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The Incidence, Recognition, and Mitigation of Radon-based Problems in Residences

Harvey M. Sachs, Ph.D.

I have been asked to talk about radon and what we can do about it. Radon is a fascinating issue for several reasons. It is a very important issue, and there is a tremendous message of hope there. As David Grimsrud eloquently outlined this morning, radon is a problem. We can haggle about exactly how much of a problem it is, but it _is_ a public health problem today. Because of the trends in our housing construction practices, if we do not begin to work on the problem, it will become much more grave over the next three to five years. The good news, though, is that we know how to work with radon. There is no reason, except ignorance, for us in 1984 to build houses which have a lot of radon in them. We can keep the radon out and build safe houses without a significant energy or initial construction cost penalty. If I forget to bring out that message of hope at the end of this presentation, please remind me.

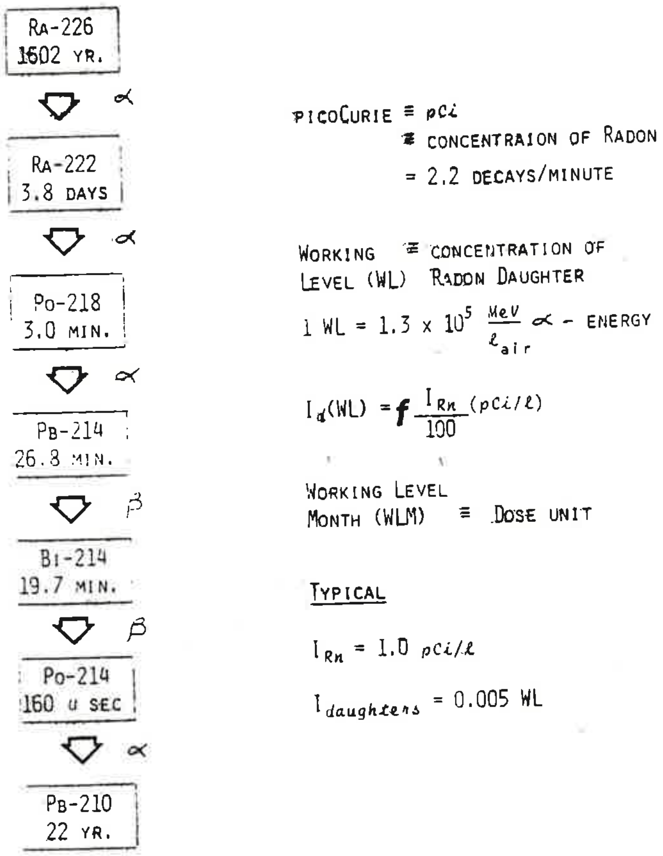


Figure 1

What we have in Figure 1 is the decay chain of uranium 238, with roughly a 4.5 billion year half-life, down to the stable lead 204. The point here is that this is perfectly natural stuff. We have a couple of parts per million (ppm) of uranium in the soil and in naturally derived materials of all kinds. This is part of the background that we humans have evolved to handle. It is perfectly ordinary, but gives rise to alpha decays. An alpha decay is the emission of an alpha particle, which is a helium nucleus. It is a charged particle; it's an extremely heavy particle that can do an enormous amount of damage if it happens to interact with tissue in its short flight. We have a number of alphas in this chain. There is a small amount of the radium 226, with roughly a 1600 year half-life, everywhere. Since it substitutes for calcium, we all have some inside us. The important part on the chain is that, when it decays by alpha emissions, we get radon. Radon is a noble gas. Like helium, argon, xenon, or krypton, it is essentially chemically unreactive. This means that it diffuses readily through solid materials. The Lawrence Berkeley Laboratory (LBL) data indicate, however, that four inches of good, well-poured concrete will absorb some 90% of the radon, in the sense that it decays before penetrating that much concrete. Yet in terms of many kinds of materials, radon diffuses readily. Since it is not chemically bound, oxidative reaction processes will not be applicable to radon.

The common unit which I like to use for radon concentration is the <u>pico-Curie per liter</u> (pCi/l). It is a concentration equivalent to 2.2 radon decays per minute per liter. How much radon does that represent? It is roughly one radon atom per each 10^{14} or 10^{15} air molecules. Obviously, there is not very much out there. In fact, if it weren't radioactive, we could not detect it, because all we do is track its decays. On the other hand, if it weren't radioactive, it would not be a problem.

Radiation units are not that simple, unfortunately. The literature is replete with hazards for those researching radon. The industrial hygienists and health physicists working in uranium mines have long used a more arcane unit, called the <u>working level</u>, (WL) as a concentration unit, and the <u>working level-month</u> (WLM) as an exposure unit. Basically, a working level is a concentration which will support 1.3 x 10^5 MeV of alpha energy per liter of air. While this is an important unit for calculating the dose in the lungs of miners, and while it is well established in the regulatory literature, I personally have some doubts about its applicability as we move from a group of healthy, active uranium miners to a group of environmentally sensitive infants, sick people, and others whose exposures are at lower concentrations but for many more hours per week. The problem I alluded to previously occurs when the radon progeny, the decay products of radon, attach to dust particles, which, in turn, are respired. These can land on a mucous membrane in the lung, and decay. The maximum energy deposition is likely to be in the basal epithelial cells. The basal epithelial cells are those which are most rapidly dividing. This means that, if such particles decay there often enough, there is a good chance they will damage the cell once in a while, and, once in a while, a lung cancer will be the result. The health hazard due to radon is, in fact, strongly associated with a particular class of lung cancer. An immediate question, then, is whether we can compare the health risks due to radon with the health risks due to something we commonly accept, like smoking. The answer is yes, but let's look at the uranium data first.

The cumulative lifetime exposure, in working level-months, versus the additional lung cancers are shown in Figure 2. At 500 WLM we see about a hundred additional lung cancers per thousand miners, or a chance of approximately an additional 10% of the miners contracting lung cancer as a result of their occupational experience. The average American is probably living down in the range of 10 or 12 working level-months per life-time, or 1 pCi/l as David Grimsrud suggested.

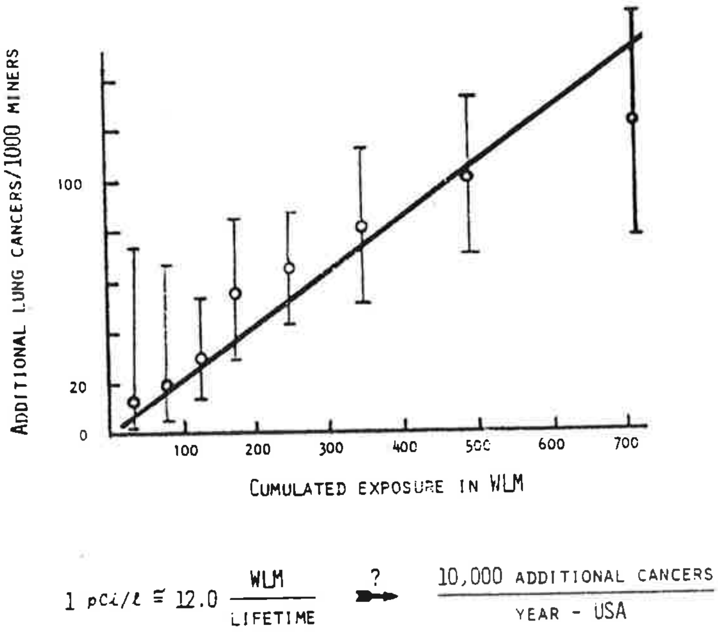


Figure 2

Our problem is one that follows from the log-normal distribution that David showed this morning: a non-trivial fraction of people are now living in houses in which the concentrations are very high, at rates corresponding to 100-500 WLM in a life's exposure - the same range as the data on miners. We are now seeing people in Pennsylvania, in Maine, and elsewhere, where a significant fraction of the population, whether it is 1, 2, or 5%, is living with enough radon that no extrapolation will be required to estimate their lifetime risk. It is within the range that is now statistically, extraordinarily well correlated from large groups of miners with development of excess lung cancer. How does this compare with the EPA's risk assessment? The EPA is a very conservative group, so it is going to give us a ninety-fifth percentile upper boundary. Basically, what that says is, if someone is exposed for, say, thirty years to a radon concentration of 10 pCi/l, he will have more than a 1% chance of developing lung cancer. That is the way Figure 3, drawn by Tom Hernandez, should be read. What we are seeing today is a significant population exposed at 8-10 pCi/l, and a smaller population at 50 pCi/l. We are starting to see risks which are scaled in the same way as the risks of smoking. They might not be quite as high, but it has led some people to use a rough guideline based on the EPA calculations. The rough guide is that 1 pCi/l concentration for a lifetime is equal to about a cigarette per day as an adult. (Most independent health physicists would drop the risk by a factor of two to four.) A result is that people in the field will talk about pack-a-day houses. It is a vivid, albeit gruesome, metaphor, especially when one considers that children are living in the houses.

I want to make one other point before we go too far with this smoking analogy. There is a fundamental difference between radon exposure and tobacco use. Some people will contract lung cancer from radon exposure. However, they will not get emphysema, throat cancer, ulcers, excess heart attacks, or all the other things that are attributable to smoking, from radon. Health authorities say we can expect about 120,000 total lung cancers each year in

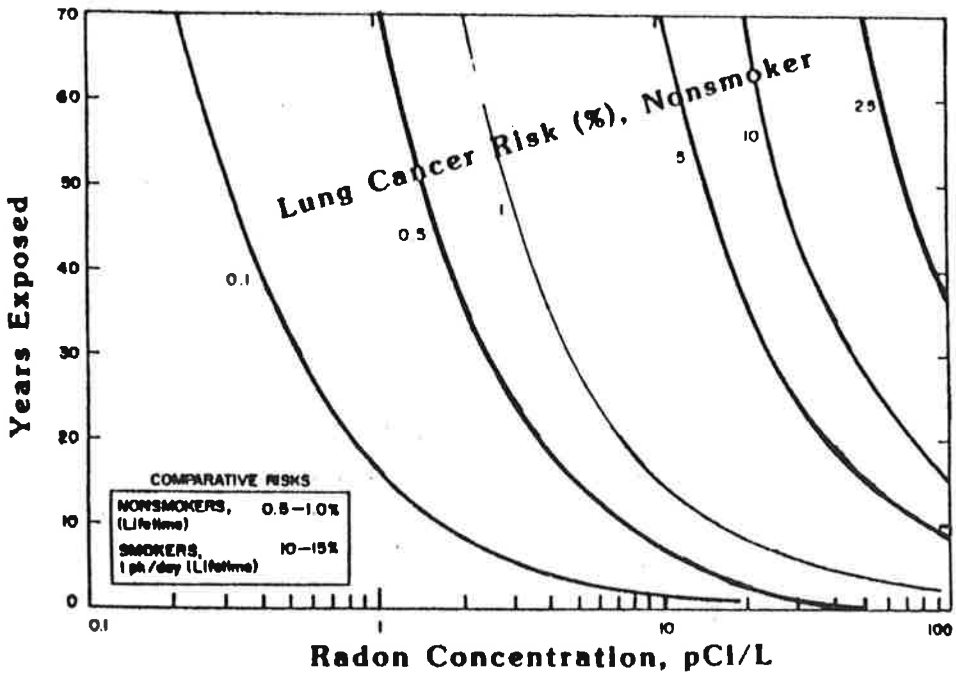


Figure 3

the United States. Eighty percent of these are the direct result of smoking. Of the remainder, a small fraction will be occupational exposure to other antagonists, such as asbestos (see Table 1). Most of the remaining 25,000 or so cases must be associated either with radon or with the effects of second-hand smoke, or passive smoking as David alluded to this morning. Most responsible authorities would suggest that somewhere between 2,000 and 10,000 lung cancers per year are attributable to radon exposure. It is down by a factor of ten from, say, automobile accidents, but, again, this is a risk we do not know about and one which offers no compensating benefits whatsoever.

Lung Cancer in the US
- Some Estimates -

Total	120,000	cases/yr
Primary Smoking	96,000	"
Radon	3,000 - 20,000	"
Secondary Smoke, Occupational	4,000 - 20,000	"

Table 1

Table 2 is from the most recent report of the Biological Effects of Ionizing Radiation Panel. It shows that the average American's exposure to radon is the dominant single exposure to radiation. It is more than medical X-rays or cosmic ray exposure. Radon is where we get most of our exposure. That suggests we have enormous leverage. If we reduce radon exposure, we reduce radioactive exposure to the population. Conversely, if we wind up in a situation that increases radon exposure, we are likely to affect health.

With this kind of uncertainty we have a tremendous variation in the kinds of standards which have been set. They run all the way down to 2 pCi/l, the current ASHRAE guideline, and all the way up into the 20's. 20 pCi/l would be the occupational guideline for forty hours a week converted, as Dr. Meyer suggested this morning, to fulltime exposure in a house. We have guidelines from Canada, from Australia, and now from our own National Committee for Radiation Protection, suggesting something in the range of 5-8 pCi/l as being a useful guideline. The EPA has adopted 5 pCi/l, for example. Now we can investigate where that radon comes from, who has too much, and what we can do.

RADIATION RECEIVED BY PEOPLE IN U. S.

I.	NATURAL			
	A.	TERRESTIAL:		
		1. COASTAL PLAIN	15 - 35	mrem/yr
		2. REMAINING U.S. (EXCEPT 3)	35 - 75	
		3. COLORADO PLATEAU	75 -140	
	B.	COSMIC RAY = $[30 + 17 + (ALT)_{km}]$	35 -100	m rad/yr
	C.	INTERNAL-RELATED		
		1. β, γ	45	m rem/yr
		2. α, EXCEPT LUNG (LET = 10x)	235	m rem/yr
		3. α, LUNG	180-530	
II.	TECHNOLOGY-RELATED			
	A.	X-RAY	100	
	B.	OCCUPATIONAL (WORKERS ONLY)	50	

Table 2 (BEIR, 1980, TABLE III-4)

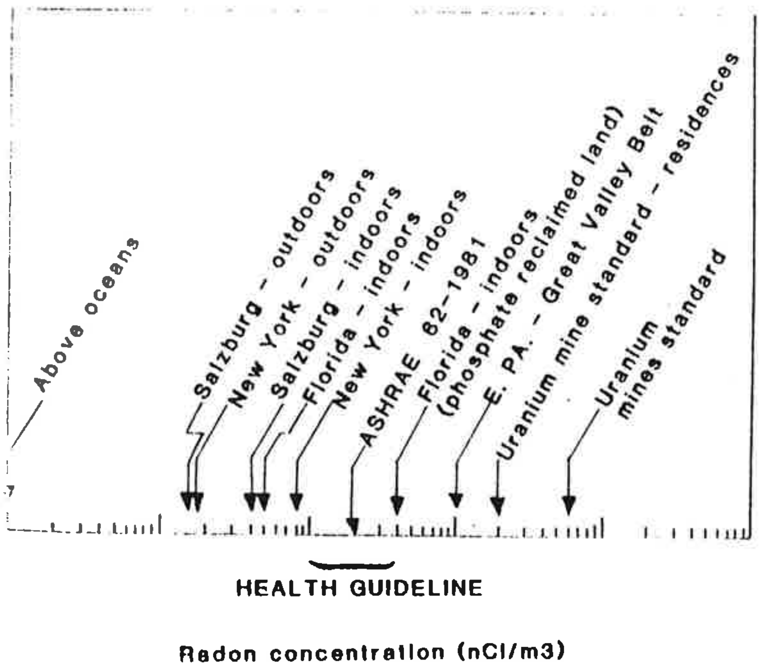


Figure 4

The first point to make is that the radon concentration in air is incredibly variable. It is not a question of ten to one among houses in the environment, but of hundreds. The scale in Figure 4 is just a logarithmic scale from the air above oceans at a range of .01 pCi/l, up to houses which are averaging 10 pCi/l in eastern Pennsylvania and the Great Valley region. The residential equivalent of the miners' occupational standard is a little higher, about 20 pCi/l. Our assumption, from Dr. Grimsrud's work and elsewhere, is that the U.S. population average is about 1 pCi/l. So we have tremendous variability. Our job today is to see if we can discover the sources of that variability and use that discovery to help ourselves avoid radon problems.

Another way of looking at this data is three studies in Houston, Maine, and Sweden. The numbers in Figure 5 are from Dick Oswald at Terradex Corp. The smallest sample was over 300 detectors. What I want to point out, again, is that we have a logarithmic axis here, .1, 1.0, 10., and 100 pCi/l. As we move from one of these regions, Houston, where the median is well under 1 pCi/l, up to Sweden, we find the median moving up to about 10 pCi/l. As we move from region to region, there are variations in the population characteristics, even though all of these are classic log-normal distributions.

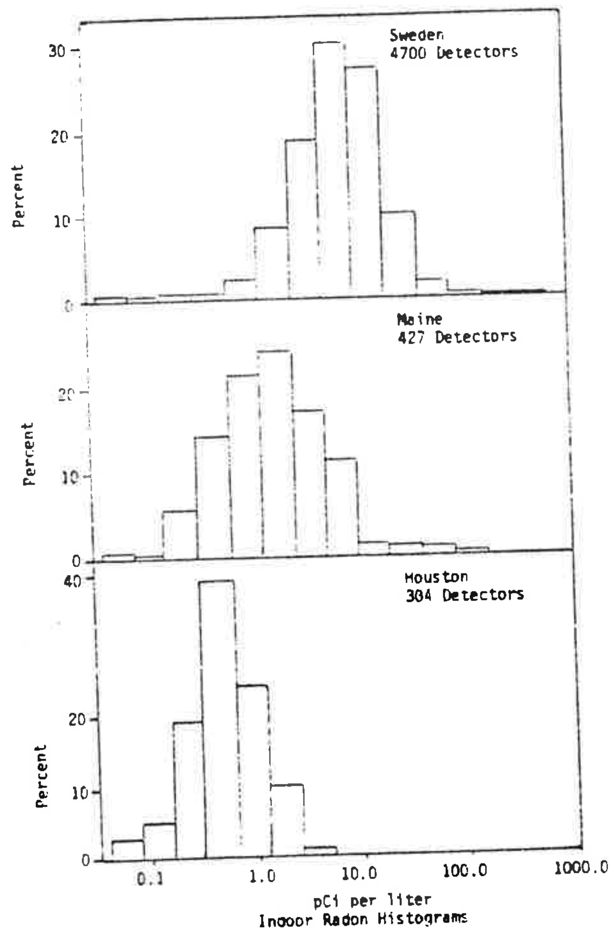


Figure 5

Where is the radon coming from? One of the sources that has been suggested a number of times is water. Professor Tom Hess at the University of Maine has thousands of measurements showing a log-normal distribution of radon in potable water supplies. The median well water sample in the state of Maine has about 5,000 pCi/l. That looks like a good source. After all, when I take a shower, I am doing two things: first, I am heating up the water so the solubility of radon goes down; then, I am dividing the water into very fine droplets, so that the particles have very little distance to move out of the water before they release into the air. All in all, showers, or the general use of domestic hot water, look like pretty efficient ways to get radon out of the water and into the air where we can use it in our lungs. In fact, the shower has one major drawback. It is a once-through mechanism and not all the radon gets out. We do a much better job with our dishwashers, which recycle the water a number of times so we can scavenge all the radon.

Actually, we are not using very much radon in a dishwasher or in our houses. The source strength is equal to the concentration times the house volume times the air change rate in units of

WHEN IS RADON FROM WATER A PROBLEM?

1. EMPIRICAL -- HESS, MAINE

   10,000 pCi/L (WATER) CORRELATED WITH 1 pCi/L (AIR)

2. A SAMPLE MODEL:

$$S = C \times V \times ACH \quad \text{(TERM)}$$

$$\left(\frac{pCi}{hr}\right) \quad \left(\frac{pCi}{L}\right) \quad (L) \quad \left(\frac{1}{hr}\right) \quad \text{(UNITS)}$$

FOR:

ACH = 0.3

V = 360,000L ($1500ft^2$ x 8ft)

C = 1 pCi/L

S = 108,000 pCi/hr

ASSUME TOTAL OUTGASSING OF 20 L/hr (EQUIVALENT TO 100Gal/Day OF HOT WATER), THEN THE WATER CONCENTRATION (C_W) IS:

$$C_W = \frac{108{,}000 \text{ pCi/hr}}{20 \text{ L/hr}} = 5400 \text{ pCi/L}$$

(WATER IS RARELY A PROBLEM, BUT IS LOCALLY SIGNIFICANT.)

Table 3

one-over-an-hour [(pCi/l x V x AC)/h]. If we go through some calculations, Table 3, what we see for typically fairly tight conditions, that is, .3 ACH, a house with a volume of 360,000 liters must have source strength of 108,000 pCi/l/h in order to get a concentration of 1 pCi/l in the house. If that is only coming out of the water, usage must be in the range of five gallons of hot water per hour, or a daily average of one hundred gallons of hot water, and that must have a concentration of about 5,000 pCi/l. This won't be the primary source of a house with 50 pCi/l radon in air! As a rough rule of thumb, something in the range of 10,000 pCi/l in water is empirically associated with, and by the model should be associated with, 1 pCi/l in the air. This agrees very well with all the work done in Maine by Tom Hess, who first pointed out this empirical association. It is well supported. In most regions, however, we do not often find wells in this country at concentrations high enough to dominate the radon source terms for houses.

We should look in a little finer detail at the radon variation in a building. There are some houses we have looked at where we have tenfold variations in radon concentrations over a period of a couple of days. That argues very strongly against just taking a grab sample and assuming we have a good estimate of what the house is like. Obviously, the seasonal variability will be very strong also. There is very little radon in a house when the windows are open in the summer, because there is very little radon outdoors in the air.

I am often asked whether we can get radon from building materials, and I am afraid the answer is, yes. The good news, though, is that we usually do not get much. A "bad" material is some old brick from a Philadelphia townhouse, which emitted some 8,000 pCi per square meter of exposed brick per hour (Table 4). This tells us that, unless we build a house that is extraordinarily tight, and build all the floors and walls out of this brick, this relatively bad material will not give us very much radon. One of the messages of hope is that, to date, in the U.S. there has only been one published episode of significantly elevated (i.e., high enough to be of concern) radon emanation from a building material. This was a concrete block material that used phosphate tailings for several tens of thousands of blocks in the southeast twenty to thirty years ago. There is a potential for abuse, however. For example, drywall is made of gypsum, and it is very easy to get gypsum out of a phosphate manufacturing process. Unfortunately, the problem is that in processing the phosphates, radium mimics the calcium in solution, so the gypsum precipitate will keep the radium with it. Then we would certainly get concentrations well in excess of a standard of 5 pCi/gram of material, if we were to use this free waste gypsum in manufacturing drywall or sheetrock. For this reason, both of the U.S. drywall manufacturers have refused to accept this lovely gift gypsum from the phosphate people.

RADON FROM OLD BRICK IN PHILADELPHIA

1. MEASURED EMANATION — 8000 pCi/m^2-hr

2. CONSIDER A ROWHOUSE WITH BRICK COMMON WALLS
   - (A) TWO WALLS: 30′ x 30′ = 900 ft^2 = 167 m^2
   - (B) MULTIPLIED BY EMANATION — x 8000 pCi/m^2-hr
   - (C) S_{tot} = 1.4 x 10^6 pCi/hr
   - (D) IF WIDTH = 20′; VOLUME (V) = 30′ x 30′ x 20′ = 18,000 ft^3 = 5.1 x 10^5 L
   - (E) $S = S_{tot} \div V$ = 2.6 pCi/L-hr
   - (F) $C_\infty = S\tau_v$

$1/\tau_v$ = ACH	C_∞
1.0	2.6
0.8	3.2
0.5	5.2
0.2	13
0.1	26

Table 4

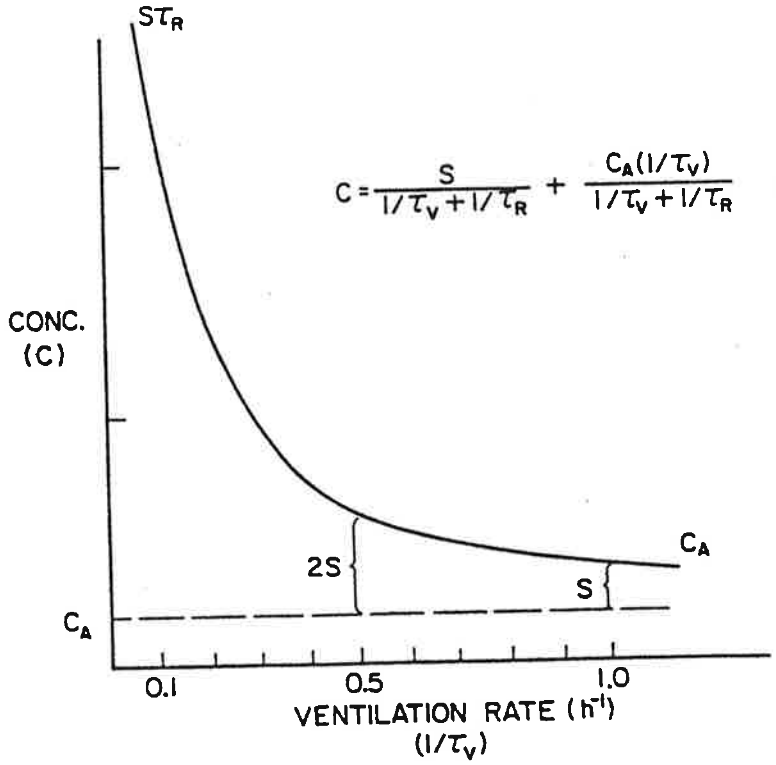
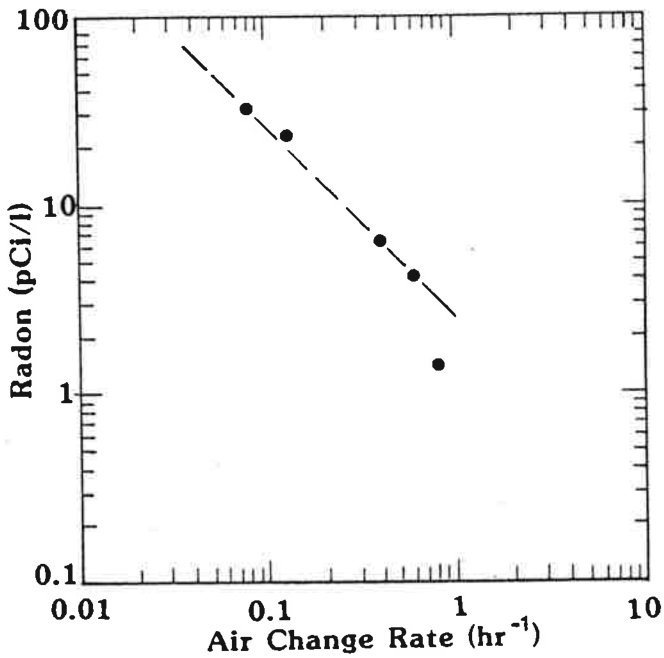


Figure 6

The curve we see in Figure 6 is a very general description of the theoretical relationship between ventilation rate and pollutant concentration. There are two points to be made about it. First, experimental curves for combustion gases and formaldehyde indicate increasing ventilation rate may not get the classic 1/Y response. In part, this is because there are active removal processes for reactive gases. In part, it is because the concentrations of these things may be high enough, particularly for formaldehyde, to get an inhibition, or back diffusion, of finite vapor pressure effect. In any case, this does not happen with radon. Doubling the ventilation rate cuts the concentration in half, within experimental statistics in every case that I have seen. In that sense radon is easy to work with.

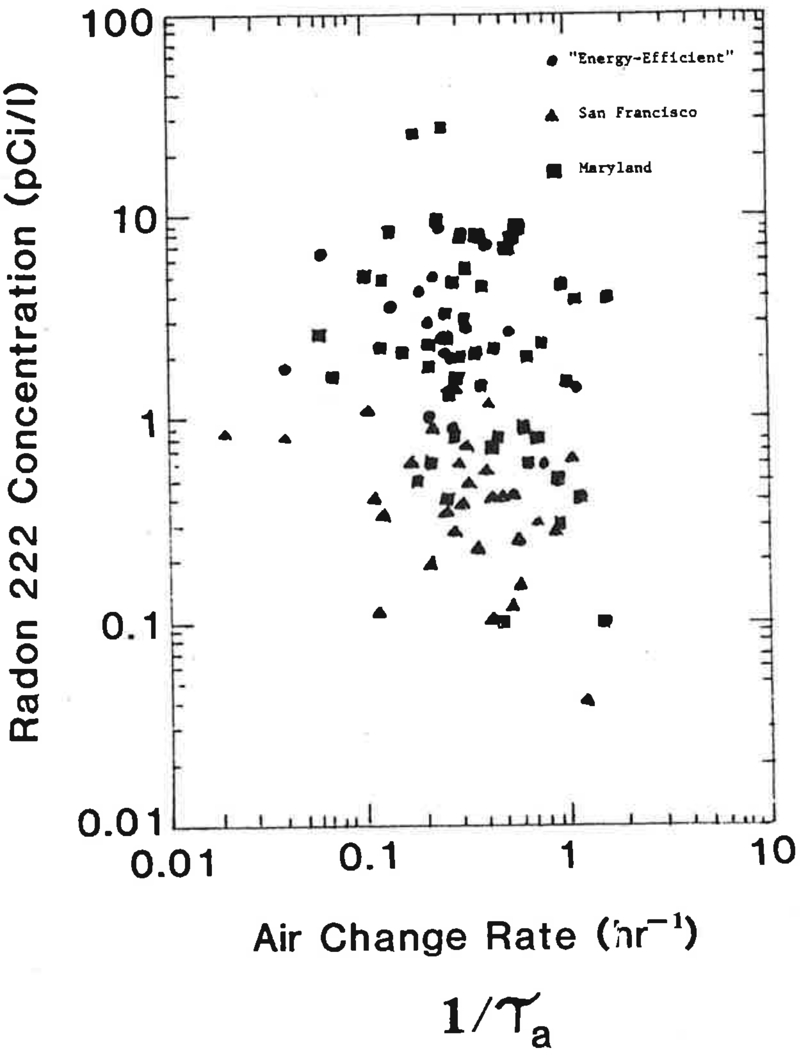
There is a second lesson here, though. If the concentrations are very high, no matter how often we double the ventilation rate, we are not going to cut the concentration to acceptable levels. If I have a house with .2 ACH and 50 pCi/l, I will have to bring fresh air flow up to very high levels, say 4-5 ACH, to control the radon by ventilation. As David Grimsrud alluded to this morning, we must attend to the source if we really have a problem. That is a very important point. The LBL data in Figure 7 suggest, empirically, if we take a single house in which we are able to monitor the air change rate from .1 to 10 ACH, the radon concentration follows very nicely on an axis from 100 down to .1 pCi/l. Empirically the relationship does work. This, in turn, suggests ventilation must be the key to radon. Looking at the rest of the LBL data (Figure 8), where we now have 99 houses divided among energy efficient houses, San Francisco houses, and Maryland houses, and comparing air change rate with radon concentration, we see a shotgun pattern of data points. There is no causal relationship between the ventilation rates and the radon concentrations for this large group of houses. While the ventilation rate is important to know, we are not going to be able to predict where the houses with high radon concentrations are by using it alone, just as we can not use information about building materials or, in most cases, water.



Average steady-state radon concentration in the EER as a function of ventilation rate. The dashed line corresponds to a constant radon source of 2.5 pCi/l/hr.

Figure 7

It is time to turn to real houses and think about real house data. How does radon get in and what do we do? Since we are forced by exclusion to take as our



Radon concentrations and Air Change Rates in U.S. Residences. The figure is a composite of results from three survey groups: "energy-efficient" houses in the United States and (one) in Canada; conventional houses in the San Francisco area; and conventional houses in a community in rural Maryland.

Figure 8

next hypothesis that radon really is coming from the soil, we need to examine how the house is connected to the ground. We should also look at what there is about the soil that might be useful and predictable. A number of years ago, when Pennsylvania Power and Light started pushing conservation hard, they also started thinking about the side effects of conservation. They got six employees in each of their service areas to put radon detectors in their homes so they could examine radon concentrations. By putting these in six different service regions they got a well distributed population (Figure 9). It was skewed, in that it was biased toward newer houses and toward electrically heated houses. It turned out that, when the houses were plotted on a geological map of Pennsylvania, there was a peculiar coincidence. The crosses on Figure 9 indicate houses with more than 5 pCi/l in the basement. What we find is that a large fraction of the houses with relatively high living area concentrations were lying on what we call Cambro-ordovician sedimentary rock. There are several hundred thousand people living in the Harrisburg, Eastern Allentown, Bethlehem, and Lancaster areas. Harrisburg is near the area of Three Mile Island. Certainly, the exposure to radon in these houses is several hundred times higher than the radiation which was announced as having been released from the Three Mile Island reactor incident. That is not a fair comparison, however. When people say Three Mile Island was a very severe accident, the problem is not what was released, but what might have been

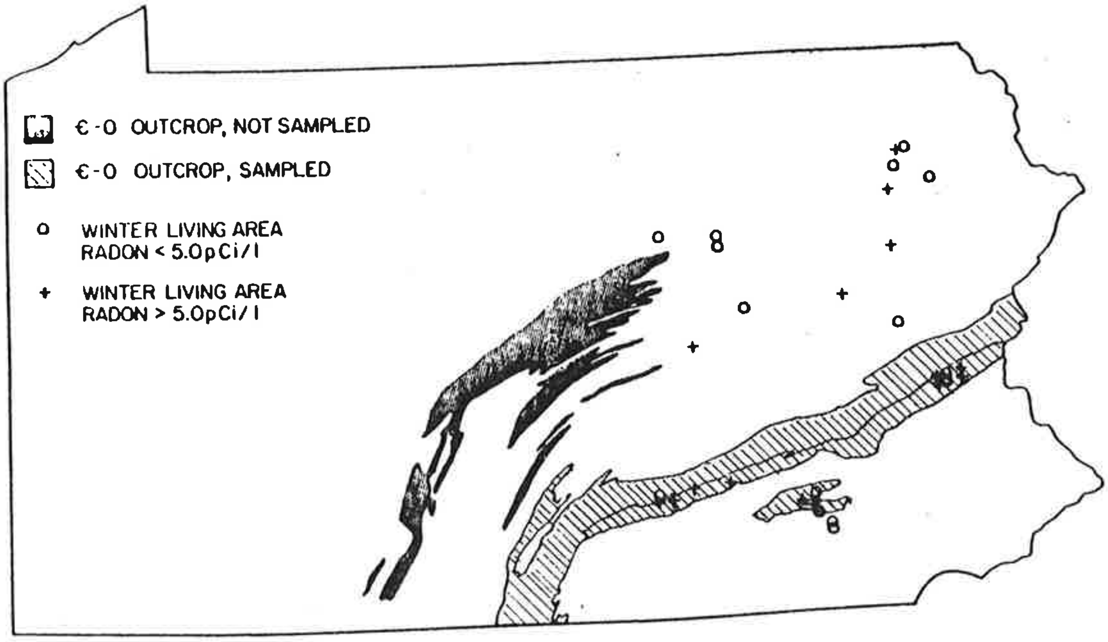


Figure 9

released if the reactor had gone to meltdown. I do want to point out the irony that this particular area has a higher fraction of high concentration houses than we have seen anywhere else in the United States.

The data is tabulated in Table 5 as to whether or not the house is over Cambro-ordovician sediment. We see, in terms of houses with winter living area concentrations greater than 5 pCi/l, 11 of 15 houses, or 73%, had such concentrations. If they were not on that set of Cambro-ordovician rocks, the odds of high concentration were only 4 of 18, or 22%. Incidentally, of these four houses, two are on a rock belt of known high uranium mineralization. It is an area which has seen

P P & L WINTER
LIVING AREA DATA
BY LOCATION

Radon Conc. (pCi/L)	Cambro-Ordovician Yes	Cambro-Ordovician No	Total Number of Houses in Range
> 10	8/15	2/18	10/33
5 - 10	3/15	2/18	5/33
≥ 5	$\frac{11}{15}$ (73%)	$\frac{4}{18}$ (22%)	$\frac{15}{33}$ (45%)

1. Skewed sampling
2. Houses on C - O three times as likely to have high values.

Table 5

mining in the past, and may again. The point to make here is a very high fraction of the high concentration homes are associated with particular rock belts which look like they yield a lot of radon. We are uncertain in most areas whether it is the rock, the soil, or the soil permeability; but I am just saying when we lay it out on a map and look at the data, the picture is coherent. The data (Table 5) are important because this was the first time ever, I believe, that we have had a strong association of high radon concentrations with sedimentary rocks, as opposed to granites. The data from Maine with high concentrations are for granitic rock. The geological map of Pennsylvania, again, just makes the point that along a distinct suite of rocks, also replicated in the Lancaster area, an anomalous fraction of houses tends to have high radon concentrations; high enough to warrant remedial action by the government.

Knowing that there is a geological signature, how can we explore for it? Several groups, like Princeton, the New York State Health Department, and LBL have attempted to use data from a national uranium resource survey. One such survey used helicopters flying low over the land to look for gamma radiation signals, assuming that where there is high gamma, there is high uranium. Or, perhaps, where there is high gamma, there is also rock which is likely to lead to excess radon. If we plot these data, perhaps we can find the belts that would be our first targets in looking for high radon concentrations. That work is proceeding now, but there has been so little work done on regional or national surveys in the United States that we are far from able to say this area or this rock, is free of potential hazards, or has a high likelihood of potential hazard. Our guess from the log-normal distribution is that we will find that some 90% of the country has low likelihood of having radon problems. What we need to accomplish that is nothing more elaborate than a large scale Nielsen-type survey. We need to put detectors in enough houses in a stratified sample. That is going to happen over the next two years in New York state; it is happening out here through BPA work; but as a national effort it is not happening. Until that happens, we will not know how to give builders and building professionals, code officials, or public health people the guidance they need. Nor will we know how to respond to the problem without unnecessary work in areas which are unlikely to have radon problems.

Before I leave the impression that geology is the whole story, let's look at the data in a slightly different cut. There is also an age signature which we believe very strongly to be a ventilation signature. In one set of about thirty-five houses in Pennsylvania (Table 6), we were able to get ventilation data with blower doors and radon concentration data. The point is that the logarithmic average radon data indicate much lower radon concentrations in older houses than in newer ones; 3 pCi/l versus 11 pCi/l. The older houses, however, are really about twice as leaky, or have twice as high an infiltration rate, at about 1 ACH versus 0.5 ACH. So the spread in the ventilation data is actually not large enough to account for the spread in radon

EFFECTS OF HOUSE AGE

1981-1982 FIELD STUDY

	OLDER			NEWER		
	N	$\bar{X}$	1 s.d.	N	$\bar{X}$	1 s.d.
RADON, pCi/L						
L.A.	16	2.9	1.3-6.2	12	10.6	2.7-40.
CELLAR		4.0	1.8-9.1		13.7	2.6-73.
VENTILATION RATE, HR^{-1} PU	18	0.99	± 0.6	10	0.49	± 0.15
(LBL)		(1.27)	(.68)		(.73)	(.22)
1 - CHAMBER L.A. SOURCE* PU pCi/L-HR	16	2.9	± 1.8	10	5.2	
(LBL)		(4.2)	(2.5)		(7.7)	

* $S = \frac{R_N}{T_V}$

PU = PRINCETON UNIVERSITY

(LBL) = LAWRENCE BERKELEY LABORATORY

Table 6

data. There is an almost unspoken fear that, over the years, the builders actually responded to market forces in building much tighter houses. Did they also, inadvertently, learn how to build their houses coupled better to the ground so they can extract more soil gas? That is an effect that comes from not knowing what we have to watch out for. The builders certainly know how to build waterproof basements, but nobody has told them to build radon-proof basements.

If we look again at some real houses in another figure adapted from LBL data (Figure 10) and think about how the radon might get into a house, we realize we have to examine how the structure is coupled or connected to the soil. Diffusion, as I indicated earlier, is not going to be an efficient mechanism for drawing soil gas into the house. A concrete slab will stop a large fraction of it. What we need to look for is convective flow through gaps where pipes are fitted, through sumps, or through french drains (which are extremely common in the East). Typical construction practice is to pour the basement footers, build the foundation wall, and then pour the slab as the last step. That leaves a gap of about an inch all the way around the basement so that penetrating water can drain out through the capillary bed, i.e. the gravel bed beneath the house. As Tony Nero from LBL pointed out, that gravel bed which serves to keep the basement dry of water, also guarantees that whatever radon diffuses out of the soil can be efficiently transported through the high

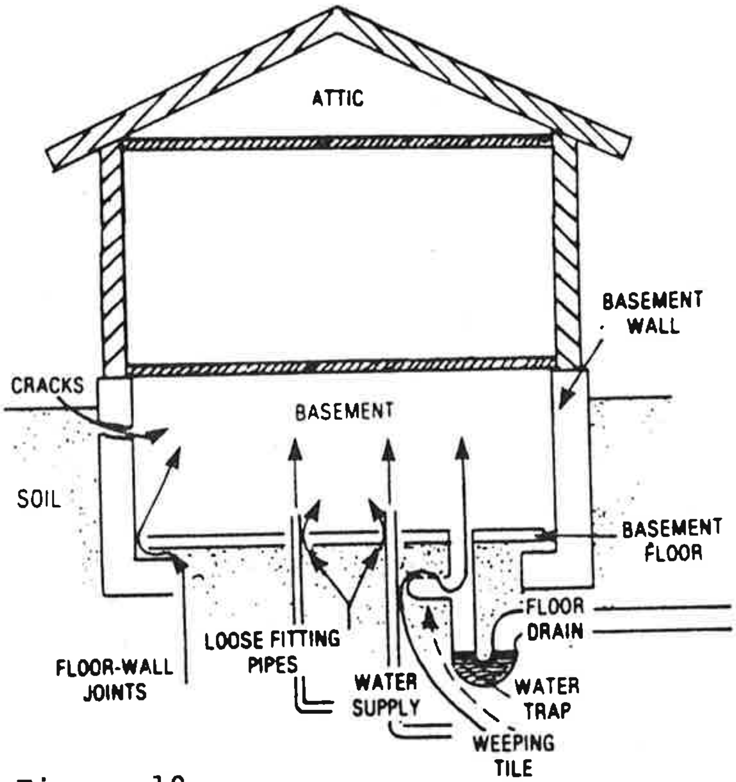


Figure 10

permeability gravel into the house, if the house has lower air pressure than the outside nearby. This happens in winter (the stack effect) and when furnaces are turned on.

One of these might be a sump in the basement of a house. It might be a steel-lined sump, but at the bottom it is dirt lined. This is an excellent connection. Another source would be to use the basement as a plenum for the heating system. This is forbidden by code in my area. The basement used as a plenum has fans which actively pump air out of the basement into the house. This maintains the entire basement at less than atmospheric pressure and draws in whatever radon and soil gas there might be, practically at maximum efficiency.

A source we have experimented with is the concrete block so commonly used for basement wall construction. Convective flows can pass right through concrete block. Of course, the water will drain down the middle of the block, but the radon will come right through. I personally do not want to use a concrete block foundation if I have any doubts about radon. In a crude experiment to capture radon, we sealed a flux bucket to the surface of a concrete wall (Figure 11). We used a common garbage can adapted with gas fittings, a flask, and a pump to see if radon is coming out of the wall. It is not a quantitative experiment, that is, we cannot quantify the amount within 10 to 20%; but if the source is big, radon will accumulate in the bucket. This process is what we call an in-growth method, or a Jonassen flux bucket method. It is a very powerful technique for finding radon sources. This can be done on any scale. In another situation, we tried to seal a somewhat larger Jonassen flux bucket to a limestone wall in a 200 year old house. It turned out the limestone was about a centimeter deep in dirt, which allowed the radon to work through cracks, so the experiment was a failure.

Because of concern about radon from building materials, we have tried this same technique on concrete slabs (Figure 12). Despite the fact that LBL has looked at hundreds of concrete samples from around the country without finding a problem, many of us live in fear that we will somewhere. Because of this doubt, it pays to check the concrete also. We hope it does not turn out to be a problem, because mitigation of radon in concrete is going to be very difficult. In looking at component materials, one of the all-time classics is the exposed dirt floor in a solar space added to a house. Something like a 12' x 6' dirt floor attached to a house in a radon prone area is not good. Exposed crawlspaces or exposed dirt are prominent points of entry.

House "N"

Radon Flux From Wall

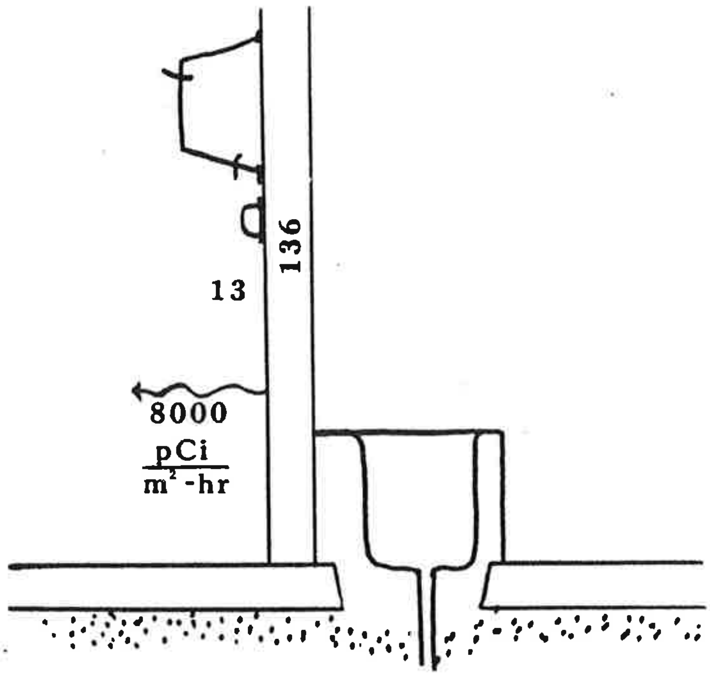


Figure 11

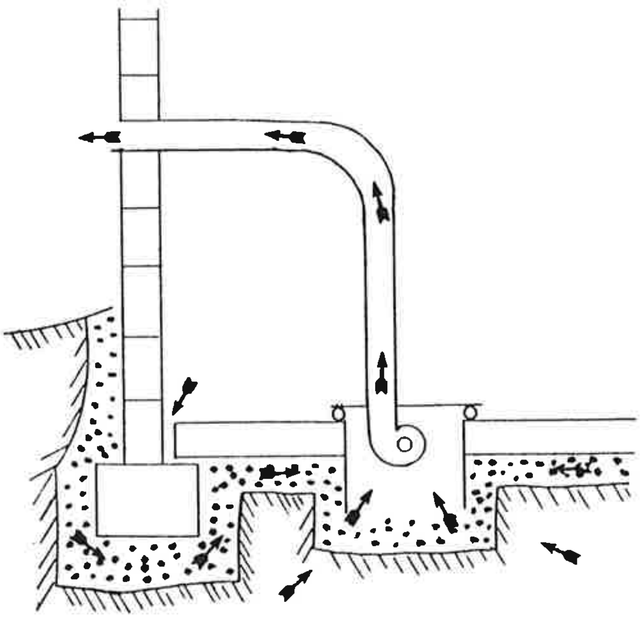


Figure 12

I want to return to the sump mentioned earlier. We were given permission by a homeowner to work on the problem after we discovered a large radon concentration in his totally conventional, split-level home in Princeton. Like many houses, this one has a sump in a basement corner, which was initially installed to give access to a sewer clean-out. The only odd thing about this one was that, lying loosely in this corner, was a funny, little clay pipe which pointed back toward the center of the house. We assumed that it was connected to a gravel bed under this fairly old house, and that gravel bed served as a source, a collector of radon from the soil. We built a lid for the sump using plywood, mylar, and aluminum foil, so we could do some experiments. We used a very large Jonassen flux bucket and, at one stage, a small fan and a dryer duct out as a temporary fix (Figure 11). We wanted to see if we could depressurize the subslab. We did not measure the extent to which the pressure gradient beneath the slab was changed, but we did make a lot of measurements of the radon concentration before and after. The basement concentrations in this house dropped from over 20 pCi/l to about 1 pCi/l. We have had almost as great success in other houses (Table 7). As far as we have been able to find out, this method was first established in a systematic way by A. G. Scott, in experiments on houses in Canada.

SUMMARY OF HOUSES

	"W"	"N"
Age (yrs)	~20	4
Local Geology	Triassic Sandstone	Schist
Construction Type	Frame Split Level	Concrete Earth-Sheltered
Heat Distribution	F.A., Ducts in Cellar	F.A., Sub-Slab Ducts
Rn, pCi/L — Pre-L.A./Cellar	6 / 21	50
Rn, pCi/L — Post-L.A./Cellar	<1 / <1	<5 / <2

Table 7

The method is not always completely successful, of course. As an example, in house "N" of Table 7, although subslab depressurization reduced concentrations by 80%, the owner insisted on adding mechanical ventilation (an air-to-air heat exchanger) to reduce the concentrations further. Working with Ian Nitschke in New York State, we found other houses where complex construction practices and local features kept "simple" depressurization from fixing all the problems of radon in some houses.

Nonetheless, we believe that there are some conclusions which can be drawn now, and they are worth reviewing:

1. Based on the scanty data available, it seems that houses in some regions are much more likely to have high radon concentrations than in other regions; we do not yet know which regions are <u>unlikely</u> to have problems.

2. In the United States, radon problems are almost always the result of radon entering from the local soil. Thus, the first key to knowing about radon is geology.

3. That means there is hope: a proper survey program could find the regions where problems are likely enough to warrant building code involvement.

4. Until we get such surveys, each builder and purchaser is on his own. We believe that the prudent builder will want to minimize the chances for radon to enter the houses he builds. This eliminates subslab ductwork, and suggests that "french

drains" and concrete block foundation walls are undesirable features. Very conservative builders and their clients may specify emplacement of PVC or equivalent perforated pipe in the subslab gravel bed, terminated in such a way that depressurization is possible if required.

QUESTION: Would you say radon leakage into houses by diffusion through materials is a substantial concern in residential housing? You mentioned that four inches of concrete will absorb most of the radon before it enters, how do wood foundation homes compare?

ANSWER: The problem is rarely the diffused flow of radon through material. It is almost always a convective, pressure-driven flow across a gap between materials. For example, some materials like polyethylene are actually porous to radon, while it will not pass through tedlar or aluminized mylar or some other common building materials. (Tedlar is only ten times more expensive than polyethylene.) Concrete illustrated the point here rather well. Ninety percent of the radon will decay before it penetrates through four inches of good concrete. If the concrete is cracked, however, with a higher pressure on the soil side, radon comes through the crack. The convective flow through the crack, then, is the important parameter. Unfortunately, we do not have any studies of wood foundation houses that I have been able to find in the literature to compare. My guess is that, because most people who are building wood frame foundations are taking extraordinary precautions to make sure there is no water coming through, these houses are very well drained below. Furthermore, if we find problems in wood frame houses, I expect they will be easy to treat with depressurization, because the things have so much permeability beneath them to make sure they do not get a water problem.

QUESTION: What are the work place and educational institution implications?

ANSWER: If building materials turn out to be a problem, all bets are off. If not, the occupational data I have seen, other than manufacturing of phosphates and materials like that, indicate that we are not going to have a radon problem, because factories and offices tend to be well isolated from the soil. We have to have an efficient mechanism for scavenging the radon from the soil to have a radon problem, as far as we know today.

QUESTION: How does the radon move from one place to another, if it goes into the atmosphere? Can it build up outside a building?

ANSWER: The dilution in the atmosphere is essentially infinite. The house is sort of like an atmosphere that is only eight or ten feet tall while the earth's atmosphere is several kilometers tall. When radon escapes, it is mixed very quickly and dilution is very effective. Concentrations in ambient air outside are rarely as high as 1 pCi/l and usually reach only a couple of tenths pCi/l.

QUESTION: Regarding ventilation, isn't the real issue whether you put the house under pressure or over pressure?

ANSWER: Good question. Is the real point whether the house, not the ventilation, is over or under pressure relative to the soil gas? We went around about this in the superinsulation community, because the superinsulation folks would very much like to keep the house under slightly negative pressure. Then, during the winter, if there are any leaks in the vapor barrier, air is being drawn from the outside into the house rather than warm, humid house air being forced into the insulation envelope where it might condense, ruin the insulation and rot the wood. I am scared of that negative pressure, but I will compromise. If you will seal the basement very carefully so we do not have radon entryways, you should be able to have a "negative pressure" house. We can make it like the space shuttle. I want the basement and the house isolated from the soil. I think all of us should be very, very firm about saying it is worth a few hundred dollars to isolate the house from the soil in areas where there is a problem, at the very least.

QUESTION: In other words, put it up on stilts?

ANSWER: Great! If it has a ventilated space underneath, you don't have a problem. Take mobile homes for example; you might have problems with formaldehyde, but not with radon.

QUESTION: Did I understand you to say polyethylene will not stop radon, but will stop convection and therefore it can be effective?

ANSWER: You did understand me to say that polyethylene is a good convective barrier and probably will help the radon problem, but that is a guess. David Grimsrud has done some experimental work on that. Would you care to comment, Dave?

DAVID GRIMSRUD: That is a relatively controversial thing. The measurements we did in Portland looked at radon concentrations in houses that had crawlspaces. Some of the crawlspaces had polyethylene sheets over the surface of the dirt. Yet we still saw substantial penetration of radon from the crawlspace into the house and substantial radon concentrations in the crawlspace. One thing we have to remember is that the numbers that we are dealing with are really very tiny.

There is a little Track Etch detector that Terradex makes, it looks like a little piece of plastic, but it is a very sophisticated device. It measures concentrations, numbers of particles, that we can't measure in other ways. We can measure parts per billion (ppb), and parts per trillion of concentrations of other chemicals, but these Track Etch are measuring parts per 10,000,000,000,000,000, or per 10,000,000,000,000,000,000. We are talking about very small numbers of atoms here. If you can in any way put a vapor barrier that does not have any penetrations on top of a soil in the crawlspace underneath the house, then it might work. If there are penetrations, the penetrations will allow the pressure difference to cause a flow through the opening and the radon can get into the house. I think that is not the way to do it. The way to do it is to seal the floor from the crawlspace and to ventilate the crawlspace well.