Pneumatic Testing, Mathematical Modeling and Flux Monitoring to Assess and Optimize the Performance and Establish Termination Criteria for Sub-Slab Depressurization Systems

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Optimization Considerations

- Current SSD design approach:
  - Apply suction and measure a vacuum
  - ASTM standard suggests 6 - 9 Pascals, but basis for this value is unclear
- Consider flow-based design approach
  - $Q_{\text{soil}}$ is about 0.1 to 10 L/min for 100 m² building
  - Average radon fan draws $\sim$3,000 L/min (overdesigned)
  - Overdesign may not be significant for single family home, but can be costly for commercial / industrial buildings
- Design analogue: groundwater pump & treat
  - Measure permeability and optimize pumping rate
Conventional Radius of Influence

Case Study: 100,000 ft² commercial building, slab-on-grade

ROI about 40 feet
Leaky Aquifer Model for SSD

Hantush & Jacob, 1955

FLOOR SLAB

GRANULAR FILL LAYER

Actual flow path

Assumed horizontal flow

Top of Native Soil

native soil less permeable than granular fill


Leaky Aquifer Type-Curves

High Purge Volume Test Kit

- Fan or Vacuum
- Bleed Valve
- Sample Port
- Vacuum Gauge
- Cored Hole
- Lung Box
In just a few minutes, you’ve got “pump-test” data
Drawdown and Recovery

Graph showing the relationship between vacuum (inches of water column) and time (seconds) with multiple cycles of drawdown and recovery.
Hantush Jacob Model Fit

Vacuum measurements 6 feet from extraction point

Very good fit between model and vacuum vs time data

Curve fitting yields $T$ and $r/B$ values

Parameters:
- $T = 175.4$ ft$^2$/day
- $S = 0.0005635$
- $r/B = 0.424$
- $K_z/K_r = 1$
- $b = 0.5$ ft
- $B = 14$ ft

Legend:
- Theis Curve (no leakage)
- Leaky-Type Curve
Tests at distances of 6 ft and 43 ft yielded almost identical Transmissivity (T) and Leakage (B) values.
Floor Slab Conductivity

\[ K' = \frac{T \cdot b'}{B^2} \]

- \( K' = \) vertical pneumatic conductivity of the floor slab \([L/t]\)
- \( b' = \) floor slab thickness \([L]\), easily measured
- \( T = \) transmissivity \([L^2/t]\), a direct output of the model
- \( B = \) leakance \([L]\), also output from the model

Therefore, if you know \( b' \) (slab thickness), you can calculate the vertical pneumatic conductivity of the slab.
Measured versus Modeled Vacuum

Vacuum = \frac{Q_w}{2 \pi T} K_0 \left(\frac{r}{B}\right)

Q_w = \text{volumetric flow rate from well (ft}^3/\text{day)}

r = \text{distance from extraction point (ft)}

K_0 = \text{Modified Bessel function of zero order}

(1 \text{ inch of water column} \sim 250 \text{ Pa})

\text{ALSO good fit of model to vacuum vs distance – unique calibration!}
Velocity versus Distance

\[ v(r) = \frac{Q_w}{2\pi b n B} K_1(r/B) \]

- \( b \) = thickness of fill layer (ft)
- \( n \) = fill layer porosity (ft\(^3\)/ft\(^3\))
- \( K_1 \) = Modified Bessel function of first order

Typical \( Q_{soil} \) divided by building area is about 0.05 ft/day
Gas within the “conventional” ROI (40 ft) gets flushed every hour and a half.

How often does it need to be flushed?
Radius of Influence as a Function of Leakage

\[ \frac{Q(r)}{Q_w} = \frac{r}{B} K_1(r/B) \]

Portion of flow from below the slab

Portion of flow from leakage

Distance from Extraction Point (ft)
Soil Gas Flow Modeling as a Tool for Soil Vapor Extraction Design

Cross Section Showing Model Layers

Atmosphere

6 inches Concrete
6 inches gravel

Silty sand soil

Water Table @ 15 ft bgs with ~200 ug/L TCE

Ka=6E7 ft/day, n =1

Kc=0.5 ft/day, n =0.35

Kg=360 ft/day, n =0.35

Ks=1 ft/day, n =0.3
Calibration to Measured Vacuum

Calculated vs. Observed Head: Steady state

Measured and modeled air pressure show good calibration.
Particle Tracks in Plan View

Particles travelling through the gravel layer

Arrowheads are only 1 hour apart - 5 hours to travel from 50 ft away

Numerical model matches analytical model – internal consistency

Q = 27 scfm
Particle Tracks in Cross Section

Limited flow through the native soil

Arrowheads are 1 day apart, so flow through the soil is very slow

Q = 27 scfm
Suction Points Required for 6 Pa

Even with 15 suction points pumping 27 scfm, there are still areas where vacuum would not meet the ASTM spec. of 6 Pa vacuum.

Almost 600,000 cubic feet per day of air flows from the building to the subsurface (energy loss).
SSD versus SSV

Maximum sub-slab concentration drops rapidly until total system flow approaches 60 scfm.

Corresponding minimum sub-slab vacuum = 1 Pa (not 6 Pa, per ASTM Spec.)
How To Measure 1 Pa Vacuum?

Typical fluctuations in cross-slab pressure are greater than 1 Pa (maybe this is why ASTM specified 6 to 9 Pa vacuum...).
Consider Mass Flux

- Upward Diffusive Mass Rate ($\dot{M}$) = $D_{\text{eff}} \times \Delta C/L \times A$ (all can be estimated)
- Extracted Mass Removal Rate by Vent Pipes = $C \times Q$ (all can be measured)
Example Vent-Pipe Data

Summa Can/TO-15 data from sub-slab probe

Waterloo Membrane Sampler data from vent pipe

TCE Concentration (µg/m³)

- 10X Site-Specific Soil Gas Screening Level (1,000 µg/m³)
- NJDEP Indoor Air Screening Level (3 µg/m³)

Dates:
- 01-Jul-07
- 17-Jan-08
- 04-Aug-08
- 20-Feb-09
- 08-Sep-09
- 27-Mar-10

Legend:
- PVE-2
- SSP-2
- OA-01*
- IA-02*
- System Installation Date (June 18, 2008)
Optimization Strategy

Measure vent-pipe mass removal rate at different flow rates
Optimize SSV extraction rate to “capture” available vapors

Background sources contribute to mass flux

Increase in Q only extracts more mass from indoor/outdoor air

SSV System Mass Removal Rate [M/T]

SSV System Flow Rate [L³/T]
Exit Strategy

Monitor SSV system mass removal rate over time
Compare to target building mass rate \( (Q_{\text{bldg}} \times RBSL_{\text{IA}}) \)
Consider rebound testing, similar to SVE systems

Consider background sources to mass removal rate
Take-Home Message

- There are several ways to monitor SSD/SSV systems
  - Vacuum ($\Delta P$)
  - Venting rate ($Q$)
  - Flux ($Q \times C$)
- We can reuse math hydrogeologists have used for decades
  - Pump tests, flow modeling, transport modeling, optimization
- Experience has shown comparable results at dozens of sites
  - Consistency in floor slab construction (see building codes)
- This allows us to answer some questions we couldn’t before
  - Optimal number of suction points, flow rates
  - Exit strategy