Air Exchange Measurements
OVERVIEW OF TRACER METHODS

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Ancient History

- Tracers for building science were a hot topic 30 years ago
  - Early investigative work
  - Model development and validation
- Standard test methods resulted
  - ASTM E741
  - ISO 12569
- Little work done after 80's.

What is a *Tracer Gas*?

- Something that can be easily added to system
- Something that can be easily detected
- Something that does not affect system to be measured
- Practical
  - Cheap; easy to acquire
  - Easy to quantitate; transportable

Tracer Gasses of Note

- Helium: Ideal gases in air
- Ethane: Hydrocarbons have nice IR spectrum
- SF_6: Low detection limits, but chemistry
- CFCs: Montreal Protocol
- PFTs: Relatively inert, no real-time
- CO_2: Cheap, large background/interference

Tracer Gas Uses

- Qualitative: Threshold detection
  - Leak Detection; Contaminant capture
  - Path tracing
- Quantitative: Concentration reduction
  - Flow through duct, pipe, etc.
  - Air exchange (dilution)
  - Follows *Continuity Equation*
    - Conservation of mass

CONTINUITY EQUATION

- Locally Covariant Derivation

$$J_\mu \cdot \partial^\mu C_T = \Lambda_T$$

- Zonal Description

$$\underline{\underline{V}} \cdot \dot{\underline{C}} + \underline{\underline{Q}} \cdot \underline{C} = \underline{F}$$

SINGLE ZONE EQUATION

- Integral Solution (S=F/V; A=Q/V)

$$C(t) = \int_{-\infty}^{t} S\, e^{\int_{t'}^{t} A(t'')\,dt''}\, dt'$$

- Local Solution (to find Air Exchange Rate)

$$A(t) = \frac{S(t) - \dot{C}(t)}{C(t)}$$

Looks Easy, But for *MIXING*

- Equation assumes every point in space is at the exact same concentration, *C*.
- Can't possibly be true
  - Tracer added at fixed number of points
  - Clean air enters at fixed number of points
  - Some parts of volume better connected than others
- Limits accuracy of experimental methods

Averaging Can Help (or Hurt)

- Spatial averaging
  - Improves precision by getting many samples
  - Can lead to bias if exfiltrating air is not “average”
- Temporal averaging
  - Reduces impacts of fluctuations (real or instrumental)
  - Assumes parameters (e.g. air exchange) not changing
- Depends on experimental approach

Commonalities

- Means for injecting tracer gas
  - On-site control, constant emission, pulse, etc.
- Distribution or mixing means
  - Central fans, local fans, time
  - Effective volume may be important
- Measure concentration
  - Spot measurement or integrated measurement
  - On-site analysis or capture/store and off-site measurement

Method Depends on Needs

- Model Calibration or Validation
  - Low bias method with appropriate time scale
- Forensic: *When you don't know what is happening*
  - Real-time, good resolution
- Diagnostic
  - Quick setup; robust
- Large study
  - Low cost; statistically useful

Simple Decay

- No injection-related errors
  - Passive system
- Short duration test (1/A)
  - Snapshot
- Averaging not needed after initial delay period
  - Mix, settle, measure
- Multipoint or integrated sampling
  - Classic is 2 points

$$C(t) = C_o e^{-At}$$

Constant Concentration

- Controlled injection
  - Active system

$$\dot{C} = 0 \quad A(t) = S(t) / C$$

- Continuous Measurement
  - Can see real-time changes
- Averaging improves control stability
  - Mixing reduces bias, instabilities, but can change system
- Requires real-time concentration measurement
  - As well as real-time injection

Constant Injection

- Constant injection
  - Active or passive system

$$A(t) = S / C(t) - \dot{C}(t) / C(t)$$

- Must be near steady state
  - Errors if concentration changes too fast
- Averaging improves precision
  - Mixing can change system
- Requires periodic concentration measurement
  - On-site or off-site

Long-Term Averages

- Average injection
  - Active or passive system

$$A = \bar{S} / \bar{C}$$

- Requires long averaging time (>>1/A)
  - Errors air change rate varies
- Averaging improves precision
  - Mixing can change system
- Requires average concentration measurement
  - On-site or off-site
- Special Case

ANALYSIS METHODS

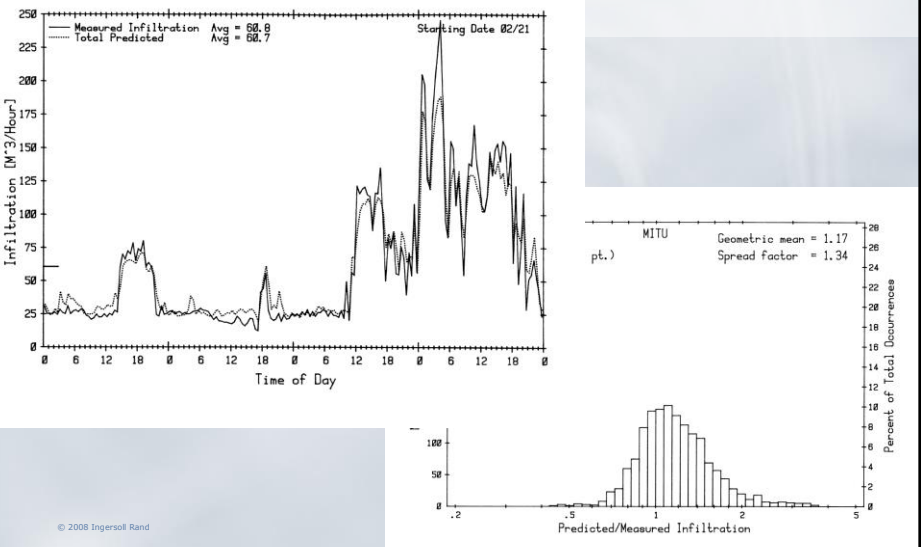
- Linear Regression
  - Classic, *Wrong*
- One-Point: Constant Concentration
- Two-Point: Decay
- IntegralAverage: Best Overall
  - Decay -> Pulse
- Time Resolution: Precision vs. Accuracy

MOBILE INFILTRATION TEST UNIT *(MITU; 1982)*

- Built For Research and Validation
  - Surface pressures; Weather tower
  - Automated tracer system
  - Adjustable leakage
- Used in Many Environments
  - Stack dominated (Sierra Nevada)
  - Wind dominated (CA coast)

MITU IN ACTION

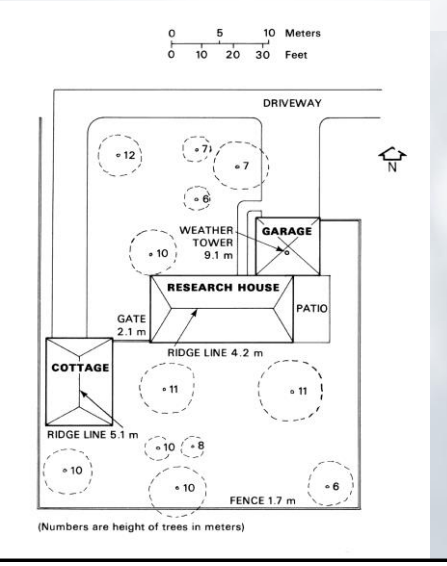
VALIDATION IN MITU

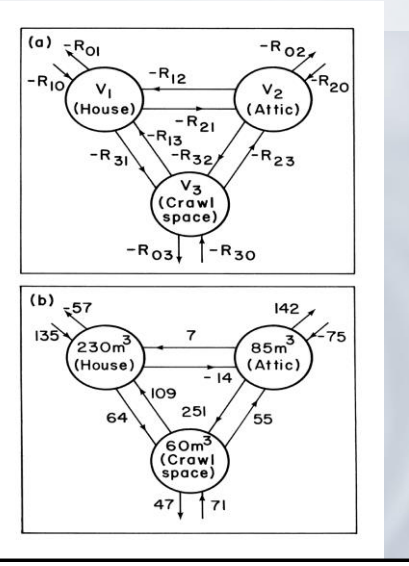


Multizone Tracer Methods

- Much more complicated
  - Research grade
- Usually need multiple tracer gasses
  - Special exceptions such as constant concentration
- Errors can compound and are correlated
  - Even lead to unphysical results
- *Can* be most appropriate approach

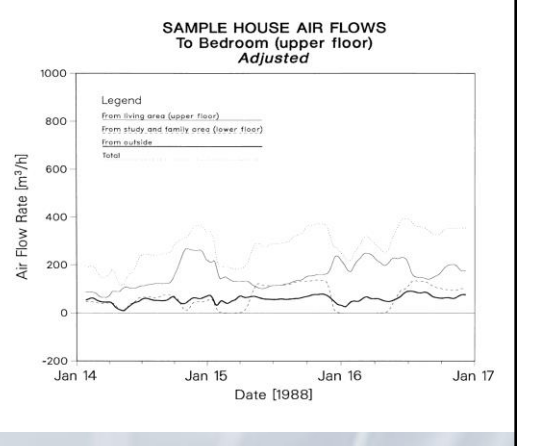
3-ZONE HOUSE EXAMPLE





MULTITRACER DATA

- MTMS Hardware
- Bayesian Analysis
- Real-Time
- Variable Internal Flows



Errors Can Ruin Data

- Precision errors are easiest to spot
  - Instrumentation, inhomogeneity, irreproducibility
- Zonal assumption often wrong
- Good mixing often not there
- Analysis biases hard to spot
- Some approaches more robust
  - Need to understand purpose of measurement

TRACER GAS SUMMARY
(except passive technique)

- Many Tracers & Approaches Possible
  - Experimental design options
- Measured in Real-Time
  - Snapshot
- Not Good for Broad Use
  - Requires training and experience
  - Time & costs usually prohibitive
- Quality Research Tool

DISCUSSION?

Thank You