A National Empirical Attenuation Factor Study to Improve Vapor Intrusion Screening

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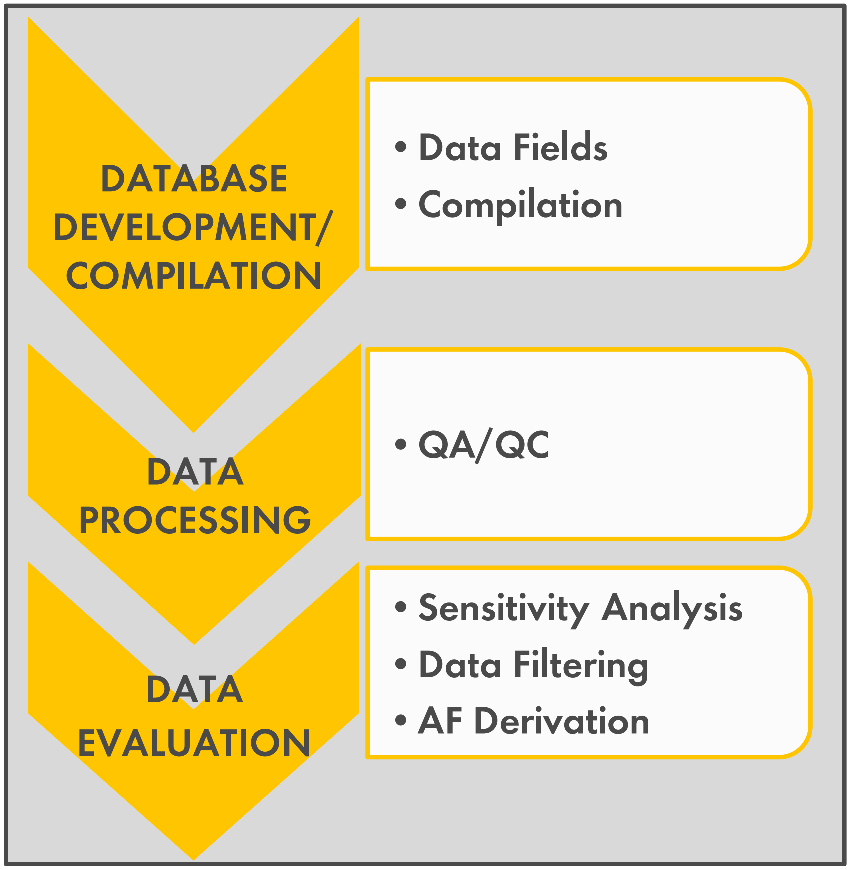
Outline

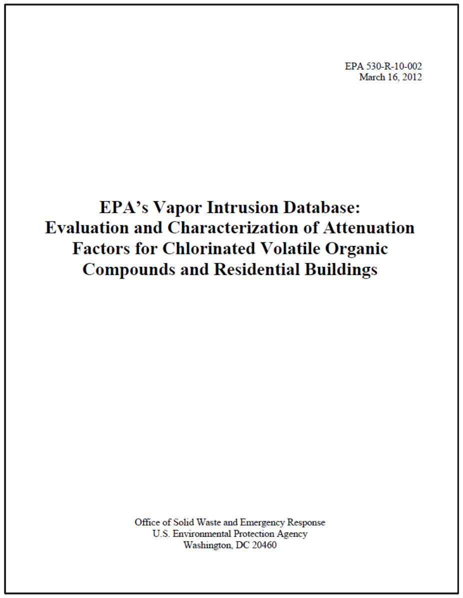
- Background
  - Motivation and context
  - Database
  - Methods for AF Derivation
- AF Sensitivity to Key Variables / Data Filtering
- AF Derivation - 3 Different Methods
- Conclusions



GOAL: a comprehensive analysis of building-specific AFs to support development of technically defensible risk-based screening levels for VI

Motivation and Context
(US EPA 2012 Study)

- most regulatory agencies base VI RBSLs in shallow soil-gas on USEPA's default (generic) AF = 0.03 derived from 2012 USEPA empirical study
- concerns exist over data that were ultimately used to derive the AF:
  - only single-family residences, primarily with basement construction (16 % unfinished)
  - no non-residential buildings
  - no soil-gas data
  - nearly 80 percent (342/431 indoor air (C_{IA})/subsurface vapor (C_{SOURCE}) data pairs) used came from 3 sites subject to relatively cold winter-time temperatures
  - no rigorous evaluation of AF sensitivity to key variables
- potential biases from background (non-VI) sources were not fully resolved (Man et al., 2022)


EPA 530-R-10-002
March 16, 2012

EPA's Vapor Intrusion Database: Evaluation and Characterization of Attenuation Factors for Chlorinated Volatile Organic Compounds and Residential Buildings

Office of Solid Waste and Emergency Response
U.S. Environmental Protection Agency
Washington, DC 20460

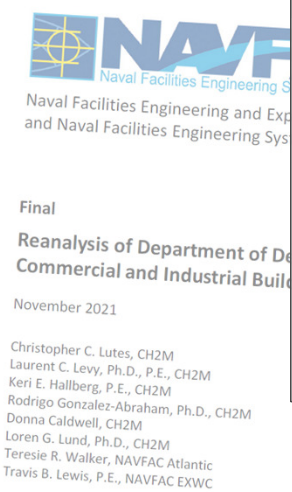
RBSLs = risk-based screening levels; AF = attenuation factor; IA = indoor air; C_{IA} = indoor air concentration; C_{SOURCE} = subsurface vapor (subslab or soil-gas) concentration

Motivation and Context

(Studies Post USEPA (2012))

- several "big data" empirical studies conducted since 2012 with significant differences in AFs compared to USEPA (2012) (different databases, some differences in methods)
- generally limited in geographical extent or subject to ambiguities from data pairing at buildings with multiple data pairs

Study	95th %ile Attenuation Factor
USEPA (2012)	0.03
Ettinger et al. (2018)	0.003
Nawikas (2019)	0.006 – 0.01
Hallberg et al. (2021)/Lutes et al. (2021)/ Levy et al., (2023)/DoD (2023a, b)	0.001
DTSC (2021)/Abbasi et al. (2022)	0.0009 – 0.005
Lahvis and Ettinger (2021)	0.0008 – 0.002
Eklund et al. (2022)	0.0003


Naval Facilities Engineering and Exp
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Reanalysis of Department of De
Commercial and Industrial Buil

November 2021

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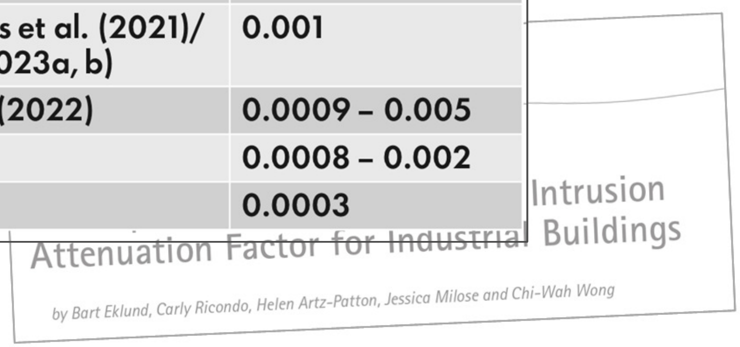
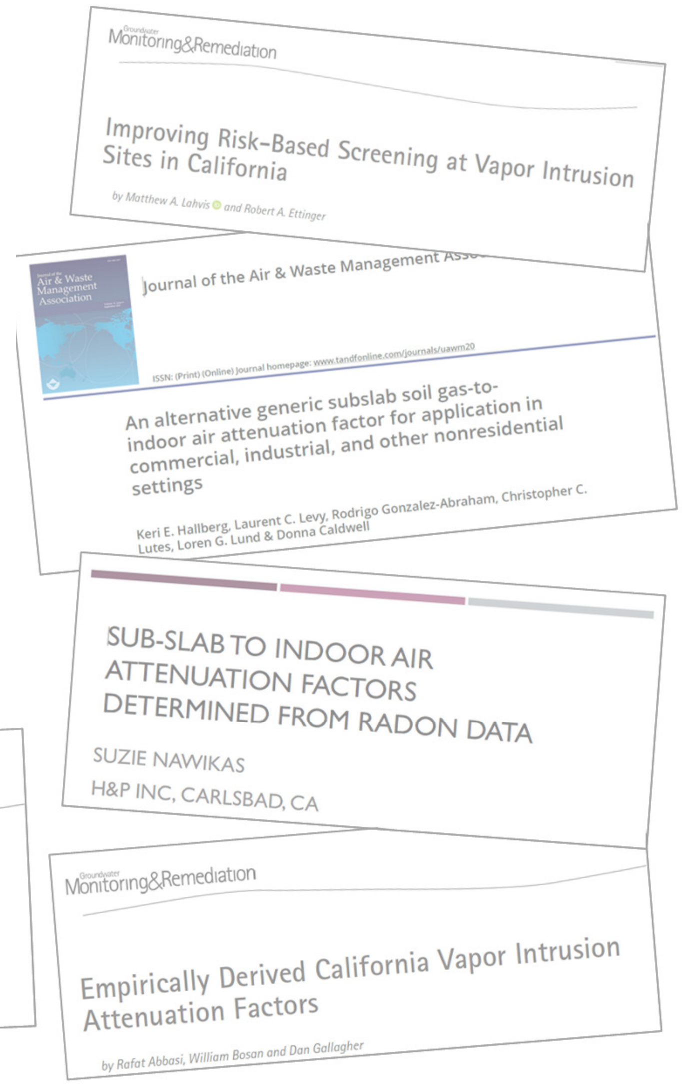

Intrusion
Attenuation Factor for Industrial Buildings

by Bart Eklund, Carly Ricondo, Helen Artz-Patton, Jessica Milose and Chi-Wah Wong


Monitoring&Remediation

Improving Risk-Based Screening at Vapor Intrusion Sites in California

by Matthew A. Lahvis and Robert A. Ettinger

Journal of the Air & Waste Management Asso

An alternative generic subslab soil gas-to-indoor air attenuation factor for application in commercial, industrial, and other nonresidential settings

Keri E. Hallberg, Laurent C. Levy, Rodrigo Gonzalez-Abraham, Christopher C. Lutes, Loren G. Lund & Donna Caldwell

SUB-SLAB TO INDOOR AIR ATTENUATION FACTORS DETERMINED FROM RADON DATA

SUZIE NAWIKAS

H&P INC, CARLSBAD, CA

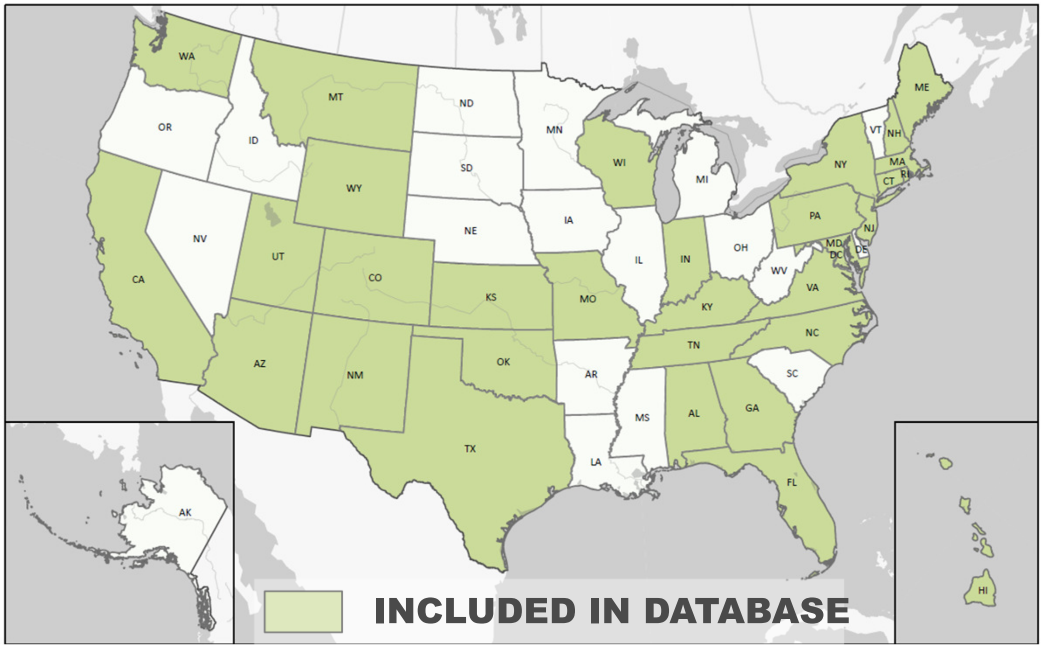
Monitoring&Remediation

Empirically Derived California Vapor Intrusion Attenuation Factors

by Rafat Abbasi, William Bosan and Dan Gallagher

National AF Study

(General Database Statistics)



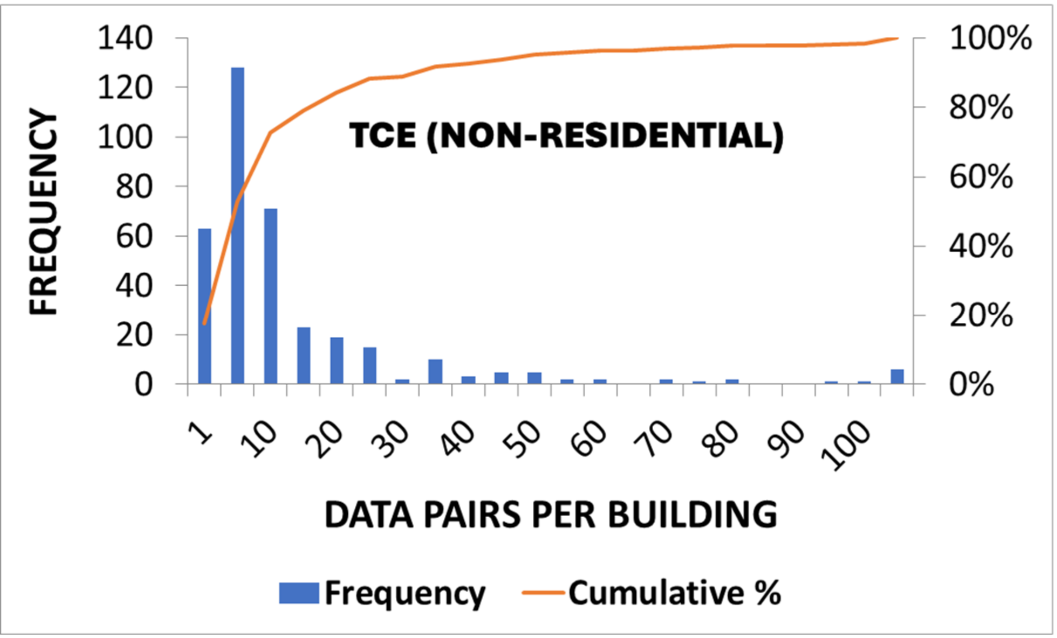
- over 26,000 vapor data pairs
- broad geographical coverage (26 states)
- database includes data on 37 chemicals from:
  - large empirical studies
  - USEPA (2012)
  - new data (11 consultancies, NCDEQ)
  - multiple variables (time lag and distance between vapor sampling, HVAC operation, building age, etc)

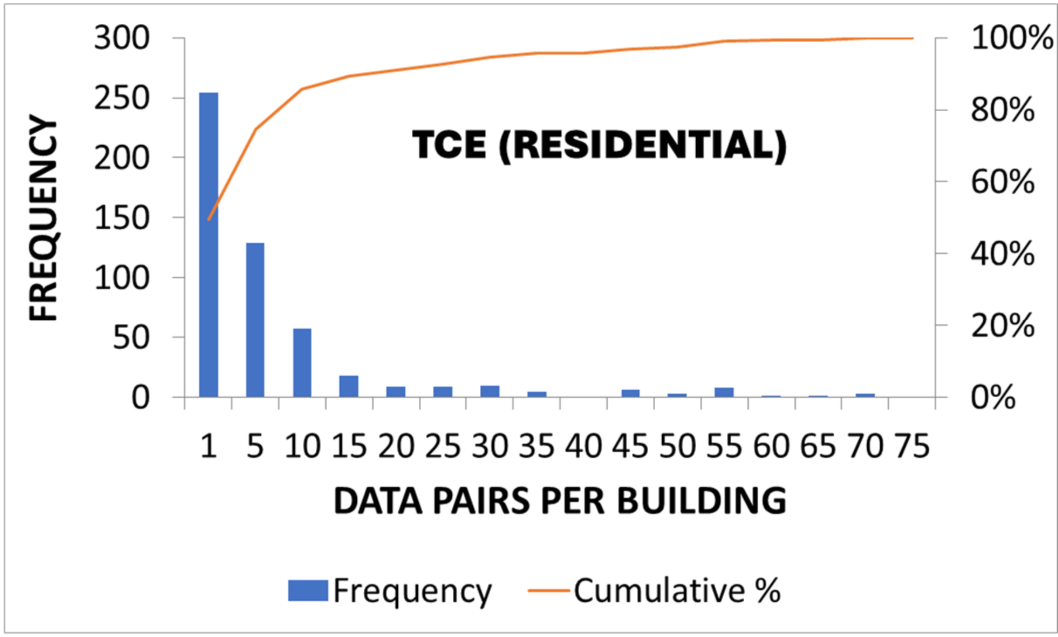
KEY POINT

- **AF database represents the most comprehensive and representative compilation of AFs to date**

Population	All Chemicals	TCE	PCE	Radon
Sites	330	143	139	157
Buildings	1,467	857	831	192
Data Pairs	26,051	8,144	6,668	277

Numerous Buildings With Multiple C_{IA} and C_{SOURCE} (Subslab and Soil Gas) Data Pairs (e.g., TCE data)



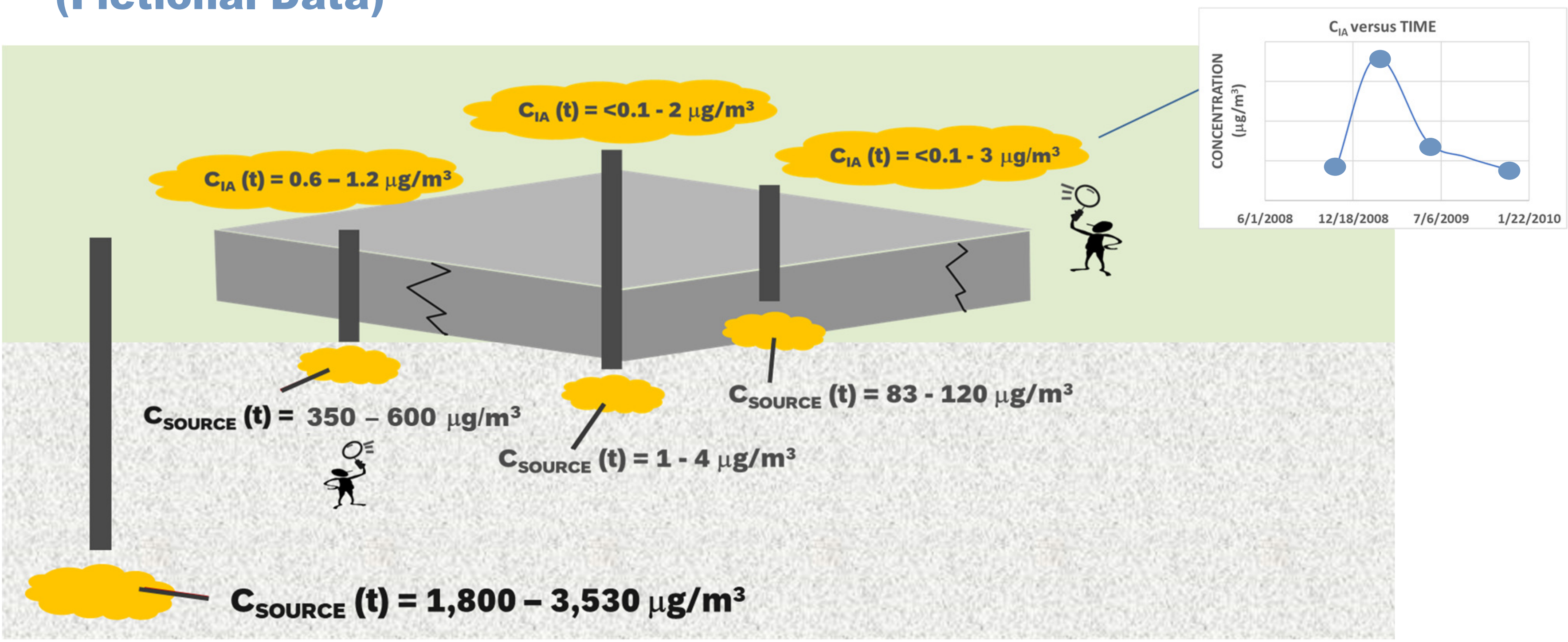


KEY POINT

- multiple C_{IA} and C_{SOURCE} data pairs from certain buildings has the potential to:
  - introduce ambiguity in AF determinations
  - bias final AF determinations

AFs Ambiguity at Buildings with Multiple Indoor air and Subsurface Data Pairs Can Be Significant

(Fictional Data)

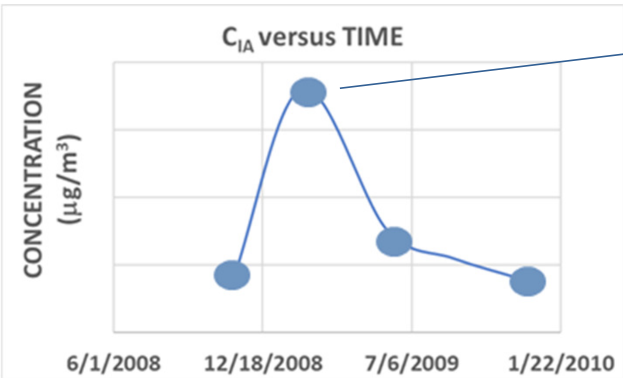


KEY POINT

- AFs for specific buildings can vary by over an order of magnitude depending on C_{IA} (concentration in indoor air) and C_{SOURCE} (concentration in subsurface vapor data pairing

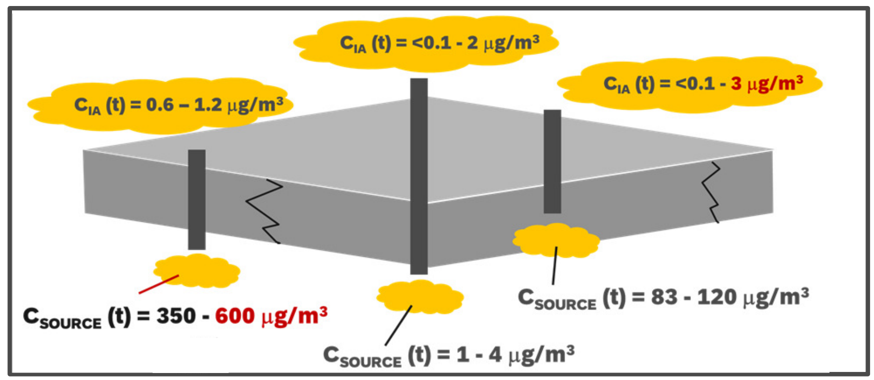
Development of Building-Specific AFs
(C_{IA} and C_{SOURCE} Data Pairing)

INDOOR AIR (C_{IA})



maximum C_{IA} over time and space (conservative)

SUBSURFACE VAPOR (C_{SOURCE})



1) maximum C_{SOURCE} (full measure of slab attenuation) over time and space
2) average C_{SOURCE} (uncertain points of vapor entry)

KEY POINT

- AFs for site screening derived using relatively conservative assumptions of max C_{IA} and average C_{SOURCE}
- AF sensitivity to key variables based generally on maximum C_{IA} and maximum C_{SOURCE}

PCE and TCE AF Populations

(Pre- and Post-Filtering)

Categories	PRE-FILTERING			POST-FILTERING			
	# of Sites	# of Buildings	# of Data Pairs	# of Sites	# of Buildings	# of Data Pairs	% of total building population pre-/post-filtering
TCE	167	1,025	8,144	75	179	1,146	51/60
PCE	143	999	6,668	62	120	610	49/40
Residential	53	1,112	5,059	22	77	531	55/26
Non-Residential	291	912	9,753	104	222	1,225	45/**74**
Subslab	144	1,395	8,761	74	189	975	69/63
Soil Gas	232	629	6,051	49	110	781	31/37
Slab-On-Grade	148	1,007	10,662	127	229	1,541	54/**82**
Basement	25	642	2,398	15	34	147	34/12
Crawl Space/Earthen Floor	14	227	2,424	6	15	42	12/6
Regions 1 – 3 (more temperate)	121	1,040	11,158	109	210	1,387	51/**70**
Regions 4 – 7 (less temperate)	48	984	3,654	46	89	369	49/30
Pre-1950 Construction	29	612	3,146	21	69	336	60/38
Post-1950 Construction	74	401	4,420	41	114	929	40/62

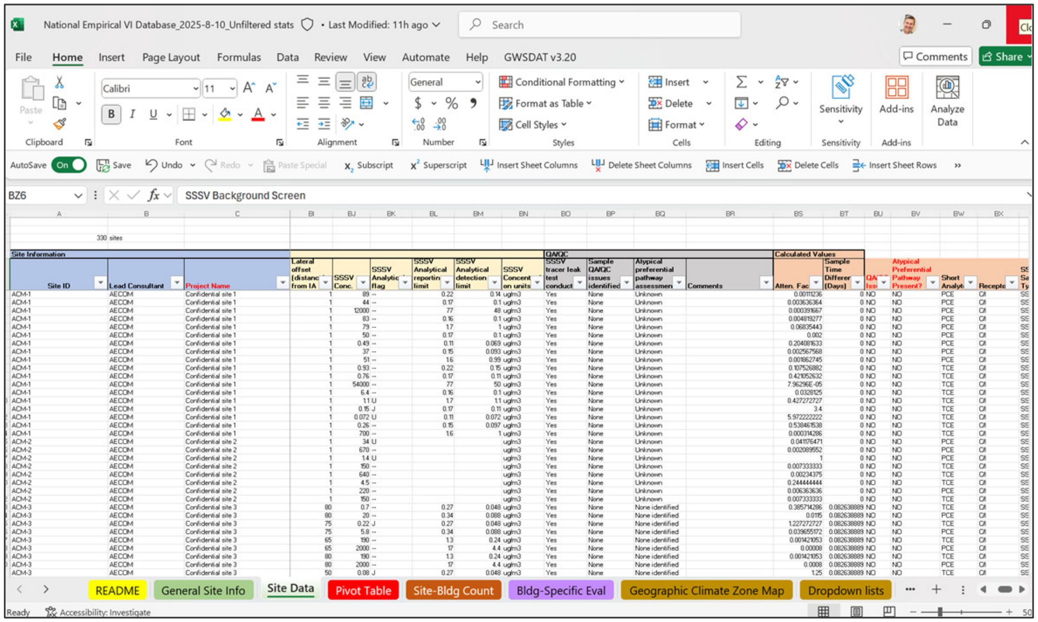
KEY POINT

- **post-filtered database (137 sites, 299 buildings, 1,756 data pairs) is over 4x larger than USEPA (2012) and more representative**
- **the 70/30 building population from Regions 1 – 3 are largely from California**

National AF Database Provides Ability to More Thoroughly Evaluate AF Sensitivity to Key Variables

(Opportunity to Adjust Default AF Depending on Site Conditions)

- land use (e.g., residential, commercial, industrial, school)
- climate (geographic) zone
- building age (pre- and post 1950)
- building size
- HVAC operation (on/off within multiple and individual buildings)
- predominant vadose zone soil type
- time between indoor air and subsurface vapor sampling (t)
- distance between subsurface and indoor air vapor sampling (x)
- soil-gas sample depth (z)
- relative source location (shallow soil, deep soil/groundwater)

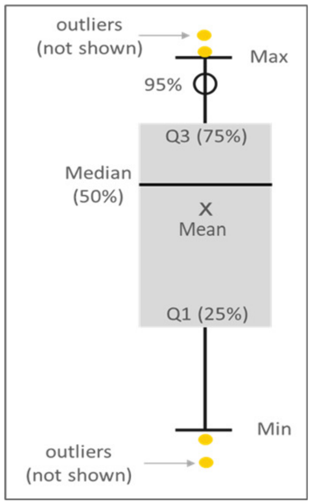


3 Methods for AF Derivation

(USEPA 2012, 2015)

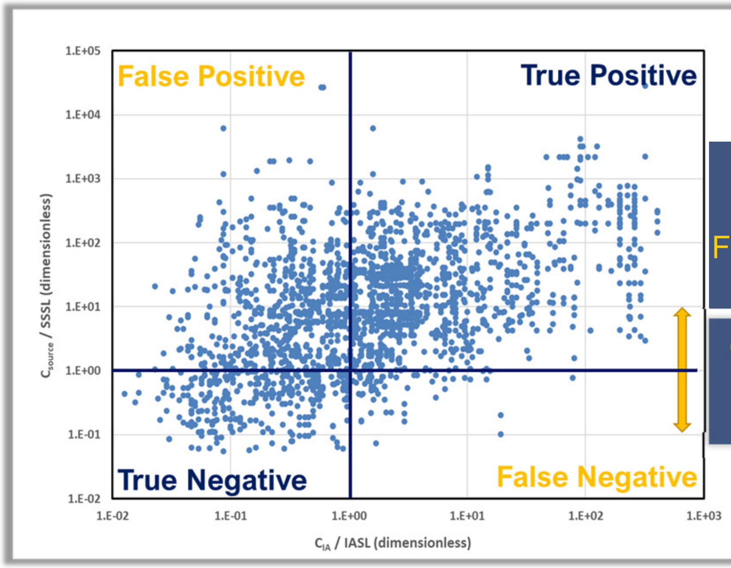
$$AF_{emp} = \frac{C_{IA}}{C_{SOURCE}} = AF_{VI} + \frac{C_{BGRD}}{C_{SOURCE}}$$

AF_{emp} = measured AF
AF_{VI} = actual AF



METHOD 1:

Descriptive Statistics (USEPA approach)

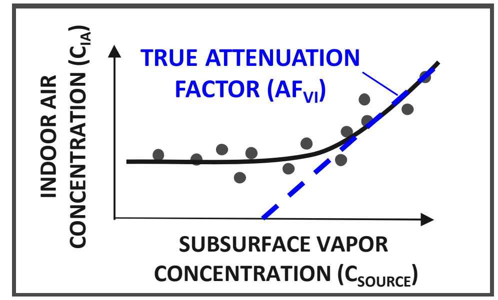


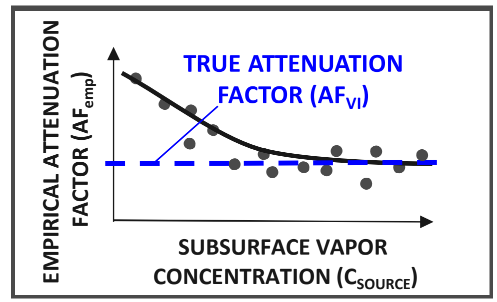
AF defined by acceptable % of False Negatives and False Positives

changing AF shifts data up/down

METHOD 2:

Reliability Analysis - USEPA (2015), Appendix A3.6)





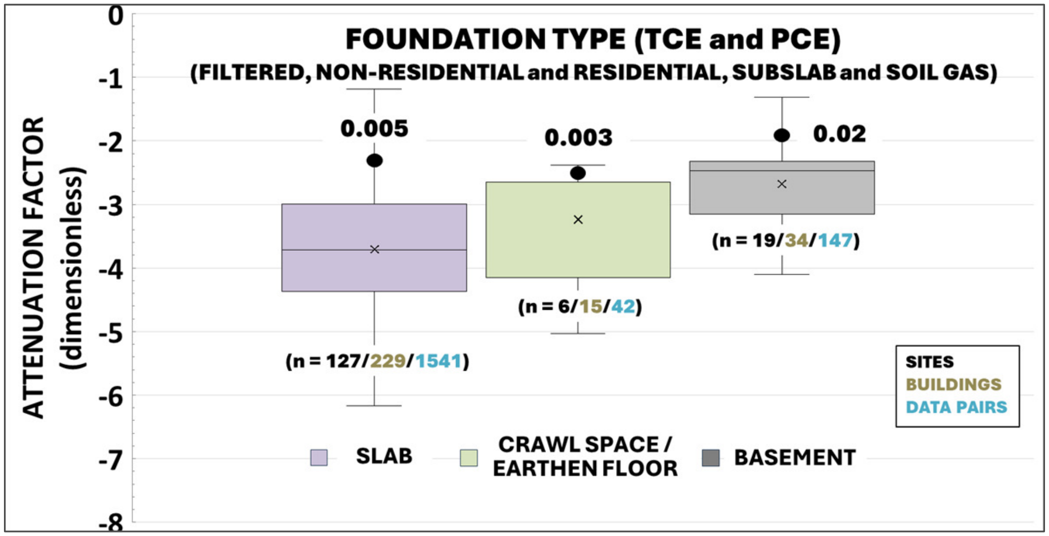
METHOD 3

Empirical AF vs. C_{SOURCE} Relations (presented in USEPA 2012)

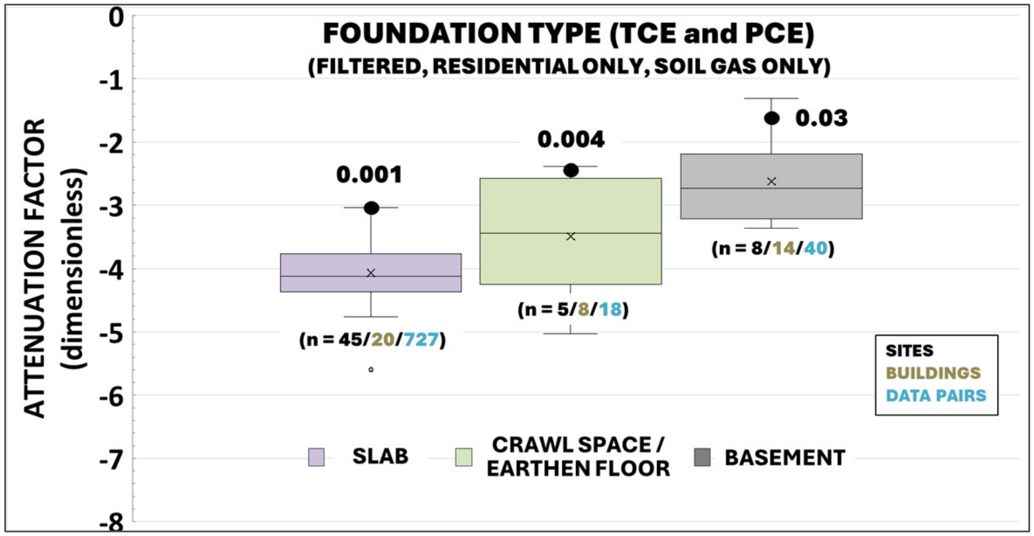
All methods done previously… but not by building

AF SENSITIVITY TO KEY VARIABLES:
VARIABLES WITH GREATEST EFFECT ON AF

Foundation Type



RESIDENTIAL ONLY

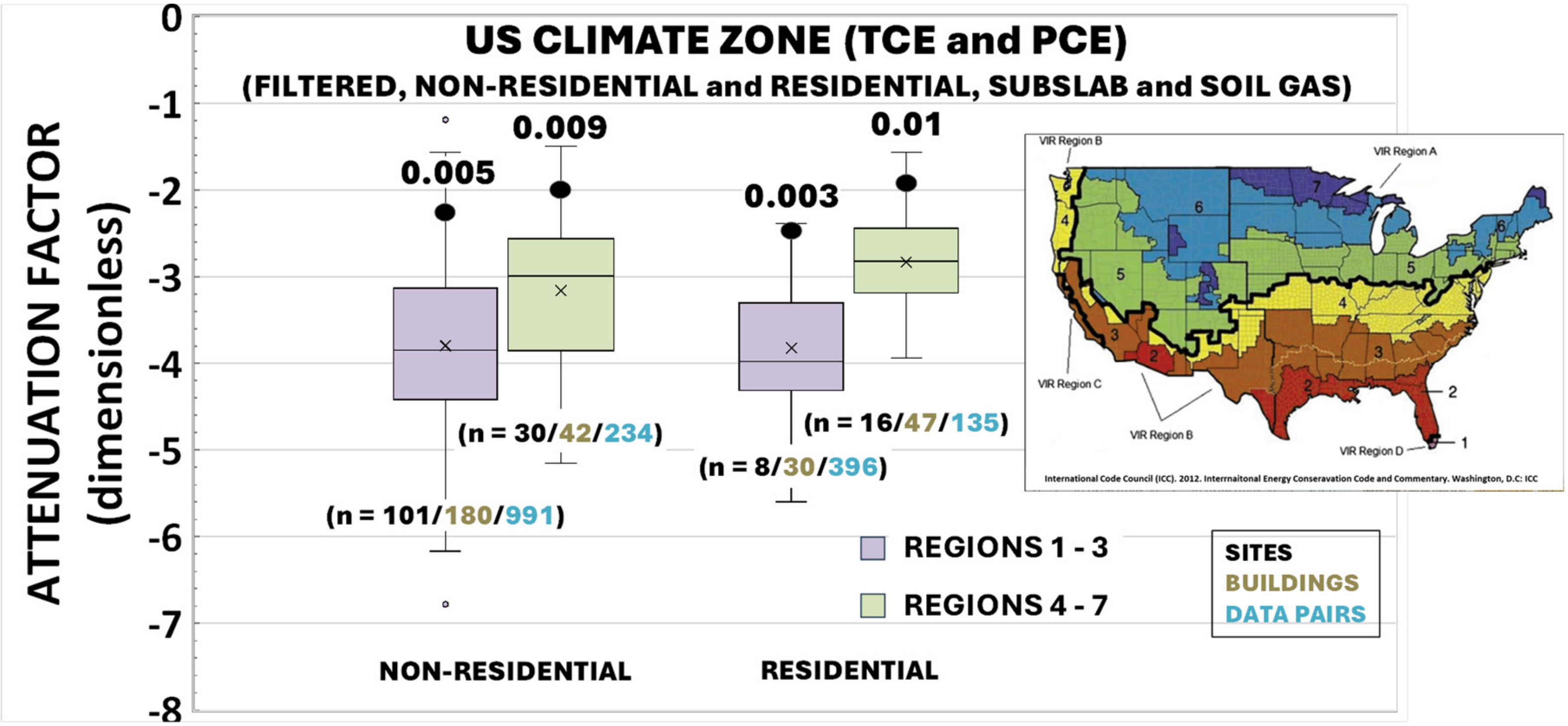


* Crawl space AFs based on soil gas (not crawl space air)

KEY POINT

- median AFs are nearly 10x higher for buildings with basement versus slab-on-grade foundations, potentially attributed to greater VI surface area
- similar differences in AFs are observed for residential-only buildings
- 95th %ile AF for residential-only buildings with basements is consistent with USEPA (2012)

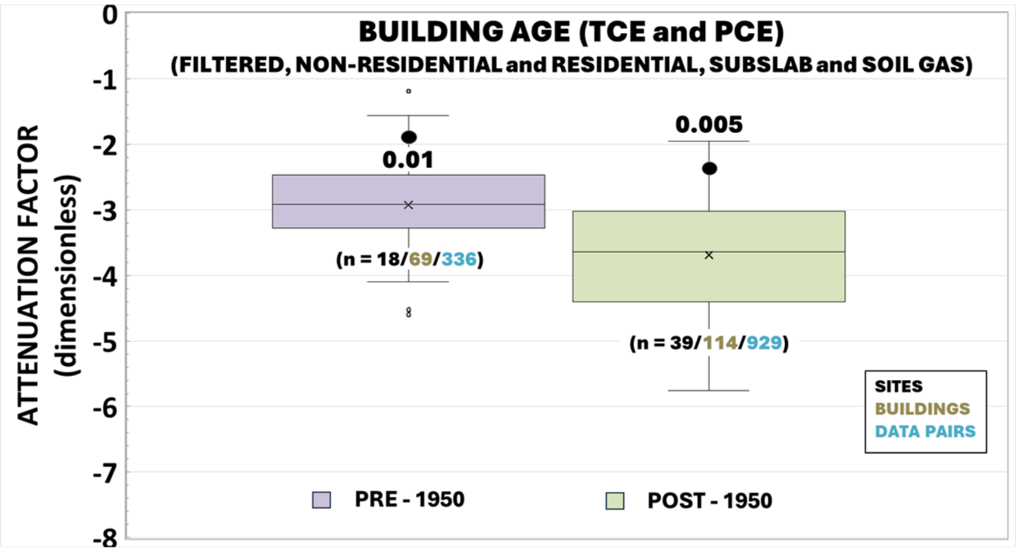
US Climate Zone

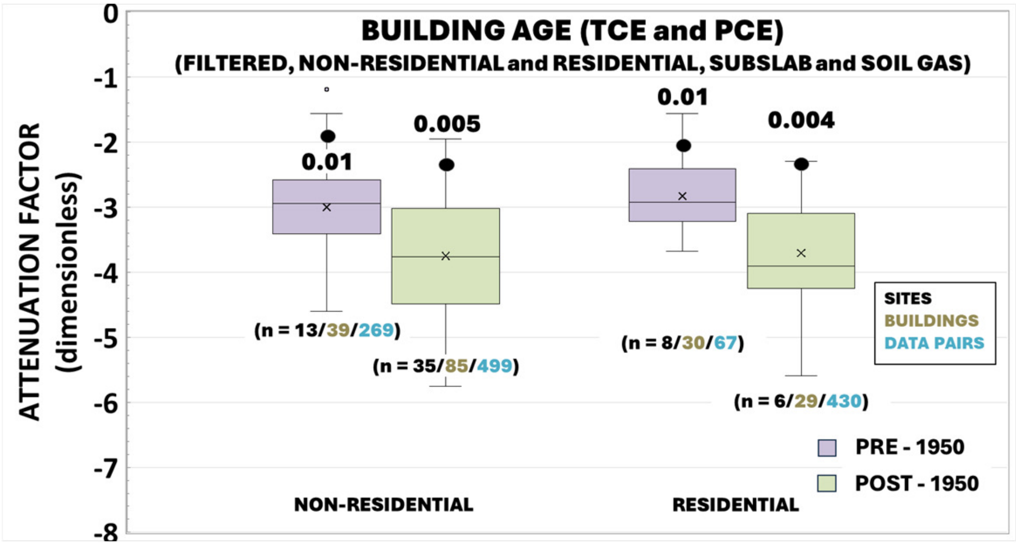


KEY POINT

- median AFs for non-residential and residential buildings are roughly 10x higher in geographic regions of the US more prone to colder winter seasons and less temperate climates
- the effect is largely independent of building type and foundation type, given that only 5 of the 42 non-residential buildings in Regions 4 – 7 have basement foundations

Building Age





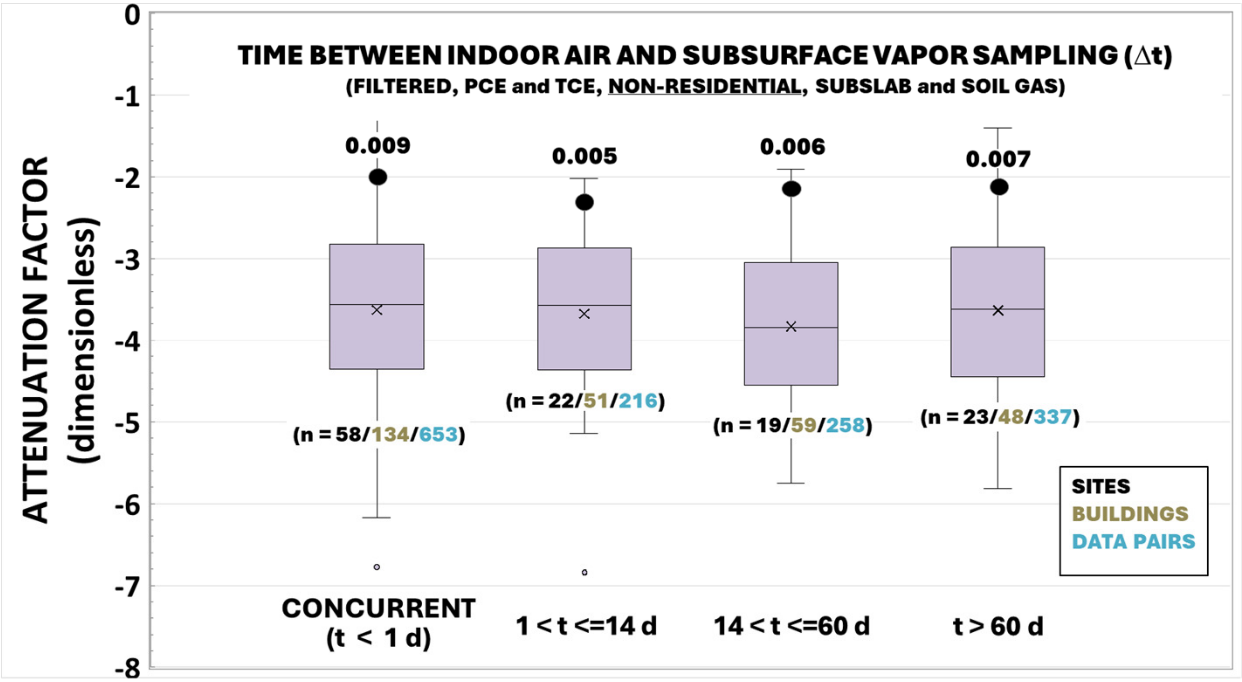
KEY POINT

- median AFs are 8 – 10x higher for buildings built prior to 1950 than after 1950
- similar relations are observed for both non-residential and residential buildings implying the effect is related to building construction and loss of slab integrity
- the median AF for buildings constructed in US Climate Region 3 constructed after 1950 is slightly less than those in other Regions implying that earthquakes have not had a significant effect on slab integrity for buildings in California (may be due to significant improvements to Uniform Building Code from 1959 through 1997)

AF SENSITIVITY TO KEY VARIABLES:
VARIABLES WITH LESSER EFFECT ON AF

Time Between Indoor Air and Subsurface Samples (Δt)

(TCE and PCE, Subslab and Soil Gas, Non-Residential)

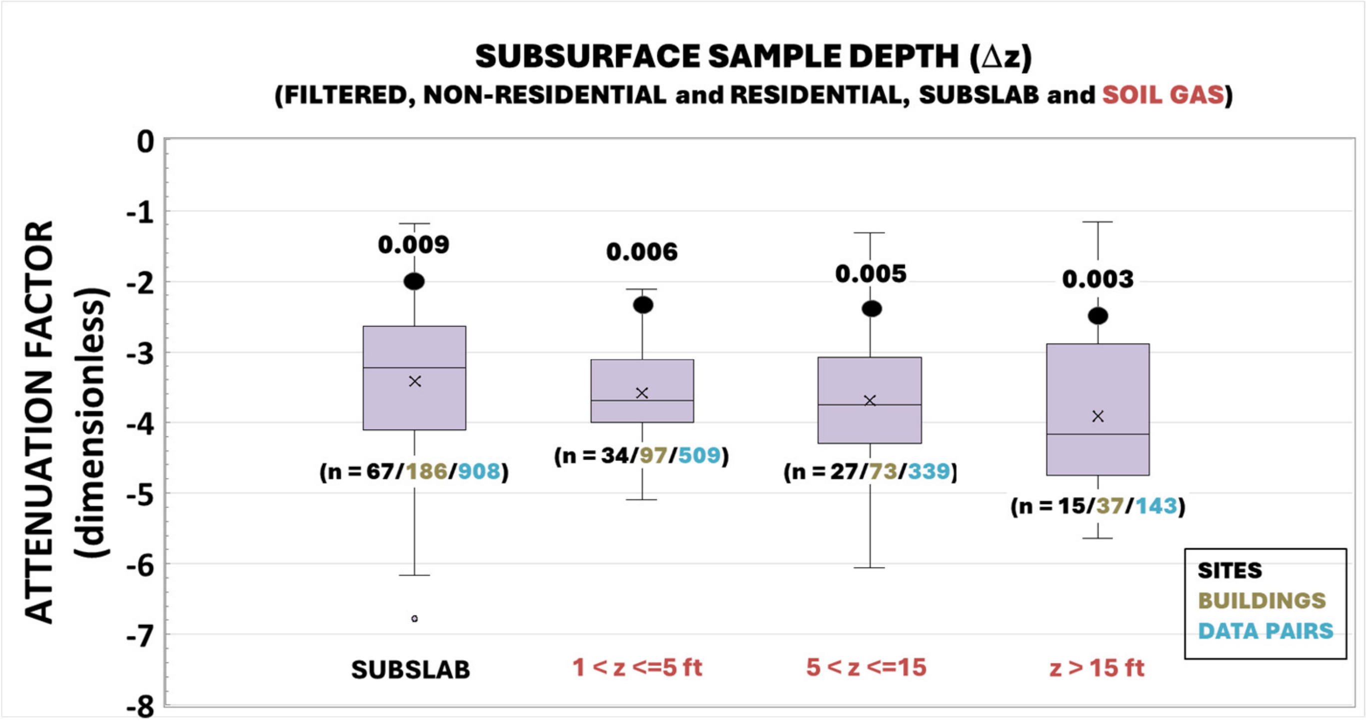


KEY POINT

- median AFs do not vary significantly with increasing time (t) between C_{IA} and C_{SOURCE} sampling, which implies that C_{IA} concentrations remain relatively constant over time in the absence of any source remediation or changes to HVAC

Subsurface Sample Depth (Δz)

(TCE and PCE, Non-Residential and Residential, Subslab and Soil Gas)

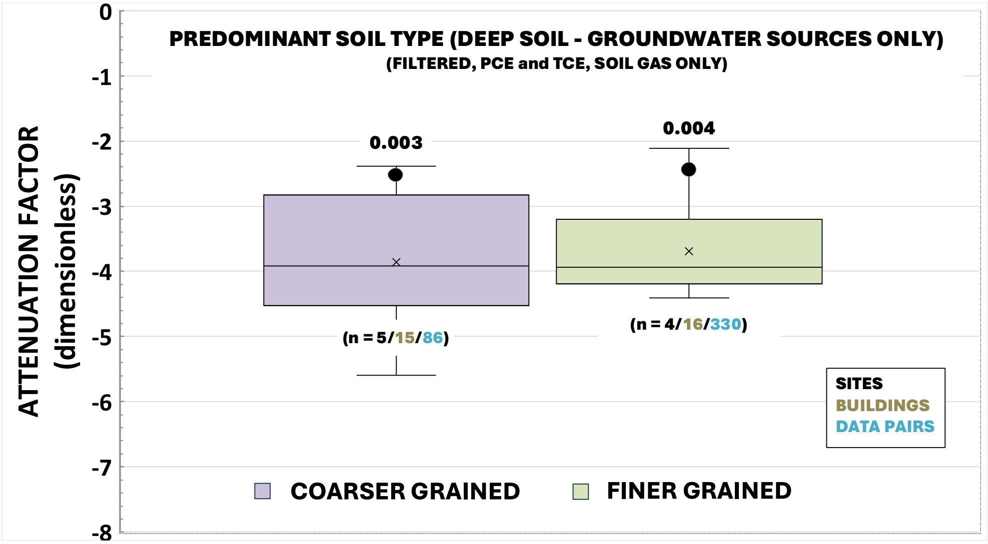


KEY POINT

- median AFs are 3x higher for subslab than soil-gas collected <15 ft bgs, which implies additional attenuation caused by vapor transport through the vadose zone

Predominant Soil Type

(Soil Gas Samples, Deep Soil/Groundwater Sources)



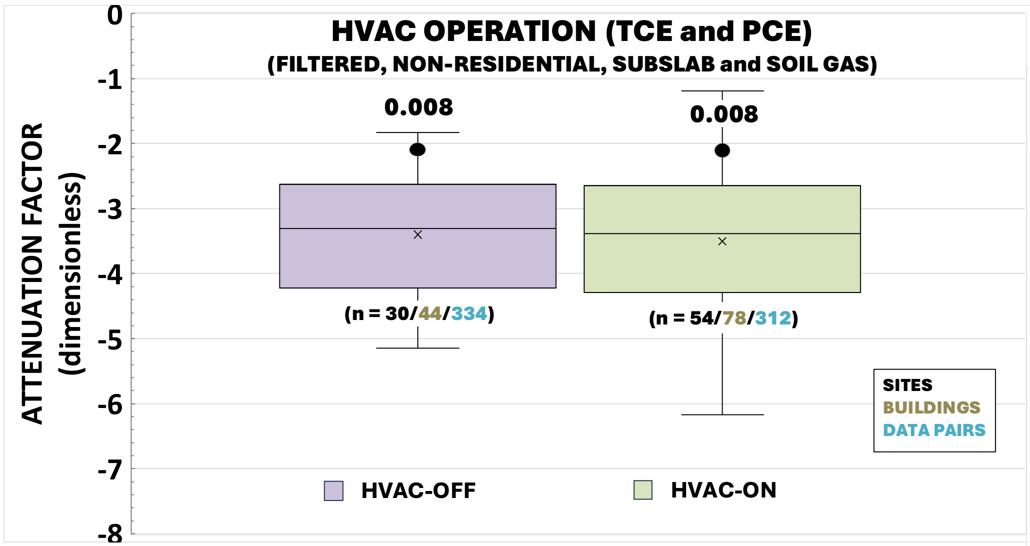
KEY POINT

- median AFs are equivalent for vadose zones consisting of predominantly coarse- or fine-grained soil based on soil gas data from sites with deep soil / groundwater sources
- lack of AF sensitivity to soil-type likely results from a high number of sites with mixed soil types
- the lesser variance in AFs observed at sites with finer-grained vadose zone systems may indicate less spatiotemporal variability in C_{SOURCE} concentrations

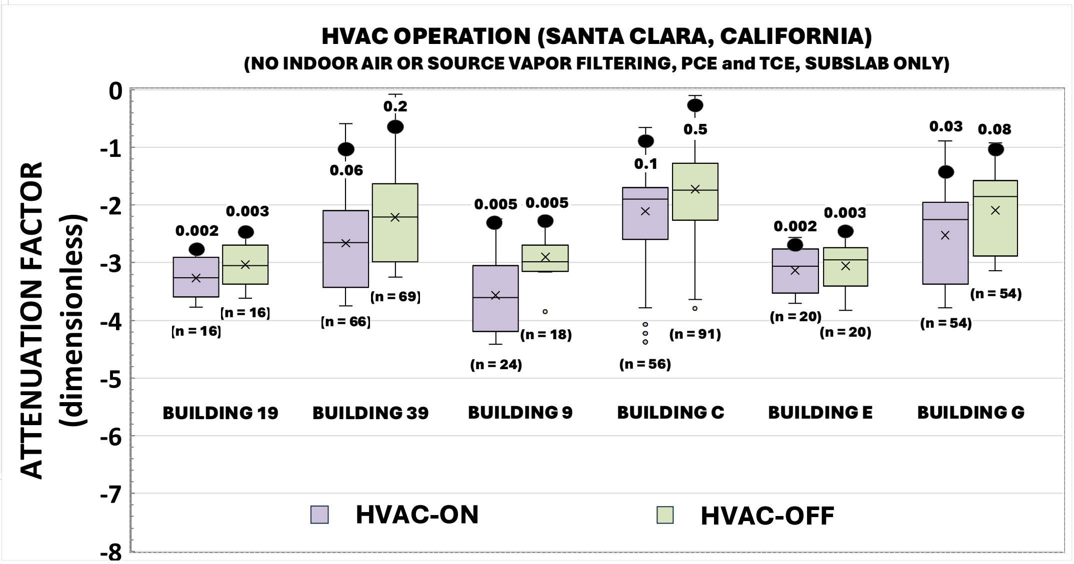
AF Sensitivity to HVAC Operation

(All sites vs. Individual Site)

HVAC OPERATION (MULTIPLE SITES/BUILDINGS)



HVAC OPERATION WITHIN SPECIFIC BUILDINGS (SINGLE SITE)



KEY POINT

- **HVAC operation appears to have a negligible effect on the AF when evaluated across multiple sites/buildings, yet median AFs can vary up to 4x in individual buildings**

AF Sensitivity to Key Variables

Greatest (5-10x) Impact	Moderate (3-4x) Impact	Lowest (1-2x) Impact
Foundation type	HVAC Operation (commercial buildings)	Lateral separation between C_{IA} and C_{source} sampling (Δx)
US Climate Zone	Sample Type (subslab vs. soil-gas)	Time difference between C_{IA} and C_{source} sampling (Δt)
Building age		Chemical type
		Predominant soil type
		C_{SOURCE} assumption (maximum vs. average)

KEY POINT

Understanding the sensitivity to key variables helps 1) understand the need for different default AFs based on site conditions, 2) sites that are more prone to VI, and 3) establish best practice for data collection

AF DETERMINATIONS (Methods 1, 2 and 3)

Method 1: 95th Percentiles

Attenuation Factor		Climate Zone 1 – 3: 95th Percentile	Climate Zone 1 – 3: Median	Climate Zone 4 - 7: 95th Percentile	Climate Zone 4 - 7: Median
Residential	**Subslab**	Insufficient Data		0.01	0.002
	Soil Gas	0.003	0.0001	Insufficient Data	
Non-Residential	**Subslab**	0.008	0.0002	0.01	0.002
	Soil Gas	0.005	0.0003	Insufficient Data	

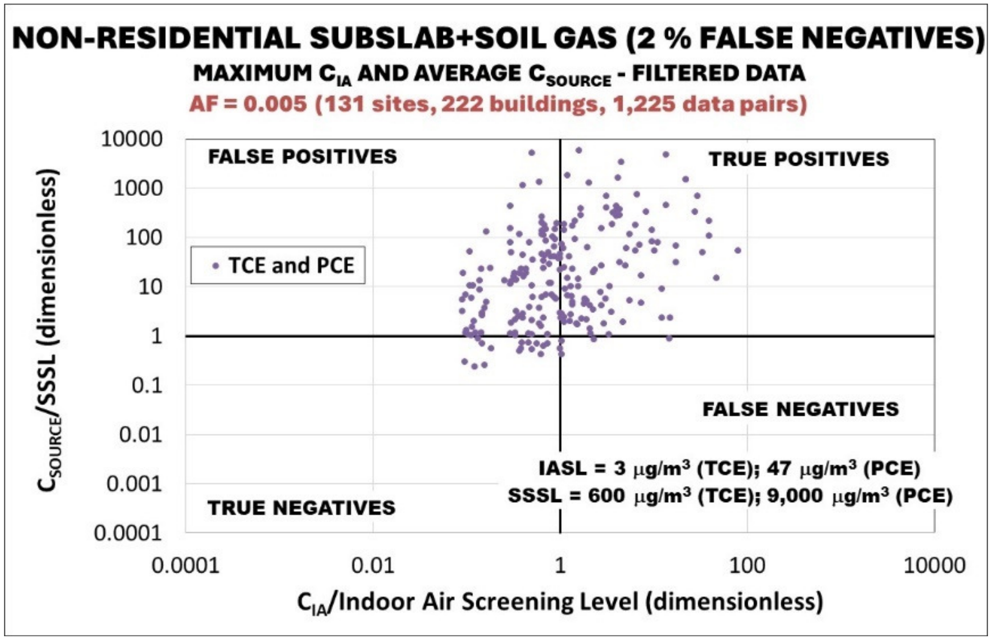
* Based on Average C_{SOURCE}

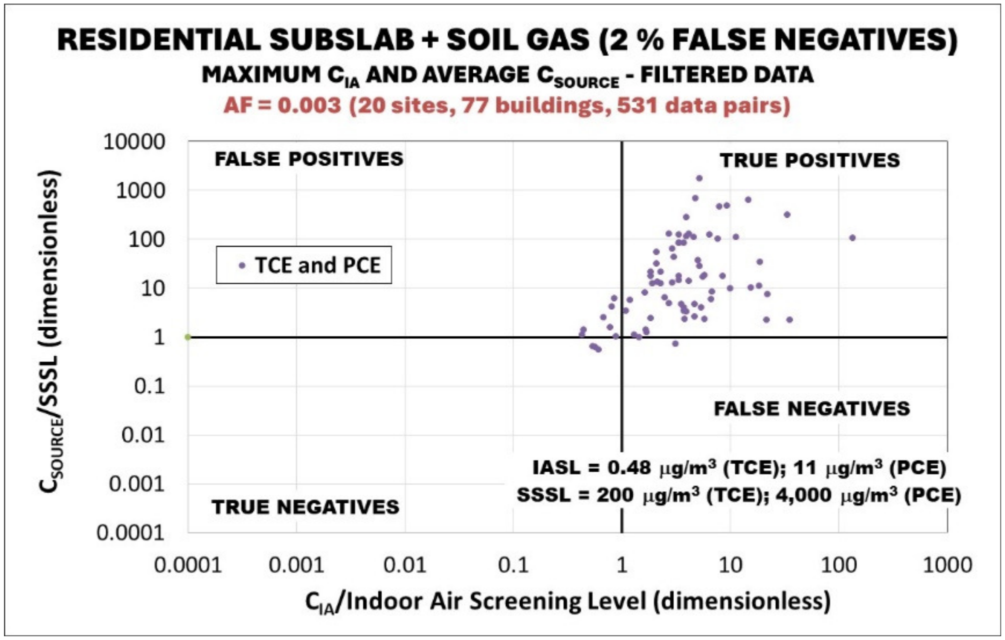
KEY POINT

- 95th %ile AFs are 3 – 10x less than USEPA AF = 0.03, depending on Climate Zone
- AFs with insufficient data could be adjusted based on AF ratios in other Climate Zones
- most sites will exhibit AFs similar to median values

Method 2: Reliability Analysis (EXAMPLE)

(Filtered TCE Database - Assuming 2% False Negatives)



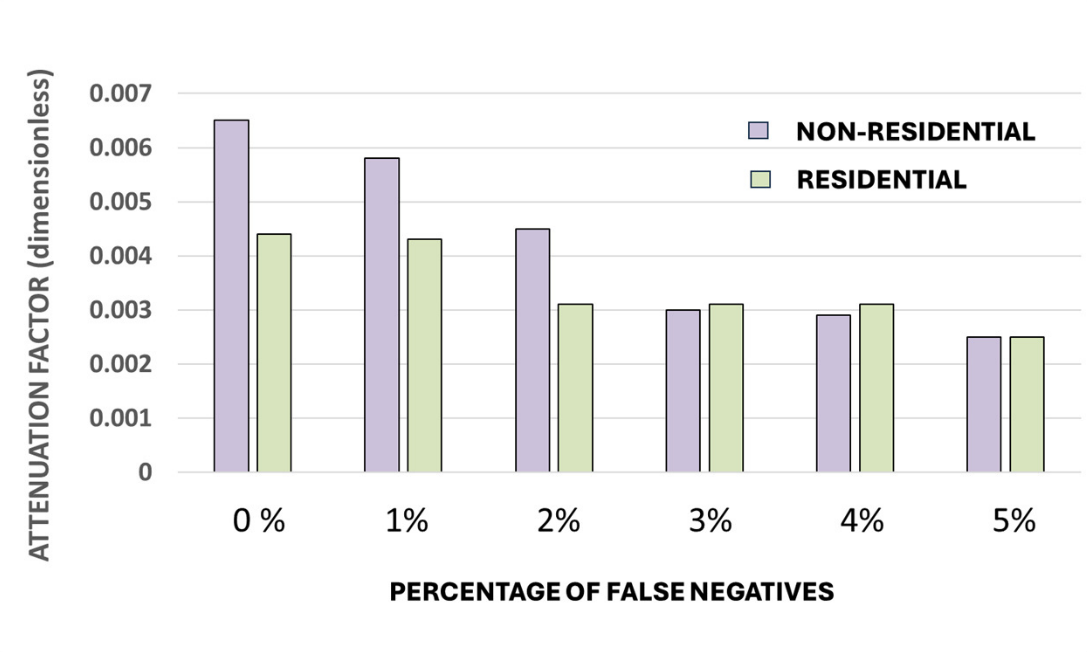


KEY POINT

- **AFs derived from reliability analyses assuming 2% false negatives for non-residential (0.005) and residential (0.003) buildings are within the range of 95th percentile AFs for non-residential (0.005 – 0.01) and residential (0.003 – 0.01) buildings based on subslab and soil-gas samples**

Method #2: Reliability Analysis (TCE and PCE)

(Filtered Data)



BASELINE FILTERS

C_{BGRD} = 90th %ile in Indoor Air

C_{SOURCE} = 500x C_{BGRD}

All Foundations

All Climate Zones

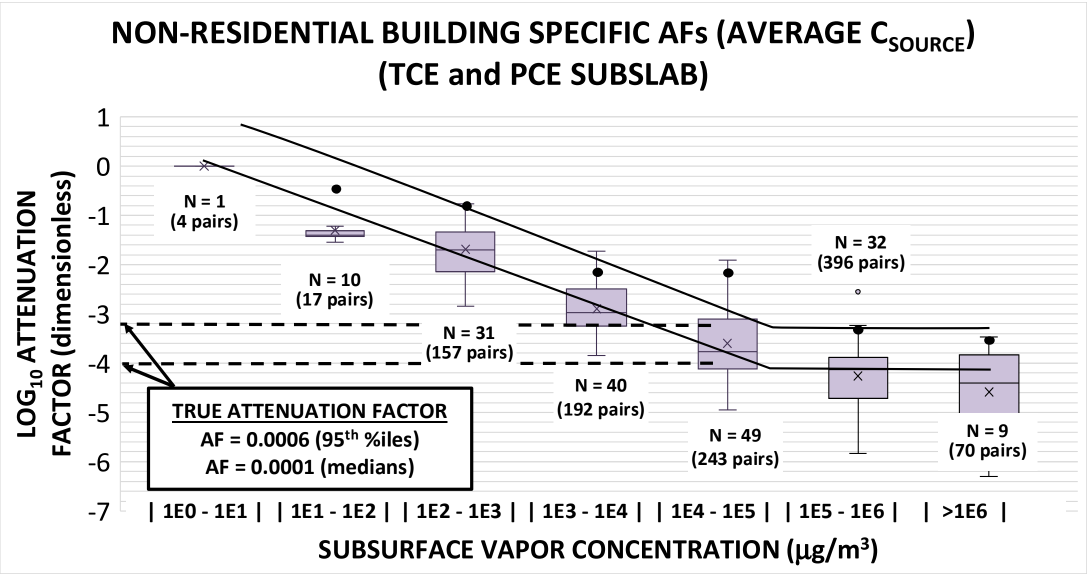
All Building Ages

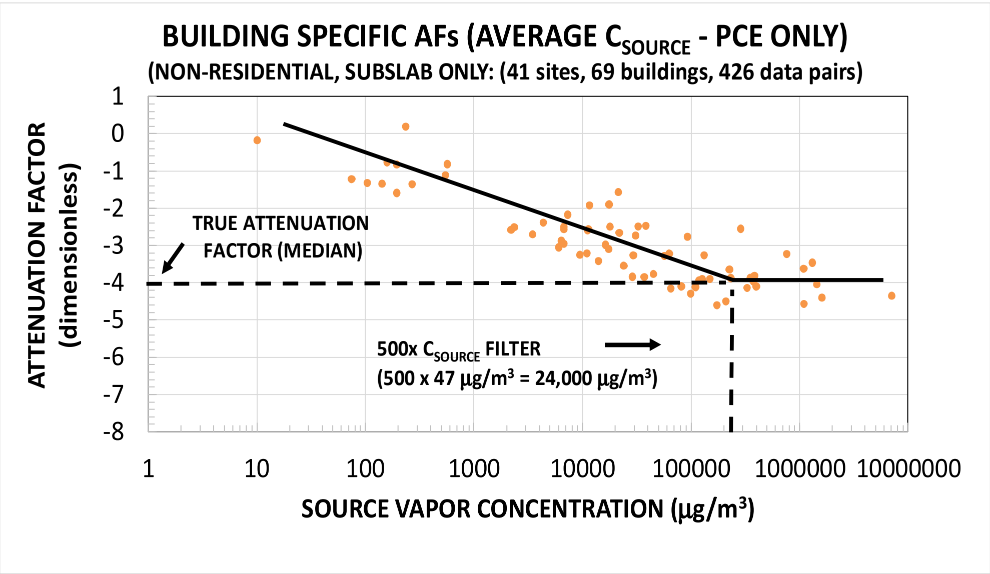
Δt = 92 days; Δx = 110 ft; Δz = 15 ft)

KEY POINT

- little change is observed in AFs based on percentage of FNs (incorrect outcome based on soil-vapor results)
- non-residential buildings exhibit higher AFs than residential buildings which is consistent with the 95th percentile AFs

Method 3: Theoretical AF vs. C_{SOURCE} Relations
(Filtered TCE + PCE Data)

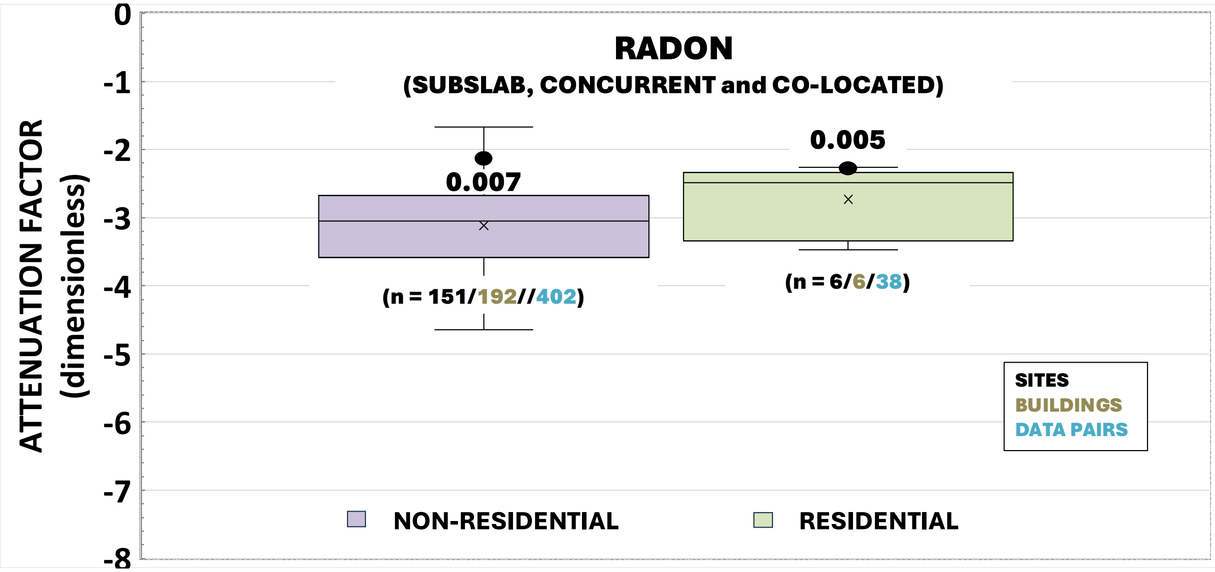


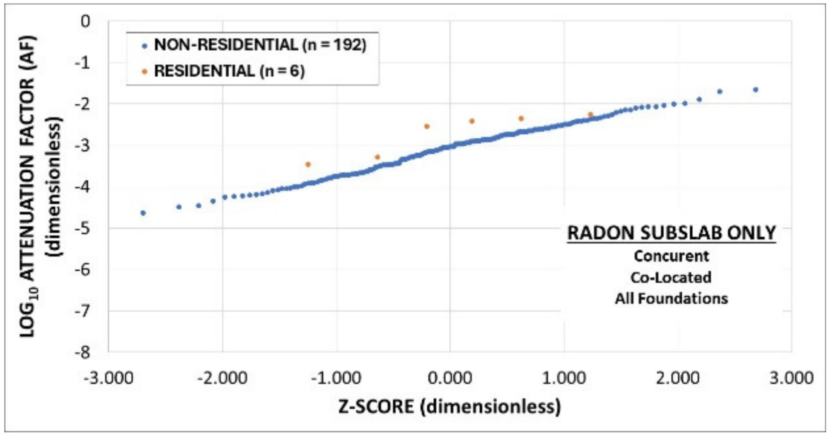


KEY POINT

- median AFs for TCE and PCE tend to asymptote at higher source vapor concentrations; for PCE this equates to a 500x multiplier of background (validation of the C_{SOURCE} filter)
- there is still lots of scatter in the data making it difficult to draw conclusions

Radon Data from California





KEY POINT

- the 95th percentile AF for non-residential buildings (0.007) is consistent with the 95th percentile for non-residential buildings (0.008) for Climate Zone (1 – 3)
- the radon exhibit a highly log-normal distribution helps support the goal of C_{IA} and C_{SOURCE} filtering

Conclusions

- AFs derived from a more comprehensive evaluation of building-specific AFs range between 3 – 10x less than USEPA's recommended value of 0.03
  - 95^{th} %ile: 0.006 (range from 0.003 to 0.01
  - median: 0.0006 (range from 0.0001 to 0.002)
- AFs derived from reliability analyses range between 0.005 (non-residential) – 0.003 (residential)
- AFs derived from AF vs. C_{SOURCE} relations - difficult to quantify but are approximately an order of magnitude less
- AF sensitivity analysis (e.g., climate, building type/age, sample type)
  - helps explain differences between previous studies
  - AFs can be adjusted based on site-specific conditions
- study provides more technically defensible default (generic) AFs that can account for variable site conditions; observed AFs will likely more closely align with median estimates

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Gina Plantz – Haley and Aldrich
Suzi Rosen – Partners Environmental Solutions
Robert Traylor – Partners Environmental Solutions
Laura Trozzolo – TRC Companies
Nadine Weinberg – ERM

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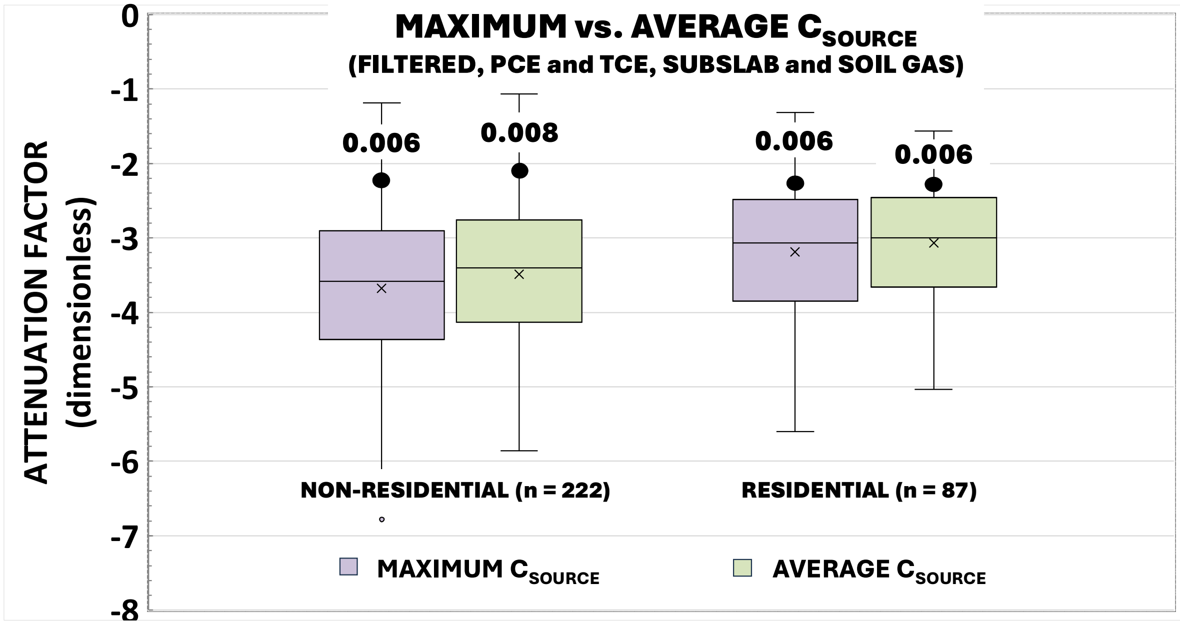
C_{SOURCE} Strength Assumption
(Maximum vs. Average)

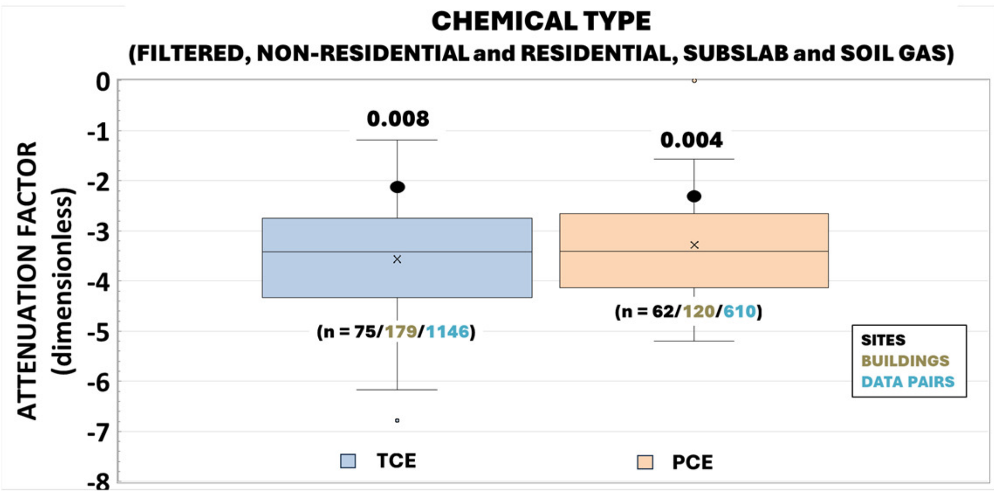


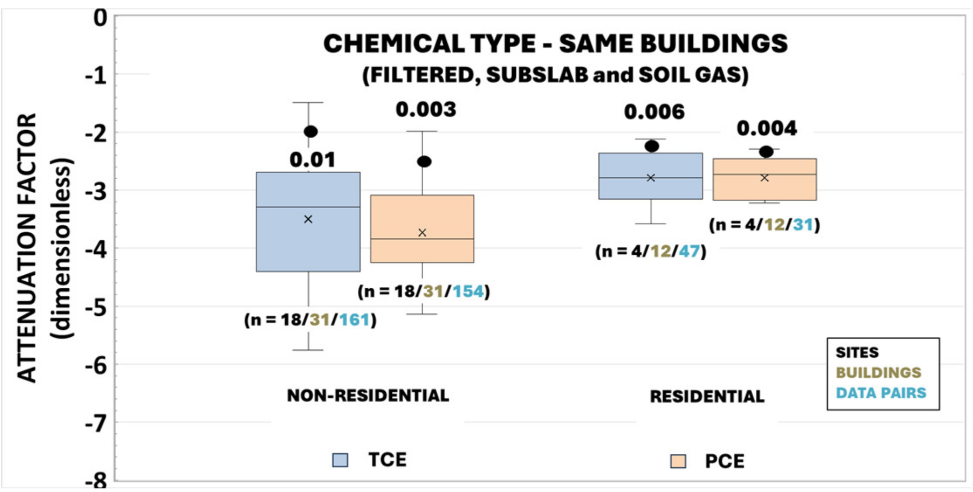
KEY POINT

- median AFs are 1.5x higher for non-residential buildings and essentially equivalent for residential buildings which is consistent with a) limited differences in maximum versus average C_{SOURCE} concentrations for relatively small C_{SOURCE} sample populations and b) lesser variability in C_{SOURCE} concentrations at residential versus non-residential buildings

Chemical Type

(Non-Residential vs. Residential, Same Buildings)



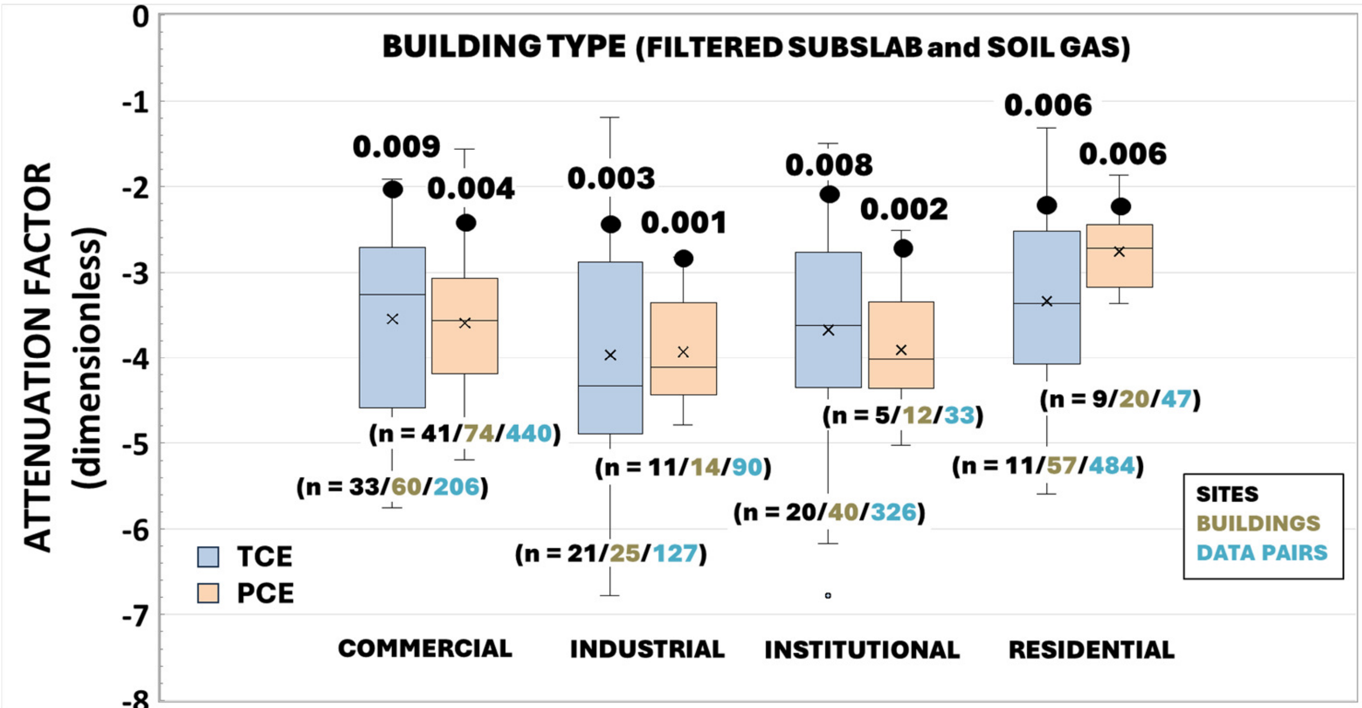


KEY POINT

- **median AFs are generally unaffected by chemical type allowing the variable to be grouped for AF determinations**

Building Type

(Non-Residential vs. Residential)



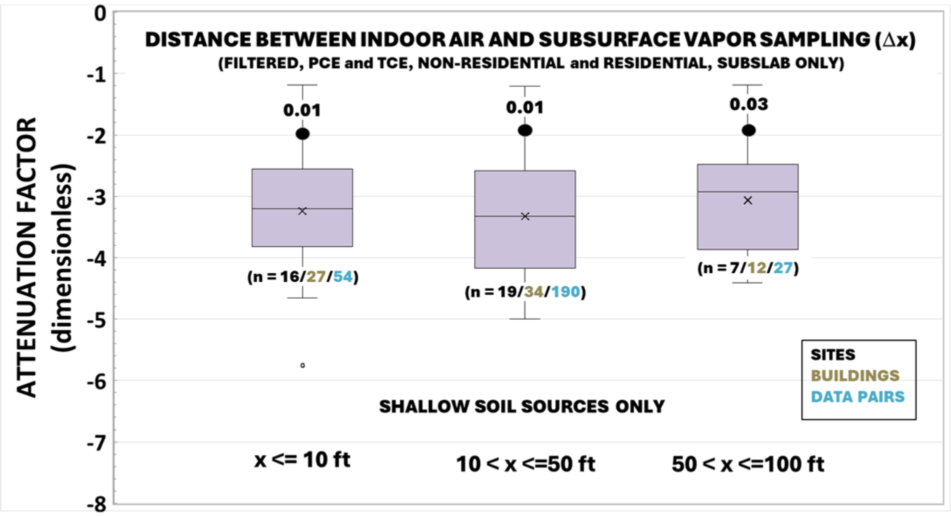
KEY POINT

- median AFs are lowest for industrial buildings which may exhibit thickest slabs and greatest ventilation in indoor air
- median AFs are highest in residential buildings which may exhibit the thinnest slabs and least ventilation in indoor air

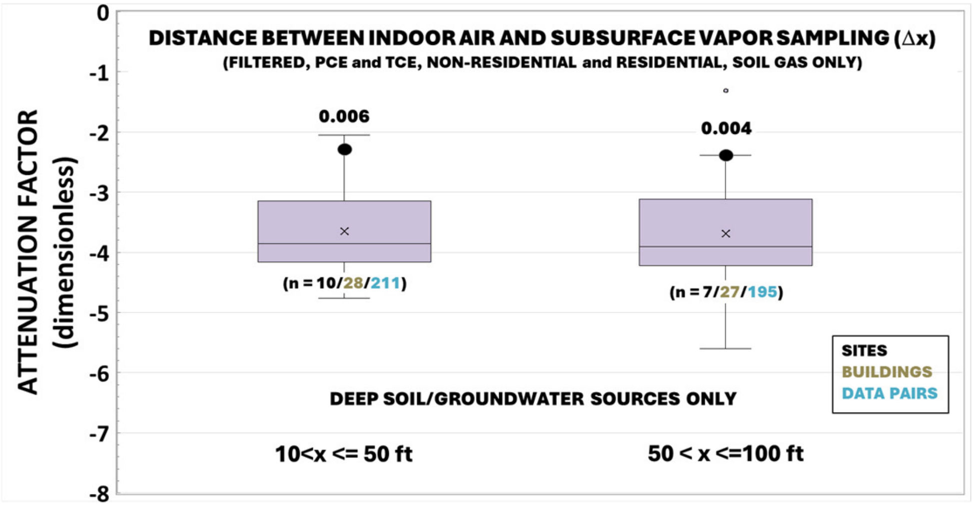
Distance Between Indoor Air and Subsurface (Δx)

(TCE and PCE, Non-Residential and Residential)

SHALLOW SOIL SOURCES (SUBSLAB ONLY)



DEEP SOIL/GROUNDWATER SOURCES (SOIL-GAS ONLY)



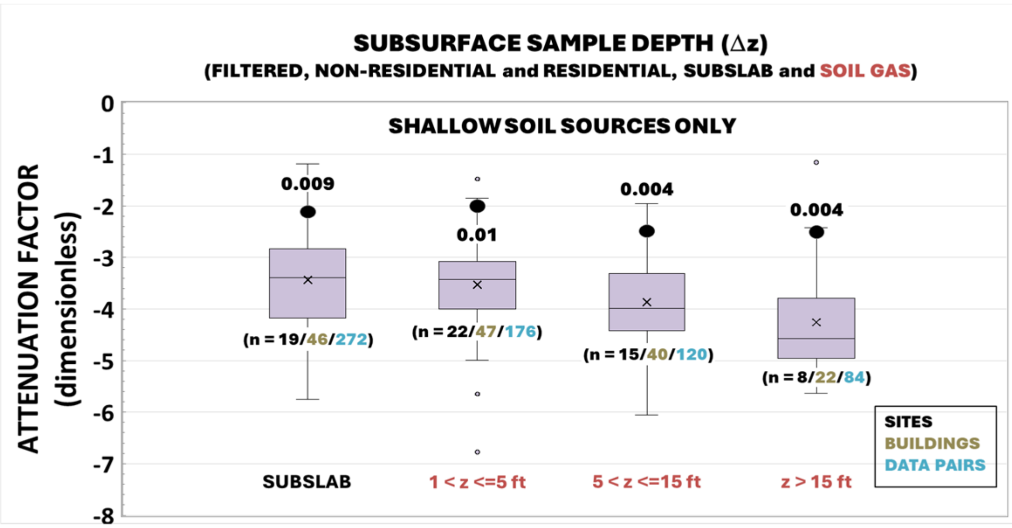
KEY POINT

- median AFs do not vary significantly with increasing distance (Δx) between C_{IA} and C_{SOURCE} sample locations for relatively shallow soil sources
- median AFs also do not vary significantly for deep soil/groundwater sources and soil-gas samples, implying that C_{IA} and C_{SOURCE} samples do not have to be co-located to be representative for VI screening

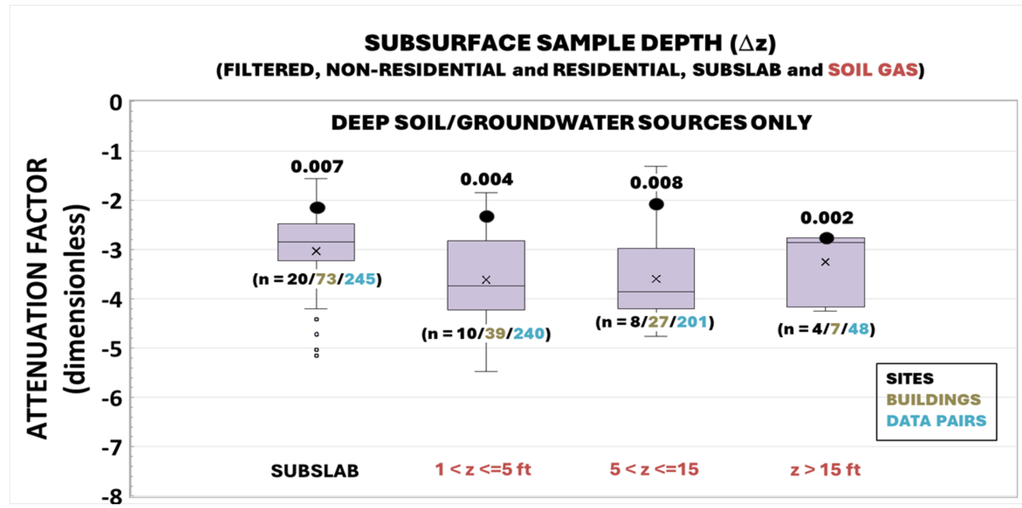
Subsurface Sample Depth (Δz)

(TCE and PCE, Non-Residential and Residential, Subslab and Soil Gas)

SHALLOW SOIL SOURCES



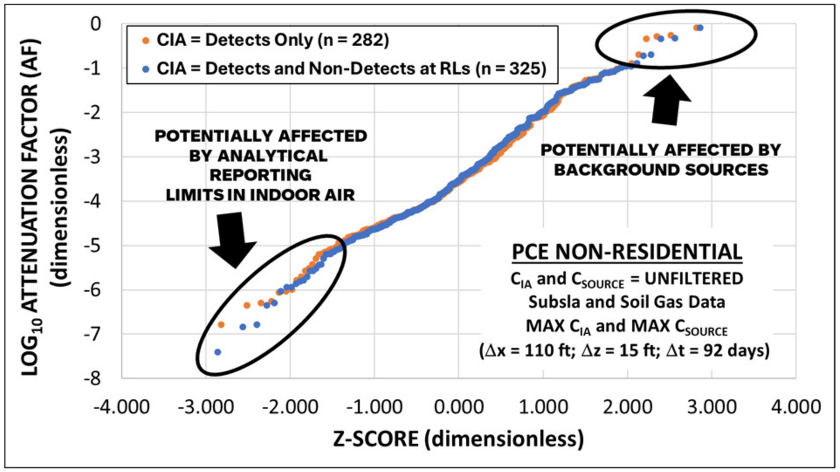
DEEP SOIL/GROUNDWATER SOURCES



KEY POINT

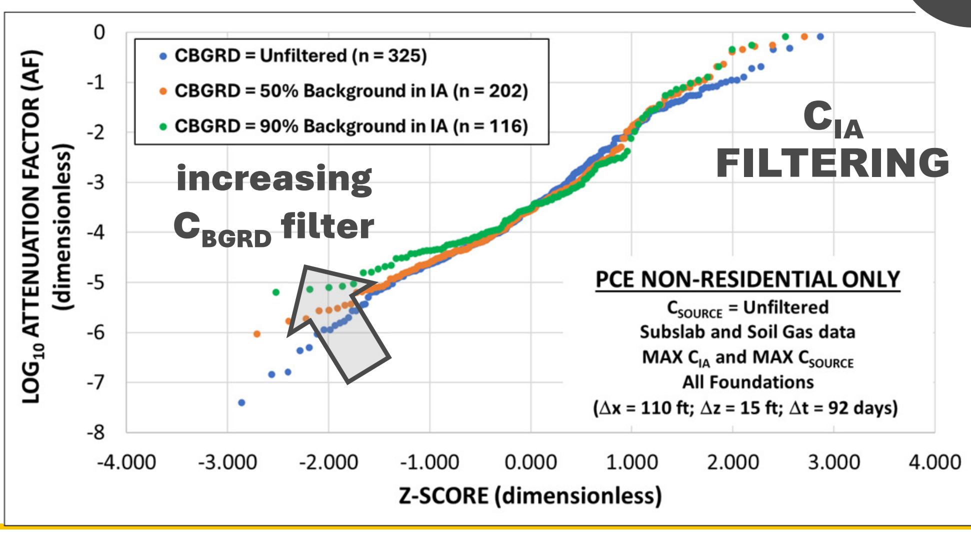
- median AFs are generally lower for soil-gas vs. subslab samples, which is consistent with additional attenuation caused by vapor transport through the vadose zone

AFs Can Be Affected by Analytical Reporting Limits, Background Sources in Indoor Air

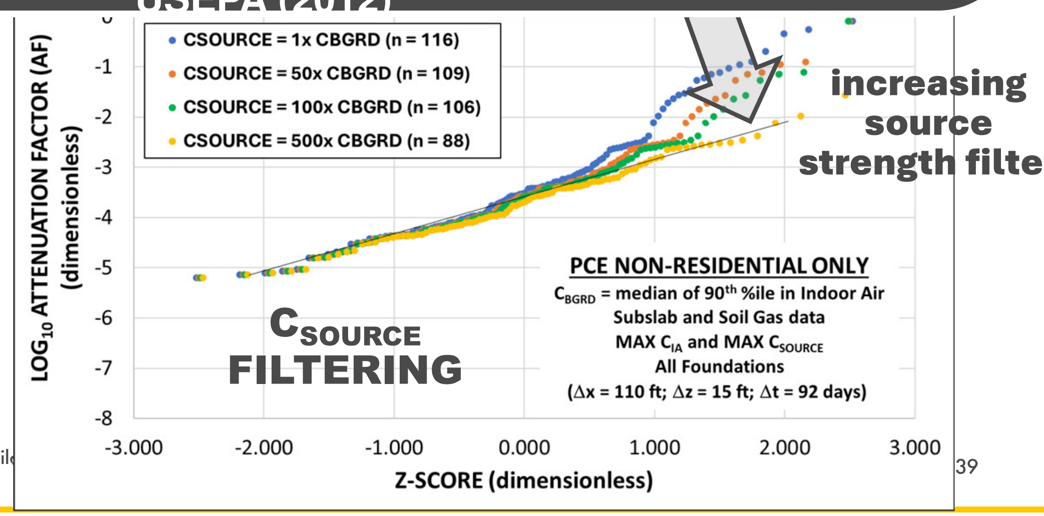


KEY POINT

- increasing C_{IA} filter establishes C_{BGRD} and reduces # of low AFs that are not log-normally distributed; increasing conservatism
- increasing C_{SOURCE} filter (multiplier of C_{BGRD}) greatly reduces very high AF (weak sources)
- analysis resulted in C_{BGRD} of 90% background in indoor air (same as USEPA 2012) and C_{SOURCE} filter = 500x C_{BGRD} (10x higher than USEPA (2012)



of Equil



Background: 3 Methods for AF Derivation - Differences

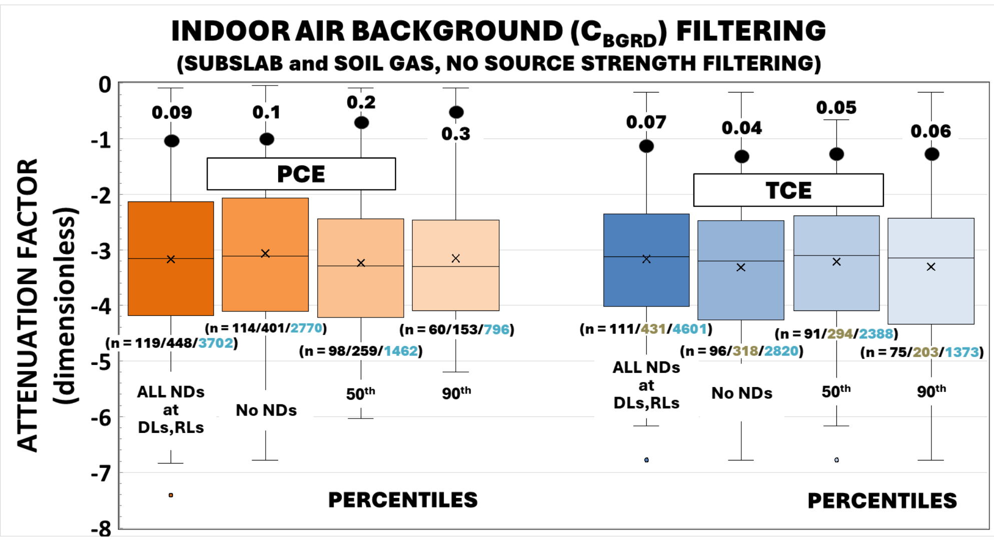
Method	Pros	Cons
Method 1: Descriptive Statistics (e.g. 95th %ile)	Approach ultimately used by USEPA (greater acceptance by wide range of stakeholders) AF sensitivity to specific variables is more easily visualized and assessed	95th %ile AFs can be strongly affected by small #s of data points (e.g., outliers), especially for small data populations AF can be sensitive to data filtering
Method 2: Reliability Analysis	More risk-based (AF defined by its ability to consistently, dependably identify sites where C_{IA} > RBSLs) AF dependence on C_{SOURCE} and C_{BGRD} filtering is reduced	Draws attention to an “acceptable” % of false negatives – requires agency decision/consensus Requires a relatively large population of data (i.e., cannot be used to assess AF sensitivity to certain variables)
Method 3: Theoretical Relations	Helps show impact of C_{SOURCE} on AF (i.e., AFs affected by background sources)	Difficult to define the AF asymptote if AF data are highly variable

KEY POINT

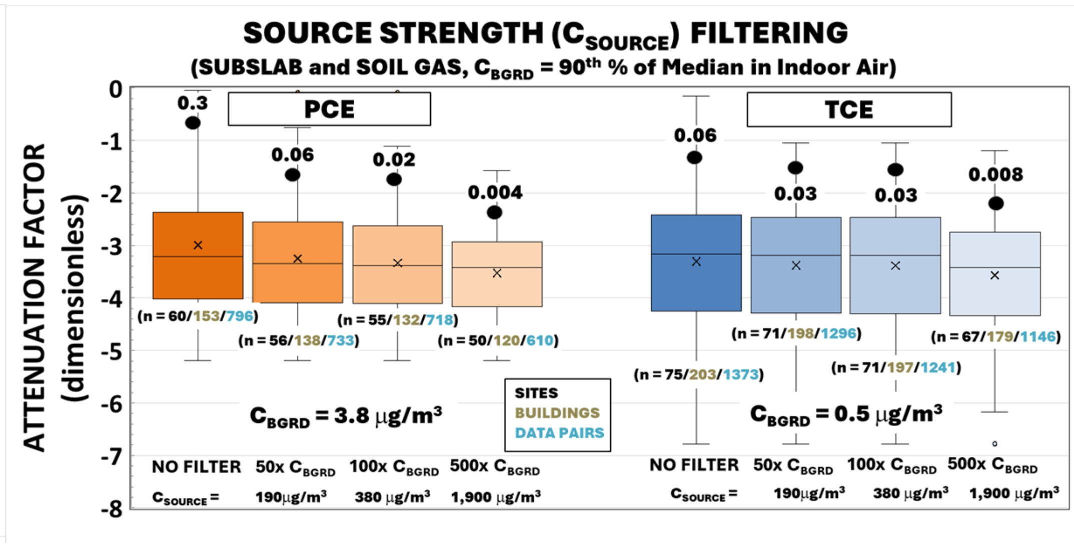
- **AFs derived using all 3 methods provides a multiple lines of evidence to support a technically defensible AF value**

Effects of C_{IA} and C_{SOURCE} Filtering on AFs

INDOOR AIR (ESTABLISHING C_{BGRD})



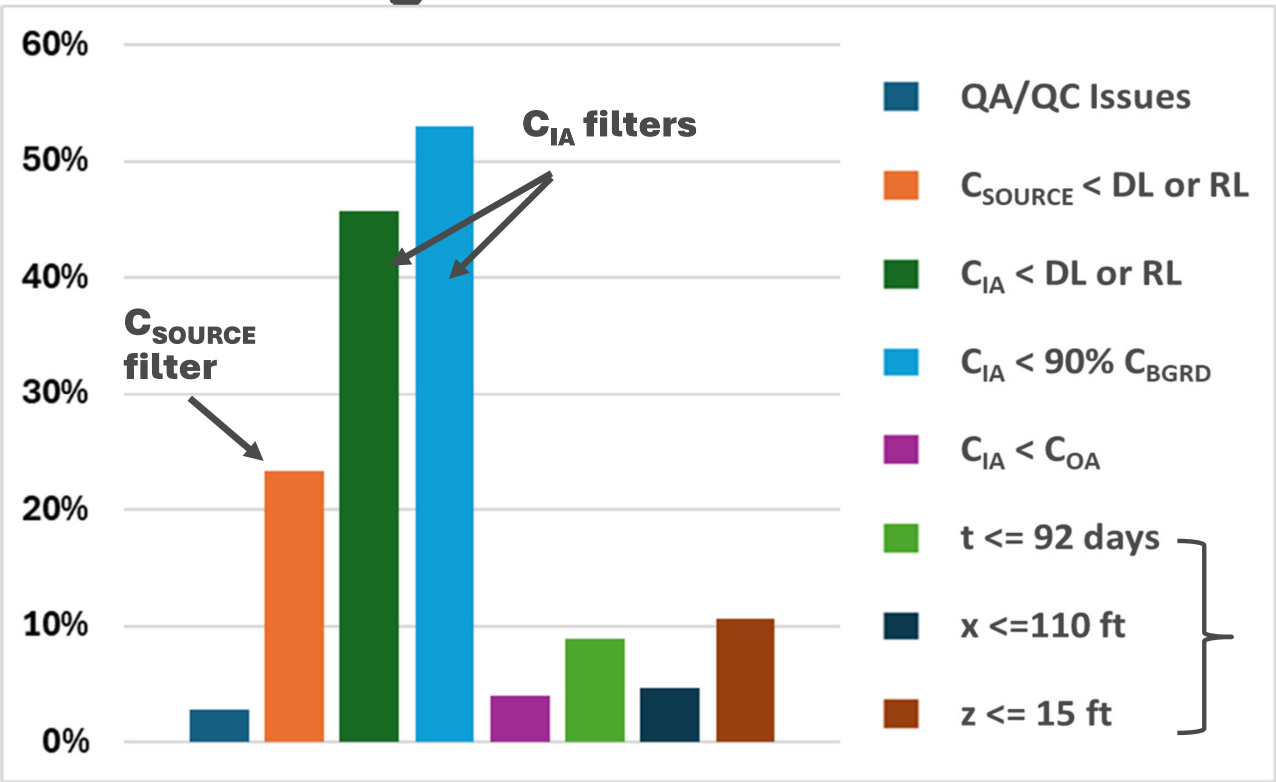
SUBSURFACE VAPOR



KEY POINT

- the most representative AF population were defined by:
  - the median of 90th %ile C_{BGRD} in indoor air greatly reduces the total PCE and TCE AF data population (2 – 3x); little effect on median and 95th % AFs (consistent with USEPA, 2012)
  - a C_{SOURCE} filter of 500x which provided the most log-normal AF distribution, eliminates high AFs (10x higher than USEPA, 2012)

Reduction in AF Data Population Caused by Data Filtering



baseline filters supported by AF sensitivity analyses

KEY POINT

- C_{IA} then C_{SOURCE} filtering; other variables have minor effect

C_{IA} = Indoor air concentration

C_{SOURCE} = Source vapor concentration

C_{OA} = Outdoor air concentration

C_{BGRD} = Background concentration in indoor air

AF Sensitivity to Meteorological Events

CONTINUOUS MONITORING @ NON-RESIDENTIAL BUILDING (SAN BERNADINO, CALIFORNIA)

Barometric Pressure

Differential Pressure

C_{SOURCE}

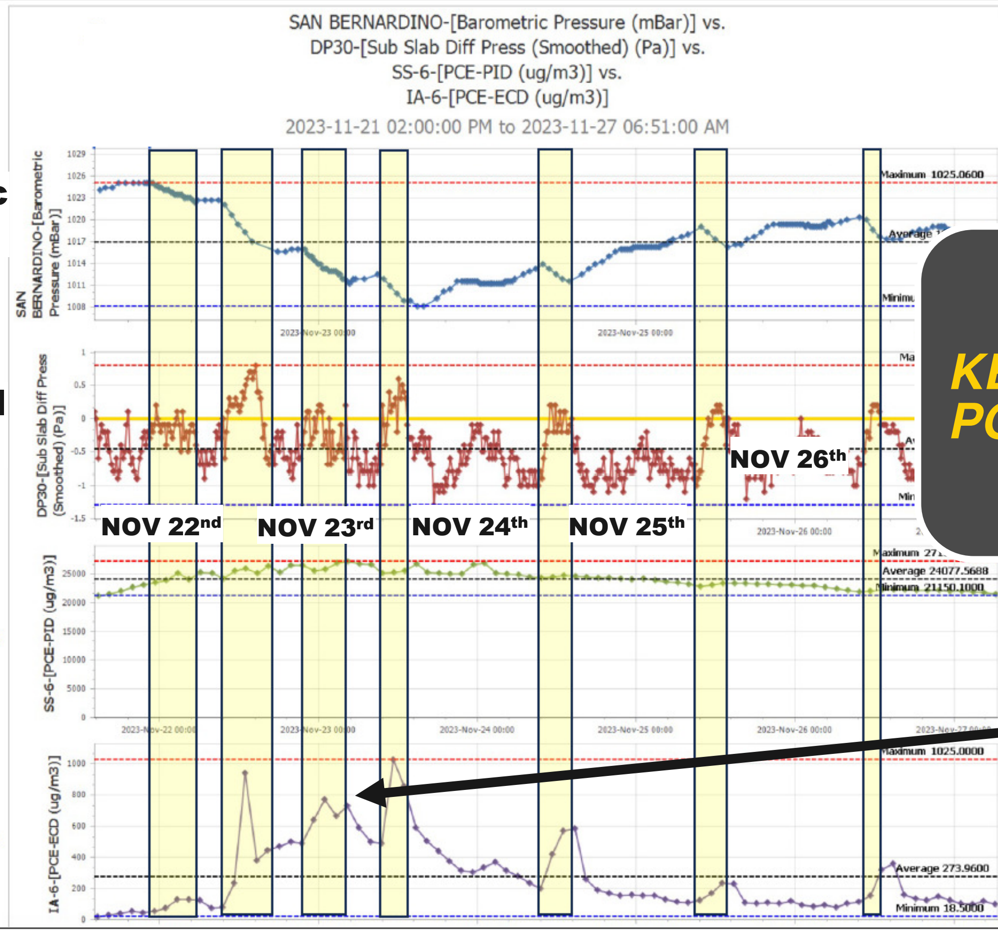
<10% rise in PCE_{SS} concentrations

PCE_{SS}

C_{IA}

OoM (100 – 1,000 μg/m³) spikes (hrs) in PCE_{IA} concentrations

PCE_{IA}



KEY POINT

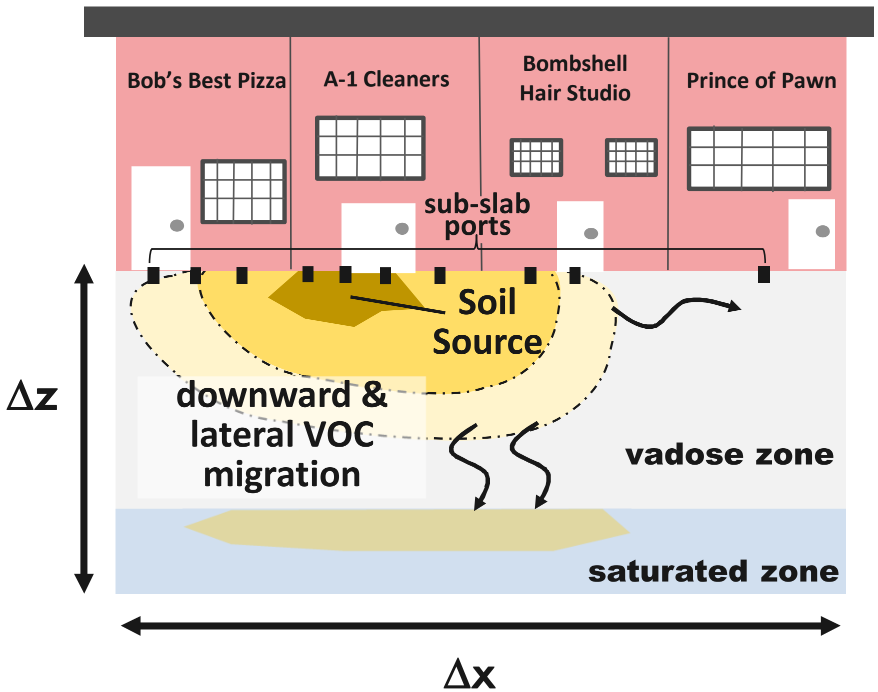
C_{IA} can spike during low and relatively rapid drops in BP, while C_{SOURCE} remains relatively constant

1-day average = 3.8x 5-day average

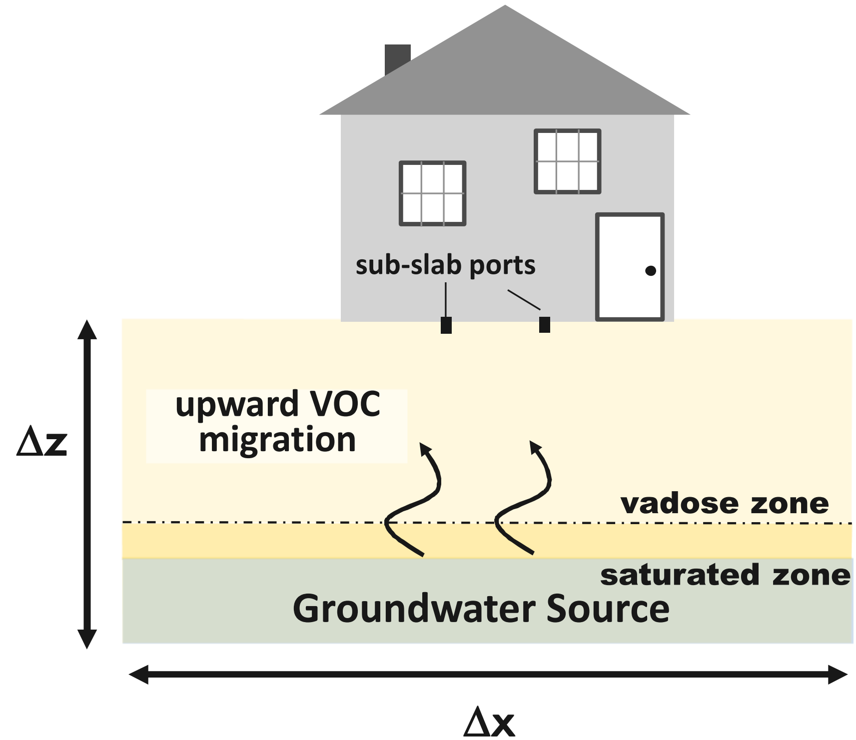
Data from Kram (2023)

Differences in Relative Source Depth Could Affect AF Determinations (Shallow Soil vs. Groundwater Source)

Non-Residential
(shallow soil sources)



Residential
(groundwater sources)



SOME OVERLAP – NOT ALL SITES