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AIRFLOW MEASUREMENT TECHNIQUES APPLIED TO RADON MITIGATION PROBLEMS

DAVID T. HARRJE AND KENNETH J. GADSBY

Center for Energy and Environmental Studies
The Engineering Quadrangle
Princeton University
Princeton
NJ 08544
USA

SYNOPSIS

During the past decade a multitude of diagnostic procedures associated with the evaluation of air infiltration and air leakage sites have been developed. The spirit of international cooperation and exchange of ideas within the AIC-AIVC conferences has greatly facilitated the adoption and use of these measurement techniques in the countries participating in Annex V. But wide application of such diagnostic methods are not limited to air infiltration alone. The subject of this paper concerns the ways to evaluate and improve radon reduction in buildings using diagnostic methods directly related to developments familiar to the AIVC.

Radon problems are certainly not unique to the United States, and the methods described here have to a degree been applied by researchers of other countries faced with similar problems. The radon problem involves more than a harmful pollutant of the living spaces of our buildings -- it also involves energy to operate radon removal equipment and the loss of interior conditioned air as a direct result. The techniques used for air infiltration evaluation will be shown to be very useful in dealing with the radon mitigation challenge.

1.0 RADON BACKGROUND INFORMATION

Although it has been stated many times before, in numerous publications on radon [1-3], it needs to be restated here that the primary source of radon is soil gas. Building materials and radon in water supplies can be important sources in specific countries or localities, but the problem of soil gas carrying radon is by far the most common cause of high radon levels in our buildings. Standards and guidelines have been set in a number of countries. In the United States the Environmental Protection Agency guideline has been set at 4 pCi/L (148 B/m^3). This guideline has been interpreted very exactly in some regions of the United States, i.e., a level of 4.1 pCi/L and you fail the test and steps must be taken to reduce the radon level prior to the sale of that house. These interpretations come from local health officials and in some cases the real estate firms involved in home sales who refuse to take any responsibility that the buyer could claim damages from them for future health problems. In many areas of the U.S. more than 30% of the houses fail to meet the guideline of 4 pCi/L. In New Jersey 64% of those houses mitigated failed to stay below the guideline value considering both professional and homeowner mitigation installations[4]. Therefore, evaluating mitigation system durability is an important subject of current research. The latest legislation would limit radon levels inside to ambient levels outside[5], making radon mitigation even a greater challenge.

Returning to the subject of radon entry with the soil gas, and the subsequent air movement through the house, the driving mechanism for these events is the stack effect. The higher the differential indoor-outdoor temperature (with possible influence of local wind effects) the greater the pressure difference between the substructures of the house and the soil that draws soil gas into basement, crawlspace, or through the floor slab. The looser the substructure construction the easier the path from the soil into the building. Unfortunately the opening need not be very large, as pointed out at the Radon Diagnostics Workshop[6], a substructure hole of only one square centimeter can result in almost all the radon gas still entering the building. Given the desire to add drains, sump holes, piping and electrical systems in our house designs, it is not hard to imagine easy entry paths for radon.

The proper perspective to always keep in mind is that radon source strength is far more important than the relative tightness of the structure. Air infiltration will normally vary only about half an order of magnitude, but source strength can vary by many orders of magnitude. We have observed soil radon levels as high as 150,000 pCi/L (5,550,000 B/m^3). High source strength coupled with good soil transport is a combination one would like to avoid.

Methods to mitigate radon-plagued buildings tend to use three strategies: pollutant source control, local exhaust near the pollutant source, and dilution via ventilation once the radon has entered the building. Because the primary health danger lies in the radon progeny, rather than the radon gas itself, one could consider another mitigation strategy of filtering out the radon progeny which consist of tiny particles of size range of a fraction of a micron. However, particle removal has all sorts of problems and other implications; first the particles are very small and not easy to filter, filtering does not remove radon gas hence any newly generated progeny have no particles to adhere to and thus can be directly ingested into the human lungs. Dosimetric models indicate that unattached progeny are largely responsible for the radiation dose (Chapter 7, Ref. 2, A.James, Lung Dosimetry).

The most popular mitigation systems seeks to remove the radon prior to house entry[7]. As shown in Figure 1, a fan, preferable placed in the attic or outside, depressurizes the volume beneath the floor slab. That subslab location hopefully is well connected by permeable soil, or the air gaps in the gravel layer (or possibly the gap between slab and soil). By mechanically depressurizing this volume not only does soil gas no longer move upwards through the slab but even soil gas penetrating the hollow block walls may be flushed away via the mitigation system[6].

2.0 DIAGNOSTIC TECHNIQUES THAT ARE APPLICABLE

Given the circumstances for radon entry into buildings and the methods applicable for radon removal, it is easy to see where many similarities exist between these circumstances and the study of air infiltration, for example:

- Below grade entry of the radon gas implies leak site detection. Where these sites are located could imply the use of methods similar to above grade site detection methods as outlined in ASTM-1186-87 Standard Practices for Air Leakage Site Detection in Building Envelopes[8]. Those methods include: combined building depressurization (or the use of pressurization) and infrared scanning; building pressurization (or depressurization) and smoke tracers; building depressurization (or pressurization) and airflow measurement devices; generated sound and sound detection to locate air leakage sites; and detection of tracer gas concentration after adding tracer gas upstream of the leakage sites.

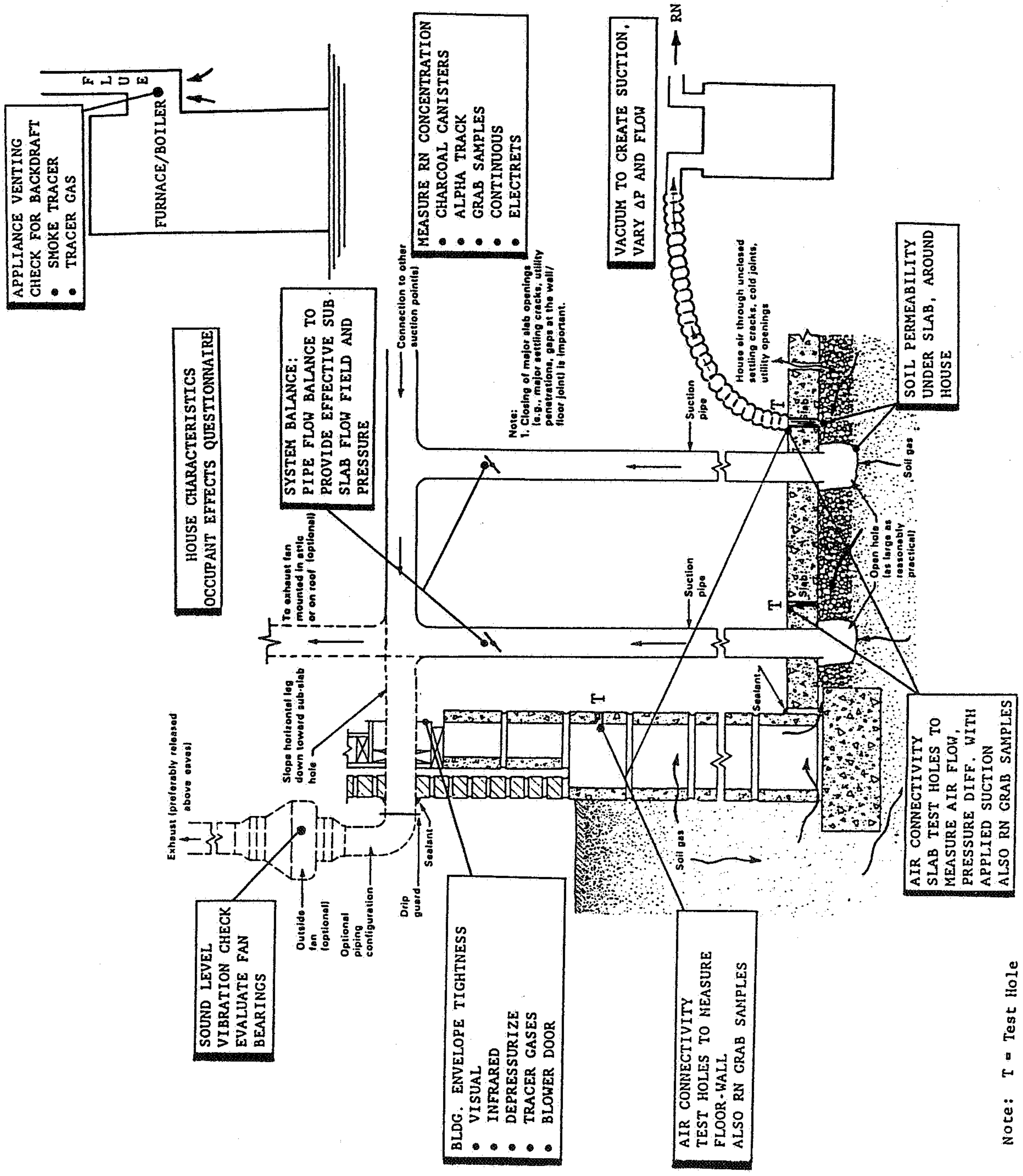

Figure 1. Subslab depressurization (SSD) system for radon mitigation. Gravel serves as a collection volume for the soil gas which contains radon. Holes through the slab are used in the diagnostic procedures[6,10] to specify the mitigation system. Diagnostic tests are specified in the blocks.

- Movement of the radon gas within the building determines which rooms exhibit the highest radon levels and how the radon reaches those rooms can be important. Tracer gas methods may be substituted for the radon to more readily evaluate the interior flow structure since the tracer gas detection equipment responds immediately to the tracer concentration. In our studies we have found two methods to be particularly useful: constant concentration tracer gas (CCTG) methods directed at evaluating local air infiltration and soil gas flows, and perfluorocarbon tracers (PFT) to map out the interroom flows as well as establish the tightness of the entire house over the longer term.

- The relationship of the radon mitigation system with the normal ventilation of the building is important. To answer the question of whether air that exhausts from a mitigation device is interior air requires that the interior air be properly identified. One approach that has proved to be very successful is using a constant concentration tracer gas system to maintain the interior air at a known tracer gas concentration. (If more than one zone is to be evaluated, multiple tracer gases need to be employed). Tracer gas levels in the exhaust air from the mitigation system is then measured and the percent indoor air evaluated from the concentration ratio (exhaust air concentrations are divided by interior air tracer concentrations). A typical trace of this concentration ratio is shown in Figure 2 and discussed in Reference 9. The flow of interior air can be a significant portion of the exhaust flow. The energy cost can easily exceed fan energy expenditure. PFT techniques may be used in a similar way to determine this important parameter.

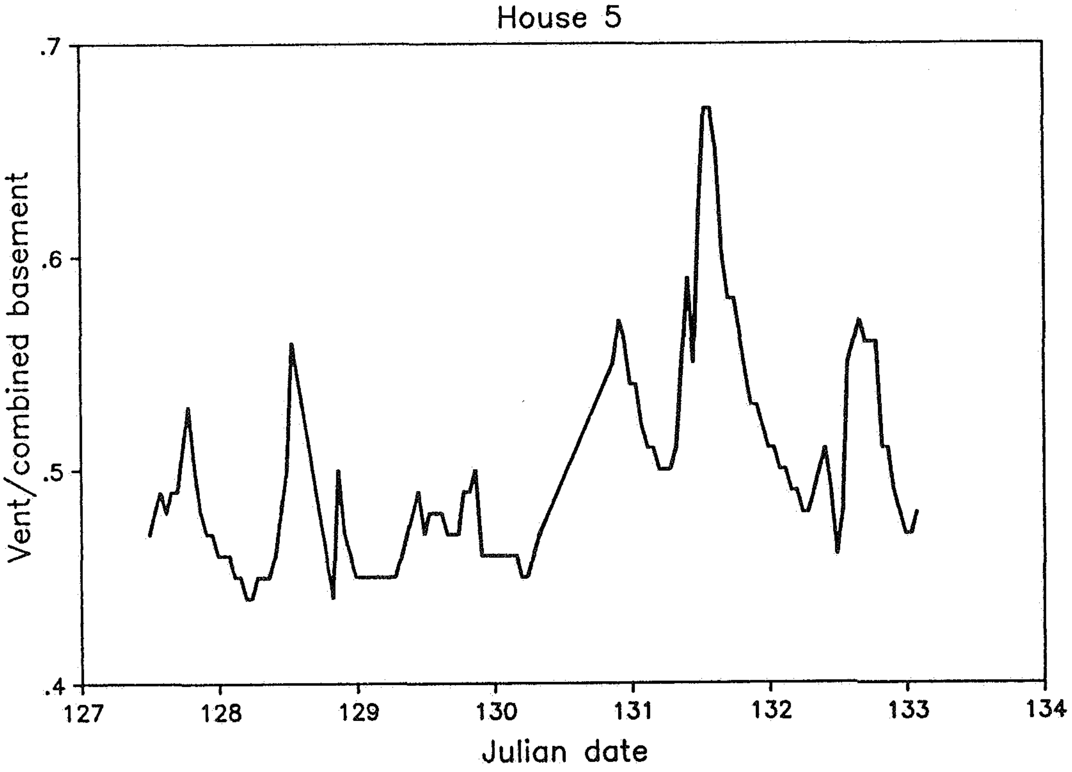

Figure 2. Ratio of the tracer gas concentration in the exhaust versus the concentration in the house. The ratio determines the exhaust rates of the interior, conditioned air and hence the energy cost.

- Early diagnostic techniques make use of the blower door and pressurization/ depressurization to evaluate the building tightness. This has several implications to the radon mitigation team. Evaluating relative tightness of basement and living space and the degree of interaction between the two zones can indicate which mitigation approaches make sense. For example, only if the zones are relatively independent of each other could one consider pressurizing the basement to prevent the entry of soil gas. If good isolation doesn't exist, pressurization of the basement could force radon gas into the living space. A blower door can also be used to determine what volume of airflow is needed to pressurize the basement.

Greater tightness of the building structure, often associated with modern buildings, does not necessarily mean higher radon levels due to reduced dilution from air infiltration, rather it can mean reduced stack effect and less radon entering the building.

- Charting the path for radon gas is not limited to the living space. Prime pathways exist beneath the floor slab of the basement, crawl space and slab-on-grade construction. What happens in hollow walls and the soil just outside the walls can prove equally important. One of the key diagnostic tests is to determine the ability to communicate under the slab, so called "connectivity." Test holes are made through the slab as shown in Figure 1, and with an industrial vacuum cleaner supplying suction at one hole, pressure and flow measurements are made at the other test holes. Pressure values reveal the extent and magnitude of the pressure field, where pressure tends to equilibrate even when the soil is tightly packed. The flow values immediately reveal the degree of communication and point out that the flow path need not be simply radial but rather the flow seeks out that soil or gravel which offers the path of least resistance[6,7,10].

- One measurement of the durability testing that we are just beginning to interpret is the concentration of radon in the exhaust from the subslab mitigation system. When this information is combined with the velocity measurement at the same mitigation exhaust pipe location, we can then proceed to calculate the total flow of radon gas from the mitigation system.

One question to be resolved is: Can we compare the amount of radon exhausted from any given house and more fully understand the role that the mitigation system is playing? One such comparison involves the natural flow of radon through the same house. To make the calculation of the natural flow requires a knowledge of the average air infiltration rate for the house, the radon concentration upstairs and in the basement/crawlspace, as well as the volumes of those zones. Figure 3 shows data on these air exchange rates using the PFT technique. The calculation proceeds as follows:

$$R = AI \times 10^3 \times \frac{(C_u \times V_u + C_{b/c} \times V_{b/c})}{(V_u + V_{b/c})}$$

where R is the radon flow, pCi/h
AI is the air infiltration, m^3/h
C is the radon concentration, pCi/L
V is the volume, m^3
u is upstairs and b/c is basement/crawl space

Comparisons for five test houses are shown in the following table.

COMPARISONS OF RADON QUANTITIES EXHAUSTED BY MITIGATION SYSTEMS AND BY NATURAL MEANS BASED ON FIVE HOUSES

House No.	Rn Level (pCi/L)		House Volume (M3)		$AI_{avg.}$ (M3/h)	Rn Level Exhaust(pCi/L)	Exhaust Vel(M/S)	Rn Quantity (pCi/h)		Ratio: Mitigation/Natural
	Basement	Upstairs	Basement	Upstairs				Exhaust	Natural	
2	22	15	219	296	398	154	3.50	15,731,000	6,974,000	2.26
3	170	70	224	469	338	946	2.65	73,167,000	34,585,000	2.16
4	29	56	211	499	283	44	8.49	10,902,000	10,478,000	1.04
5	60	35	371	398	135	435	4.55	57,767,000	6,353,000	9.09
7	33	18	199	392	203	504	2.63	38,687,000	4,680,000	8.20

The ratio of the radon gas exhausted from each house via the mitigation system is compared to the radon natural flow value. Ratios vary from one to more than nine. We can ask, "what is special about house #4 which has the same radon gas flow via mitigation system or natural means, i.e., ratio one?" It is the home with the least porous soil -- that is basically pure clay. It is a home where high ventilation rates, e.g., using a blower door or opening windows will depress the radon levels, and then it takes many hours for the house to return to the previous elevated radon levels. Such behavior could be interpreted as evidence of a limited radon entry rate. However, just comparing the natural radon entry rate with those of the other homes would not single out this house. In fact, looking at natural radon entry rates, it is evident that house #3 stands out with a rate far above the others ~ 35 x 10^6 pCi/h versus 7.5 ± 3 x 10^6 pCi/L for all the rest. House #3 has a soil condition of high porosity, i.e., stone flour roughly 1/8 inch diameter and a good gravel bed, just the opposite of house #4.

The total amount of radon gas mechanically exhausted from the soil varies by a factor of seven in these homes. The lowest value is for house #4 with the clay soil. The highest value is for house #3 with the very porous soil. The two highest houses (#3 and #5) were the houses with reoccurring periods of above guideline levels of radon which is a critical durability characteristic. However, house #7 has a considerable amount of clay soil and still ranks third.

Again, this is a preliminary review of such radon exhaust data and it may possibly hold important clues to those homes most and least susceptible to reoccurring radon problems.

Some of the diagnostic techniques just described will encounter difficulty in below grade applications. Masonry construction tends to mask the temperature of the soil gas. The soil gas temperature may not be different enough from the basement temperature to make air leakage sites evident via infrared techniques. Sound sources, unless placed beneath the slab, would seem to have little chance of working effectively. Soil properties can vary from site to site and even from one house site to the other. To summarize, while there are similarities in the demands of the two applications there are enough differences that each application must be carefully considered.

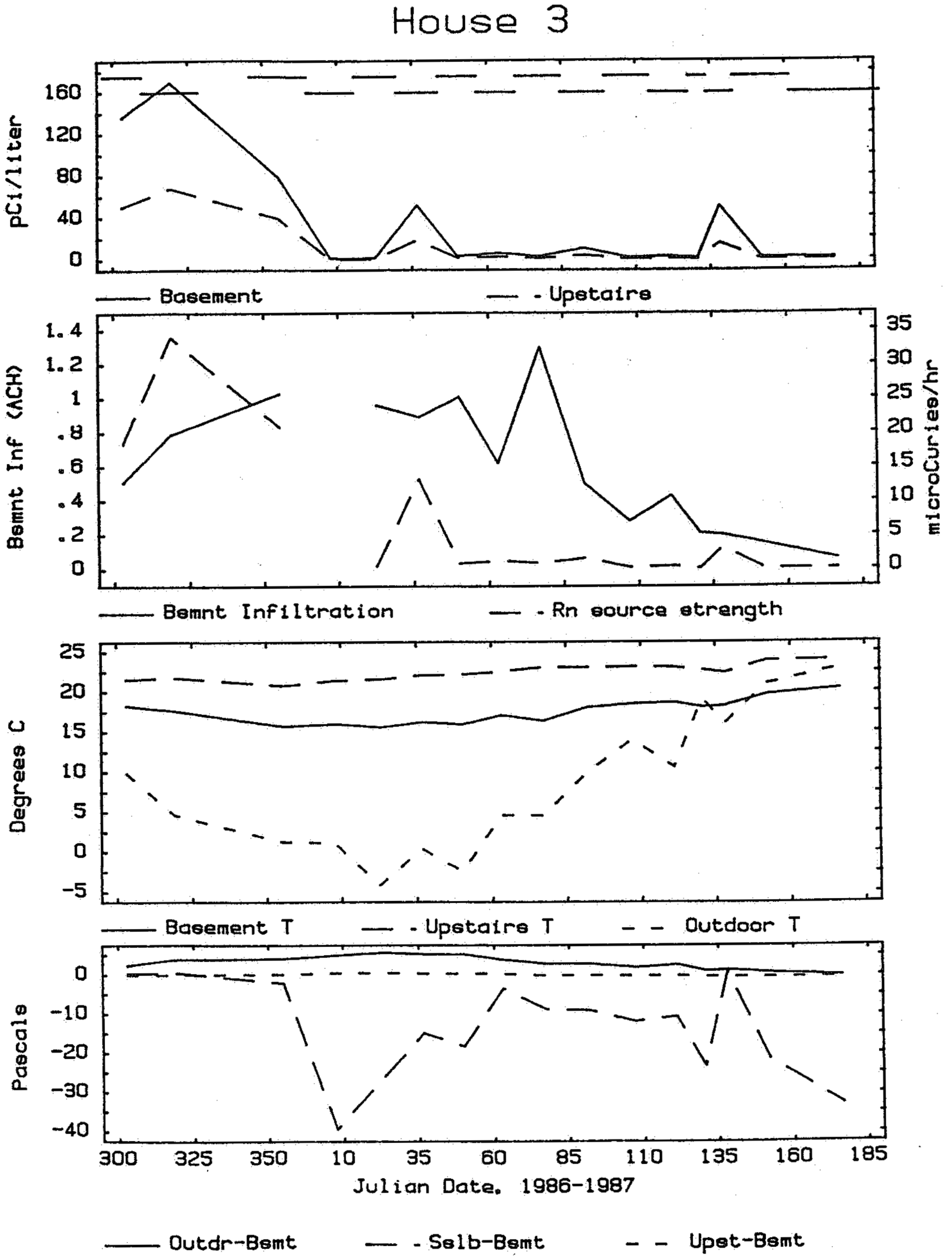

Figure 3. Profiles of radon concentration and air infiltration rates aid in the analysis of how the IAQ of the house is being affected by airflow patterns and radon sources. The top box in the figure shows the radon concentrations in the basement and upstairs. Also, at the top of the box, the dashed lines indicate the periods over which PFT measurements were taken. 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 differences between the outdoor/basement, subslab/basement, and upstairs/basement pressures. The greater these differences, the greater the relative depressurization of the basement. The points from which each line is plotted are the parameter averages during the tracer gas time period. Each time period is 10 to 14 days long.

3.0 CASE STUDY

To illustrate the application of some of the techniques just discussed, we will use test home #21 in Princeton that has experienced basement radon levels in the 200 pCi/L range for significant parts of the year. Our task was to analyze the cause of the problem and propose solutions. Part of the evaluation of the solution is how much energy will be used and how does the mitigation system influence the air exchange rate by exhausting interior air.

The house plan is shown in Figure 4 and points out that only part of the house has a basement; the remaining substructure is made up of shallow crawl spaces, approximately 25cm high, above a concrete slab.

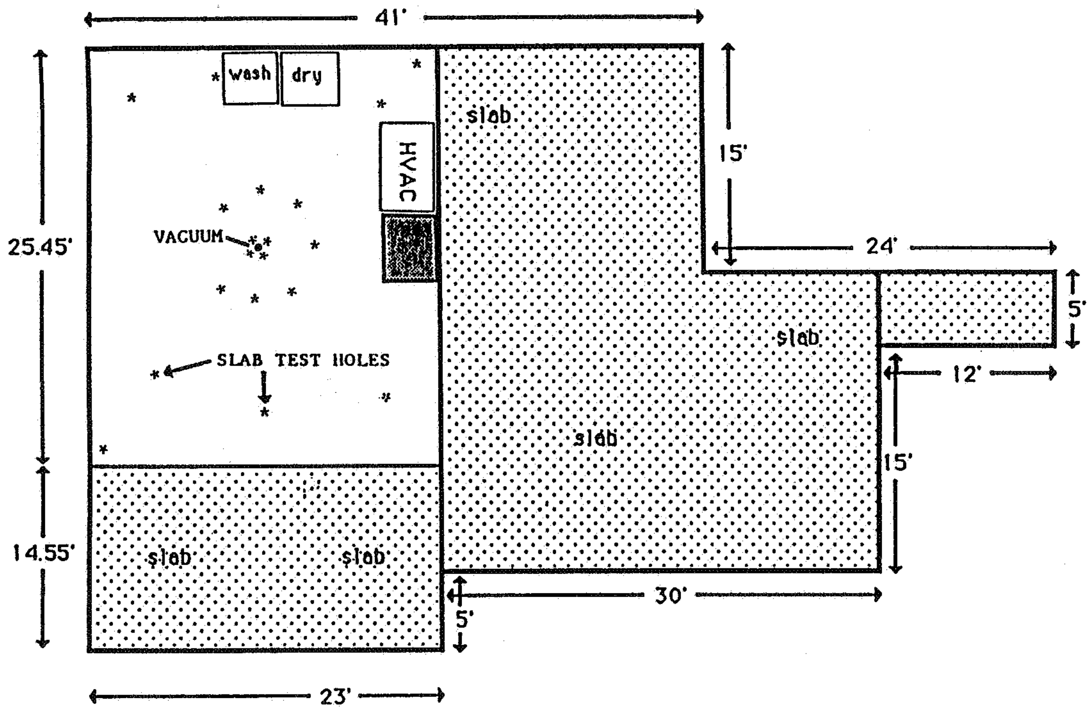

Figure 4. Plot plan of substructure of test house #21 pointing out basement and crawl space areas (noted slab) and details of where the suction is applied ●, and where pressure and velocity measurements are made *.

Tests of the soil immediately under the basement slab and in the hollow basement walls revealed radon levels no higher than 3,000 pCi/L, not exceptionally high for the geographic location and noticeably less than other test houses which exhibited much lower interior radon levels.

The blower door test revealed test house #21 to be very ordinary for its period of construction ~ 1960. The air exchange rates were shown to be approximately 13 ACH for 50 Pacals differential pressure whether or not the basement door is open. This is because of the warm air ducting system in the home. R^2 values are in the .999 range for each of the tests, indicating good repeatability. Clearly these results discourage one from being able to pressurize the basement as a mitigation scheme. ELA values also remain basically unchanged, thus yielding a similar diagnosis.

Influence of the heating method on interior radon concentrations can also be traced to the warm air ducts and the use of a central furnace fan that tends to mix the air in the house as well as generate a variety of pressures in different zones [10]. To point out these effects, experiments in test house #21 involved heating the house alternately with electric resistance heaters installed on the living level, and with a gas combustion furnace in the basement connected to a whole house air distribution system, driven by the furnace fan. The gas combustion heating system usually runs on an automatic setback mode, during which the thermostat automatically sets back to 55°F (13°C) at midnight and turns back up to its previous setting of 68°F (20°C) at 8:00 A.M. The data show that the furnace fan has a large effect on pressure differences across the building shell, and on the distribution of the radon indoors. These effects can be compared to the time periods when the furnace fan was not operating.

Figure 5 shows the radon concentrations, measured each half-hour, in the basement and in the subslab during gas combustion with automatic setback period along with the pressure differences between the outdoors and the basement and between the subslab and the basement, and the percent time the furnace fan is on during each half-hour. Figure 6 shows the same parameters for an electric heat period. The sharp rises in the pressure differences in Figure 5 coincide with the time the furnace fan is on. During the same periods, the basement radon decreases while the subslab radon increases. Increased mixing of the basement air with the upstairs air by the furnace fan causes the decrease in basement radon concentration. The variation in the upstairs radon during the furnace fan use, not plotted in Figure 5, closely parallels the pattern of the subslab radon concentration, and the upstairs radon increases by roughly the amount of radon the basement looses (considering the volumes involved).

Operation of the furnace fan is the main driving force for the variation in the radon concentration during the gas heating. The furnace fan depressurizes the basement compared to the outdoors by 1.8 Pa, and between the basement and the subslab by 0.9 Pa. The increased pressure difference increases the air infiltration into the basement. This increased air infiltration includes both soil gas and outdoor air. Each house will have a different ratio between the degree of leakiness to the soil gas and the degree of leakiness to the outdoors. This ratio determines whether increased air infiltration raises or lowers the indoor radon concentration. If, for example, the basement is very leaky to outdoor air but fairly well isolated from the soil gas, outdoor air will make up most of the increased infiltration and thus dilute the basement radon. It would be helpful to know how much this quantity varies among different houses. If it remains relatively constant among similar housing types built on soils with similar permeabilities, it may be possible to design a measurement to characterize the potential radon problem on a building site based on the soil permeability and radon content. With the limited data available to date there is no indication that generalization can be made at this time.

The pressure field can be established even if the soil is rather tightly packed. Flow measurements quickly reveal the degree of connectivity that is present. One researcher has referred to this

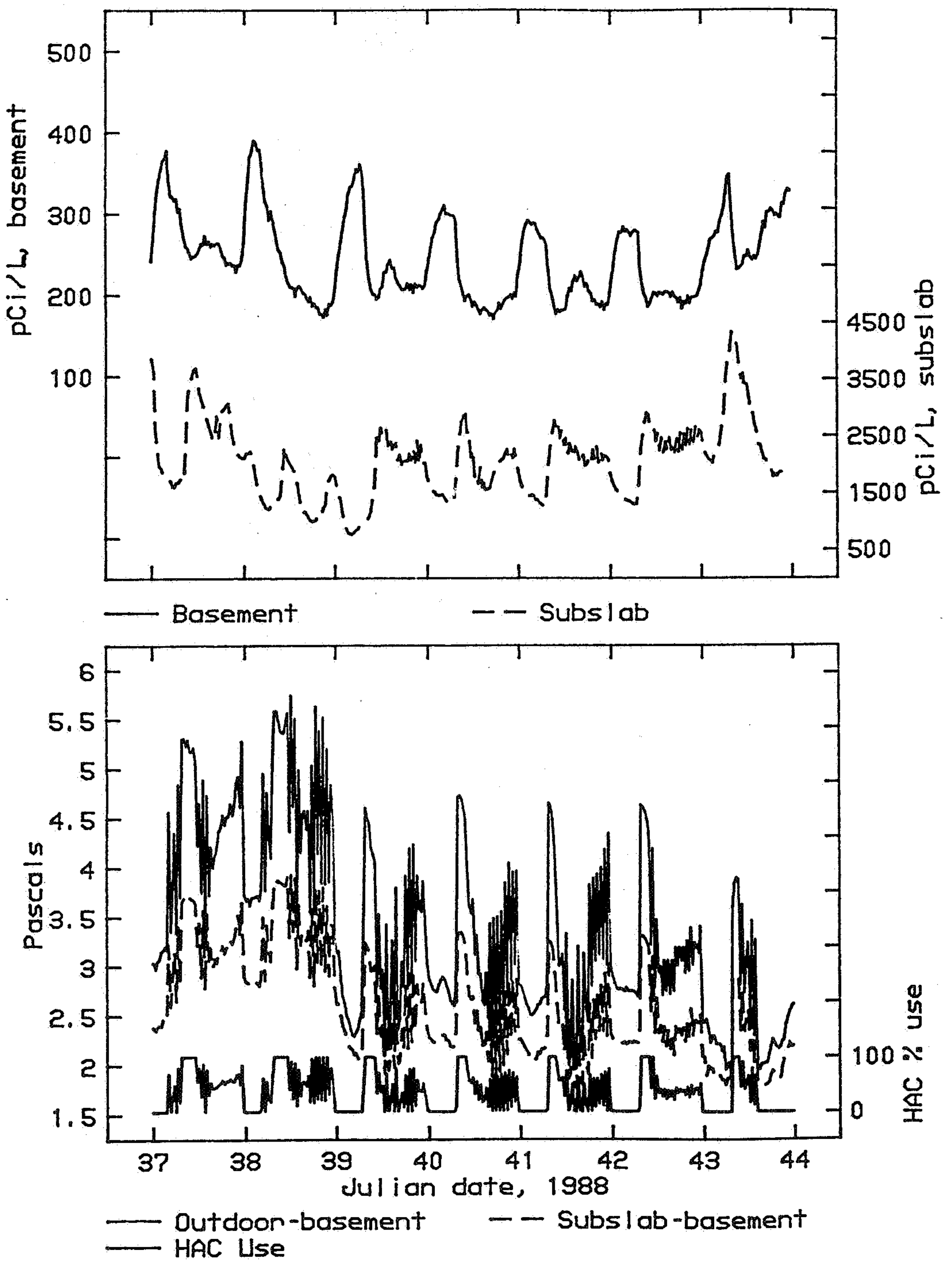

Figure 5. Half-hour radon concentrations in the basement and subslab for eight days in February 1988. Pressure differences between outdoors and basement, and subslab and basement are shown for the same period correlated to furnace fan use (heating, air conditioning, HAC) for the gas combustion form of heating.

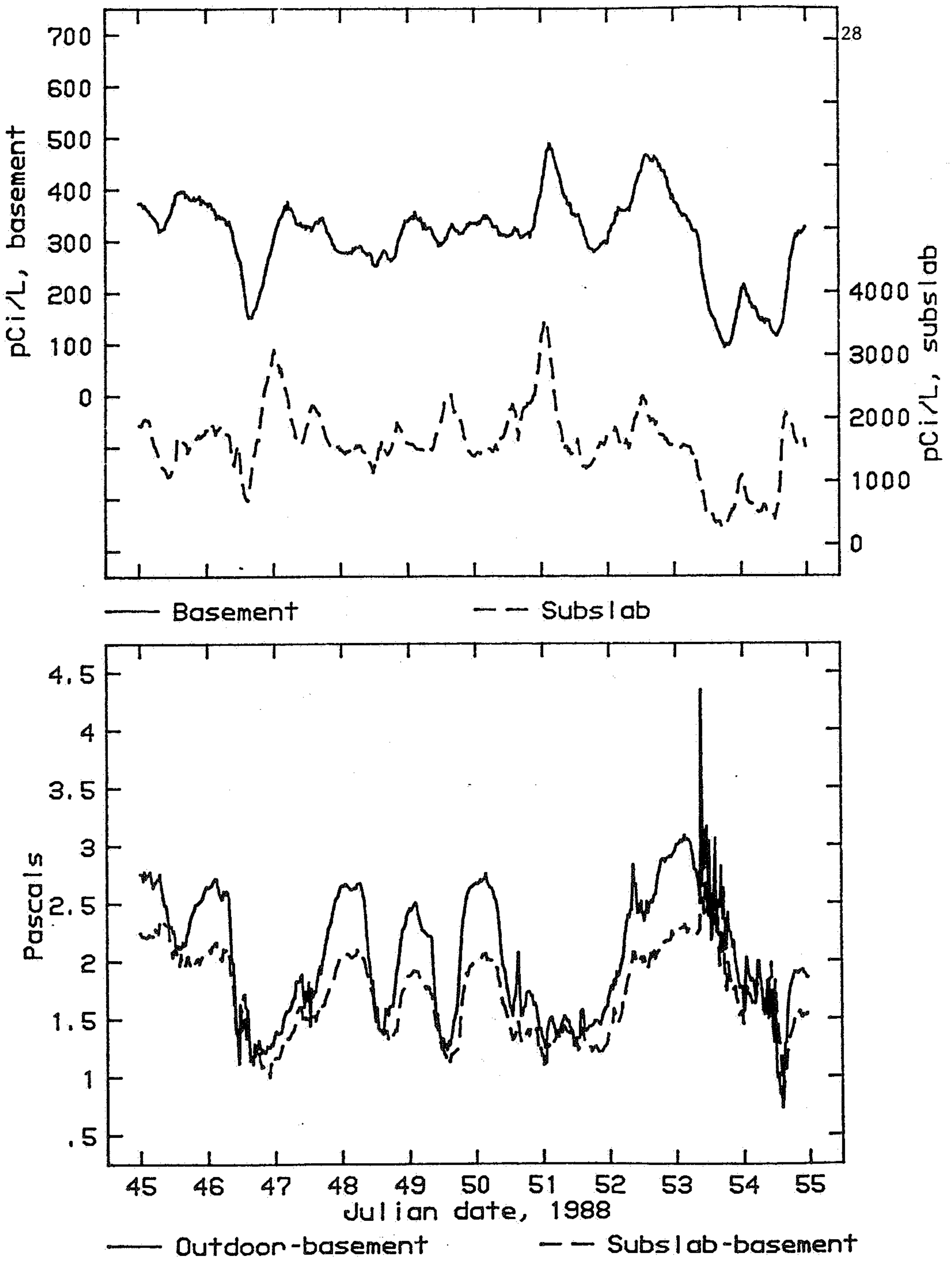

Figure 6. Electrical heating of the same home as in Figure 5 pointing out the lag between basement radon and subslab radon concentrations.

measurement technique and interpretations as a "blower floor" related to a blower door.[6] Typical of these measurements is the plot of data from house #21 shown in Figure 7. The relatively even radial distribution of pressure can be seen in the profile map, however, the wild variations in flow rates which are not shown appear to indicate no simple radial "highway" but rather the airflow under the slab is searching for paths of easier flow to the exhaust point.

Tests of soil porosity, connectivity, radon source strength, etc., all reveal key characteristics of a particular site and building. We are trying to finalize a rapid diagnostics protocol emphasizing what key measurements should be made. The problem is that the protocol should not extend beyond two hours if it is to have an impact in the market place. Unfortunately, it is difficult to stay within the two-hour constraint and supply all the needed information for the proper choice of mitigation system. The goal is to avoid the high failure rate, greater than 50%, of systems that fail to perform within the radon guidelines over the long term.

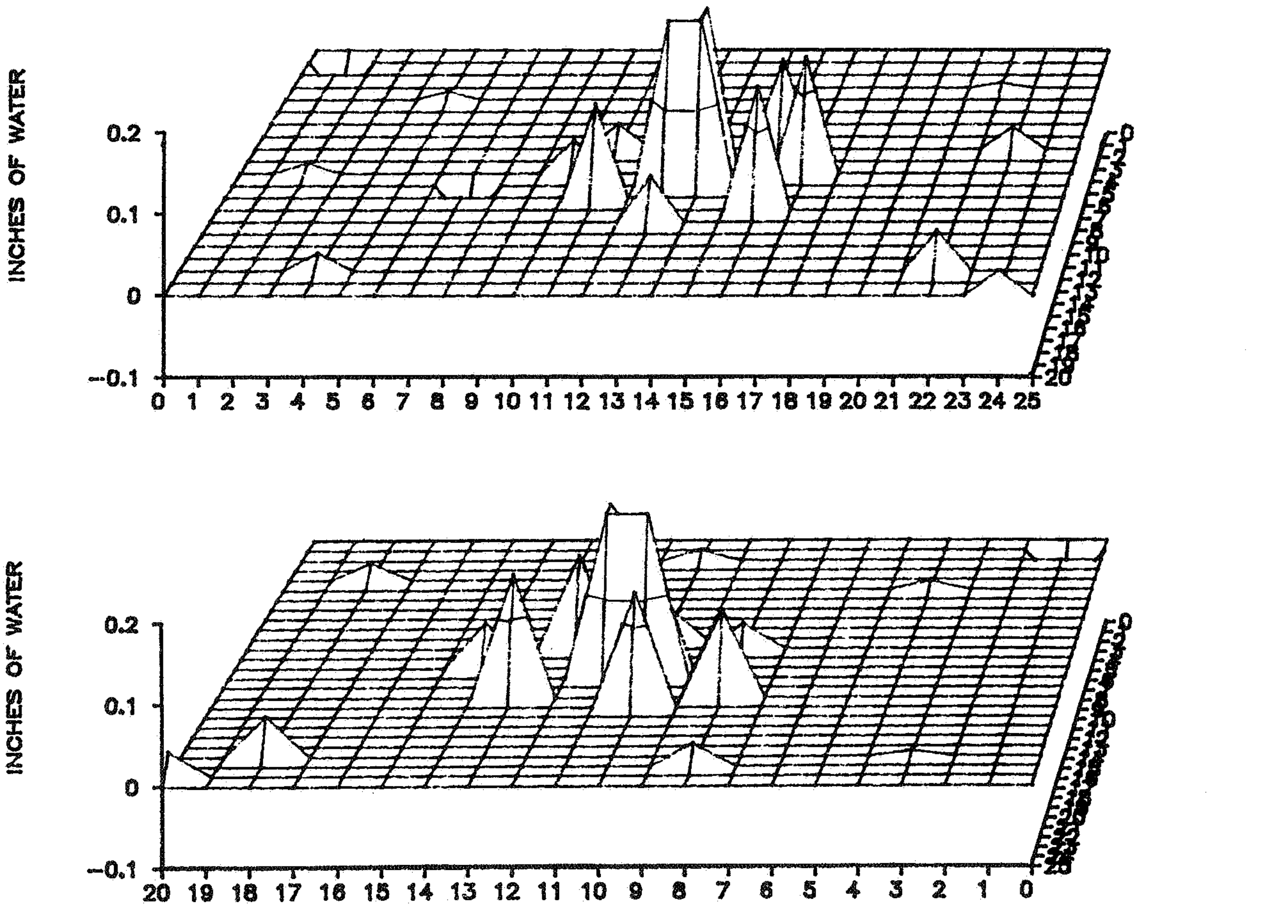

Figure 7. Graphical representation of the pressure profiles viewed from two directions in house #21. The individual points where the pressure measurements have been made are noted in Figure 4. These are negative pressures because of the industrial vacuum cleaner which has been used in this diagnostic procedure.

4.0 SUMMARY

We hope this exposure to the world of radon diagnostics and mitigation, with the realization of how closely many of the methods coincide with previous experiences in air infiltration measurement, will encourage you to pose new innovations in this discipline. The substructure of buildings can prove to be a very difficult test site. One desires to search out radon entry points, but one is confronted with the fact that any oversight of leakage area may mean no radon reduction. Small temperature variations between soil gas and substructure, as well as the presence of porous media such as block walls, encourages radon intrusion. Test procedures are not only concerned with airflow paths and therefore the paths of radon through the home, but also pathways beneath the structure can be assessed by methods using both pressure and flow indications. These methods evaluate connectivity and the ability to mitigate. Mitigation can take many forms but the efficient subslab depressurization system has been demonstrated to prevent more than 90% of the radon from entering the home. In the radon removal process, the system may be removing as much as ten times the natural flow of radon from the soil, possibly causing higher ambient levels of radon near the home. Interior conditioned air is normally removed as part of the mitigation procedure and these energy implications can outweigh the electrical costs for the mitigation system fan. With all of these factors in mind, well thought-out diagnostic procedures are essential if the job is to be done correctly. The radon research community welcomes new thinking on this subject as it works toward more cost effective and durable solutions to this indoor air quality problem which ranks very high in terms of human health risk.

ACKNOWLEDGMENTS

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Discussion
Paper 14

Jorn T. Brunsell (Norwegian Building Research Inst.)

Have you tried to blow room air into the ground to make a "pillow" of radon free air under the house?

David Harrje (Princeton University, USA)

This method can be used to pressurize the basement/crawl space if there is a good preparation between basement and living space (i.e. an airtight floor). If air is blown under the slab, the results have been mixed. The danger is that while a higher pressure may be established under the slab to prevent radon entry, because of openings in the wall construction, radon may be forced into the building. Using depressurization, walls tend to be evacuated of radon at the same time the subslab is purged. Some studies in the Pacific Northwest, USA, have shown subslab pressurization to actually outperform depressurization when soil conditions and construction features were favourable.