

Relationships between the Building and Indoor Chemistry

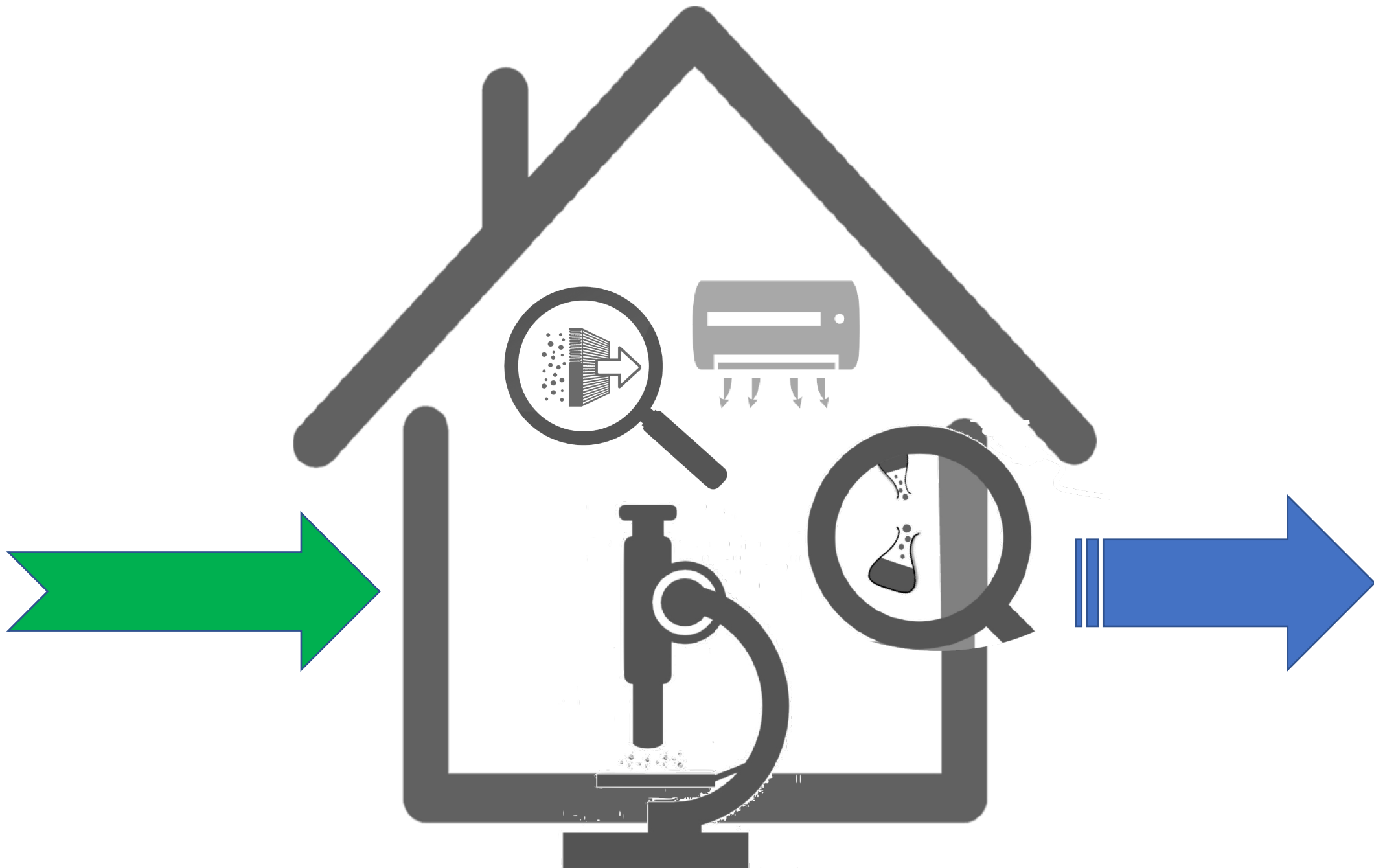
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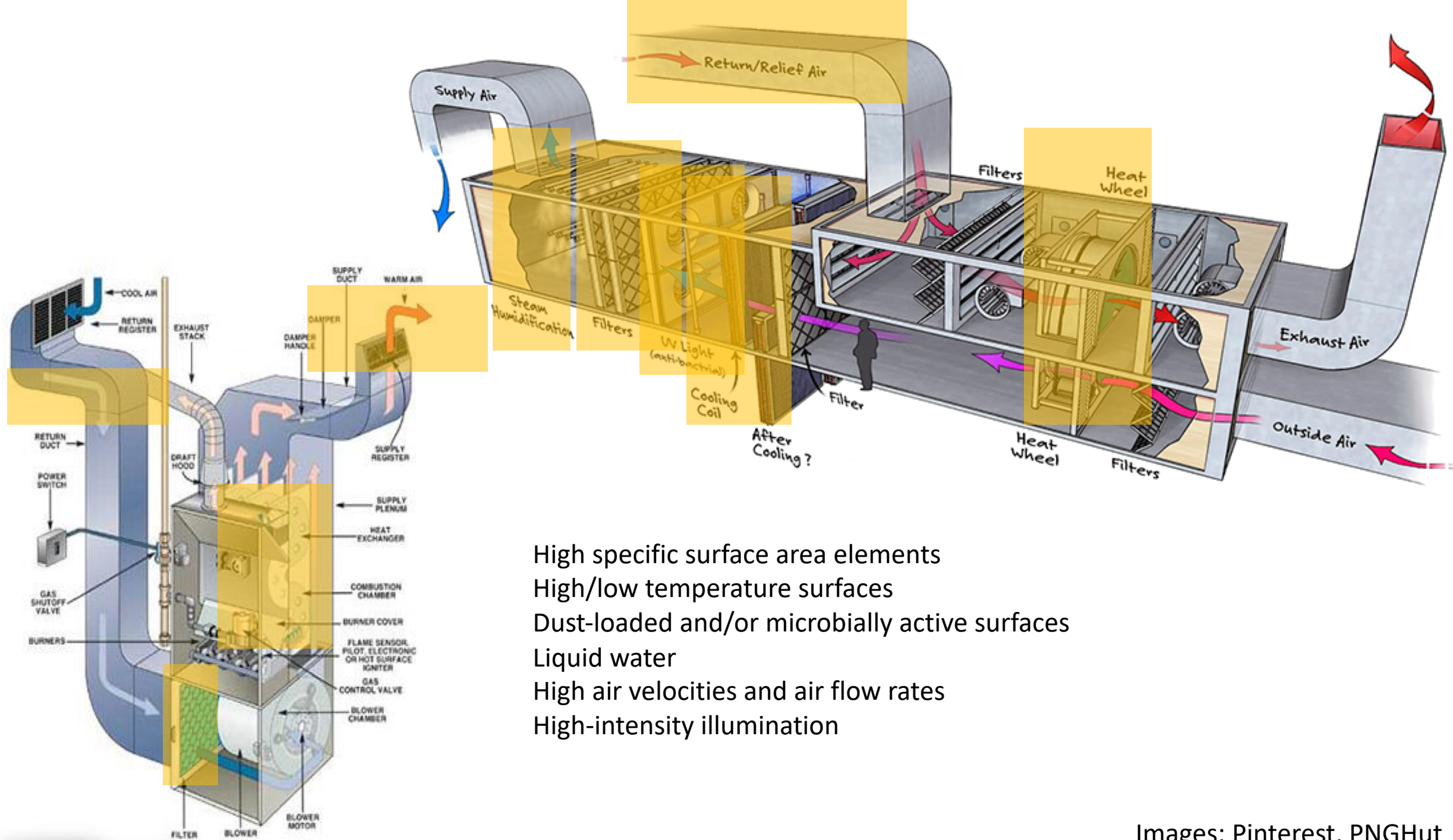


Two Specific “Systems”

- Heating, ventilation, and air conditioning (HVAC) systems
 - Unseen and interstitial spaces
- High surface area to volume ratio
 - High dust/contamination concentrations
 - Condensed water
 - Extreme temperatures and humidities

Table 1. Emission sources and problems identified in HVAC systems

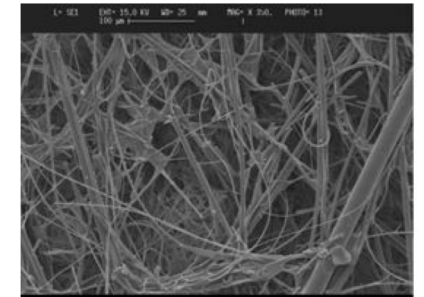
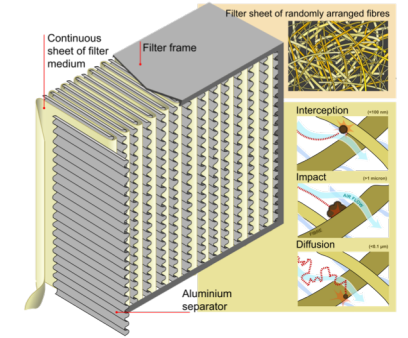
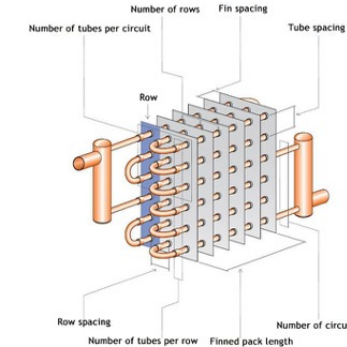
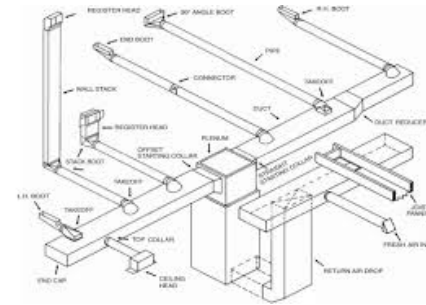
SOURCES AND PROBLEMS	TYPICAL EXAMPLES
Intrinsic emission sources	
1. <i>Seals, caulks, adhesives</i>	outgassing of VOCs, deterioration
2. <i>Fibers</i>	asbestos, fiber shedding
3. <i>Metal degradation products</i>	deterioration and entrainment of coatings, platings, metal surfaces
4. <i>Lubricating oils, etc.</i>	fans, motors in the air stream
5. <i>Ozone</i>	release by electrostatic air cleaners
Emission sources resulting from contamination	
1. <i>Dust</i>	construction material, skin cells, etc., with accumulation possibly leading to microbial contamination, VOC sorption-desorption, and low flows
2. <i>Other organic debris</i>	leaves, bird droppings
3. <i>Growth of microorganisms</i>	growth and aerosolization of bioaerosols and VOCs from micro-organisms at sites including: cooling coils, drain pans, drains, traps and sumps, filters, insulation, duct surfaces, plenums, humidifiers and evaporative coolers, cooling towers
4. <i>VOC sinks</i>	filters, sound absorbers, insulation materials, deposited dust
5. <i>Cleaning compounds and biocides</i>	biocides, disinfectants, deodorizers
6. <i>Boiler steam</i>	anticorrosives, biocides, slimicides, oxygen-scavenging or filming chemicals, anti-corrosives, pH control neutralizers
Design/operational effects on IAQ	
1. <i>Entrainment and re-entrainment</i>	leaks, polluted outside air, building exhaust
2. <i>Rotary heat exchangers</i>	sorption-desorption of VOCs
3. <i>Building pressurization</i>	intake of polluted outside air
4. <i>Transport</i>	odor, VOC and particle migration
5. <i>Climate control</i>	high humidity
6. <i>Ventilation and air exchange</i>	inadequate dilution of internal sources, inadequate outside air



High specific surface area elements
 High/low temperature surfaces
 Dust-loaded and/or microbially active surfaces
 Liquid water
 High air velocities and air flow rates
 High-intensity illumination

HVAC System Physical Properties

- Clean surface area to volume ratios
 - Ducts ($\sim 1\text{-}10/\text{m}$)
 - Heat exchangers ($100\text{-}1000/\text{m}$)
 - HVAC filter ($\sim 100/\text{m}$)
- Air velocities and airflows
 - $1\text{-}5\text{ m/s}$
 - $1\text{-}10$ building volumes/h
- Temperatures
 - $50\text{-}80\text{ }^{\circ}\text{C}$ heat exchangers & radiators
 - $5\text{-}15\text{ }^{\circ}\text{C}$ cooling coils



Images: <https://www.pickhvac.com/hvac-ductwork-cost/>, <https://www.dh-ts.com/power-generation-industrial-products/coils/>, <https://en.wikipedia.org/wiki/HEPA>, <https://medium.com/>

Air Distribution Systems

- Sheet metal (+rubber, plastics, insulation)
- Even when “clean”: Sealants, lubricants, cutting oils, gaskets

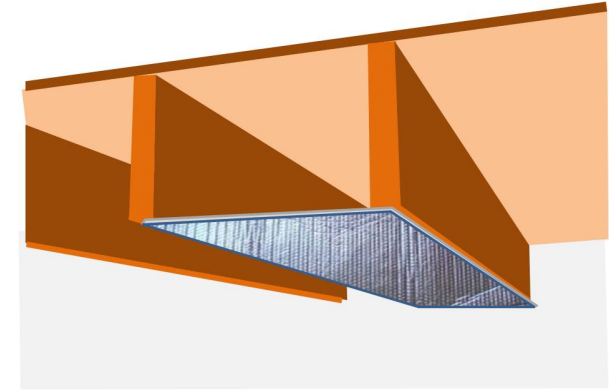


Image: basc.pnnl.gov

Table 1. Emission rates of total volatile organic compounds (TVOC) and aldehydes from duct components. ^a

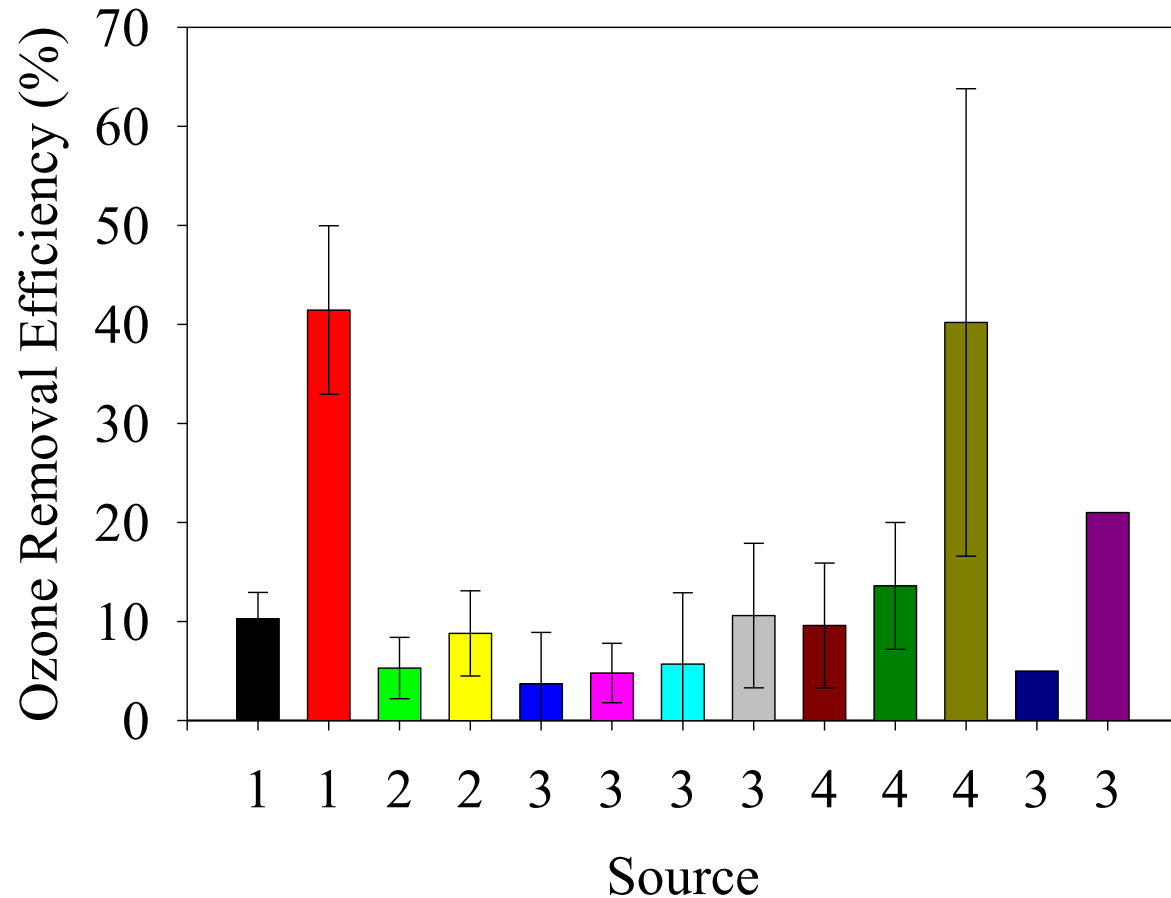
Material	TVOC	Emission Rate ($\mu\text{g m}^{-2} \text{hr}^{-1}$) ^a			
		HCHO	CH ₃ CHO	Acetone	C ₅ -C ₁₀ Aldehydes
<i>new duct liners</i>					
NDL2	b	b	b	29	b
NDL3	b	40	b	b	b
<i>used duct liners</i>					
UDL2	950	b	b	87	220
UDL3	1280	37	b	38	260
UDL4	b	29	25	b	b
UDL5	b	b	b	b	b
<i>used fan-box</i>					
insulation	1140	d	d	b	b
neoprene gasket	7200	b	b	b	b
<i>duct connector</i>					
duct sealant	8800	b	67	b	760
<i>spiral-wound duct</i>					
galvanized	b	b	b	b	b
<i>sheet metal</i>					
air filters	b	b	b	b	b
AF1	b	b	b	b	b
AF2	b	b	b	b	b
AF3	550	b	20	57	b
AF4	430	38	b	b	b

Table 3. Emission rates of total volatile organic compounds (TVOC) and aldehydes from duct components after exposure to ozone for 24 hr.

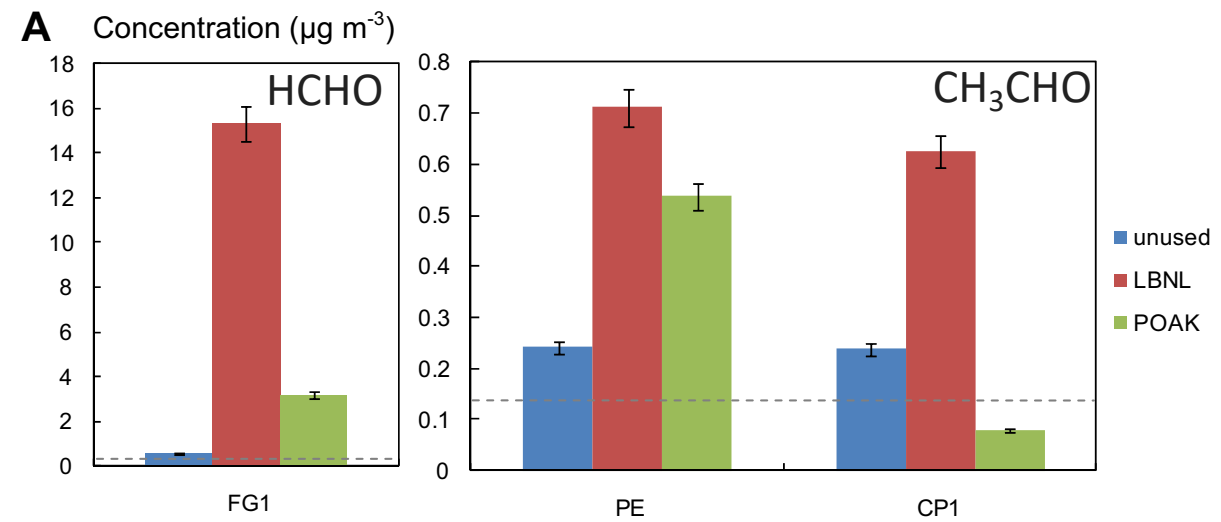
Material	TVOC	Emission Rate ($\mu\text{g m}^{-2} \text{hr}^{-1}$) ^a				Ozone (ppb)	
		HCHO	CH ₃ CHO	Acetone	C ₅ -C ₁₀ Aldehydes	Inlet	Chamber/Outlet
NDL2	550	b	20	166	380	110	72 ± 12
NDL3	b	60	b	b	b	140	31 ± 8
neoprene gasket	6400	b	b	120	330	140	65 ± 9
duct sealant	4000	24	290	b	660	100	27 ± 15

Morrison et al. (1998) *JAWMA*

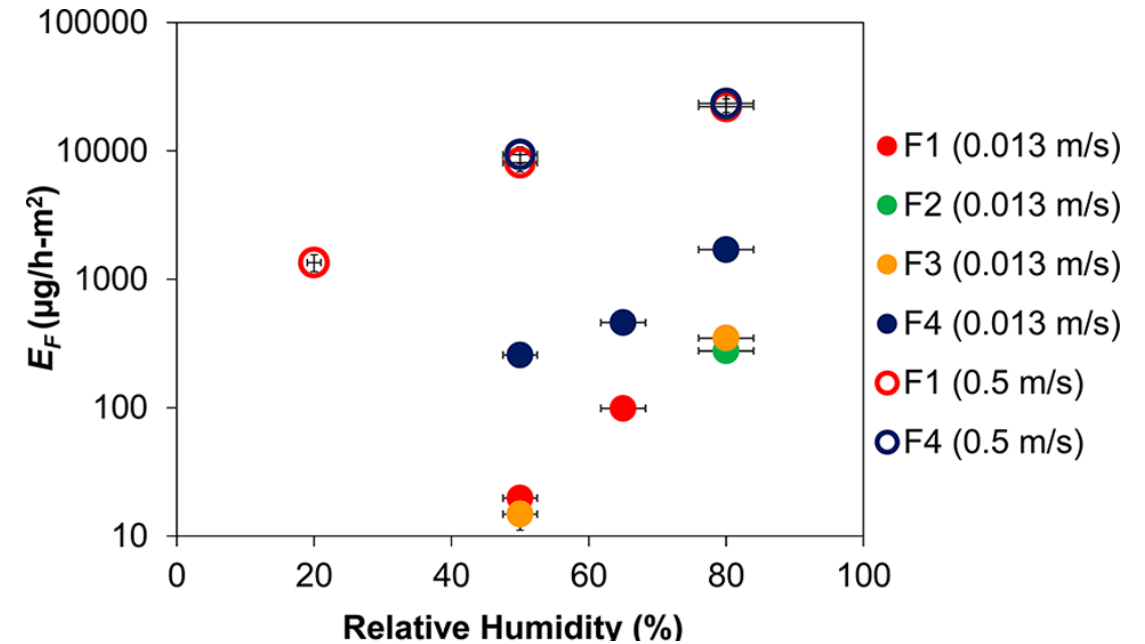
Clean And Used Filters



1. Zhao et al. (2007) *Atmos Environ*
2. Beko et al. (2006) *Indoor Air*
3. Hyttinen et al. (2003) *Indoor Built Environ*
4. Hyttinen et al. (2006) *Atmos Environ*



Destailats et al. (2011) *Atmos Environ*



Sidheswaran et al. (2013) *Environ Sci Tech*

Heating Heat Exchangers

“Heat treatment induces a significant increase in the number of emitted sub-micron particles, probably dominated by condensation particles. This occurs even at low temperatures, (50–100 °C), which are often present in an indoor environment.”

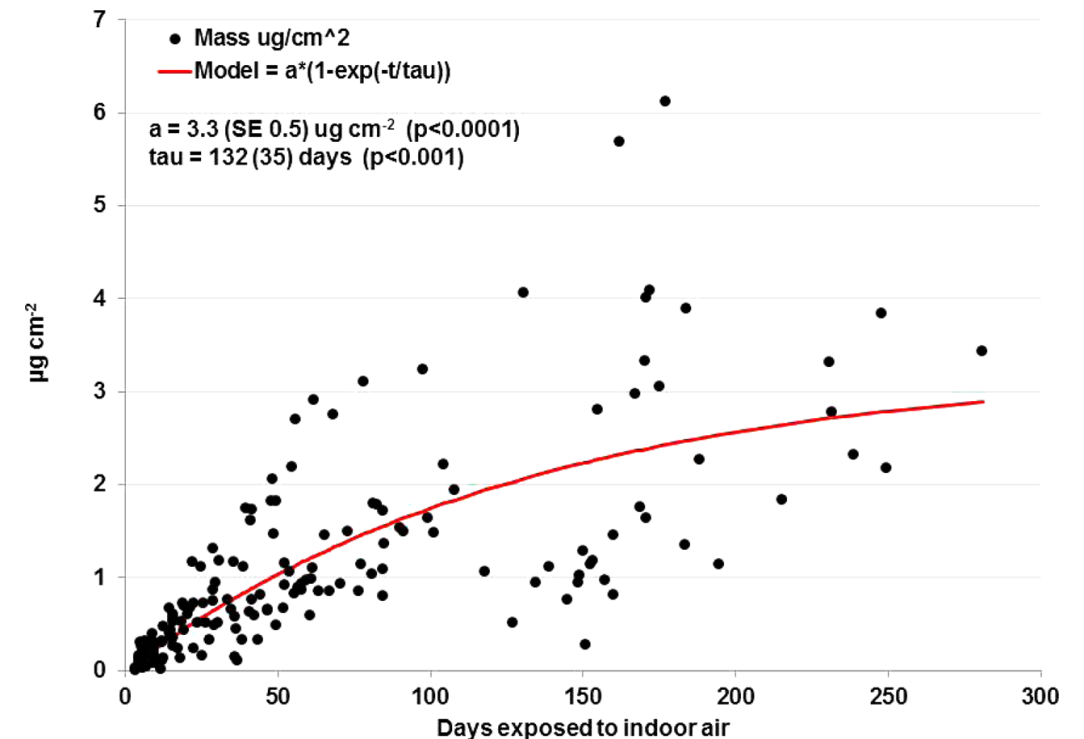
Pederson et al. (2001) *Atmos Environ*

UFP source	C_{ind} (particles/cm ³)	Estimated source strength (particles/min × 10 ¹¹)
Flat iron (without steam) on a cotton sheet	550	0.007
Flat iron (with steam) on a cotton sheet	7200	0.06
Air-freshener spray	29,900	2.34
Scented candles	69,600	0.88
Pure wax candle	241,500	3.65
Electric stove	111,500	6.8
Radiator	218,400	8.84
Vacuum cleaner with full bag	21,400	0.35
Vacuum cleaner (motor) without bag	38,300	0.38
Cigarette	213,300	3.76
Gas stove	79,600	1.30
Heater	116,800	3.89
Frying meat	150,900	8.27

Afshari et al. (2005) *Indoor Air*

“Emissions of volatile organic compounds from heated dust from different sources were surprisingly similar. However, the temperature at which the emission of volatiles started varied with the dust source.”

Pederson et al. (2003) *Indoor Air*



Wallace et al. (2017) *Environ Sci Tech*

Cooling Coils

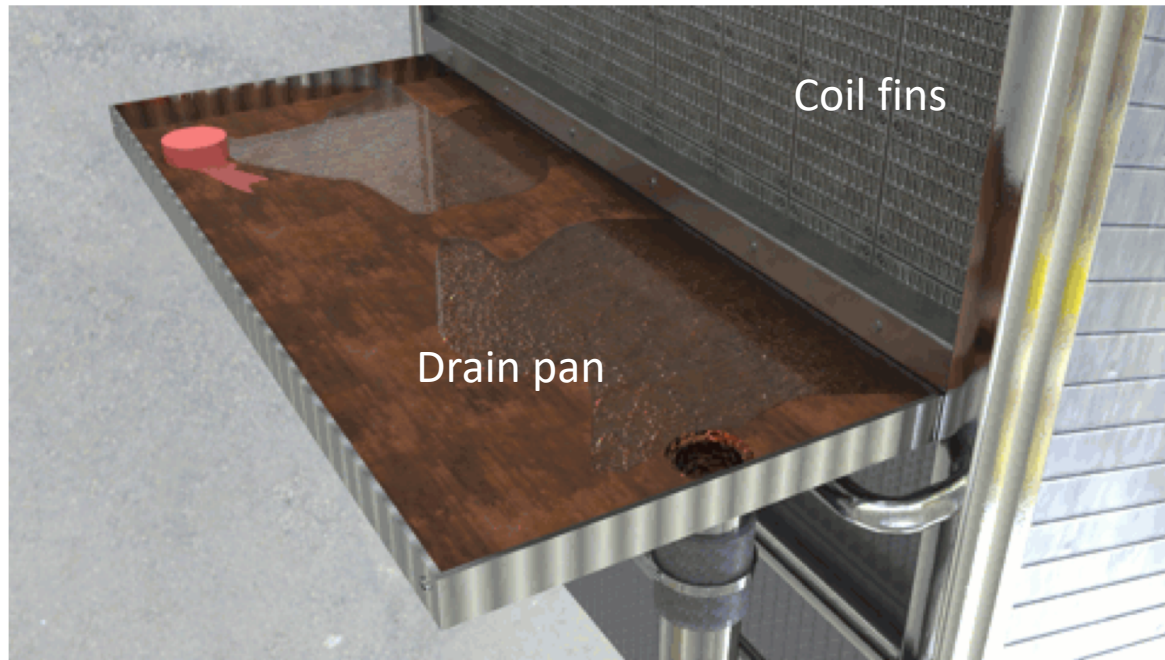
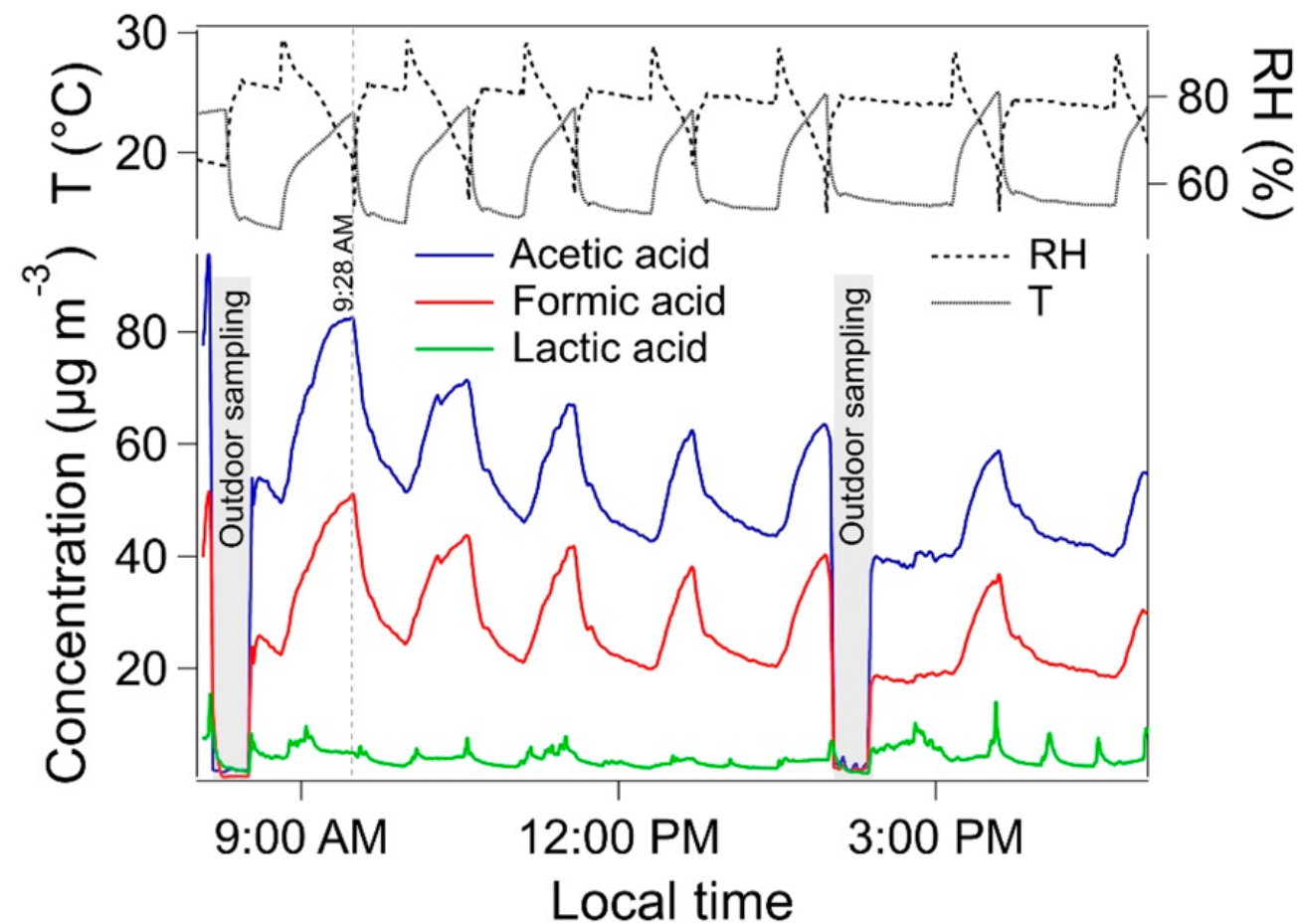
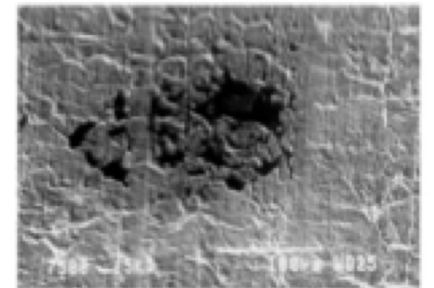


Image: <https://www.brodi.com/hvac>

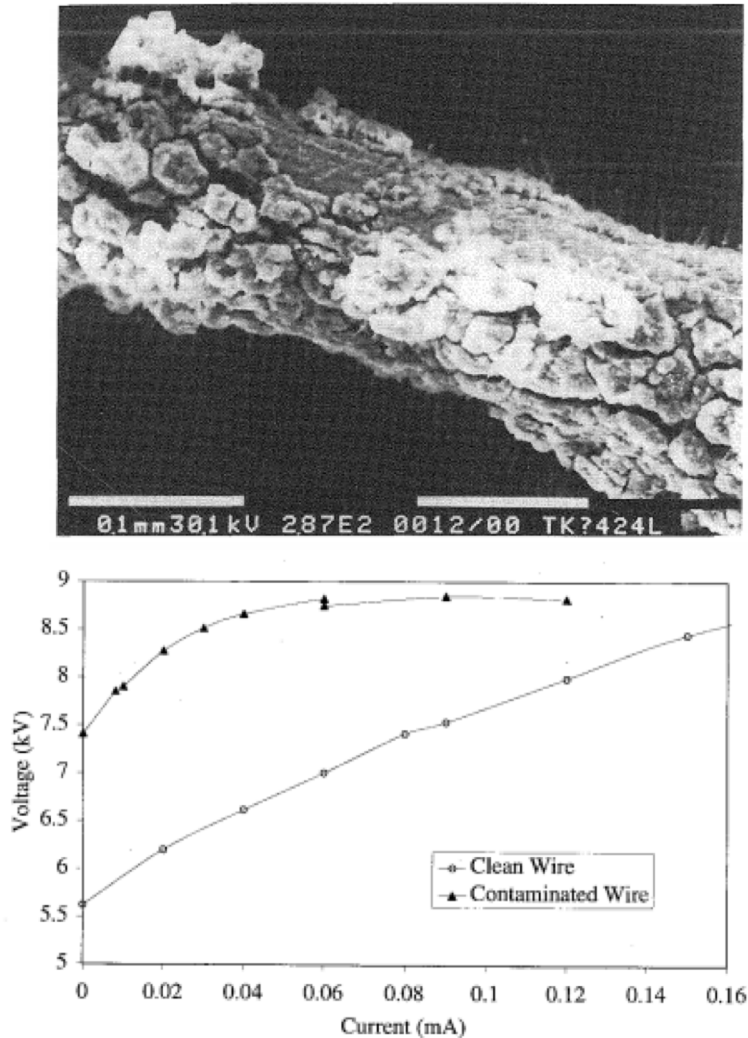


Duncan et al. (2019) *Environ Sci Tech*

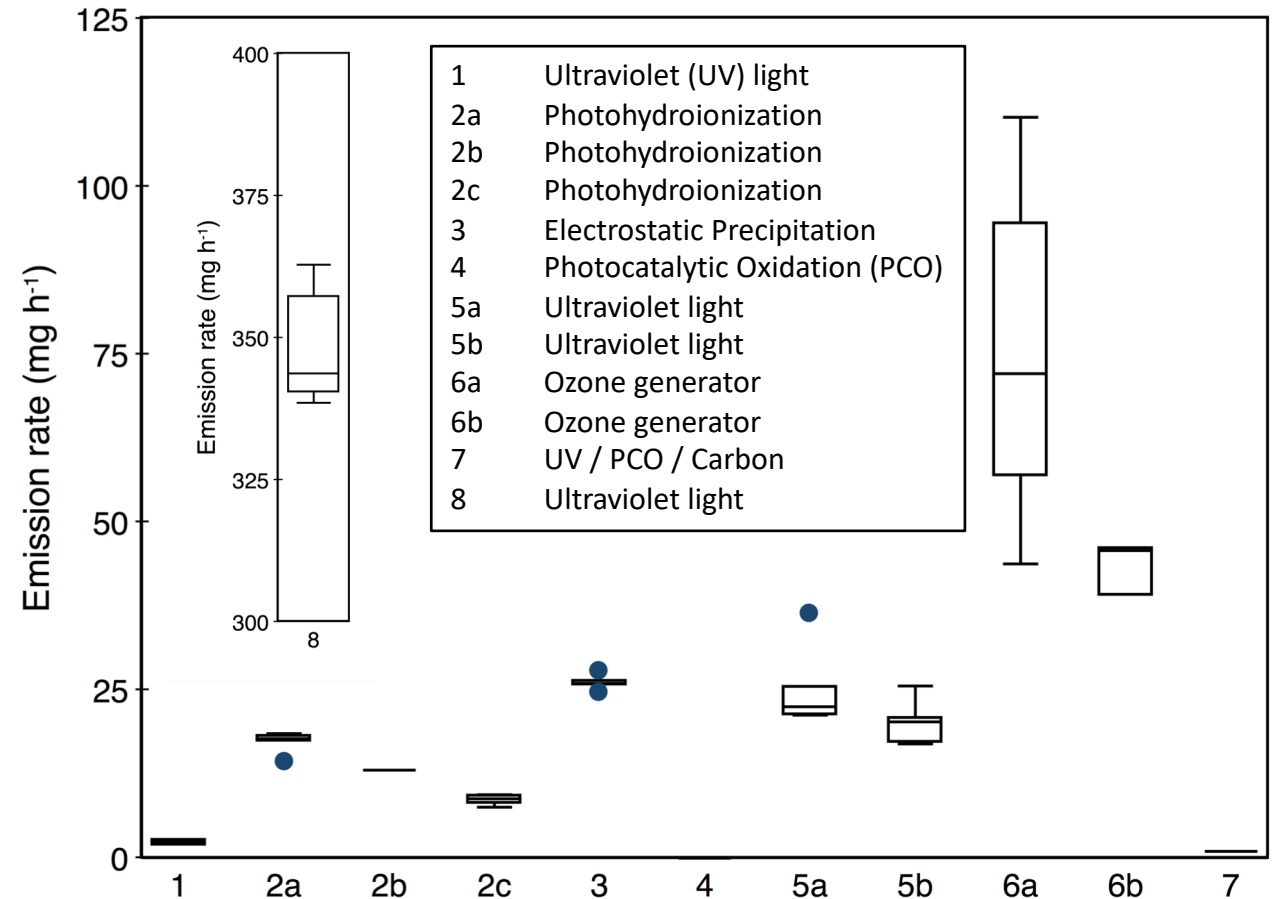


Bastidas et al. 2006 *Copper Conf.*

Air Cleaning (Electrostatic Precipitators +UV)

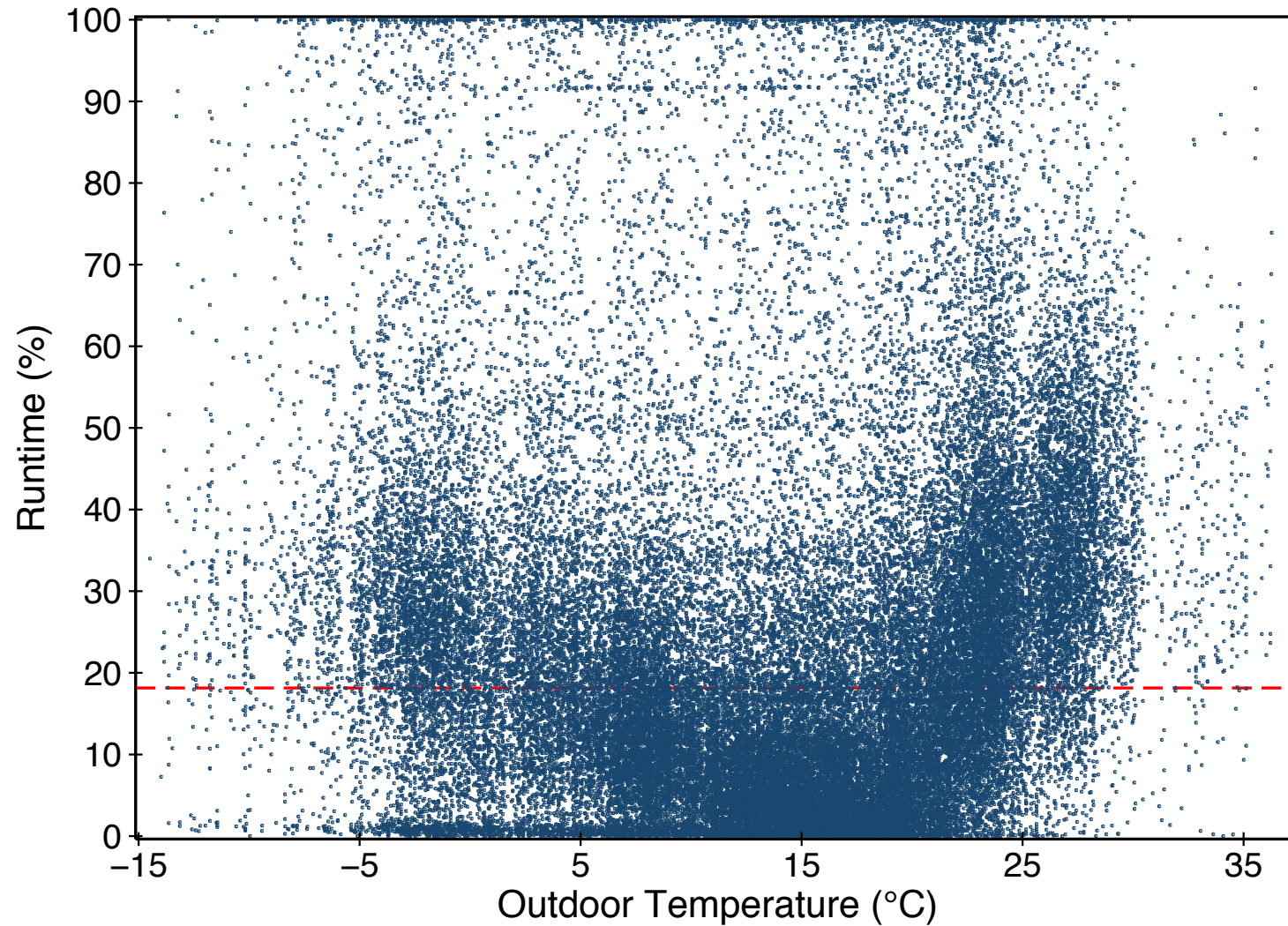


Davidson and McKinney (1998) *Aerosol Sci Tech*



Siegel et al. (2014) *Indoor Air Conf*

Cycling Behaviour



Touchie and Siegel (2018) *Indoor Air*

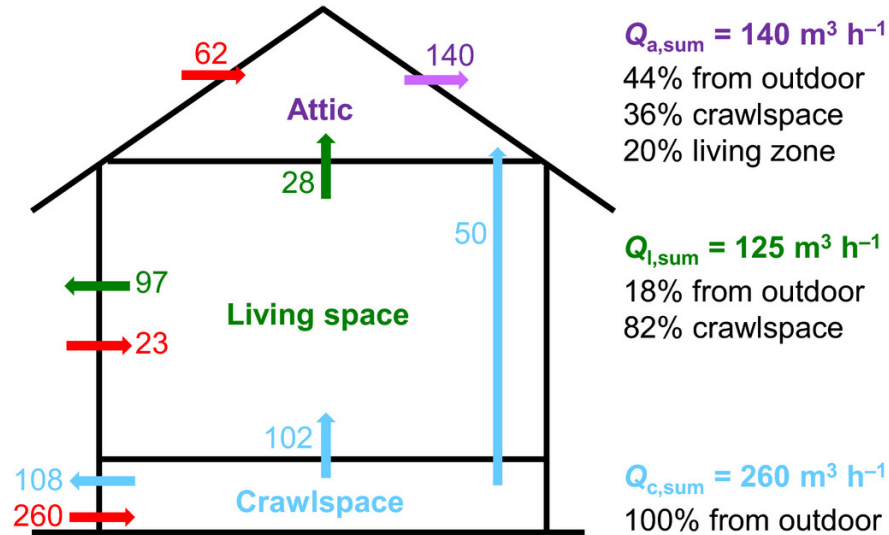
From HVAC Systems to Unseen Spaces

- High surface area to volume ratios
- Not cleaned
- Condensation + high humidity
- Thermal extremes
- Insulation and building materials

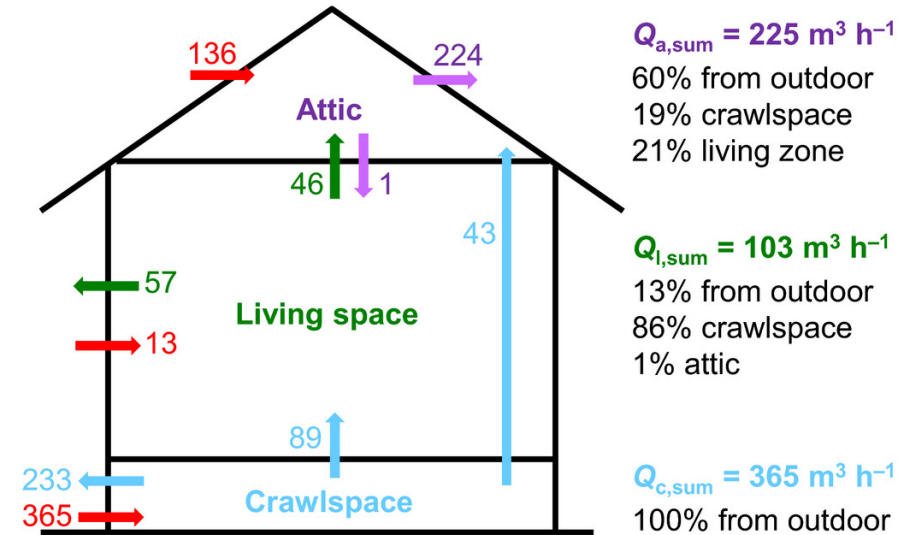


Images: [greenbuildingadvisor](#), [iko.com](#),
[jadelearning.com](#), [Inspectapeida](#),

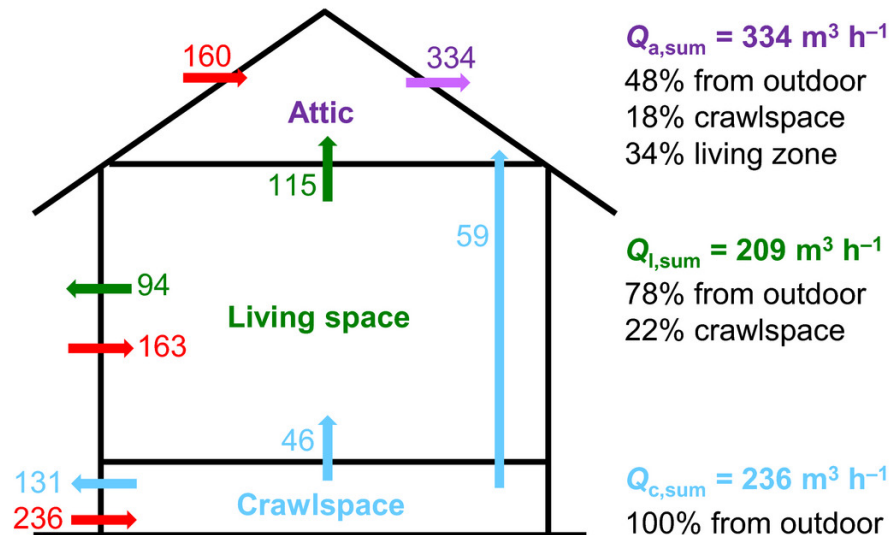
(A) Summer 03:00 - 07:00



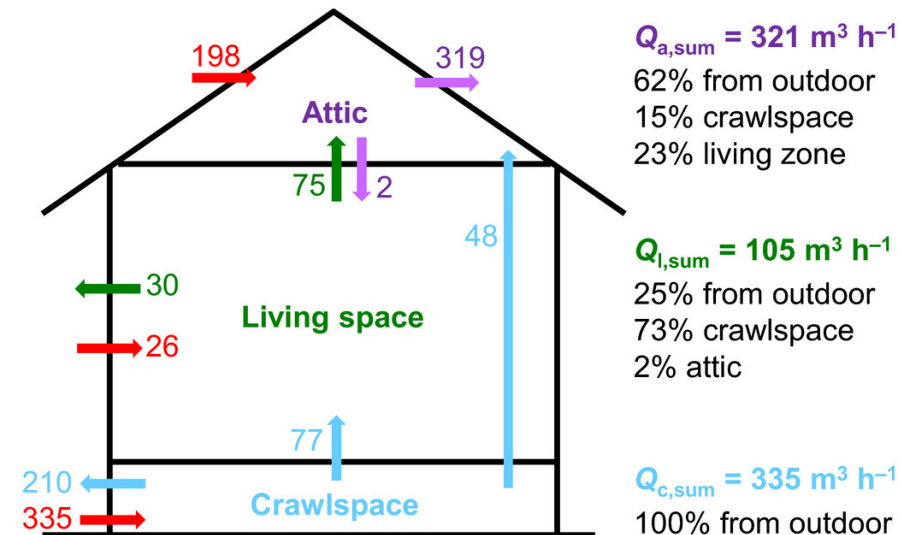
(B) Winter 03:00 - 07:00



(C) Summer 16:00 - 20:00



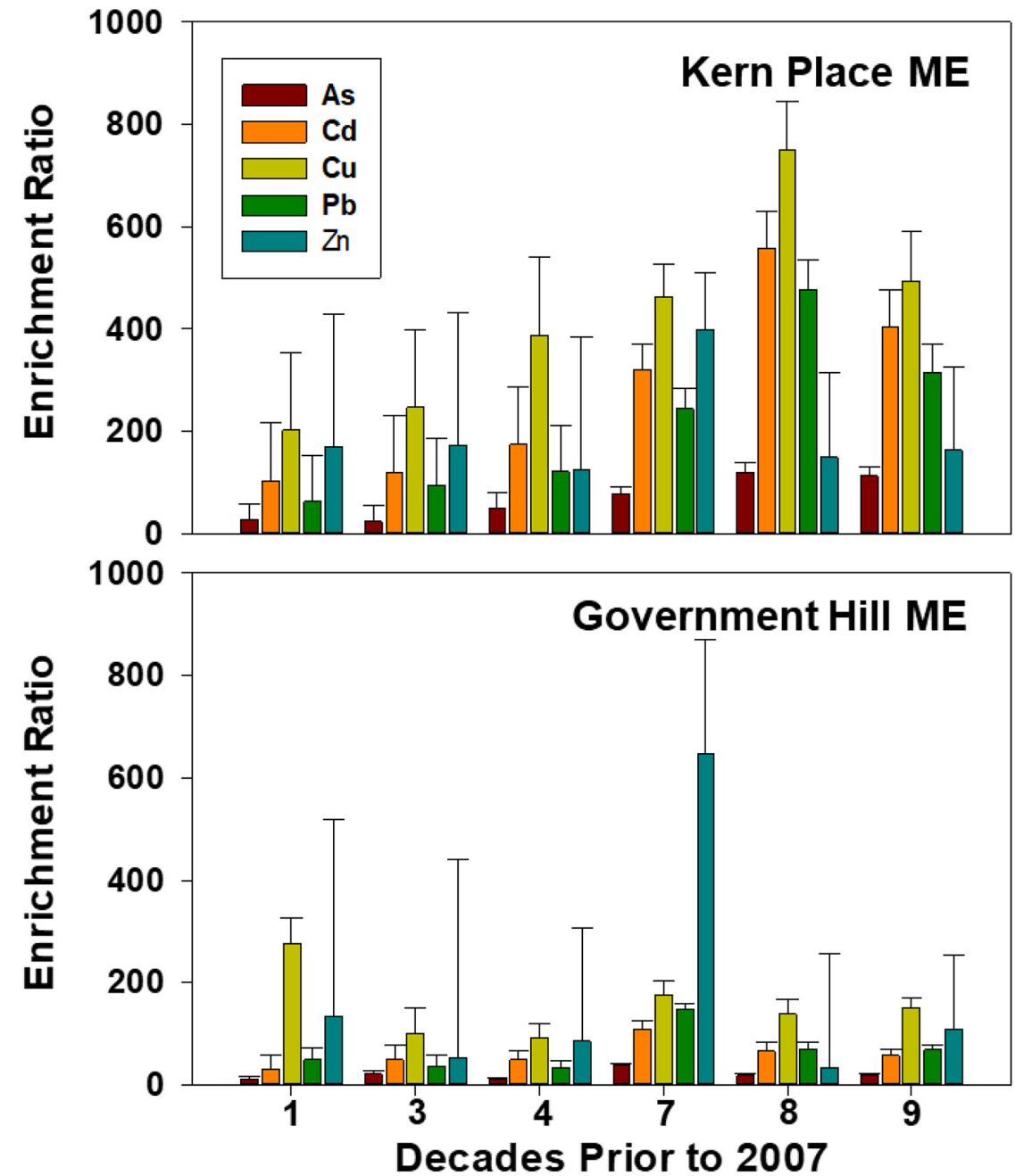
(D) Winter 16:00 - 20:00



Attic Chemistry

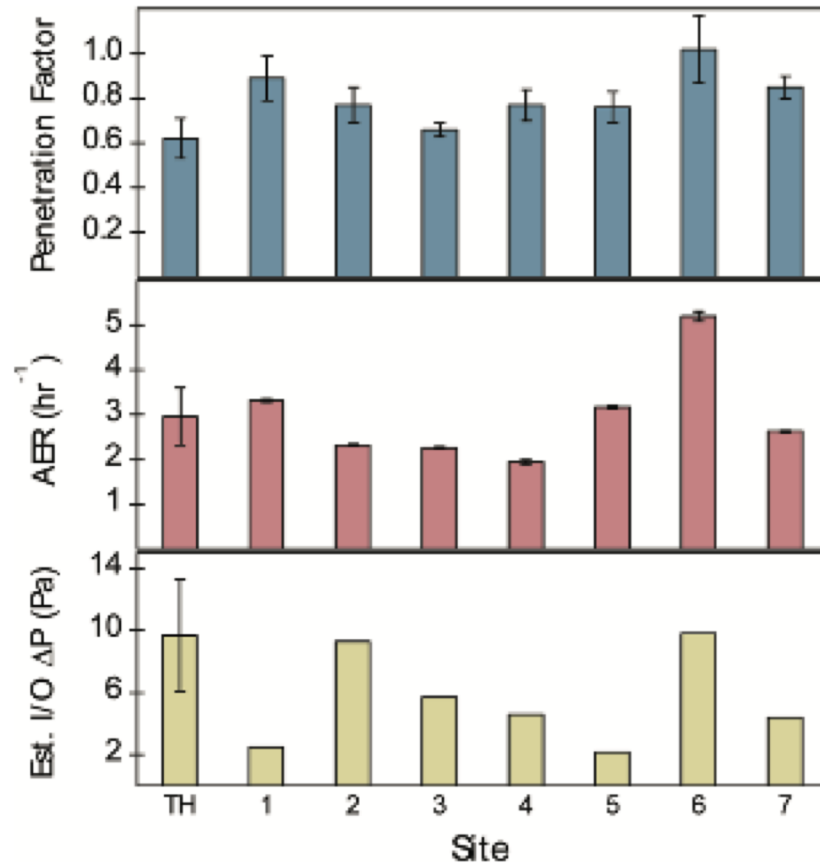


Image: beautyharmonylife.com/



Van Pelt et al. (2020) *J. Geochem Explor*

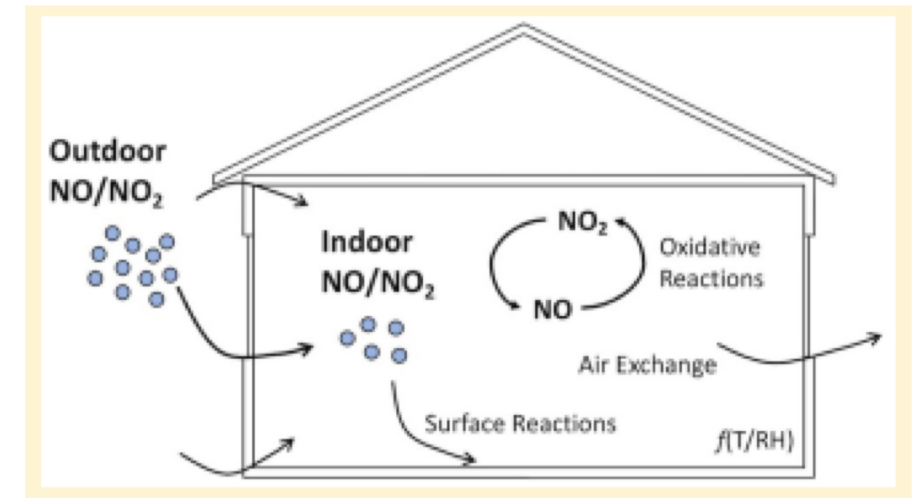
Chemistry in the Building Enclosure



Stephens et al (2012) *ES&T*

Date	P (Equation 7) (-)
June 17, 2014	0.37 ± 0.04
June 27, 2014	0.41 ± 0.03
July 9, 2014	0.49 ± 0.04
July 15, 2014	0.74 ± 0.06
July 17, 2014	0.63 ± 0.02
July 18, 2014	0.68 ± 0.02
July 18, 2014	0.48 ± 0.02
July 19, 2014	0.52 ± 0.02
July 22, 2014	0.69 ± 0.02
July 25, 2014	0.60 ± 0.03
July 25, 2014	0.61 ± 0.02
July 31, 2014	0.52 ± 0.03
July 31, 2014	0.53 ± 0.03
August 5, 2014	0.54 ± 0.02
August 7, 2014	0.44 ± 0.02
August 7, 2014	0.58 ± 0.02
August 10, 2014	0.50 ± 0.03
August 10, 2014	0.56 ± 0.03
August 22, 2014	0.40 ± 0.05
August 26, 2014	0.47 ± 0.03
September 29, 2014	0.59 ± 0.03
Mean	0.54
s.d.	0.10

Zhao & Stephens (2016) *ES&T*

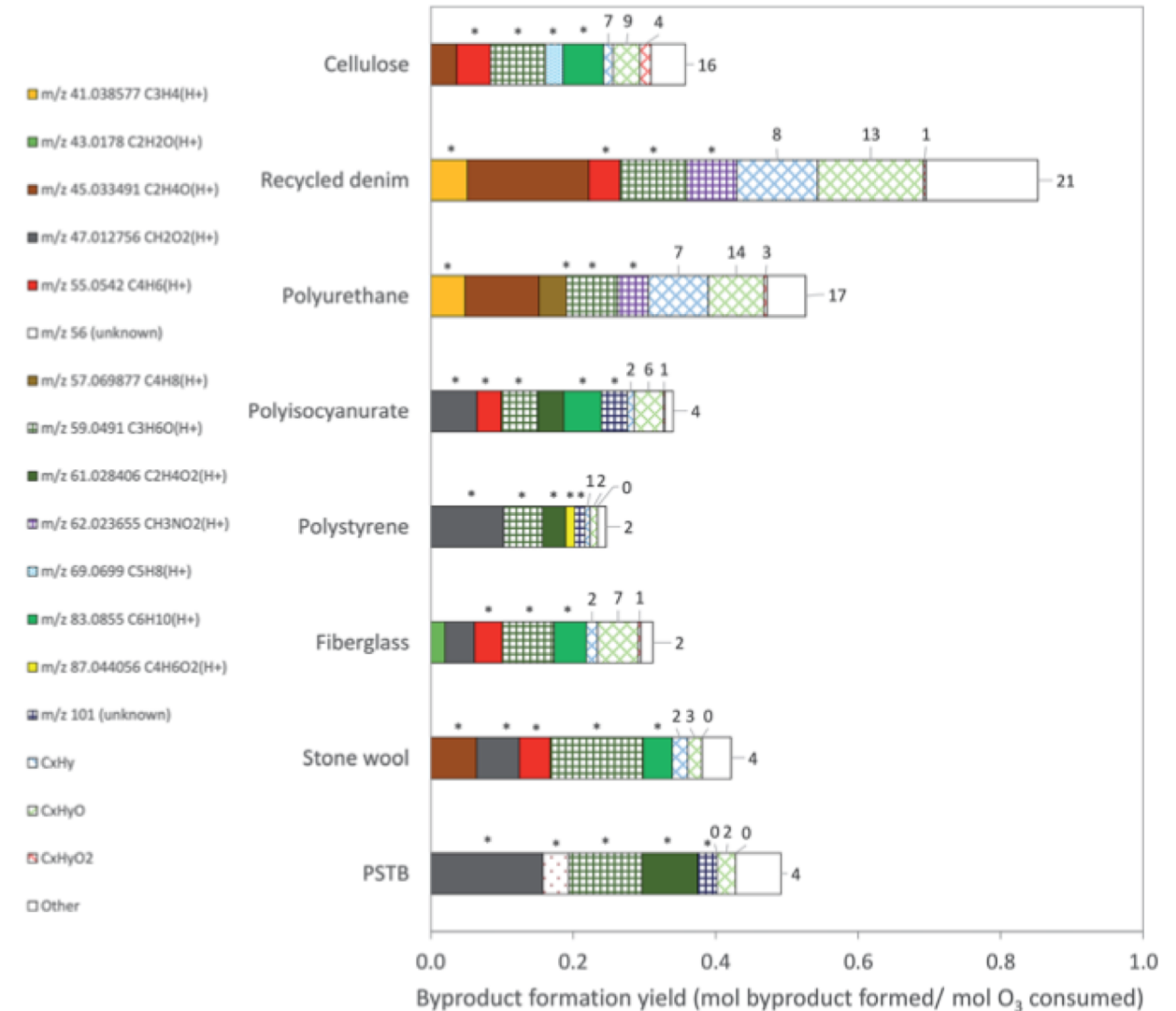
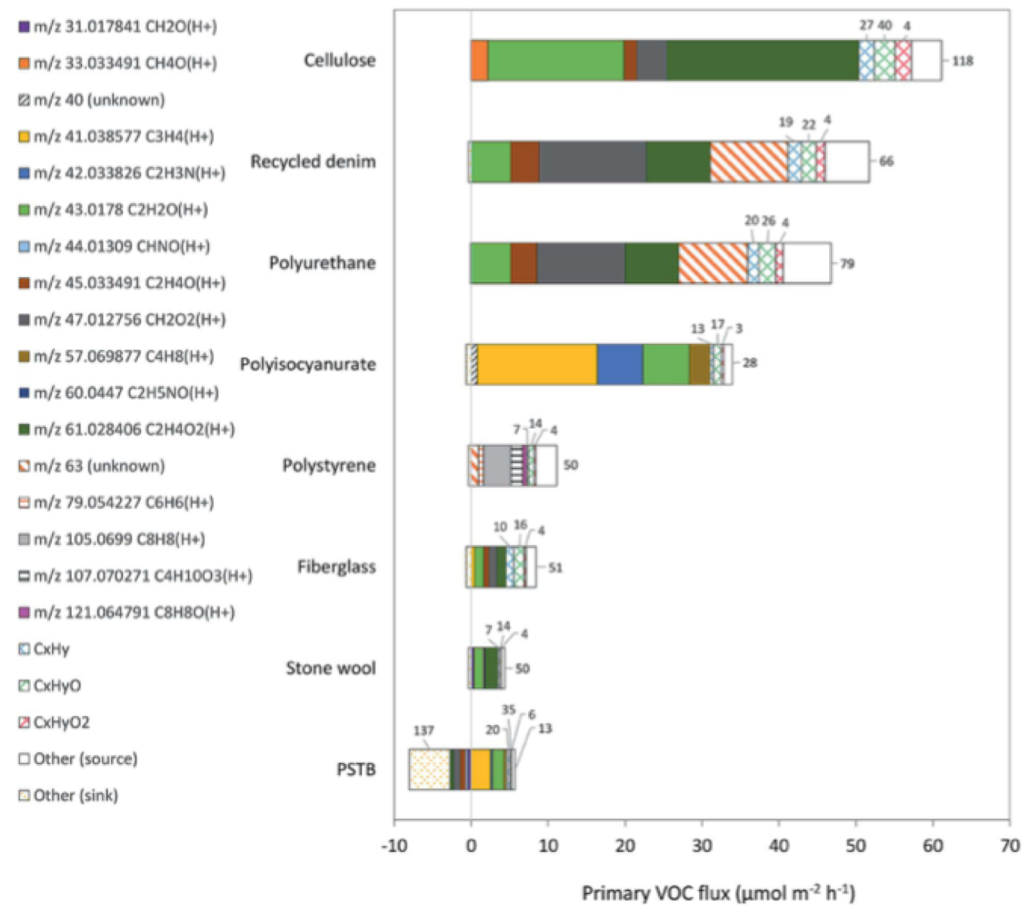


$$P_{\text{NO}} = \sim 1$$

$$P_{\text{NO}_2} = 0.72 \pm 0.06$$

Zhao et al. (2019) *ES&T*

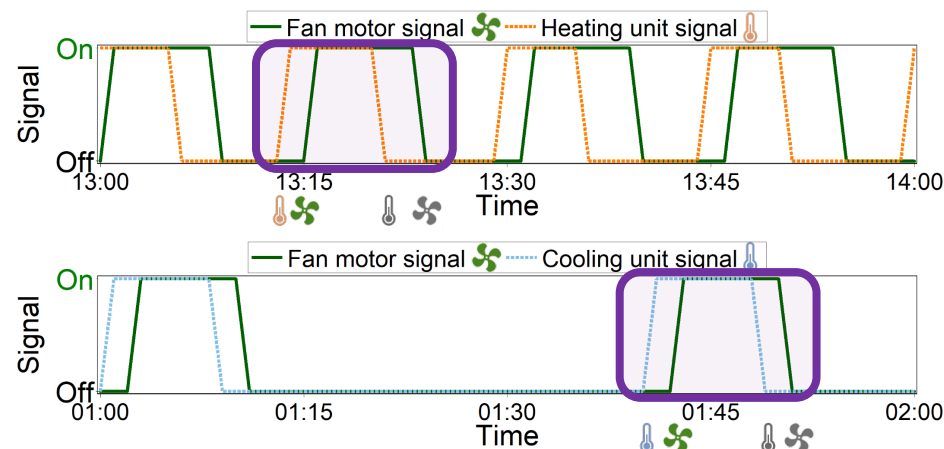
Insulation – Emissions and Chemistry



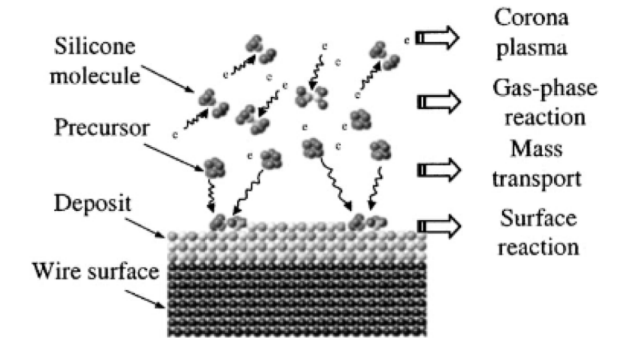
Chin et al. (2019) Env Sci Processes Impacts

Research Needs

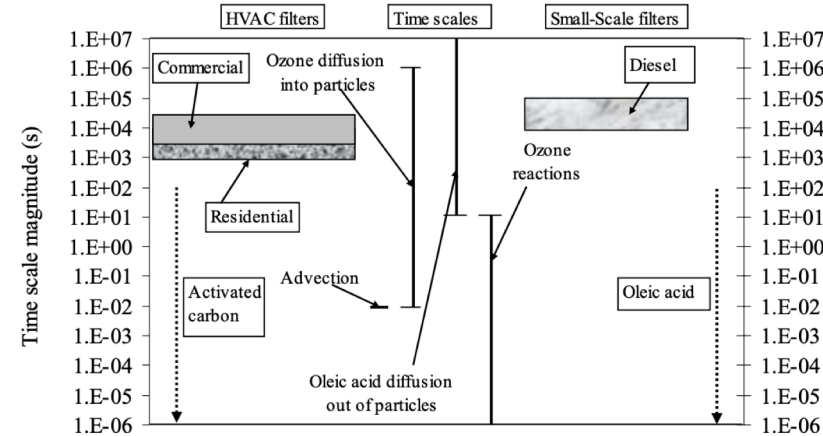
- Need a framework to understand when different processes are important
 - Climate and context
 - Building materials
 - “Taxonomy” of HVAC systems
 - Temporal dynamics



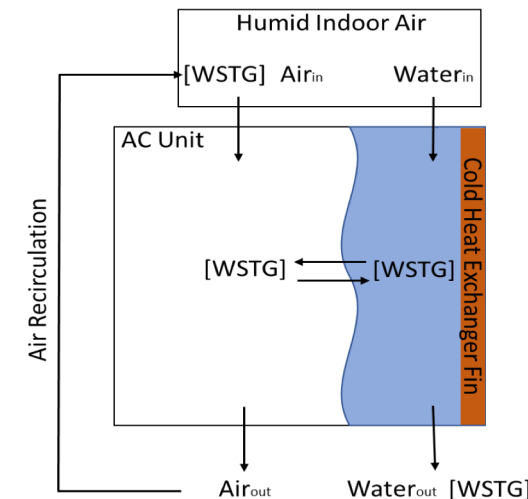
Li and Siegel (2018) *Indoor Air Conf*



Chen and Davidson (2004)
Plasma Chem Plasma Process



Zhao (2006) PhD Thesis UT Austin



Schwartz-Narbonne et al. Submitted

If you want to understand indoor chemistry, you have to understand the building and its systems.