Chapter 6

The Myth of the Quick Test

> The use of short-term measures for mitigation decisions creates all kind of problems.
>
> —Richard Sextro

The context of radon testing is explained directly by the myths of the hot house and Reading Prong. The U.S. geologic radon policy has been driven by the image of the Watras experience and by the tail of the lognormal curve, the specter of extreme hot houses exposing their residents to extraordinary risk. Abetted by the scientific consensus over risks in hot houses, EPA has crafted a policy that espouses much broader goals (the 4 pCi/l guidance and even ambient levels), but in effect focuses on finding hot houses and hot regions. Given this policy focus, the primary objective of radon testing has been to "screen" buildings to find the hot ones, to the exclusion of other objectives that should be central to a comprehensive policy for radon risk reduction.

Moreover, this emphasis upon screening for hot houses demanded a quick, inexpensive, and easy measurement approach that came to dominate U.S. radon testing. By the myth of the quick test, we refer to the inherent delusion underlying radon policy that such screening measurements, made over time intervals of only a few days, accurately reflect the risk from radon exposure in a given building. Despite serious validity questions, such tests have been widely employed for all uses. As a result, the majority of those testing have used inappropriate tests for their objectives and possibly drawn inaccurate conclusions regarding the safety of buildings, the need to remediate, and whether to proceed to purchase a house. The myth of the quick test has led policymakers, experts, and even consumer groups to create misleading programs and to provide wrong advice. We see this impact clearly when we examine error in radon testing.

Errors in Radon Testing

In our view, the challenge in radon testing has less to do with the technical problems of how to detect radon than with the central question of whether information gleaned from tests provides a valid indication of the average radon level and, particularly, the exposure of building occupants to radon. Validity requires the elimination of testing errors that might lead us to obtain false results, to make false conclusions, and to make inappropriate responses. Also requisite for validity is repeatability, since we can have no confidence in results that cannot be replicated. Validity is threatened by six potentially interacting types of error, all found in the U.S. radon testing program.

- *Error of Policy.* Are we asking the right questions? Are we clear enough about what our goals are to select the appropriate testing methodology and technique?
- *Methodological Error.* Have we adequately sampled for radon so that our findings represent radon levels in the test setting?
- *Device Error.* Might error result from the inherent shortcomings of the radon detector that we are using, whether a charcoal canister, an alpha track detector, or an electret?
- *Measurement Error.* Is the testing device properly used and are there situational factors that might contribute to error?
- *Analysis Error.* What are the potential laboratory errors in the analysis of the radon collected in test devices?
- *Interpretation Error.* Are correct conclusions drawn from the measurement?

We will now examine how each of these errors affects radon testing policy and practice.

Errors in Policy

The primary cause of "policy error" has been a failure to clearly delineate the different goals that exist for testing and to consider whether given testing techniques achieve desired objectives. Tests valid in all other ways may fail simply because the information they provide is neither what we need to know nor, having been misled, what we think it is.

At least seven different testing goals and objectives are reflected in common practice (see table 6.1), yet these goals and the techniques most appropriate for achieving them have never been adequately differentiated in radon policy. When a careful comparison of the goals and objectives is made, some striking conclusions about radon testing and measurement can be drawn that reflect policy error. After reviewing the key questions posed by the seven different policy goals and objectives, we will examine the case of screening and the myth of the quick test more closely. Note that EPA testing protocols cited here were originally published in the 1986 *Citizens' Guide to Radon*; reference to updated protocols relies upon the revised 1992 *Citizens' Guide* (EPA 1986; 1992f). Unless noted, these two protocols were in agreement.

Table 6.1 Goals, Objectives, Location, Time, Cost, and Problems of Various Types of Measurements

Goal	Objective	Location	Time	Cost	Problems
Screening	Is the house hot? Is it above 4 pCi/l?	Lowest potential livable (lived-in) space	Short—days to a few months	Low	High false negatives and positves
Follow-up	Is remediation needed and how soon?	2(1) lived-in levels	1 yr. if greater than 4 or less than 20; short if greater than 20	Low	Inaccurate if closed house or short test
Household character-ization	What is the health risk?	2 lived-in levels	1 year	Low	Long testing Interval
Diagnostis	What is the best mitigation choice?	Suspected entryways	Short—grab or sniffing	High	Requires high tester skill level
Mitigation evaluation	Did mitigation work?	2 lived-in levels	Same as premitiga-tion	Low–high	Unreliable
Realty transfer	Can safety be warranted?	Generally in lowest livable (lived-in) space	Short	Low–high	Unreliable
Institutional exposure	Are public buildings safe?	Generally in lowest occupied space	Short	Low–high	Unreliable

Source: Summarized from NYSEO, 1989; EPA, 1986; EPA, 1989a; and EPA, 1992f.

Note: Items in parentheses reflect May 1992 EPA recommendations.

Screening: Is the House Hot?

"Screening measurements" are quick initial tests for identifying houses having high concentrations of radon—the so-called hot houses. Screening seeks to measure the highest radon concentration in a building. To achieve this end, "closed-house" conditions are employed and tests were originally taken in the lowest potentially livable level of the building, later changed to the actual lowest lived-in level. Because screening measurements theoretically capture the highest radon levels found in the home, it is well recognized that they have an inherent tendency to exaggerate results. Therefore, the intended use of the screening measure is to sort buildings into those requiring further confirmatory measurements and those deemed to be safe (i.e., not a hot house). Accordingly, screening measurements are by definition quick and dirty—and relatively cheap. But, while helpful, perhaps, for a rough sorting of houses, the screening test is not helpful in determining the actual risks associated with a building or in determining whether remedial action is required. Moreover, because of sampling and other errors discussed below, short-term testing is an unreliable method for estimating lower radon levels, particularly around 4 pCi/l.

Follow-up: Is Remediation Necessary?

"Confirmatory testing" involves follow-up measurements made in upper levels or lived-in portions of the house for the purpose of estimating potential health risks and the need for remedial action. EPA recommended confirmatory testing after an initial screening test indicated a result in excess of 4 pCi/l. The urgency of the follow-up test and the resulting actions are determined by the radon level found. Screening results between 4 and 20 pCi/l (later revised to between 4 and 10 pCi/l) were to be followed by a year-long radon characterization study (now revised to a long-term test over ninety days unless results are needed quickly).[1] Should levels be confirmed, remediation is to occur within a few years. Radon screening results between 20 (now 10) and 200 pCi/l are to be followed by confirmatory tests under closed house conditions and, if confirmed, remediation is to occur within several months.[2] And screening values over 200 pCi/l do not require confirmation, rather remediation is recommended within a few weeks.

Household Characterization: What Is the Health Risk? Is My House Safe?

"Household characterization" seeks to estimate the long-term yearly average radon exposure in living areas in order to provide more reliable information on health risk for the occupants. House characterization should not be confused with confirmatory testing because the latter, as practiced, rarely gives a long-term average. House characterization may be made by using an alpha track detector or electret for a year or averaging four short-term charcoal canister detectors, one over each season. The only context wherein an EPA guidance ever explicitly called for house characterization was in the confirmatory testing recommendation originally made for screening results between 4 and 20 pCi/l. Health risk was to be computed by averaging tests conducted on each occupied level of the building (EPA, 1986). Even this minimal use of house characterization disappeared with the 1992 revised guidance.[3] In any case, we never heard of any testing or mitigation firm that followed the first guidance. For such firms, year-long testing is impractical; if confirmatory tests are done at all, they are most likely to be short-term tests, most often charcoal canisters prone to serious sampling error. Overall, relatively little house characterization has occurred, even though this approach is the only one that addresses the ostensible concern of occupants, namely, determining their actual exposure to radon and the safety of their building.

Diagnosis: What Is the Best Mitigation Choice?

"Diagnostic testing" is sometimes carried out for buildings greater than 4 pCi/l in order to determine the sources and entryways for radon, and, therefore, the likely options for remediation (NYSEO, 1989, III-24). Such testing is generally done by experts, employing short radon gas measurement techniques such as grab sampling (where air is scooped up in a container for testing) or continuous monitoring (capable of "sniffing" or giving a quick, crude indication of relative radon levels). While diagnostic testing is a tool for understanding the radon dynamics in a building, and useful for tailoring a custom solution to the building, mitigators increasingly employ cookbook remediations requiring little if any diagnosis (see chapter 7).

Evaluation: Did the Mitigation Work?

"Postmitigation evaluation" is conducted to see how well a completed mitigation works. In order to reduce the variability of readings, these measures are ideally compared to premitigation radon tests similar in such sampling and measurement characteristics as ventilation and pressure conditions, weather, time of year, and detector placement. The comparison of premitigation and postmitigation measures determines whether the mitigation succeeded in lowering radon levels and whether the reduction is sufficient (NYSEO, 1989, III-23). Preliminary data from such mitigation evaluations indicate that many mitigations fail (see chapter 7). Furthermore, because buildings change over time, it is quite possible that radon levels will also change. For these reasons, whether the house has been mitigated or not, repeated tests over time are prudent. There is no evidence that many such measurements are taken, however.

Realty Transfer: Can a Building Be Warranted As Safe? Is Radon a Threat to a Building's Value?

"Realty" and "new construction" testing involve the effort to warrant that a building is free of radon problems that would be passed on to a new owner. The demands of real estate transfer often require quick answers, leading to a reliance upon short-term testing despite the inability of such measurements to do more than screen the house. As a result, many houses have been mitigated because they fell at 4 pCi/l or just above on a crude measurement, while other buildings deserving of mitigation may have been missed. While this sampling error must be addressed, realty transfer of used or new buildings represents a logical point for finding and lowering radon levels. Indeed, in the absence of government mandate, considerable market pressure has developed to force accountability on radon, particularly in areas where radon problems are known. Yet, EPA has lagged seriously in addressing the realty context. The 1992 *Citizen's Guide* blithely suggested that homeowners test their homes (and fix them) well before they intend to sell, while ignoring the well-known threats to testing validity—fraud and the quick test. It was not until 1993 that a formal guidance on real estate was issued by EPA, the *Home Buyer's and Seller's Guide to Radon*. Overall, real estate transfer has been a blatant instance where science, the radon industry, and government have bowed to economic pressure rather than to sound practice. We return to realty testing in chapter 8.

Institutional Testing: Are Public Buildings Safe?

"Institutional testing," involving measurements in public schools, day care centers, and government office buildings, became a major EPA focus by the late 1980s due to congressional mandate. Preliminary data from around the country indicated that there was some cause for concern. While the health guideline for public buildings is the same as for residences (4 pCi/l), development of testing guidelines is hampered by complex sampling questions, such as whether buildings should be tested while they are occupied or unoccupied; on weekdays or on weekends or evenings; and with heating, ventilation, and cooling on or off. Tight economics and the feared complications and costs of mitigation hampered many school districts from attending to the radon issue quickly.

Policy Error—The Case of Screening

EPA radon policy has focused upon screening measurements, with the goal of identifying hot houses and hot regions. Implementation of screening relied on finding a quick and inexpensive technique of sorting for hot houses. The tool of choice for screening was the charcoal canister, a government developed, inexpensive and easily handled testing device.[4] Screening as a policy was wedded to the charcoal canister and thus to the myth of the quick test, the assumption that radon levels could be assessed in a few days so as to provide valid information about longer term average radon levels in the building. One might even conjecture that screening became the policy goal of choice because the charcoal canister was so readily available and its best application was for screening.

The policy error in emphasizing screening should have been evident from the onset. It was well recognized in 1985 that the greatest public health risk was not to the few families living in hot houses, but to the multitudes living with much lower levels of radon. However, the myth of the hot house was so persuasive with its demand to screen for hot houses that EPA even ignored its own radon guidance, whereby the clear need for testing was to accurately discriminate between values below and above 4 pCi/l. The charcoal canister is particularly ill suited to this task, giving large numbers of false negative and false positive results (see for example, Scott, 1988b; Mose et al., 1988; Steck 1988, 1990, 1992; GAO, 1989). Thus, the primary emphasis on screening at best has been confusing, and, at worst, has provided wrong information to those testing their homes. Significantly, most homeowners who test their homes have a different goal than that embodied in screening; they seek to identify whether their homes are safe.

The issue of safety is best answered by household characterization, which attempts to define the annual average radon level to which occupants of the building are exposed, and not by screening. A strategy based upon household characterization would find the hot houses, but would also give building occupants valid information about their annual average exposure. That information could then be utilized to project risks associated with the building. Informed decisions about needed remediation based on risk could be made. An additional advantage is that testing protocols could be simplified. Furthermore, a characterization-based policy is consistent with the national goal of lowering buildings to ambient radon levels, thought to average somewhere in the 0.3–1.0 pCi/l range. Most homes have a radon problem needing to be addressed according to the ambient goal. While reliable and economical measurement at such low levels is inherently problematic, short-term screening is certainly too inaccurate to reliably measure low radon levels required by this policy.

In summary, the dominant reliance upon screening represents a serious policy error for the EPA. Screening asked the wrong question; by focusing on maximum values in the basement, its findings are hardly applicable to the issue of safety and risk in most houses tested. Neither did screening address the public health risks posed by the vast majority of houses at lower radon values. And screening relied on short-term tests that were highly susceptible to sampling error. By taking on the impractical objective of screening for hot houses, EPA missed the opportunity to implement a policy based upon household characterization that would have both addressed risk and identified hot houses.

While a combination of the Watras discovery and limited available information might excuse EPA's initial adoption of screening, what is surprising is that the policy has persisted in the face of firm evidence of its inadequacy. In the wake of the Indoor Radon Abatement Act of 1988, with its ambient goal, together with the increasingly recognized inadequacy of short-term sampling (see GAO, 1989), a shift away from screening would have been expected. However, in 1991, EPA proposed new guidelines for doing exactly the opposite: a one-step testing process enthroning the screening measurement with all its problems as the predominant radon test. Finally, in May 1992, the new *Citizen's Guide* moved even further from household characterization with its emphasis on shorter term tests, although it did recommend measuring in lived-in (rather than potentially livable) levels.

Methodological or Sampling Error

The key methodological error affecting the validity of radon testing involves sampling error caused by the heavy reliance on short-term testing and resulting insufficient sampling time.[5] Put simply, radon concentrations are often sampled over a time span that is too limited to fully assess the phenomenon being measured: one cannot validly predict a long-term average exposure from a short-term measurement. Blinded by the myth of the quick test, experts in government and the private radon sector continue to ignore ample evidence that radon is just too variable in many cases to reliably measure it over time periods of only a few days or less. Such variability is evident in radon's predictable fluctuations, those for which known variables have been identified related to weather and other natural conditions and to human behavior and house design. Radon also undergoes erratic or unpredictable fluctuations for which there is currently no acceptable explanation.

Radon's Predictable Variability

Radon and daughter concentrations indoors have been related to a variety of natural and human-caused conditions (see NYSEO 1989, II-23 to II-29).

Naturally Induced Radon Variations. Natural environmental factors that affect radon emanation from the soil include specific soil and weather conditions, daily or diurnal (day/night) weather cycles, and longer term cycles. The dynamics of some variations are well understood; in other cases, known variables cause less predictable outcomes.

There are many weather conditions that affect radon levels. For example, high winds can induce pressure-driven flows of soil gas from the ground into the house. Large barometric pressure changes accompanying storms can also affect radon levels. Rain, snow, and freezing ground can enhance the entry of radon into houses by preventing the escape of soil gas directly to the outside air surrounding a building (Nazaroff and Nero, 1984; Nazaroff et al., 1988b, pp. 92–97). Seasonal and even yearly variations in radon levels have been found by many researchers (Cohen and Gromicko, 1988b; George and Hinchcliffe, 1986; Sextro, 1990; Martz et al., 1991b).

There are also short-term fluctuations in radon levels observed on diurnal cycles. As shown in figure 6.1, such differences between night and day are probably caused by temperature and wind changes that accompany day/night changes (Scott, 1988b; Sextro, 1990). Such diurnal differences suggest a pattern of change that can be eliminated as a testing variable if tests begin and end at the same time of day (Scott, 1988b).

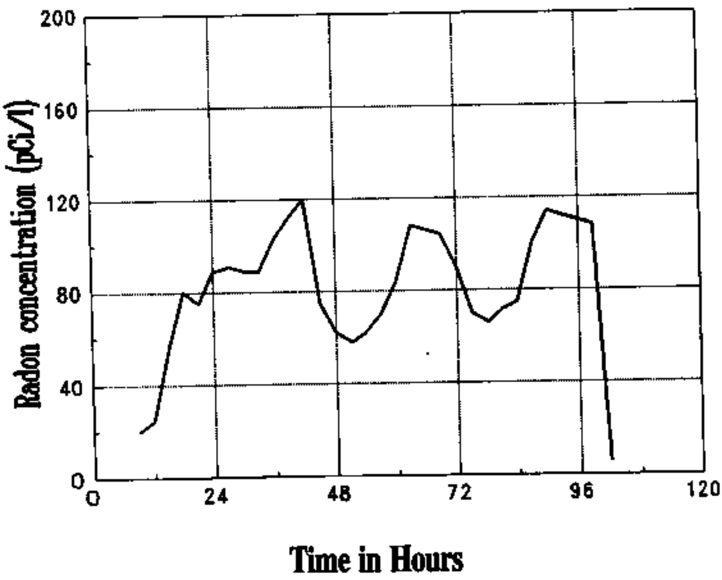

Fig. 6.1 Thermally induced diurnal radon cycles in summer (*Source*: Scott, 1988)

However, natural radon cycles of longer term also occur that would not be addressed by diurnal sampling. These longer-term cycles relate to high and low pressure systems, the weather patterns that continually cross over the continent bringing changes in temperature, wind, moisture, and atmospheric pressure. These patterns change approximately every three or four days, as shown on figure 6.2. A sampling interval capable of averaging the variations surrounding several pressure system shifts would require about fifteen days of integrated testing (Scott, 1988b).

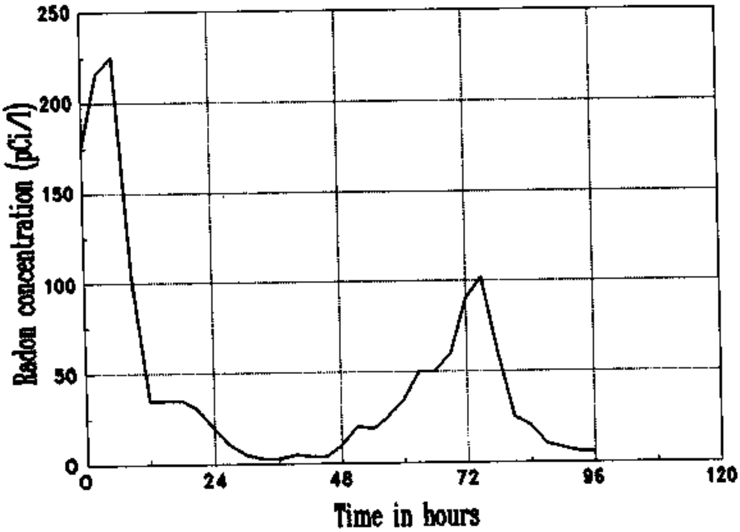

Fig. 6.2 Extreme long-term radon variation (*Source*: Scott, 1988)

Building and Occupant-Induced Variability. It is well documented that radon levels in houses are affected by such house conditions as whether the house is closed up (doors and windows are shut), whether ventilation fans are on or off, and whether the furnace is operating (EPA, 1989a; Scott, 1988b). Generally, open houses during warm weather have lower radon levels because air exchange dilutes the internal atmosphere. However, there are exceptions to this rule. If air exchange increases negative pressure in the building, more radon may be drawn in from the soil. In fact, such actions as blowing air out of a basement window or using a whole house fan, by serving to increase the negative pressure in a basement, may enhance radon entry.

Similarly, conventional rules regarding radon concentrations within different spaces in a building can also be proven wrong. Two such rules, that basements have higher radon values than do upper levels of the house, and that upstairs rooms have less radon than downstairs rooms, may be contradicted if air handling systems circulate radon from the basement or the ground to upper levels of a house, causing higher levels there, or if thermal bypasses enhance air flow and radon to upper-level rooms, again inverting the normal behavior. Radon outgassed from water could give larger values upstairs in rooms where water use is greatest.

Radon has been found to vary spatially for other reasons (Steck, 1992). For example, rooms over different types of foundations (slab, crawl space, or full basement) may have varying amounts of radon. Bathrooms and kitchens may be affected by ventilation devices. Locations near HVAC vents, doors, windows, and exterior walls may be affected by drafts. Locations near the floor or ceiling are often not representative of other locations in the room. These factors are recognized in EPA measurement protocols and are the basis for the recommendations for controlling testing conditions.

Occupant-driven changes in house conditions such as ventilation, water use, or appliance use may also affect radon levels in extreme and sometimes unpredictable ways. The use of cook stove fans, bathroom fans, and clothes dryers may enhance negative pressure, and thus radon entry. If high amounts of radon are found in water, the radon concentrations in the internal air may well vary with water use. An example of this variation is offered in figure 6.3 (Scott, 1988b). The variations shown in figures 6.1–6.3 were all obtained under closed-house conditions and following all EPA protocols for assuring reproducibility. In all of these cases, however, short-term tests are seen to be particularly vulnerable to distortion from fluctuating radon levels.

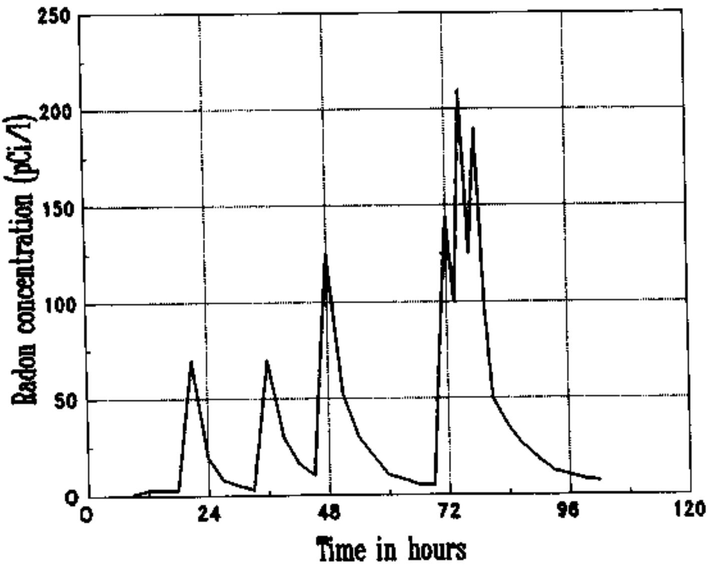

Fig. 6.3 Variations produced by radon in water (*Source:* Scott, 1988)

Radon's Erratic Variability

Aside from the somewhat predictable cycles associated with weather, time of day, and human use of the building, there is also evident an element of the erratic in the behavior of radon that upsets conventional wisdom about where and when to find maximum radon values in a building. Researchers have observed significant changes in radon levels over just a few weeks within a house—sometimes of more than a factor of twenty—that cannot be readily explained by any of the factors discussed above. Such "unusual variations" in radon emanation may be caused by seasonal changes in radon levels in soil air combined with wind direction changes. In other instances, soil and bedrock conditions combined with topographical factors may be involved; examples include conditions of exceptionally high permeability found with limestone cavities, shattered shale, or sand combined with sloping surface land forms (NYSEO, 1989, II-27 and II-29). Such extreme exceptions to the rules are not infrequent; several buildings out of every hundred or so studied seem to defy conventional assumptions about radon behavior (Camroden Associates, 1989).

Implications of Variability for Screening

While a radon measurement of any time interval is likely to introduce some error in estimating average radon levels for a longer time interval, in general this sampling error will increase as the time of measurement decreases. Indeed, studies show that short-term measurement devices such as the charcoal canister have a considerable sampling error (see Scott, 1988b; Mose et al., 1988; Steck, 1988, 1990, 1992; Dudney and Hawthorne, 1989; Granlund and Kaufman, 1987; GAO, 1989; Sextro 1990). Sampling error poses a major problem when using a short-term measurement to screen or characterize radon levels in a building where radon levels are highly variable. Since variability is inherently unknown, the degree of actual sampling error in a given test is also unknown. It cannot be assumed that the shorter term test is representative for the long-term average radon exposure.

There are ample proofs of the limits for generalizing screening tests. When short-term charcoal canister measurements were compared with seasonal and annual average alpha track tests made in Maryland and Virginia, the screening measurements had a 90 percent uncertainty in approximating year-long house characterization radon levels. In other words, the short-term measure is a relatively poor indicator of long-term average results (Mose et al., 1988).[6] Similar problems were found in a Minnesota and Wisconsin study of charcoal measurements. In 20 percent of the houses tested, screening results were less than 4 pCi/l, while long-term house characterization results exceeded 4 pCi/l. In contrast to these false negative results, in another 30 percent of the houses, false positive results were found. That is, screening measurements were greater than 4 pCi/l, but subsequent long-term follow-up measurements were found to be less than 4 pCi/l. In all, 50 percent (20 percent false negative and 30 percent false positive) of the screening measurements gave a wrong message (Steck, 1988, 1990).[7]

Finally, a summary of data from several researchers on the seasonal and spatial variations in indoor radon concentrations found that daily variations in radon cause large inherent measurement uncertainties ranging from 20 to more than 100 percent. Even monthly average radon concentrations were found to vary by large factors, so that measurements taken for periods of less than three months may only be reliable to within a factor of two or greater. In addition, the aggregate data for houses tend to give a ratio between basement screening and annual living space average that varies regionally around the country. There is also a large variability in these ratios within regions indicating that little can be assumed about the individual house based on the basement screening measurements that original EPA guidances recommended (Sextro, 1990; Steck, 1992).[8]

It should be noted that the sampling errors mentioned here are not indigenous to the charcoal canister; it just so happens that the charcoal canister is most often used. Any detector used for short-term measurements may produce similar sampling biases. That it is common practice to engender this error—albeit often unknowingly—suggests that officials, professional testers, and the public have just not recognized sampling error as the problem that it clearly is. The fact that rampant error is found in the EPA's preferred approach to radon testing suggests the need to look more closely at the adequacy of the EPA protocols and quality assurance program.

Inadequacy of EPA Protocols to Address Sampling Error

EPA protocols attempt to address sampling error by recommending minimum sampling times for different kinds of radon test devices, and by recommending a standardized set of conditions (environmental, house, and occupant behavior) for testing. However, because these recommendations were based on early and inadequate information and assumptions, they do not adequately address the issue of what sampling interval is necessary to validly measure radon levels. Clearly the minimum recommended times for screening measurements are often too short to account for radon variability. As a result, conventional wisdom about radon fundamental to the screening approach has been often contradicted. For example, closed-house wintertime conditions have often been found to yield lower radon levels than have characterization tests measuring average annual radon concentrations so that you cannot assume maximum radon levels will be found by screening. Similarly, basements do not always yield highest levels (see Scott, 1988b; Steck, 1988, 1990; Mose et al., 1988; GAO, 1989; Sextro, 1990). Perhaps of even greater concern, the protocols and recommendations are often so complicated that they are hardly followed. As we mentioned earlier, most professional testers did not perform house characterization tests to follow up screening measurements between 4 and 20 pCi/l, even when it was recommended by EPA prior to 1992. The new *Citizen's Guide* recommendations (EPA 1992f), by excluding a specific recommendation for house characterization, makes it unlikely that many homeowners would seriously consider it as well.

There is, of course, an even greater problem. An EPA study showed that over 85 percent of homeowners in the Washington, D.C. area who screened their homes for radon and received greater than 4 pCi/l did not perform a follow-up measurement of any type (GAO, 1989, p. 5). The absence of confirmatory testing places an even stronger onus on screening measurements that the screening approach is totally incapable of meeting.

Cumulative Effects of Sampling Error

The significance of sampling errors was shown by a study examining how cumulative errors affect false negative readings (Bierma et al., 1989). Monte Carlo sampling methods were used to simulate various errors at different radon levels and specified monitoring scenarios. At the guideline of 4 pCi/l, three-day charcoal canisters tests gave 36.6 percent false negatives and three-month alpha track detectors yielded 30.2 percent false readings. At 8 pCi/l, the three-day charcoal gave 11 percent false negatives while the three-month alpha track gave only 2.2 percent. These projections are probably underestimates given conservative assumptions about spatial and seasonal variation (Sextro, 1990). Perhaps more surprising is that the sequential testing approach recommended by the EPA (screening then follow-up) would give 67–70 percent false negatives at 4 pCi/l. This high figure is understandable if one considers that about one-third of the houses didn't follow up because of the false negative reading on the original screening measurement, while about half the remainder could be expected to fall below 4 pCi/l on the follow-up test based on statistical error. These results illustrate the problems of setting an artificial guideline at 4 pCi/l and the inherent futility of the screening approach.

Conclusions Regarding Methodological Error

The evidence on radon variability explains why quick tests are conducive to methodological or sampling error. While some of the factors that affect radon variability are under the control of the tester, many are not. The whole logic of screening with short-term measures relies on the notion of searching for maximum radon levels within a building. In a significant number of cases, however, it is not known where or under what conditions these maximum levels will be found. Maximum levels may not be encountered with basement tests under closed-house conditions. Furthermore, short-term testing cannot, by definition, account for significant radon fluctuations that are not sampled for. For these reasons, any measurements using short-term testing with any type of detector are particularly prone to methodological or sampling error that limits their utility. These problems are further compounded when we examine device error.

Device Error

Each testing device brings significant advantages and disadvantages to the testing task that make it more suitable for application to certain objectives than to others. Here we focus specifically on "device error," the intrinsic or inherent limitations of testing instruments that limit the validity of their findings. Table 6.2 summarizes major characteristics of the three most common passive radon detectors. The shortcomings of the charcoal canister are of particular note given its central role in screening policy. Also notable is the extent to which the myth of the quick test blinded EPA and others to these limitations, as well as to the advantages of the alternatives.

Table 6.2 Comparison of Passive Integrating Radon Detectors

Characteristics	Charcoal canister	Alpha track detector	Electret detector
Integration time	2–7 days	2 weeks to a year	Few days to a year
Cost	Low	Low	Low
Integration ability	Fair	Good	Good
Environmental limitations	Sensitive to temperature and humidity	Few limitations	Sensitive to temperature, background gamma, and temperature during analysis
Precision	Good	Low at low concentrations or short sampling times	Good
Analysis location	Laboratory	Laboratory	Field or laboratory
Major shortcomings	Limited sampling time; desorption with varying radon concentration	Low precision at short sampling times	Care must be taken to not inadvertently discharge electret

Source: NYSEO, 1989; EPA, 1989a; and Kotrappa et al., 1990.

Charcoal Canister

Charcoal canisters use activated carbon to absorb radon by molecular diffusion over an integrating period of between two and seven days. The tight-fitting cover is removed from the canister at the onset of testing and is resealed upon completion, preventing the escape of the charged heavy metal particles belonging to the radon daughters polonium, bismuth, and lead present due to the decay of radon gas that entered the canister during the test period. After return to the laboratory, the canister is placed on a detector that counts gamma rays emitted in a particular energy range from the radon daughters lead 214 and bismuth 214.

The charcoal canister provides relatively precise results over fairly short periods of measurement. Its strength lies in the ability to reduce statistical error through detection from the absorbed radon of a large number of gamma counts given off during daughter decay. This advantage is offset, however, by the characteristics of the physical test device and the fact that charcoal canisters can be used only for tests of brief duration, typically a few days, and are thus highly susceptible to sampling error. This short test time is necessitated by radon's half life of only 3.8 days. Short-lived daughters from radon collected early in sampling preferentially decay away before analysis can take place, weighting the latter part of the measurement. As a result, the canister may easily misrepresent average radon levels if radon variability is sufficiently significant to make the test period unrepresentative of the longer-term average. Furthermore, the ability of charcoal canisters to integrate radon levels over time is limited because radon will desorb from the canister depending on temperature and relative radon concentrations in the canister and the room. Thus, two-day charcoal canister tests will preferentially weight the last twelve or so hours. These variations may add an additional 50 percent uncertainty to the measurement (Sextro, 1990). By using a charcoal canister equipped with a diffusion barrier, the time-integration error can be reduced from 30 percent to 8 percent with additional improvements in averaging over diurnal variations. However, the modified canister requires an exposure of seven days (Martz et al., 1991a; Field and Kross, 1990). The charcoal medium is also sensitive to temperature and humidity effects, a problem that can add to the error associated with these detectors (Bierma et al., 1989).

Alpha Track Detectors

An alpha track detector consists of a plastic film placed inside a small plastic pillbox container. Since only radon diffuses through the filter, any microscopic tracks etched into the plastic from alpha emission will indicate the presence of radon and its daughters. Thus, the more tracks over a given time period, the greater the radon concentration. After its return to the laboratory, the film is "developed" in a sodium hydroxide solution that etches the tracks, which are then counted.

The alpha track detector is one of only two devices (with the electret) that cheaply and easily performs an integrated radon measurement over time periods significantly longer than a week. Alpha track detectors do not exhibit errors due to time integration, temperature, or humidity. Measurements using alpha track detectors are typically made for at least two to three months or for a year where an annual average exposure is desired. The alpha track detector is sometimes used for shorter measurement periods if the expected concentrations of radon are sufficiently high or if, by counting a larger area, a more sensitive reading of the detector is made. A major disadvantage of the device is that precision is limited at relatively low levels of radon and/or for shorter test periods simply because there are few tracks on the film to count (EPA, 1989a). The device has from time to time been plagued by bias and precision errors (Field and Kross, 1990; Martz et al., 1991a; Scott and Robertson, 1991; Yeager et al., 1991; Pearson et al., 1992).

Electret Ionization Chamber

The electret ion chamber emerged as an testing device around 1988, challenging the other passive detectors with its similar range of applications and several distinct advantages. Radon gas enters the chamber by diffusing through filtered openings. A permanently charged electret (an electrostatically charged disk of Teflon) is used to collect ions (charged particles) formed by alpha, beta, and gamma radiation emitted during the subsequent decay of radon and radon daughters. Because negative ions attracted by the electret during decay serve to reduce the electret's surface voltage, the loss of voltage becomes the measure of radon concentration. The average radon level in pCi/l is found directly by dividing the voltage difference by a calibration factor and the time of exposure. A correction may be made for external background gamma radiation. Two versions of the device are made, one for use in short-term tests of between two and fourteen days and one for longer term measurements of between two weeks and a year (NYSEO 1989, III-10; EPA, 1989a; Kotrappa et al., 1988).

The electret shares the advantages of both the charcoal canister and the alpha track detector. Plus, it adds two major advantages of its own. First, while the charcoal canister cannot be used for sampling for longer than several days and the alpha track detector is inadequate for short-term tests, the electret device functions over any time span from a few days to a year. It further avoids the tendency of two-day charcoal canisters to overemphasize the last twelve hours of testing, integrating the entire time period equally. Second, analysis of the electret can be done immediately in the field by testing professionals using a surface voltage meter (EPA, 1989a; Kotrappa et. al., 1988). On the negative side, care must be taken to correct for sensitivity to temperature at the time of analysis and in handling the device when it is removed from its protected plastic case in order to avoid uncontrolled effects on the charge of the unit. The electret ion detector also is subject to correction errors from background gamma radiation. Finally, this test device requires testing by an expert, increasing costs and creating a potential conflict of interest for having analysis done by testing firms having a direct interest in whether mitigation is required.

Conclusions Regarding Device Error

Device error is rarely a major threat to validity in and of itself. Limitations of various instruments are well known and are often subject to correction in analysis. Manufacturers and the EPA provide recommendations for the avoidance of device error. Accordingly, our concern mostly involves device error's compound effect when interacting with already troublesome levels of policy and methodological/sampling error. The charcoal measurement's overall error raises the possibility of unacceptably large numbers of false positives and negatives in detecting whether buildings require remediation.

Measurement Error

Over the time interval during which radon is measured by any given device, there is a risk of measurement error. Such error occurs when conditions before or during the test depart from the standardized conditions for the test and cause the device to give an inaccurate or irreproducible result.

Measurement Error and EPA Protocols

EPA protocols for radon testing devices make recommendations for the standardization of testing in order to enhance the reproducibility of results. These protocols include specifications for house conditions, detector placement, occupant behavior, and operation guidelines for various types of detectors and for different measurement goals (EPA, 1989a). General EPA protocols call for location of detectors away from sources of air turbulence and drafts, away from obstructions that would block radon from reaching the device, away from pets and children who might damage the device, and away from heat sources. Devices are to be located within the average breathing zone, typically three to five feet from the floor. EPA also generally recommends that testing be done under closed-house conditions and in the absence of air exchange systems that would mix inside and outside air. For test samples of three days or less, closed-house conditions are also recommended for at least twelve hours prior to testing. EPA and manufacturers have further developed some targeted protocols for specific testing devices.

Deliberate Measurement Error

We have seen that there are substantial opportunities for error in the way that measurements are done. These may occur accidentally or due to carelessness. However, there is a third possibility—deliberate measurement error. The potential, indeed, the likelihood, of such error exists when test conditions are controlled by those who have a direct vested interest in the test outcome. Such deliberate error has been widely noted in real estate testing, where the person selling the building benefits directly if no appreciable concentrations of radon are found (see chapter 8). Radon testers have also been known to fudge results as well, although most often they hurt validity by being sloppy or incompetent in providing accurate test analysis and adequate quality control (GAO, 1989, p. 5). Overall, measurement error due to any cause is a threat to test validity.

Analysis Error

After the measurement has been taken, an instrument either has recorded a certain number of counts or tracks representing radioactive decays of radon and/or its daughters or has absorbed radon in charcoal. Analysis error refers to the error introduced when the raw data are read and converted into radon concentrations (pCi/l) or daughter concentrations (WL). Several types of analysis error can be delineated. These are statistical error, calibration error, background error, and human error.

Statistical Error—Getting Enough Counts

Typically, error margins of plus or minus 10–30 percent are assigned to most radon devices, reflecting the statistical error and/or the ability to reproduce the measurement under a fixed set of conditions (NYSEO, 1989, III-30).[9] Generally, less error is expected when greater numbers of decays are counted. Thus, for a given concentration of radon, statistical error is more likely when the device is less sensitive, the air volume tested is small, or when counting times are short. Clearly, decisions made about sampling times and the type of instrument will affect analysis error. Protocols address statistical error by suggesting minimum times for sampling for different test instruments. Additionally, analysis procedures can be modified to reduce this error factor. For alpha track detectors, for example, increasing the area of the film that is analyzed will produce more counts and reduce error. For charcoal canisters, increasing the length of time during which gamma rays from the daughter products are counted gives more counts and reduces statistical error.

Statistical analysis error can affect the overall accuracy of a measurement program. Substantial analysis errors are thought to have occurred after the 1988 assistant surgeon general's pronouncement on the health effects of radon. Tens of thousands of concerned citizens screened their homes in the wake of the warning, and swamped charcoal canister laboratories with detectors way beyond their capacity. As these canisters waited for analysis, radon and radon daughters decayed away, leaving fewer counts for analysis. Some laboratories also reduced counting times to deal with the overload. While a statistical error of between 10 percent and 30 percent is typical for such analysis, in this instance, analysis error was thought to be considerably increased.

Calibration Error—Are Instruments Calibrated to a Standard?

All analysis methods depend on a calibration factor used to convert counts measured over some time interval into a radon concentration in pCi/l or a radon daughter concentration in WL. However, if the calibration number obtained is either too high or too low, a bias or systematic error is introduced into the analysis. By analogy, the biased calibration factor is the rough equivalent of measuring distances with a ruler that is stretched or contracted; all measurements would be off in one direction or the other. EPA's Radon Measurement Proficiency (RMP) program provides for a check of bias error by comparing the average of a large number of detector measurements of the same type with a standardized value. Most detectors reviewed under the RMP program have been found to produce a bias error of less than 10 percent (Wing and Mardis, 1987), although it appears that actual bias under more realistic conditions might be greater (Yeager et al., 1991).

Background Error—Is the Analysis Contaminated from Another Source?

Background radiation may also limit the accuracy of measurement. This source of error is particularly a problem for low counting rates associated with low radon concentration samples because, in these samples, background makes up a comparatively large proportion of the measured counts. The EPA provides device-specific recommendations for reducing the background error (EPA, 1989a).

Human Error

There are numerous mistakes that can be made during analysis, all exacting a toll on accuracy. Canisters can get mixed up, numbers can be misread, incorrect calibration factors can be used, and delays in analysis can occur. The number of possibilities are almost endless, indicating a vast human ingenuity for fulfilling Murphy's Law—if it can go wrong, it will. Performance evaluation tests of detector firms indicate that human errors are not uncommon (Yeager et al., 1991).

The Radon Measurement Proficiency (RMP) Program

The EPA, through its RMP program, has tried to limit some of the analysis error, including statistical, bias, background, and human errors, that are inherent when a testing company produces a radon or radon daughter measurement with a testing device. The RMP program was initiated in 1986 by the EPA "to allow organizations offering measurement services to consumers a means to demonstrate their proficiency in measuring radon" (Jalbert et al., 1991). This voluntary quality assurance program has a twofold purpose. First, it promotes standard measurement procedures. Second, it encourages quality assurance procedures by all companies in the radon measurement business. In effect, the RMP program focuses on analysis and device error.

In the RMP program, detectors belonging to participating companies are exposed to undisclosed calibrated levels of radon and radon daughters at an EPA radon chamber.[10] The detectors are then analyzed by the testing firm, and results are submitted to EPA for comparison with the radon chamber values. Proficient performance is defined as a screening measurement that lies within plus or minus 25 percent of the chamber value. Companies passing the RMP proficiency tests are listed in a public document that is distributed by EPA to state agencies and to the public. While the RMP program is voluntary, states led by New Jersey quickly began to require passing the RMP proficiency test as a precondition for testing in the state. Firms are required to renew their proficiency on a regular basis. Since its inception, the RMP program has mushroomed with the increasing numbers of test firms and testing devices (see chapters 3, 8, and 10).

The major advantage of such a program is that it provides some degree of control over the proliferation of inept or fraudulent companies and inaccurate testing devices in the radon testing field. It does provide a minimum standard of performance for companies who desire to be on the proficiency list. However, there are some key limitations to the RMP program that relate specifically to measurement and analysis error (GAO, 1989). The program does not test detectors under realistic conditions where radon variability may be large. Testing is often done at much higher radon levels than is typically found in homes. The program hardly measures how well firms do on a day-to-day basis; firms have treated their EPA detectors with special reverence. Even so, the quality of results from different testing firms for the same type of testing device can be quite variable (Martz et al., 1991a; Pearson et al., 1992). Numerous rumors hint of industry cheating on the RMP proficiency tests. And, unless states require participation in the RMP program, it is purely voluntary. Thus, many firms can avoid this minimal quality control altogether. Recognition of these problems has led to the application of remedies such as the use of double-blind testing, where firms would not know which tests coming to their lab were from the RMP program. When EPA applied double-blind tests in 1989, 20 percent of the firms that had shown proficiency in 1988 failed (GAO, 1990). The EPA is also considering radon chamber testing under variable conditions. A GAO (1990) study recommended that EPA require that firms participating in the RMP program demonstrate a minimum quality assurance capability, and that EPA issue guidance on what an effective state program should do to assure accurate radon measurements. In the meantime, the growing number of states requiring RMP participation will close an important loophole. However, the RMP program hardly addresses policy, interpretation, and sampling error (see chapter 10).

Interpretation Error

After a radon test result is received, the findings must be interpreted. Interpretation error occurs when inaccurate conclusions are drawn about the meaning of a test result. Interpretation errors are often secondary effects of other validity threats, such as policy error. In particular, radon policy is plagued by a prevalent interpretation error originating from confusion over the meaning of screening, follow-up, and house-characterization measurements.

Screening and Follow-up Confusion—the Problem of False Negatives

EPA's 1986 and 1992 guidelines for screening and confirmatory testing created rampant false interpretations among testers and the public. The most significant interpretation errors are due to the myth of the quick test, the assumption that short-term tests can provide valid indicators of a building's radon level, and, therefore, give an accurate health risk estimate.[11] The error of interpretation is a secondary impact of methodological and policy errors whereby screening and confirmatory testing are confused with household characterization. When people conclude that their homes are safe based upon screening results less than 4 pCi/l, a confusion invited by EPA guidelines, they are making this serious error. We have seen above that short-term screening tests coupled with radon variability and erraticness can lead to a significant number of false positives and false negatives. Since EPA guidelines invite people receiving scores of 4 pCi/l or more to do additional testing, false positives have a chance of being addressed. However, false negatives are never checked. Those incorrectly told that their levels are less than 4 pCi/l are not likely to do further testing. Such errors were compounded when few homeowners and relatively few testing professionals followed EPA's original recommendations to use household characterization as a means of confirming screening results between 4 and 20 pCi/l. Instead, follow-up testing would use charcoal canisters under closed house conditions. The methodological problems with the charcoal test bias these results. When they are interpreted as though they provided information about the safety of the building and health risk, interpretation error occurs. Revised EPA guidelines assure this error.

Assumption of Safety below 4 pCi/l

Beyond compounded methodological error, there is a serious interpretation error in the very perception that radon levels below 4 pCi/l are safe. Despite EPA's disclaimers that their 4 pCi/l guidance is not a standard separating safe from unsafe levels, the public has clearly treated 4 pCi/l as a magic divide or threshold. The seriousness of this interpretation error was key to Congress's dictate of an ambient goal for radon exposure and its charge to EPA to clarify the meaning of 4 pCi/l in the revised *Citizen's Guide*, which was finally issued in May 1992 (see chapter 9).

Ambiguity in Making Health-Risk Estimates

Another source of interpretation error stems from the inherent uncertainty of estimating unknown health risks. At 4 pCi/l, the EPA estimates that between one and five lung cancers will develop in one hundred people exposed over a lifetime of seventy years. Such ranges of risk, while reflecting our state of scientific knowledge, are confusing. Additionally, these risk estimates are not easily interpreted or understood when applied to shorter exposure times. What is the risk to people who were exposed for only five years, who spend only a small amount of time at home or who are younger than seventy? These points of ambiguity suggest that some members of the public will discount a risk of concern to others.

Ambiguity in Converting from pCi/l to WL

Given that radon daughters, not radon per se, is the source of hazard, conversion between radon and its daughters is necessary in order to project health effects. EPA generally assumes that 200 pCi/l of radon is equivalent to 1 WL of daughter activity based on a condition of equilibrium where half the daughters have plated out and, therefore, do not contribute to health effects. In actual buildings, this assumption may be misleading. For example, buildings with significant airflow, particularly larger buildings with air-handling systems, have conversions on the order of 400 pCi/l for 1 WL. Similarly, there may be less risk in houses with hot-air-circulation systems or whole-house air conditioning. If incorrect assumptions are made about equilibrium conditions, incorrect interpretations about safety are likely.

Conclusion Regarding Interpretation Error

We see that significant interpretation errors are invited by current radon policy. Our tendency has been to discuss these in light of the effort of home occupants to determine their risk. However, interpretation error also has major implications for realty transfer. Perhaps the major "market" for radon testing, we see here that realty decisions based upon short-term measurements are likely to suffer from the same extreme level of error as do the measurements themselves.

Radon Testing in Water and Soil

Many of the validity threats seen with testing for radon in air also occur when we examine radon in water and soil. We previously noted the tendency to overweight the significance of radon in water, which is in fact unlikely to be a problem in the absence of an airborne radon problem.[12] Still, radon in groundwater has been recognized as a serious issue (see chapters 3, 4, and 10) given values as high as one million pCi/l. Air tests are frequently used to screen for waterborne radon; a low value suggests that little radon is being released from the water supply. Approaches that directly measure radon in water include laboratory analysis of water samples using a liquid scintillation method or by counting gamma emissions, measuring the outgased radon from a sample of water with an electret ion chamber (Kotrappa and Jester, 1993), and placing a special integrating alpha track detector in the toilet tank for several months (NYSEO, 1989). These tests all suffer from various validity errors. However, of greatest interest with radon tests in water are interpretation errors. At a general conversion of 6,000–10,000 pCi/l in water to 1 pCi/l in air, 24,000–40,000 pCi/l in water would be required before the guidance level of 4 pCi/l in air would be triggered. The state of Maine has utilized 20,000 pCi/l in water as a level suggesting the need for mitigation. Nevertheless, the sheer size of these radon amounts can easily frighten an ill-informed homeowner into carrying out water system mitigations not called for by airborne radon levels (NYSEO, 1989).

Soil testing also confronts serious limitations. While it is simple to test soil for radon using grab samples or with integrating devices placed in the soil for a period of time, these tests have little predictive validity. Most critical are measurement or sampling problems due to the variability of radon levels in soil over very short distances and over time. As a result, the number of tests required to accurately represent a complex soil geology is quite large. Furthermore, even if the site is adequately sampled prior to construction, disturbance of the ground may alter the emanation of radon at a given location and make the transport of radon much easier. Of course, soil radon values are only one factor in determining what a house radon value will be. Soil permeability, weather conditions, and house construction and operation are also important (see chapter 5).

Conclusions about the Myth of the Quick Test

We have seen that, of the six types of error discussed, the validity of radon testing is most affected by fundamental policy and methodological errors leading to interpretation error. Simply stated, the combination of screening policy with the use of short-term testing provides too many false negatives and false positives at and around the guideline of 4 pCi/l. Perhaps some 50 percent of those testing for radon under the EPA protocols for screening have received wrong information. Short-term screening, as it is currently done, works for the much fewer hotter houses at the expense of the vast numbers of marginal houses at and around 4 pCi/l where the bulk of the health risk is located (Harley, 1990). Furthermore, screening measurements fail to provide a significant margin of safety. Ultimately, both screening and short-term testing fail due to the nature of radon variability in houses. Given that EPA protocols and the RMP program legitimize these problems, they also fail.

Prospects for House Characterization

Testing error can best be addressed through a change of testing policy to house characterization, based upon the use of an integrated annual radon level. This approach eliminates significant policy error by refocusing radon policy on the actual distribution of risk. Interpretation error is limited because the results of characterization may be directly applied to the radon risk charts. Methodological errors are minimal because house characterization is not affected by radon variability and, therefore, sampling error is not an issue. Also, there is no potentially incorrect assumption of a maximal value in the basement, as in screening. While even a year-long measurement offers a significant statistical chance that a house with a radon value at or slightly above 4 pCi/l will measure below 4, it offers the most valid and reliable information available about risk at a reasonable cost and is the most logical approach to radon measurement (Nero et al., 1990).

A shift to house characterization faces serious obstacles, however. The revised 1992 EPA *Citizen's Guide* avoids any discussion of the accuracy or validity of measurements and removes the minimal recommendation for house characterization found in the 1986 guide. While the agency purports to believe in the myth of the quick test, using elaborate excuses to justify its policy (see chapter 12), another reason for the agency's intransigence may simply be the difficulty of admitting that they were wrong. Reissuing new protocols on lengthening the sampling time for measurements might make EPA look foolish and raise complex questions of liability. All short-term tests below 4 pCi/l would have to be repeated in order to identify the 20 percent of false negatives. The radon industry's heavy reliance upon the short-term test, encouraged by EPA, would cause serious disruptions.The repudiation of short-term tests (including expensive continuous monitor tests) would invalidate the bulk of real estate transaction measurements.

Of course, continuing with the present testing policy has its own set of problems. First, EPA's current screening policy has created a major credibility problem. In many states, EPA and others have found, it is difficult enough to get people to screen for radon, let alone to retest later (GAO, 1989; Evdokimoff and Ozonoff, 1992). As homeowners begin to realize how little they learn from a short-term screening test, there is little motivation to retest or to expend a significant sum of money for mitigation based on relatively unreliable information. Neither can it continue to be argued that the present screening approach is cheaper when it so miserably fails to sort houses by risk and may have resulted in remediation of a substantial number of buildings at sale based upon false positive readings. There is precedent for EPA to revise protocols based on new information, as was done previously to eliminate grab sampling as a screening and follow-up measurement method because of unacceptably high error in sampling. In the instance of the quick test, one would be hard put to argue that the situation is much better.[13]

The real goal of policy should be to motivate accurate house characterization, thereby giving people more reliable information on health effects. EPA's radon policy relies on a screening approach, originally designed to motivate testing, that backfired by asking the wrong questions and failing to provide valid and reliable means of measurement. For a responsive radon policy to exist, the myth of the quick test must be finally laid to rest. In the next chapter, we see that there are also problems with the quick fix.

Notes

1. These tests do not require closed-house conditions and can be made either with a year-long alpha track or electret detector or by repeating a charcoal canister test over each of the four seasons and averaging the results (EPA, 1986).

2. The new version of the *Citizen's Guide* (EPA, 1992f) suggests a second immediate short-term test if the screening result is above 10 pCi/l, or if results are needed quickly. Also, the new guidelines suggest averaging screening and follow-up results rather than taking follow-up results on two lived-in levels of the house.

3. Following screening results between 4 and 10 pCi/l, the 1992 EPA guidelines recommend only a long-term test of greater than ninety days, although there is no explicit recommendation for a full year test. The guide additionally suggests averaging screening and follow-up tests even if they are both short term and ignores taking follow-up tests on two lived-in levels. When screening radon levels are higher than 20 pCi/l (10 pCi/l under the 1992 recommendations), shorter-term testing under closed-house conditions is recommended.

4. There were not really any other options available. Grab samples were fast, but they were known to be inaccurate. Like continuous monitoring, they were extremely expensive because skilled labor was required. The alpha track detector was a patented invention, not available for free use by government. The electret had not as yet been invented.

5. Sampling time refers to the length of time of the test. Three common approaches to sampling radon have been used (George, 1988). Grab sampling collects a sample of air over a short time interval, typically minutes, essentially providing an instantaneous snapshot of the radon or daughters in the building at the time the sample was collected. Because radon levels may vary considerably in a given building over time, grab sampling is unlikely to provide a valid picture of the long-term average radon value. Continuous sampling uses sophisticated monitors to repeatedly sample air, typically averaging over one-half to one-hour intervals, and provides detailed information on the variation of radon over time. This method is limited by complexity and cost. Finally, integrated sampling uses detectors to average radon or daughter concentrations over a few days to a year or more, giving a single number, the average, as the result. The commonly used devices, the alpha track detector, the charcoal canister, and the electret, are based on integrated sampling. We focus on integrated measurements in the text.

6. Interestingly, when three-month alpha track results were also compared to yearly averages, a 50 percent uncertainty was found. Thus, the three-month sample is considerably better, but hardly good, at approximating annual averages.

7. One remedy for addressing the particularly alarming number of false negatives—alarming because they falsely reassure the building occupants—would be to drop the radon action level to 2 pCi/l from 4 pCi/l. Under these circumstances, false negatives might drop to 5 percent, but false positive occurrences would become correspondingly more frequent. Steck suggests that a more reasonable corrective would be to eliminate screening measurements altogether.

8. EPA guidances from 1986 to 1992 called for measuring the radon level in the lowest potentially livable area and, after 1992, measuring in the lowest lived-in area.

9. Typically, two-thirds of the measurements made with the same type of detector under the same conditions and time interval would be expected to give a result within plus or minus 10–30 percent of the result obtained. This statistical error in percent is estimated by dividing the square root of the number of counts by the number of counts and multiplying the entire quantity by one hundred.

10. A radon chamber is simply an air tight box in which a known radon source produces a measured radon concentration. The chamber allows calibration factors to be determined for detectors, or it may be used to check the ability of a company to measure the radon level in the chamber, presumably unknown to them.

11. It is interesting that when EPA decided to get a more accurate distribution of actual radon exposure to the population, they took year-long measurements (see chapter 5). Yet when it comes to individual homeowners making expensive decisions about mitigation, the agency considers the short-term test to be adequate.

12. Radon is unlikely to be concentrated in water when the building draws its water supply from a large municipal source, since reservoirs will lose their radon to the outdoor air and large systems based on groundwater take so long to deliver water that most radon is decayed.

13. Given evidence of radon variability and an unacceptable rate of false negatives, it would be prudent to increase sampling times for other measurement methods. Indeed,

in December of 1990, the EPA revised its screening and follow-up protocols for testing to a minimum of two days. Although it is a step in the right direction, this clearly doesn't go far enough. Scott (1988b) and Sextro (1990) suggest something on the order of fifteen to thirty days in order to average over recurrent weather cycles. While still having some of the limitations of a quick test, the two-week to one-month measure may be the shortest duration having any possible claims to validity.