Vapor Intrusion:
Lessons from Radon Studies

FRTR Meeting

Crystal City, VA

November 10, 2009

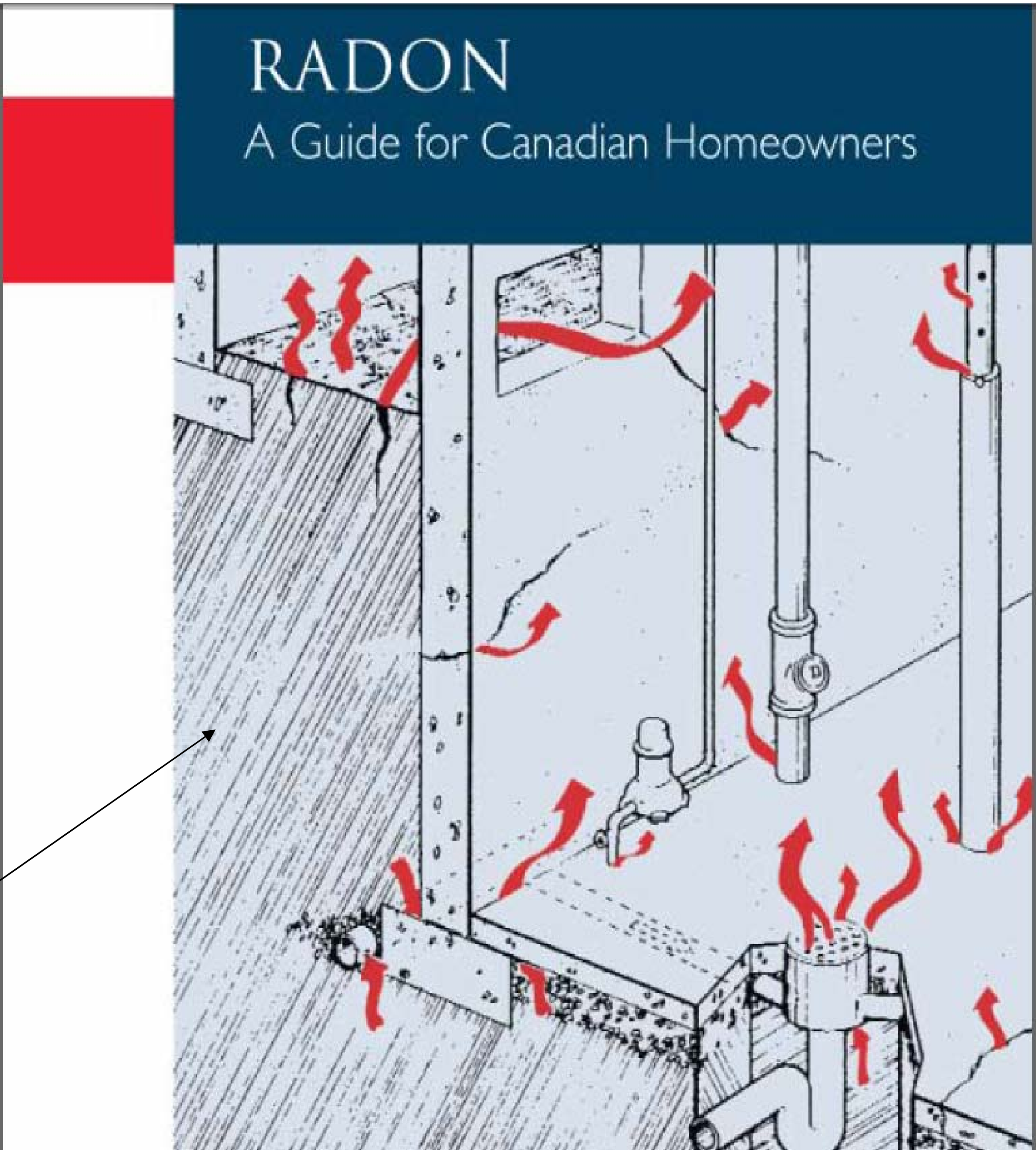
Presented by:

Henry Schuver, DrPH

USEPA – Office of Resource Conservation & Recovery

See: http://iavi.rti.org & www.envirogroup.com/vaporintrusion

Radon workers are ahead of us



Samples out here can't reflect building features, or atmospheric effects

Using Radon Studies to Improve our Understanding of Vapor Intrusion

- Radon intrusion is analogous to chemical Vapor Intrusion (VI) (Mosley 2004; Mosley 2007, McHugh 2008)
  - Long history of Radon studies
    - >30 yrs of global effort (EPA a leader in 1980s - 90s)
    - 1000s of researchers & papers & studies continue:
    - Can to break the topic into three types of studies:
    - **1) *External*-based Studies**
    - **2) *Indoor* Air-based Studies**
    - **3) *Health* Outcome-based Studies**

<u>External</u>-based **Radon** Studies Overview

- Despite initial presumptions of predictability based on external data ('85)

- > 20 yrs later:

  – We are continuing to study and model the
  – "<u>great number of parameters and processes</u>"
  – affecting radon in indoor air (Font 2003)

VI Factors studied 1

Factor	**Radon VI Ref.***	***Chemical VI Ref.***
Diffusion-based transport	Tanner 1964	
Energy conservation, reduced ventilation	Budnitz 1979	
Radium (source) Concentration & Distribution, Soil:	Tanner 1980	
Porosity, Permeability, Moisture, Meteorological	Tanner 1980	
Rainfall & surface saturation capping effect	Schery 1984	
Crawlspaces (>50% enters house)	Nazaroff 1985	
Convective-based transport	Sextro 1987	
Building Construction, Stack Effect, Wind	Nazaroff 1987,88	
Season	Borak 1989	*Kuehster 2004*
Soil Temperature	Washington 1990	
Heavy rain	Mose 1991	*Lundegard 2008*
Convective air flow in **Karst** geology	Wilson 1991	
Depth to (chemical) Source		Johnson 1991
Modifications in Bldg. structure	Steck 1992	
Minor modifications to heating systems	Steck 1992	
Heat distrib. Type	Klotz, 1993	
Bldg. Age (of construction)	Klotz, 1993	
Soil classification, Bedrock type, Water table depth	Steck 1996	
Bldg Basement or not	Price 1996	
Rate-of-change in Atmospheric Press. Fluctuations	Robinson 1997	

VI Factors studied 2

Factor	**Radon VI Ref.***	***Chemical VI Ref.***
• Atmospheric Press. Fluctuations & Soil Properties	Robinson 1997	
• Soil response time, Soil capacitance	Robinson 1997	
• Bldg Heating type: fire or elec.	Mose 1997	
• Bldg. Concrete poured or block, **home use patterns**	Mose 1997	
• Living Habits	Miles 1998	
• Independent heat (vs. shared apt.)	Gallelli 1998	
• Type of **window frames & # panes**, Bldg. Story level	Gallelli 1998	
• Local geology, Superficial cover	Miles 1998	
• Air/barometric pressure, **wind direction**	Riley 1999	
• **Fluctuation** in wind **direction**, Wind speed	Riley 1999	
• **Fluctuation** in wind **speed**, Wind (loading)	Riley 1999	
• HVAC/Ventilation systems (installed, & operations)	Riley 1999	
• Combined Surface Geology, Topo. & Wind Direction	Keskikuru 2000	
• Soil-gas pressure (wind induced)	Keskikuru 2000	
• Indoor-Attic space	Keskikuru 2000	
• Soil-indoor pressure difference	Font 2001	
• **Frozen soil** as cover (temp. & water)	Winkler 2001	*Mickunas 2007*
• Saturated soil as cover (Summer)	Winkler 2001	
• Sunshine duration, Snow cover, **fuel prices** (insulation)	Papp 2001	

VI Factors studied 3

Factor	**Radon VI Ref.***	***Chemical VI Ref.***
Outdoor air **temperature** (alone)	Marley 2001	
Water vapour pressure	Marley 2001	
Maximum variation Outdoor Temperature	Rowe 2002	*Lundegard '08*
Weather fronts, Occupied bldg or not	Rowe 2002	
Substructure type, Cellar ventilation	Wang 2002	
Increased Energy Efficiency	Darby 2005	
Building as cover (capping **flux**)		*Abreu 2005*
Building as cover (**decreased moisture underneath**)		*Tillman 2007*
Stable **rural vs. recently urbanized**	Zunic 2007	
Combined effects of contrast in Outdoor & Soil Air …		
Temperature (Gas density-driven flow) in setting w/ …		
coarse surface geology & terrain elevation	Sundal 2008	
Chemical properties, Degradation (bio+)		*Lundegard '08*
Oxygen content, Oxygen & Distance		*Lundegard '08*

External-based Studies

- Can ***not*** represent:

- 1) the influence of building factors
  - – e.g., open staircases to upper floors (Makelainen 2001)
  - – e.g., modest structural changes (Steck 2007)
- 2) the interaction of the building with meteorology (the entry driving forces)
- 3) the influence of occupant behaviors
  - – e.g., sleeping with windows open (Makelainen 2001)
    - » Also, Mose (1997), Miles (1998), Krewski (2005)

Steck 2007

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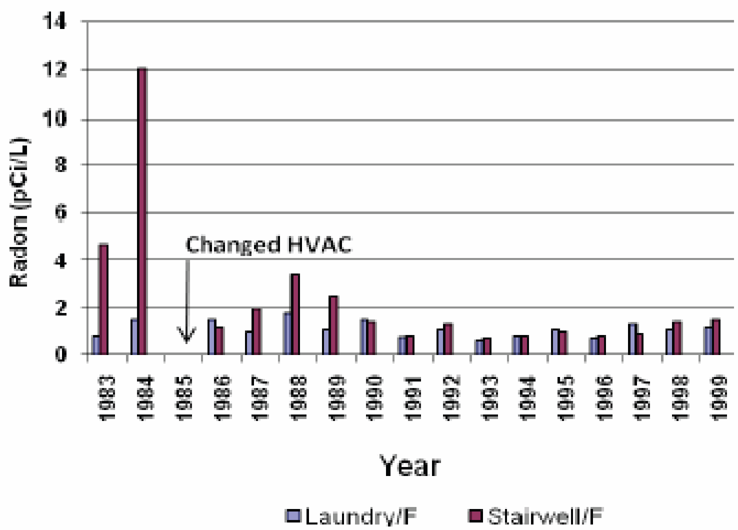


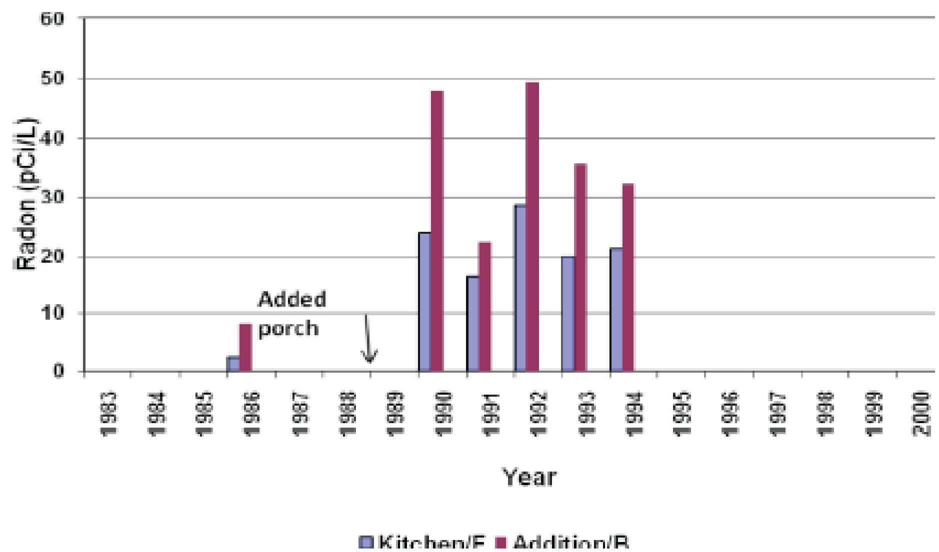


Figure 4 Examples of large radon changes created by house modifications

http://www.aarst.org/proceedings/2007/8-SteckYTYRnvariation07.pdf

Conclusion from 30 yrs of Study

- When assessing indoor levels (#) in **individual** buildings:
  - Radon intrusion studies have only reinforced the advantages and **necessity** of testing **indoor air**
    - e.g., look to EPA's experiences & 1994 decision

Lessons from Radon Studies cont.

– "The U.S. Surgeon General and EPA recommend that all homes be ***tested***" (http://www.epa.gov/radon/).

  – **Not modeled** or **estimated from exterior** measurements

- The rigorous *scientific* analyses of *both high and low* indoor air sample screening results have revealed the full nature of the now well-documented *confidence intervals* surrounding radon screening results (relative to year-long results) even when using multi-day-long indoor air sample durations.

- Awareness of these radon study results can *save* years of VI workers *re-learning* these lessons and accelerate the appreciation of the uncertainties in typical VI screening results.

Indoor-Air-based **Radon** Studies Overview

- **Only Indoor Air Integrates:**
  - Three major categories of VI variables:
    - Sub-surface (source & migration) factors
    - Building factors
    - Above-ground environmental factors
- **Variability** in indoor air reflects **cumulative variability** in:
    - Sub-surface (source & migration) factors
    - Building factors
    - Above-ground environmental factors
  - Variability is primarily Temporal

Summary of Indoor Radon Conc.

(pCi/L)

Steck ≤ 2004 (Minn.)

Sample	Factor	M-M Range	Avg.	Period
Hour	10x	<1 to 10	3.8	1st 3 mo. '95
2-Day	4x	1 to 6	3.8	1st 3 mo. '95
Week	2.5x	2 to 5	3.8	1st 3 mo. '95
Month	30x	<.3 to 10	3.5	**6 yr.** '88-93
Year	2.1x	2.2 to 4.6	3.55	15 yr. '83-98

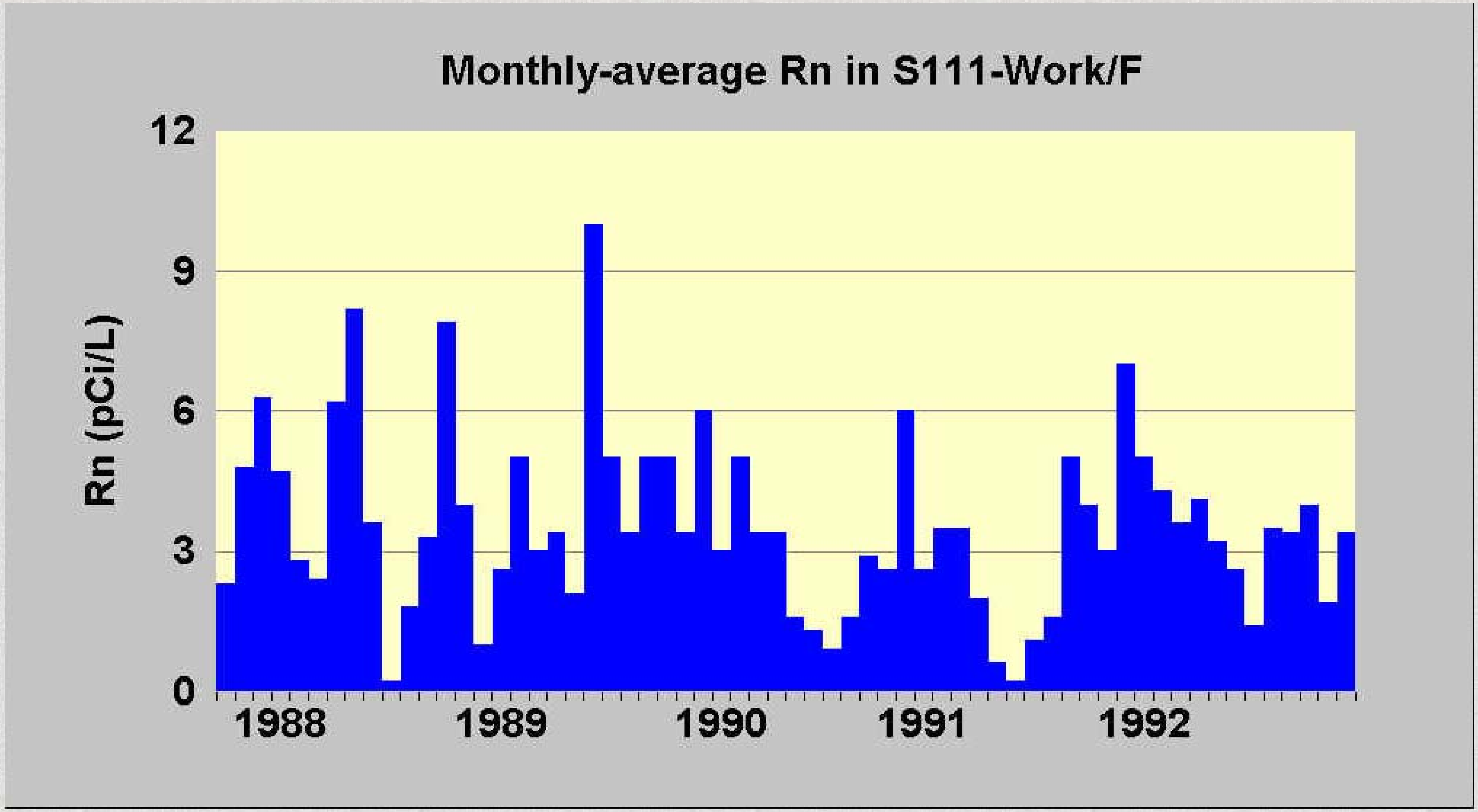
- Yr. Avg. from 100 homes vary 25% (e.g., 4 ~ 3 to 5 (+/- 1) pCi/L)

Steck ≤ 2004

http://www.csbsju.edu/MNradon/indoor_radon_variation_over_time.htm

Month-to-month

Here is a graph of the monthly average radon in a house for the period from the beginning of January 1988 to January 1993. Note that the average radon concentration ranged from a high of 10 pCi/L to less than 1 pCi/L. The true average over the period was 3.5 pCi/L. Even a month-long measurement can be quite far from the long-term average.



If you analyze this graph for seasonal variation, you will find the highest readings in spring and fall, with summer being the lowest. Spring and fall are seasons of active weather at this site that often requires that the house be closed and heated. heating

STUDIES ON TEMPORAL VARIATIONS OF RADON IN SWEDISH SINGLE-FAMILY HOUSES

Lynn Marie Hubbard, Hans Mellander, and Gun Astri Swedjemark
Swedish Radiation Protection Institute, S-171 16 Stockholm, Sweden

Environment International, Vol. 22, Suppl. 1, pp. S715–S722, 1996

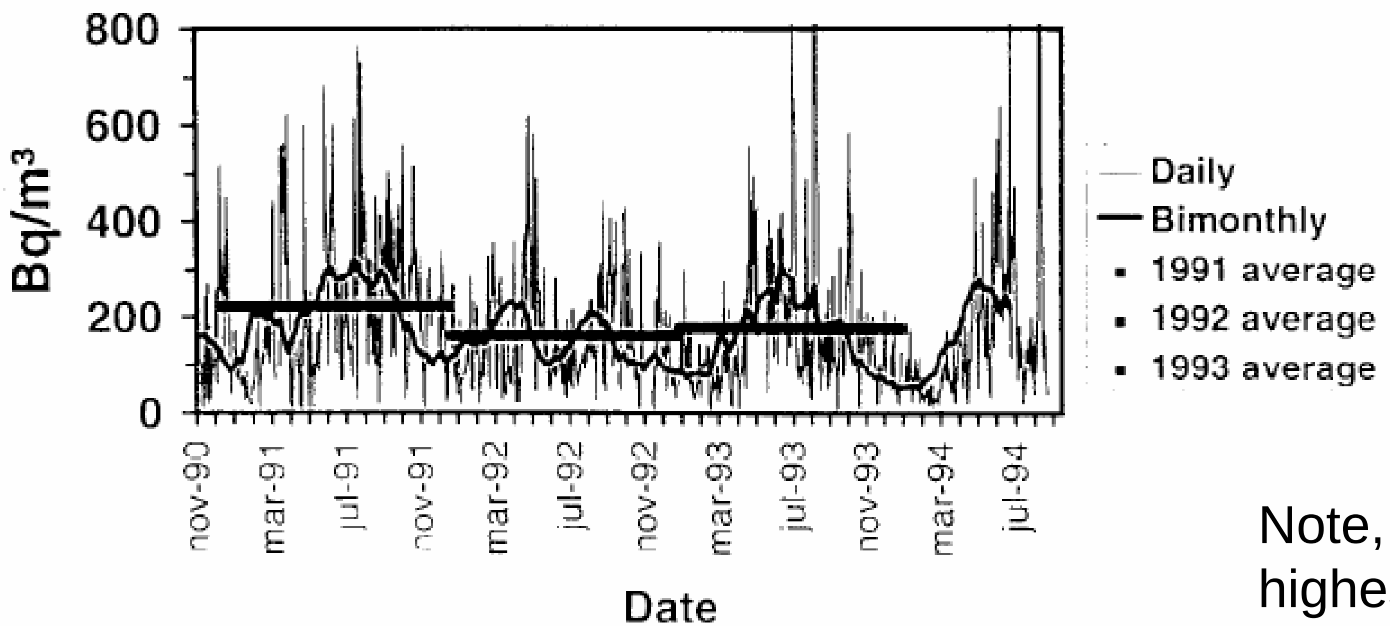


Fig. 1. Daily, bimonthly, and yearly averaged indoor radon concentration.

Note, highest in spring & fall

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Summary of Radon Conc. (Bq/m^3) Hubbard et al. 1996 (Sweden)

Sample	Factor	Range	Avg.	Period
Year	1.3x	180 to 230	-	4 yr. '90-94
2-Week	4.3x	70 to 300	yr.	4 yr. '90-94
1-Day	100x	~8 to 800	yr.	4 yr. '90-94

- ~ four year period Nov. 1990 – July 1994

Folkes et al., 2009
1-Day samples (chemicals)

- Using 715 indoor air samples of 1,1-DCE collected over ***24-hrs*** found variations to range from 45 unmitigated (low conc.) homes from quarterly to annual frequencies for 2 to 10 years
  - "The [indoor air] normalized [by property annual average conc.] values ranged [max.-min.] from about *10%* … to about *ten times* the *annual average* of the home"
    - 100% of samples w/n **+/-** 10x of the home's annual mean
      - **Range of variation = 100x**
    - 68% of samples w/n **+/-** 2 to 3x of the homes annual mean
      - **Range of variation = 4 to 9x**
  - "Short term variability can overwhelm any seasonal trend" [very similar to comment by Rowe '02]

Multiple (**2-Day**) Sample Events White et al. (1994)

- Collected measurements of indoor radon in 480 houses in 11 states for over one year:
  - Relative to a concurrent one-year measurement (for a Annual Living Area Average (ALAA)) they found:

Events	95% CI	Comp. Period	Example; CI = Confidence Interval
1 season	+/-2.5 (6)x ALAA	1 yr	If 100 Bq/m^3; 95% CI = **40-250**
2 seasons	+/-2.2 (5)x ALAA	1 yr	If 100 Bq/m^3; 95% CI = **45-220**
4 seasons	+/-2.0 (4)x ALAA	1 yr	If 100 Bq/m^3; 95% CI = **50-200**

  - If more precision (less than a factor of +/-2.0x) is required then an:
    - "alternative procedure to using short-term measurements for estimating ALAA should be employed" e.g., **year-long samples**

Steck 2005

Residential Radon Risk Assessment: How well is it working in a high radon region?

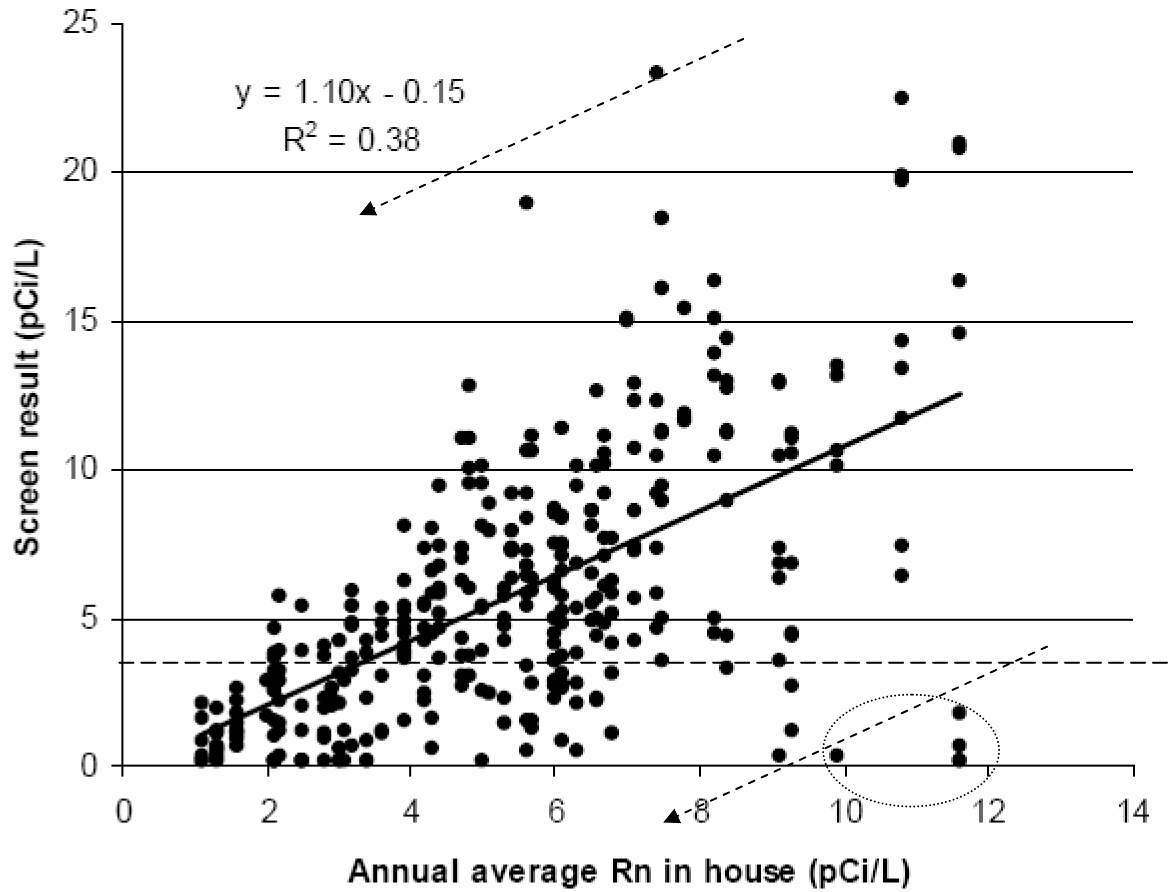

Figure 3. Linear regression between ST screening measurements and the annual average radon in the house (one high radon house is not shown) in the Temporal survey

Note – vast majority (~95%) w/n +/- 3x of annual avg.

(see added dashed lines)

Steck 2005

- Longer duration samples are less variable

Table 3. Comparative variations of different averaging periods and operating conditions at the primary measurement site in the Temporal survey

Measurement Type: House conditions	COV about the annual average[1]
Two day: closed	76%
Four day: closed	70%
Monthly: normal	40%
Seasonal (90 day) average: normal	25%
Semi-annual average: normal	17%

[1] Corrected for instrumental variation

COV = Coefficient of Variation = (1 std. dev. / mean)

Steck 2007

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Typical year to year radon variation (COVs ~25%)
at sites in a low, medium, and high radon home

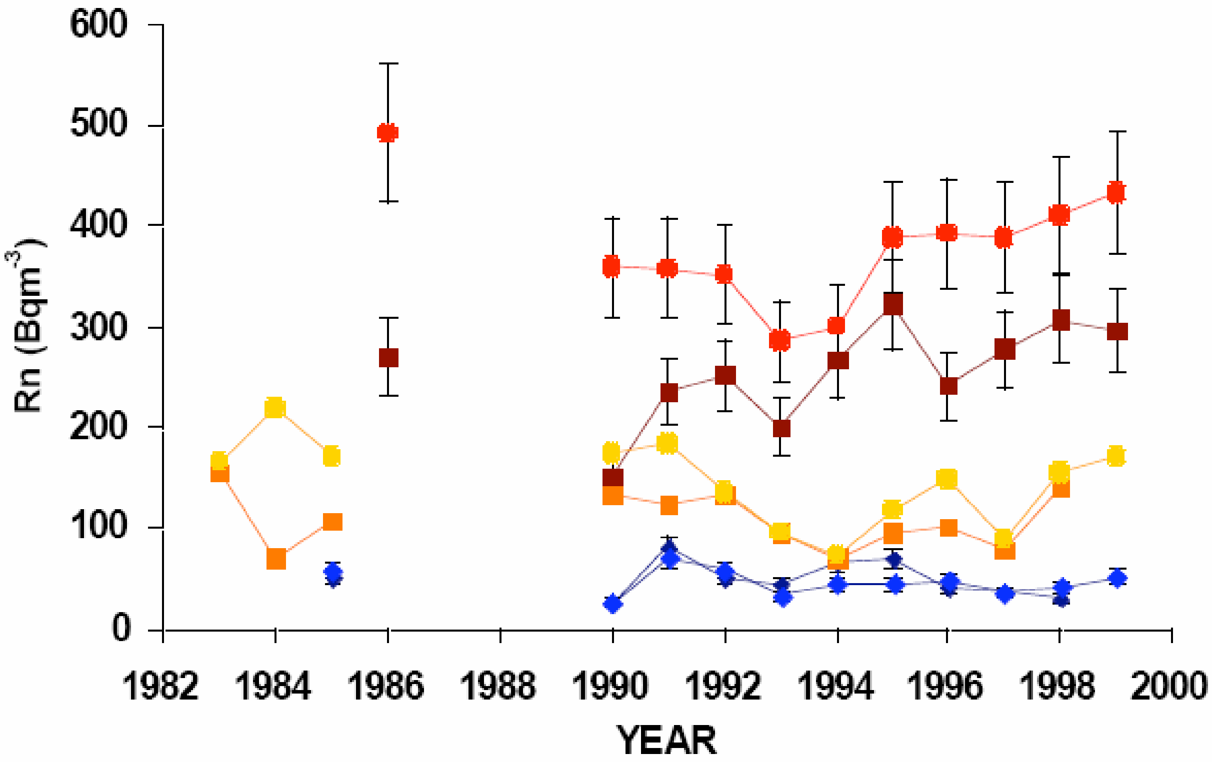


Figure 2 Sample year-to-year radon changes in houses without persistent trends and median COVs.

http://www.aarst.org/proceedings/2007/8-SteckYTYRnvariation07.pdf

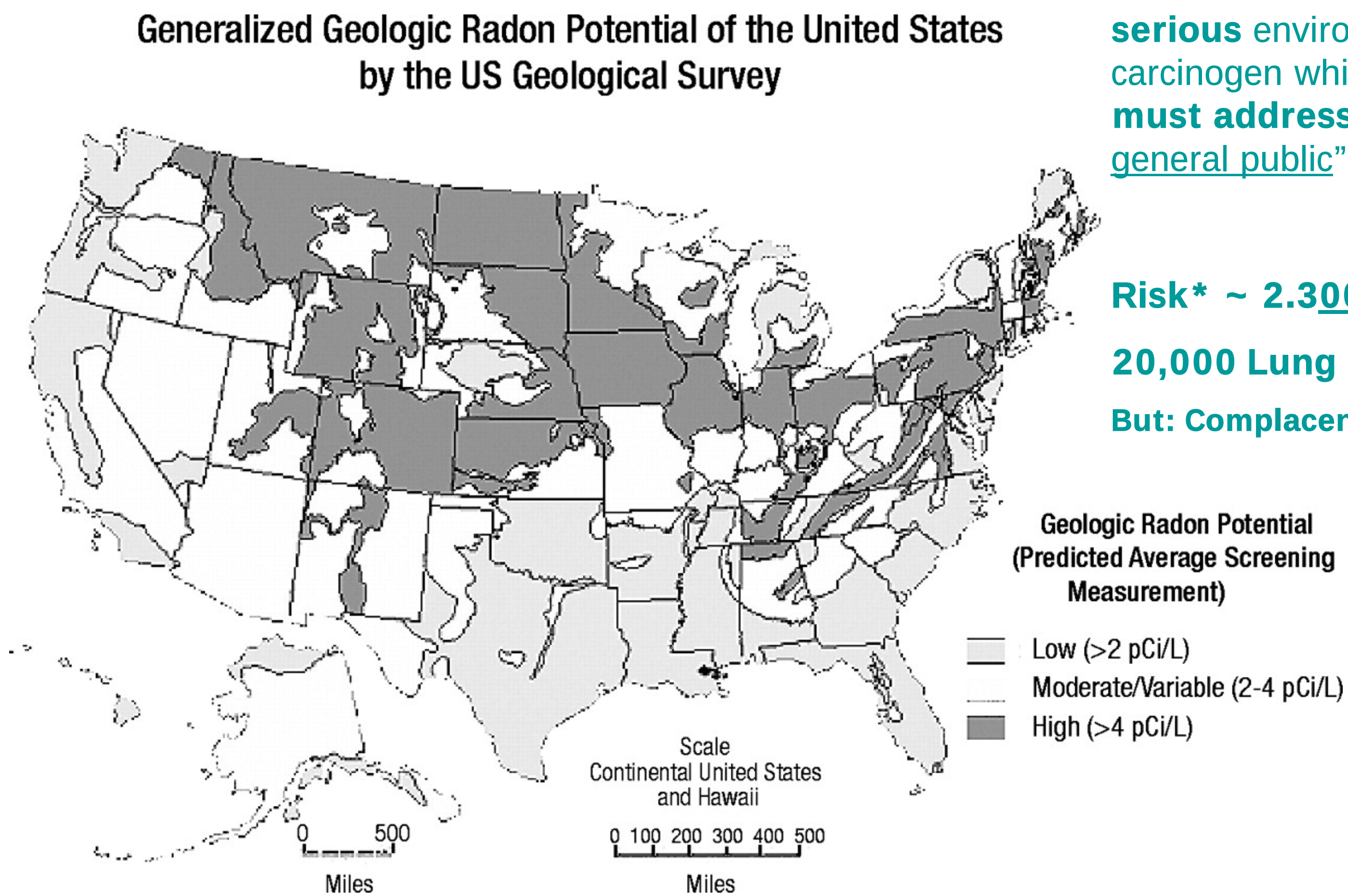
Are chemicals more predictable?

- Little evidence to indicate chemical vapor intrusion is any more predictable than radon.
  - In fact, some features suggest chemical VI prediction may be even more difficult; such as:

  - 1) Spatial heterogeneity of the chemical contaminant source zones
    - (e.g., large areas with 0 conc.) vs. radon is almost everywhere
  - 2) Temporally varying horizontal extent of a mobile source plume
    - (e.g., vapor or groundwater plume hor. & vert. migration)
  - 3) Transient vertical (non-equilibrium) delay from a new location
    - (prior to equilibrium being established to surface)
  - 4) Temporally varying concentration at a given point w/n plume
    - (e.g., 10x pulses w/n GW in Redfield, Folkes et al. 2009)
  - 5) Variable degradation rates
    - Less (Chloro-) to More (petroleum) and constant for Rn
  - 6) Chemicals influenced by deeper geology than 3 Rn ½ lifes

RADON

FIGURE 1



EPA's Perspective on Risks from Residential Radon Exposure

"Indoor **radon** ... **the most serious** environmental carcinogen which the **EPA must address** for the general public" Puskin 1989

Risk* ~ 2.3000 % (4pCi/L)

20,000 Lung Cancers/yr

But: Complacency & Costs

Jalbert, 2004

* adult cancer

From Frumkin, H. et al.
CA Cancer J Clin 2001;51:337-344.

The same VI pathway

Real 'background' for chemical VI

Chemically exposed get **both**

CA
A Cancer Journal for Clinicians

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Summary of Lessons from Radon Studies we could use to Improve our Understanding of Vapor Intrusion

- Lessons from the three types of Radon studies:
  - **1) *External*-based Studies**
    - If you want to know what is in indoor air, you measure indoor air
  - **2) *Indoor* Air-based Studies**
    - The longer you measure indoor air the better
  - **3) *Health* Outcome-based Studies**
    - Radon is a significant health risk & actions reducing it may be the most important health decisions we will ever make