Vapor Intrusion – Applied Mitigation Theory

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Providence, RI and Chelmsford, MA
June 11 and 12, 2007

Outline for Presentation

- Active and Passive Mitigation
  - Active
    - Principles of Design
    - case study
  - Passive Systems and Barriers:
    - Passive Stack Mitigation
      - Sealing
      - Liquid Boot® Geovent
    - Passive Barriers
      - Spray-applied rubberized membranes (e.g., Liquid Boot®)
  - Performance Assessment

Planning Mitigation: things to consider

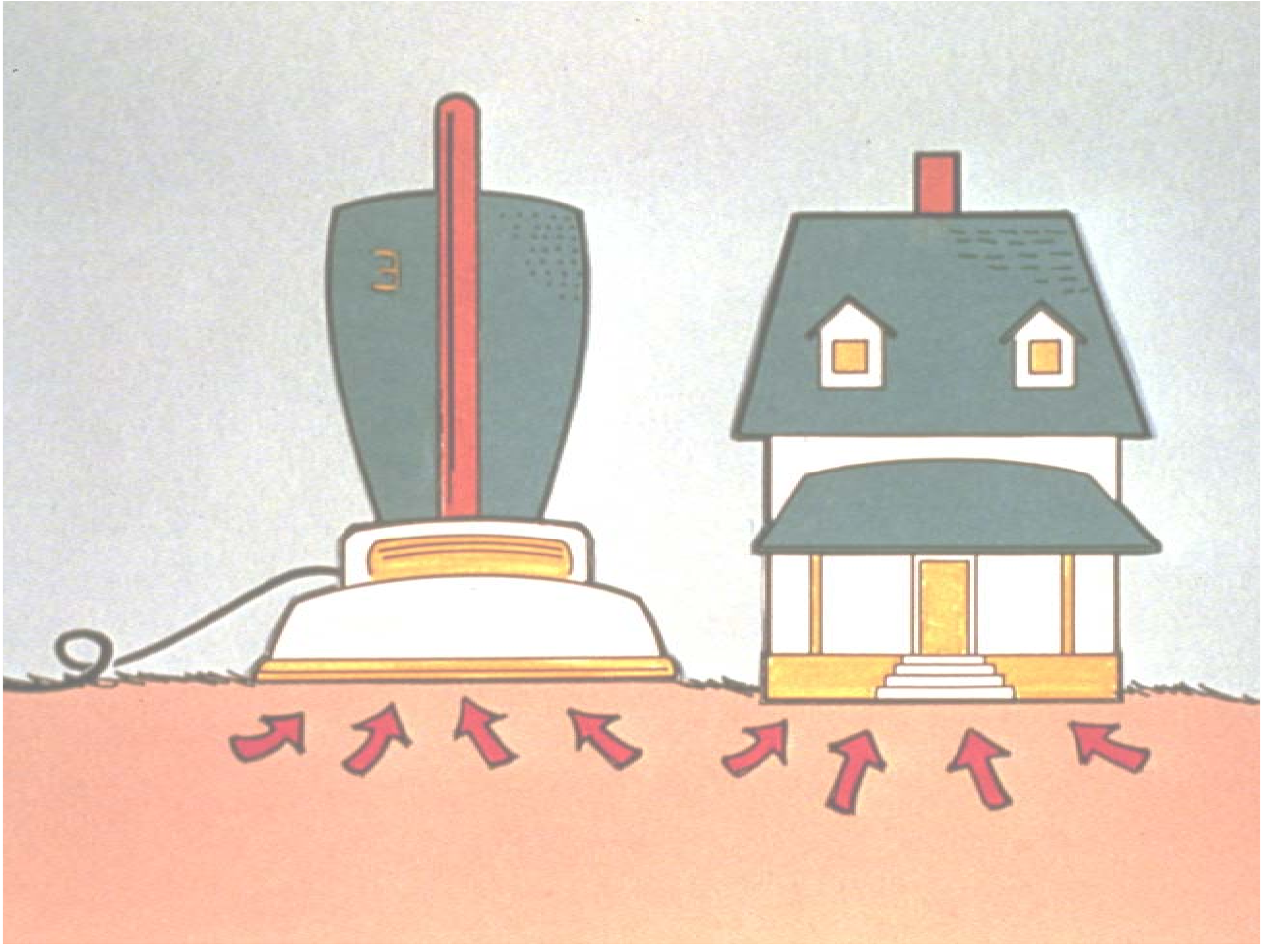
Some things to think about up front:

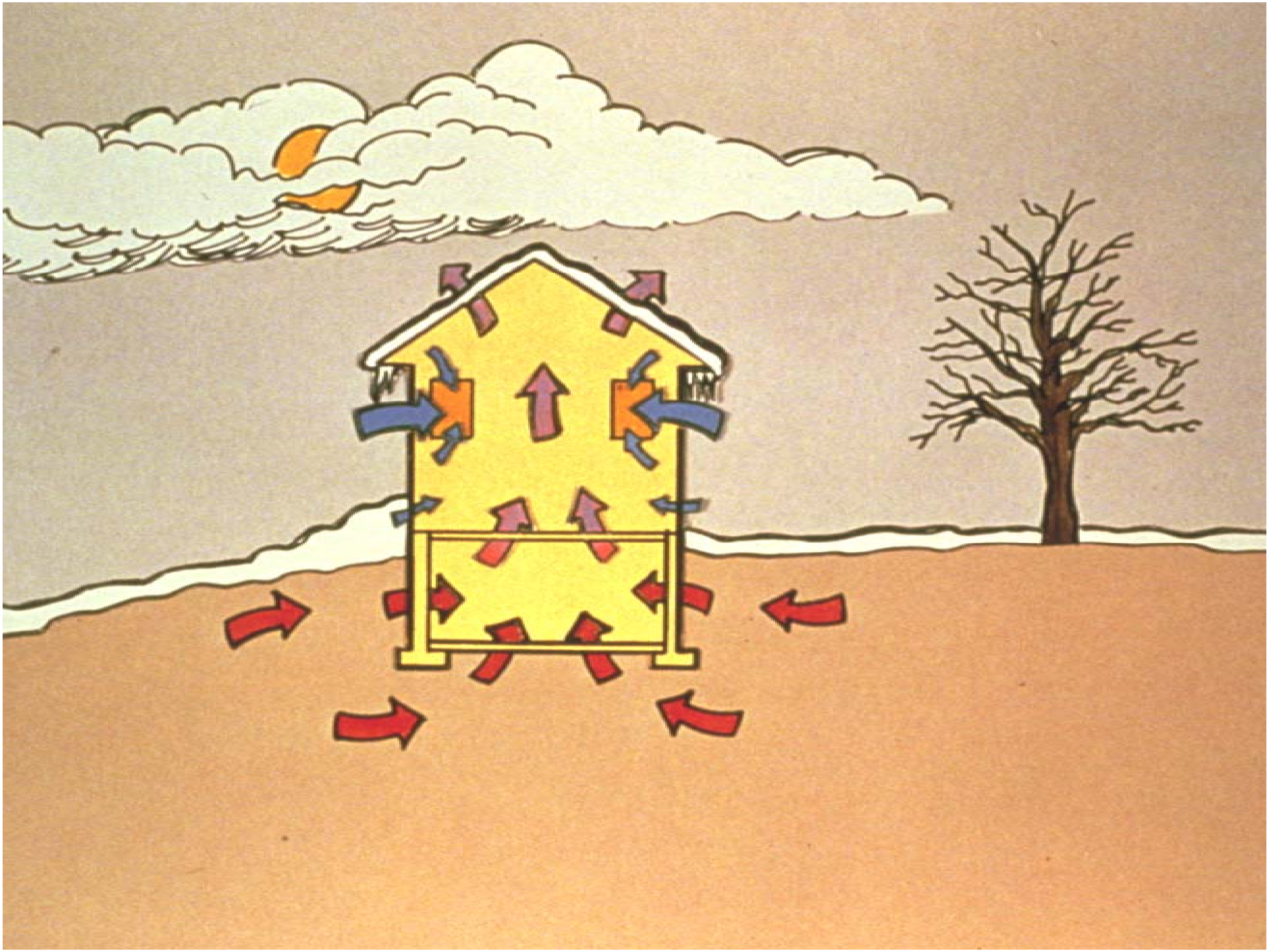
- Phased or Full-Scale Implementation
- **_Active or Passive Mitigation_**
- Engineered Design or Radon Contractor
- New or Old Construction
- Cost
- **_Monitoring and Performance Assessment_**
  - Installation
  - Startup
  - Monitoring: when, for what and how / where?
  - Maintenance
  - Addn: Dovetail Characterization into Performance?
- Reporting
- **_Community relations with homeowners:_**
  - avoid precedent-setting cost increases (e.g., new concrete floors).
  - locating system components (e.g., stacks).
  - Is homeowner responsible for operating system?

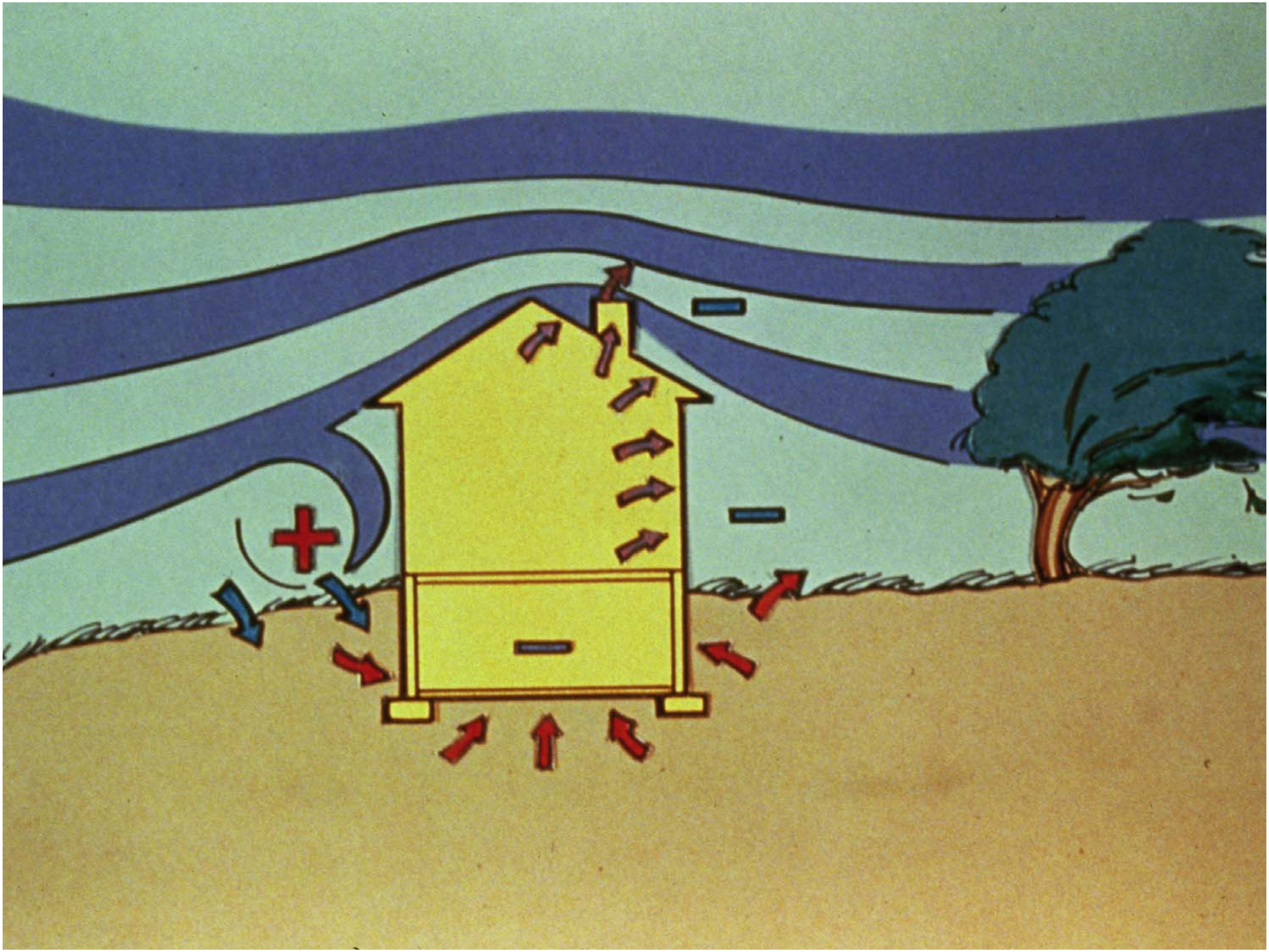
Background

For Vapor Intrusion to occur, there must be:

- Sources
- Entry paths
- Driving forces







Units of Pressure

1 Pascal (Pa) = 0.004 in.H_2O

(1 in H_2O = 248 Pa)

1 atmosphere (atm) = 101,000 Pa =

33.89 <u>ft</u> H_2O = 29.92 in Hg

Units of Pressure [cont]

Soil / Building Depressurization:

- Range of depressurization (i.e., stack effect):

  1 - 30 Pa

- **Average range of depressurization:**

  2-10 Pa → **0.008-0.04 in H_2O**

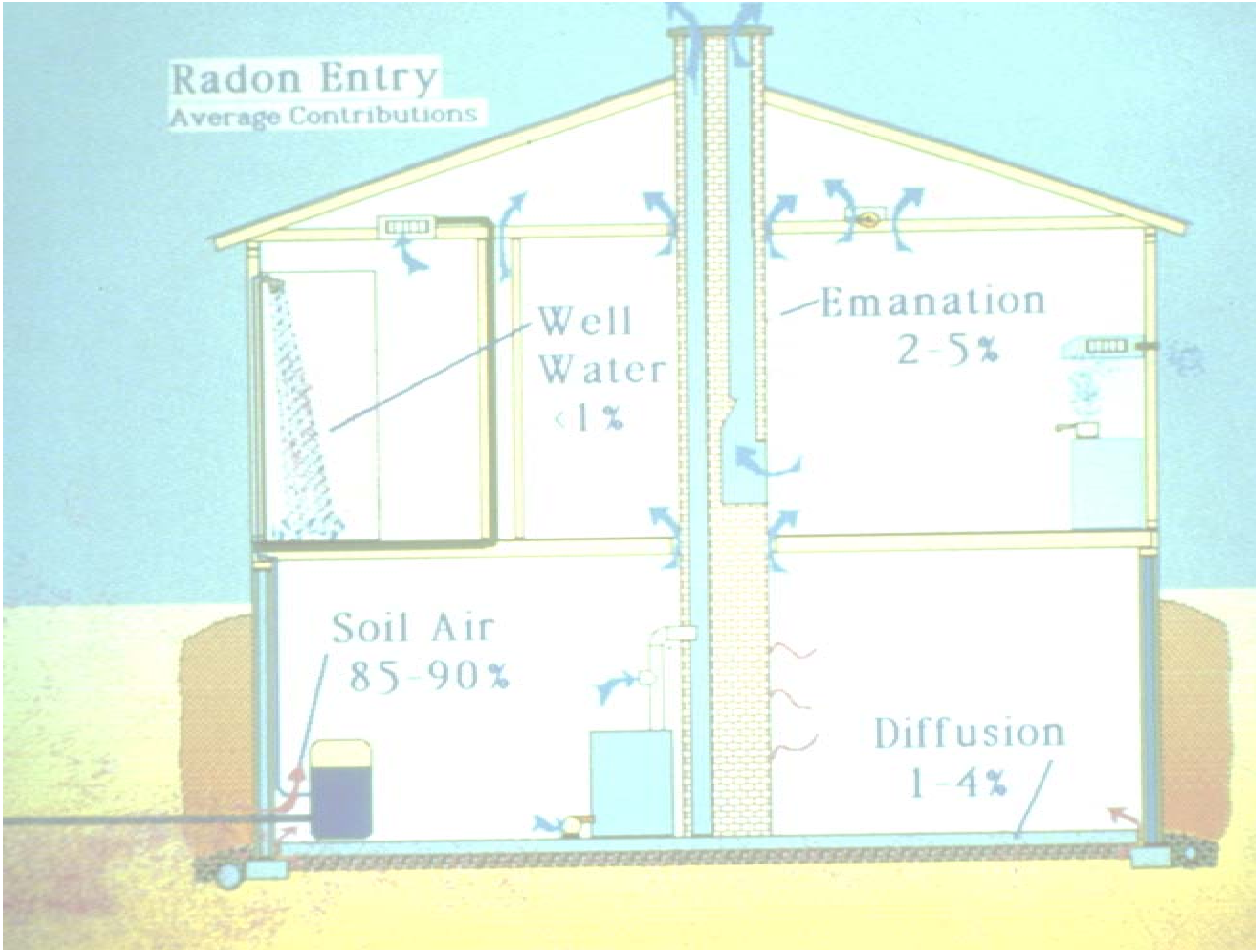
Sealing Entry Routes

To improve the performance of active and passive systems and barriers, you want to **seal entry routes** that allow soil/GW contaminants to enter.

- openings around chimney's, plumbing chases, pipes, fixtures, elevator shafts
- openings to the attic (if any)
- fireplaces, wood stoves, furnaces, clothes dryers and water heaters
- windows and exterior doors
- recessed ceiling lights (Type IC recommended)
- HVAC systems designed to avoid "depressurization"
- cracks and other openings in and around the foundation or floor slab

"A thorough job of sealing entry routes will **typically** result in a **50-70% reduction** in radon." U.S. EPA, Application of Radon Reduction Methods, August 1988, p. 62, EPA/625/5-88/024

"***EPA does not recommend the use of sealing alone to reduce radon*** *because, by itself, sealing has not been shown to lower radon levels significantly or consistently.*" U.S. EPA, Consumer's Guide to Radon Reduction at p. 9, Revised February 2003, EPA 402-K-03-002 http://www.epa.gov/radon/pubs/consguid.html


Radon Entry
Average Contributions
Well
Water
<1%
Emanation
2-5%
Soil Air
85-90%
Diffusion
1-4%

Active Systems

Mitigation Design: Active Systems

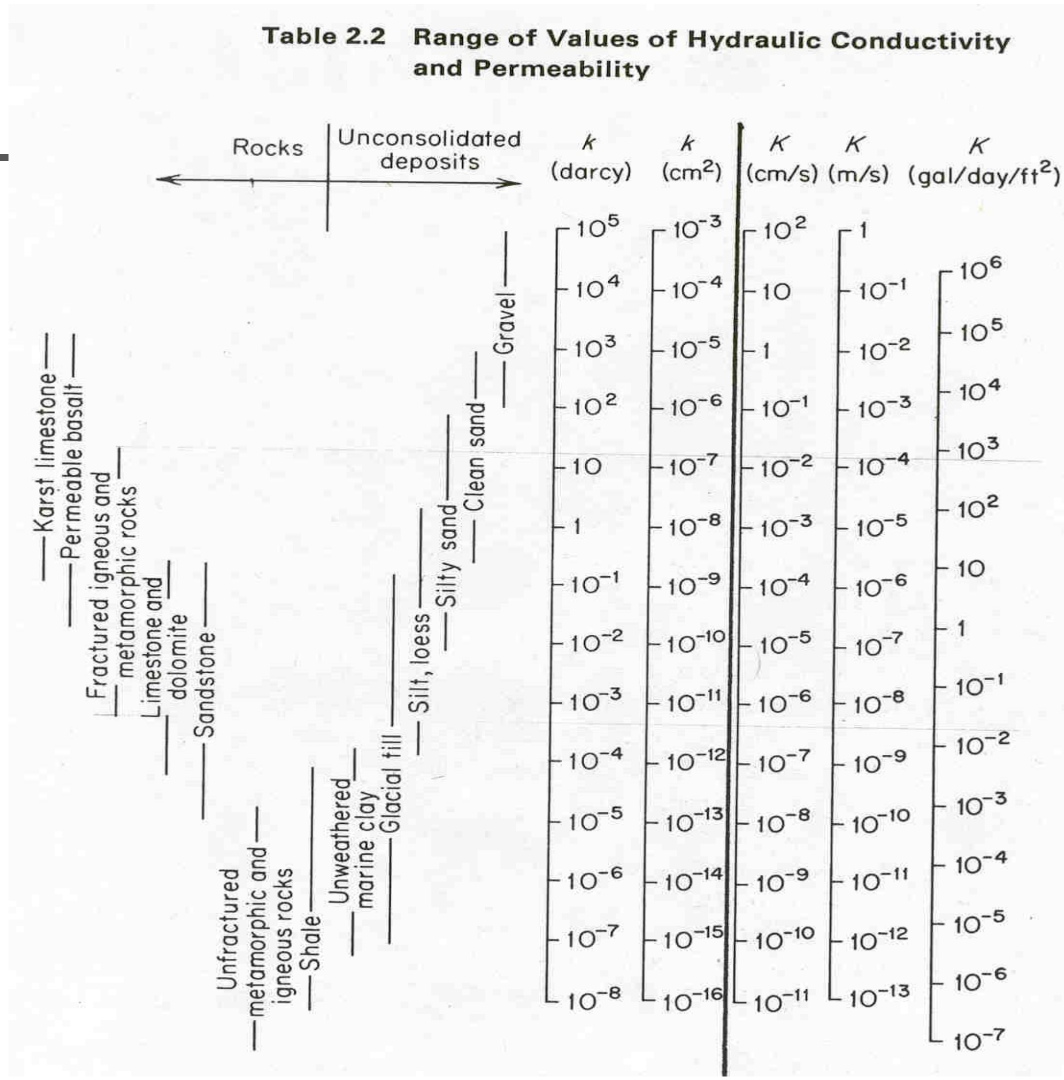
- **Pressure Field Extension (common).** Apply vacuum at a test extraction well (TEW) and measure vacuum at one or more probes installed into the sub-slab at varying radial distances from the test hole. Base full-scale design on achieving some level of sub-slab pressure distribution at a representative compliance point by varying the vacuum at the TEW during simple pump tests. Often used for SVE system design.

  May be based on:
  - U.S. EPA (1991) Handbook Sub-Slab Depressurization for Low-Permeability Fill Material: Design & Installation of a Home Radon Reduction System, and/or
  - U.S. EPA (1993) Radon Reduction Techniques for Existing Detached Houses: Technical Guidance (Third Edition) for Active Soil Depressurization Systems

- ***Air Flow Modeling* (uncommon).** Conduct pump tests similar to above but use air flow equations to translate pressure measurements into pore volume exchange rates. Used mostly for source reduction where air flow is required (e.g., SVE).

- **Result:** Base system design on depressurization. Achieve that level of sub-slab depressurization that compensates for building depressurization. The challenge will be to do so at flow rates that do not translate into over-sized systems (energy, size, noise).

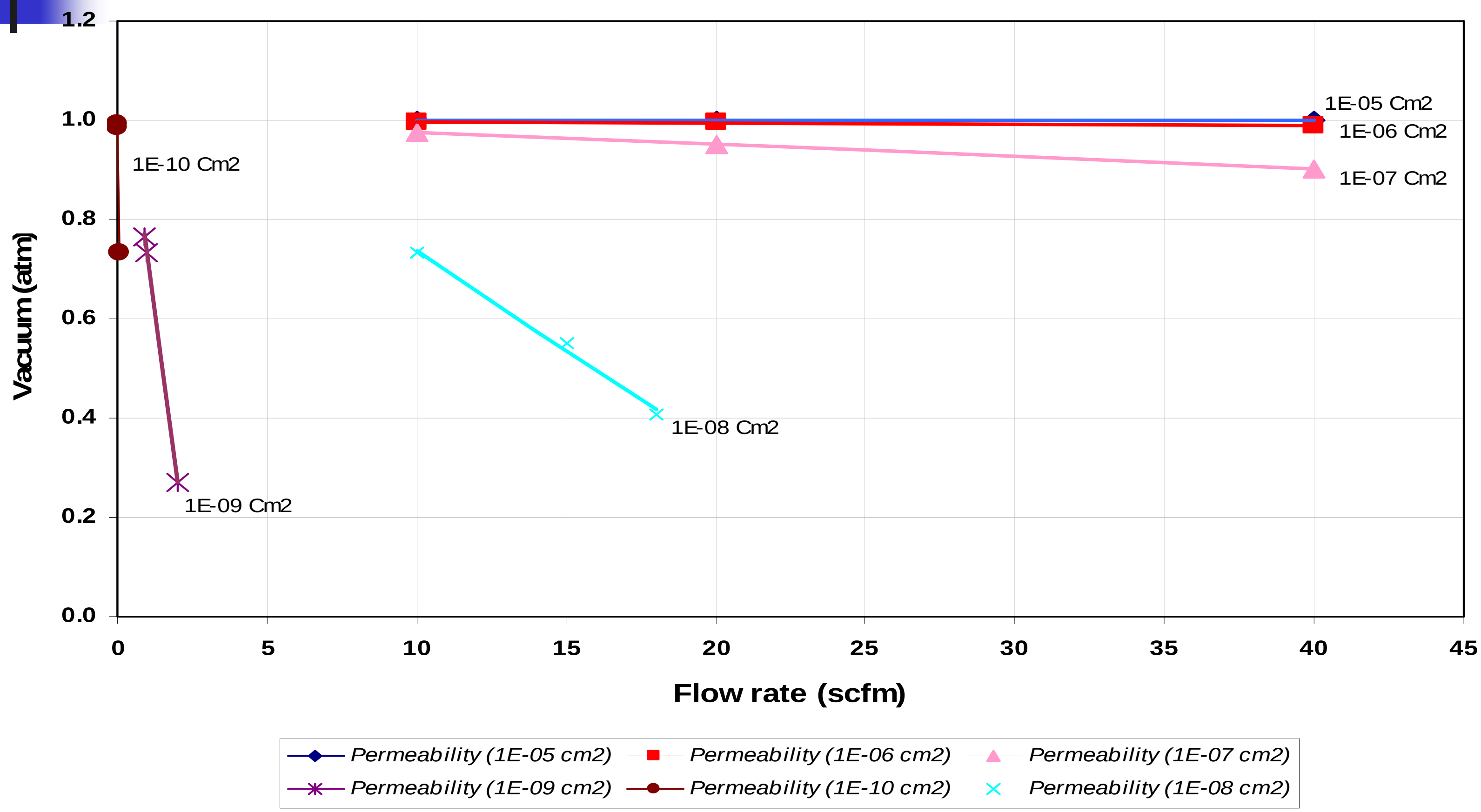
Pressure v. Air Flow



Source: Freeze and Cherry, Groundwater, Prentice-Hall, Inc., p. 29 (1979)

Pressure v. Air Flow

Vacuum v. Flow as a function of Soil Permeability



Courtesy of Mike Marley, Xpert Design and Diagnostics (XDD), Stratham, NH www.xdd-llc.com

Active Mitigation Systems: Fans

Fan Specs
Source: RadonAway™
http://www.radonaway.com/rpseries.htm

The following chart shows performance of **RP Series** fans:

		Duct	Maximum	Typical CFM vs Static Pressure WC"				
Models	**Watts***	**Diameter**	**Pressure**	**0.0"**	**0.5"**	**1.0"**	**1.5"**	**2.0"**
RP140	14-20	4"	0.8" WC	134	68	-	-	-
RP145	37-71	4"	2.1" WC	173	132	94	55	11
RP260	52-72	6"	1.8" WC	275	180	105	20	-
RP265	86-140	6"	2.5" WC	327	260	207	139	57

*Typical monthly electric cost $2.50 - $4.50 depending on model, electric rates & operating conditions.

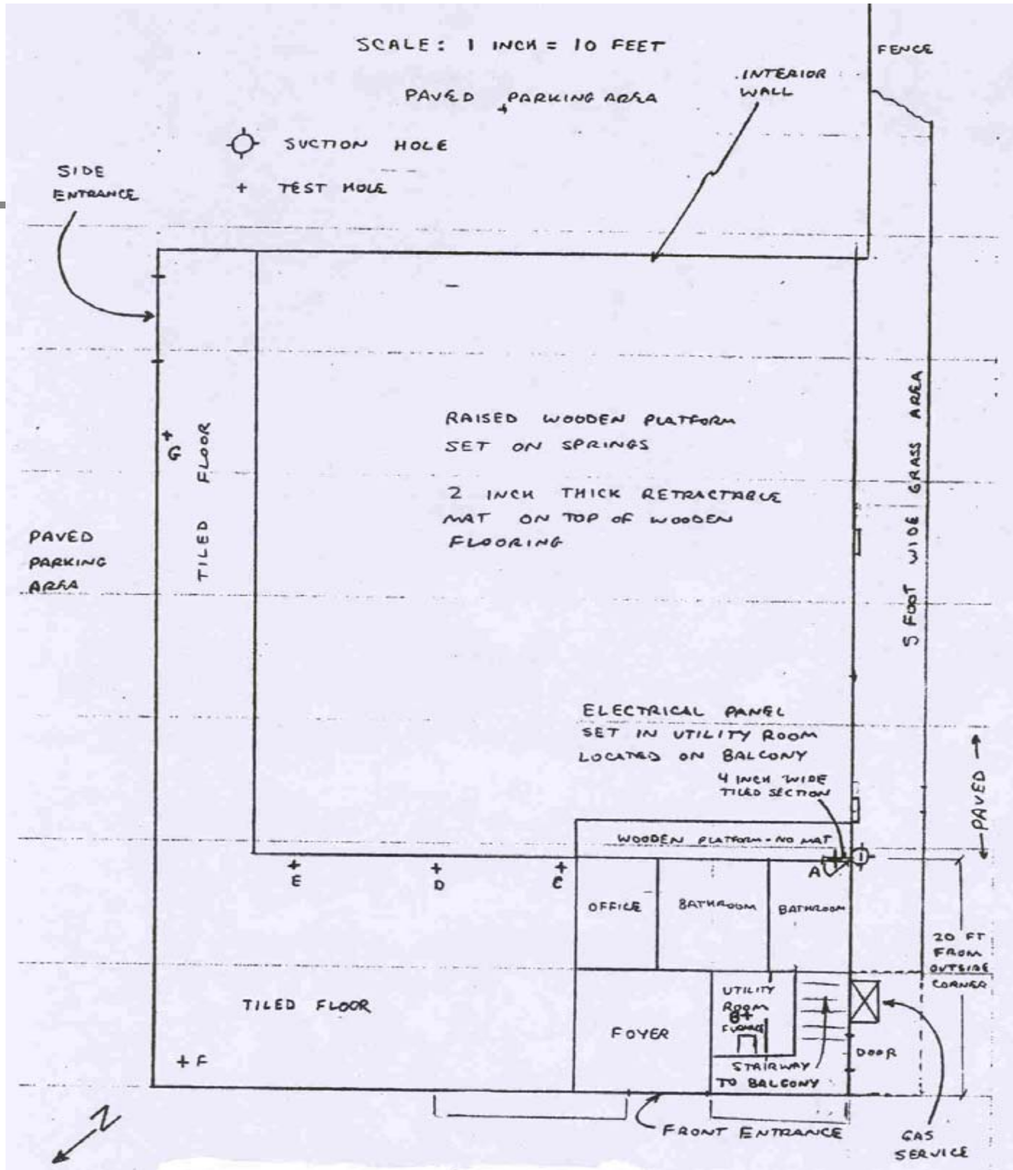
Active System Design: Case Study

Floor Plan

Probe Distance from Suction Point (ft):

A - 2
B - 15
C - 21
D - 30
E - 40
F - 51
G - 60

Approx. area of floor: 3,412 ft2



Active System Design: Case Study

Design Data

Pump Test #1 (*Falling flowrate and suction*)

Time	Test Duration (min)	Flowrate (CFM)	Suction (negative in. W.C.) TH-1	TH-2	TH-3	TH-4	TH-5	TH-6
9:45 AM	0	--	--	--	--	--	--	--
9:55 AM	10	125-150	2.46	0.04	0.02	0.009	0.005	--
10:08 AM	23	--	1.89	0.05	0.02	0.010	0.006	--
10:15 AM	30	--	1.69	0.06	0.02	0.002	0.003	--
10:30 AM	45	--	1.44	0.06	0.02	0.004	0.003	--
11:00 AM	75	--	1.13	0.08	0.02	0.003	0.004	0.004
11:15 AM	90	--	0.90	0.08	0.01	--	0.004	--
11:30 AM	105	--	0.87	0.08	0.01	--	0.004	0.001
12:30 PM	165	85	--	--	--	--	--	--

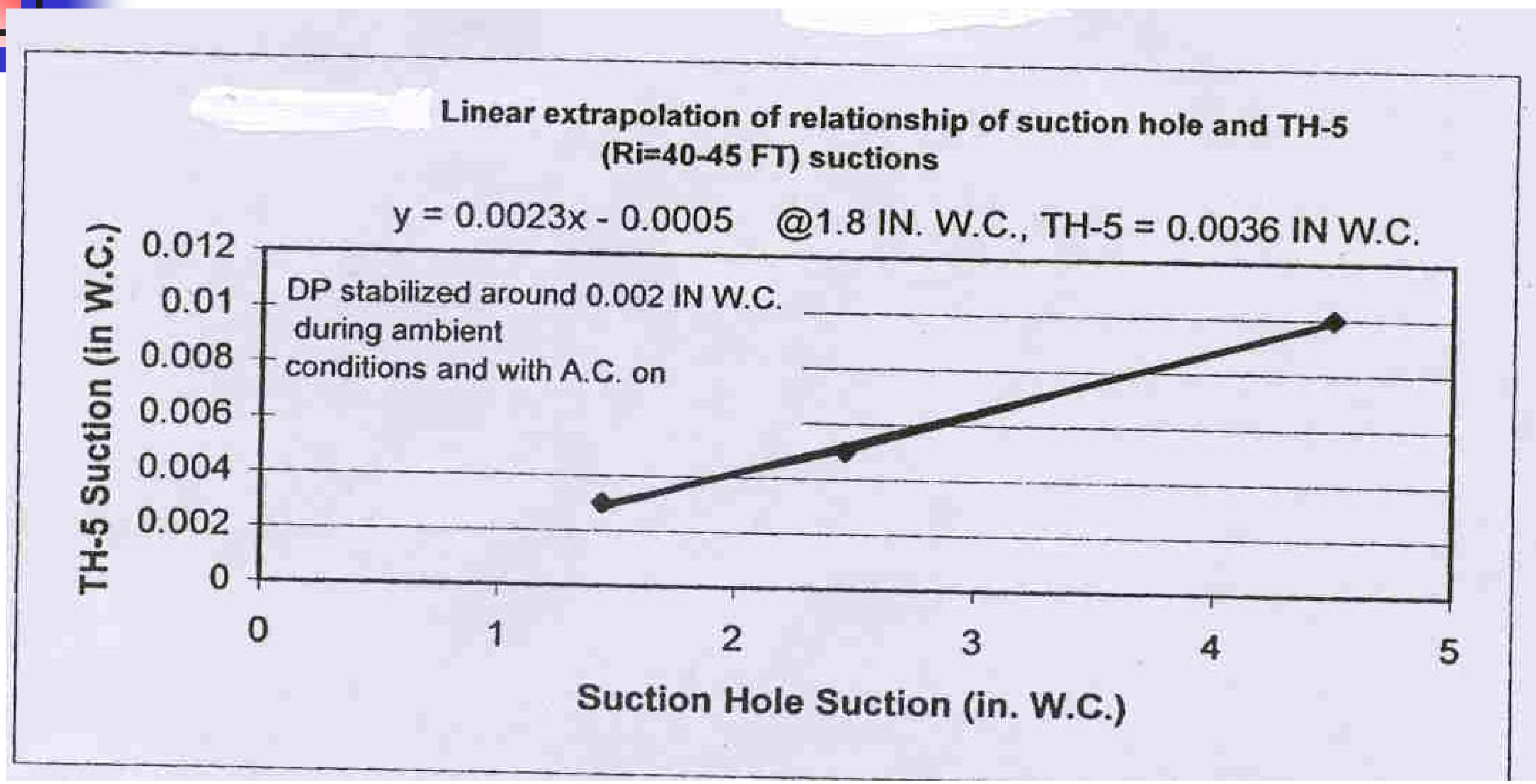
Pump Test #2

Time	Test Duration (min)	Flowrate (CFM)	Suction (negative in. W.C.) TH-1	TH-2	TH-3	TH-4	TH-5	TH-6
1:40 PM	0	--	--	--	--	--	--	--
1:45 PM	5	200	4.54	0.04	0.02-0.03	0.003-0.008	0.003-0.008	--
2:05 PM	25	202	4.52	--	0.03	0.010-0.012	--	0.002
2:10 PM	30	203	--	--	--	--	0.007-0.01	0.000-0.005
2:30 PM	50	--	4.52	0.03-0.032	0.02-0.03	0.01-0.011	0.001-0.003	0.002-0.004
2:45 PM	65	--	4.50-4.54	0.031-0.035	0.03-0.04	0.008-0.02	0.002-0.004	0.002-0.005

Flowrate vs Suction

Flowrate (CFM)	Suction (negative in. W.C.) TH-1	TH-2	TH-3	TH-4	TH-5
150	4.11	--	0.02-0.03	0.01-0.02	0.001-0.004
129	3.13	--	0.01-0.03	0.001-0.002	0.000-0.001
118	2.38	--	0.01-0.02	0.001	--
103	2.02	--	0.01-0.03	--	--

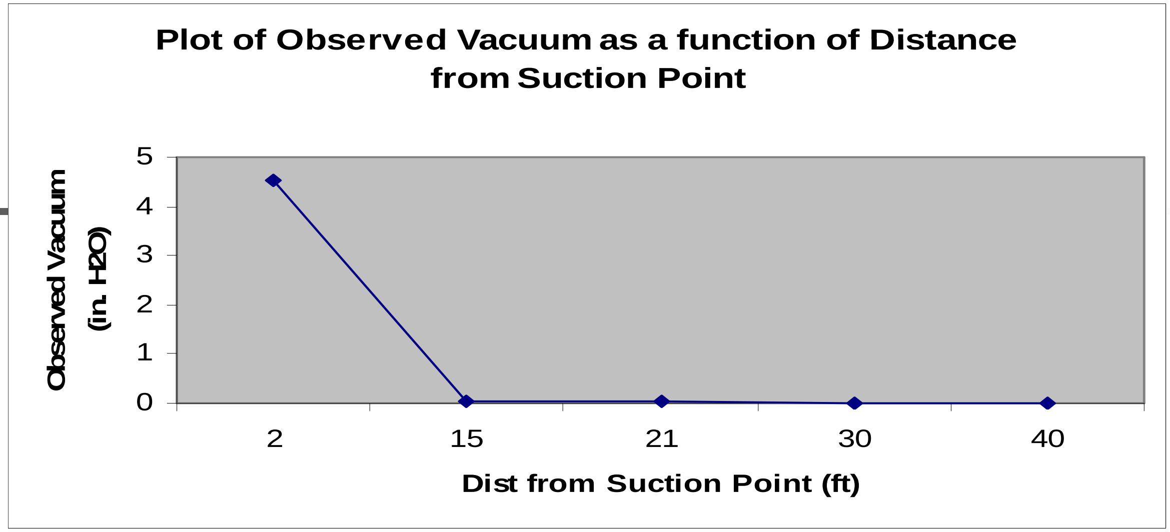
Active System Design: Case Study



Design Extrapolation

Active System Design: Case Study

Fig. 1: Plot of Actual Data



looks very much like . ..

Fig. 2: Theoretical / Classic Pressure Distribution

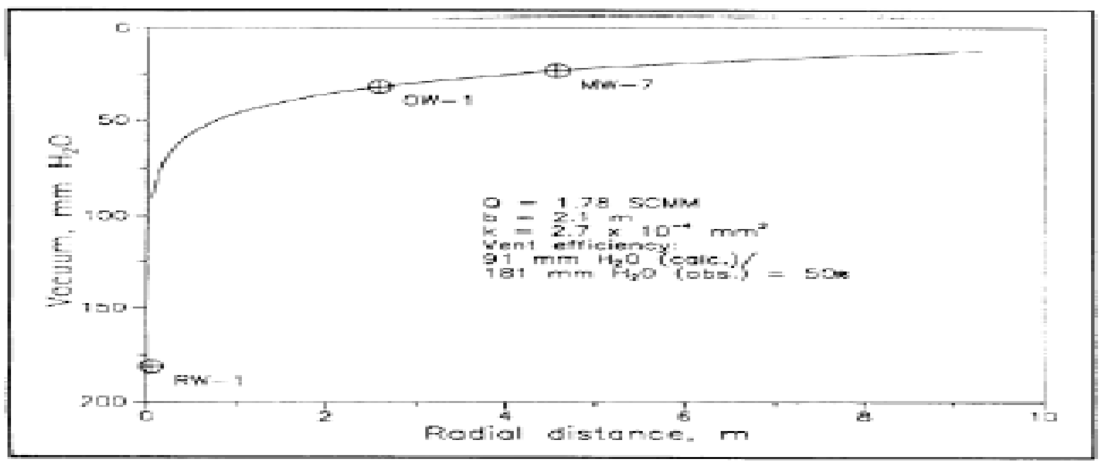


Figure 4-14 Steady-state pump test

- **Source:** Fig. 2: U.S. ACE, Engineering and Design – Soil Vapor Extraction and Bioventing, June 3, 2002, Pub. No. EM1110-1-4001 http://www.usace.army.mil/usace-docs/eng-manuals/em1110-1-4001/ at Chapter 4, p. 31

Active System Design: Case Study

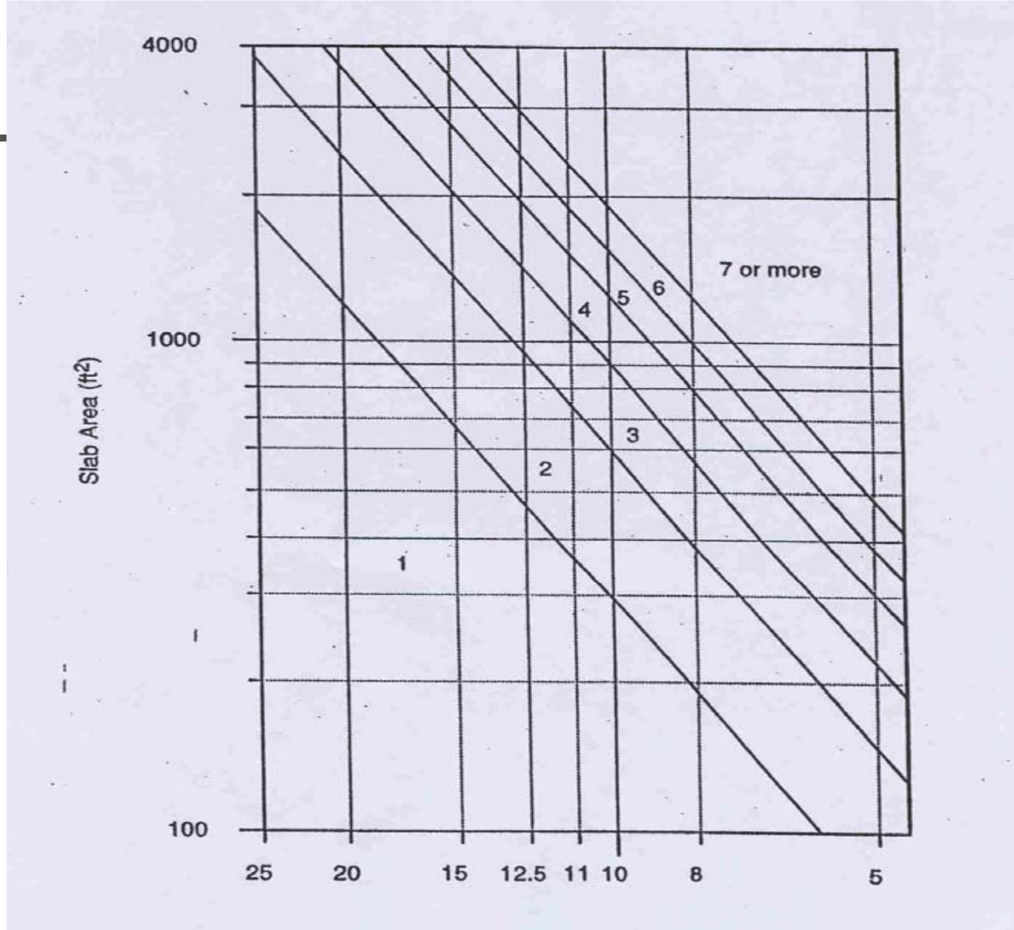


FIGURE 4.
MINIMUM NUMBER OF SUCTION HOLES BASED ON EFFECTIVE RADIUS OF SUCTION FIELD, r, AND SLAB AREA

(SOURCE: EPA 1991)

Active System Design: Case Study

- Design and Full-Scale System Start-up & Operation:
  - Two (2) RadonAway RP-275 fans: 180 scfm @ 0.5" H_2O
  - Performance Assessment:
    - Start the fans
    - Confirmatory Indoor Air Sampling:

Location of Summa Canisters: along wall, ~23 ft from SE Corner of Bldg

Compound	Before (ppbv) June 2001 (Avg of 2)	After (ppbv) Feb 2002
Benzene	0.58	0.38
1,2-DCE	12	NR
1,1,1-TCE	19	1.0
TCE	9.3	0.18
Toluene	2.5	1.4
Vinyl chloride	ND	NR

Active System Design: Case Study Analysis

- **Problems with This Design:**
  - Observed sub-slab pressure distribution over building footprint below typical building depressurizations. In fact:

    "[I]t is estimated that the **sub-slab pressure differential** depressurization around the slab perimeter **must be at least 0.015 in H_2O (about 4 Pa)** to prevent soil gas entry when the basement becomes depressurized under normal conditions." U.S. EPA, Application of Radon Reduction Methods, August 1988, p. 35, EPA/625/5-88/024.

  - System based largely or principally on air flow (F) should consider whether major VI entry routes are mitigated by F (where F >>> diffusion/advection of contaminants)

Incidental: Benefit of sub-slab (SS) sampling protocol published by U.S. EPA ORD (March 2006, EPA/600/R-05/147) is that SS sampling probes may be used for post-mitigation performance assessment

Active System Design Recommendation

Design Target:
r_e ~ -4 Pa
(but radon = $2.3E^{-2}$ risk)

so, VOC's ???

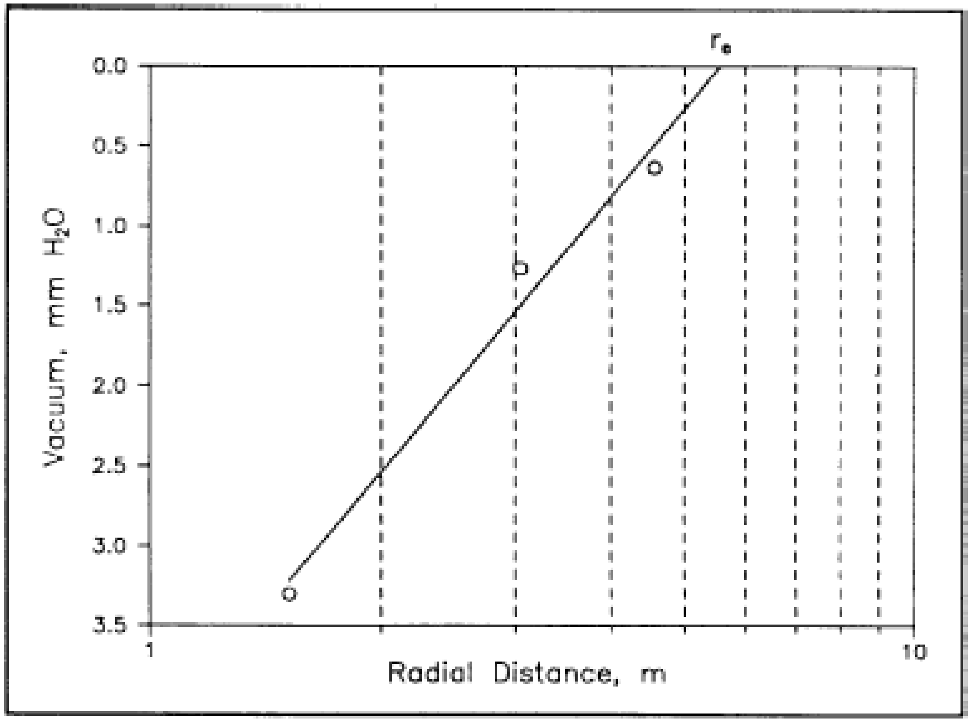


Figure 2-5 Use of distance-drawdown graphs to determine r_e

- U.S. ACE, Engineering and Design – Soil Vapor Extraction and Bioventing, June 3, 2002, Pub. No. EM1110-1-4001 http://www.usace.army.mil/usace-docs/eng-manuals/em1110-1-4001/ at Chapter 2, p. 16.

Performance Assessment

Less Difficult

There are various ways to assess mitigation system performance . ..

PHYSICAL PARAMETERS (only)

- Simply confirm **fan starts!** . .. **wrong**
- **Measure** full-scale startup **fan** physical operating parameters. Compare w/ design parameters.
  - Pressure
  - Flow
- **Measure** full-scale **system** physical operating parameters startup, **including monitoring probes** for:
  - subslab vacuum / pressure field distribution and/or
  - air flow distribution using **smoke stick** (*see* Ron Mosley *.ppt).

  Compare to design pressure distribution.

Performance Assessment

Add: CHEMICAL PARAMETERS

(Note: May depends on Flow v. Pressure design; strength of source)

- Measure fan / system physical operating parameters and monitor system discharge
  - At **startup** (only)
  - At startup and as a **function of time** (continuous for a limited time, periodic, continuous (i.e., permanent))

  and . ..

  - **Radon**
    - System discharge
    - Indoor Air – measure change in concentration (pre- & post-system)

      E.g., RadonAway™ RadStar RS500 Continuous Radon Monitor - assume active and passive operation
  - **VOCs**
    - System Discharge
      - ppbRAE
      - Modified TO-3 (e.g., tenax / silica gel / charcoal)
      - Summa Canister?
    - *Indoor Air – measure change in concentration (pre- & post-system)

More Difficult

Performance Assessment

Why Monitor at Startup?

Typical / Theoretical SVE Discharge Curve

(extraction well in source area, source depletion)

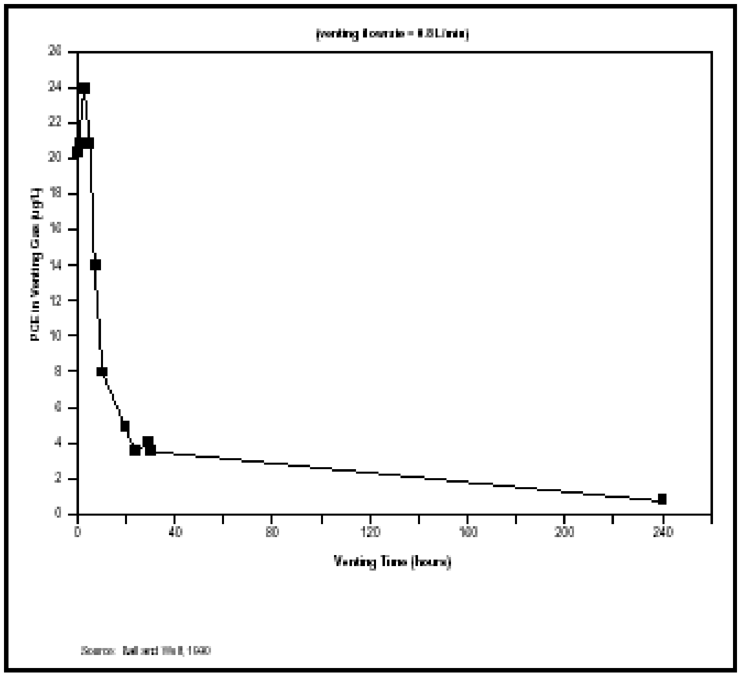


Figure 4-18 Tetrachloroethylene (PCE) venting curve

(c) Figure 4-18 is typical in shape of the curves expected from a full-scale SVE system. The decreasing slope (indicating mass removal rate) is primarily due to two effects: 1) the diminishing mass transfer of the PCE from the soil and liquid phases into the vapor phase; and 2) the diluting effect of the airflow, which implies that as concentrations diminish in a constant vapor flow rate, the mass removal rate must also diminish. The curve of vapor concentrations versus time obtained from the column test was a good predictor of full-scale performance at this relatively homogeneous, sandy site (Ball and Wolf 1990; Urban 1992).

- U.S. ACE, Engineering and Design – Soil Vapor Extraction and Bioventing, June 3, 2002, Pub. No. EM1110-1-4001 http://www.usace.army.mil/usace-docs/eng-manuals/em1110-1-4001/ at Chapter 4, p. 41

Performance Assessment: Radon

RadonAway™ RadStar RS500 Continuous Radon Monitor

- Provides hourly and average readings.
- AC power / battery operation.
- Keyed operation.
- Keypad lockout.
- Instrument motion sensor.
- Silicon photodiode detector.

Source: http://www.radonaway.com/whatsnew/RadStar.htm (no longer available as of April 2007). *See also*, http://www.genitron.de/ (AlphaGUARD) and http://www.pylonelectronics.com/ (Pylon).

Performance Assessment: ppbRAE (total VOC)

The rugged ppbRAE Plus is the most sensitive handheld volatile organic compound (VOC) monitor in the world. Its Photoionization Detector (PID) provides true parts-per-billion (ppb) detection for applications from indoor air quality (IAQ) to HazMat/Homeland Security.

The ppbRAE Plus detector can be made wireless with the use of RAELink2. This allows real-time monitoring information from the detector to be integrated into an existing AreaRAE system. A wireless, RF (radio frequency) modem allows detectors equipped with Firmware version 1.20 or higher to communicate and transmit readings and other information on a real-time basis with an AreaRAE base controller located up to 2 miles away.

The ppbRAE Plus monitor has replaced the original ppbRAE monitor. Any current customers with a ppbRAE monitor may send it to the factory for an upgrade to the ppbRAE Plus monitor for a nominal fee. For further information on this detector, please contact your appropriate RAE Systems distributor / representative.

RAE Systems ppbRAE

Source: http://www.raesystems.com/product/1086

Active Mitigation Systems: Fans

Fan / Blower Specs

Source: RadonAway™

http://www.radonaway.com/rpseries.htm

The following chart shows performance of **RP Series** fans:

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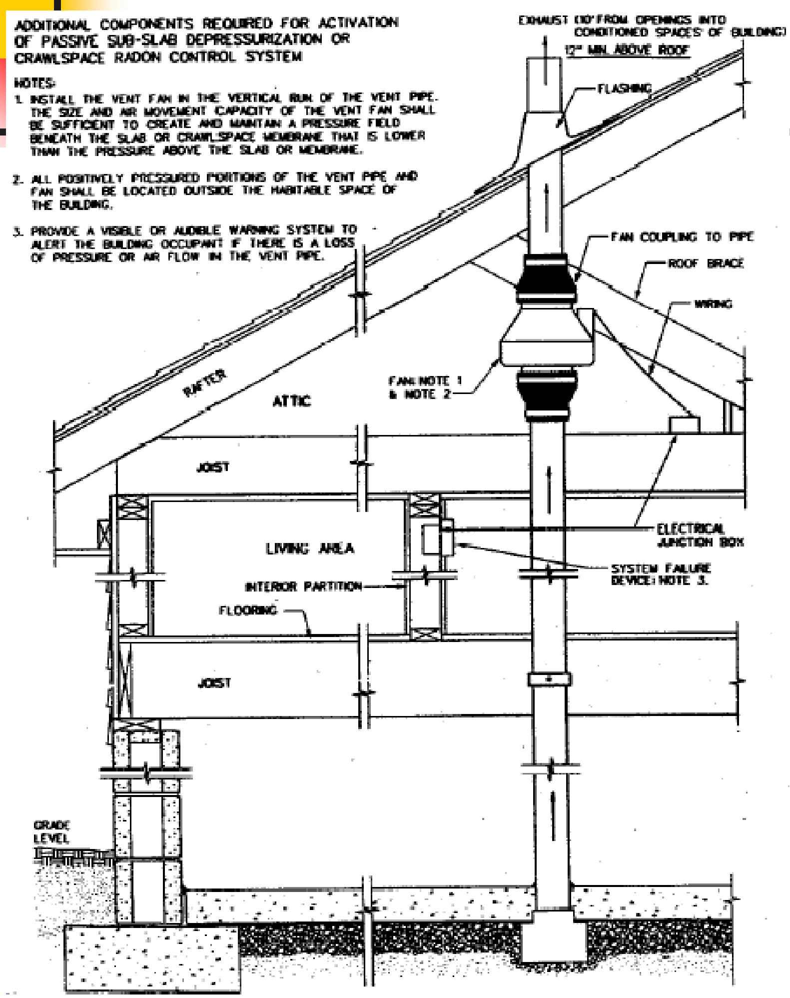
*Typical monthly electric cost $2.50 - $4.50 depending on model, electric rates & operating conditions.

Fan / Stack Location: Attic Configuration



Source: Photo: Integrity Radon Control, http://www.integrityradoncontrol.com/index.php Schematic: U.S. EPA, Building Radon Out: A Step by Step Guide to Building Radon-Resistant Homes, April 2001, p. 77, http://www.epa.gov/radon/images/buildradonout.pdf

Fan / Stack Location: Exterior Configuration

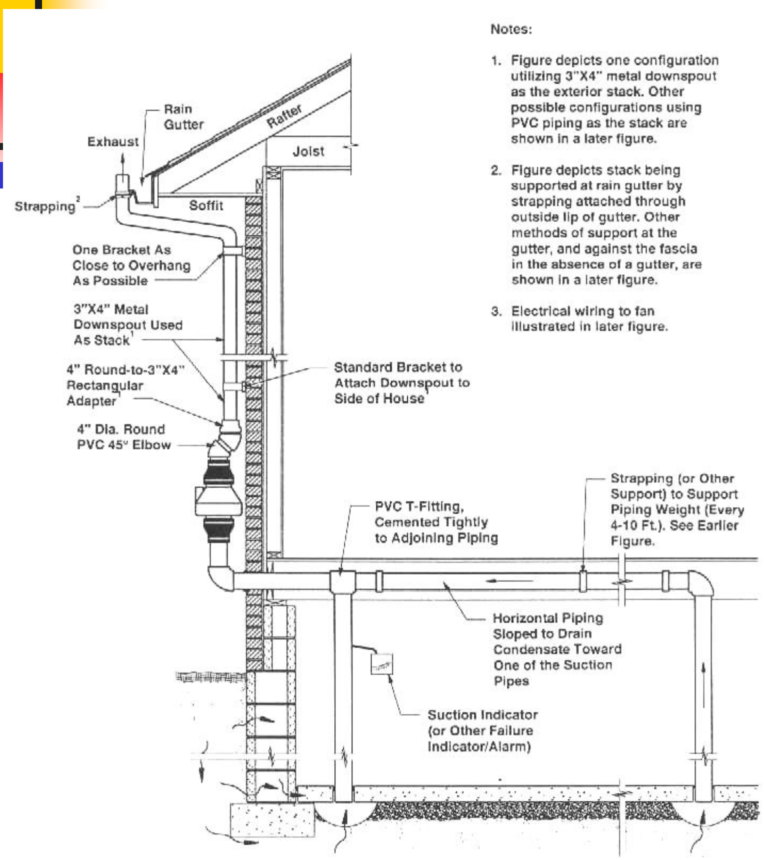


Figure 21. One representative SSD piping configuration illustrating an exterior exhaust stack.

142

Source: Photo: Infiltec http://www.infiltec.com/
Schematic: U.S. EPA, Radon Reduction Techniques for Existing Detached Houses: Technical Guidance (Third Edition) for Active Soil Depressurization Systems, October 1993, EPA 625/R-93-011

Fan / Stack Location: What <u>not</u> to do

Close-in view of RP145 fan, pressure gauge, indicator light, and one inch PVC line.

View of interior SSD system components.

View of exterior SSD system components.

Why you need to consider soil moisture (colder climates)

Estimate per day rate of condensation for 180 scfm (84 L/s) fan during the winter.

Assume: soil vapor is at 100% RH, soil temp = 10oC, ambient temp = 0oC.

1. From psychrometric chart:

- Conc. of water vapor (at 10oC) = 7.66 g/kg
- Conc. of water vapor (at 0oC) = 3.79 g/kg
- Condensate = difference = 3.87 g/kg = 3.9E-3 kg/kg

2. Density of Air (Dair) at 0oC = PM/RT where M = molecular mass of water

- Dair = (1 atm)(18 g/mol)/(0.0821 L atm / g mol)(273oK) = 0.80 g/L = 8E-4 kg/L

3. Flow rate x concentration of condensate at Dair:

- (3.9E-3 kg/kg)(8E-4 kg/L)(84 L/s)(86,400 s/day)(1 L/kg) =

22.6 L/day (6 gal/day)

At a minimum, all piping must slope back to ground.

Passive Systems

Passive Stack Mitigation

- Passive Stack Mitigation

  The stack produces a low pressure zone below the house which prevents radon-bearing soil gas from entering the house. This process is driven entirely by the surrounding environmental conditions. Since the system is not controlled by mechanical devices, understanding the effects of wind and stack height on overall performance is crucial. http://baba.astro.cornell.edu/research/radon/

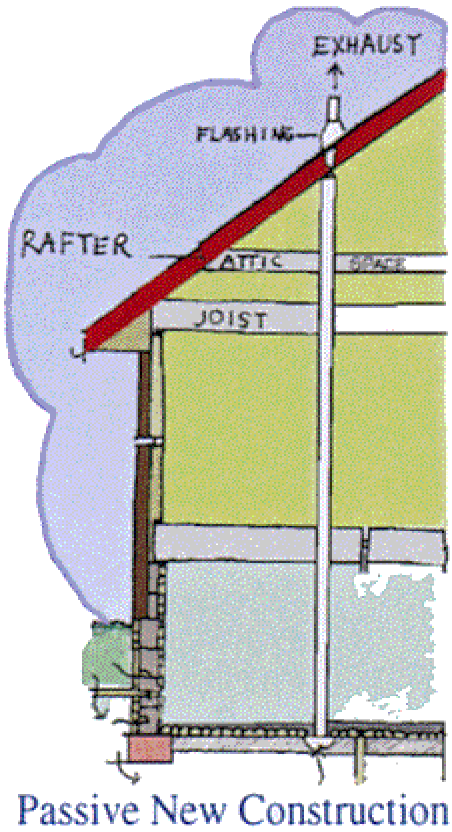
  - principle of operation:
    - Stack Height (temperature)
    - Wind Velocity

    Note: Drag on flow (i.e., friction) equates to pressure drop:
      - **Length** of pipe – linear with length
      - Pipe **Diameter** – biggest effect. Standard is 4", but depends on where you can put it in the house
      - **Bends** in pipe – affect pressure difference and could compromise system performance.

      You want the largest diameter straightest pipe you can put in.

    See American Society of Heating, Refrigerating and Air-Conditioning Engineers (**ASHRAE**) Fundamentals Handbook. http://www.ashrae.org/
    2001 Handbook replaced by the 2005 Version in June. ~$155.00.

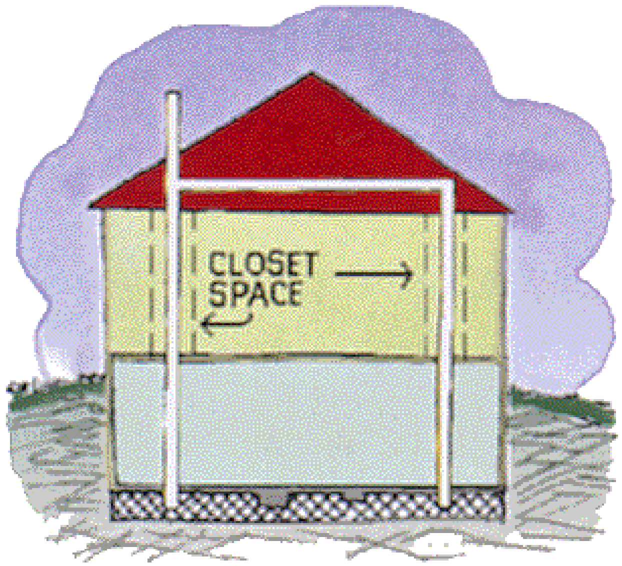
Passive Stack Mitigation



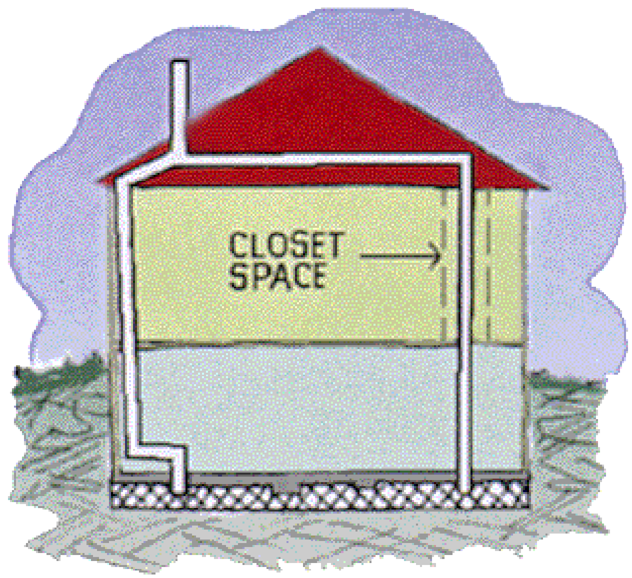
Source: Illinois Department of Nuclear Safety, Guide to Radon Mitigation http://www.state.il.us/idns/html/radon/prgdeser/mit.asp

Source: Integrity Radon Control, Medina, OH http://www.integrityradoncontrol.com/mitigation.php

Passive Stack Mitigation



Skeletal New Construction



Skeletal New Construction

Source: Illinois Department of Nuclear Safety, Guide to Radon Mitigation
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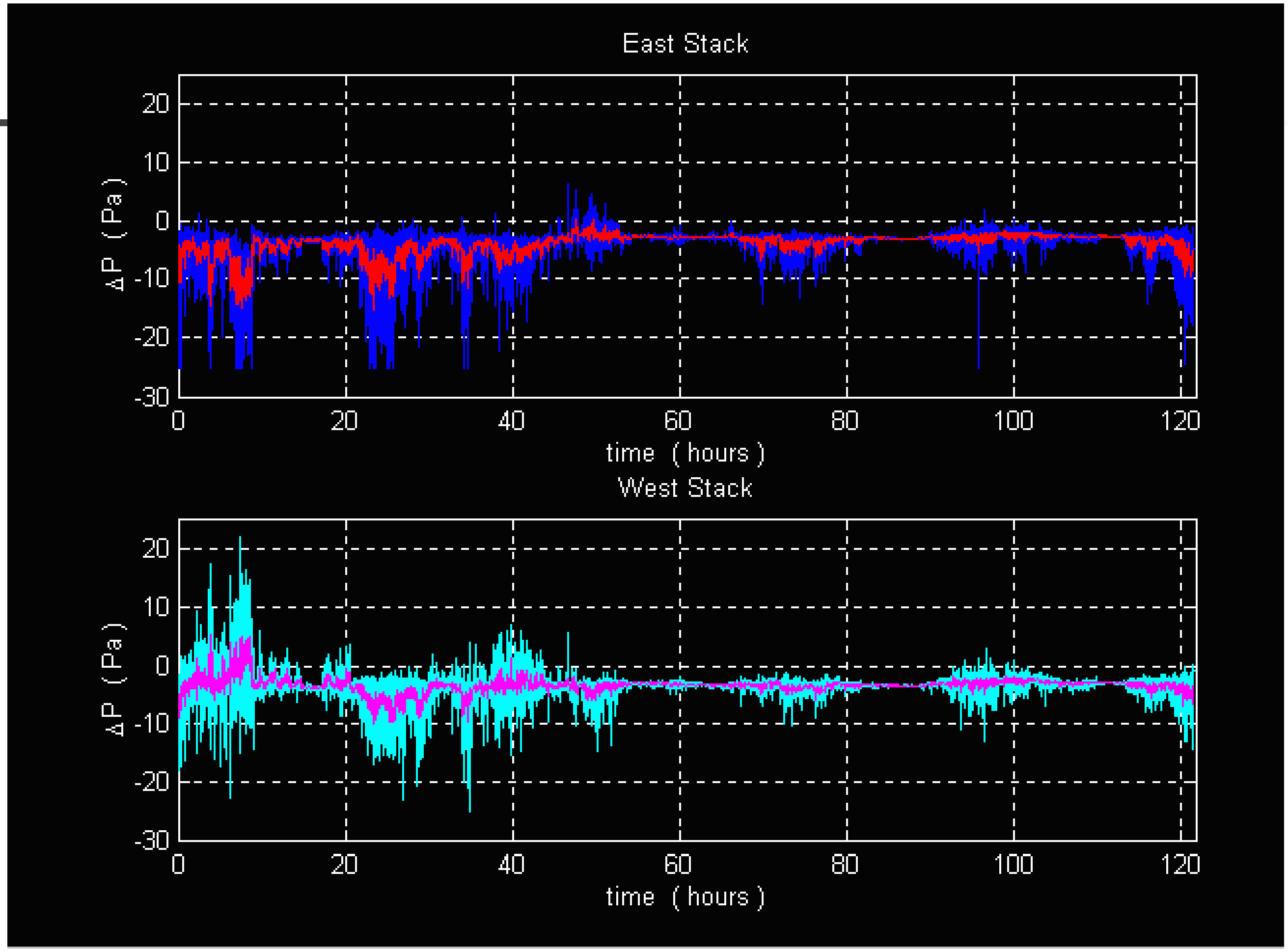
Passive Stack Mitigation



Source: Steve Drasco, The Passive Stack Radon Mitigation System, Ernest Orlando Lawrence Berkley National Laboratory http://baba.astro.cornell.edu/research/radon/analysis.html

Passive Mitigation (policy)

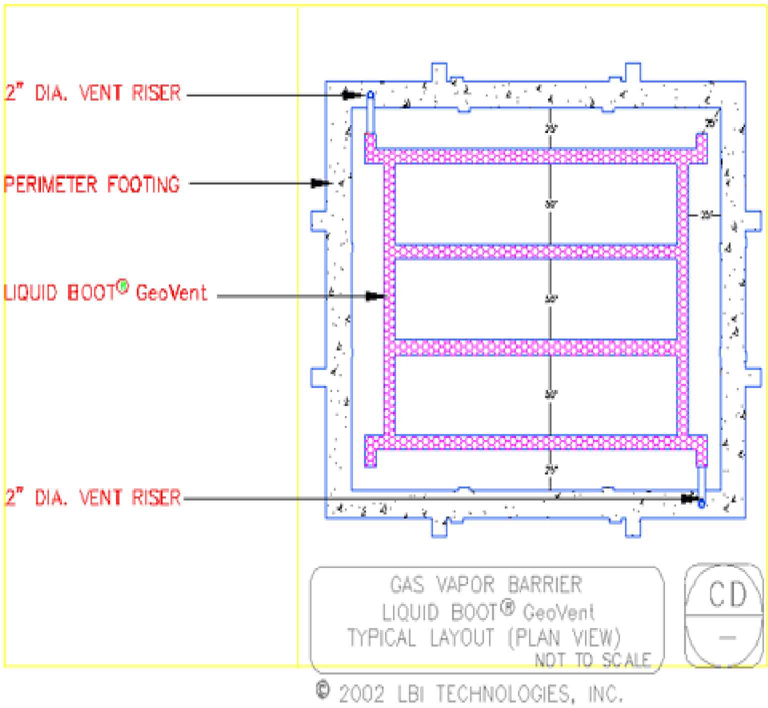
Consider . ..

- *Passive* or *skeletal new construction systems* are **not acknowledged mitigation systems** and may or may not reduce radon concentrations in homes to below the USEPA's Action Level, 4.0 picocuries per liter of air (4pCi/L). DNS encourages homeowners to test their home to determine the actual radon levels. **With test results of 4 pCi/L or more**, ***passive*** and *skeletal new construction* ***systems*** **should be converted to active soil depressurization systems** by mitigation professionals licensed by DNS.

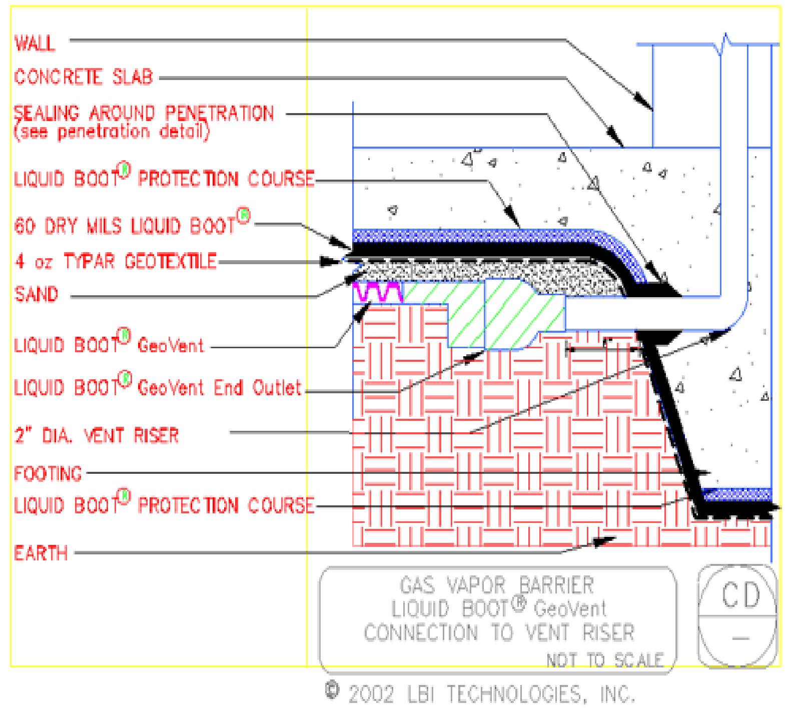
Source: Illinois Department of Nuclear Safety, Guide to Radon Mitigation, http://www.state.il.us/idns/html/radon/prgdeser/mit.asp

Liquid Boot® GeoVent: New Construction

A "composite low profile pressure relief, collection and venting system (PRCVS) consisting of a 3-dimensional vent core and wrapped with a non-woven needle punched filter fabric."



(a) Typical Layout



(b) Connection to Vent Riser

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers

Source: Liquid Boot®, www.liquidboot.com

Passive Barriers

Passive Mitigation: Sealing → Gas Vapor Barriers / Membranes

Recall . ..

"*EPA does not recommend the use of sealing alone to reduce radon because, by itself, sealing has not been shown to lower radon levels significantly or consistently.*" U.S. EPA, Consumer's Guide to Radon Reduction at p. 9, Revised February 2003, EPA 402-K-03-002 http://www.epa.gov/radon/pubs/consguid.html

Older Technologies: e.g., 3 to 6 mil Polyethylene Sheeting

- Problems **sealing** sheeting around protrusions and sheeting seams
- Sheeting can be **damaged** during construction

Newer Technologies: **Spray-applied membranes**

- Liquid Boot® Cold Spray-Applied Membrane http://www.liquidboot.com/gvb/index.asp
- Polyguard Underseal™ XT http://www.polyguardproducts.com/products/Underseal/index2.htm

Liquid Boot® Gas Vapor Barriers

Liquid Boot® Cold Spray-Applied Rubberized Asphalt Membrane
http://www.liquidboot.com/gvb/index.asp

Can be applied to:

- Walls
- Under Slab
- Between Slabs
- Penetrations

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers: Walls

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers: Protrusions

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers

Use w/ old construction. Will it bind to old fieldstone foundation walls? Does basement need to be specially-prepared or retrofit?

Liquid Boot® Gas Vapor Barriers

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers

Source: Liquid Boot®, www.liquidboot.com

Liquid Boot® Gas Vapor Barriers

- **Lack of Performance Data.** Currently, there is a **lack of performance data** (e.g., confirmatory indoor air testing) demonstrating the effectiveness of these membranes in the short and long terms.
- **Membrane as a Source of IA Contaminants?** Membrane is Asphalt-based → does the membrane itself emit **PAH's** and/or other VOCs into indoor air? Has any IA testing for these constituents been done?
- **Permeability and Resistance to High Source Terms.** How do these membranes behave if in contact with residually saturated soils or high gas / vapor source terms **(e.g., gasoline spills).**
- **Long-Term Performance.** Does it maintain integrity over the long term under typical environmental conditions?

Performance Assessment for Passive Systems

Measure indoor air concentration:

- **before** and
- **after** passive system installed

if asphalt-based spray-applied membrane, consider measuring PAH's . ..?

Mitigation Systems / Barriers:
Advantages and Disadvantages

Advantages

Reduction / Elimination of:

- Moisture / Humidity (i.e., dampness)
- Mold
- Radon
- Methane
- Pesticides
- Termites
- Rodents

Disadvantages

- Actual or perceived diminution of real estate value
- Aesthetics
- Cost: Installation and Energy
- Maintenance
- Noise from improperly installed fan

Mitigation References

- EPA's Radon Program: http://www.epa.gov/radon
  - U.S. EPA, Application of Radon Reduction Methods, August 1988, EPA/625/5-88/024
  - U.S. EPA, Radon Prevention in the Design and Construction of Schools and Other Large Buildings, 3rd Printing with Addendum, June 1994, EPA/625/R-92/016
  - U.S. EPA, Model Standards and Techniques for Control of Radon in New Residential Buildings, March 1994, EPA/402/R-94-009, http://www.epa.gov/radon/pubs/newconst.html
  - U.S. EPA, Building Radon Out: A Step by Step Guide to Building Radon-Resistant Homes, April 2001, EPA 402-K-01-002, http://www.epa.gov/radon/images/buildradonout.pdf
  - U.S. EPA, Consumer's Guide to Radon Reduction, Revised February 2003, EPA 402-K-03-002, http://www.epa.gov/radon/pubs/consguid.html
  - U.S. EPA, Radon Mitigation Standards (RMS), October 1993 (Revised April 1994), EPA 402-R-93-078, http://www.epa.gov/radon/pubs/mitstds.html

Mitigation References

- Massachusetts DEP Guidance: Guidelines for the Design, Installation and Operation of Sub-Slab Depressurization Systems, December 1995
  http://www.mass.gov/dep/nero/bwsc/files/ssd1e.pdf

- Cal. EPA, Department of Toxic Substances Control, Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air, Interim Final, December 15, 2004 (Step 11; page 35)
  http://www.dtsc.ca.gov/ScienceTechnology/HERD_POL_Eval_Subsurface_Vapor_Intrusion_interim_final.pdf

- NYS Dept. of Health, Guidance for Evaluating Soil Vapor Intrusion in the State of New York, February 2005 Public Comment Draft, Section 4.0: Soil Vapor Intrusion Mitigation
  http://www.health.state.ny.us/nysdoh/gas/svi_guidance/

- Engineering Controls for Soil and Groundwater Vapors: Design, Installation and Maintenance Guidelines, In ASTM Standard Practice / Guide for Application of Engineering Controls to Facilitate Use or Redevelopment of Chemical-Affected Properties (Currently Under Development).