

UNCERTAINTIES IN AIR EXCHANGE USING CONTINUOUS-INJECTION, LONG-TERM SAMPLING TRACER-GAS METHODS

Max Sherman, Lawrence Berkeley Laboratory
Melisa Lunden, Iain Walker

Special Case Technique

- ❖ **PerFlourocarbon Tracers technique**
 - ❖ Named for tracer gasses used (“PFT”)
 - ❖ Not for experimental approach
- ❖ **CILTS defines approach for any tracer**
- ❖ Continuous Injection (*i.e. constant emission*)
 - ❖ Long-Term Sampling (*i.e. average concentration*)
- ❖ **Most widely used method**
- ❖ i.e. cheapest
 - ❖ Not necessarily research grade

Derived from “Ancient” Techniques

❖ “Pro”s

- ❖ Inert (i.e. “good”) tracer gas
- ❖ Simple field application
- ❖ Averages (maybe)

❖ “Con”s

- ❖ Assumptions (stationery, well-mixed, etc.)
- ❖ No time-series data (to understand system)
- ❖ Dependent on many calibrations

Do We Know How Good It Is?

❖ **No comparative studies in literature!**

❖ **Some experimental errors evaluated**

- ❖ Calibration: analyzers and emitters
- ❖ Repeatability: blanks and duplicates

❖ **Key systematic errors ignored**

- ❖ Well-mixed assumption
- ❖ Stationary assumption

❖ **We set out to answer this question.**

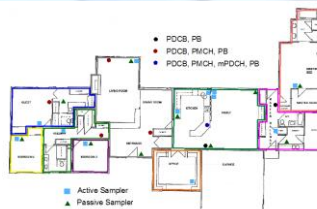
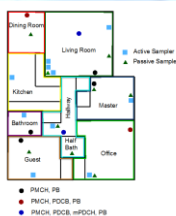
- ❖ Experimentally and theoretically

Experimental Approach

- ❖ **Oversample, oversample, oversample**
 - ❖ In time and space
- ❖ **Use research-grade techniques**
 - ❖ High precision & accuracy equipment
 - ❖ Well-characterized experiments
- ❖ **Multiple, overlapping experiments**
 - ❖ 4 simultaneous tracers deployed differently
- ❖ **Different weather; different buildings**
 - ❖ Wind effect, stack effect, etc.

3 Houses; Many Configurations

- ❖ **Houses: Compact, ranch, 3-story**
- ❖ **Central Fan: Off, intermittent, on**
- ❖ **Emitters: Spread, selected, concentrated**
- ❖ **Economizer on house 2 (ranch)**
- ❖ **Range-hood test on house 3 (3-story)**
- ❖ **Windows open vs. closed**



Emitters were made to be constant



- Individually made
- Lab Calibrated
- Temperature Controlled
- Weighed Daily
- Continually monitored
- 3-day tests typical

10-12 Samplers in Dwelling

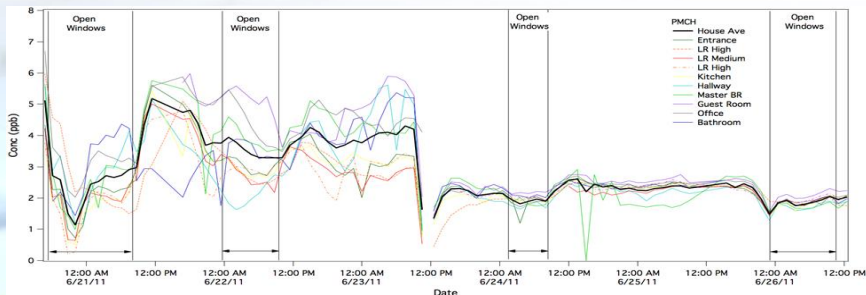


- Active: 1-3 hour averages
 - Samples stored in multiple bags
- Standard tubes as well



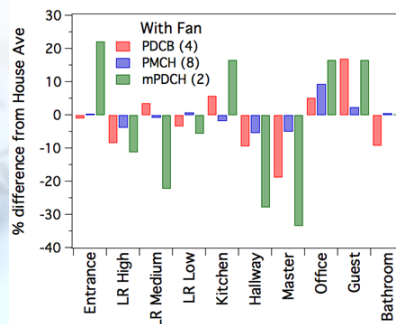
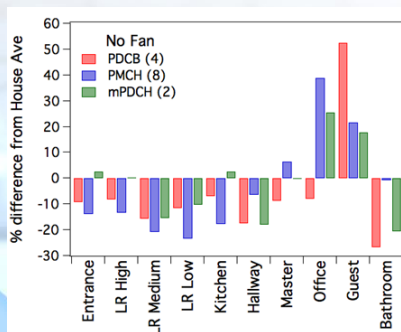
Time Series in "Good" house

- ❖ For 1 tracer: others similar
- ❖ Sometimes zones are very different



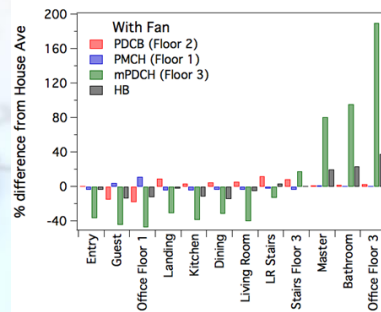
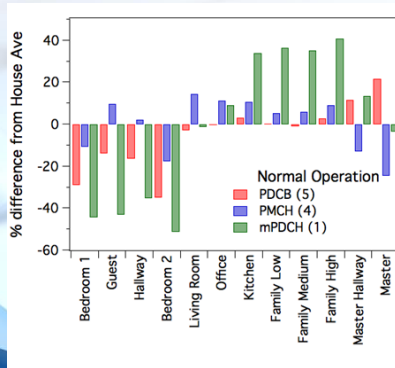
Spatial Concentrations By Gas

- ❖ 3-day averages: w & w/o mixing
- ❖ % differences from global mean



Wind & Stack Makes It Worse

- ❖ Central HVAC operating
- ❖ Houses 2 & 3



But What Does That Mean?

- ❖ **Does all that variation average out?**
 - ❖ People seem to assume so
- ❖ **Do zonal difference matter?**
 - ❖ People seem to assume not
- ❖ **Need proper error analysis**
 - ❖ Then compare with data

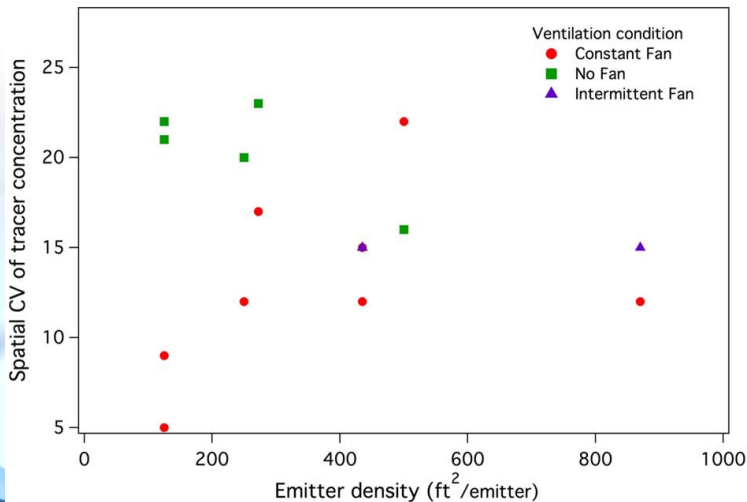
Theoretical Analysis of Errors

- ❖ Standard analysis assumes well-mixed, single-zone, steady-state, stationary.
- ❖ We used dynamic, multizone model
- ❖ Found error terms one normally expects
- ❖ PLUS RMS Concentration error term

$$\sqrt{N_{zones}} \frac{\delta C_{rms}}{C_{ave}}$$

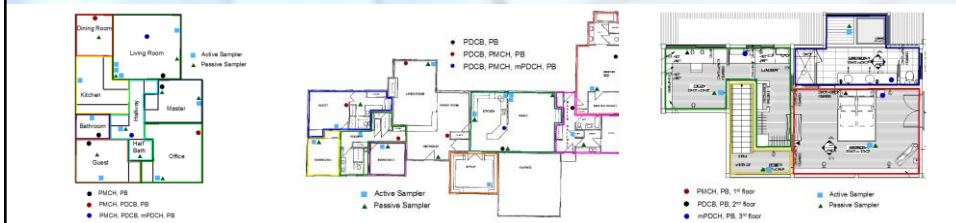
- ❖ Which can be bigger than all the rest!

How big is that % RMS Variation?



Now for Air Change Rate Estimates

- ❖ Houses: Compact, ranch, 3-story
- ❖ Central Fan: Off, intermittent, on
- ❖ Emitters: Spread, selected, concentrated
- ❖ Economizer on house 2 (ranch)
- ❖ Range-hood test on house 3 (3-story)
- ❖ Windows open vs. closed



House 1: simple floor plan

	# of emitters	No Fan			Continuous Fan		
		ACH (hr-1)	Spatial CV (%)	Error (%)	ACH (hr-1)	Spatial CV (%)	Error (%)
Tracer 1	4	0.48	20	41	0.81	12	25
Tracer 2	8	0.47	21	42	0.76	5	12
Tracer 3	2	0.60	16	33	1.23	22	44
Tracer 4	8	0.43	22	44	0.62	9	19
Average		0.5 ± 13%	20 ± 12%	40	0.87 ± 29%	12 ± 52%	25

House 2: Ranch Style-Wind bias

		Normal Operation			Continuous Fan			With Economizer		
	# emit	ACH (hr-1)	CV (%)	Error (%)	ACH (hr-1)	CV (%)	Error (%)	ACH (hr-1)	CV (%)	Error (%)
Tracer 1	8	0.29	15	46	0.46	12	37	0.301	21	63
Tracer 2	4	0.27	15	46	0.39	12	37	0.282	10	31
Tracer 3	1	0.31	28	84	0.45	22	66	0.305	24	72
Tracer 4	8	0.24	15	46	0.37	15	45	0.253	25	75
Ave		0.27± 10%	18± 30%	55	0.42± 9%	15± 27%	46	0.29± 7%	20± 30%	60

House 3: Stack Dominated

	# emit	Floor	No Fan			No Fan w Exhaust			Cont Fan w Exhaust			Continuous Fan		
			ACH (hr-1)	CV (%)	Error (%)	ACH (hr-1)	CV (%)	Error (%)	ACH (hr-1)	CV (%)	Error (%)	ACH (hr-1)	CV (%)	Error (%)
Tracer 1	3	1	0.41	54	93	1.01	81	142	0.59	19	33	0.32	10	17
Tracer 2	3	2	0.26	27	47	0.63	111	192	0.47	29	50	0.32	5	9
Tracer 3	3	3	1.30	122	211	0.54	196	339	0.62	146	253	0.98	72	125
Tracer 4	9	All	0.26	23	41	0.26	68	118	0.35	62	107	0.30	17	29
Ave			0.56± 78%	57± 70%	98	0.52 ± 59%	114 ± 44%	197	0.51 ± 21%	64± 78%	111	0.48 ± 60%	26± 103%	45

Our Experiments

- ❖ **Minimized all sources of error**
- ❖ **Could achieve 20% concentration variation**
 - ❖ When emitters used wisely
- ❖ **Could get 10-30% repeatability**
 - ❖ When emitters used wisely
- ❖ **But 40-50% systematic error**
 - ❖ When emitters used wisely

Spatial Take-Aways

- ❖ **Use Emitters Wisely!**
 - ❖ Unfortunately you can't unless you know the answer
 - ❖ More is not always better unless good mixing
- ❖ **Research-Grade Testing: 50% Uncertainty**
 - ❖ But there are better research-grade approaches
- ❖ **Field-Study-Grade Testing: Factor of 2**
 - ❖ Is that good enough for your purposes?
 - ❖ If not, consider alternatives

Temporal Take-Aways

- ❖ **Make sure experiment is not too short**
 - ❖ Technique assumes concentration is in equilibrium
- ❖ **Make sure experiment is not too long**
 - ❖ Technique assume air change does not change
- ❖ **Make sure temperature does not change**
 - ❖ Emitters are temperature sensitive
- ❖ **Make sure mixing is more than ACH**
 - ❖ Open windows are problematic

To Get The Most Out of CILTS

- ❖ **Steady-state system**
 - ❖ You don't get average, you get bias
- ❖ **Inject proportional to local infiltration**
 - ❖ With as much homogenization as you can get
- ❖ **Sample proportional to local exfiltration**
 - ❖ Average concentration is not what you want
- ❖ **Know the answer before you measure**

What about Multizone Multitracer?

- ❖ **Can reduce bias from zonal assumption**
- ❖ **Can provide inter-zonal flows**
- ❖ **Introduces new error sources**
 - ❖ Low signal-to-noise
 - ❖ Relative calibration biases
 - ❖ Longer equilibration times
- ❖ **Needs similar investigation**
 - ❖ To understand balance

