U.S. EPA "State of VI Science" Workshop

Reducing Vapor Intrusion Uncertainties by More Frequent Simple Measurements and Community Involvement

Sampling Confidence Analysis for Multiple Sites: Flowcharts, Methods and Probability Concepts

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Presentation archived at https://iavi.rti.org/

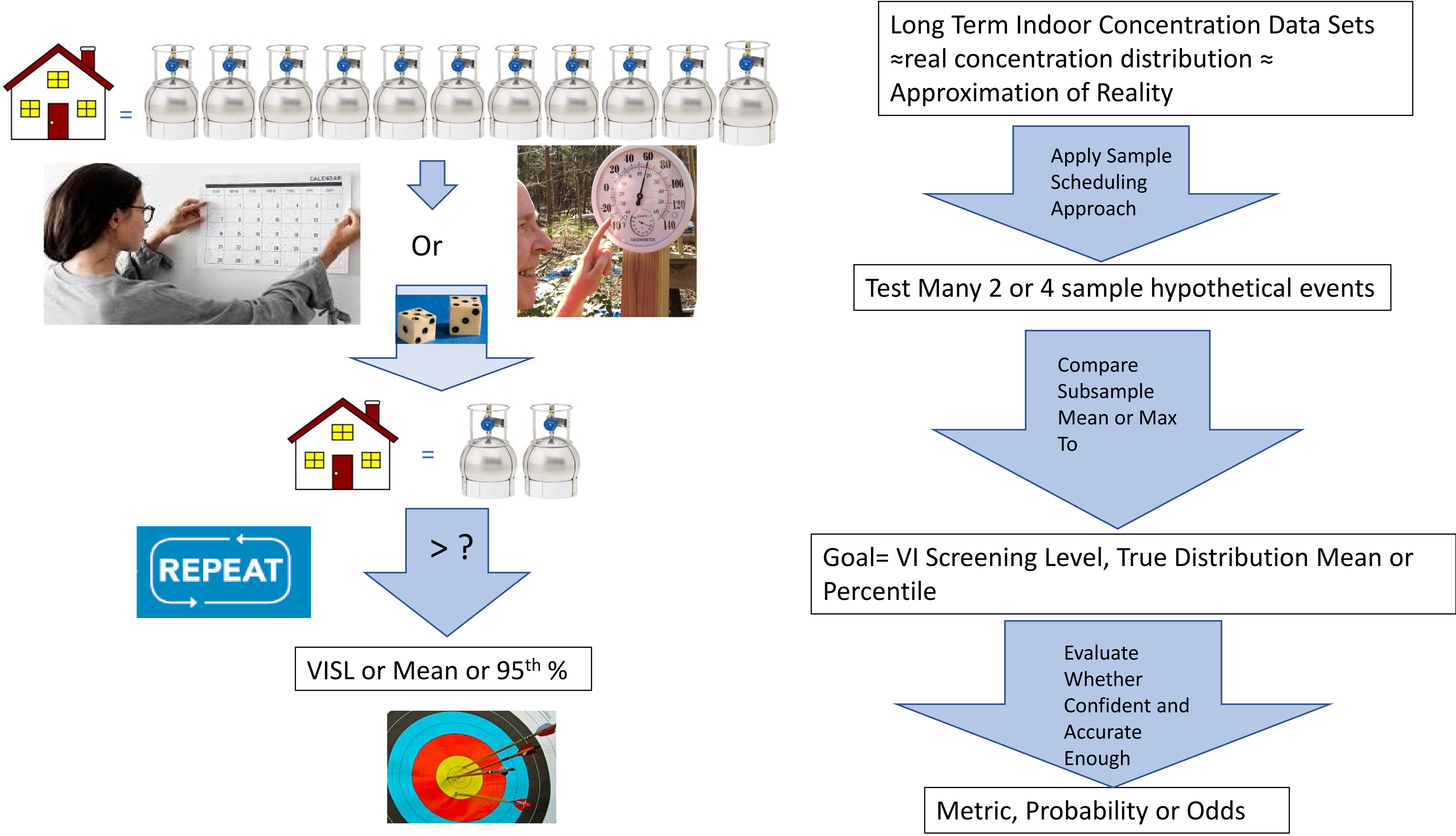
Presentation Outline

- How the effectiveness of various sampling scheduling approaches were tested. (How do project teams decide when to collect indoor air samples? What is the exposure assessment strategy behind that?)

- How the various sampling approaches performed at specific sites

- How easy is it to determine various metrics – mean concentration, 95^{th} UCL on mean, 90^{th} percentile, 95^{th} percentile?

- How the various sampling approaches performed across all sites


=
Or
=
> ?
REPEAT
VISL or Mean or 95th %
Long Term Indoor Concentration Data Sets ≈real concentration distribution ≈ Approximation of Reality
Apply Sample Scheduling Approach
Test Many 2 or 4 sample hypothetical events
Compare Subsample Mean or Max To
Goal= VI Screening Level, True Distribution Mean or Percentile
Evaluate Whether Confident and Accurate Enough
Metric, Probability or Odds

Data Sets Tested in This Study (n is # for VOCs)

- Sun Devil Manor (Residential); unoccupied, with land drain open, without blower door, n=342 daily averages
- Indianapolis Duplex (Residential) – unoccupied, data from two floors; without mitigation; n=58 weeklong samples or 49 weeklong with high time resolution radon ; n=136 daily averages
- Moffett Field Building 15 (Commercial) – normal operating conditions; n =156 daily averages
- Gaffney Alaska (Commercial) – normal operating conditions, n= 27 days of sampling
- Virginia Site A (Industrial) – two locations – normal operating conditions n=589 daily averages

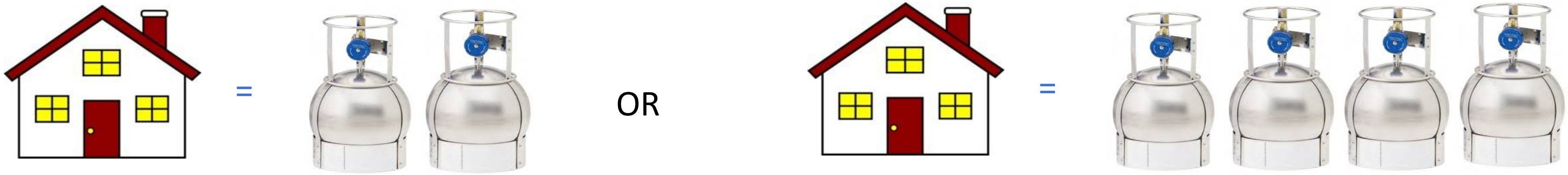
Sample Scheduling Approaches Tested in this Study

- One sample per calendar season (Winter = Dec 1 to Feb 28, Spring March 1 to May 31…..) – either winter/summer or four quarterly samples
- Half the samples in heating season (November 1 to March 31st), half not in heating season
- All samples in heating season.
- Rounds begun based on change in temperature – a decrease day over day of 5 F (in either daily low or daily average)

- Rounds begun based on an indoor/outdoor differential temperature of 15 F
- Rounds begun based on a negative differential pressure of 0.01 inches of water or 2.49 Pa or more negative
- Rounds begun based on a day over day increase in radon concentration of 0.5 pCi/l

- Rounds of sampling based on a threshold Level of > 2 pCI/l in radon
- Rounds based on exceeding the 90th percentile of radon levels expected for the structure either based on the first month of sampling or the full data set.

Commonly Used Sampling Assumptions Tested



- Most Scheduling Approaches Tested with 2 vs. 4 Samples
- Assumed computer or person would “evaluate” previous data at midnight to decide whether to sample that day (starting in theory at 12:01 AM).
- Evaluation could be automated/triggered sampling; human in the decision loop, weather forecast, or calendar based.
- All allowable combinations of sampling days based on scheduling approach considered equally likely.
- Days to be sampled will be defined as 24-hour block averages because that is the most common sampling technique in the field overall and how even continuous data is often evaluated. This was then either one Summa sample or a daily average GC result.

Goals for a Sampling Strategy

- Is a >95% confidence in making the assessment decision about an individual structure required? (<5% false negative?)

- Sampling strategies should be applicable to a wide variety of buildings, using a minimum of easily available preexisting information.

- Sampling strategies should be robust – perform well across a variety of situations.

Metrics, Probabilities, Tested

- At least one sample of the two or four samples collected will equal or exceed the “true” mean concentration
- The mean of the two or four samples taken will be within an order of magnitude range around the true mean concentration (i.e., if true mean concentration is X, then mean between X/3.3 and 3.3X).
- At least one of the two or four samples will exceed the 90^{th} percentile of the underlying distribution
- At least one of the two or four samples will exceed the 95^{th} percentile of the underlying distribution
- At least one of the two or four samples will be within a factor of 3.3x of the 95^{th} percentile of the underlying distribution
- At least one of the two or four samples taken will be equal to or exceed the 95% UCL on the mean of the VOC distribution.

Simplified Data Processing Example

Full Dataset

Mean VOC = 8.5

1/01/2010 VOC = 12 Rad = 2.1
1/02/2010 VOC = 1 Rad = 3.3
1/03/2010 VOC = 10 Rad = 2.8
1/04/2010 VOC = 8 Rad = 0.4
1/05/2010 VOC = 2 Rad = 0.6
1/06/2010 VOC = 7 Rad = 5.8
1/07/2010 VOC = 12 Rad = 5.2
1/08/2010 VOC = 16 Rad = 1.4

Apply Sampling Approach Decision Rule: For example, Radon > 2 pCi/l

Sampling Approach Dataset

Selects only samples meeting rule criteria

1/01/2010 VOC = 12 Rad = 2.1
1/02/2010 VOC = 1 Rad = 3.3
1/03/2010 VOC = 10 Rad = 2.8
1/06/2010 VOC = 7 Rad = 5.8
1/07/2010 VOC = 12 Rad = 5.2

Apply Test: sample is > VOC mean of full dataset?

Test Dataset

Fails Test Criteria

Meets Test Criteria

1/01/2010 VOC = 12 Rad = 2.1	Meets Test Criteria
1/02/2010 VOC = 1 Rad = 3.3	Fails Test Criteria
1/03/2010 VOC = 10 Rad = 2.8	Meets Test Criteria
1/06/2010 VOC = 7 Rad = 5.8	Fails Test Criteria
1/07/2010 VOC = 1.2 Rad = 5.2	Fails Test Criteria

Calculate Probability

Meets Test = 2
N in test dataset = 5

Prob = 2/5 = 40%

The Performance of Purely Random Sampling Can Be Determined Mathematically if the Metric is the 90th Percentile of the Distribution

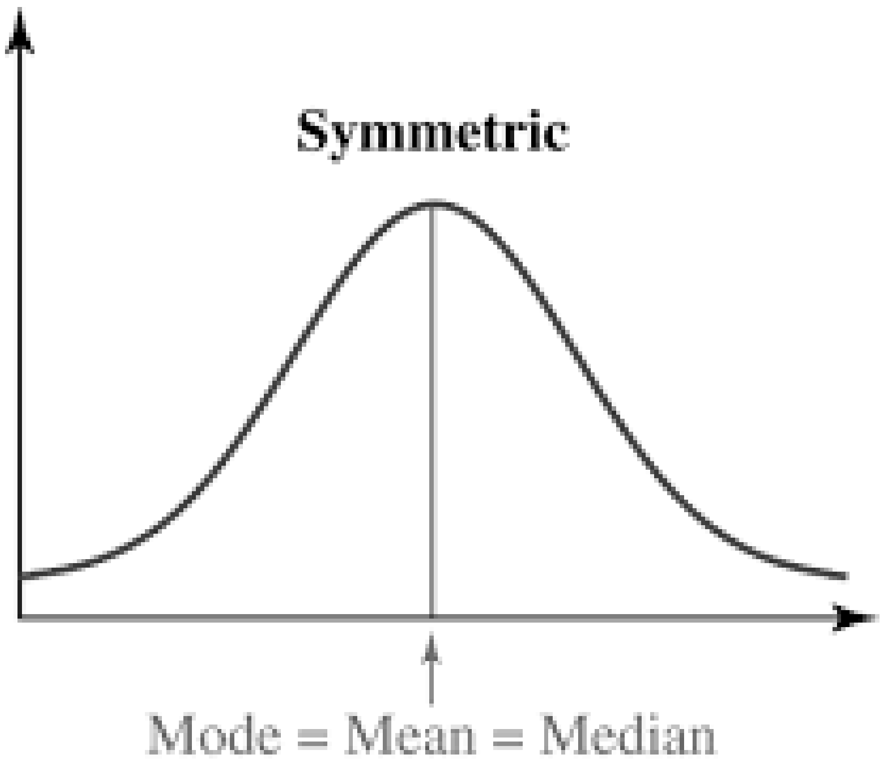
- You have a 10% chance with one random sample of observing the >90th percentile of any distribution.
- You have a 19% chance with two random samples of observing the >90th percentile of any distribution.
- You have a **34%** chance with **four** random samples of observing the >90th percentile
- You have a 95% chance with 28 random samples of observing the 90th percentile once

The Performance of Purely Random Sampling Can Be Determined Mathematically if the Metric is the 95th Percentile of the Distribution

- You have a 5% chance with one random sample of observing the >95th percentile of any distribution.
- You have a 9.7% chance with two random samples of observing the >95th percentile of any distribution.
- You have a **18.5%** chance with **four** random samples of observing the >95th percentile
- You have a 95% chance with 58 random samples of observing the 95th percentile once

If The Distribution is Symmetrical (or Normal) It is Relatively Easy to See the Mean With a Few Samples

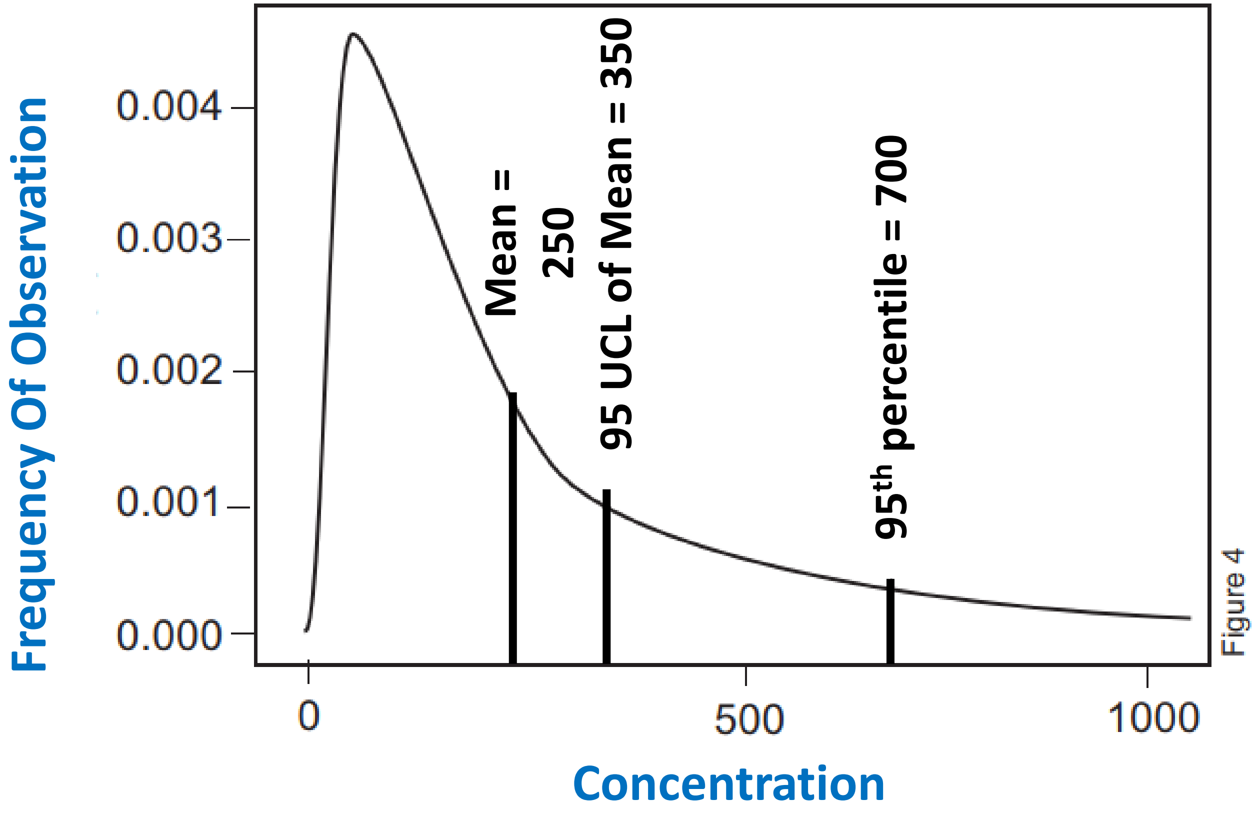
Frequency
Of
Observation



Concentration

With a symmetrical distribution you have a 50% chance to be above the mean with at least one sample and a 75% chance to be above the mean with at least one of two samples.

But: It is Much Harder to Observe the True Mean With a Small Number of Samples When the Distribution is Skewed



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Reducing Vapor Intrusion Uncertainties by More Frequent Simple Measurements and Community Involvement

Sampling Confidence Analysis for Multiple Sites: Results, Presented By Site

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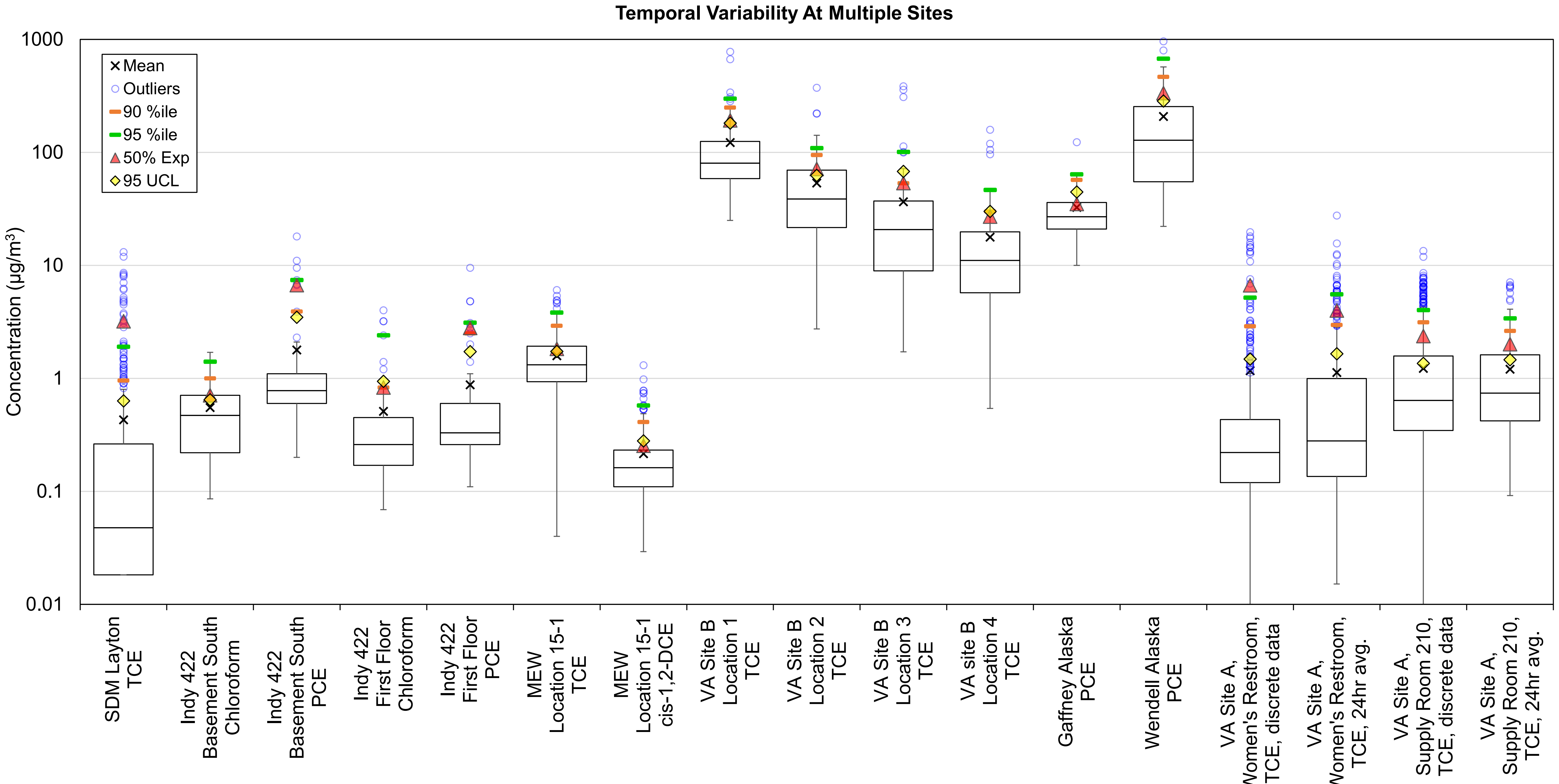


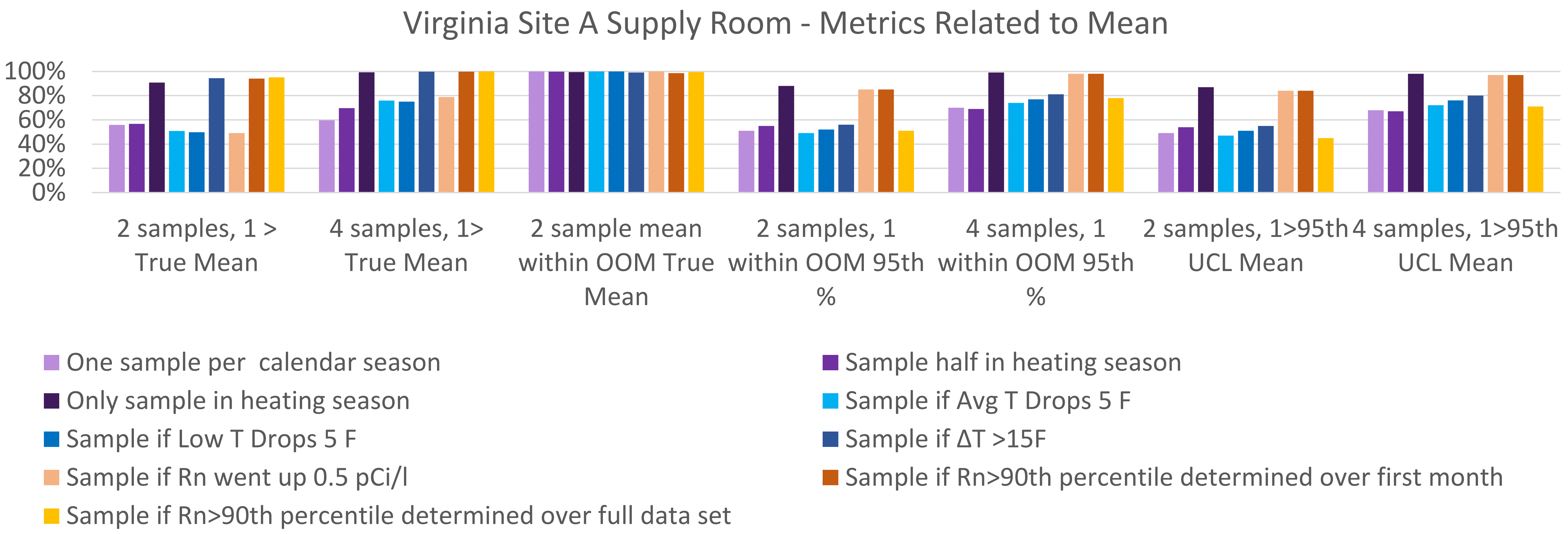
Key point: Degrees of temporal variability across sites compared. Various upper end measures in skewed distributions are shown.

Results

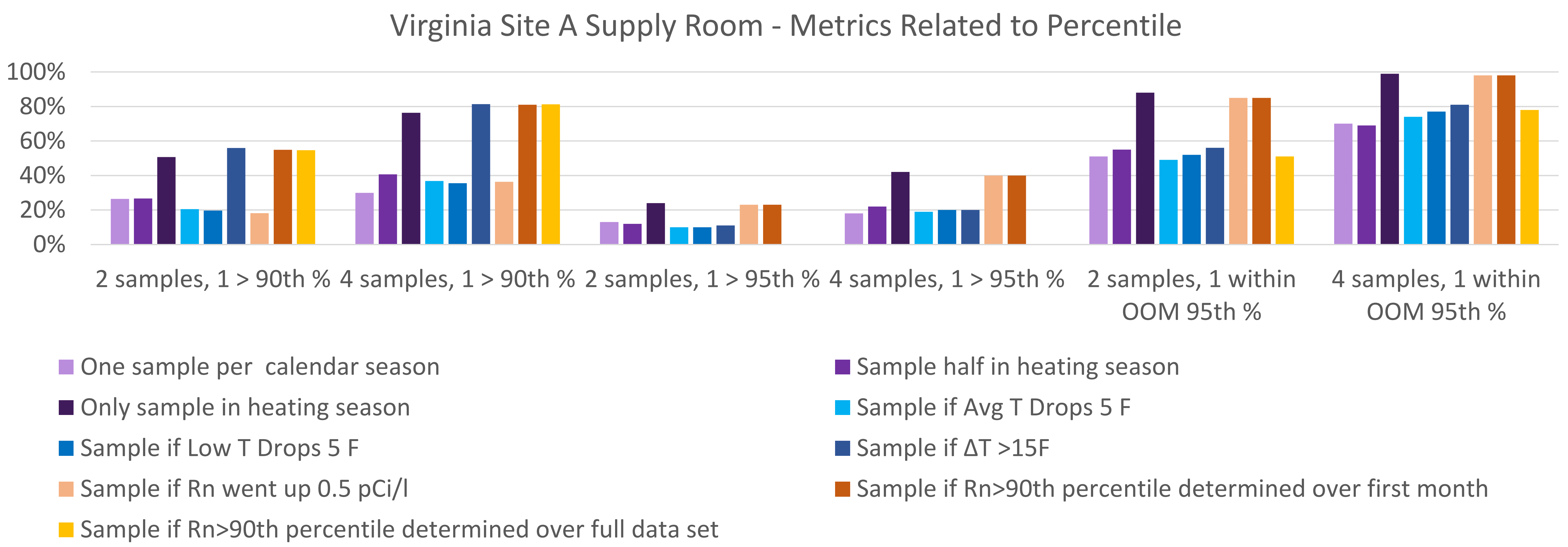
- These are results from a very recently completed analysis, that have not been peer reviewed
- The results are expressed as the percentage chance that each sampling approach provides of observing the target metric in a particular dataset.
- Results are presented by building after a brief summary of the building characteristics
- The same results “sorted a different way” will be presented later.

VA Site A – Building Characteristics

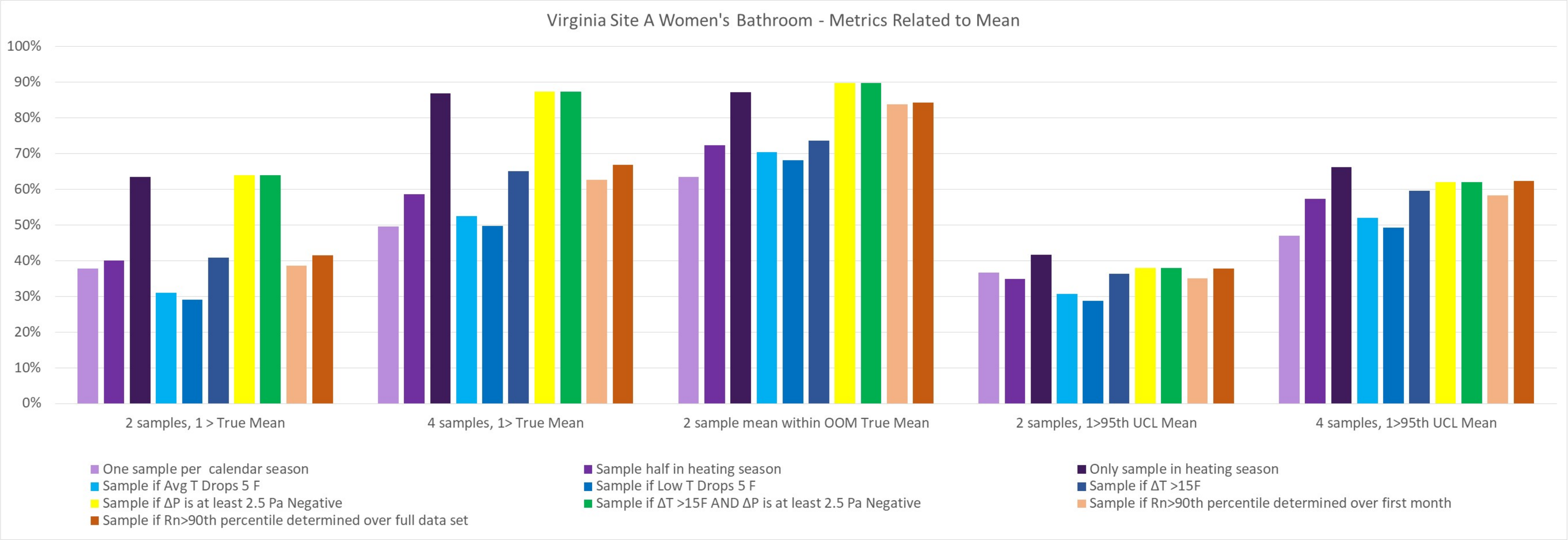
- ~120,000 ft^2 building constructed of brick with a poured concrete slab and divided into three large bays. The slab is generally 6 to 8 inches thick.
- Heat provided by steam-fired unit heaters with overhead fans in the warehouse/storage bays.
- No centralized cooling system within the warehouse space. During Summer, bay doors are kept open and portable fans provide airflow.
- Various wood-framed office areas constructed separately within the bays with separate ceilings and HVAC units.
  - Separate spaces operate as ”zones within larger zones”
- 18 months of frequent GC Concentration observations used.



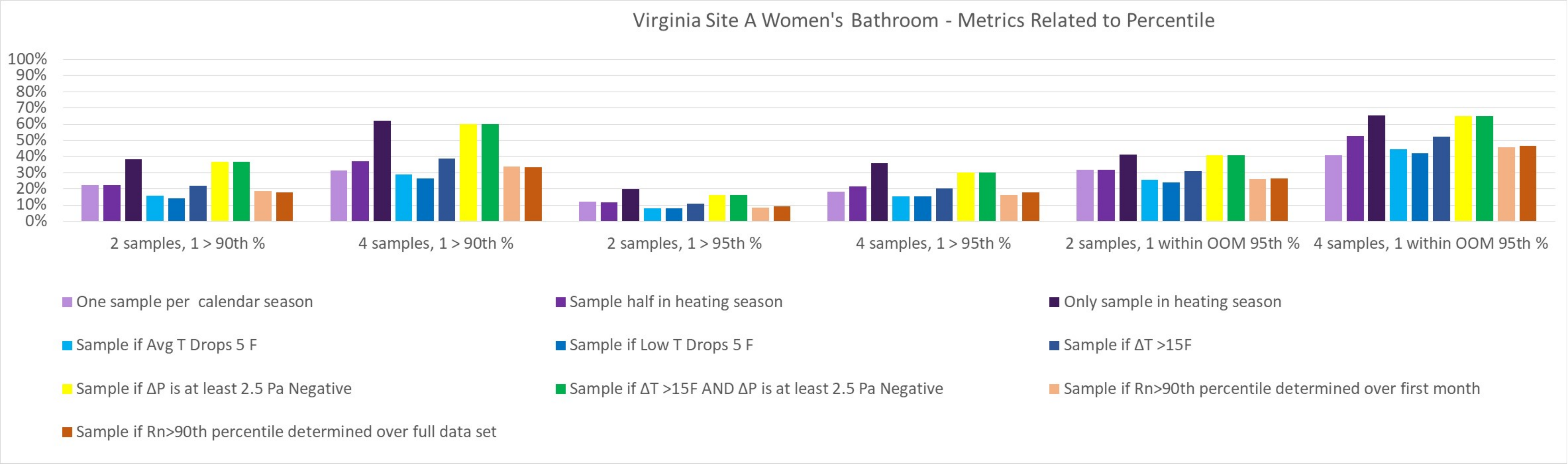
- Recall that this zone has "classical stack effect" behavior – thus our sampling approaches generally perform better here than at other locations/sites.
- Sampling approaches calling for sampling only during the heating season with a minimum differential temperature OR with >90% radon performed very well (>99% chance of seeing at least one sample > mean with four samples). With only two samples the chances were >89% using any of those approaches). For comparison one sample in each season was 60%.
- The radon percentile-based approaches performed best at having at least one sample exceed the 95% UCL of the mean (>84% with two samples, 97% with four samples). Four seasonal samples was 68%.



- Sampling approaches calling for sampling only during the heating season (76%), with a minimum differential temperature (81%) or at >90% radon (81%) performed the best when seeking to observe the 90th VOC percentile using four samples. Four seasonal samples was only 30%.
- No sampling approach gave more than a 42% chance of observing the 95th percentile in four samples.
- Allowing an order of magnitude range around the 95th percentile substantially increased the likelihood of any sampling approach succeeding.



- Among the calendar-based approaches, sampling only during the heating season performed the best with a 87% chance of observing a concentration > mean by sampling four times only in the heating season.
- The differential pressure-based approach performed equally well (87%) at observing a concentration > mean
- The temperature-based approaches performed less well at exceeding the true mean. The best of those was differential temperature (65% in four samples).
- One sample in each season gave only a 50% probability of observing a concentration > mean

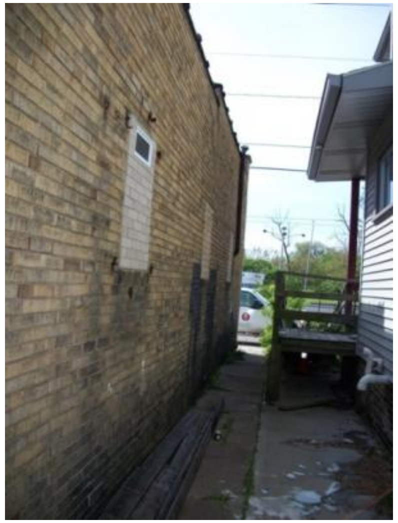


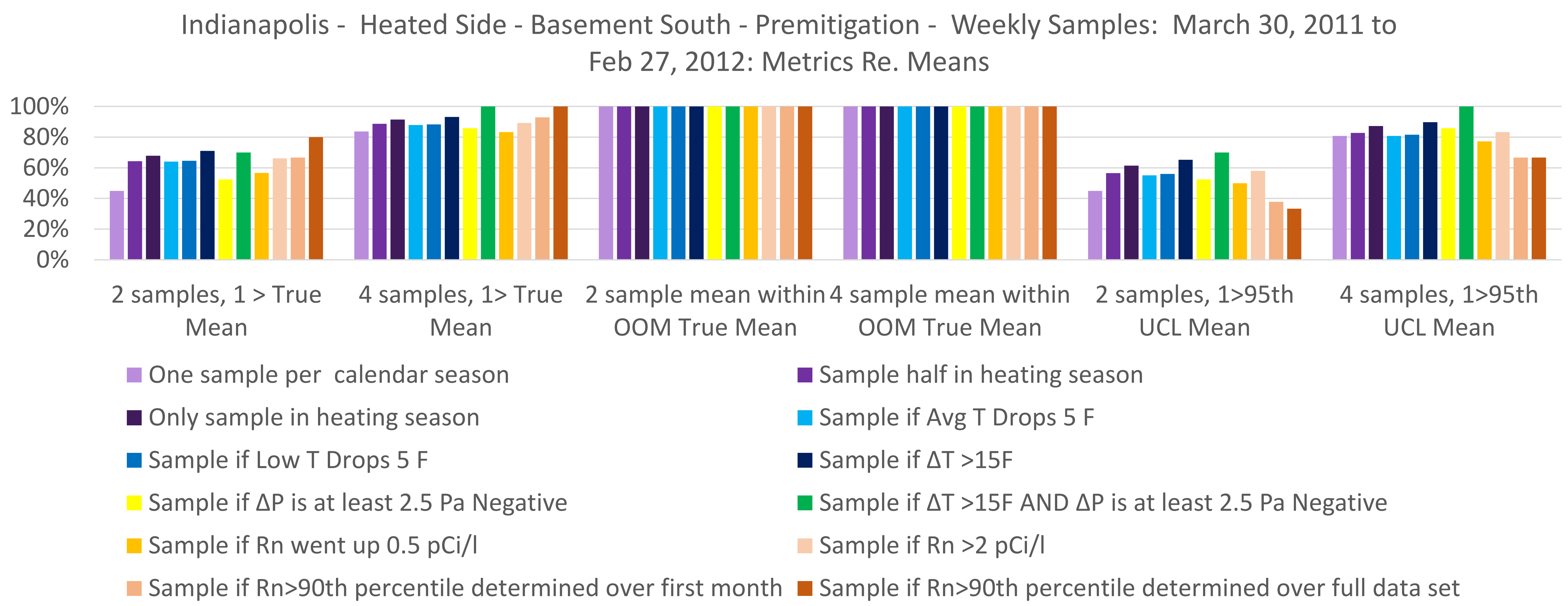
- The best approaches for observing the 90th percentile were sample only during heating season (62% with four samples) or using differential pressure information (60% with four samples). For comparison one sample in each season was 32%.
- No approach gave more than a 36% chance of observing the 95th percentile with four samples.
- The heating season only, and pressure-based approaches were equally effective at getting within 3.3x of the 95th percentile (65%).
- The radon threshold and radon change sampling approaches were never triggered. The radon percentage-based methods worked to some extent, but weren't the best approach on any metric at this location. That agrees with other analyses of this dataset.

Indianapolis Duplex

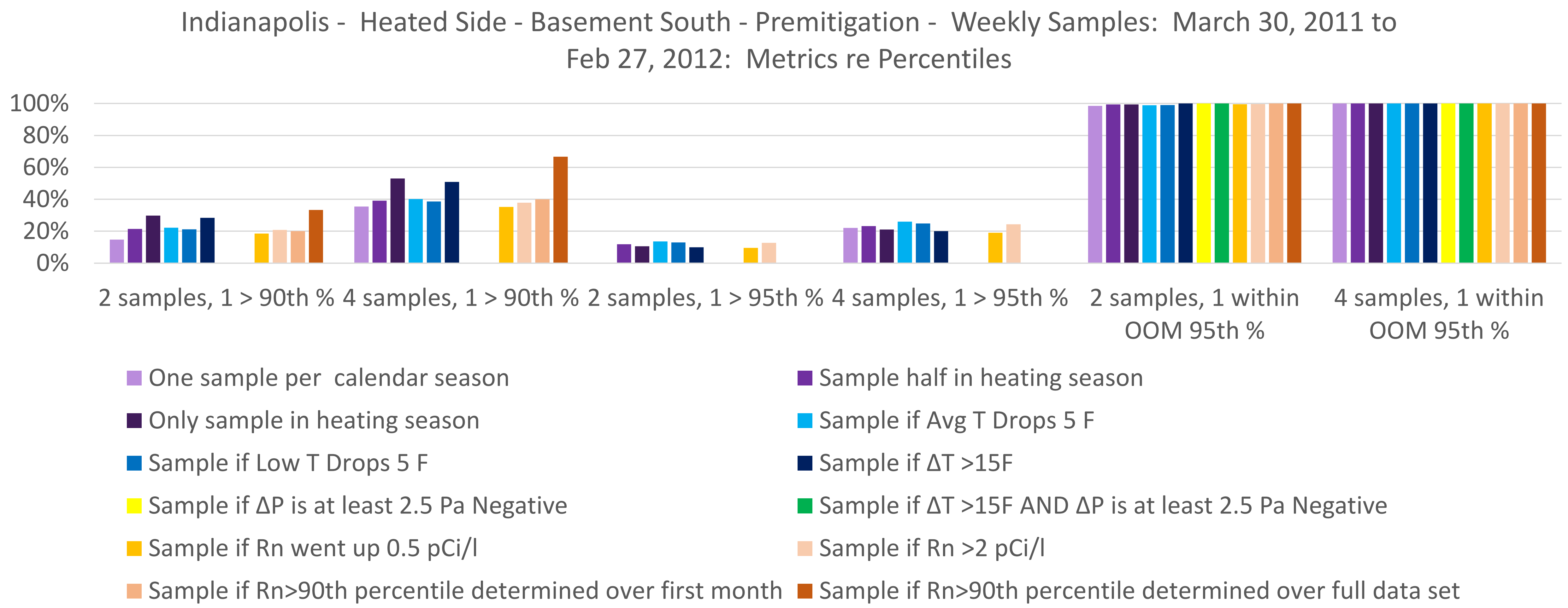
- Study duplex on 1915 Sanborn Map
- Basement +2 overlying floors
- Unoccupied, unfurnished
- Heated and unheated sides
- Top 7-8 ft: topsoil, cinders (fill); sandy silty clay loam (till).
- 8-25 ft: sand, gravel, cobbles (very coarse outwash).
- Depth to water (10.5 to 18.5 ft) rapidly fluctuates with nearby creek
- Year long weekly passive sampling campaign
- Selected periods of high frequency GC Data

Cracks in basement concrete floor and brick walls

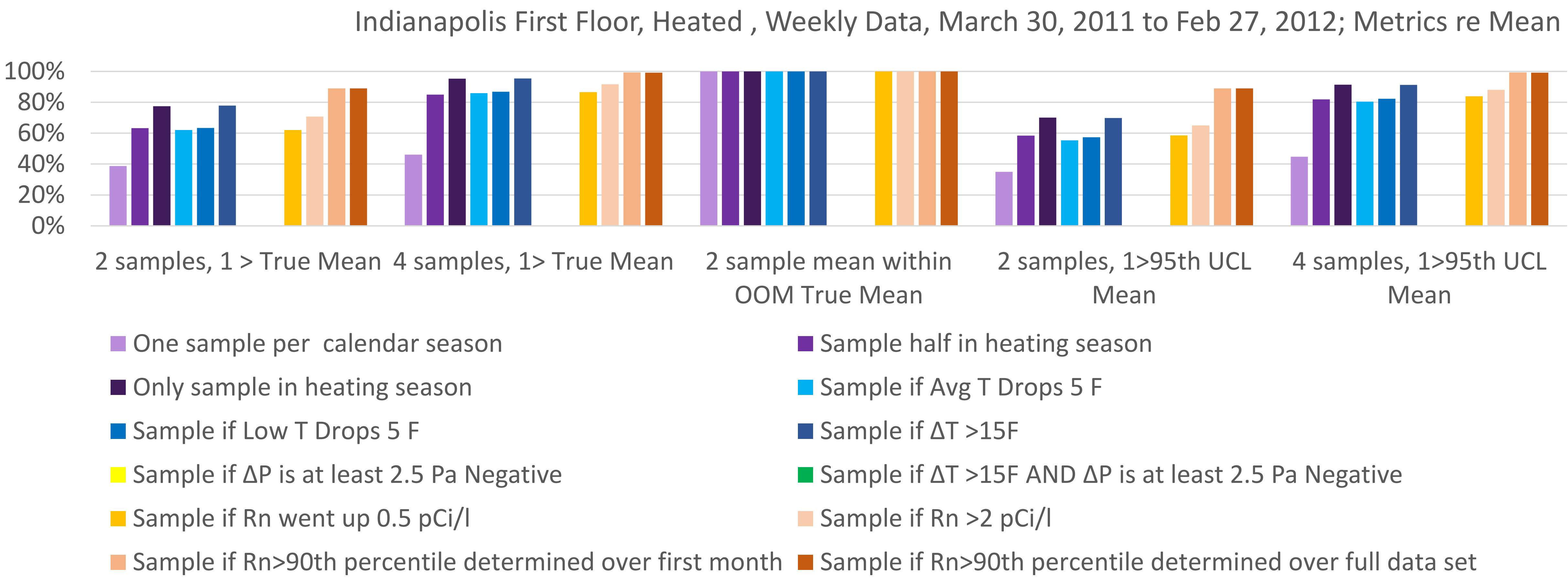




- The approaches that had the highest probability of at least one of four samples being above the long-term mean included the combined differential temperature and differential pressure approach (100%), radon percentile (100%) and heating season only sampling (92%) and differential temperature (93%).
- The approaches with the best probability to have at least one sample out of four above the 95% UCL on the mean were combined differential temperature and differential pressure approach (100%) and heating season only sampling (87%), differential pressure only (86%), differential temperature only (90%).

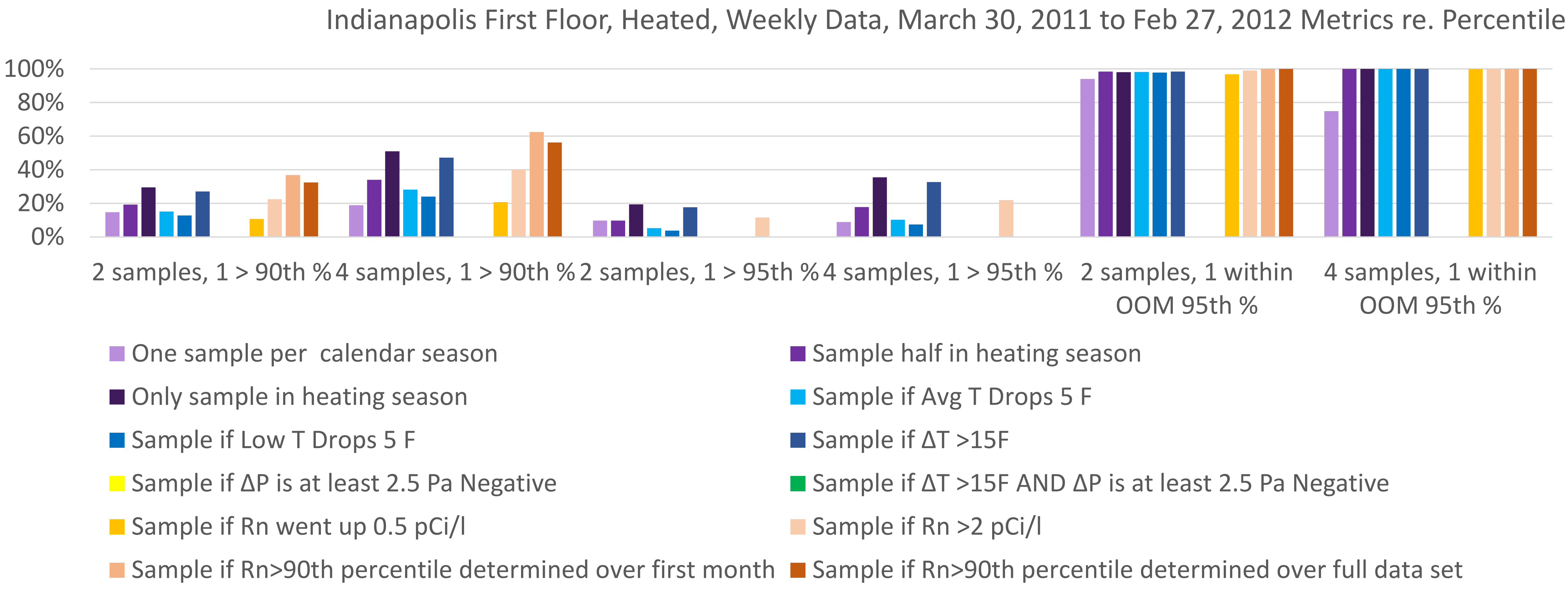


- The approaches with the best probability to have at least one sample in four above the 90^{th} percentile were radon $>90^{th}$ percentile (67%), differential temperature (51%), and sample only in heating season (53%)
- No approach had more than a 26% chance of observing the 95^{th} percentile with four samples.
- If an order of magnitude uncertainty range around the 95^{th} percentile was allowed all approaches got >99%

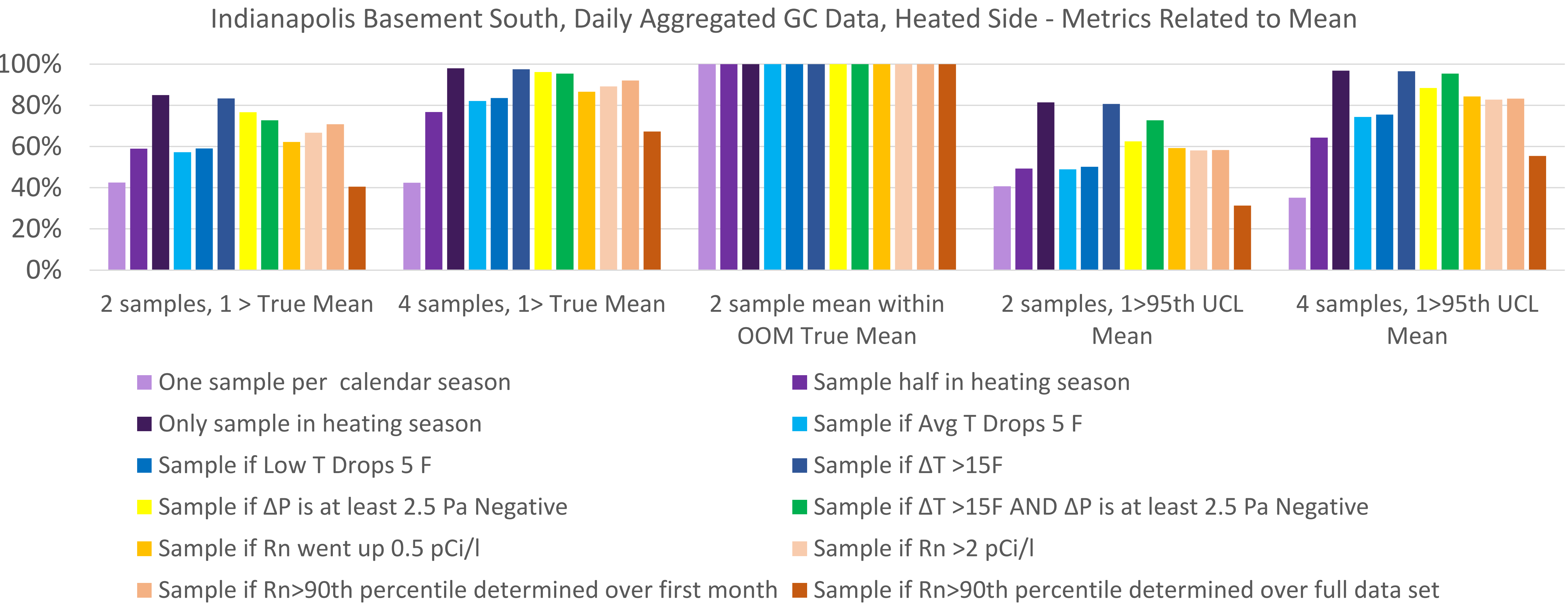


- The approaches that performed best in providing at least one sample out of four over the long-term mean were sample in heating season only (95%), differential temperature (95%) and guided by radon percentile (99%).

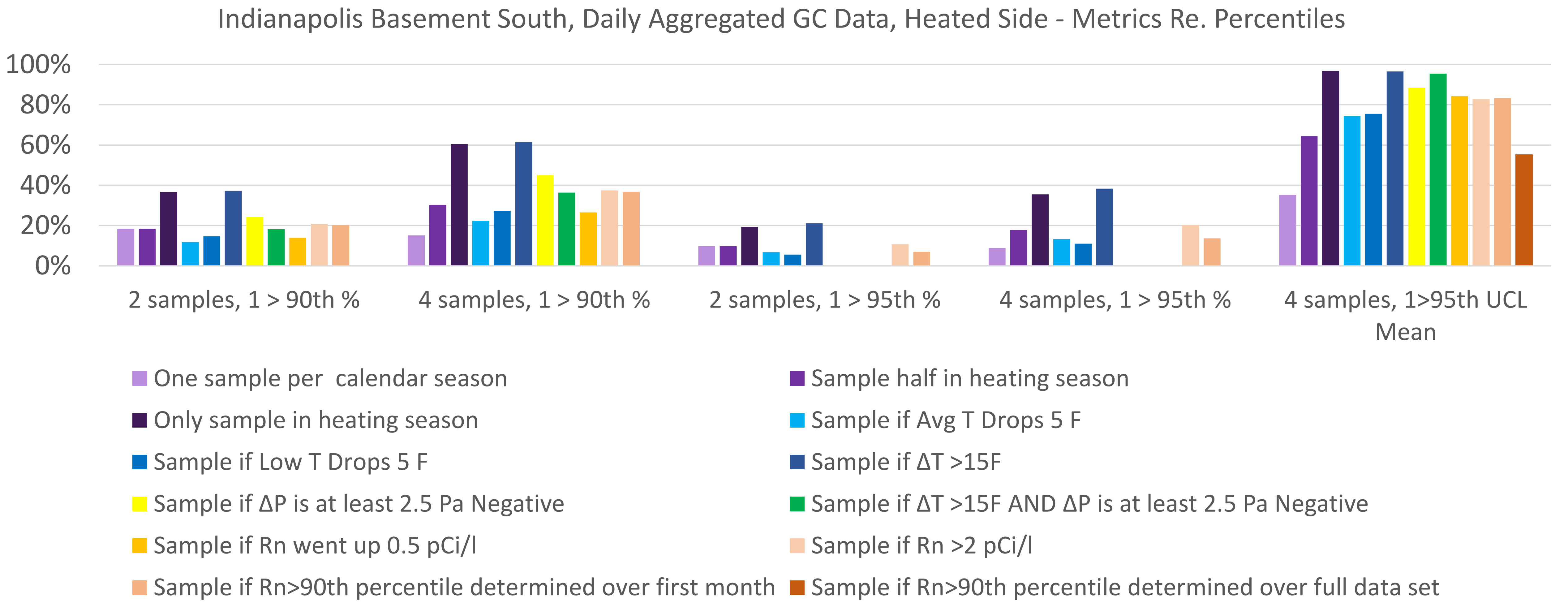
- The approaches that had the highest probability of producing at least one sample of four over the 95% UCL of the mean were sample in heating season only (91%) differential temperature (91%) and radon percentile (99%).



- The approaches that had the highest probability of producing at least one sample of four over the 90th percentile of the VOC distribution were heating season only (51%), differential temperature (47%) and radon percentile (62%). Four seasonal samples was only 19%.
- No approach had more than a 35% chance of observing the 95th percentile in four samples.
- With an order of magnitude tolerance around the 95th percentile almost all approaches performed very well (>94% with even 2 samples).



- Many approaches provided a high probability of at least one sample out of four exceeding the long term mean including: heating season only (98%), differential temperature (97%), differential pressure (96%) and radon percentile based on first month (92%). For comparison one sample per season was 42%.
- Many approaches also provided a high probability of at least one sample out of four exceeding the 95% UCL on the mean heating season only (97%), differential temperature (97%), differential pressure (88%) and radon increase 0.5 pCi/l (84%). For comparison one sample per season was 35%.



- Observing the 90th percentile with at least one in four samples was much harder, the best approaches were differential temperature (61%) and heating season only (61%). One sample per season was only 15%.
- No sampling approach gave better than a 35% chance of observing the 95th percentile with four samples.

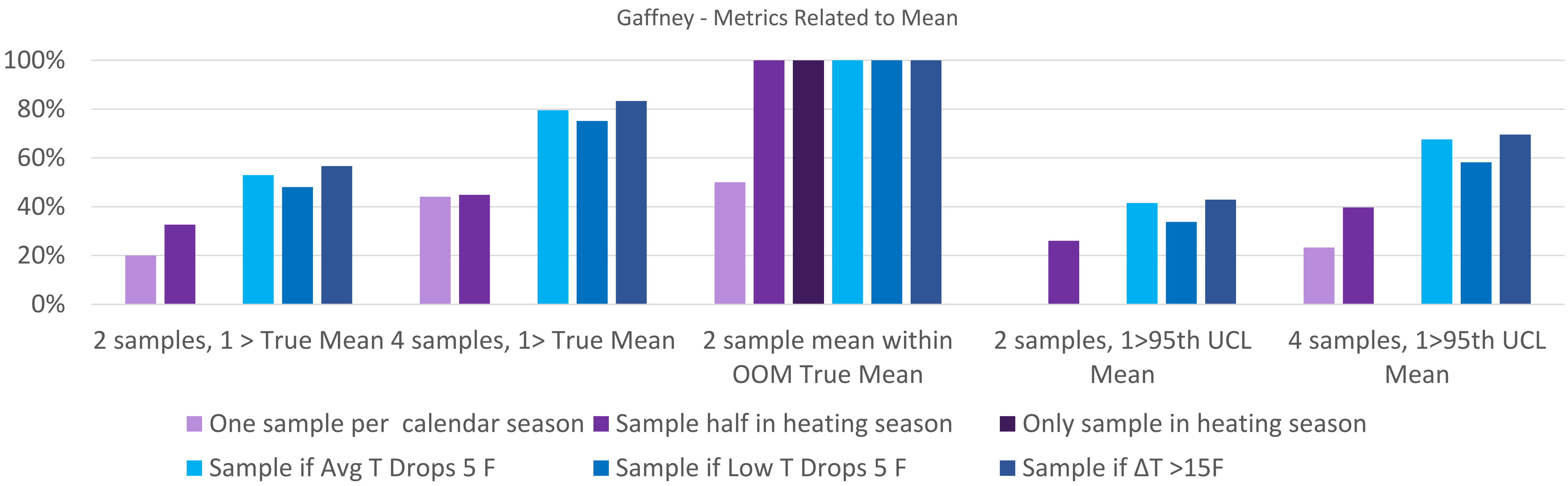
Results: Indianapolis Basement, Residential, Heated, Daily Samples, Without Mitigation

- Many approaches provided a high probability of at least one sample out of four exceeding the long term mean including: Radon percentile based on first month (98%), heating season only (98%), differential temperature (97%), differential pressure (96%). For comparison one sample per season was 42%.
- Observing the 90^{th} percentile with at least one in four samples was much harder, the best approaches were radon percentile based on first month (61%), differential temperature (61%) and heating season only (61%). One sample per season was only 15%.
- Many approaches also provided a high probability of at least one sample out of four exceeding the 95% UCL on the mean radon percentile based on first month (97%), heating season only (97%), differential temperature (97%), differential pressure (88%). For comparison one sample per season was 35%.

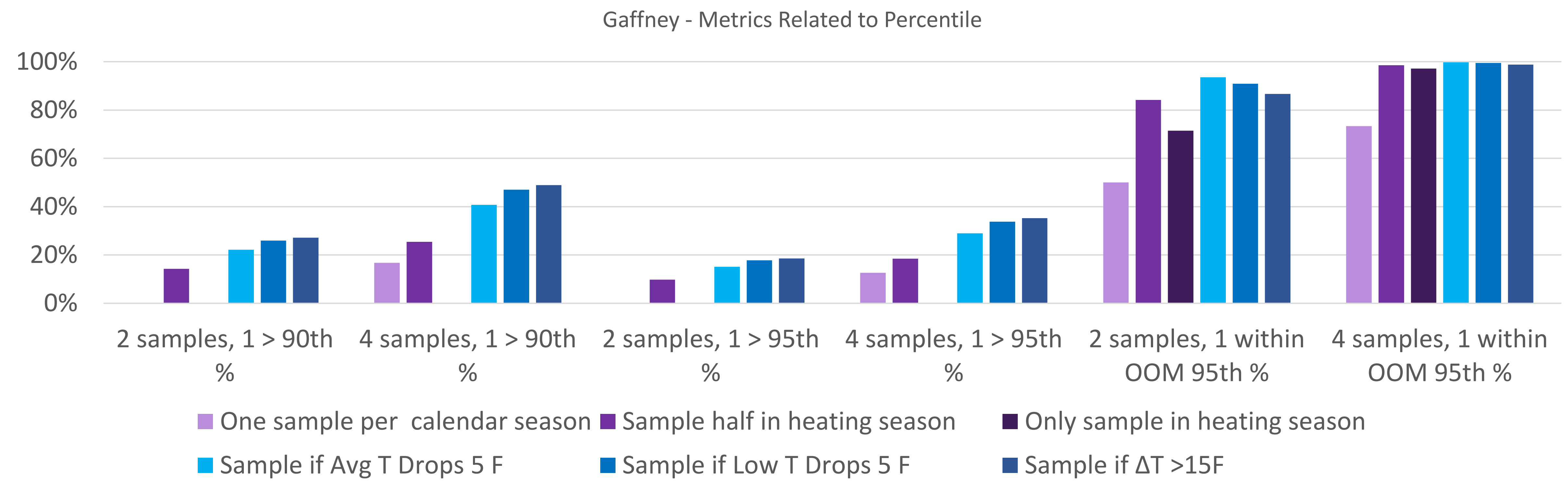
Book Store Study Site – Gaffney – AK, Commercial

- Heated connected storeroom
- Slab-on-grade foundation
- Unventilated
- Former dry-cleaning facility - occupied by a bookstore
- Slab-on-grade, hot-water baseboard radiant heating system
- Max soil concentration = 1.3 mg/kg at 1.5-3.0 m bgs
- Max GW concentration = 1.3 mg/L at 5.3 m bgs
- Higher concentrations at this site were observed in the late summer and attributed to soil temperature effects on shallow source term volatility (Barnes, 2017)

Wood stave pipe image from http://www.sewerhistory.org/photographics/pipes-wood/ Courtesy of the Idarado Mining Company, Ouray, Colorado.



- There was only 45% chance of one sample out of four would be above the true mean using the calendar-based scheduling approaches (either one per season or half in heating season).
- The approach of sampling only in the heating season (NJ definition) performed poorly because the highest concentrations were seen in late summer/early fall. 0% probability of achieving many metrics! This isn't too surprising given how different NJ and Fairbanks are climatologically.
- Rules based on temperature change or differential temperature performed much better – giving probabilities of one sample out of four above the mean ranging from 75 to 83%. This is probably because high concentrations were associated with late summer/early fall.

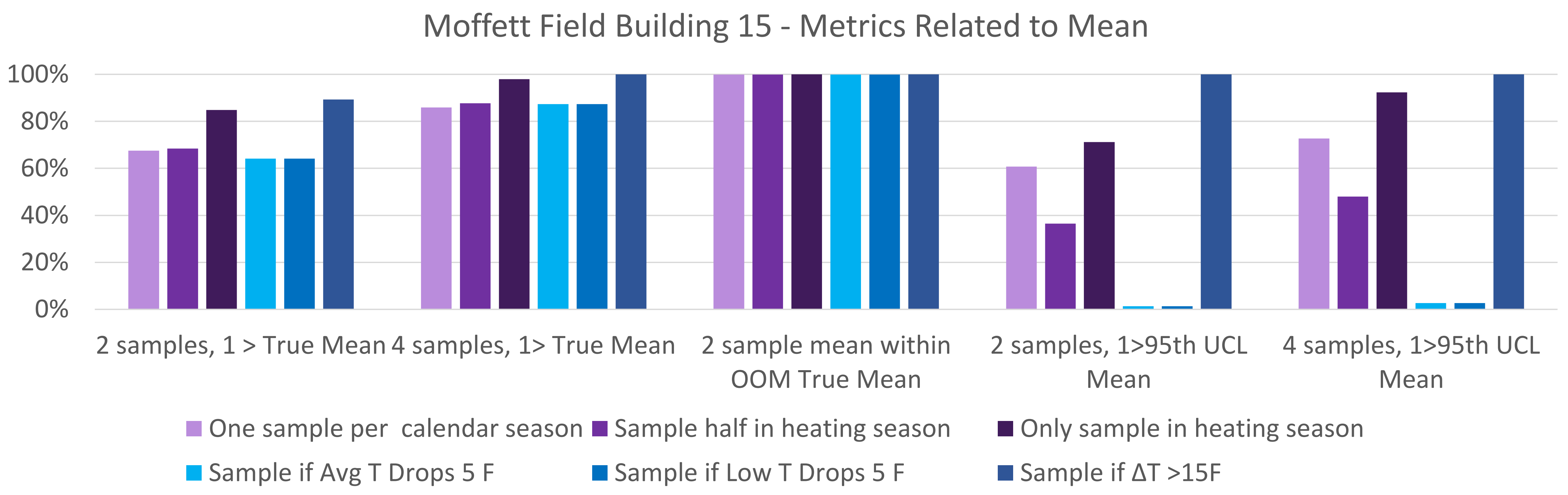


- There was a 17 - 25% chance of exceeding the 90th percentile with one of four calendar-based samples.
- There was a <18% chance of exceeding the 95th percentile with one of four calendar-based samples
- Metrics that allowed an order of magnitude range around the 95% were achieved 99% of the time with several scheduling approaches because the range of the data was comparatively narrow.
- No radon or differential pressure data available so those rules not tested.

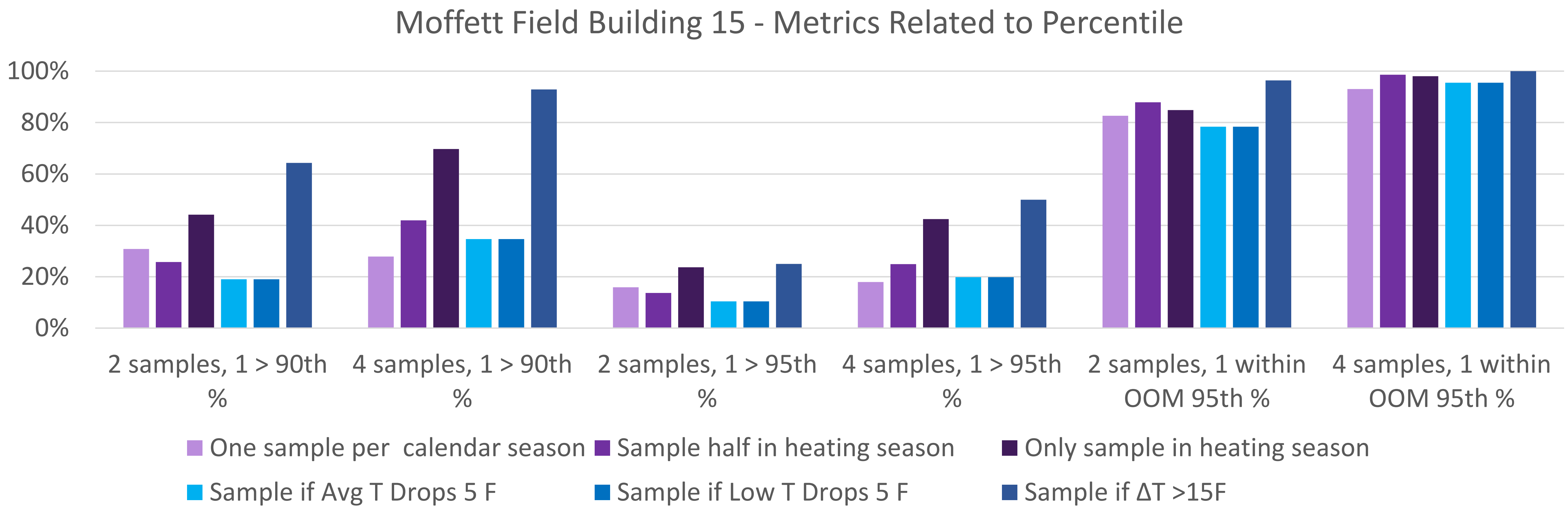
Moffett Field Building 15, Northern CA, Commercial

- 11,900 square foot
- Portions occupied 24 hr / 7 d
- Steam - heated with air conditioning, two HVAC zones
- Main portion and west wing office space; HVAC equipment and garage in east wing
- HVAC adjusted in May 2003 to increase outside air supply, reportedly reducing TCE in indoor air
- Shallow groundwater source

Photos reprinted from: https://historicproperties.arc.nasa.gov/map_reuse/reuse_forms/15_reuse.pdf



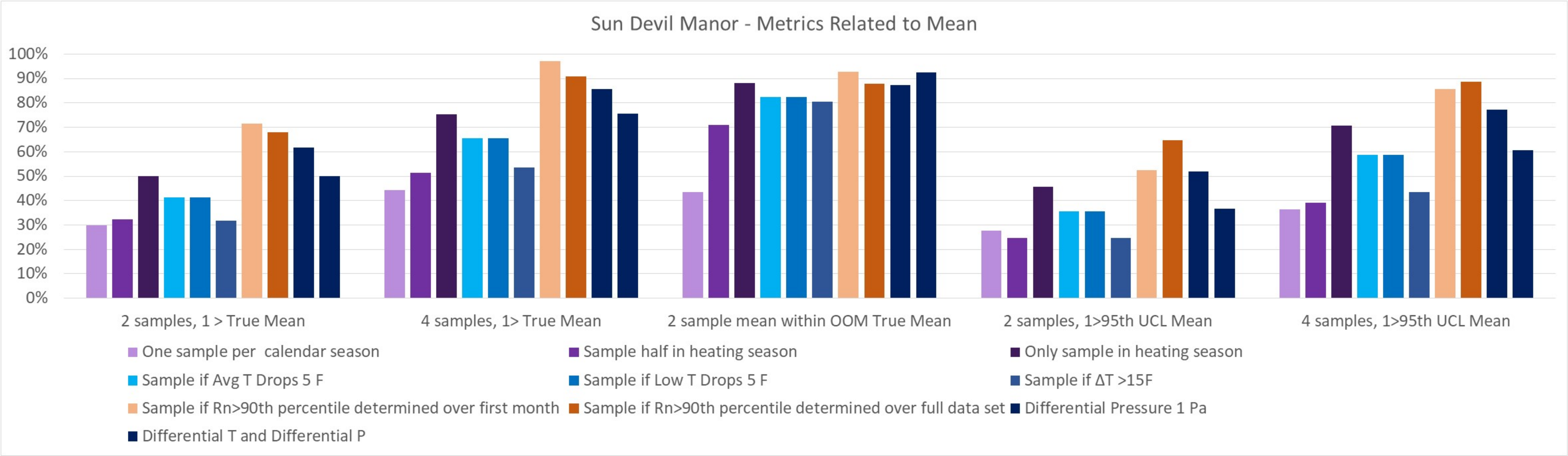
- Mild Northern CA climate
- There was 86-88% chance of one sample out of four would be above the true mean using calendar-based scheduling approaches (either one per season or half in heating season). 98% chance with four samples in heating season.
- Sampling approaches based on temperature change or outdoor temperature had 87-100% chance of exceeding the mean with one sample out of four.
- The highest probability of observing the 95% UCL on the mean was with differential temperature (100% probability with only two samples).



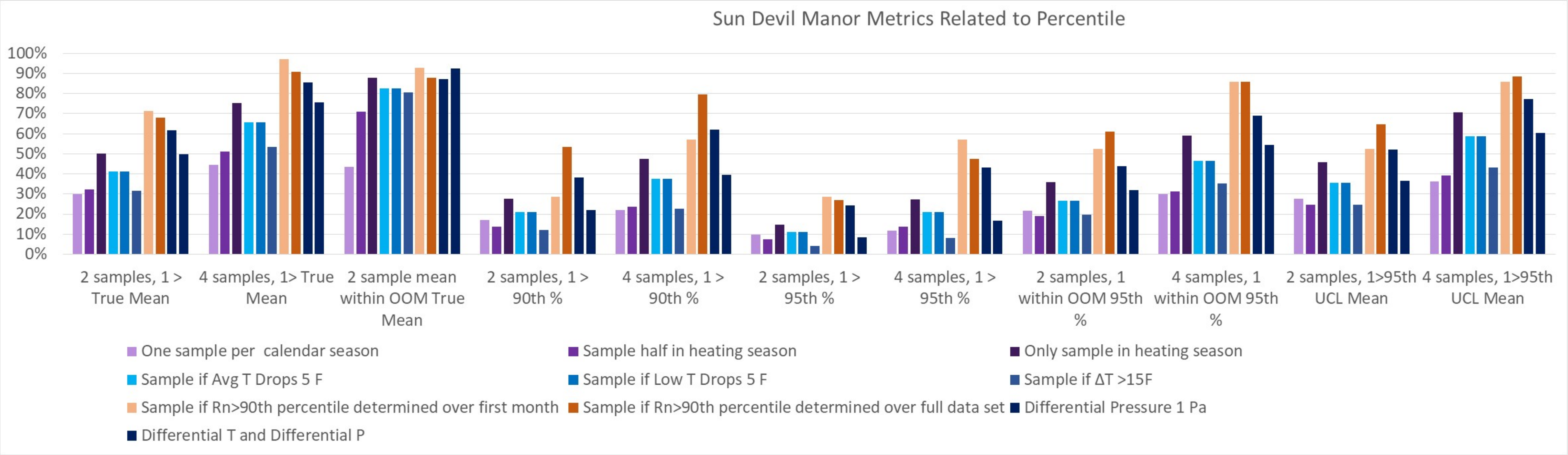
- The only sampling strategies with a >50% chance of observing > the 90th percentile in the highest of four samples were those for sampling only in heating season or sampling with cold outdoor temperatures.
- The best strategy to observe the 95th percentile was differential temperature, which gave a 50% chance with four samples
- Metrics that allowed an order of magnitude range around the 95th percentile were achieved >95% of the time with four samples with a variety of sampling strategies. This occurs because the range of the data is relatively narrow.
- No radon or differential pressure data available so those rules not tested.

Sun Devil Manor, Layton, Utah

- Two-story, split-level home on gradual slope, built in 1991
- Occupied 10-30% of time, HVAC settings for full time occupancy
- Fine sandy silt with fine sand stringers
- Depth to water 10-12 ft bgs, 10-50 µg/L TCE
- Over two years indoor air sampling, sampling at 2–4-hour intervals, converted to 24- hour data set
- Conduit VI pathway, land drain to subslab to indoor air



- Among the calendar-based approaches, sampling only during the heating season performed the best with a 88% chance of observing a concentration > mean sampling four times.
- The approaches based on temperature change or differential temperature did not outperform sampling only heating season in observing concentrations above the mean.
- A version of the radon 90th percentile approach performed the best of all the approaches when seeking:
  - One sample above the mean (97% with four samples and full period of radon data)
  - One sample above the 95% UCL of the mean (86% with four samples and month radon, 89% full radon data)



- A version of the radon 90th percentile approach performed best of all the approaches when seeking:
  - One sample above the 90th VOC percentile (80% with four samples and the full period of radon)
  - One sample above the 95th VOC percentile (57% with four samples and the first month’s radon data)
  - One sample within 3x of the 95th percentile (86% with four samples and the first month’s radon data)
- The approach based on differential pressure initially performed poorly on all metrics because the differentials observed were not high enough to trigger sampling at 2.5 Pa. Using 1 Pa as the metric produced rules that worked well on most metrics, but not quite as well as the radon percentile rules.
- Sampling only in heating season was the best of the calendar based rules, but not as well as radon or differential pressure.

Median Percentile Across All Data Sets Tested								
	1 of 2 >mean	1 of 4 > mean	1 of 2 >90th	1 of 4 >90th	1 of 2 >95th	1 of 4 > 95th	1 of 2 > 95% UCL on Mean	1 of 4 > 95th UCL on Mean
Seasonal Sampling	39%	46%	20%	22%	10%	15%	36%	45%
Half in heating season	58%	73%	20%	34%	11%	21%	51%	66%
All in heating season	77%	95%	37%	61%	19%	35%	66%	89%
Differential temperature	74%	94%	28%	50%	18%	33%	60%	85%
Differential pressure	25%	48%	0%	0%	0%	0%	21%	41%
Radon percentile based on 1st month	72%	96%	24%	43%	6%	13%	67%	93%
Radon percentile based on full period	80%	99%	33%	67%	0%	0%	71%	93%

Key Points: All in heating season, differential temperature based and radon percentile based were the best approaches. Four samples are better than two. The 95^{th} percentile is very hard to observe.

Summary Across Multiple Sites

- Results for two sample strategies were rarely highlighted here because they were generally substantially lower then the four sample strategies.
- Sampling four times based on differential temperature performed fairly well at all sites.
- Sampling four times in heating season worked well at most sites, but very poorly at Gaffney.
- Sampling once in each of four seasons often performed poorly.
- Sampling with Radon guidance based on a percentile of radon set using the first month's radon data worked well, including for observing upper percentiles, but not all sites had radon data to test.
- Sampling approaches performed better at the sites/locations that fit the classical stack effect and winter worst theory.
- VI sampling approaches may need to be tailored to specific climate zones.
- Sampling rules give better reliability in predicting the mean than predicting the upper percentiles of the distribution.
- Seeing the 90th or 95th percentiles directly requires many samples even with guidance.
- Allowing a 3.3x tolerance factor (order of magnitude range) around the target it substantially increases the ability to predict using any sampling rule.

Sources of Uncertainty in this Effort

- The cases tested here do not represent the full diversity of US climates or building types.
- Even a continuous data set for one year is an imperfect estimate of long term exposure, because a "cold winter" and "warm winter" can be very different from each other.
- The smaller data sets (i.e. Gaffney, Moffett are incomplete samples of even the years they were taken in because not every day was sampled).
- Cases that have a significant percentage of nondetects in indoor air (i.e. SDM) have greater uncertainty.
- The accuracy of concentration measurements generally decreases as concentrations approach the detection limit. High concentrations may also be underestimated in some cases because they may be off calibration curve.

References/Acknowledgements Gaffney Site

- Barnes, David L., and Mary F. McRae. "The predictable influence of soil temperature and barometric pressure changes on vapor intrusion." *Atmospheric Environment* 150 (2017): 15-23.
- *Quantifiable Building and Environmental Factors Influencing Vapor Intrusion;* Presentation at AEHS Fall Conference 2019; David Barnes, University of Alaska Fairbanks https://iavi.rti.org/workshops.html

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References/Acknowledgements Moffett Building 15

- Brenner, David. "Results of a long-term study of vapor intrusion at four large buildings at the NASA Ames Research Center." *Journal of the Air & Waste Management Association* 60, no. 6 (2010): 747-758.
- Brenner, D. and M. Walraven "Revised Human Health Risk Assessment NASA Research Park Moffett Field, California July 28, 2003 " https://www.sec.gov/Archives/edgar/data/1664703/000119312518190488/d96446dex106.htm
- Haley and Aldrich 2009 "Final Supplemental Remedial Investigation Report for Vapor Intrusion Pathway Middlefield-Ellis-Whisman Study Area, Mountain View and Moffett Field, California, June. https://www.navfac.navy.mil/niris/SOUTHWEST/MOFFETT_FIELD_NAS/N00296_003903.PDF
- Haley and Aldrich 2009 "Final Supplemental Feasibility Study for the Vapor Intrusion Pathway Middlefield-Ellis-Whisman Study Area; June 29, 2019 https://semspub.epa.gov/work/09/2324674.pdf
- Haley & Aldrich, 2011 "Site-wide Vapor Intrusion Sampling and Analysis Work Plan for Response Action Testing" September 29. https://semspub.epa.gov/work/09/100002742.pdf
- Mactec Engineering and Consulting Inc. 2005 "Report on Long-term Indoor Air Quality Monitoring; Buildings 15, 16, 17, 20, n-210 and N243" NASA Ames Research Center, Moffett Field California
- Mills, William B., Sally Liu, Mark C. Rigby, and David Brenner. "Time-variable simulation of soil vapor intrusion into a building with a combined crawl space and basement." *Environmental science & technology* 41, no. 14 (2007): 4993-5001.
- Noreas for NAVFAC "Draft 2019 Installation Restoration Site 28 Air Sampling and Vapor Intrusion Tier Response Evaluation Report, July 2019 https://semspub.epa.gov/work/09/100018154.pdf

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References/Acknowledgements – VA Site A

- Part of the data collection program at VA Site A was funded by the U.S. Navy under NESDI Project 554 and part under EPA ORD Large Buildings VI Project
- Jacobs, 2021, "NESDI 554 – Findings Report Assessing Temporal Variability in Industrial Buildings during Vapor Intrusion Evaluations," Draft, Prepared for NAVFAC EXWC, January
- Lutes et al., 2021, "Driving Forces and Indicators of Vapor Intrusion Temporal Variability in an Industrial Building." Poster presented at the 30th AEHS West Conference, March 2021, https://drive.google.com/file/d/1DNMmnRtFpKG941KUU17FOiXDUS0i3dXB/view
- Lutes et al., 2021, "Temporal Variability in an Industrial Building –Time Series and Machine Learning Analysis," accepted for publication in GWMR
- Previous presentation as part of this workshop, including
    - Hallberg et al., 2020, "Vapor Intrusion (VI) Indicators, Tracers, and Temporal Variability of cVOCs in Industrial Buildings, DoD Virginia Site A – Climate Zone 4," https://iavi.rti.org/assets/docs/05B_VA_site_A_Mar2020.pdf
    - Hallberg et al., 2020, "Putting Spatial and Temporal Variation Together, DoD Virginia Site A – Climate Zone 4," https://iavi.rti.org/assets/docs/07b_Spatial_Temporal_Mar2020.pdf
    - Lund et al., 2019, "Vapor Intrusion (VI) Indicators, Tracers, and Temporal Variability of cVOCs in Industrial Buildings, DoD Virginia Site A – Climate Zone 4," https://iavi.rti.org/assets/docs/05_Lund_DoD%20VA%20Site%20A_EPA%20VI%20Wkshp_AEHS_Oct2019.pdf

Indianapolis Site References/Acknowledgements

- *Fluctuation of Indoor Radon and VOC Concentrations Due to Seasonal Variations*, 2012; EPA/600/R-12/673 https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=247212
- *Assessment of Mitigation Systems on Vapor Intrusion: Temporal Trends, Attenuation Factors, and Contaminant Migration Routes under Mitigated and Non-mitigated Conditions.* U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/397, 2015. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=308904
- *Simple, Efficient, and Rapid Methods to Determine the Potential for Vapor Intrusion into the Home: Temporal Trends, Vapor Intrusion Forecasting, Sampling Strategies, and Contaminant Migration Routes*. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-15/070, 2015. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NERL&dirEntryId=309644
- *Indianapolis Research Duplex Total Database* https://catalog.data.gov/dataset/indianapolis-research-duplex-total-database
- Lutes, C. C., Truesdale, R. S., Cosky, B. W., Zimmerman, J. H., & Schumacher, B. A. (2015). Comparing Vapor Intrusion Mitigation System Performance for VOCs and Radon. *Remediation Journal*, *25*(4), 7-26.
- McHugh, T., Beckley, L., Sullivan, T., Lutes, C., Truesdale, R., Uppencamp, R., ... & Schumacher, B. (2017). Evidence of a sewer vapor transport pathway at the USEPA vapor intrusion research duplex. *Science of the Total Environment*, *598*, 772-779.
- Zimmerman, J. H., Lutes, C., Cosky, B., Schumacher, B., Salkie, D., & Truesdale, R. (2017). Temporary vs. permanent sub-slab ports: A comparative performance study. *Soil and Sediment Contamination: An International Journal*, (just-accepted), 00-00. http://www.tandfonline.com/doi/full/10.1080/15320383.2017.1298565
- Numerous conference presentations on this and other projects at: https://iavi.rti.org/WorkshopsAndConferences.cfm

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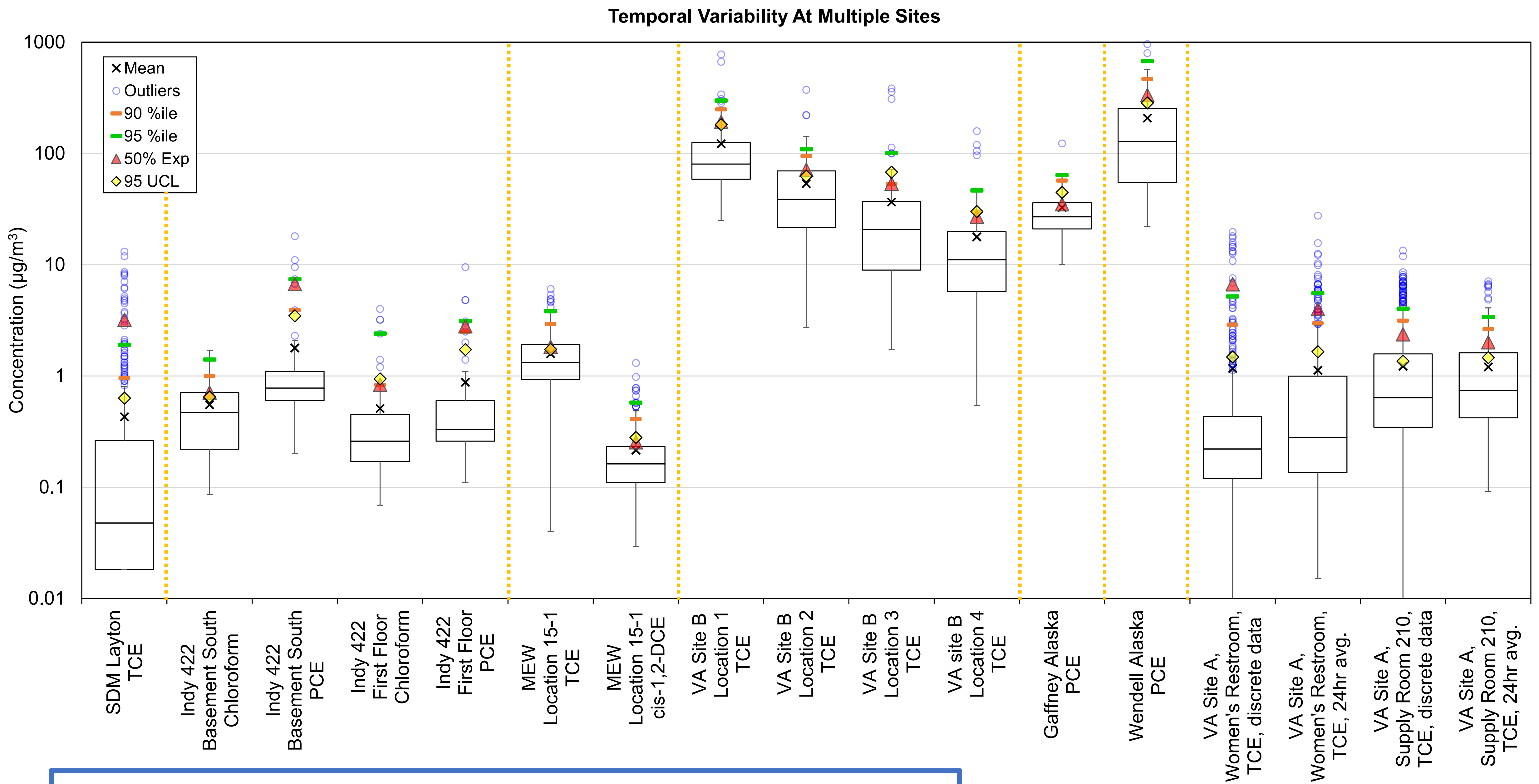
References/Acknowledgements Sun Devil Manor

- Holton, C., Luo, H., Dahlen, P., Gorder, K., Dettenmaier, E., Johnson, P.C. Temporal Variability of Indoor Air Concentrations under Natural Conditions in a House Overlying a Dilute Chlorinated Solvent Groundwater Plume. *Environmental Science & Technology*, 2013, 47, 13347-13354. https://doi.org/10.1021/es4024767
- Holton, C., Guo, Y., Luo, H., Dahlen, P., Gorder, K., Dettenmaier, E., Johnson, P.C. Long-Term Evaluation of the Controlled Pressure Method for Assessment of the Vapor Intrusion Pathway. *Environmental Science & Technology*, 2015, 49, 2091-2098.
- Guo, Y., Holton, C., Luo, H., Dahlen, P., Gorder, K., Dettenmaier, E., Johnson, P. C. Identification of Alternative Vapor Intrusion Pathways Using Controlled Pressure Testing, Soil Gas Monitoring, and Screening Model Calculations. *Environmental Science & Technology*, 2015, 49, 13472-13482.
- Johnson, P. C., Holton, C., Guo, Y., Dahlen, P., Luo, H., Gorder, K., Dettenmaier, E., Hinchee, R. E. 2016. Integrated Field-Scale, Lab-Scale, and Modeling Studies for Improving Our Ability to Assess the Groundwater to Indoor Air Pathway at Chlorinated Solvent-Impacted Groundwater Sites. Strategic Environmental Research and Development Program (SERDP) Project ER-1686. Final Report, July. Available at https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-1686/ER-16862
- Holton, C., Guo, Y., Luo, H., Dahlen, P., Gorder, K., Dettenmaier, E., Johnson, P. C. Creation of a Sub-Slab Soil Gas Cloud by an Indoor Air Source and Its Dissipation Following Source Removal. *Environmental Science & Technology*, 2018, 52, 10637-10646. DOI: 10.1021/acs.est.8b01188.
- Guo, Y., Holton, C., Luo, H., Dahlen, P., Gorder, K., Dettenmaier, E., Johnson, P. C. Influence of Fluctuating Groundwater Table on Volatile Organic Chemical Emission Flux at a Dissolved Chlorinated Solvent Plume Site. *Groundwater Monitoring & Remediation*, 2019, 39(2), 43-52.
- Guo, Y., Dahlen, P., Johnson, P. C. Temporal Variability of Chlorinated Volatile Organic Compound Vapor Concentrations in a Residential Sewer and Land Drain System Overlying a Dilute Groundwater Plume. *Science of the Total Environment*, 2020, 702, 134756. https://doi.org/10.1016/j.scitotenv.2019.134756
- Shirazi, E., Hawk, G. S., Holton, C., Stromberg, A. J., Pennell, K. Comparison of Modeled and Measured Indoor Air Trichloroethene (TCE) Concentrations at a Vapor Intrusion Site: Influence of Wind, Temperature, and Building Characteristics. *Environmental Science: Processes & Impacts*, 2020, 22, 802-811.
- Past conference presentations available at https://iavi.rti.org/workshops.html

Studies by researchers at Arizona State University (**SERDP ER-1686**), ASU and Colorado School of Mines (**ESTCP ER-201501**), and several others

Selected Results VA Site A Supply Room

Sampling Approach	Two samples, one > Mean?	Four Samples, one > Mean?	Two Samples, one >90th Percentile?	Four Samples, one >90th Percentile?
One sample per calendar season	52%	72%	23%	34%
Sample half in heating season	56%	70%	23%	37%
Only sample in heating season	89%	99%	42%	66%
Sample if Avg T Drops 5 F	50%	75%	18%	33%
Sample if Low T Drops 5 F	53%	78%	19%	34%
Sample if ΔT >15F	58%	82%	21%	37%
Sample if ΔP is at least 2.5 Pa Negative	85%	98%	41%	66%
Sample if ΔT >15F AND ΔP is at least 2.5 Pa Negative	85%	98%	41%	66%
Sample if Rn went up 0.5 pCi/l	62%	87%	0%	0%
Sample if Rn >2 pCi/l	93%	100%	0%	0%
Sample if Rn>90th percentile determined over first month	77%	95%	31%	53%
Sample if Rn>90th percentile determined over full data set	94%	100%	51%	76%

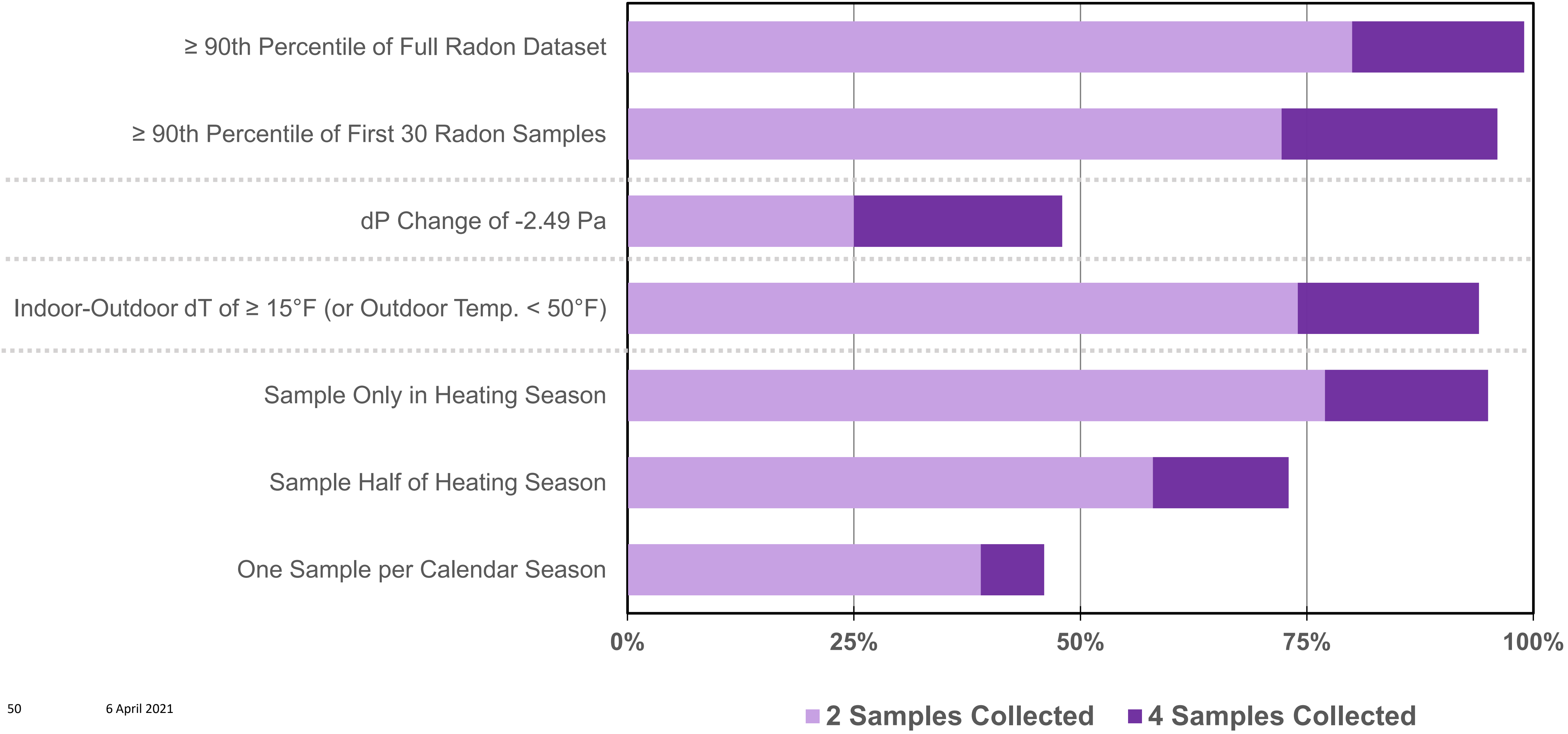


Temporal variability across sites, 24-hour and Discrete Sampling Results

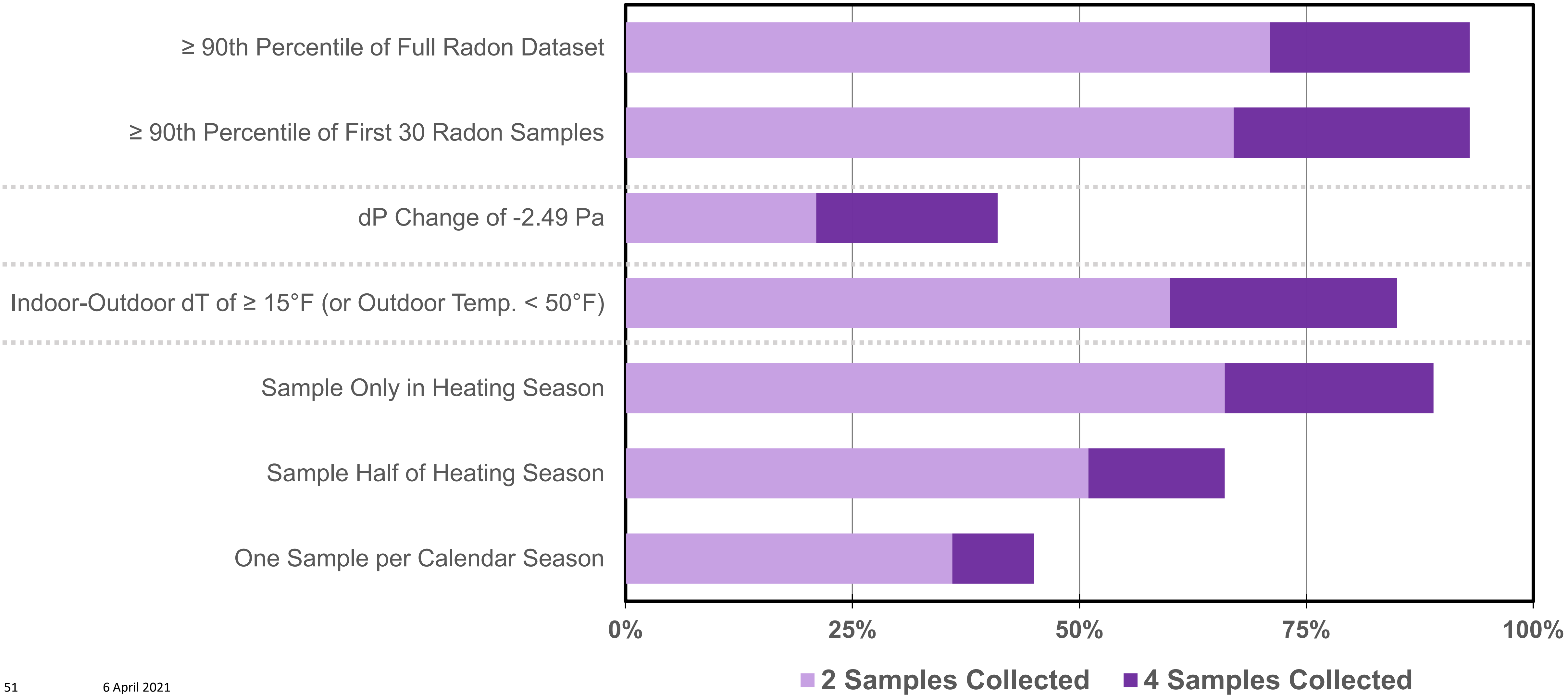
Median Percentile Across All Data Sets Tested								
	1 of 2 >mean	1 of 4 > mean	1 of 2 >90th	1 of 4 >90th	1 of 2 >95th	1 of 4 > 95th	1 of 2 > 95% UCL on Mean	1 of 4 > 95th UCL on Mean
Seasonal Sampling	39%	46%	20%	22%	10%	15%	36%	45%
Half in heating season	58%	73%	20%	34%	11%	21%	51%	66%
All in heating season	77%	95%	37%	61%	19%	35%	66%	89%
Differential temperature	74%	94%	28%	50%	18%	33%	60%	85%
Differential pressure	25%	48%	0%	0%	0%	0%	21%	41%
Radon percentile based on 1st month	72%	96%	24%	43%	6%	13%	67%	93%
Radon percentile based on full period	80%	99%	33%	67%	0%	0%	71%	93%

Key Points: All in heating season, differential temperature based and radon percentile based were the best approaches. Four samples are better than two. The 95^{th} percentile is very hard to observe.

Probability At Least One Sample Exceeds **Mean**, Median Across All Sites Tested



Probability At Least One Sample Exceeds **95% UCL**, Median Across All Sites Tested



Takeaways for Discussion

- Season and weather-based sampling approaches may improve chance of detecting upper end of indoor air concentration distribution
- Value of short-term sampling during suspected or known inactive VI periods (e.g., summer months)
- Indoor air radon data is useful in guiding sampling for upper end of indoor air VOC concentration distribution; although supporting data is limited and spatial differences apparent