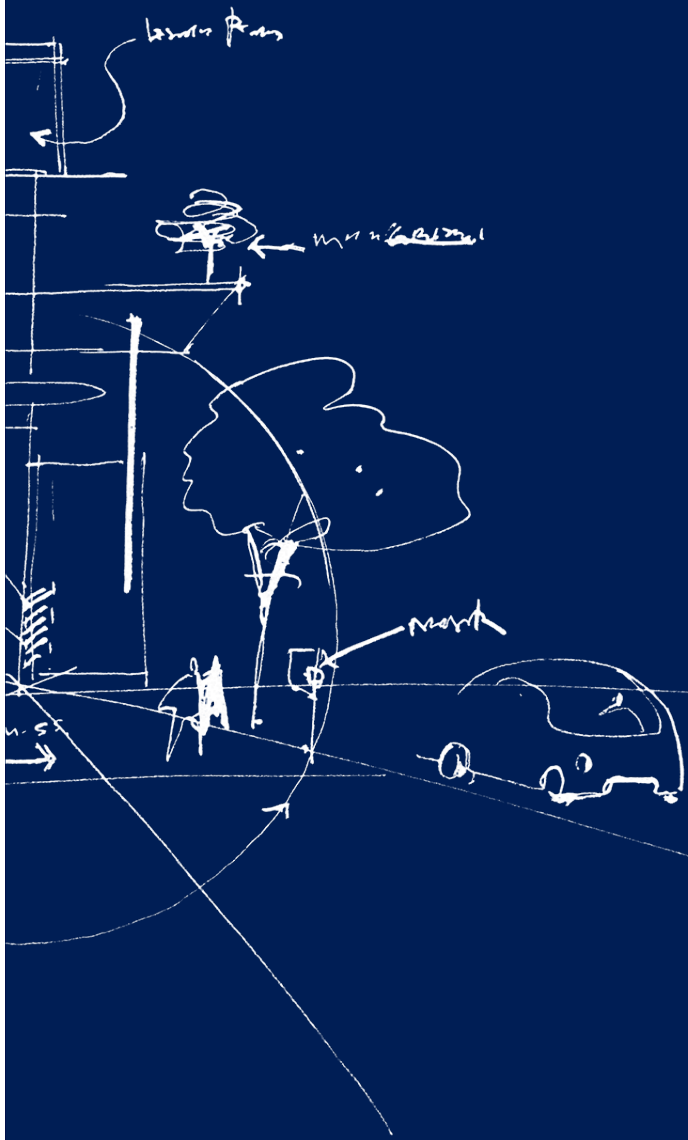
Challenging today.
Reinventing tomorrow.

A New Look at Diffusion and Subslab Vapor Intrusion Sampling: Passive Adsorption Diffusion Samplers

Ben Thompson, Michael Niemet, Loren Lund (Jacobs)
Harry O'Neill (Beacon Environmental)

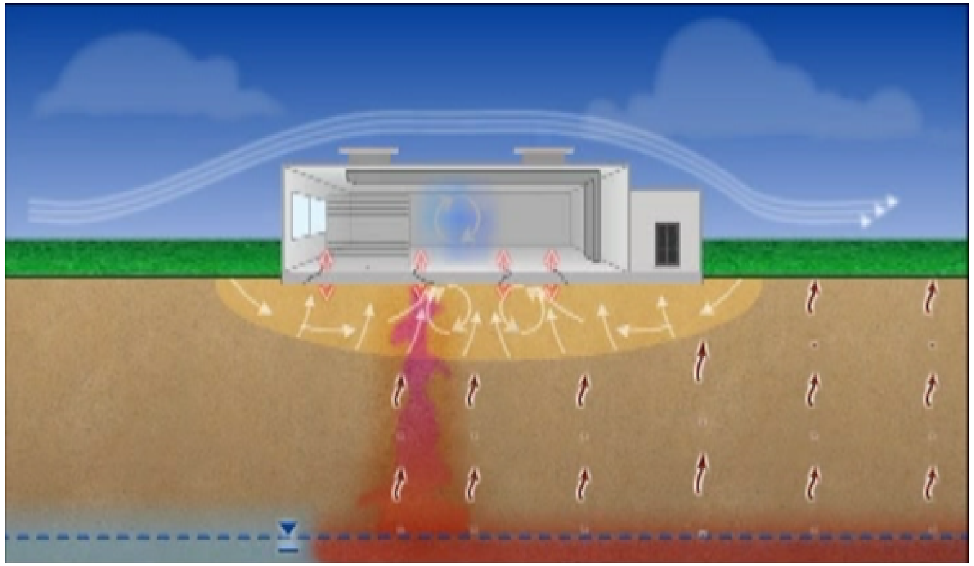
Agenda

- Introduction
- Vapor Intrusion Mechanics
- The Device
- Diffusion Theory
- Case Study
- Conclusions



Vapor Intrusion Mechanisms

- Vapor intrusion (VI) through a building slab/floor is a significant issue associated with volatile organic compound (VOC) contamination
- Two primary VI mechanisms:
  - Advection
    - Macroscopic openings
    - Driven by pressure gradients
    - Can be confirmed (e.g., with field GC, etc.)
    - Widely presumed the predominant VI mechanism
  - Diffusion
    - Microscopic pores
    - Driven by concentration gradients
    - Flux chambers are primary tool available
    - Not often included in indoor VI investigations



Source: Jacobs

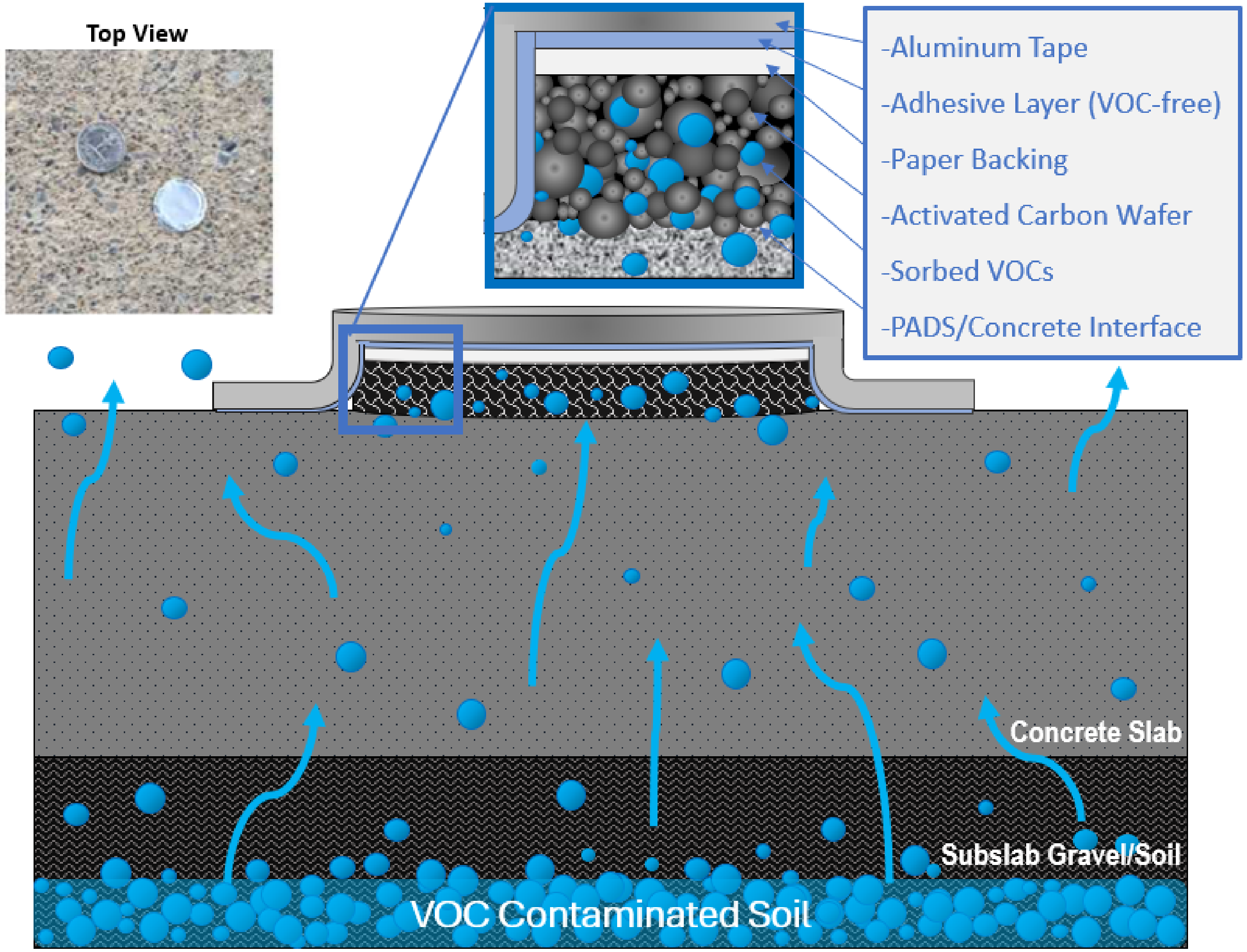
- Cracks and gaps may be very small portion of the slab. Diffusion has the potential to occur over a vastly larger area.
- Diffusion occurs continuously, not just when there is an upward pressure gradient across the slab.

What was the Need?

- Find a simple and convenient way to measure flux through the slab directly to determine if diffusion is significant?
- Obtain high resolution data without the need for:
  - Drilling holes through the slab
  - Installing sample ports
  - Doing helium leak testing
  - Renting and shipping bulky boxes and equipment
- Something that can be deployed at numerous locations across the entire building slab to quantify the building-wide mass transfer through the slab
- Something that can be used as a screening tool to prioritize traditional sampling locations, if required
- An additional tool to inform mitigation, if necessary
- Simplicity = potentially lower cost

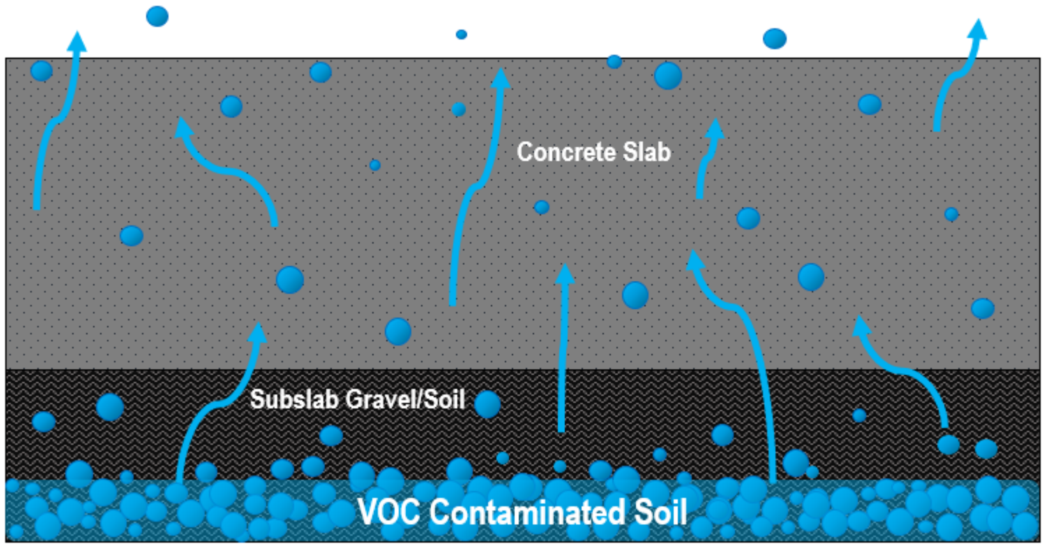
Passive Adsorptive Diffusion Sampler (PADS)

- PADS = Passive Adsorptive Diffusion Sampler
- Concept to make a sampler like a 'band aid'
- Initial laboratory testing using solvent extraction
- Obtained a patent in 2018
- Partnered with Beacon Environmental in 2018
  - Switched to thermal desorption for better sensitivity
  - Developed methodology for desorbing VOCs from sorbent wafer



Source: Jacobs

Diffusion Theory



Source: Jacobs

Fick's First Law of Diffusion:

$$F_d = -D_{eff}\frac{dC}{x} = D_{eff}\frac{(C_{ss} - C_{ia})}{x} \approx \frac{D_{eff}C_{ss}}{x}$$

F_d = diffusive flux or the mass transfer rate per unit area *m/t/A* (µg/h/m^2)

D_{eff} = effective diffusion coefficient through concrete (m^2/h)

dC = the concentration differential (µg/m^3) across the slab

C_{ss} = subslab vapor concentration (µg/m^3)

C_{ia} = indoor air concentration (µg/m^3)

x = slab thickness (m)

Effective Diffusion Coefficient = D_{eff}

<u>Johnson and Ettinger Model</u>

$$D_{eff} = D_a\left(\frac{\theta_a^{3.33}}{n^2}\right) + \frac{D_w}{K_h}\left(\frac{\theta_w^{3.33}}{n^2}\right) \times 0.36$$

D_a is the diffusivity in air (square centimeters per second [cm^2/s]) = 6.87 x 10-2

D_w is the diffusivity in water (cm^2/s) = 1.02 x 10-5

K_h is the Henry's law constant at the system temperature (unitless) = 0.316 @ 20 C

n is the total porosity (unitless) = 0.1

θ_a is the air-filled porosity (unitless) = 0.05

θ_w is the water-filled porosity (unitless) = 0.05

0.36 converts from cm^2/s to m^2/h

D_{eff} for TCE = 1.15 x 10^{-4} m^2/h

- USEPA (VISL Workbook)
- Green et al. 2012 for concrete parameters

The Study Building

- Large vacant warehouse (concrete slab on grade) with historic TCE use

	Value
Slab area, *A*	10,740 m^2 (115,000 ft^2)
Slab thickness, *x*	0.24 m (9.6 in)
Internal volume, *V*	56,600 m^3 (2,000,000 ft^3)

	Value
Interior height, *H*	5.3 m (17.3 ft)
Air exchange rate, *R*	0.1 h^{-1}

Determined empirically via ASTM E779-10 with HVAC off

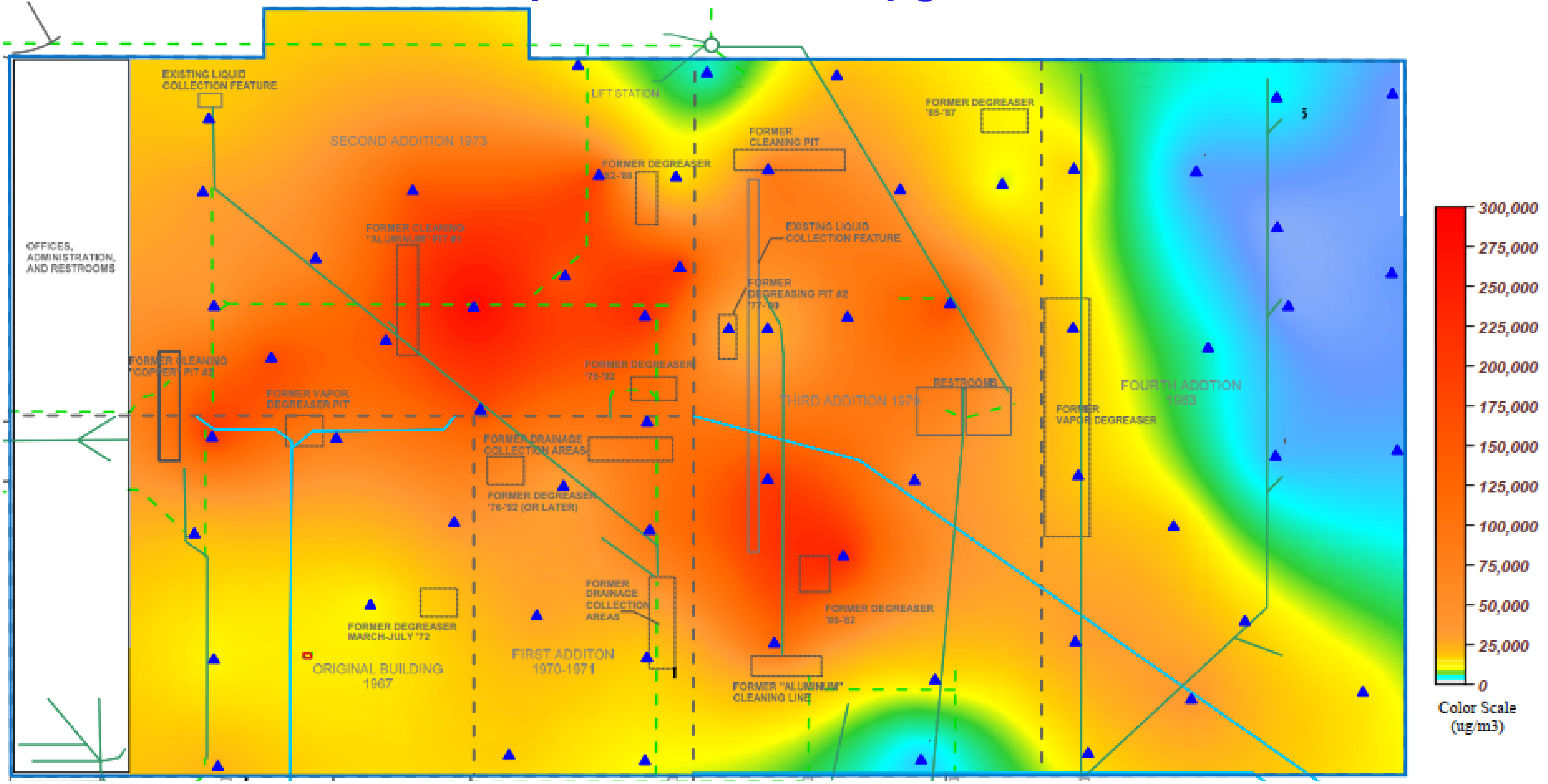
- Summa canister samples from 2015 showed high TCE

	Maximum (μg/m^3)	Average (μg/m^3)	Median (μg/m^3)
Subslab vapor (8 samples)	1,910,000	250,000	16,800
Indoor air (6 samples)	121	59.8	56.3

- Beacon Environmental passive subslab samples from 2017

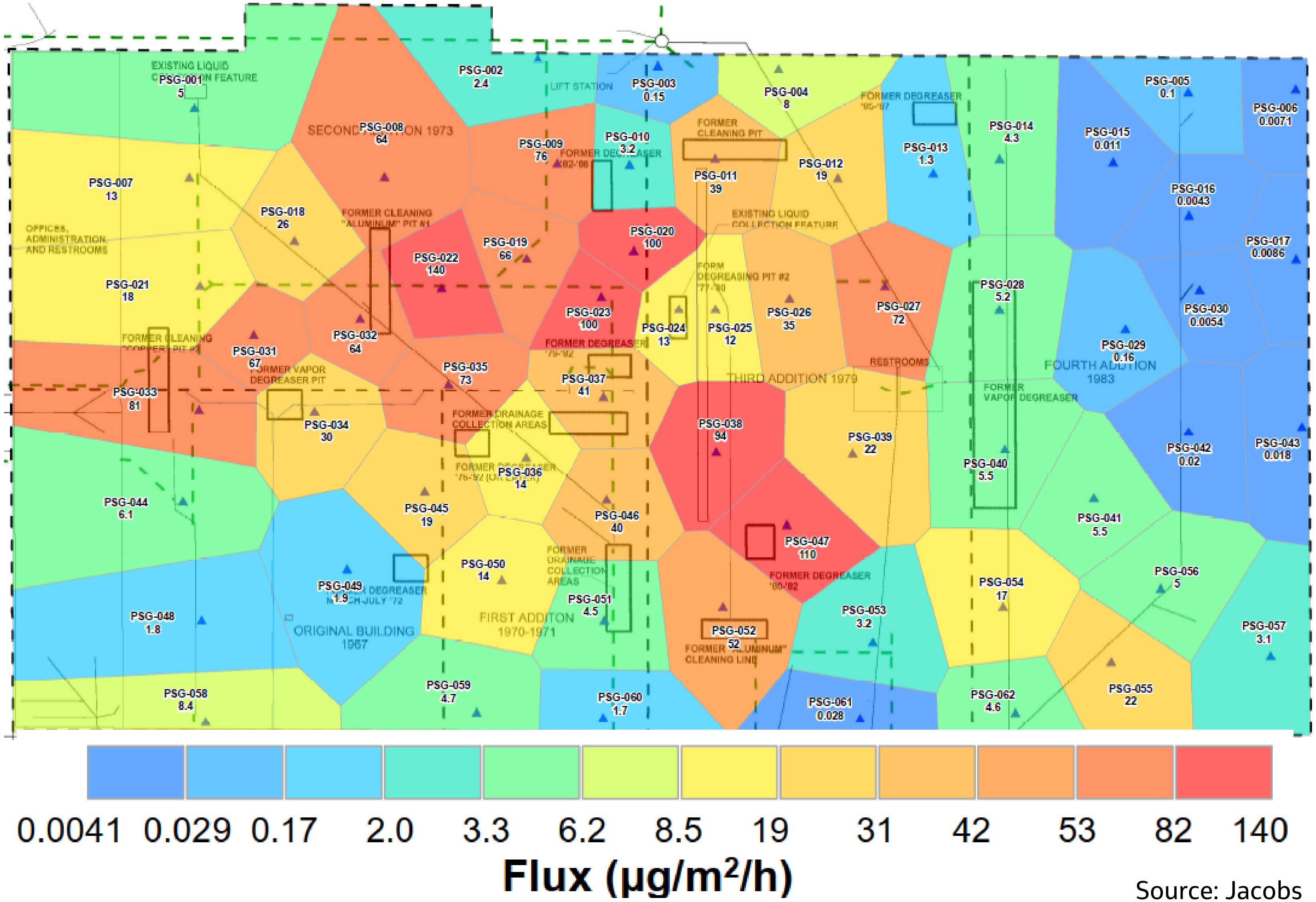
	Maximum (μg/m^3)	Average (μg/m^3)	Median (μg/m^3)
Subslab vapor (60 samples)	290,000	52,900	20,100

2017 Passive Subslab Vapor TCE Results (μg/m³)



Source: Beacon Environmental

2017 Theoretical Building Wide flux for TCE



Source: Jacobs

<u>Building-wide area-weighted theoretical averages for TCE:</u>

F_d = (251,074 μg/h) / (10,740 m²) = 23.4 μg/m²/h

Average Area-Weighted C_{ss} = 48,800 μg/m³

Arithmetic*

Min. = 9 μg/m³

Median = 20,100 μg/m³

Average = 52,900 μg/m³

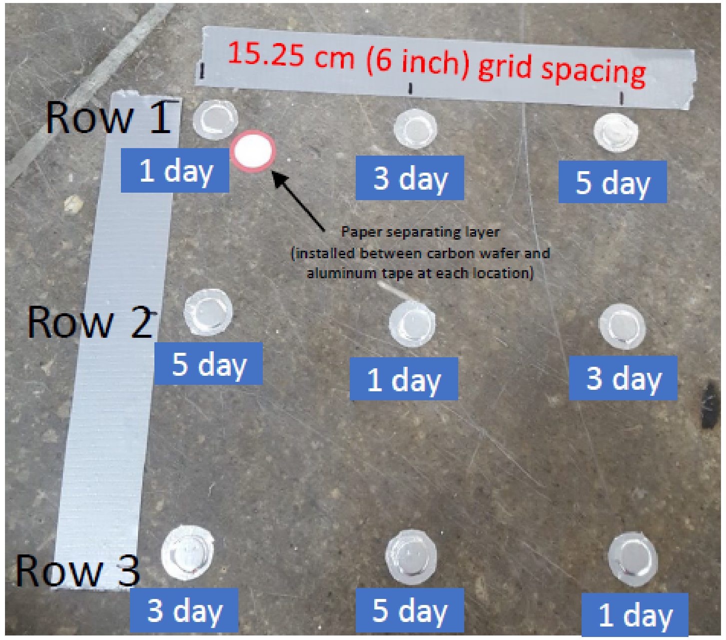
95th % = 151,000 μg/m³

Max. = 290,000 μg/m³

* 2017 Passive subslab vapor results

PADS Deployment - 2021

- 18 PADS in Areas A and B in 3x3 grids
  - 1 day (24 hours)
  - 3 days (72 hours)
  - 5 days (120 hours)
- 12 PADS distributed across the building slab
  - 3 days (72 hours)
- 2 passive indoor air samples
  - 5 days (120 hours)



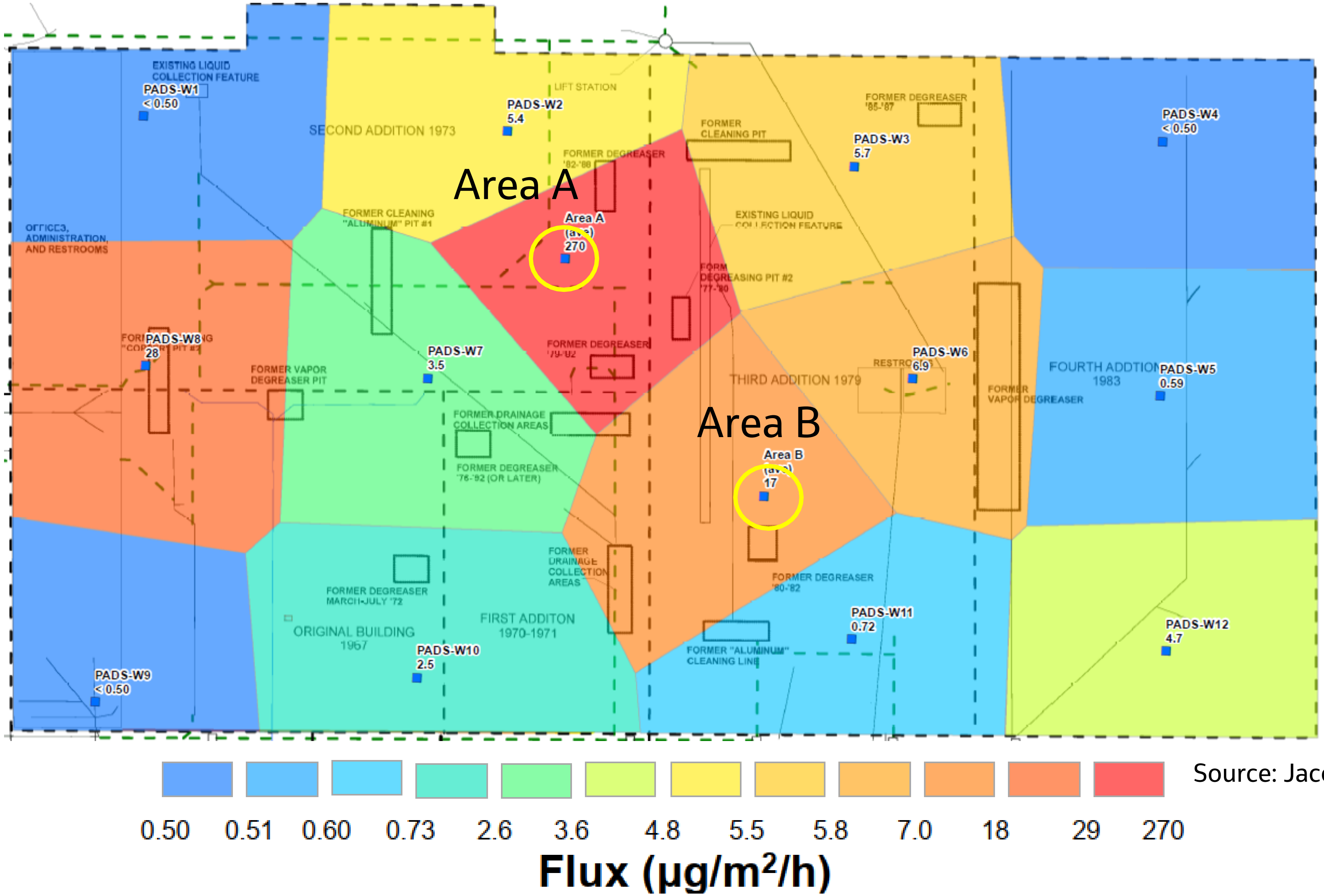
Area A

Area B

Source: Jacobs

Variability of an order of magnitude at each study location observed. Not unexpected. Variability of concrete, aggregate, moisture, etc…
Used an average of 9 PADS for evaluation at each location

Calculation of Building-wide TCE Flux from PADS Measurements



Source: Jacobs

<u>Building-wide area-weighted averages:</u>

F_d = (225,000 µg/h) / (10,740 m^2) = 21 µg/m^2/h

Calculated from Fick's law: 23.4 µg/h/m^2

C_{ss} = (21 µg/m^2/h) * (0.24 m) / (1.15 x 10^{-4} m^2/h) = 44,000 µg/m^3

Measured in 2017*: 48,800 µg/m^3

* 2017 Passive subslab vapor results

Expected Versus Measured Indoor Air TCE Concentrations

$$C_{ia} = \frac{F_d}{HR}$$

C_{ia} = indoor air concentration (µg/m²)
F_d = diffusive flux or the mass transfer rate per unit area *m/t/A* (µg/h/m²) – measured with PADS
H = average height of interior space (m) = 5.3
R = air exchange rate of the interior space (h^{-1}) = 0.1

Measured indoor air during PADS deployment:

Sample 1 = 36.5 µg/m³
Sample 2= 41.2 µg/m³
Average = 39.0 µg/m³

	F_d (µg/h/m²)	C_{ia} (µg/m³)
PADS Building-wide Results	21	40

Diffusion alone appears to account for virtually all of the TCE observed in indoor air under building test conditions.

Conclusions

- Multiple lines of evidence supported that PADS produced direct measurements of diffusive flux through the slab. These flux measurements can then be used to calculate other parameters, including:
  - Indoor air concentration: $C_{ia} = f(H, R)$
  - Subslab vapor concentration: $C_{ss} = f(x, D_{eff})$
- Diffusive flux through concrete can be significant and can be the predominant VI mechanism – should not be overlooked.
  - Direct flux measurements consistent with Fick's First Law calculations assuming J&E D_{eff}
- Flux through slab can be highly variable at sub-meter scale due to variability in D_{eff}
  - But when averaged on building wide scale, D_{eff} determined from flux approached J&E D_{eff}

Copyright notice

Thank you!