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RADON ENTRY INTO DETACHED DWELLINGS: HOUSE DYNAMICS AND MITIGATION TECHNIQUES

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Abstract — Researchers from Princeton University, Oak Ridge National Laboratory, and Lawrence Berkeley Laboratory conducted a twelve-month field study on the mechanisms of radon entry and the effectiveness of mitigation techniques in fourteen similar houses in New Jersey. Continuous monitoring of a variety of parameters before and after mitigation has provided a very rich data base. Continuous data were obtained for radon concentrations and temperatures in different zones in the house, under the slab, and in the walls, for pressure differences across the basement perimeter, for operation of the central air distribution system, and for basic weather variables. Several-day averages of air infiltration rates, both between individual zones and outside air, and between pairs of zones, were obtained throughout the period. The mitigation systems tested were sub-slab pressurisation and depressurisation with and without sealing, basement sealing, and basement pressurisation. An evaluation of the efficacy of the particular mitigation techniques tested in two single-storey test houses is presented as well as a discussion of how mitigation affected air infiltration and radon source strengths. The amount of air infiltrating each basement from the soil gas is also discussed.

INTRODUCTION

The Piedmont Study was a detailed radon mitigation and diagnostic study conducted in fourteen houses in north-eastern New Jersey. From September 1986 to September 1987 Princeton University (PU) and Oak Ridge National Laboratory (ORNL) worked together in seven houses while the Lawrence Berkeley Laboratory worked in seven other houses in this region[1–2]. This paper discusses data from two of the PU/ORNL houses. Diagnostic measurements, confirming earlier work in this field[3], indicated that the prime source of radon was soil gas entering through the substructure. One goal of the research was to determine the effectiveness of alternative mitigation techniques. This evaluation was aided by continuous measurements of (1) basement and upstairs radon concentrations, (2) pressure differences across the basement/sub-slab, basement/upstairs and basement/outdoor interfaces, (3) temperatures in basement, upstairs and outdoors, and (4) central air handler usage. A weather station located at House 5 monitored wind speed and direction, barometric pressure, precipitation, soil temperature, outdoor temperature, and relative humidity. A time-averaged value of the above parameters was recorded every 30 minutes. Several additional parameters were monitored on an intermittent basis in the test houses. These parameters included multizone air infiltration rates using passive perfluorocarbon tracers (PFT) in all houses, and using a constant concentration tracer gas system (CCTG) in one house[7].

Both of the test houses discussed here are large ranch houses, built less than 10 years ago, with a full basement and an attached garage built on a slab. House 1 has a gas furnace with forced air distribution, and House 5 has an electric heat pump with oil combustion back-up and forced air distribution. Both basements have hollow cinder-block walls, a perimeter drain around a floating slab, and a sump (a collection pit for water, cut into the basement floor). The soil gas below House 1 has a much higher radon content than that below House 5 — fifteen times higher (111,000 as against 7400 Bq.m^{-3}) as measured by grab samples taken below the two slabs in the pre-mitigation period. Nonetheless, the average pre-mitigation basement radon concentrations are similar in the two houses, with House 5 actually higher, (2220 rather than 1369 Bq.m^{-3}), for two reasons: (a) the soil around House 5 is more permeable, so more soil gas can enter the basement for the same pressure difference between sub-slab and basement, and (b) House 5 has a much tighter basement, with roughly four times smaller air exchange rate with outside air (0.8 and 0.2 basement air exchanges per hour for Houses 1 and 5 respectively, averaged over two months pre-mitigation). Despite such important differences in radon environments, the mitigation results in the two houses will be seen below to be quite similar.

MITIGATION TECHNIQUES

Sub-slab and/or wall depressurisation was particularly successful in mitigating the Piedmont Study houses. The ease of installation, relatively low costs of installation and initial maintenance, unobtrusiveness, and efficacy in reducing radon levels made it the most desirable mitigation system. Previous studies[4,5] have drawn similar conclusions. The Piedmont study was nearly unique, however, in implementing several mitigation systems serially in the same house. Figures 1 and 2 show the average radon concentrations in the basement and upstairs before and during different phases of mitigation in Houses 1 and 5. In both cases, the final mitigation configuration was sub-slab (and wall for House 1) depressurisation, with the perimeter drains sealed to form perimeter drain ducts.

The initial mitigation system in House 1 consisted of two penetrations through the substructure: a single penetration into the centre of the basement slab for sub-slab depressurisation and another into the centre of the hollow block wall between the basement slab and the garage slab for wall depressurisation. Neither the perimeter drain nor any cracks were sealed. Figure 1 shows that three-fourths of the eventual radon reduction was already achieved by this system. During the second phase of mitigation, cracks and holes in the penetrated hollow block wall were sealed, but no significant improvement in radon reduction occurred.

The final two phases consisted of sealing the perimeter drain to form a perimeter drain duct, sealing the sump, and either pressurising or depressurising the sub-slab and hollow wall by reversing the fan. Figure 1 shows that sub-slab (plus wall) depressurisation was the most successful mitigation configuration.

Figure 2 shows the average basement and upstairs radon concentrations for the mitigation systems tested at House 5. The two initial mitigation systems were basement pressurisation, with and without sealing of cracks and the sump, the perimeter drain, and the largest leaks between the basement and the upstairs. The basement radon concentration decreased by 25%, and the upstairs radon concentration remained about the same. Our tracer gas measurements show that the flow of air from the basement to the upstairs increased from a two-month pre-mitigation average of 95 $m^3.h^{-1}$ to 170 $m^3.h^{-1}$ during the pressurisation time period. Thus, the radon source strength to the upstairs, which is the product of the radon concentration in the basement and the airflow from the basement to the upstairs, remained about the same before and during the basement pressurisation test.

The third mitigation system tested at House 5, basement sealing without pressurisation, did not

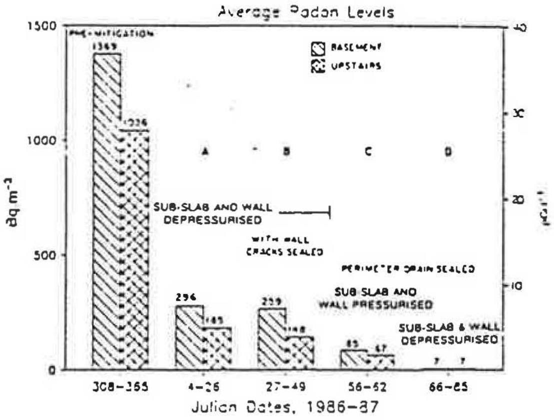

Figure 1. Average basement and upstairs radon levels in House 1 at each phase of mitigation. The number on top of each rectangle is the average radon concentration for that time period.

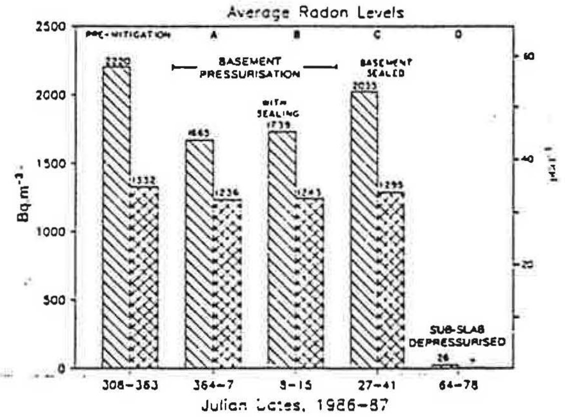

Figure 2. Average basement and upstairs radon levels in House 5 at each phase of mitigation. The number on top of each rectangle is the average radon concentration for that time period.

significantly reduce radon. The sealing was the same as in the second mitigation system. The fourth and final mitigation system involved sub-slab depressurisation, using two penetrations into the sub-slab in opposite corners of the basement. One of these penetrations was through the sump which was sealed and provided with a submersible pump. Figure 2 shows that this system was very effective in reducing the indoor radon concentration.

The final sub-slab depressurisation mitigation systems in Houses 1 and 5 used six-inch duct fans, installed in a duct system of four-inch plastic pipe. The exhaust was directed through the garage roof at House 1 and through the basement wall at House 5. After the fan was tuned to maximum efficiency (i.e.

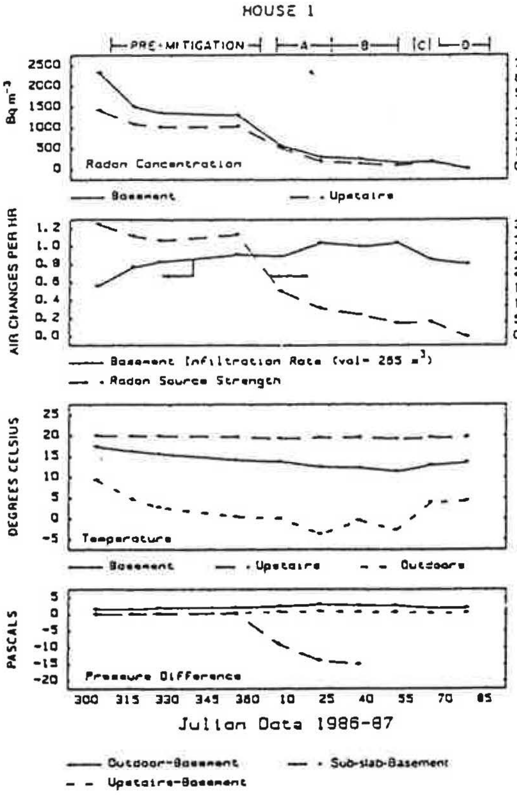

Figure 3. Pre- and post-mitigation data for House 1. The top box in each figure shows the radon concentrations in the basement and upstairs. The second box shows the basement air infiltration rate (solid line) and the radon source strength (broken line). The third box shows the basement, upstairs, and outdoor temperatures. The fourth box shows the difference between the outdoor, sub-slab, and upstairs pressure and the basement pressure. The more positive these differences are, the greater the relative depressurisation of the basement. The points on each line represent the parameter average during the PFT time period. Each time period is 10 to 14 days long. The time periods marked A to D correspond to the mitigation time periods in Figure 1.

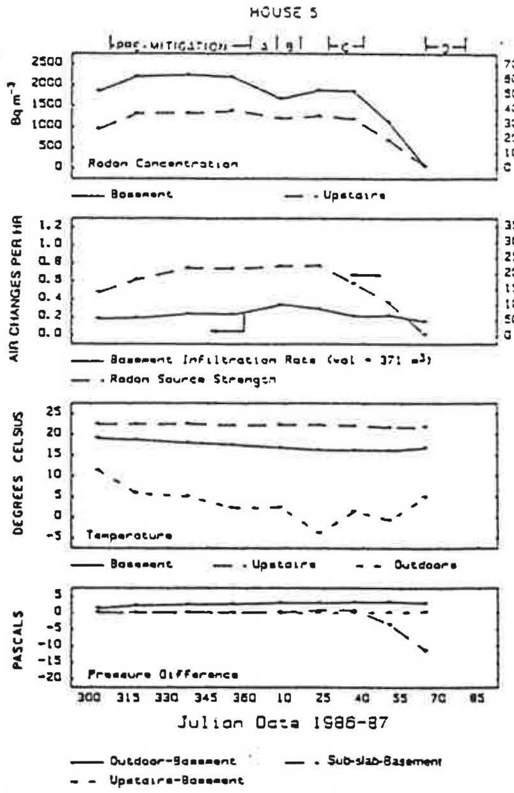

Figure 4. Pre- and post-mitigation data for House 5. Data are organised as in Figure 3.

minimum flow necessary for keeping soil gas out of the building) the mitigation system exhaust airflows were 0.04 $m^3.s^{-1}$ and 0.02 $m^3.s^{-1}$ at Houses 1 and 5, respectively.

AIR INFILTRATION AND RADON SOURCE STRENGTH

Our simultaneous perfluorocarbon tracer (PFT) gas measurements provide information on the airflow patterns before and after mitigation in these houses[8]. The PFT system uses passive sources and samplers to measure interzone airflow rates as well as outdoor infiltration in multizone buildings, averaged over periods of roughly two weeks. PFT monitoring in all test houses began when the instrumentation packages were installed at the end of October, 1986, and was continuous except for brief gaps during mitigation installation.

To combine the PFT data with the other measurements, the continuously logged parameters were averaged over the intervals between replacement of the PFT samplers. Figures 3 and 4 show these averaged data for Houses 1 and 5.

The radon source strength, displayed in the second box of Figures 3 and 4, is obtained by assuming that radon enters the house through the basement and that the radon and the PFT tracer gas behave similarly in the basement:

$$[\text{Source(PFT)/Concentration(PFT)}] = [\text{Source(Radon)/Concentration(Radon)}] \quad (1)$$

The PFT source strength and PFT concentration refer to the tracer gas emitted and measured in the basement. Basement radon concentrations recorded from the continuous monitors are averaged over the entire PFT placement period. Knowing these three quantities gives the radon source strength.

Figures 3 and 4 describe some interesting differences between the two basements. The initial, pre-mitigation radon concentration in House 1 is 62% of the radon concentration in House 5, while the House 1 basement infiltration is about four times greater (compare the second box Figure 3 and 4). It follows that the radon source strength is about two times larger in House 1 than in House 5.

Two terms make up the total basement infiltration – the infiltration from the soil gas and the infiltration from the outdoor air. During sub-slab depressurisation, the entry of soil gas into the basement should go to zero, the basement pressure should exceed the sub-slab pressure, and the radon source strengths and radon concentrations should drop dramatically in both houses. Figures 3 and 4 confirm these expectations.

We can estimate the soil gas flow into the basement if we assume the source strength is equal to the product of the flow from the soil gas and the radon concentration in the soil gas, and also assume that other sources of basement radon, such as from upstairs air, are negligible. Measured soil gas concentrations before mitigation (grab samples under the slab at House 1 and continuous measurements under the slab at House 5) are 111,000 and 7400 $Bq.m^{-3}$, respectively. The volume of basement 1 is 265 m^3 and the volume of basement 5 is 371 m^3. Using the average pre-mitigation radon source strength obtained from the tracer gas measurements, 320 and 180 $kBq.h^{-1}$, we estimate the contribution to the basement air infiltration which comes from flow from the soil gas for House 1 is 3 $m^3.h^{-1}$ or 0.01 ACH and for House 5 is 25 $m^3.h^{-1}$ or 0.07 ACH. Comparing Figures 3 and 4, we see that in House 1 soil gas is 1% of the total air infiltration into the basement and in House 5 it is 40% of the total. These numbers are obtained assuming the radon concentration in the soil gas flowing into the basement and the amount of flow into the basement are uniform.

The comparison of interzone flows during pre-mitigation and after sub-slab depressurisation is consistent with this analysis. In House 5 the post-mitigation basement infiltration is down by about 40% and in House 1 it remains about the same. The total airflow into the basement (which includes flow from the upstairs) decreased in House 5 by about 25% and increased slightly in House 1*. The mitigation system in the depressurised mode can pull air from the basement into the system, and thus increase the flow from the upstairs to the basement. This could be happening in both houses, with House 5 showing a decrease in total flow into the basement because of the loss of the comparatively large contribution from the soil gas flow. In fact, the upstairs to basement flow does increase slightly in both houses during sub-slab depressurisation.

NEW QUESTIONS

Ongoing analysis of these data and those from the other five Piedmont houses will provide more details on the changes in airflow patterns indoors due to depressurisation of the sub-slab and hollow wall cavities, including interactive effects with the heating and cooling systems. It would be interesting to see if, when the mitigation systems are turned off for research purposes, the total flow into the basement from the soil gas increases; this effect could happen if sub-slab depressurisation dried out the soil.

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*This estimate was obtained using the basement infiltration data from PFT time periods pre- and post-mitigation when the differences between the indoor and outdoor temperatures were similar, to minimise error associated with the change in air infiltration with variation in the stack effect. The 40% decrease in air infiltration pre- and post-mitigation is not obvious from Figure 4: the average basement infiltration rate from days 330 to 364 was 88 $m^3.h^{-1}$ and from days 59 to 71 it was 55 $m^3.h^{-1}$.

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