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RADON CONTAMINATION OF RESIDENTIAL STRUCTURES III: AN OVERVIEW OF FACTORS INFLUENCING INFILTRATION RATES

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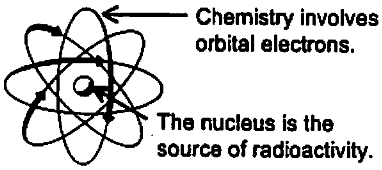
ABSTRACT

Given a radon source in the underlying geology, soil structure conducive to its movement, and entry pathways into a structure, radon infiltration is an entirely weather-driven phenomenon. Infiltration rates are significantly affected by a number of structural, physicochemical, and environmental factors. First, a brief overview of radioactive decay processes as they relate to the origin of radon is provided. It serves as a foundation to the discussion of a number of important factors that bear upon radon infiltration rates. Next, the complexity of their interplay and their relative impact on the long-term radon profile in typical residential structures is discussed. Supporting the review are correlative results of a substantial and ongoing study of the radon profile in a normally occupied midwestern residence

RADON: ITS ORIGIN AND GENEALOGY

The U.S Environmental Protection Agency (EPA) characterizes radon as the leading cause of lung cancer among non-smokers. Radon is a colorless, odorless, tasteless, chemically inert, radioactive noble gas originating in the radio-decay of uranium in soils. Because it is generated in soil from which it gradually diffuses into the atmosphere, radon occurs in outdoor air at levels of less than 1.0 pCi/L. If entry pathways exist between its points of origin in soil and a building, radon may be drawn or forced into the structure by weather-driven processes.

The EPA recommends that homes with radon levels of 4.0 pCi/L be mitigated to a level as low as reasonably achievable. In the United States, radon is measured in units of picoCuries per litre (pCi/L) of air. In Europe, the unit is the Becquerel per cubic metre (Bq/m^3) where 1 Bq/m^3 = 37 pCi/L. Both represent a measure of radon decay per unit volume of air.



Radioactive decay is defined as the emission of high energy particles and / or electromagnetic radiation from the nuclei of unstable atoms. Radiodecay may be likened to a continuing series of atomic explosions occurring at random inside the nuclei of individual atoms. Radioactive emanations of interest to this discussion occur in three forms: alpha particles – relatively massive high energy helium nuclei consisting of two protons and two neutrons, beta particles (sometimes referred to as beta rays) – high energy electrons expelled from the atomic nucleus, and gamma rays – bursts of electromagnetic waves emanating from the nucleus. It is such radioactive emanations that pose a threat to public health. Radioactive decay that produces radon, its isotopes, and daughter products involve all three decay modes.

Nuclides (isotopes) are different mass forms of an element. Specific nuclides are denoted by their elemental name followed by their mass number. Only three of the seven known isotopes of radon play a role in the what has become referred to as "the radon problem." All but one of the radon decay products (RDPs) are electrically charged, radioactive solids which remain essentially immobile in soil. That having been said, if radio-decay occurs after the gas enters the home, the RDPs can attach themselves to airborne dust particles which may be inhaled — thus, the health hazard. Those that attach to surfaces from which they are not displaced pose no threat to health.

Science knows of no process that can alter rates of radioactive decay – thus, the constancy of half lives (a measure of nuclide lifetime) and the persistence of the problems posed by long-lived isotopes. Radon-222, the major isotopic contributor to the radon problem, has a half-life ($t_{1/2}$) of 3.82 days. That is, in a time-span of 3.82 days, a fixed initial quantity of radon will have undergone nuclear decay such that only half of the original amount is present. In another 3.82 days only one-quarter of the original amount remains; in still another 3.82 days, only an eighth remains. Whatever the decay mode or rate, in general, passage of about ten half-lives is sufficient for virtually all of the radioisotope to decay to a level indistinguishable from background terrestrial radiation.

In a series of radio-decay events, uranium-238 is transformed into radium-226, thence to radon-222, and finally to lead-206. Intermediate in the overall sequence is the radio-decay of radon-222 atoms. These are transformed into a family of solid daughter isotopes terminating with lead-206 which is stable. Major decay sequences (and half lives where: y = yr, d = day, m = min, s = sec) from uranium-238 to lead-206 are:

U-238 ($t_{1/2}$= 4.5x10^8 y) ⇒ Ra-226 ($t_{1/2}$= 1600 y) ⇒ **Rn-222 ($t_{1/2}$= 3.82 d)** ⇒ Po-218 ($t_{1/2}$= 3.11 m) ⇒
Pb-214 ($t_{1/2}$= 26.8 m) ⇒ Bi-214 ($t_{1/2}$= 19.8 m) ⇒ Po-214 ($t_{1/2}$= 0.0002 s) ⇒ Pb-210 ($t_{1/2}$= 22 y) ⇒ Pb-206

It is the infiltration of radon-222, the isotope most commonly associated with the "radon problem," that poses the most significant health hazard to occupants of radon-contaminated buildings. Two other noteworthy, though somewhat less important, gaseous radio-decay products are thoron, Rn-220 ($t_{1/2}$= 55 seconds) and actinon, Rn-219 ($t_{1/2}$= 4 seconds). Of these, radon-219 poses an almost insignificant risk because it has an exceedingly short half-life. Furthermore, its parent isotope, uranium-235, is relatively scarce in soils. The precursor isotope of radon-220 is thorium, a radioactive element somewhat more abundant than uranium-238. The longer half-life of thorium ($t_{1/2}$= 1.4x10^{10} y) enables generation of radon-220 at about the same rate as radon-222. Even so, the short half lives of both radon-219 and -220 limit the time available for their migration through soil interstices. This, of course, enhances the likelihood that when they do decay their RDPs will remain trapped in the soil.

It is important to distinguish between "radio-decay rate" and "emanation rate" — these terms are not equivalent in meaning. Radio-decay rate, in the present context, refers to the rate at which uranium releases radon into soil micro-channels that may ultimately provide an unencumbered pathway into a building. Notwithstanding the constancy of radon's origin and decay rate, emanation rates are not constant because they represent the speed at which infiltration factors are able to facilitate or hinder movement of soil gases. Emanation rates depend on soil composition, soil granularity and porosity, soil chemistry, and water content (1). And, too, they are strongly influenced by weather effects (2,3).

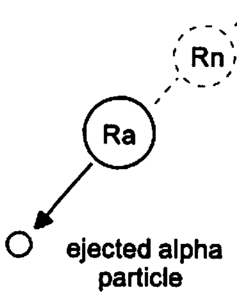
SOME SOURCES AND FACTORS INFLUENCING RADON INFILTRATION RATES

In general, the remainder of this discussion will focus on significant infiltration factors that should be considered when a radon-contaminated site is to be tested and/or mitigated. If, as is suggested by the EPA, new structures are intended to be built as radon-resistant as is economically feasible, these same factors merit attention. In other words, an understanding of infiltration factors enables construction of radon-resistant structures. Taking the long view, when infiltration factors are evaluated in the light of their complex interplay, we are led to recognize that the only "constant" in the radon problem is the constant rate at which radon decays.

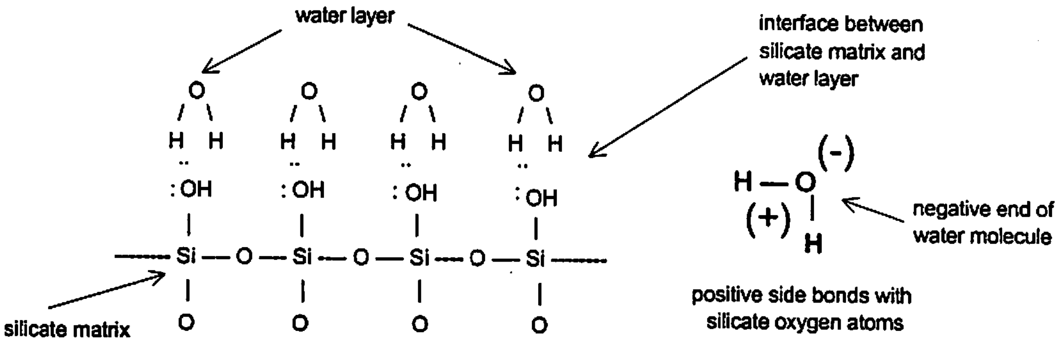
Soil composition, adsorptivity, permeability, water content, and temperature:

Radon is common to all soil types because its progenitor (uranium) is widely found in the earth's crustal rocks at concentrations of about 1-3 parts per million by weight. Even so, there are significant variations in its distribution from place to place. Ore deposits with uranium concentrations suitable for mining are of the order of several thousands of parts per million. If the uranium concentration in soil is relatively high, structures built on or in such soils are certain to be exposed to high levels of radon.

When a radium atom decays within soil, it emits an alpha particle and a daughter radon atom. When the alpha particle is ejected from the radium nucleus, the daughter radon atom recoils in the opposite direction as illustrated here. It is the origin and destiny of the radon atom that is the most significant determinant in the rate at which the daughter atom can become part of the radon problem. If the radio-decay of the radium atom occurs within a soil grain, the alpha particle is absorbed and the radon atom remains embedded within the grain where it continues to decay harmlessly. If, however, the decay occurs on or very near the surface of the soil grain, the radon atom may be ejected into the pore space between grains. Should these pores be open and dry, the radon atom is free to diffuse about randomly or follow any induced flow of air between soil grains.



If, as is almost always the case, soil interstices are filled with (or at least coated with adsorbed) water, a solubility-factor comes into play. Water (H_2O) molecules are dipolar, that is they are electrically dissymmetric as illustrated below. Though overall the molecule is electrically neutral, a drift of its bonding electrons toward the more electronegative oxygen atom causes it to possess weak positively and negatively charged regions. In a somewhat similar manner, and for essentially the same reason silica (SiO_2), a glass-like substance common to all soils also has a dissymmetric charge distribution on its surface. Polarities of water and silica cause them to be attracted to each other. The positive (hydrogen) side of the water molecule is attracted to the negative charge on the silicate oxygen atoms residing on the surface of the soil grain.



As illustrated in this diagram, the result is a rather tenacious bond between water molecules and silica. This is, in fact, why water wets and adheres to glass. Even when wiped dry, a film of water clings to the surface. The bond is quite strong; the film can be driven off only by prolonged heating at a temperature above the 100 C (212 F) boiling point of water. The implications of the bond between water and soil grains are not insignificant to radon's movement in soil. Water trapped between (and bound to) soil grains serves as a solvent for radon and other soil gases. Where the water flows, radon goes.

Carbonated beverages are made by dissolving carbon dioxide (CO_2) gas at elevated pressure and low temperature in cold water. In a somewhat analogous manner radon is also water soluble. Though only about a third as soluble as CO_2, radon is, as shown in this table, ten times more soluble than is oxygen. And it is far more soluble than all other noble gases and other common gaseous components of the air. The significance of radon's high solubility in water is important to the understanding of one of its major transport mechanisms from soil to indoor air.

Solubility of Gases in Water (mL gas @ STP / mL water)

Temp (C)	Argon	Xenon	Radon	Carbon Dioxide	Oxygen	Air	Nitrogen
0	0.05	0.24	0.51 (10X)*	1.71	0.05	0.03	0.02
10	0.04	0.17	0.326 (9X)	1.19	0.04	0.02	0.02
20	0.03	0.12	0.222 (7X)	0.88	0.03	0.02	0.02
30	0.03	0.1	0.162 (6X)	0.67	0.03	0.02	0.01
40	0.03	0.08	0.126 (5X)	0.53	0.02	0.01	0.01
60	0.02		0.085 (4X)	0.36	0.02	0.01	0.01

*** (Radon / Oxygen solubility ratio)** **Lange's Handbook of Chemistry 13th Edition 1985**

Any water entrained in and moving between soil grains serves as a reservoir of and transport medium for dissolved radon. Radon-bearing water that may enter through leaky walls and/or floors, including that which may enter a sump from a sub-slab or perimeter drain system, exacerbates a home's "wet basement problem" by giving it a radon problem as well.

Radon content of the domestic water supply:

In spite of the fact that radon is highly soluble in water, ordinarily not much radon is introduced into a home via its potable (drinking) water supply. It takes about 10,000 pCi/L radon in water to produce a 1 pCi/L contribution to indoor air (4). Municipal treatment plants subject the water supply to considerable handling and aeration during the purification process. This provides ample opportunity for radon to escape harmlessly into the air long before it enters the supply lines to homes.

On the other hand, homes drawing drinking water from individual domestic wells are the more likely candidates for a radon problem. Because of their depth, the cooler temperature of groundwater, and the lack of opportunity for aeration, wells subject radon-contaminated water to a hydrostatic pressure and relatively low temperature that favors high gas solubility. Even so, the actual radon concentration in well water will depend strongly on the uranium content of the rocks through which the water flows. Dark uraniferous granites, shales, and phosphate-bearing rocks are more important contributors of radon than are lighter igneous rocks and quartzite sands. Still, even though there are many locations that have radon-prolific underlying geology, not all are radon problem areas. Clearly, there is much more to the radon situation than geology alone – before radon can enter a structure, there must be a transport pathway and a driving force.

The radon content of the home's natural gas supply:

Because both are gases and both come from the earth, radon can be present in fuel-grade natural gas. Nevertheless, this matter is more of a non-problem than a major concern. In the time required to extract, process, store, and transport gas from its points of origin to domestic points of use, any radon which might have been present will have decayed significantly. A time-span of one month represents almost ten half-lives for radon-222. By then, it would have decayed to background level.

Radon from an unusual source:

Orange-colored Fiesta Ware, a once-common and popular dinnerware has been accused of contributing to a radon problem because the glaze contains uranium-238. A single dinner-plate in an unventilated room was alleged to generate a radon level of 28 pCi/L (6). We are currently investigating that assertion.

RADON ENTRY: PATHWAYS

Of all naturally occurring gases, radon is the most dense – it has the greatest weight per volume, 9.7 g/L at STP. It has a boiling point of 4.4 C (39.2 F), (5). Radon freely mixes with the air in soil pores and, like all gases, is able to diffuse from its points of origin. Even so, once inside a building, its high density causes it to accumulate in the below ground level parts of the structure. Radon entry is facilitated by air flow from the soil into the basement whenever a transport pathway exists and there is a driving force to enable movement.

Home construction, design, siting, and age:

Given that radon emanation is a characteristic of uraniferous rocks, homes which are built of brick, concrete, and stone – materials all derived from the earth – have a radon potential that can exceed that which might be associated with metal or wood frame construction. Basements in the newest construction are almost always made of block and/or concrete which can be a source of indoor radon. Fortunately, the matter of radon emanation from concrete is minimal and rather well understood. In general, unless the product is manufactured with sand and aggregate of high uranium content (a practice long since abandoned) concrete will not be a significant source of radon. The quantity of soil-generated radon able to enter a structure will almost always greatly exceed that which might be contributed as a result of emanation from concrete. Except for rare occurrences, radon emanation from construction materials is more of an academic potential to be recognized rather than actual contributor to the radon problem.

In order to achieve energy savings, the current move toward highly insulated and sealed structures, as well as the increasing popularity of bermed and underground residences, is a trend that could lead to radon problems. Such homes, unless properly designed, can be so well insulated that ventilation is impaired — thus, the accumulation of indoor radon. This represents an example of modern construction methodologies being a solution to one problem while at the same time the source of another.

Because they frequently have a higher air exchange rate attributable to poor sealing and insulation, the "drafty" older home may actually be less likely to have a radon problem. However, older homes often have poor or nonexistent perimeter or sub-slab drainage systems. In many, the basement floor was poured directly on rammed earth. That they may be well-ventilated does not insure that older homes are necessarily always radon-free. Lacking any easy means by which air can move around and under the slab, any such homes that do have a radon problem are often more costly to mitigate.

Preventative Measures:

Home design and construction methods are the most important controllable factors when planning a finished structure that will be radon resistant. To prevent dampness, the outside walls of foundations are usually coated with tar or some other water-impermeable sealant. Increasing awareness of the radon problem has encouraged builders to consider more effective sealing materials and measures. Newer termite barriers placed atop concrete block walls can effectively eliminate block cores as radon conduits. Intact plastic membranes placed around and under new construction can completely block radon entry. Neither the gas nor its alpha radiation can penetrate a properly installed, intact membrane. However, in order for this approach to be effective, membranes must be placed with care, properly sealed, and protected from perforation as construction proceeds. Even when high water tables and their accompanying drainage problems are not anticipated, homes should still be constructed on a bed of clean one inch gravel or crushed stone in order to facilitate sub-slab air movement. Homes so constructed are much less expensive to mitigate, should they later be discovered to have a radon problem.

Soil compaction and vegetation:

Other factors equal, newer homes can often exhibit a radon profile that improves with their advancing age. This seemingly unusual circumstance can be attributed to soil compaction. Uncompacted soil has rather larger interstices which enable radon to move more freely than it otherwise could through well-packed soil. When a home is new, the deep soil around the foundation has not yet settled to a density comparable to the otherwise undisturbed surrounding earth. The looser the soil, the more free the movement of soil gases toward and into the structure.

All vegetation and organic construction debris should be removed before the basement floor is poured and the foundation backfilled. This is more than a mere matter of good housekeeping and termite avoidance. Abandoned wood scraps, and even the condition of nearby landscape vegetation, can play a role in radon infiltration. When nearby major trees and shrubs are cut off, and their roots left underground, decay of any abandoned debris and root structure leaves porous pathways through which radon may move toward the basement. It can take many years for such channels to be closed by natural soil compaction.

Radon access through cracks, pores, and openings in basement walls and floors:

It is said, "There are two kinds of concrete: ... concrete that has cracked, and concrete that will crack." The merits of such wisdom ought not go unheeded. After all, because the rate at which radon is able to diffuse through intact concrete is exceedingly low, if there were no openings through the sub-structure, radon would have no path of entry. Thus, basement floors and walls should be painted with a high-quality elastomeric sealant that can stretch sufficiently to accommodate inevitable minor structural cracking. The interior floor-wall joint should be carefully cleaned of debris and filled with a concrete-compatible calk. In like manner, pipe chases through floors and walls should be carefully sealed.

Crawl spaces are major points of soil gas origin and entry. They should be covered with an intact plastic membrane whose underside is power-vented to the outside. Sump pits, if required for potential drainage problems, can be designed to be placed outside. This eliminates delivery of dissolved radon in sump waters to the interior of the basement. It eliminates, as well, another radon entry point. When sumps are dry and open to the basement, they serve as an unhindered conduit to soil gases from around and under the structure. Existing interior sumps should be covered, sealed, and power-vented to the outside in accordance with EPA protocols.

RADON ENTRY: DRIVING FORCES

Radon entry pathways are the inevitable result of natural processes and imperfect construction methodologies. Their presence is unavoidable. The radon problem is exacerbated by the naturally occurring – and largely uncontrollable – forces which deliver the gas into the structure.

The season: open-vs closed-house conditions:

One direct way to keep radon levels low is to bring in a copious supply of fresh outdoor air to dilute it. In those rare locations where heating and cooling costs are unimportant, the method eliminates the radon problem completely. However, ordinarily the cost of heating/cooling losses cannot be ignored. Although summer-time conditions may encourage a carefree, windows-open lifestyle with its ample exchange of indoor and outdoor air, such is not the case in cold weather. When the home is closed up, ventilation rates go down and radon levels go up.

Indoor / outdoor temperature differences and the stack effect:

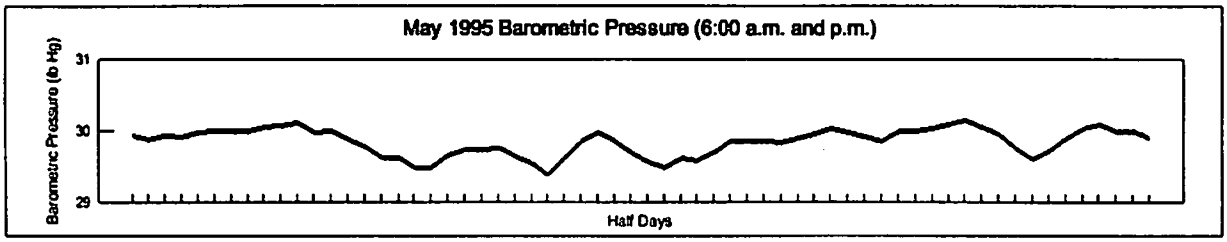
Other factors equal, radon infiltration is at its most serious when a well-sealed home is closed and the outdoor air is colder than indoor air. Under such conditions, volumes of exfiltrated warm air flowing to the outside are significantly replaced by the inflow of air and gases from any below ground level openings that may lead to the soil. A warm house in winter acts somewhat like a weak, low-capacity vacuum cleaner or chimney by exerting a weak updraft (suction) on the soil around and under the structure. This phenomenon is referred to as the "stack effect." Of all factors bearing on radon infiltration rates, the weather-induced stack effect is the most significant.

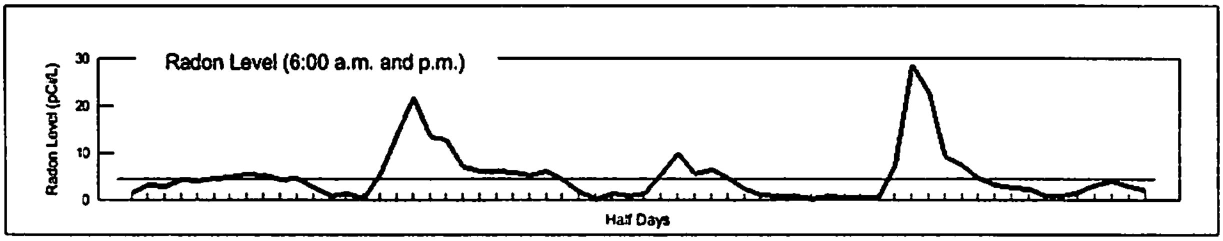
Wind velocity and direction:

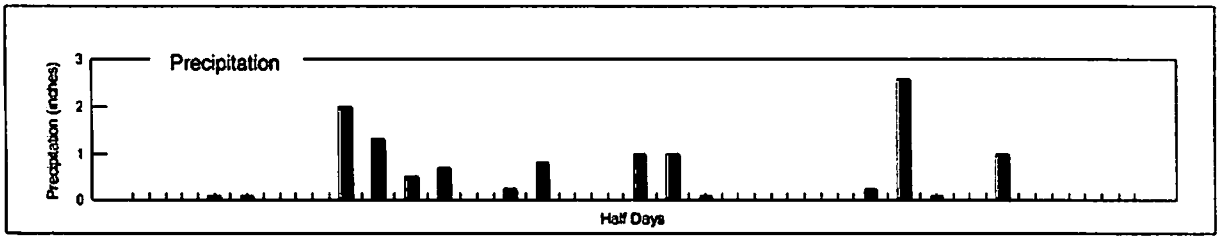
Bermed homes are often sited with the bermed side toward the prevailing winds so as to deflect the brunt of the cold air blast over the home. Appealing as such siting may at first appear, it can contribute to a radon problem by producing a Bernoulli effect: "Where the velocity in a moving fluid is greatest, pressure on any adjacent surface is least." High winds around and over a structure create a low pressure zone laminar to the walls and roof. The result is a partial vacuum created within the home. This reduces interior pressure and exacerbates the stack effect.

EXPERIMENTAL: A LONG-TERM SITE STUDY

In an ongoing and almost five year study of a normally occupied midwestern residence, weather changes were found to have a dramatic effect on its radon profile. The home is single story and of wood frame construction. Two thirds of its approximately 2000 square foot area is built on a slab. The remainder rests over an insulated and well-ventilated crawl space. It is sited in a 40 acre, tree-sheltered area atop a steep promontory between two valleys. Since late 1992, radon levels and eight weather-related parameters were logged and recorded hourly. Because this is producing a substantial and somewhat unwieldy database of almost 44,000 hours duration and almost 400,000 individual data points, graphics shown in this discussion were prepared from an abbreviated data-set by including only those readings logged at approximately 6:00 a.m. and 6:00 p.m. for each day of the study.

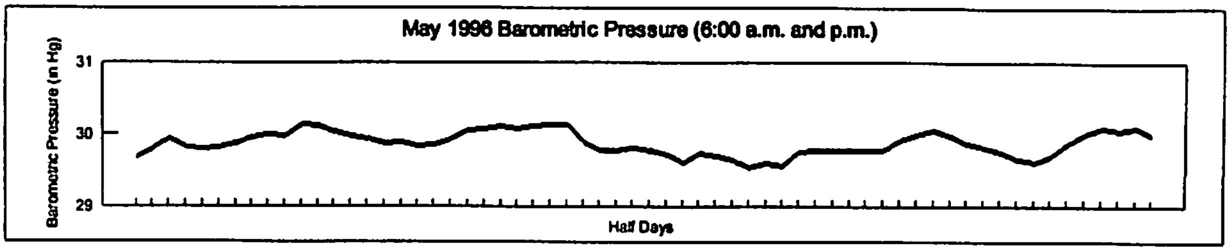


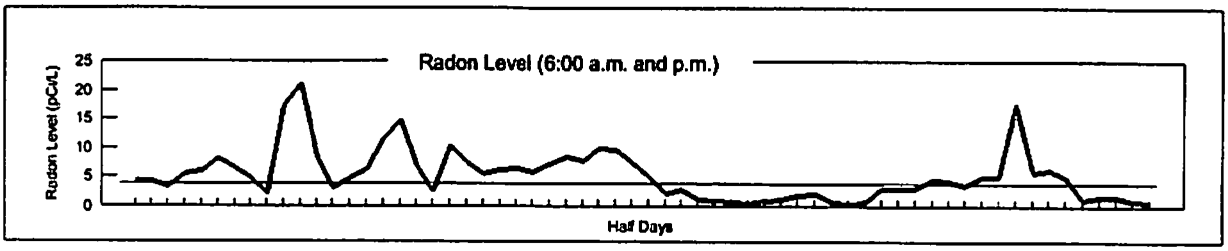


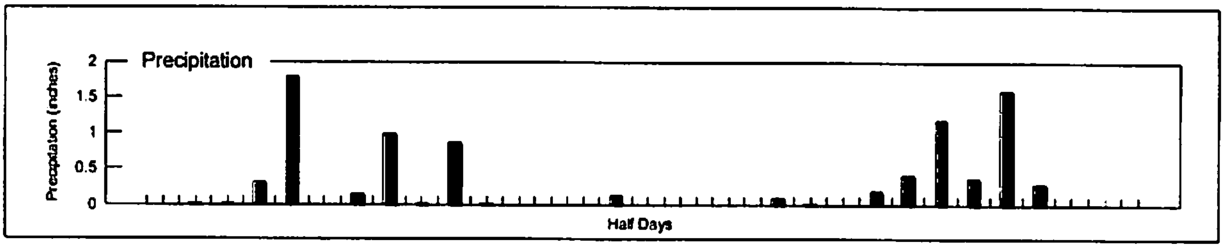


Variations in barometric pressure:

As illustrated in the figure shown here, interior radon levels tended to inversely track changes in barometric pressure. When the barometric pressure falls, radon levels tend to rise during and shortly after onset of the pressure change. That levels tend to fall when the barometer is on the upswing can be accounted for by recognizing the flow dynamics of soil-gas migration. Barometric pressures act inside as well as outside the home. Elevated pressure inside can be quickly transmitted to the walls and floors, thereby causing exfiltration of air through any cracks or pores present there. The outflow tends to diminish the rate at which soil gases are able to enter. Correspondingly, low barometric pressures relieve the confinement of the atmosphere thereby tending to enhance infiltration. The slight mis-alignment between the onset of the pressure change and the corresponding radon response is attributable to the very convoluted path taken by soil gases around and under the structure. Put another way, ambient (outdoor) pressure changes cannot be instantly relayed to the below-ground gases because the pressure wave must be relayed through the tiny, meandering channels between soil particles. Thus, although indoor barometric pressure tracks almost exactly changes in outdoor pressure, such is not the case for soil gases whose flow is encumbered by tortuosity factors. The result is a delayed below-ground pressure wave that lags in time any open-air barometric pressure change.





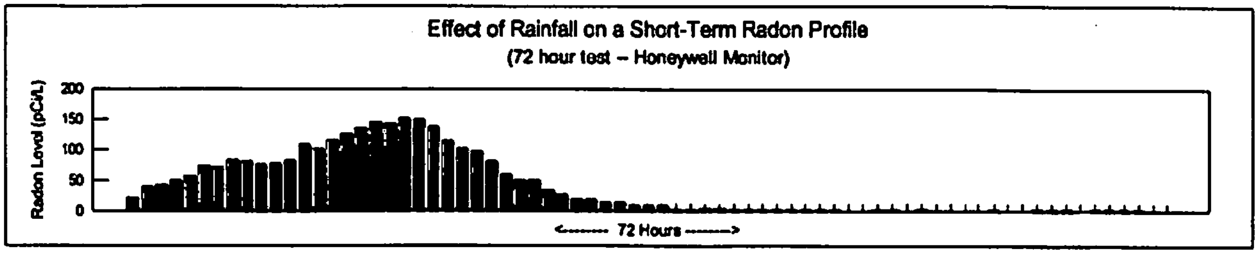


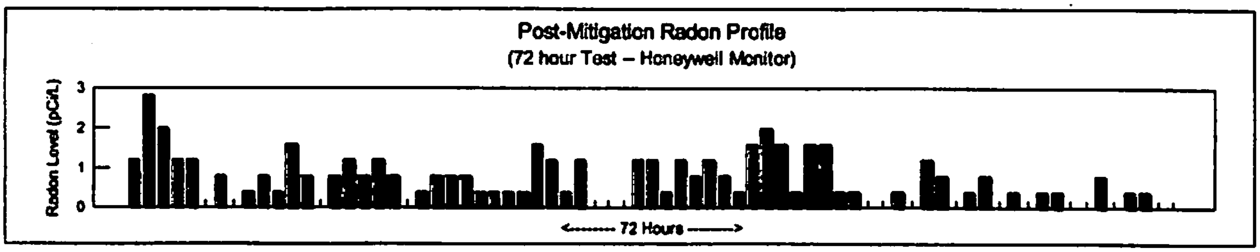
<u>Rainfall amounts and intervals:</u>

Like the preceding figure, the graphic shown here illustrates another important weather effect. Rainfall intervals and amounts can have a significant impact on radon infiltration rates. Thus far during the study of this residence, well over half the 60 monthly barometer / radon / rainfall profiles resemble those shown here. During normal rainfall cycles when the soil was receiving only intermittent rains, precipitation events of only a few tenths of an inch had little effect on the monthly radon profile. However, more significant rainfall amounts of the order of 0.75 to 1 inch would often have a pronounced effect resulting in very large radon surges.

Moderate rainfall initially seals the soil with a gas-impermeable and incompressible liquid. As the water interface percolates downward, soil gases are both dissolved and driven along and into openings in the below ground level parts of the home. Although quite pronounced radon surges were overall somewhat rare, the overall data-set supports the correlations illustrated in the previous two graphics.

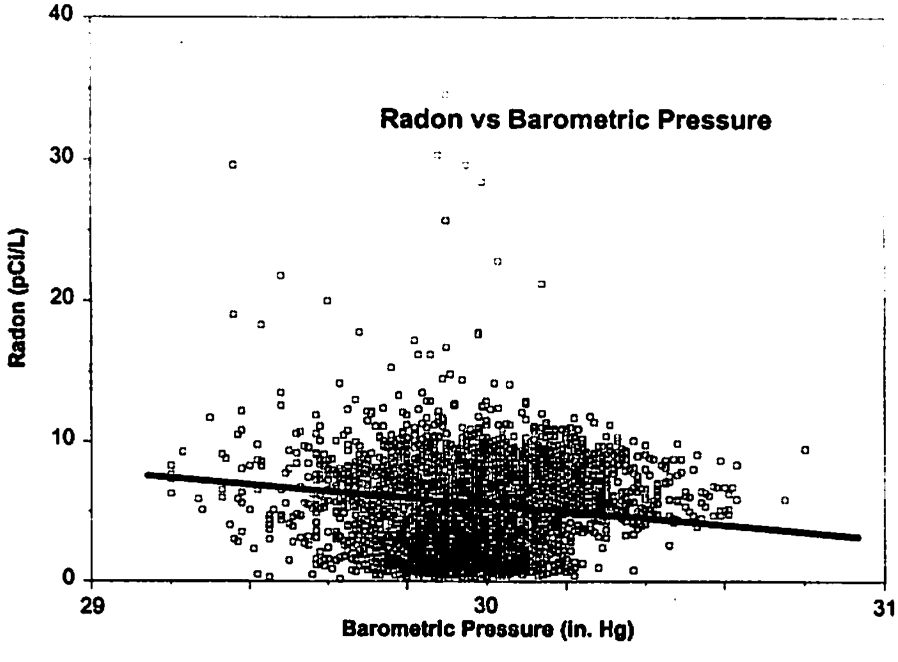
A remarkable example of the rainfall effect was encountered in early 1997 during a three day (continuous electronic monitor) test of a relatively new home sited on well-drained, unfrozen, sandy soil. The residence had a poured concrete basement with an indoor relative humidity of about 40% – a sign of a home without a wet basement problem. In fact, the (open) sump pit was completely dry — it had never even been equipped with a pump. On the day the monitor was placed, the barometer was trending downward and a light rain was just starting to fall. As the day wore on, the rain became more copious. A moderate, yet steady, four to five inch rain continued over a period of about 14 hours. The next day the barometer was on the rise and clear weather returned. As illustrated in the





upper radon profile shown above, during this particular weather incident the home's radon response was dramatic. As rainfall became more pronounced, the hourly radon level ramped steadily upward to a maximum of 152 pCi/L. The surge spanned about half the three day test interval. It peaked at a time nearly coincident with the end of the rainfall event. By the midpoint of the 72 hour test the level had fallen to about 1 to 2 pCi/L where it remained to the end of the third day. There was no sign of water entry through the home's basement floor or walls. The sump pit had received no inflow. In fact, the drain tiles leading into it were dry.

The above pre- and post-mitigation radon profiles of this residence illustrate the role played by rainfall on detected radon levels during a short term test, as well as the effectiveness of mitigation. Apparently at this site there is a substantial source of radon in the underlying geology. Coincidentally, the water table is well below the basement floor. In dry weather, the porosity of the soil allows soil gases to escape freely into the air. However, a heavy rain seals the soil and extends the low pressure field surrounding the house. Because the water table never rose high enough to cut off soil-gas migration, the hydraulic effect of the percolate injected soil gases into the basement via the empty sub-slab and perimeter drain system It is likely that in the absence of large rainfall incidents, this particular structure would have scored well below the EPA action guideline of 4.0 pCi/L. Unfortunately, we were unable to test that hypothesis because the home was mitigated within a week of the first radon assessments.

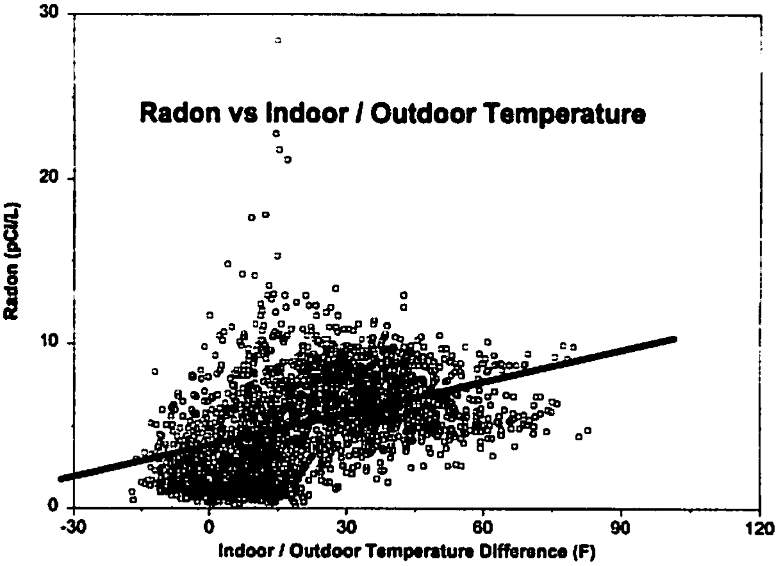


Synergy effects:

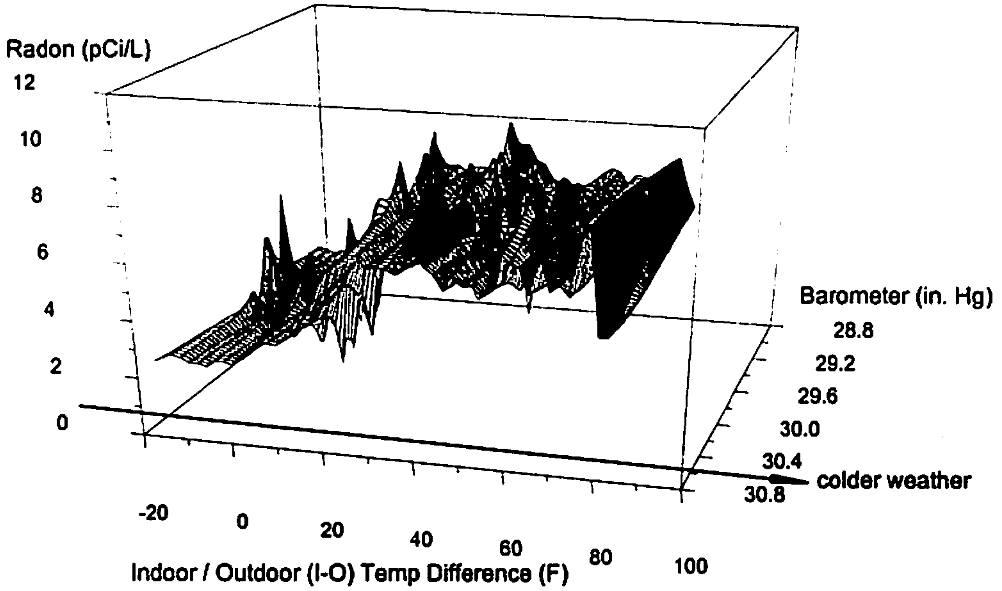
Drawn from across the entire five-year data-set, the following three linear regression scattergrams illustrate relationships between: Radon /

Barometric pressure, Radon / Indoor-outdor temperature difference, and Radon / Rainfall.

The gentle downward slope of trend-line in the radon vs barometric pressure graph shown at the bottom of the previous page is indicative of a weak negative correlation between radon level and changes in barometric pressure. As the barometer drifted higher, radon levels tended to move lower. This response was especially apparent under low wind conditions when the soil was relatively dry.

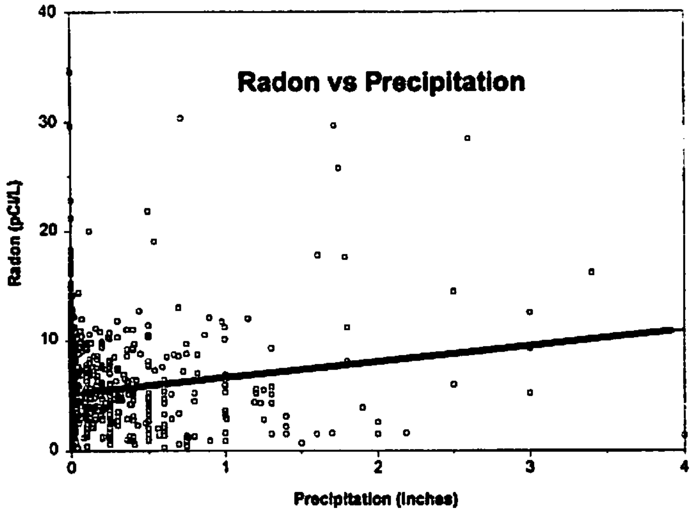


As shown at right, when radon is plotted against the indoor-outdoor temperature difference, the trend-line exhibits a gentle slope upward and a positive correlation. When the difference between indoor and outdoor temperature grows larger – typical of winter conditions – radon levels trend upward. In winter when the indoor-outdoor temperature difference is maximal, the radon level can be elevated for prolonged periods of time because the house is exposed to the full impact of the stack effect.



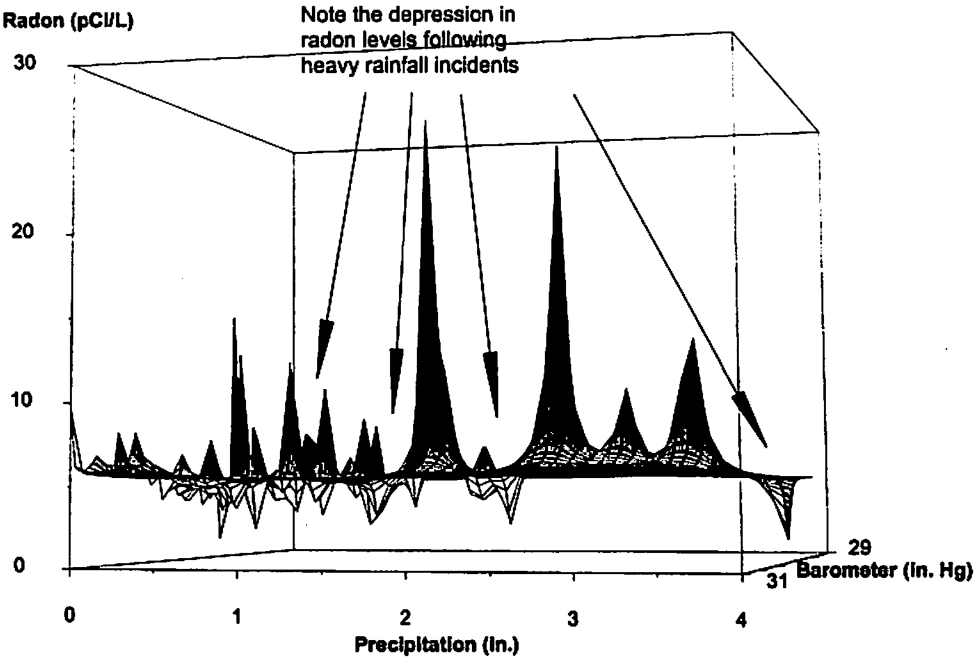
The larger the temperature difference, the higher the radon level.

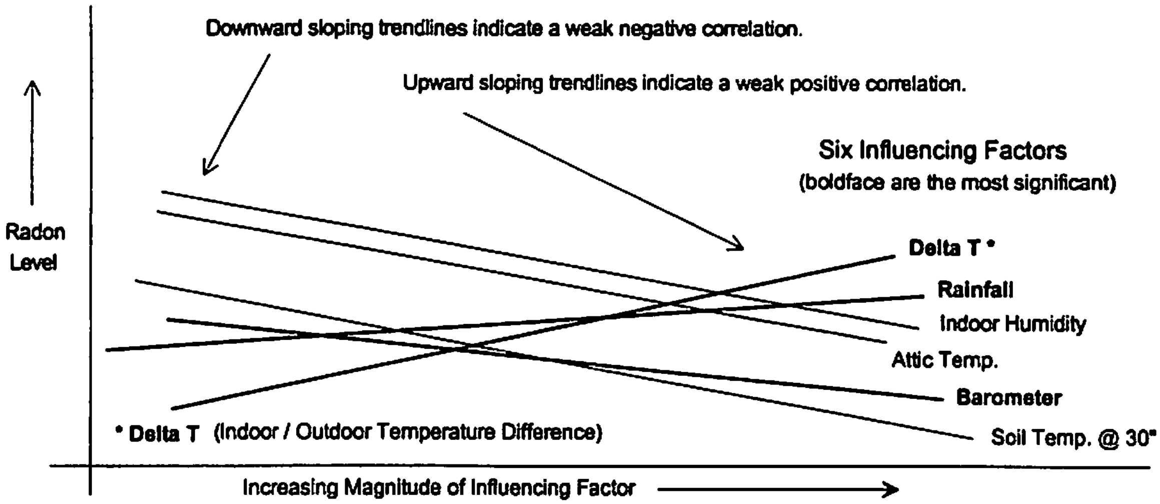
The above graphic (covering the same part of the data-set) depicts the stack effect in still another way. Note the low radon levels occurring when the temperature differences are least. Also, as indicated earlier, the more prominent radon peaks tend to be at the lower barometric pressure end of the plot.



Finally, when radon is plotted against precipitation, as illustrated in the final scattergram shown above, the trend-line again slopes upward indicating a positive correlation. In so far as any major radon surges were concerned, significant rainfall events (greater than about 0.75 inch) were certain to cause a substantial increase in radon during and immediately following the incidents. However, shortly after heavy rain, radon levels tended to fall below the level recorded just before – as illustrated in the surge profiles cited earlier.

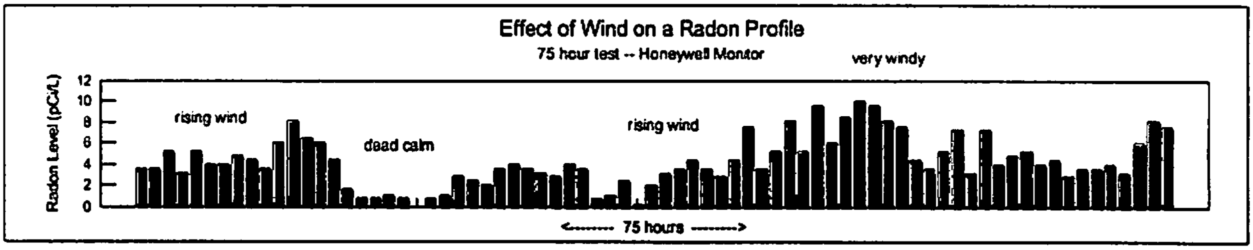
The high water solubility of radon and its pronounced effect on radon levels are illustrated in the 3-axis weather plot shown below — rotated upward to show both rainfall-induced radon surges and the depressions which follow the heavier precipitation incidents. Shortly after substantial rainfall events, radon levels tend to fall temporarily as the gas is "washed" below the foundation level. In time, after the water soaks away and air re-enters the soil matrix, radon is again mobilized in the gas phase, levels are re-established and the profile returns to a level comparable to that occurring before the rainfall incident.

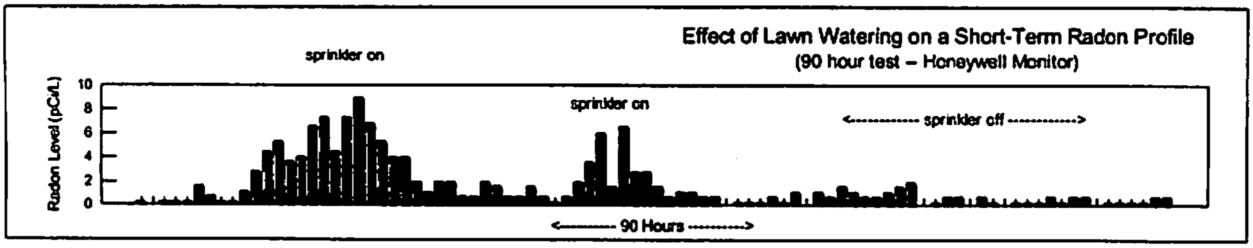


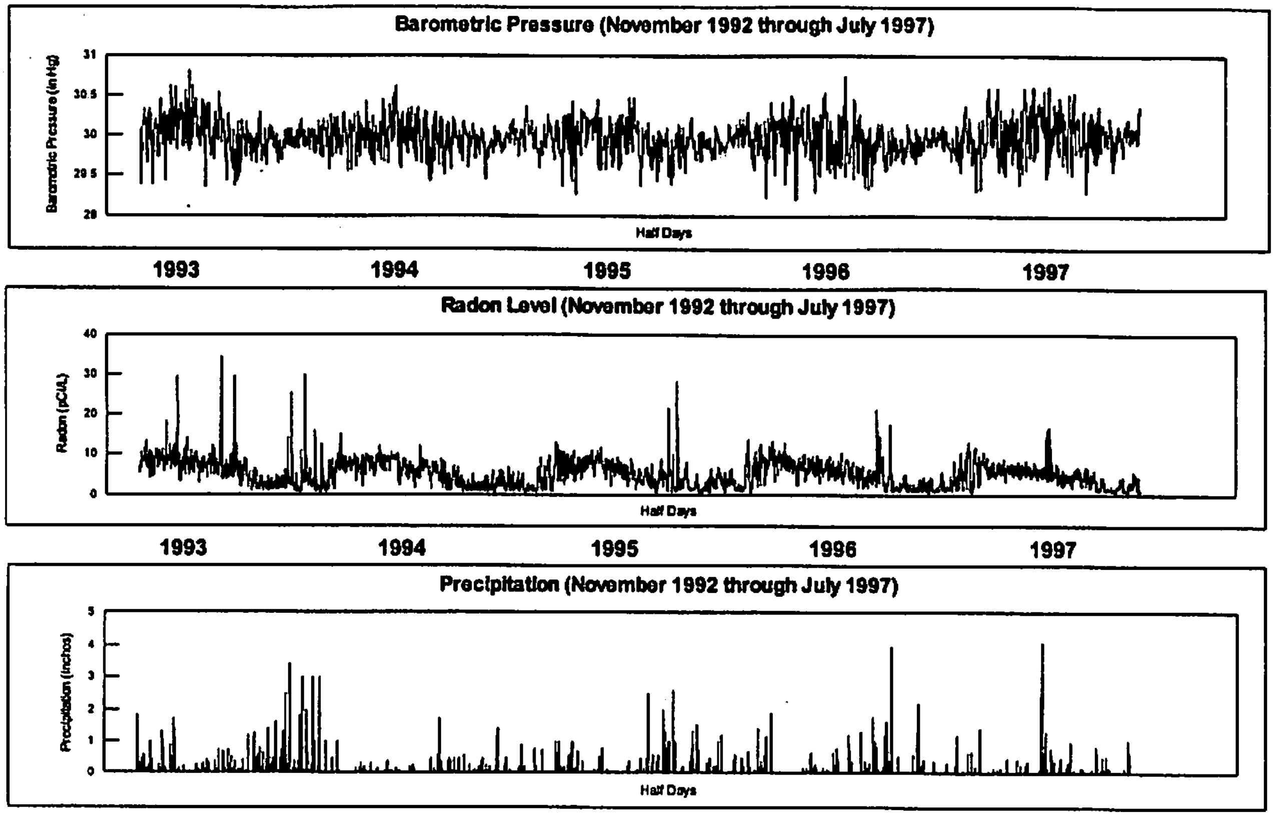


The five-year data-base has been used to produce correlations between radon and six other weather parameters. The diagram shown above represents superimposed linear regression plots of radon vs the six factors significant to this study. Most notably, when major weather factors such as changes in barometric pressure and rainfall events coincide, radon levels can rise markedly as illustrated in the graphic shown immediately at the bottom of the previous page – and in the sample radon/weather plots for May 1995 and 1996 shown earlier. In general, although the correlation between radon and any given influencing factor appears weak, because the factors affecting radon infiltration rates are numerous and subtle, they can be pronounced in their additive effect. Our research into the interplay of weather factors as they affect radon levels serves as a reminder of just how unreliable a short-term radon test can be. The importance of this observation cannot be overstated in light of the standing accorded the short-term test in many real estate transactions.

The graphic shown immediately below illustrates the effect of windy conditions on a short-term radon profile. Data were collected during a weather change accompanying the approach of a high-pressure front characterized by recurring wind gusts of up to 40 mph. The bottom graphic represents the effect of an artificial rainfall incident. This test was done during a prolonged dry period during which the lawn at the test site had been twice watered for several hours during the 90 hour span of the radon measurement.







The summary graphic above illustrates the long-term impact of two major weather factors – rainfall incidents and barometric pressure changes – during the (almost) five year span of this study. Offering the long view, it illustrates the little-acknowledged impact of the weather effect on long-term seasonal variations in radon levels which might be recorded in any normally occupied home. And, too, it raises a question about the long-term validity of the long-term radon test.

The unreliability of the short-term radon test as a predictor of long term radon conditions is, by now, well-established. However, the very long duration of this study points out a situation not ordinarily considered when evaluating even a single **long-term** test. When the radon profile for the year 1994-1995 (a relatively dry year) is compared with those for the years 1993-1994 and 1995-1996 (years of greater rainfall) it becomes clear that even a year-long "long-term" test can result in a radon average that isn't very "average" at all. In light of the graphics derived from this study, even if geological and structural conditions could remain stable for a great many years, can a single long-term test be counted upon to reflect the average radon profile of a structure over that same time span? The impact of the "weather effect" indicates the answer is no.

DISCUSSION

There is overwhelming evidence that the short-term radon test common to real estate transactions can make little contribution to an accurate assessment of any long-term radon condition. The sum and substance of the radon problem is its complexity. A predictive model for long-term radon levels will not be easy to construct. Long term, weather changes are unpredictable. Short term weather effects are capricious, fleeting in duration, and pronounced in their impact on radon transport. Our five year data-base reveals significant annual radon level differences between wet and dry years. Thus, even the long-term test is subject to yearly variations.

Home buyers, sellers, and realtors should be aware of this situation and appreciate the uncertainties inherent in both kinds of test. As citizens gain a better understanding of the radon problem, they may be moved to have their homes tested annually with a long-term device both for the health and safety of the occupants, and as a kind of "preventative maintenance" in anticipation of the day when the home will be placed on the market. Certainly, homes that fail any single long term test should be mitigated. However, once done, the home owner / occupant should not conclude that the problem is permanently solved. Geological, structural, and environmental changes do occur. Over time, these can change infiltration rates. It is, therefore, worthwhile to recognize that the radon problem is as enduring as its source in the soil. Given the seriousness of the radon problem as a matter of public health and the economic impact radon testing has had and will continue to have on the real estate market, radon scientists should make every possible effort to educate the public and lawmakers about the weather effect and its impact on the efficacy of radon test protocols.

TECHNICAL NOTES

Radon data for this study were obtained from simultaneous, side-by-side operation of multiple Honeywell Professional Radon Monitors, model A9000A, and a Honeywell model Q901 data logger / printer. Time-base synchronized radon / environmental data were collected with a Genitron Instruments AlphaGuard 2000 Professional Radon Monitor. All monitors were calibrated in accordance with EPA protocols and periodically cross-checked against each other and against multiple Air-Chek charcoal packets testing the same environment.

Time-base synchronized radon/environmental data was fed to a Hewlett Packard Omnibook 425 notebook computer and down-loaded to Hewlett Packard Vectra 486/33ST, RS/25, and XU 6/200 computers for processing with Lotus 1-2-3® and StatMost®, scientific / statistical / graphical data processing software.

Barometric pressures were monitored with a temperature-compensated Taylor aneroid barometer daily checked against pressure readings reported by the National Weather Service in Peoria, IL. Continuous barometric pressure readings were recorded on a continuing monthly basis with a similarly checked / calibrated, temperature-compensated Oakton recording barograph.

SOURCES OF ANALYTICAL EQUIPMENT, COMPUTERS, AND SOFTWARE:

Air Chek
570 Butler Bridge Road
Fletcher, NC 28732

DataMost Corp.
(StatMost)
P.O. Box 65389
Salt Lake City, UT 84165

Honeywell Inc.
1885 Douglas Drive N
Golden Valley, MN 55422

Rad-Elec, Inc.
1206 East Ash Street
Goldsboro, NC 27530

Aware Electronics Corp.
P.O. Box 4299
Wilmington, DE 19807

Genitron Instruments Gmbh
Heerstrasse 149 D-60488
Frankfurt am Main,
Germany

Lotus Development Corp.
55 Cambridge Parkway
Cambridge, MA 02142

Solar Electronics International
156 Drakes Lane
Summertown, TN 38483

Cole Parmer Instrument Co.
P.O. Box 48898
Chicago, IL 60648

Hewlett Packard Company
Corvallis Division
1000 N.E. Circle Blvd.
Corvallis, OR 97330

Oxford Tennelec/Nucleus, Inc.
601 Oak Ridge Turnpike
Oak Ridge, TN 37831

Toshiba America, Inc.
Computer Systems Division
9740 Irvine Blvd.
Irvine, CA 92716

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6. Boylance, F.D., Article in The Baltimore Sun accessed via the Fiesta Ware home page on the Internet at http://www.ir.net./~felenzer/radon/htm