Measurement of BTX Vapour Intrusion into an Experimental Building

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Presentation Outline

- Chatterton site research program overview
- Why measure VOC intrusion?
- Conceptual models
- Mathematical models
- Experimental methods
- Measured BTX flux and soil gas flow rates
- Model comparisons
- Conclusions and research needs
Research Objectives

1. Conduct **field-based** project at **hydrocarbon (BTX)**-contaminated site (“Chatterton” research site).

2. Conduct **integrated** study addressing both **vadose zone hydrocarbon transport** and **building intrusion**.

3. Identify key processes & conditions affecting transport.

4. Incorporate results of other case studies including building science, radon & methane research.

5. Validate available screening level models, develop new (numerical) models.

6. Develop new or improved field methods.

7. Develop guidance or protocol addressing framework, model selection and use, and input parameters.
Project Scope

Comprehensive, multi-year program
Construct new building (greenhouse) with controlled building properties, monitor old building

Field program:
1. Baseline characterization, lab testing
2. Vadose zone monitoring
3. **BTX intrusion measurements**

Model development (numerical model for transport & intrusion)

Model validation

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**Data Types**
- chemical distribution
- chemical properties
- environmental/meteorological
- soil properties
- building properties

**Measurement Techniques**
- soil vapour profiling
- push-pull diffusion
- in-situ respiration
- soil-air permeability
- continuous $\Delta P$, $O_2$, $T$
- flux chamber
- tracer tests

**Data Quality & Quantity**
- uncertainty/statistics
- analytical
- seasonal effects
- transient effects
Why Measure VOC Intrusion?

Focus for this talk is building foundation and near-surface soils.

Our understanding of vapour migration through building foundations is poor (more emphasis has been placed on vadose zone transport).

Evaluate importance of building depressurization and cracks.

Research may lead to practical techniques.

To validate models for this pathway, reduce uncertainty.
VADOSE ZONE COMPARTMENT (Far-field)

Moisture Content
Biodegradation Rate
DIFFUSION
BIODEGRADATION

CONTAMINATION
BUILDING FOUNDATION & SUBSOIL COMPARTMENT (Near-field)

CONTRIBUTION OF ADVECTIVE FLUX TO VOC INTRUSION GREATEST WHEN

- $\Delta P$, $K_{soil}$, $K_{slab}$, high
- $D$ low
- Tight above-grade building envelope

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Advective Processes

Driving forces include:

- temperature difference (stack effect) - probably most significant
- unbalanced ventilation, heating systems
- wind, temperature (diurnal), barometric pressure

Site-specific factors (construction, soil type, subsurface utilities) and relative permeability of soil and foundation are critical
Mathematical Models for Soil Gas Advection through Building Foundation

1. Flow to Perimeter Crack Model (analytical sol’n steady-state 2-D flow to horizontal drain) (Soil & Foundation)

\[ Q = K \frac{b \, w \, \delta h}{\delta L} \]

\[ L K = \frac{\rho_{air} g b^2}{12 \mu} \]

2. Flow through Foundation Model (Hagan-Pouisselle relationship for laminar flow through parallel plates or tube (Just Foundation))

\[ Q = 2\pi k_{air} \Delta P_{x_{crack}}/\mu \ln(2z_{crack}/r_{crack}) \]

3. Numerical model - How to couple flow in soil with flow through small cracks? One possibility is to adapt MODFLOW (ASTM 5719-95)
From chapter 4
Air, Weather and Moisture Barriers
and Vapour Diffusion Retarders
Possible Approaches to Estimate VOC Vapour Intrusion

1. Measure VOC concentrations (indoor & outdoor air, groundwater &/or soil vapour, ventilation)
   - vapour attenuation ratio (\(\alpha\))
   - using mass balance approach:
     - VOC mass flux
     - soil gas flow rate (assumes mass flux by advection)

2. Flux chamber measurements (cracks)
   - VOC mass flux
   - soil gas flow rate

3. Tracer test (inject SF\(_6\), use radon)
   - infer VOC flux and soil gas flow rate

Background?
Sensitivity
Scale Up?
Boundary conditions?
Experimental Methods

Constructed building with controlled properties

Used VOC measurements & flux chamber tests to estimate (i) vapour attenuation ratio, (ii) BTX flux into building & (iii) soil gas flow rate into building.

Natural ("Diffusion") Cases - $\eta = 0.00033$, 2 tests

Depressurized ("Advection") Cases - Fan Induced

i) 2.5 Pa, $\eta=0.0001$  
ii) 10 Pa, $\eta=0.0001$  
iii) 10 Pa, $\eta=0.00033$  
iv) 30 Pa, $\eta=0.00033$

Extensive sub-slab monitoring BTX vapour, $O_2$, pressure, temperature
Flux Chamber Testing Protocol

Test flux chamber blanks - a challenge!

Depressurize greenhouse

Purge 5 chamber volumes

Adjust flux chamber flow rate to equalize pressure in building and chamber (developed Q vs. $\Delta P$ curve for various leakage elements to assist in this)

- Edge Crack - Q on order of 500 ml/min @ 10 Pa (sample without replacement)
- Hairline Crack - Q on order of 10 ml/min @ 10 Pa (sample with replacement)

Collect samples over several hours using sorbant tube (Supelco 300)
Flux Chamber Design

- Valve #4
- Valve #3
- Pump
- Valve #2
- Valve #1
- Charcoal Filter
- Pressure Monitoring Port (Typ.)
- Base Plate (for blank tests)
- Rubber Seal
- Thermal Tubes
- P₁, P₂, P₃
- 90mm
- 909mm

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Soil Gas Flow Through Edge Crack

Differential Pressure Between Flux Chamber & Greenhouse (Pa)

Flow Rate (litre/min)

PRESSURE IN FLUX CHAMBER GREATER THAN GREENHOUSE

PRESSURE IN FLUX CHAMBER LESS THAN GREENHOUSE

Edge Crack -20 Pa
Edge Crack -33.5 Pa
Soil Gas Flow Through Hairline Crack & Capped Drain Pipe

![Graph showing the relationship between differential pressure and flow rate for different conditions. The graph includes lines for Drain -38.5 Pa, Drain -20 Pa, Drain -30 Pa, Hairline -38.5 Pa, Hairline -30 Pa, and a Leak Test.](image-url)
BTX Vapour Intrusion Measurement Results - Natural ("Diffusion") Case

no significant difference in indoor & outdoor BTX concentrations

no measurable flux by flux chamber

BTX vapour concentrations below slab stayed low, O₂ below slab remained elevated
Oxygen Concentrations Below Centre Building - Natural Conditions

**BELOW BUILDING (SG-BC)**
- Oct 3/97
- Oct 17/97
- Nov 19/97
- Nov 19/97
- June 24/98
- Mar 9/99

**NATURAL SOIL COVER (SG-BR)**
- May 15/97
- Sept 27/98
- Sept 28/98
- Nov 17/98
- Nov 30 & Dec 4/98
- Mar 9/99
BTX Vapour Intrusion Measurement Results - Depressurized ("Advection") Case

$\Delta P = 10 \& 30 \text{ Pa}$:
- Sub-slab BTX vapour levels increased, $O_2$ decreased
- Indoor BTX concentrations significantly higher than outdoor concentrations
- High BTX flux through cracks

$\Delta P = 2.5 \text{ Pa}$:
- Increase in BTX vapour and decrease in $O_2$ only below centre of slab
- Indoor BTX concentrations only slightly higher outdoor concentrations
- Low BTX flux through cracks

Chatterton site conditions conducive for advective transport of BTX into building (shallow contamination, permeable soil/slab, high $\Delta P$)
Effect of Depressurization on Soil Gas Benzene Profile - Dynamic Conditions

Benzene Concentration (mg/L)

Depth Below Top of Slab (m)

-30 Pa Depressurization
-10 Pa Depressurization

-2.5 Pa similar to 10 Pa case
Chatterton Benzene Vapour Concentrations Directly Below Slab Depressurized $\Delta P=10$ Pa, $\eta=0.0001$

Edge Crack

Vapour Probe

1130 Benzene Conc (ug/L)
Chatterton Benzene Vapour Concentrations Directly Below Slab Depressurized $\Delta P = 2.5$ Pa, $\eta = 0.0001$

Vapour Probe Concentration (ug/L)

- Edge Crack
  - Concentration: 0.040
  - Location: 790

- Concentration: 3810
  - Location: 0.049

- Concentration: 1130
  - Location: 0.049

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Benzene Flux Through Cracks Measured Using Flux Chamber

<table>
<thead>
<tr>
<th></th>
<th>Average Flux Chamber Flow Rate (ml/min)</th>
<th>Average Benzene Flux (mg/min-Pa-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge Crack (~2mm)</td>
<td>460</td>
<td>0.016</td>
</tr>
<tr>
<td>Hairline Crack</td>
<td>11</td>
<td>0.00023</td>
</tr>
</tbody>
</table>
Soil Gas Flow into Building

Measured soil gas flow rates:
  mass balance approach:  \(~ 2.7\) to \(4.2\) L/min
  flux chamber: on order of \(2\) to \(4\) L/min

Predicted soil gas flow rates:
  flow to perimeter crack model:  \(8.2\) (10 Pa) to \(29\) L/min (30 Pa)
  MODFLOW simulations:  \(4\) to \(5\) L/min (10 Pa)
    – soil permeability most important
    – over 90 % through open portion of 2 mm edge crack
    – remainder through hairline cracks
MODFLOW DOMAIN

- Impermeable boundary
- Slab
- Crack
- New sand $k=25$ darcy
- Old sand $k = 10$ darcy
MODFLOW RESULTS

Equipotentials

Flow Lines
# Source $\alpha$ - Direct Measurements

<table>
<thead>
<tr>
<th>TYPE</th>
<th>SITE</th>
<th>CONDITIONS</th>
<th>CHEMICAL</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTEX</td>
<td>Chatterton</td>
<td>$\Delta P=0$ Pa $\eta=0.00033$</td>
<td>B&amp;T</td>
<td>$&lt;1.2E-6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta P=2.5$ Pa $\eta=0.0001$</td>
<td></td>
<td>$5.0E-7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta P=10$ Pa $\eta=0.0001$</td>
<td></td>
<td>$1.1E-4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta P=10$ Pa $\eta=0.00033$</td>
<td></td>
<td>$2.0E-5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta P=30$ Pa $\eta=0.00033$</td>
<td></td>
<td>$1.4E-5$</td>
</tr>
<tr>
<td></td>
<td>Alameda</td>
<td>$\Delta P\approx3$ Pa (wind)</td>
<td>benzene</td>
<td>$&lt;9E-6$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slab-on-grade</td>
<td>pentane</td>
<td>$&lt;9E-7$</td>
</tr>
<tr>
<td></td>
<td>Paulsboro</td>
<td>SFR w\ bsmt $\Delta P=?$</td>
<td>benzene</td>
<td>$&lt;1E-6$</td>
</tr>
<tr>
<td></td>
<td>CS CDOT HDQ</td>
<td>Apartment/SFRs</td>
<td>Avg 4 CS</td>
<td>$3.0E-5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90th% 4 CS</td>
<td>$6.5E-5$</td>
</tr>
<tr>
<td></td>
<td>Redfields</td>
<td>SFRs w\ bsmt or cs</td>
<td>Avg DCE</td>
<td>$7.6E-5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90th% DCE</td>
<td>$1.2E-4$</td>
</tr>
<tr>
<td></td>
<td>Lowry AFB</td>
<td>Apartments Sept 97</td>
<td>Avg TCE</td>
<td>$\sim 1E-3??$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Apartments/SFRs</td>
<td>Avg TCE</td>
<td>$&lt;1$ to $6E-5$</td>
</tr>
</tbody>
</table>

CS = chlorinated solvent, SFR = single-family residence

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## Subslab $\alpha$ - Tracer Tests & Radon Studies

<table>
<thead>
<tr>
<th>TRACER</th>
<th>SITE</th>
<th>CONDITIONS</th>
<th>$\alpha$</th>
<th>$Q_{soil}/(Q_{b}\Delta P)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTEX</td>
<td>Chatterton</td>
<td>$\Delta P \geq 10$ Pa</td>
<td>$3E^{-4}$ to $6E^{-4}$</td>
<td>$0.005 - 0.01$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slab-on-grade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF$_6$</td>
<td>Alameda</td>
<td>$\Delta P \approx 3$ Pa</td>
<td>$2E^{-4}$ to $4E^{-4}$</td>
<td>$\sim 0.006$</td>
</tr>
<tr>
<td></td>
<td>Fischer, 96</td>
<td>Slab-on-grade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF$_6$</td>
<td>Central CA</td>
<td>$\Delta P = 30$ Pa</td>
<td>$\sim 0.001$</td>
<td>$0.02$</td>
</tr>
<tr>
<td></td>
<td>Hodgson. 92</td>
<td>SFR w/ bsmt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF$_6$</td>
<td>Ben Lomand</td>
<td>Experimental bsmt</td>
<td>N/A</td>
<td>$0.04$</td>
</tr>
<tr>
<td></td>
<td>Garbesi, 93</td>
<td>3 mm edge crack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rn</td>
<td>Spokane R.</td>
<td>SFR slab-on highly permeable sand &amp; gravel, winter</td>
<td>$7.9E^{-3}$ to $1.4E^{-2}$</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Valley Rez-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>van, 92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rn</td>
<td>Indoor Rn</td>
<td>SFRs</td>
<td>$1.6E^{-3}$</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>USA Little '92</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Implication $\alpha$ generally $< \sim 0.001$ for sub-slabb vapour source**

$Q_b$ = building ventilation rate, $Q_{soil}$ = soil gas flowrate, $A$ = subsurface foundation area
Comparison Measured to Predicted (J&E) $\alpha$

- Upper Building Range
- Lower Building Range
- Alameda benzene
- Paulsboro benzene
- Chatterton B&T
- Redfield DCE
- CDOT HDQ
- Lowry AFB TCE

<table>
<thead>
<tr>
<th>Building Property</th>
<th>Upper Range</th>
<th>Lower Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEH</td>
<td>0.25</td>
<td>1.0</td>
</tr>
<tr>
<td>Height</td>
<td>2.4 m</td>
<td>4.8 m</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.005</td>
<td>0.00005</td>
</tr>
<tr>
<td>Cracks</td>
<td>Dry</td>
<td>Moist</td>
</tr>
<tr>
<td>$\theta_{soil}$</td>
<td>15 L/min</td>
<td>1L/min</td>
</tr>
<tr>
<td>$A_{build}$</td>
<td>100 m$^2$</td>
<td>100 m$^2$</td>
</tr>
</tbody>
</table>

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Conclusions

Techniques were developed to measure soil gas & BTX intrusion into building

Flux chamber testing challenging

Advective processes significant:
- natural case: while there were diurnal & barometric pumping effects, no measurable intrusion
- sustained depressurization > 2.5 Pa: high BTX intrusion

Advection primarily controlled by $\Delta P$ & soil permeability

Intrusion through hairline cracks does occur!

Good comparison between measured & model-predicted soil gas flow rates into building
Conclusions

J&E model conservative, except for $\Delta P > 2.5 \text{ Pa}$

Building properties and interaction between building and vapour fate and transport is important ($\Delta P$ effects, barometric / temperature pumping)

Significant uncertainty associated with this pathway - will be difficult to reduce this uncertainty