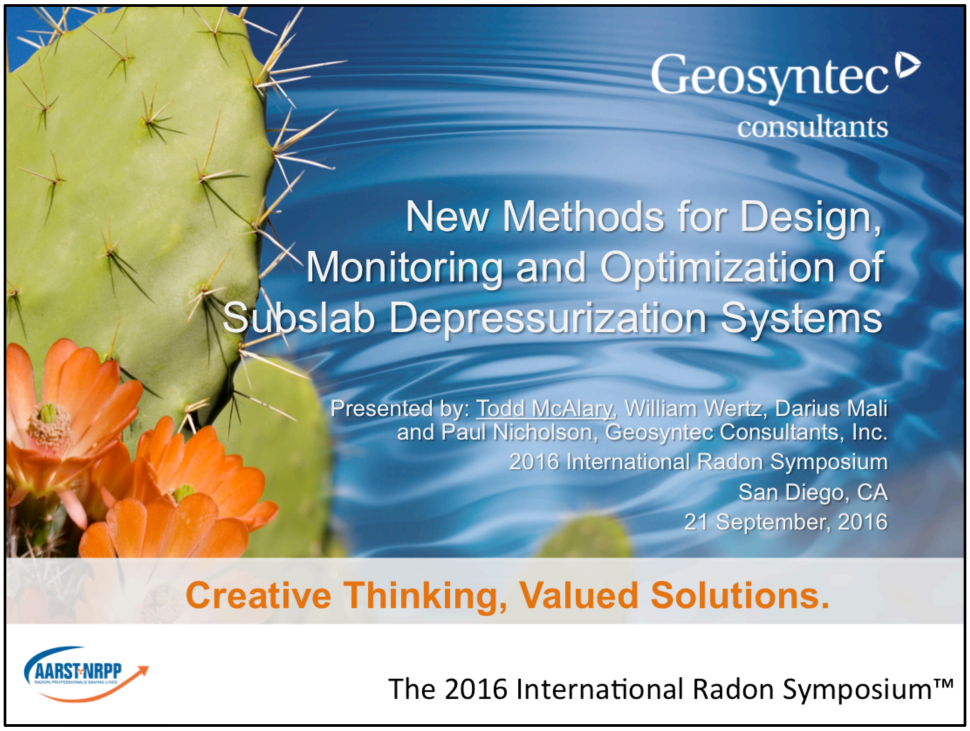
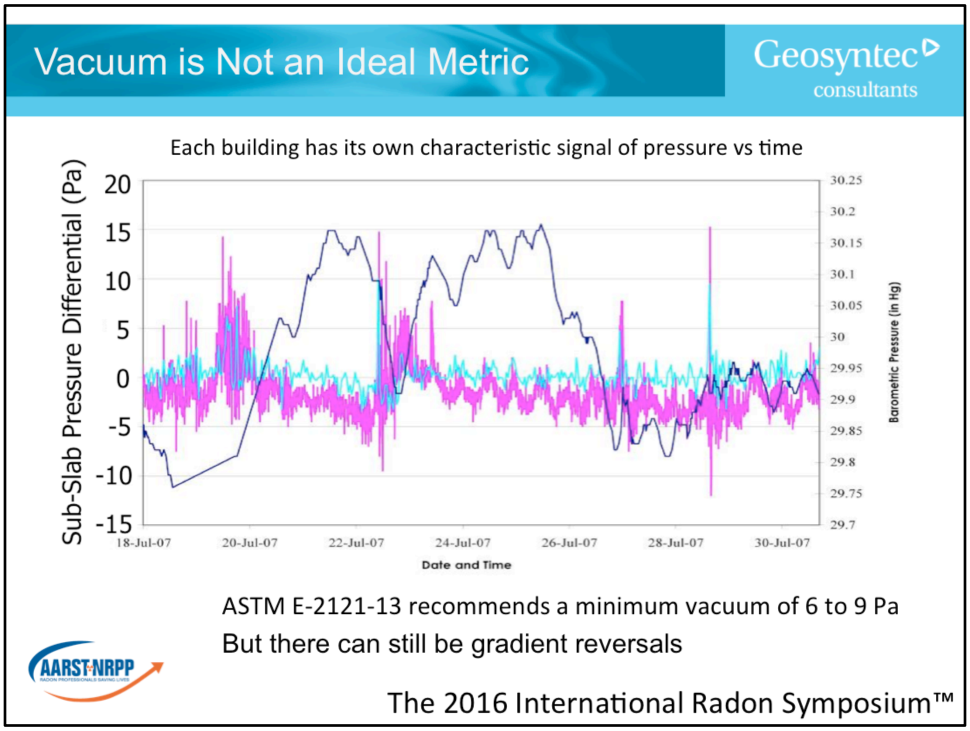


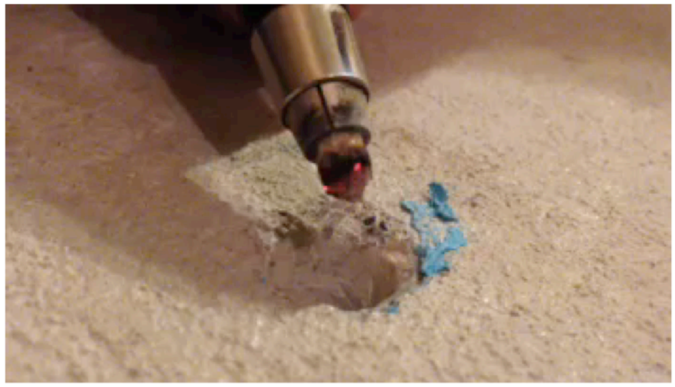
This talk is based on research performed for the United States Department of Defence under their Environmental Security Technology Certification Program (ESTCP). Further information is available at:
https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-201322/ER-201322



Radon mitigation systems are usually designed to achieve a certain level of vacuum below a floor slab, however, the magnitude of the ambient fluctuations in cross-slab pressure difference are not constant and vary from building to building, maybe also between heating and cooling seasons and potentially in response to wind, barometric pressure and other factors. ASTM E2121 (Standard Practice for Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings) specifies a target vacuum of 6 to 9 pascals, but there may be occasional gradient reversals even at this level. So vacuum alone is not an ideal metric because there is a “signal to noise” challenge.

Current SSD Design Focuses on Vacuum

Geosyntec consultants



Plenty of downward flow occurs here at <1Pa vacuum

(this measurement took 20 seconds)

AARST-NRPP

The 2016 International Radon Symposium™

This slide included a video that shows smoke from a smoke pen being drawn strongly into a hole drilled through the concrete floor of a residence with a radon mitigation system. There was no measurable vacuum at this location (<1 Pa), but no smoke escaped until the pen was held at least an inch above the floor and the tip of the pen glowed dramatically when it was held close to the floor, demonstrating lots of downward flow. This begs the question of whether vacuum or flow is the preferred metric. Or perhaps both. If there is no vacuum and there is no significant flow, the effectiveness would not likely be as good as the case shown here.

Flow, Vacuum and Permeability

Geosyntec consultants

$$Q = \frac{-kA}{\mu}\frac{\Delta P}{\Delta L}$$

(Darcy's Law, 1856)

Q = discharge (m^3/s)
k = intrinsic permeability (m^2)
A = cross sectional area (m^2)
P = pressure (Pa)
L = length (m)
μ = viscosity (Pa s)

Unfortunately, it is hard to directly measure air velocity <70m/day

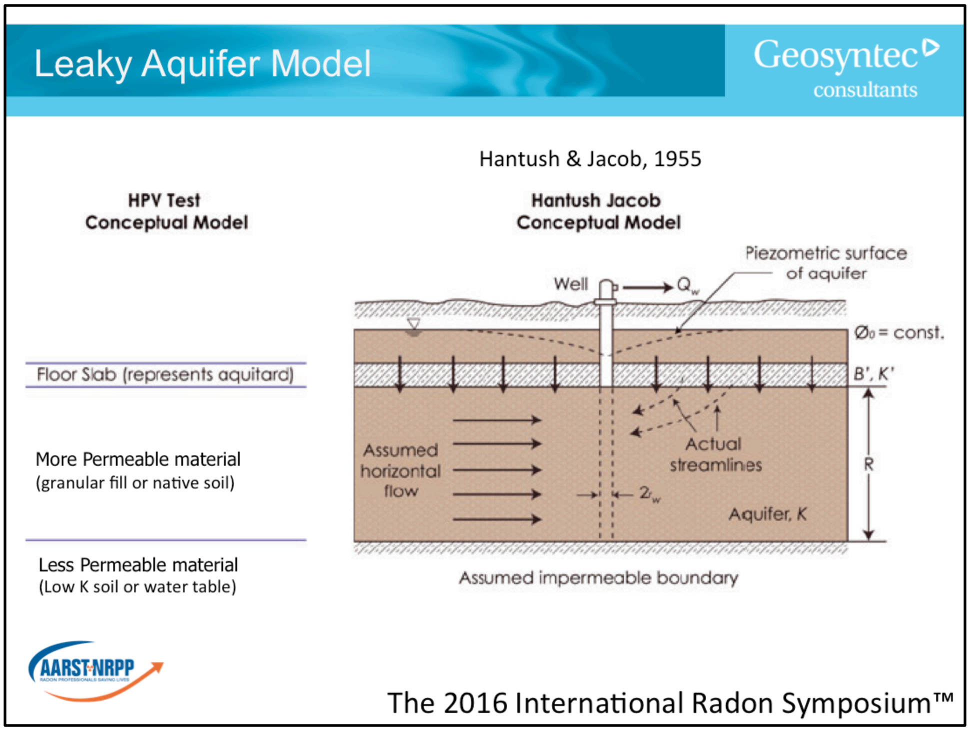
But flows of 1 m/day are considered sufficient for SVE (U.S. ACoE, 2002)

Permeability of silt through gravel spans a range of up to 1,000,000,000-fold

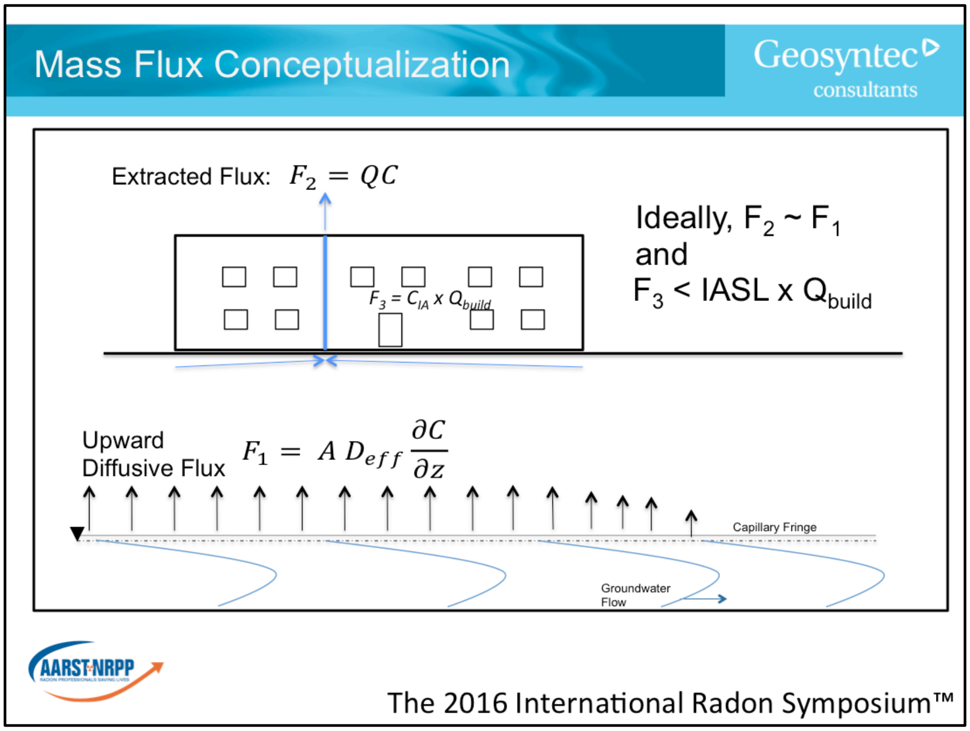
AARST-NRPP

The 2016 International Radon Symposium™

Vacuum and flow are related through permeability, according to Darcy's Law. The material below a concrete floor slab is often granular fill (3/4-inch Crusher Run, Granular A, Dense Grade Aggregate, Quarry Process, or similar as described in ASTM D 692 and ASTM D 1073), which usually has a fairly high permeability to air. Permeability spans a range of many orders of magnitude depending on the proportion of fine-grained materials (silts and clays). Permeability is much easier to measure than flow, but if you measure pressure gradient and permeability, you can calculate the flow via Darcy's Law, or variations of it.



Permeability is measured by hydrogeologists as a routine part of their work. Several mathematical equations have been developed for a variety of geologic scenarios, one of which is very similar to the scenario typically encountered for radon mitigation systems: the Hantush-Jacob Leaky Aquifer Model (Hantush, M.S. and C.E. Jacob, 1955. Non-steady radial flow in an infinite leaky aquifer, Am. Geophys. Union Trans., vol. 36, no. 1, pp. 95-100). In this scenario, flow occurs horizontally through a deeper layer and vertically across a shallower layer, which is similar to downward leakage of air across a floor slab with horizontal flow through soil or granular fill below the slab. This was originally derived for use with water, so a correction is required to account for the different density and viscosity of water and air. Otherwise, the equations of fluid flow through porous media are the same. The model assumes each layer is uniform, homogenous, isotropic and infinite, all of which are approximations. The fit between measured data and the model provides insight into how well the site conditions match the model assumptions, as described further below.

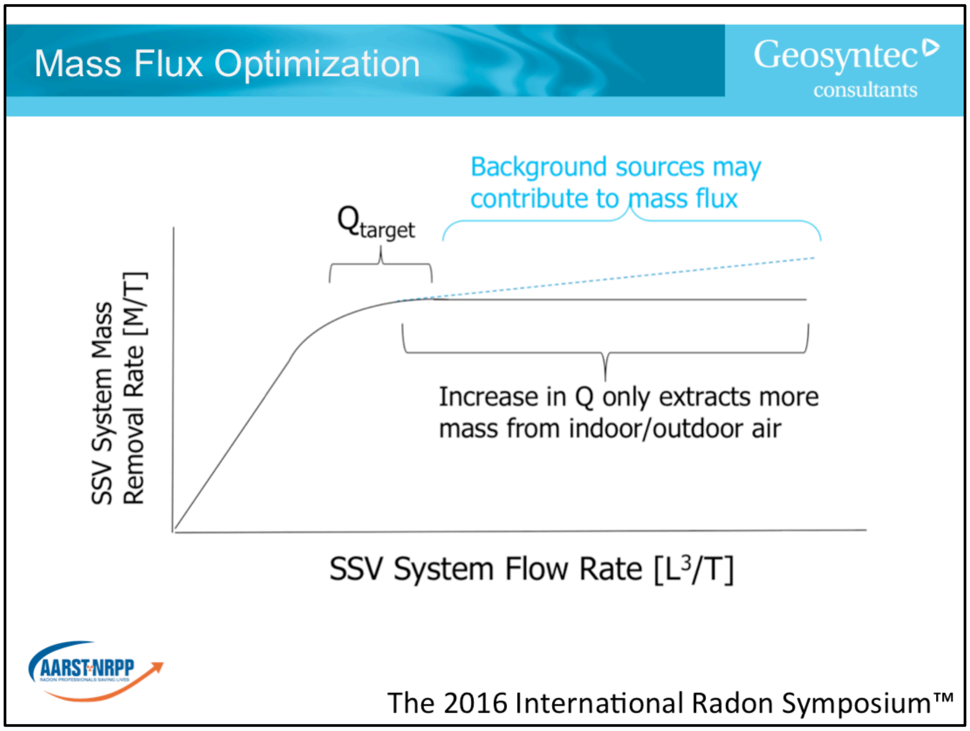


Another line of evidence for mitigation system performance is mass flux monitoring.

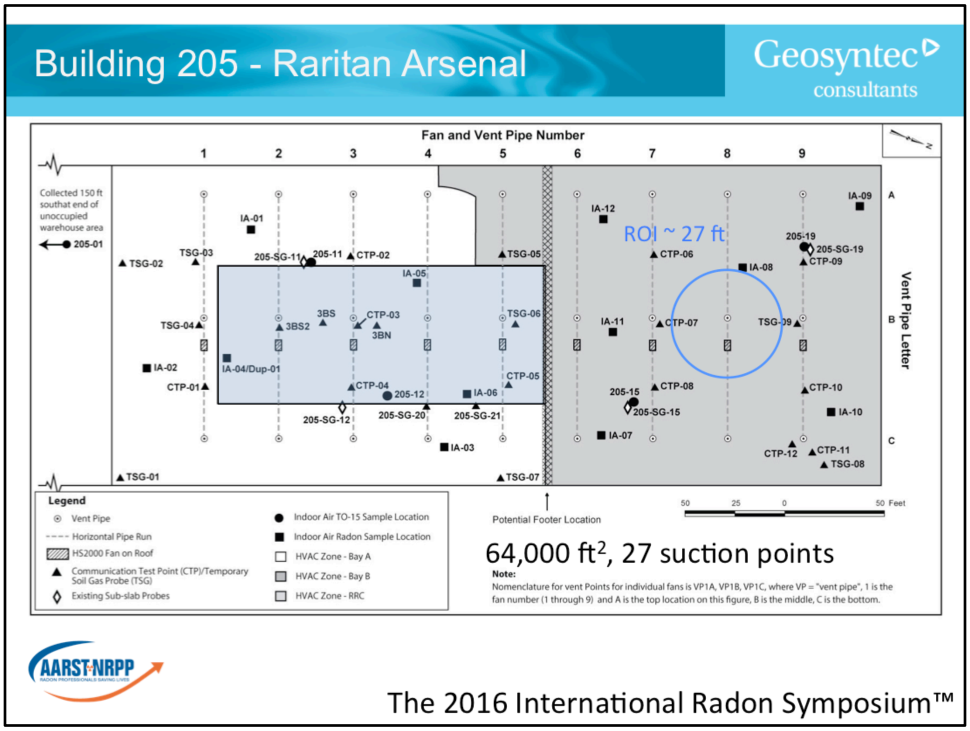
In theory, there is a certain rate of "supply" of wither VOCs or radon below a building. For VOCs, the supply is usually driven by upward diffusion from some source beneath the building according to Fick's First Law of diffusion (F1). The flux removed by the venting system (F2) is simply the concentration (C) in the vent pipe(s) multiplied by the flow rate (Q). If F2>F1, the system will be protective. If F2<F1, there will be some flux through the building (F3), which is the indoor air concentration (Cia) multiplied by the flow rate through the building at the time Cia is measured (Qbuild).

F1 can be calculated if the source depth and concentration is known (to calculate the vertical concentration gradient), and the soil porosity and moisture are known (to calculate the effective diffusion coefficient Deff). For Radon, the source is immediately below the building, so this is a bit more challenging to measure.

F2 can be be calculated by measuring the flow in the vent-pipe using a thermal anemometer or pitot tube and collecting a sample of the extracted gas for analysis. For VOCs, this can be done with a Tedlar bag/vacuum chamber, Summa canister or permeation passive sampler. For radon, it can be done with a Durridge RAD7 or similar instruments.



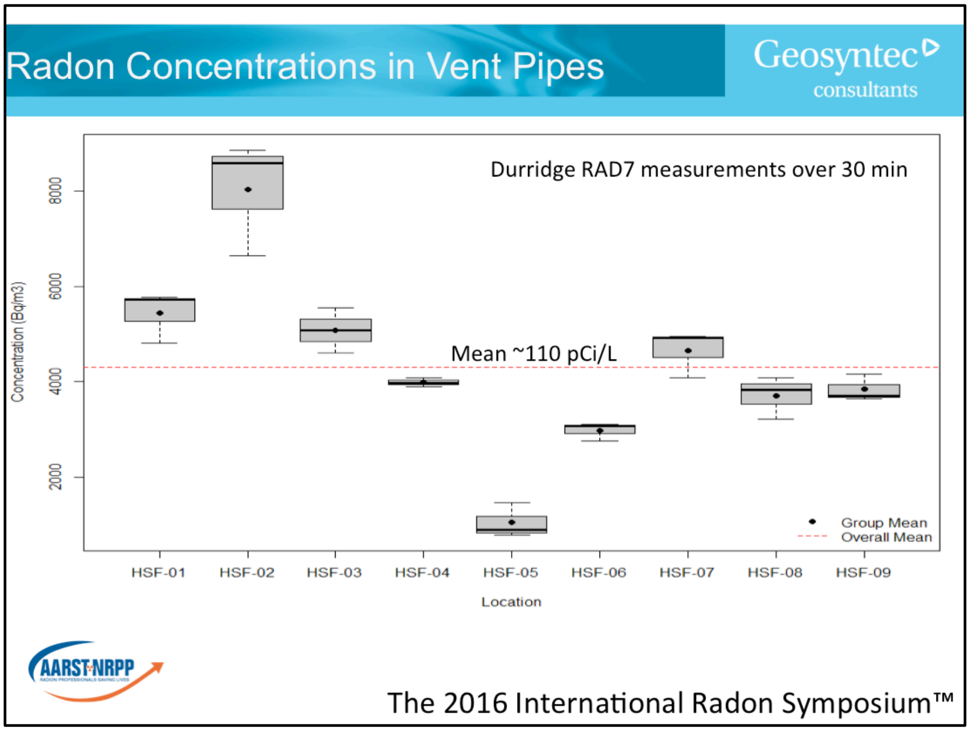
The mass flux removed by the venting system (F2) would be expected to increase as the flow rate increases, but at some level, all of the VOCs or radon would be captured and the mass removal rate would level off. Higher flow rates would then result in no added protection, and would just be a waste of energy for powering the fans and draw more conditioned indoor air through the floor (which is also a waste of the energy used to heat, cool, humidify, dehumidify, filter, or otherwise condition the air). About 30% of the cost of operating a commercial or industrial building is spent on conditioning the air, so this component of the energy cost can be significant. The pneumatic testing part of this research can be used to assess the amount of leakage across the floor, so the energy cost of loss of conditioned air can be calculated.



Four Case Studies will be used to demonstrate and validate the technology. The first is a commercial/industrial building at the former Raritan Arsenal in New Jersey, once owned by the Army Corps of Engineers and now occupied by the United States Environmental Protection Agency. Trichloroethene (TCE) was detected in nearby groundwater and in sub-slab samples at concentrations above risk-based screening levels, so a mitigation system was installed about a decade ago. The system consists of 27 suction points and 9 high suction fans, each fan is connected to three suction points through a header that runs below the roofline. The building is 64,000 ft2, so each suction point covers 2,370 ft2, which is equal to an average radius of influence of 27 feet.

For reference, there are numbers 1 to 9 across the top of the floorplan to indicate the fan numbers and letters A, B and C down the right side to identify the three rows of suction points. Suction point 1A is at the upper left corner, for example. Sub-slab probes were installed at selected locations, for example, between suction points 3A and 3B (labeled 3AB), or a few feet to the right or left of the central suction point, perpendicular to the line between the suction points. These locations provide for certain symmetries in the data analysis, all of which can be handled by the AQTESOLV software.

The fans are on the rooftop, and the combined flow is about 500 standard cubic feet per minute (scfm). The portion of the building to the right of this image is a warehouse that is not routinely occupied and was therefore not mitigated.



The radon concentrations in the vent pipes were measured using Durridge RAD7 over a period of 30 minutes each, with the results shown in this figure. 7 of the 9 fans had results close to the mean of 110 picocuries per liter (pCi/L). Fan 2 had a higher concentration and fan 5 had a lower concentration, which may indicate that the amount of leakage across the floor is less near fan 2 and more near fan 5.

Mass Removal Rate

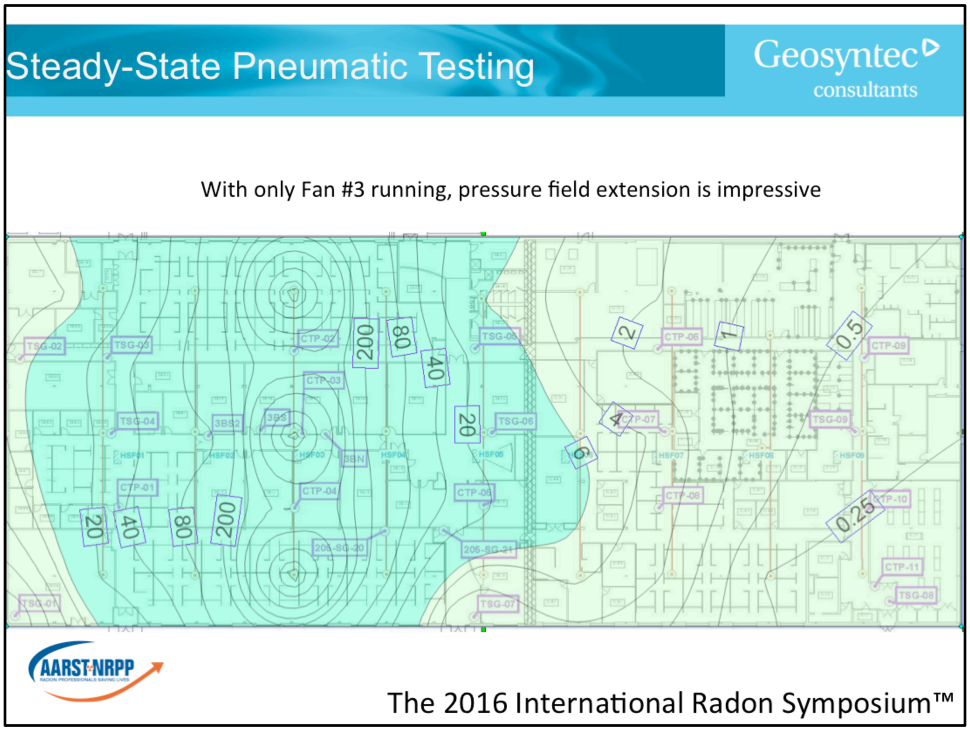
Geosyntec consultants

Fan ID	Fan Q (scfm)	Fan Q (m^3/min)	TCE Conc. (ug/m^3)	Mass Flux (g/d)	Proportion of MF
HSF-01	30.41	0.861	100	0.124	27%
HSF-02	26.54	0.751	58	0.063	14%
HSF-03	30.52	0.864	100	0.124	27%
HSF-04	46.45	1.315	49	0.093	20%
HSF-05	63.50	1.797	9.3	0.024	5%
HSF-06	72.40	2.049	3.4	0.010	2%
HSF-07	72.35	2.048	2	0.006	1%
HSF-08	73.04	2.067	3.4	0.010	2%
HSF-09	73.35	2.076	1.4	0.004	1%
			Total MF (g/d)	**0.458**	

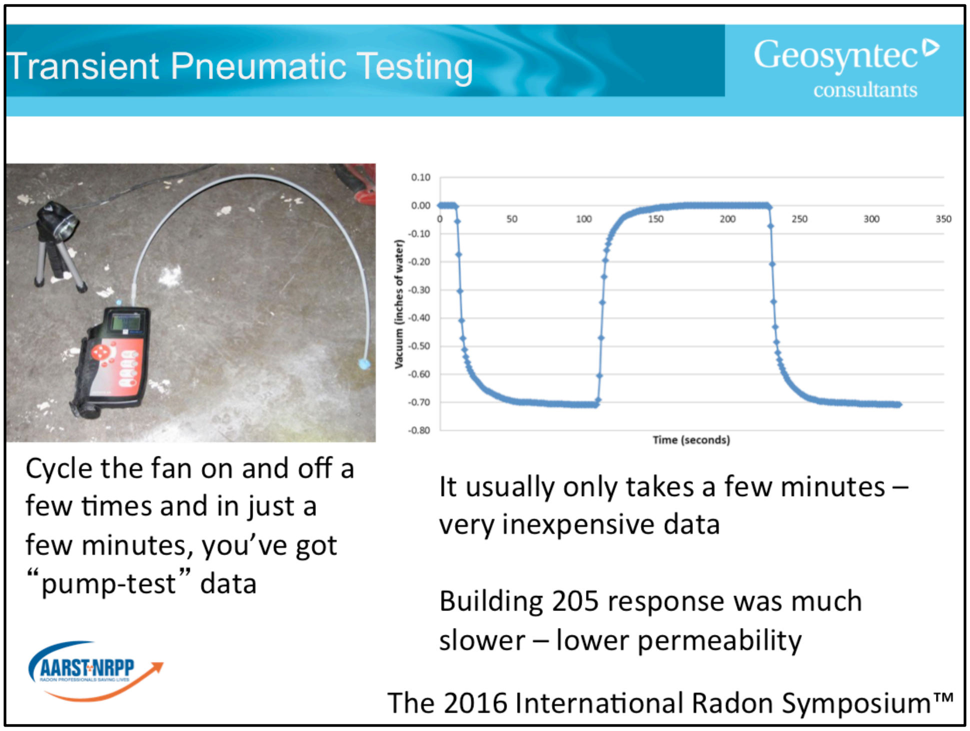
Average [TCE] less than industrial IASL

The 2016 International Radon Symposium™

TCE concentrations were also measured in each fan (over 30 days using a Waterloo Membrane sampler), and the mass flux of TCE was calculated as a the product of the flow rate and concentration. The total mass removal rate was 0.46 grams per day, which was dominantly from fans 1 through 4.



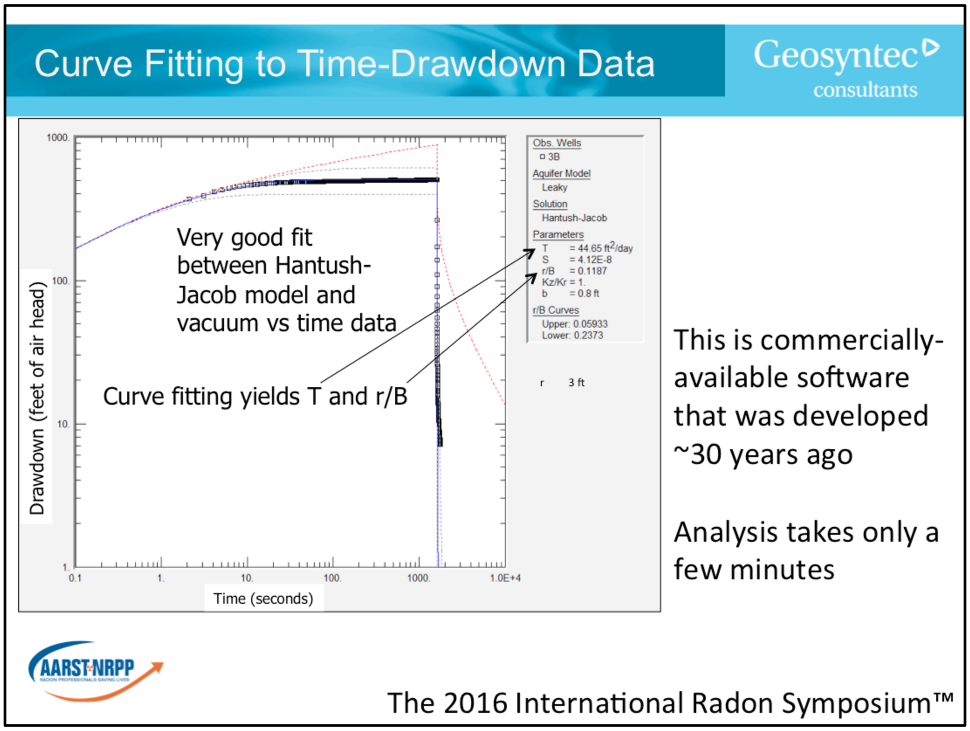
8 of the 9 fans were turned off and sealed overnight on a weekend to assess the pressure field extension. Fan 3 alone achieved a vacuum under the areas of TCE distribution. A measurable vacuum (>1 Pa) was observed up to about 200 feet from the suction points. This alone might have been sufficient diagnostics for an adjustment to the system operations, but the goal of this research was to test several lines of evidence to assess their relative costs/ benefits and capabilities/limitations. Furthermore, VOC vapor intrusion guidance documents promote the use of multiple lines of evidence, so pneumatic and mass flux monitoring was also performed.



Pneumatic testing included measuring steady-state vacuum as a function of radial distance from the suction points (slide 12), and transient vacuum response at selected probes. Vacuum vs time and vacuum vs distance are two independent data sets that can be used collectively to fit to the Hantush-Jacob Model. Using two data sets provides a unique solution of the two key parameters: 1) the transmissivity of the material below the floor (T) and the leakance of the floor (B).

This plot shows a typical set of transient response data (not from Building 205). The pressure below the floor is initially neutral, and after a few seconds when the fan is turned on, the vacuum established and eventually stabilizes (usually within a few minutes or less). With fast response, the test can be repeated to verify reproducible results. Two cycles are shown in the plot above within 5 minutes.

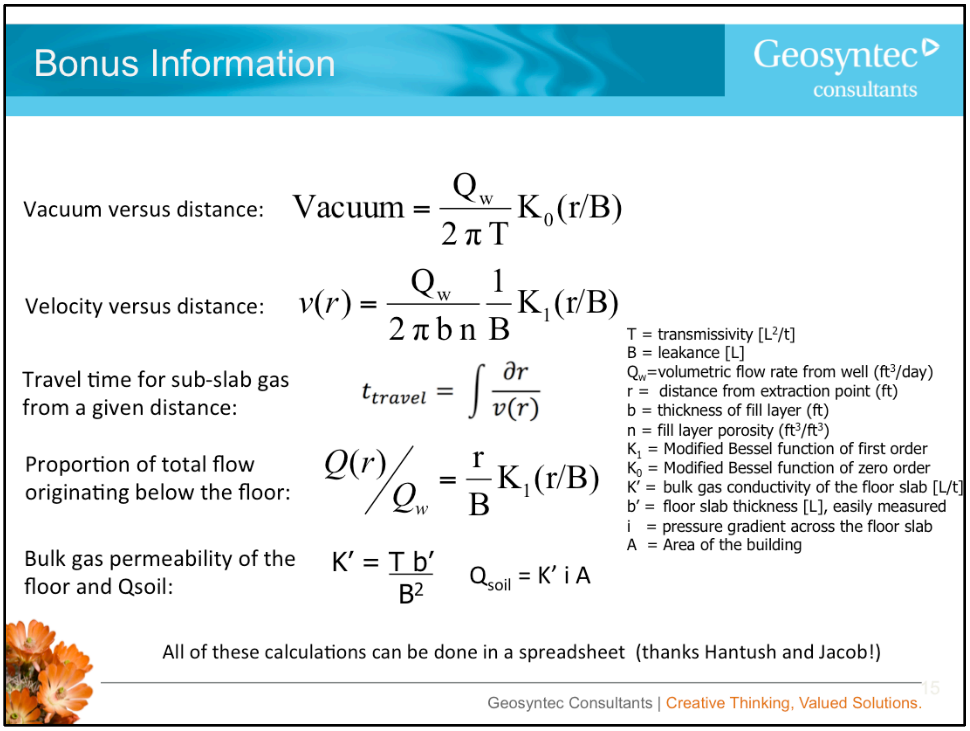
At Building 205, the time to stabilize was about 30 minutes – even without mathematical analysis, it should be obvious that the material below the floor and the floor itself can't be very permeable if it takes a very long time for vacuum to dissipate after the fan is turned off.



The vacuum versus time data are converted from pascals or inches of water column to feet of air head and a similar correction is done for the viscosity of air compared to water (Thrupp, G., J. Gallinatti, and K. Johnson, 1996. Tools to Improve Models for Design and Assessment of Soil Vapor Extraction Systems. Subsurface Fluid-Flow Modeling, ASTM STP 1288, eds. J.D. Ritchey and J.O. Rumbaugh, American Society for Testing and Materials, Philadelphia, pp. 268-285.)

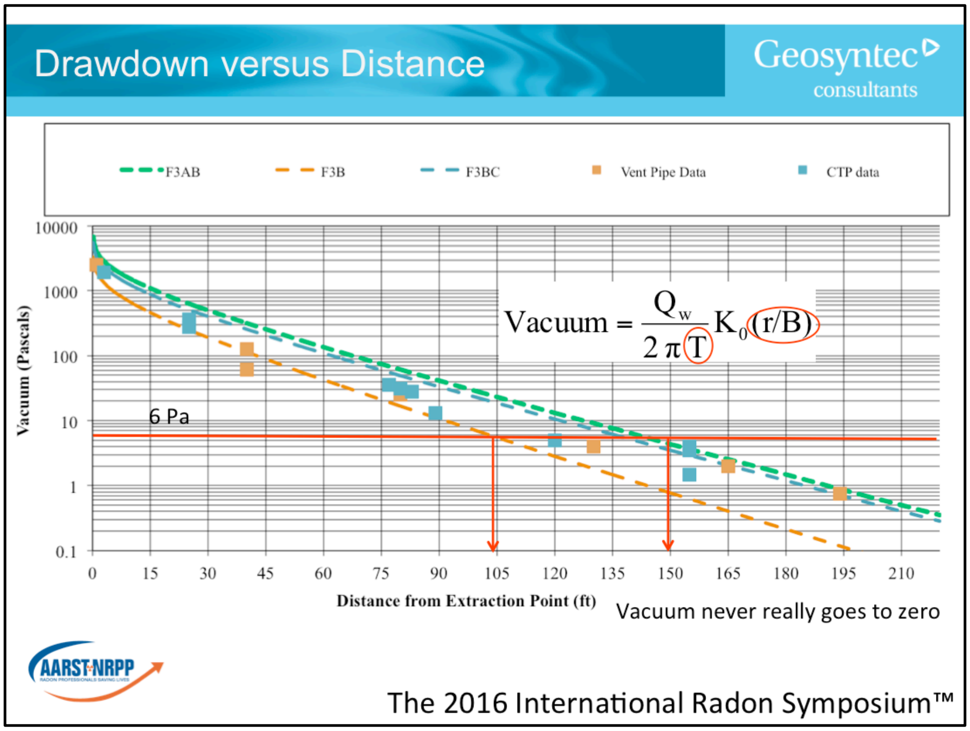
The data are analyzed using AQTESOLVE (http://www.aqtesolv.com), a commercially-available software package for groundwater hydraulic test analysis. The software provides automated fitting between the model and the data, and the result is usually a very close fit, as shown in this plot. If there are conditions below the floor slab that are not uniform, homogenous, or isotropic, the data may deviate from the model in predictable ways. The art of interpreting the deviations is well established for groundwater pumping tests, but not as much so yet for sub-slab pneumatic test analysis.

The fit to the time-drawdown data is not unique, there are two parameters (T and B) and only one set of data in this plot, so an increase in one parameter and a decrease in the other may still provide a good fit. However, the distance vs vacuum data shown on slide 16 is also fit using the T and B parameters, so the analysis consists of iterating between fitting the vacuum vs time data and the vacuum vs distance data until one unique set of T and B values fits both sets of data.



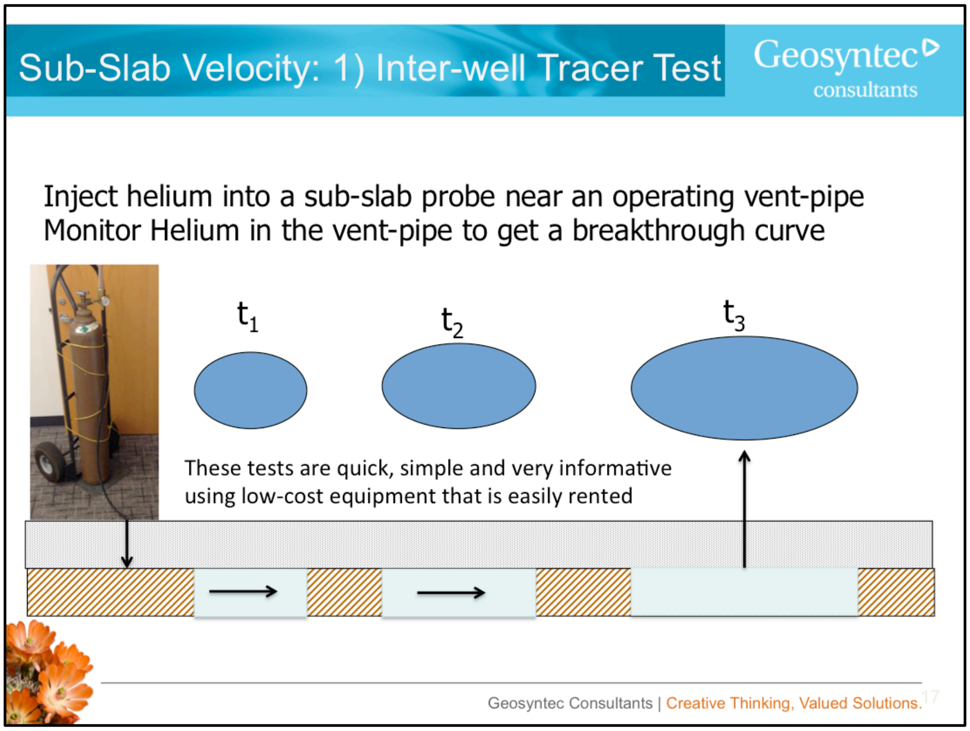
Once the T and B values are know, several relationships can be calculated as a function of radial distance from the point of suction: vacuum, velocity, travel time, and the proportion of flow from above vs below the floor. These equations can all be performed using Microsoft Excel or other spreadsheets. The vacuum vs distance plot is shown on slide 16, along with measured vacuum data to show the model calibration. Travel time versus distance is shown on slide 21 along with helium tracer test data which also can be used to verify the model calibration.

The bulk average vertical gas conductivity of the floor (K') can also be calculated if the thickness of the floor slab (b') is known. The ambient level of soil gas flow across the floor slab (Qsoil) can also be calculated if the ambient pressure gradient across the floor (i) is known. The pressure gradient is easily measured with a pressure transducer / data logger over time, but the pressure differential is not constant, so the Qsoil value is also variable. Some judgment is needed to select values of interest from the frequency distribution (e.g., a 95th percentile value is usually considered protective for human health risk assessment under Superfund).



This plot shows the sub-slab vacuum measured with only Fan 3 running as a function of distance from the nearest vent pipe. The dashed lines represent the relationship calculated using the Hantush-Jacob model and T and B values derived from 3 probes: 1) F3AB – located in between the "A" and "B" suction points for fan 3, 2) F3B – located about 3 feet beside suction point 3B, in a line perpendicular to the line between the three suction points, and 3) F3BC – located between the "B" and "C" suction points. Refer to slide 8 notes for more description of the locations. The transient response is unique for each location, which is why the three dashed lines are not identical. The fit between the distance vs vacuum data is not as good as the time vs vacuum data, which is because pneumatic properties have spatial variability, but not temporal variability (at least not over the course of the transient pneumatic tests).

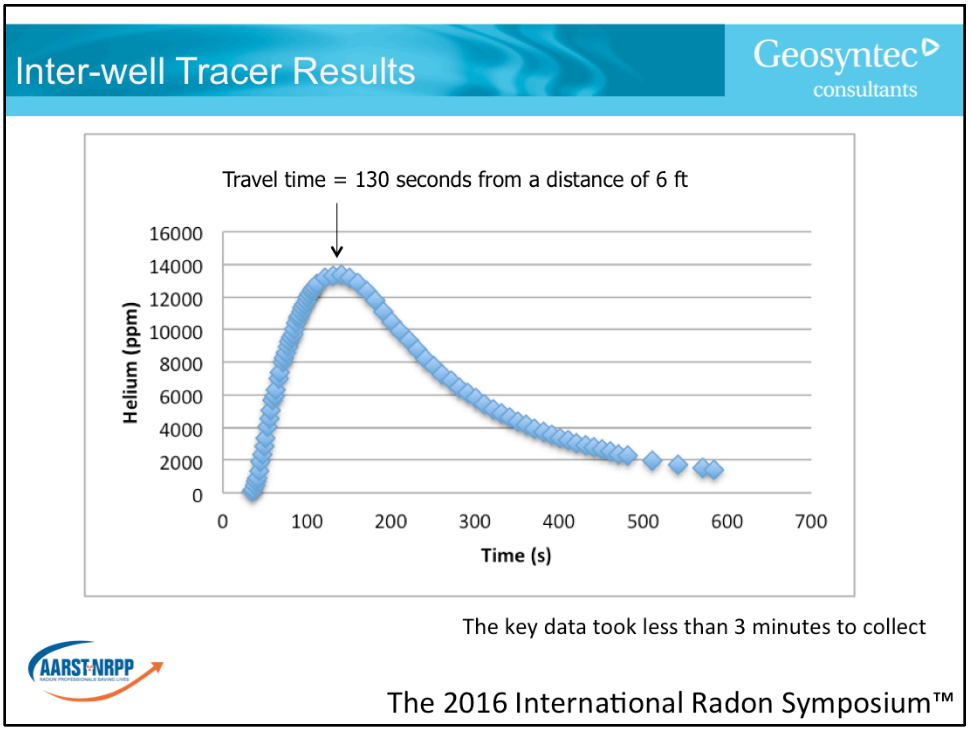
Note that the maximum measured vacuum is about 2000 pascals and the minimum measured vacuum is about 1 pascal, and the model curves have a trend that is similar to the data throughout this range. Having a vacuum measurement that is very close to the suction point is actually very useful for constraining the slope of the dashed lines, which helps minimize uncertainty in the T and B values derived from the model fitting. Vacuum measured in the vent-pipes and measured in sub-slab probes were similar for any given radial distance. A vacuum of 6 pascals was achieved to a distance of about 100 to 150 feet, much larger than the average radius of influence



Flow velocity may provide a useful metric. In the field of soil remediation for VOCs using soil vapor extraction, a target velocity of 1 m/day is considered a reasonable minimum design goal (USACOE, 2001, USEPA, 2002). It can be difficult to measure a velocity this low, but it is possible to measure the travel time for a tracer through the flow-field. Two tests are relatively easy to implement: 1) the inter-well tracer test, and 2) the tracer flood test.

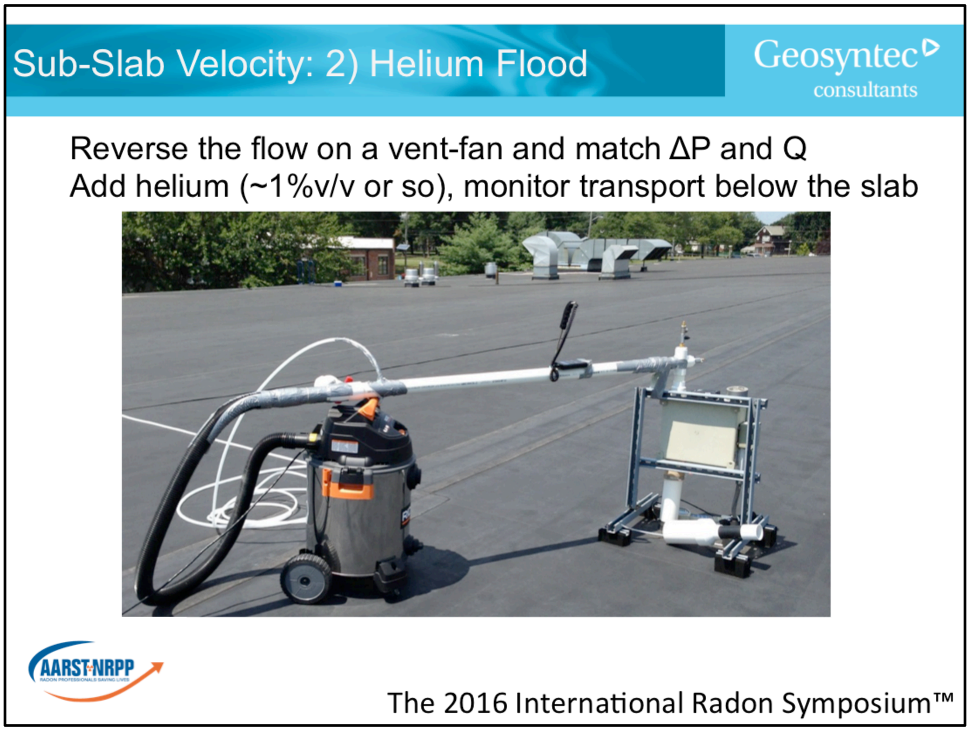
In the inter-well test, a tracer (in this case, helium) is injected into a sub-slab probe near a suction point and the concentration in the gas extracted through the suction pipe is monitored as a function of time since the midpoint of the injection. For a probe within about 10 to 20 feet of the suction point, a volume of about 10 L of 100% helium will provide a signal that can be easily measured in the vent-pipe. Resulting data is shown on the next slide.

USACOE 2002. Engineer and Design - Soil Vapor and Bioventing Engineer Manual. U.S. Army Corps of Engineers. EM-1110-4001. June, 2002.
U.S. EPA. 2001. Development of Recommendations and Methods to Support Assessment of Soil Venting Performance and Closure. Washington, DC: Office of Research and Development. EPA/600/R-01/070, September 2001.

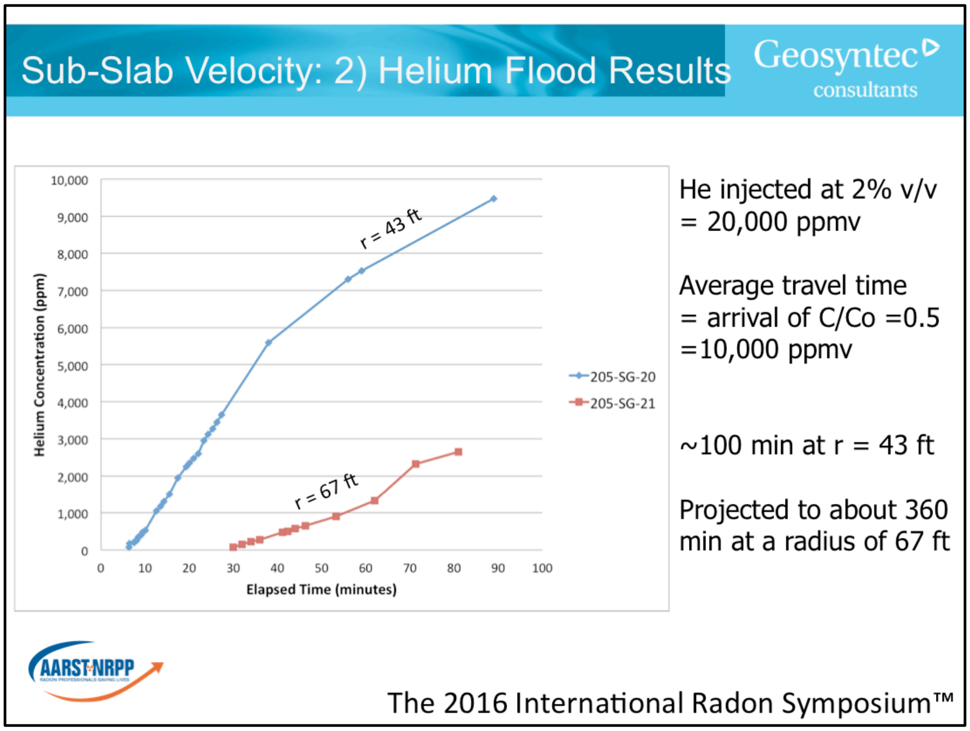


The breakthrough curve for an interwell tracer tests looks like this plot. The time for the concentration to reach the peak value is the average travel time, in this case, 130 seconds from 6 feet (this is for a low permeability scenario; tests in high permeability cases have shown similar travel times for distance of 75 feet).

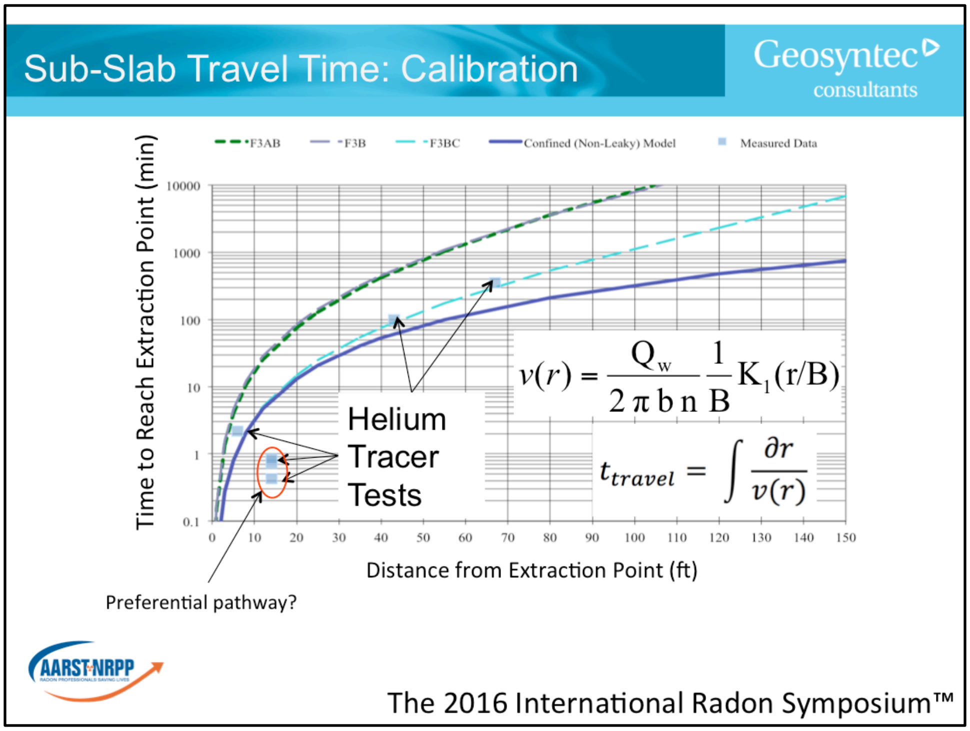
Note that the curve has some spread from first arrival (about 30 seconds) to last arrival (>600 seconds), which is attributable to diffusion and dispersion. For tests originating at progressively farther distances from the point of suction, the duration of the test increases, and the spread increases as well, until at some distance, the test results show a very broad curve that is not as easily interpreted. This test should work well in most domestic residences, but has limitations for larger commercial buildings. For larger distance, the tracer flood method described below is preferable.



The tracer flood method (in this case helium was the tracer) uses a fan or blower (in this case a Shop Vac) to blow air into the mitigation system, and force it to distribute below the floor. In this photo, the exhaust port of the Shop Vac is connected to a hose that is connected to the High Suction fan, which is turned off. A bleed air valve is in-line between the ShopVac and the radon fan that allows the operator to adjust the applied pressure. When the pressure is dialed to be equal in magnitude to the normal operating vacuum, the system will be operating at the same flow rate as normal operations, but in the opposite direction. The white tube at the upper left is connected to a helium cylinder on the ground, and helium was added at about 2% by volume (1% is also adequate for easy detection). A portable helium instrument was used to monitor the arrival of helium at several sub-slab probes at progressively farther distances from the vent-pipes. The longer the test, the greater distances helium will migrate. In this case, the test was run for 90 minutes.

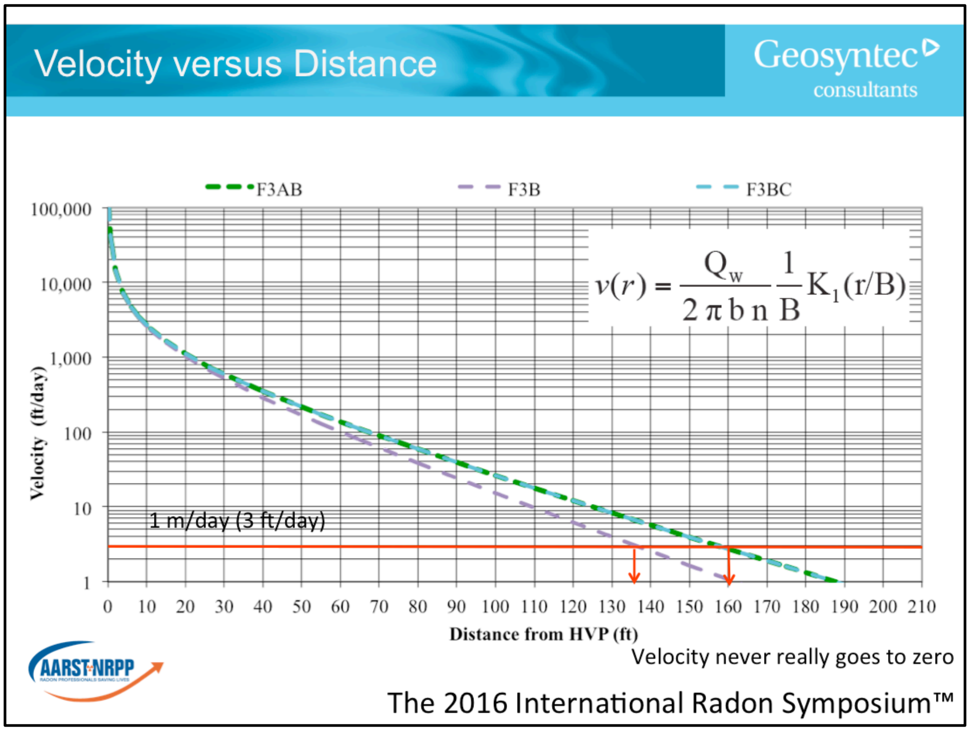


The breakthrough curves for the tracer flood test rise until the concentration equals the injected concentration, then level off. The average travel time is the time required to reach a concentration 50% of the injected concentration. At a distance of 43 feet, this was about 100 minutes. At a distance of 67 feet, the helium concentration reached only about ¼ of the target concentration before time ran out. Considering that the data from 43 feet took about 4 times longer to reach 10,000 ppm than the time required to reach 2,500 ppm, it could be estimated that the data from 67 feet might have reached 10,000 ppm at a time of about 4 x the test duration, or about 360 minutes. These travel times are plotted on slide 21 along with inter-well tests and compared to the travel times calculated using the equations on slide 15 as an additional verification check on the applicability of the Hantush-Jacob model.



This plot shows 6 tracer tests and the profile of travel time versus distance calculated using the Hantush-Jacob model (dashed lines). Three of the tracer tests match up well with the model results and three of the tracer tests show a much faster velocity (lower travel time) than the model would predict. The three fast tracer tests were performed along a wall internal to the building running down the centerline of the building, which may have been a structural wall and had a footing, so the results may indicate preferential flow through granular fill surrounding the footing (this would require independent verification, which was not possible during the time available for field testing). The tracer testing method might be able to help identify preferential pathways below a floor, which is a topic area of increasing concern for VOC vapor intrusion following publication of several articles on a residential building that was purchased by Arizona State University for applied research (SEDRP Project ER-1686 https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-1686/ER-1686 and ER-2015-01, https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-201501/ER-201501).

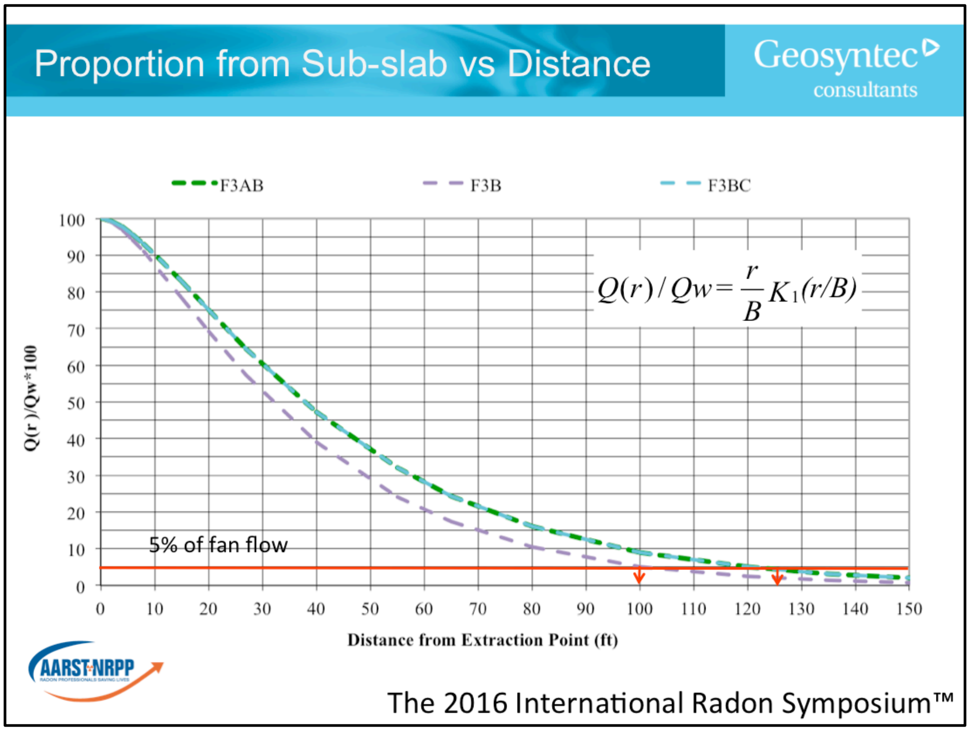
At a radius of 100 feet, the model predicts a travel time in the range of 1000 to 10000 minutes (0.7 to 7 days). Slide 16 indicates this corresponds to a vacuum of >6Pa, which would normally be considered sufficient for protection from vapor intrusion. Note that the velocities would be much faster if the material below the floor was more permeable.



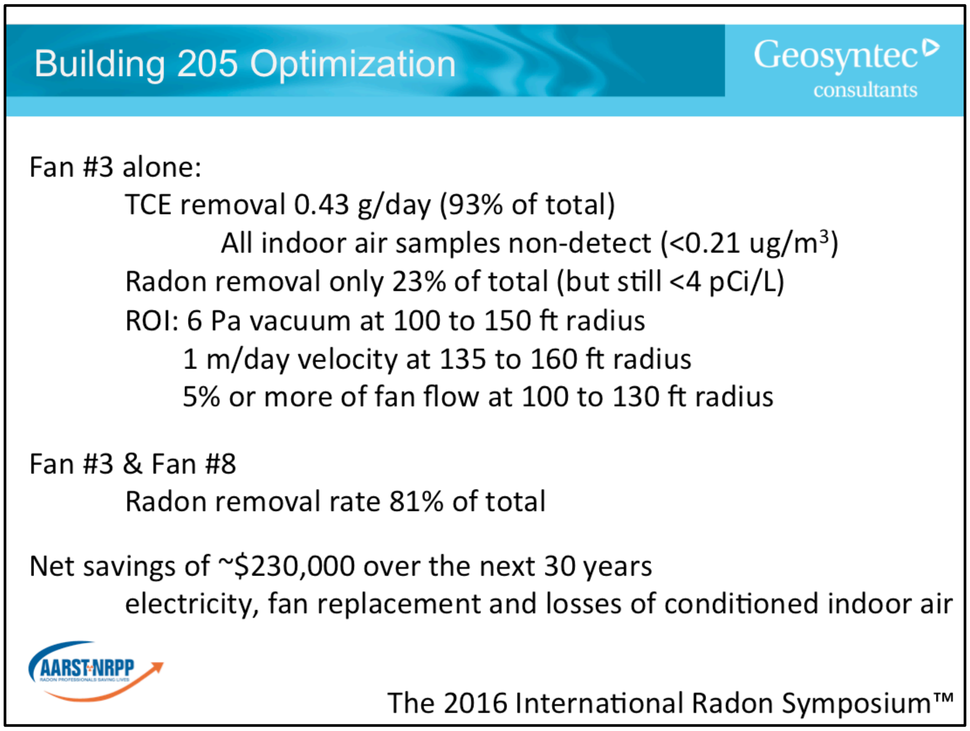
The velocity profile corresponding to the previous slide is shown here for comparison. At a radial distance of 100 feet, the velocity is in the range of 13 to 30 feet per day (N.B., recall that this radius corresponds to vacuum >6 Pa), and the velocity increases as the distance to the suction point decreases with a maximum velocity of about 1 ft per second at the suction point.

At a radial distance of 135 to 160 feet, the model predicts a flow velocity of about 1 m/day, which is considered effective for soil vapor extraction systems for remediation of VOCs in soil (USACOE, 2002, USEPA, 2001). This corresponds to a vacuum as low as about 1 Pa (see slide 16).

USACOE 2002. Engineer and Design - Soil Vapor and Bioventing Engineer Manual. U.S. Army Corps of Engineers. EM-1110-4001. June, 2002.
U.S. EPA. 2001. Development of Recommendations and Methods to Support Assessment of Soil Venting Performance and Closure. Washington, DC: Office of Research and Development. EPA/600/R-01/070, September 2001.



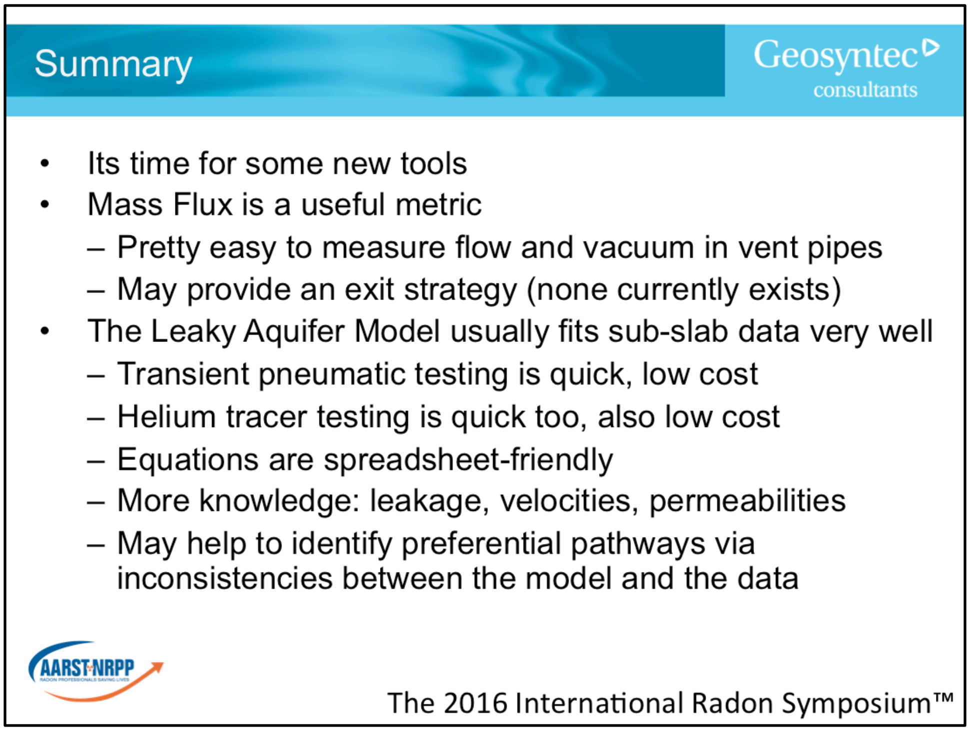
The calibrated model can also be used to predict the amount of indoor air leaking across the floor slab. At a radial distance of 100 to 125 feet, for flow originating from below the floor is 5% of the total fan extraction rate. In other words, 95% of the air extracted by the fan originated as indoor air within that radius. This can be used to calculate the energy cost associated with leakage across the floor slab (see slide 24).



Running Fan 3 alone captured 93% of the total TCE that was captured by running all 9 fans and resulted in indoor air TCE concentrations <0.21 micrograms per cubic meter (ug/m3), which is more than 10 times lower than the risk-based target concentration for commercial buildings (3 ug/m3). However, this only removed 23% of the total radon loading (although all indoor air radon concentrations were still less than 4 pCi/L).

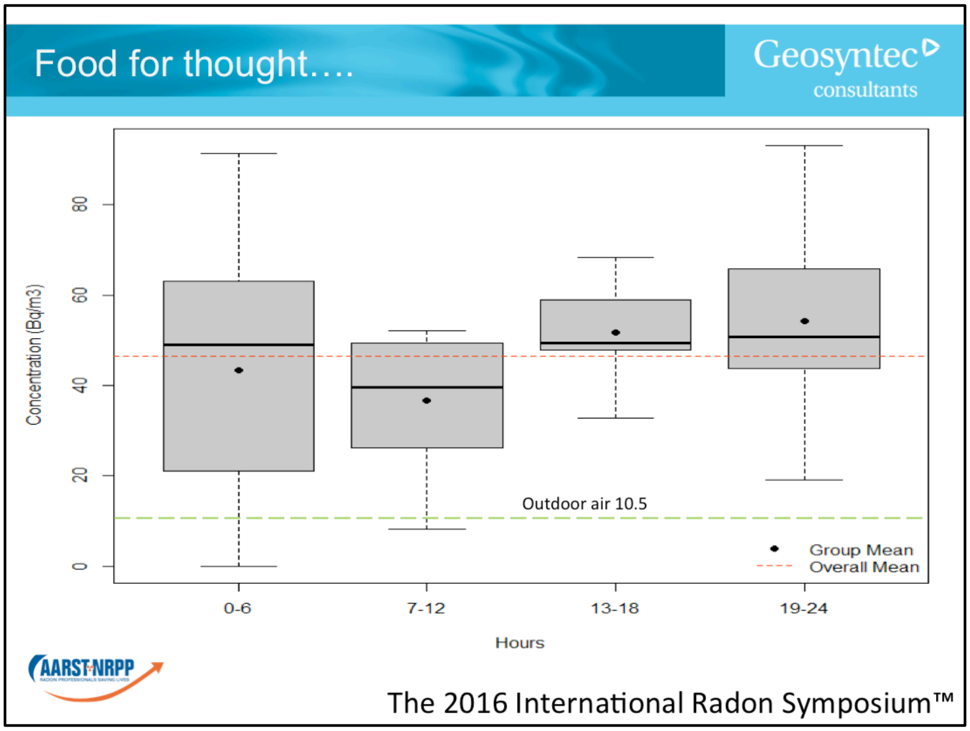
Running Fans 3 and 8 resulted in removal of 81% of the total radon loading, and was adopted as an optimized mitigation scheme.

The total flow from the two fans was about ¼ the flow of the original system. Savings included reduced costs for fan replacements, reduced cost of energy losses from electricity to operate the fans and reduced loss of conditioned indoor air, totaling about $7,700 per year, or $230,000 for a 30 year total (with no discounting).

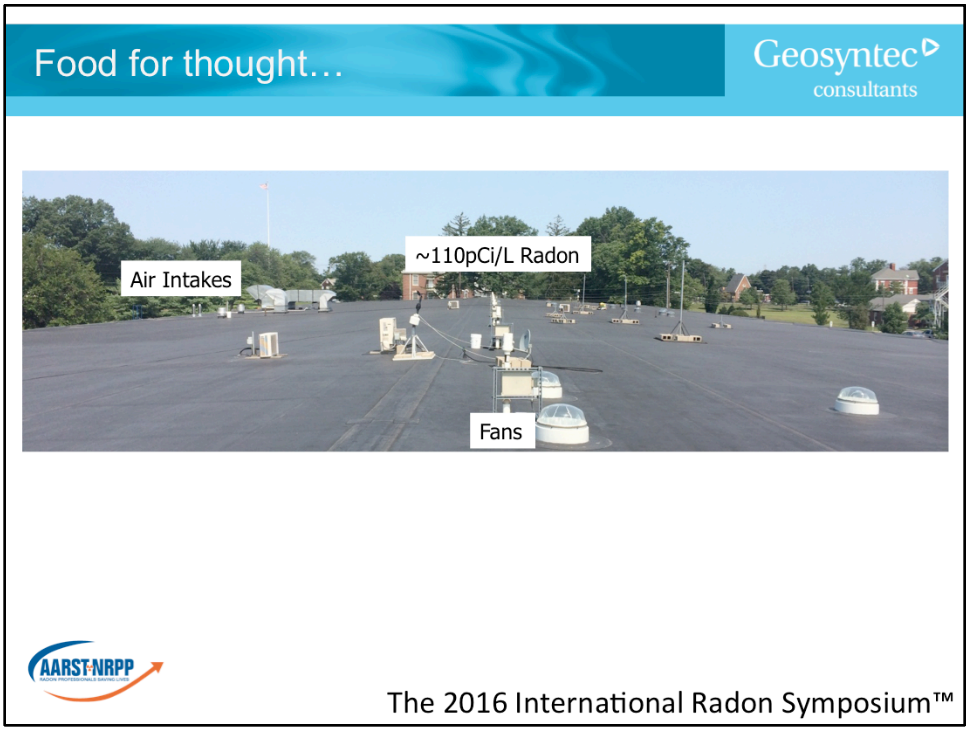


Research is ongoing, and testing has been done now at two residential size buildings, with one more test planned for a medium size commercial building. The relative merits of the various test methods described here will be weighed after the testing program is complete to develop a strategy for mitigation system design and performance monitoring that will provide protection and energy efficiency for both radon and VOCs. AARST may wish to incorporate some or all of these findings in their guidance documents and standards.

ESTCP Project # ER-2013-22 will provide publications and reports to document the research on building system optimization. https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-201322/ER-201322



As an aside: indoor air radon concentrations were elevated above outdoor air concentrations when all 9 fans were running (which was arguably an over-designed system). Why?



Perhaps there was some recycling of the discharge from the fans (about 3 feet above roof level), considering the air-intakes are also about 3 feet above roof level. On days with minimal wind, the radon discharged from the fans may not disperse effectively enough to avoid re-entrainment. This should be a consideration during the design and installation of a venting system.

Feel free to contact the author with any questions:

Todd A McAlary, Ph.D., P.Eng., P.G., CUT
Practice Leader – Vapor Intrusion Services
Geosyntec Consultants, Inc.
And Adjunct Professor, U. of Toronto
3250 Bloor Street West, Suite 600
Toronto, Ontario M8X 2X9
Direct: 416.637.8747
Cell: 905.339.7066
Fax: 647.775.1501
www.Geosyntec.com
click here for Geosyntec's Vapor Intrusion SOQ