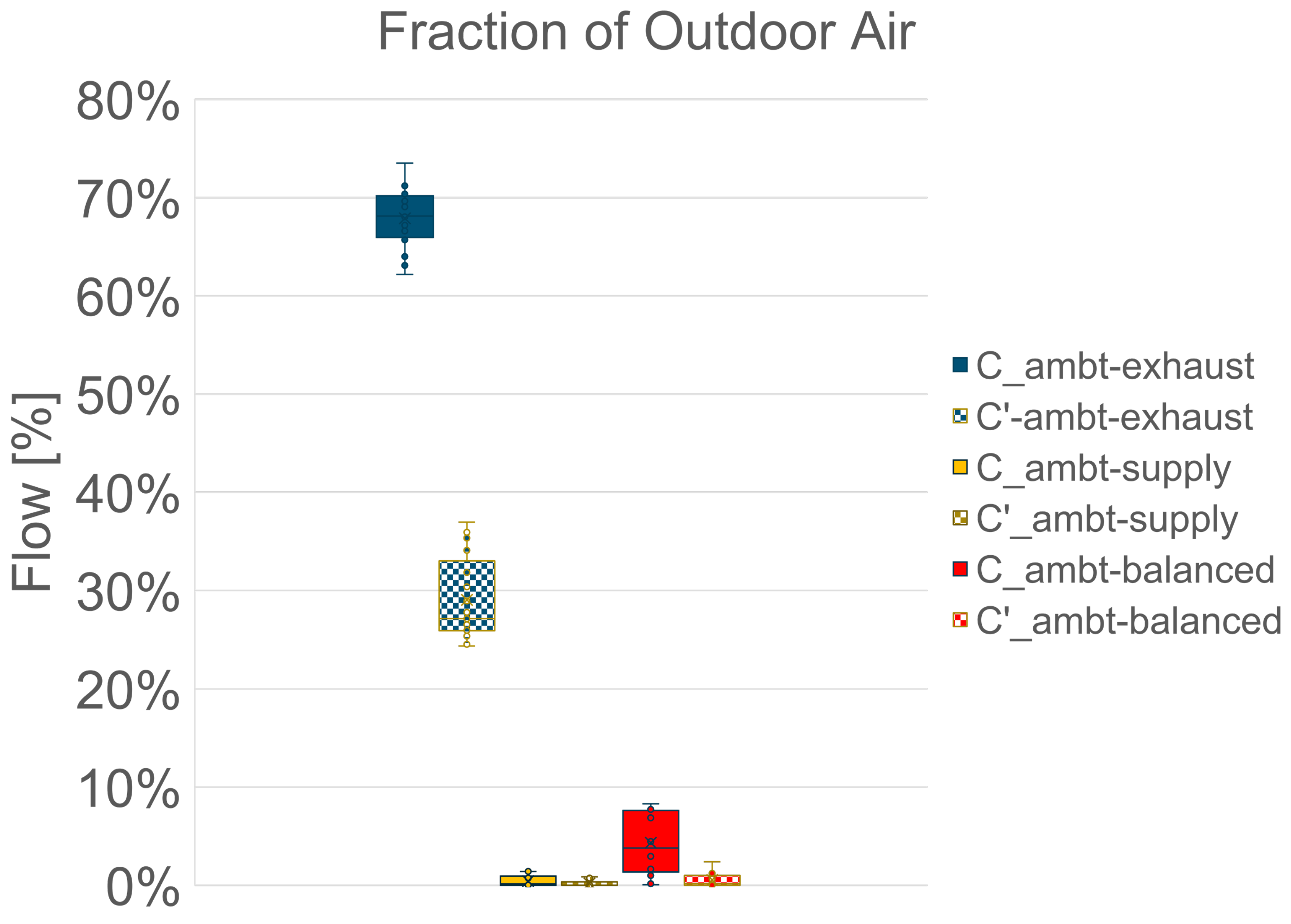
Modeling Results: Leakage Impacts on C_6H_6

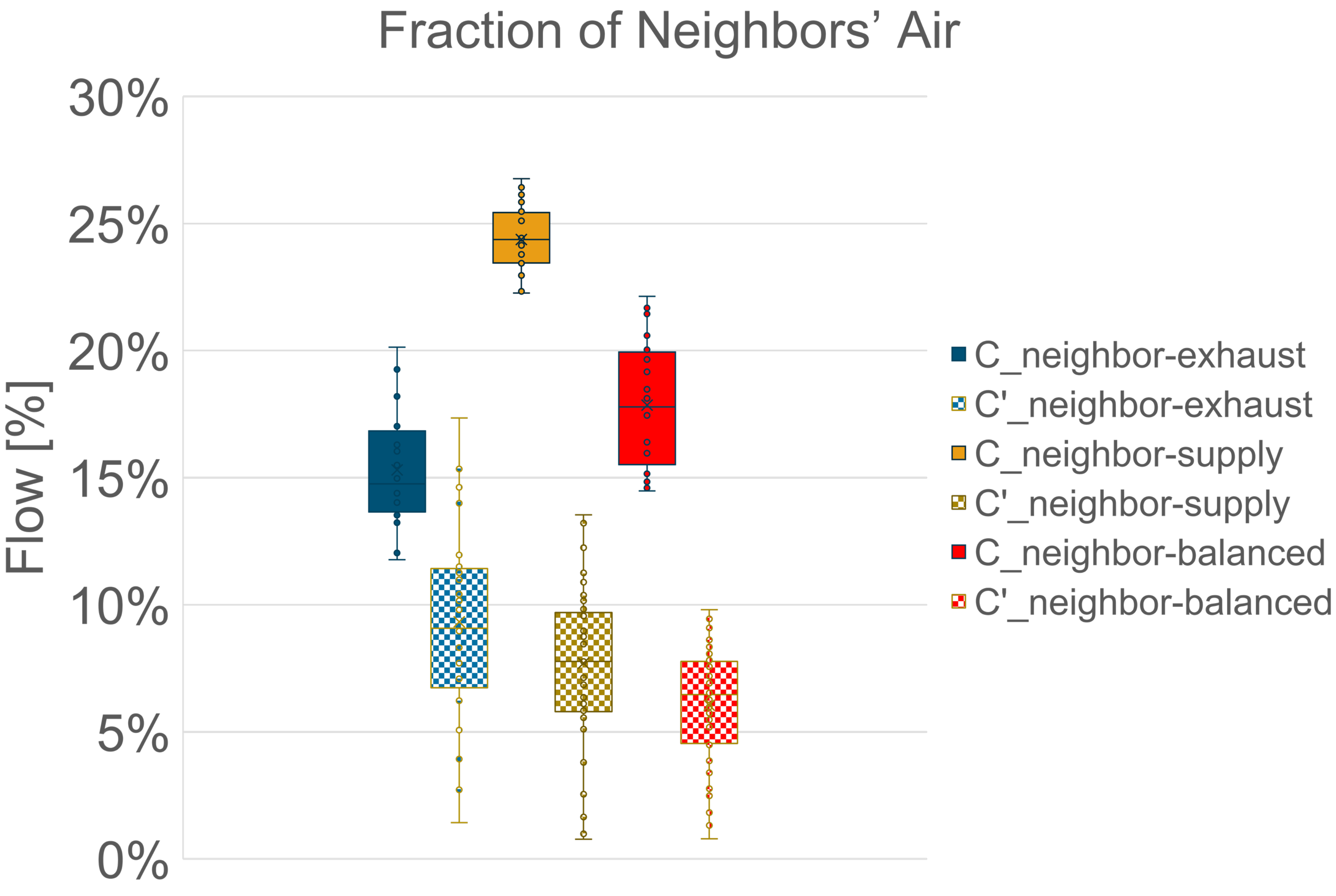




- Average exposure to Benzene (from cigarette smoke) was elevated above the one-in-a-million cancer risk level for leakier simulations

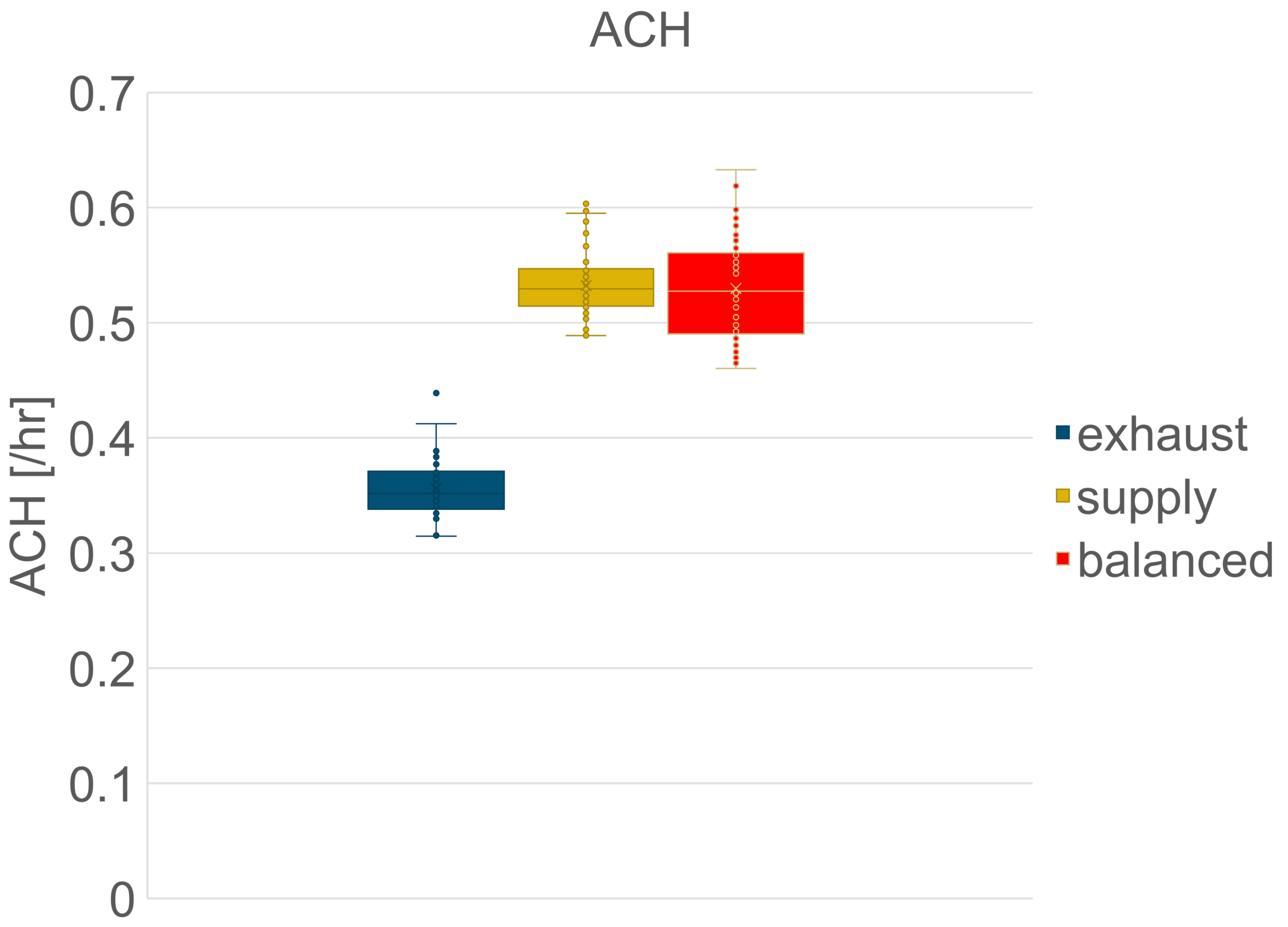
Modeling Results: Ventilation-Type Impacts on Individual Units

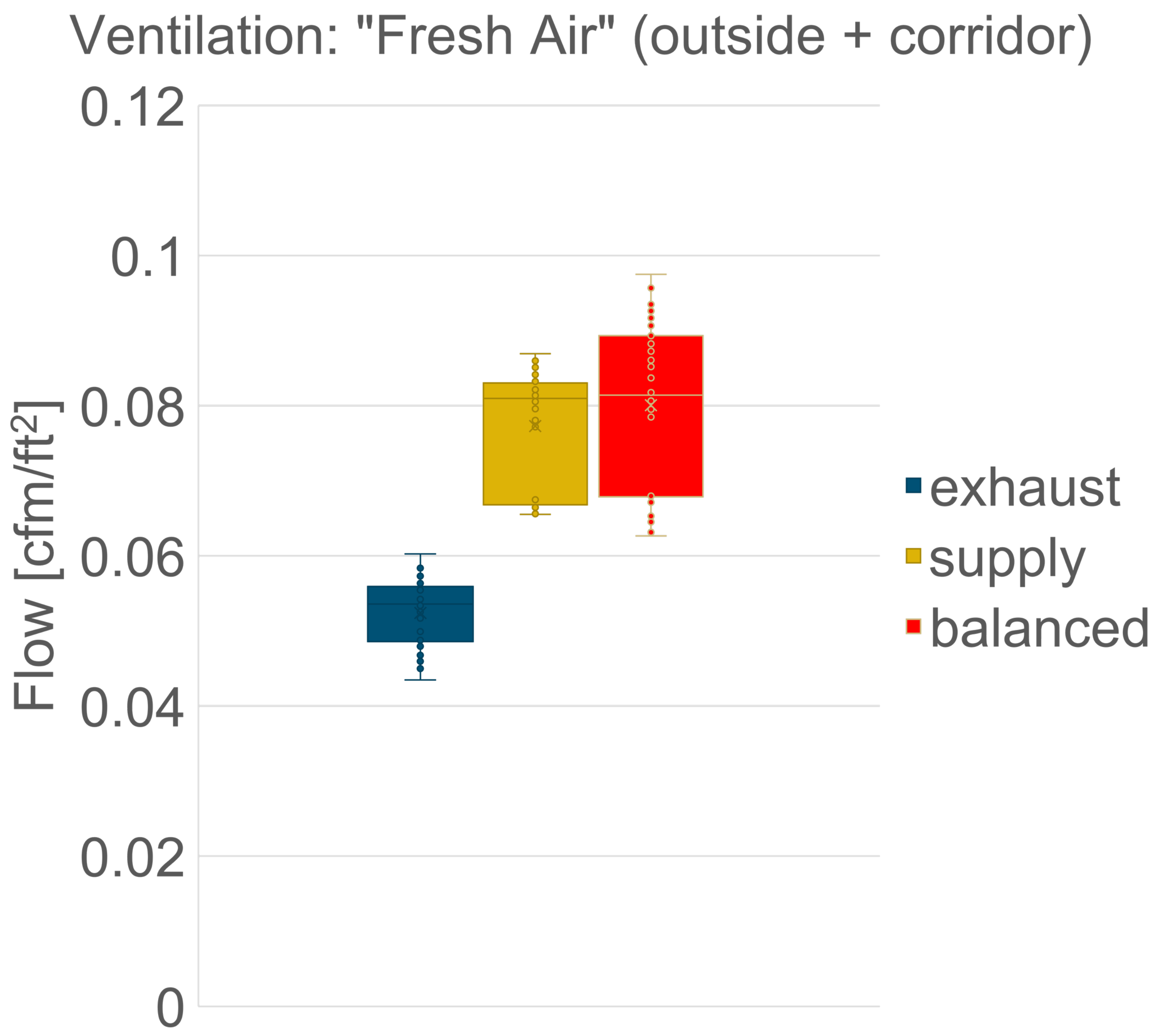




- Supply and balanced systems showed very little infiltration, suggesting balanced systems with heat recovery could save significant heating and cooling energy
- C is the corner unit, C' is the middle unit

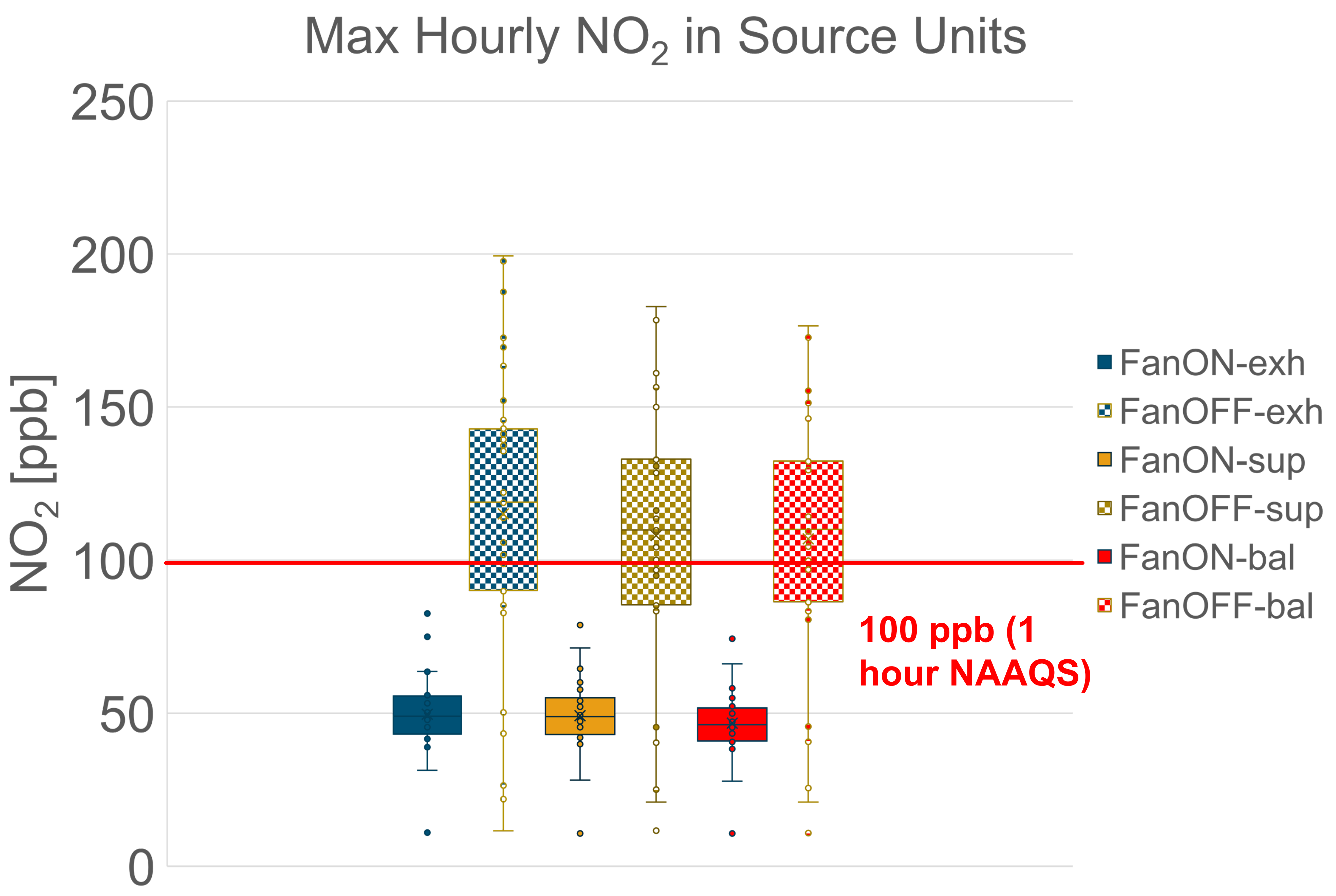
Modeling Results: Ventilation-Type Impacts on Ventilation

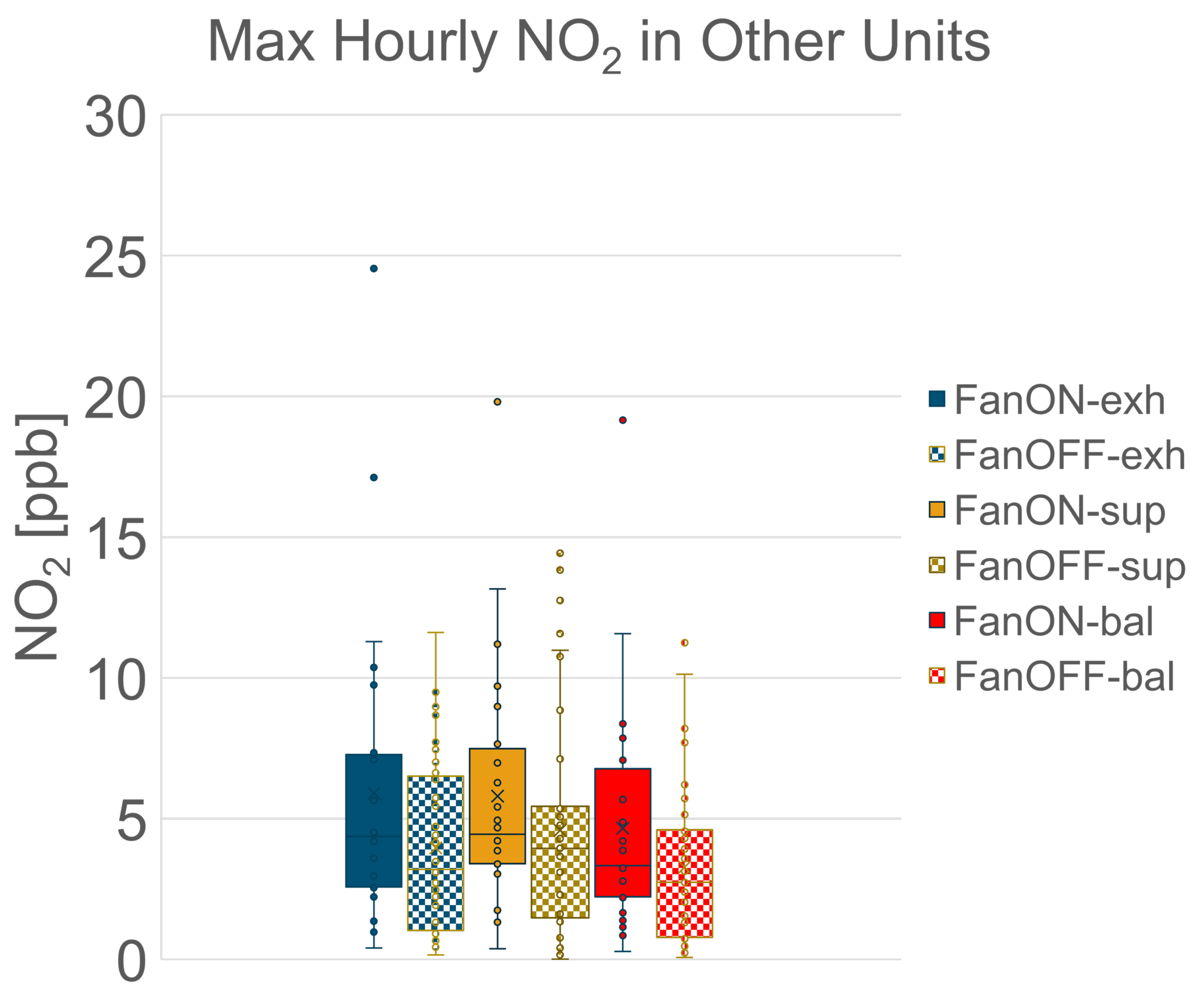




» Balanced and supply ventilation systems showed higher ACH and "Fresh-air" ventilation rates than exhaust-only systems, primarily because the corridor was positively pressurized

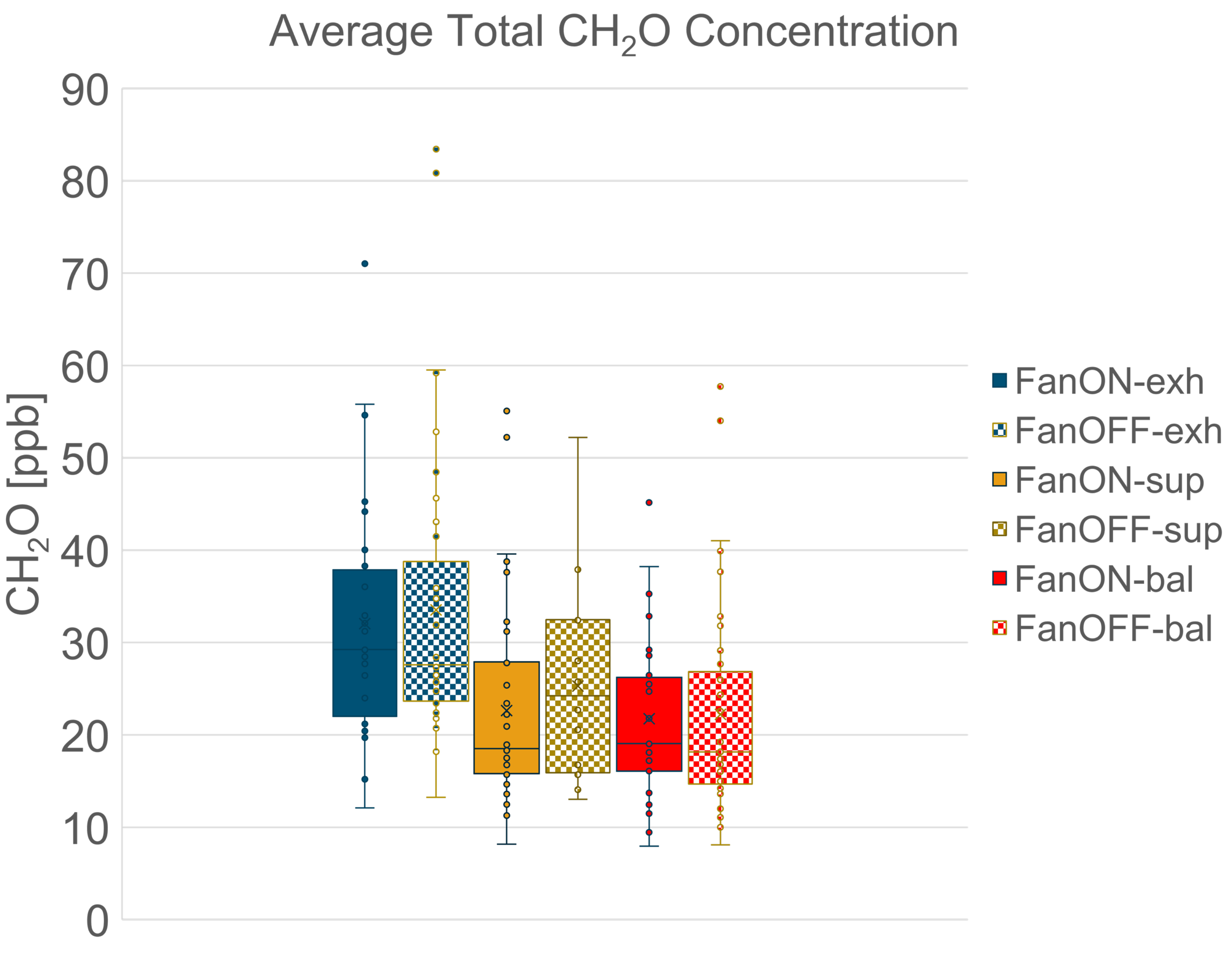
Modeling Results: Ventilation-Type Impact on NO_2

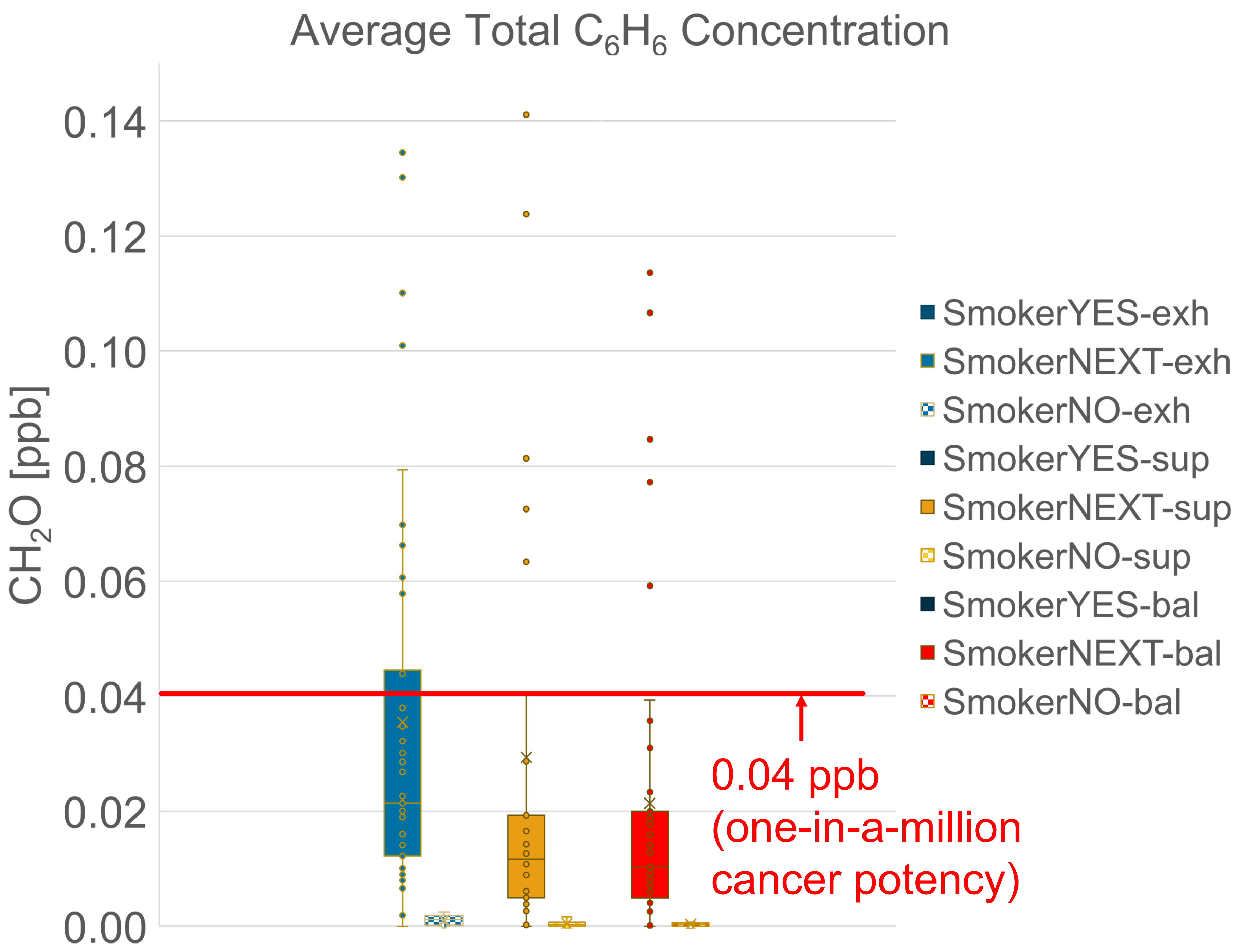




- Kitchen fan operation was a determining factor for acceptable NO_2 exposure
- Units with supply and balanced systems showed lower NO_2 concentrations originating from other units than ones with exhaust systems due to higher ventilation rates

Modeling Results: Ventilation-Type Impact on CH_2O & C_6H_6



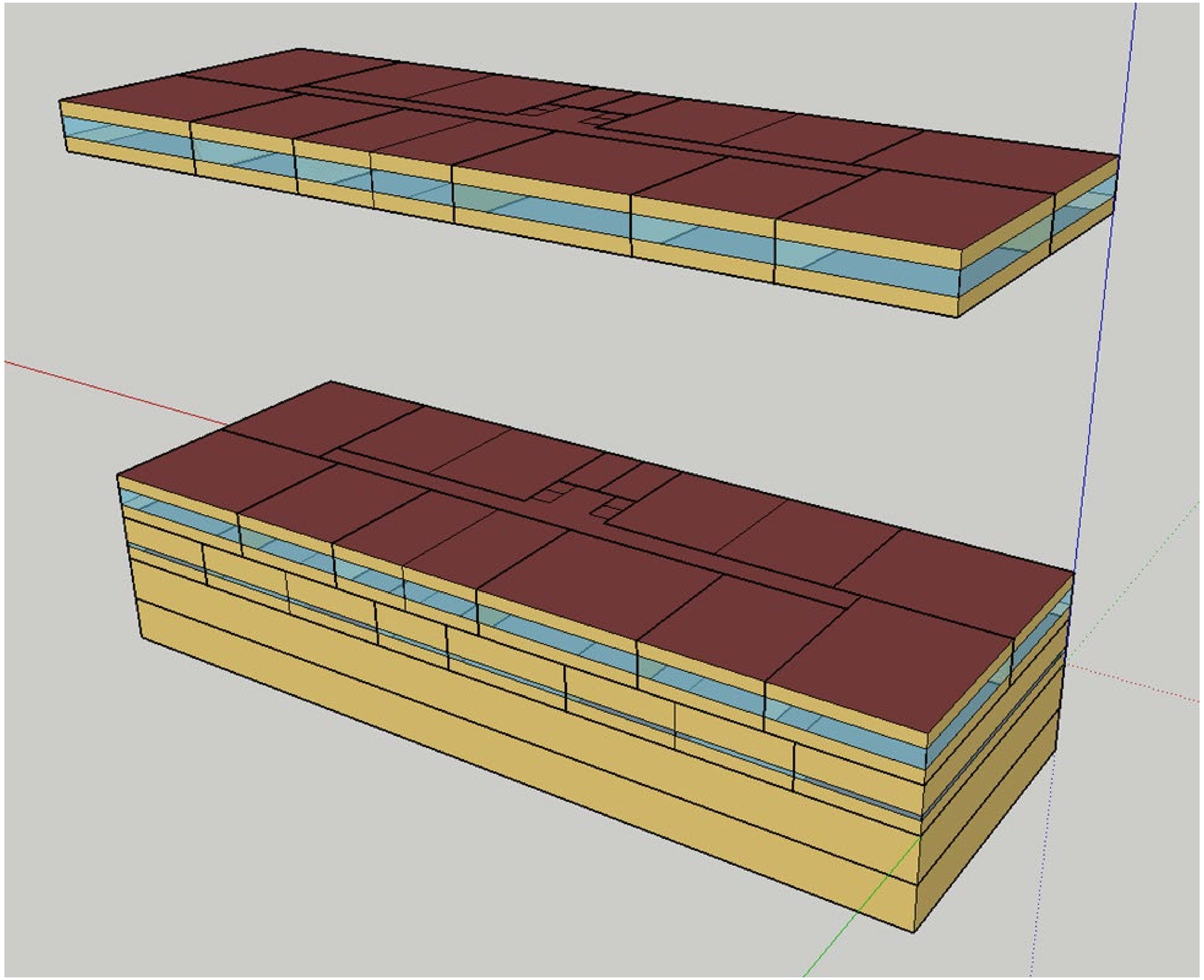


- Formaldehyde and benzene decreased in the supply and balanced models due to higher ventilation rates
- Benzene in SmokerYES units is off scale so not shown.

EnergyPlus Modeling

» Building Specification

- Multifamily IAQ CASE report building
- Total Building outputs halved to go from ten to five stories
- DOAS central supply air pre-heating/cooling coils deleted
- Entire space conditioning load met by in-unit Packaged Heat Pumps

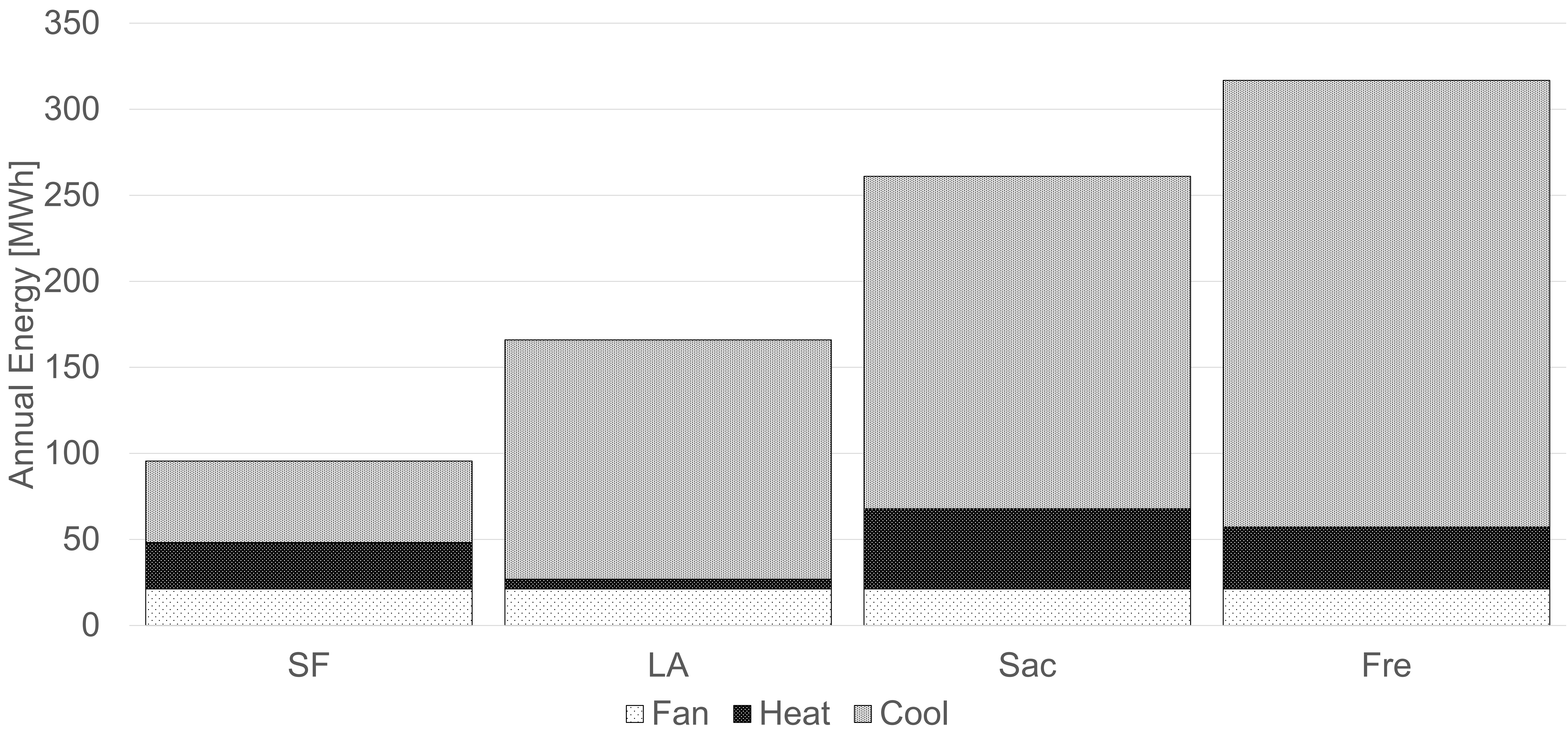


EnergyPlus Modeling

» Combination with CONTAM

- Outdoor air flow (infiltration plus supply ventilation) from CONTAM subtracted from EnergyPlus base case value
- Change in outdoor air flow combined with TMY weather data to calculate changes in heating/cooling loads (product of change in airflow and enthalpy differential) for each timestep
- Load changes combined with HVAC efficiencies for each timestep to calculate energy implications of different cases (i.e., leakage levels, ventilation systems)

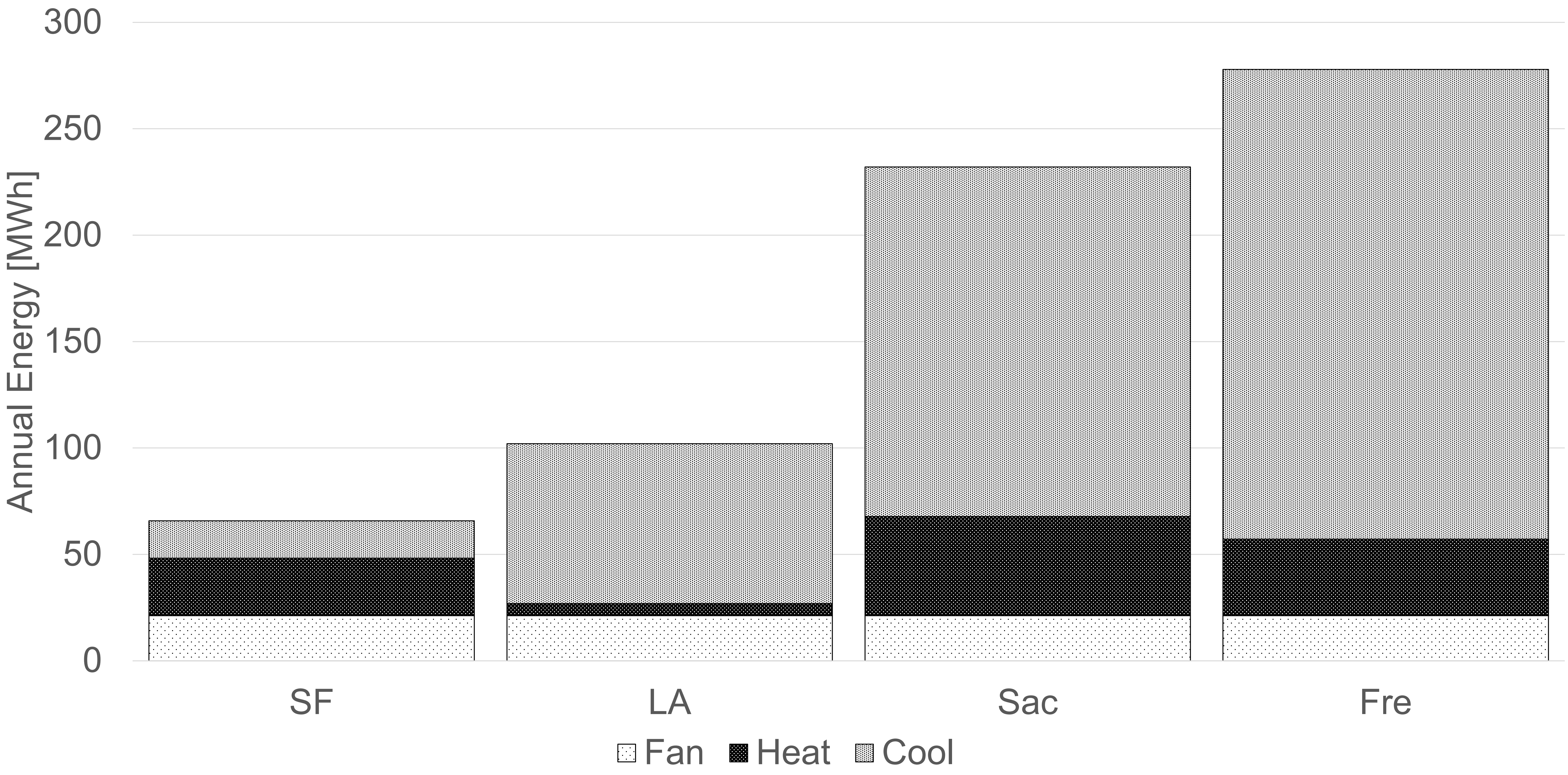
EnergyPlus Modeling – Original Results



EnergyPlus Modeling

» Impact of not allowing Window Openings
  - Reducing unit leakage wound up increasing cooling loads – due to loss of free cooling from excess outdoor air flow in leaky units
  - Developed post-processing methodology to eliminate cooling loads in periods when the outdoor conditions support opening windows (or running an economizer) to maintain comfort
    - Identified all hours during which EnergyPlus showed a cooling load with the outdoor air enthalpy being lower than indoor enthalpy
    - Eliminated the cooling load for that hour, and assumed that window-opening or economizer operation produced an outdoor airflow of 200 cfm for that hour
    - Assumed that the percentage reduction in cooling load for other hours with cooling is equal to the percentage savings for hours with heating

EnergyPlus Modeling – with Window Opening



Impacts on Energy and GHG

Climate	Ventilation	Leakage [cfm50/ft^2]	Annual HVAC Energy Use [MWh]	HVAC-Energy (GHG) Savings [%]	GHG Savings [t CO_2e/30 yrs]
Sac	bal	0.15	222	6%	45
Sac	bal	0.3	228	3%	23
Sac	bal	0.45	235		
Sac	bal-hx	0.15	167	29%	231
Sac	exh	0.15	197	16%	130
Sac	sup	0.15	207	12%	96

Conclusions – Building Characterization

- Measured Unit Leakage Levels were **~50%** lower than code: **A tighter standard is achievable**
- Unit leakage and ventilation flow rates varied with a standard deviation of **~10-15%**

Conclusions – Indoor Air Quality

- Compartmentalization to **Stricter Leakage Targets Results in Lower Gaseous Pollutant Transfer**
- No observed particulate transfer between units in buildings tested
- For units with gas stoves, NO_2 exposure was higher than the outdoor regulatory level (the NAAQS for 1-hour NO_2) if the kitchen exhaust fan was not used
- Modeling the highest leakage level (0.45 cfm_{50}/ft^2), units living next to a smoker have benzene exposure above the 1×10^{-6} cancer risk level

Conclusions – Energy Use and Greenhouse Gas Emissions

- HVAC energy and GHG savings of **4-6%** by tightening from 0.45 cfm_{50}/ft^2 to 0.15 cfm_{50}/ft^2
- Additional **5-20%** of HVAC energy and GHG savings by going from balanced to single-fan ventilation OR **16-26%** by adding heat exchangers to balanced systems (not including pressure losses)
- EnergyPlus results had to be modified to account for window openings – otherwise simulates San Francisco as a cooling-dominated climate
- EnergyPlus dramatically overestimates infiltration

Conclusions – Potential Code Implications

- Tighter leakage targets in the code are clearly achievable
- Modest energy and GHG savings and measurable IAQ improvements can be achieved with Tighter leakage targets in the code
- More significant energy and GHG savings can be achieved by either
  - Eliminating two-fan energy use by using either supply-only or exhaust-only ventilation OR
  - Adding heat exchangers to balanced ventilation systems
    - Climate dependent
    - Pressure-drop increases not analyzed

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