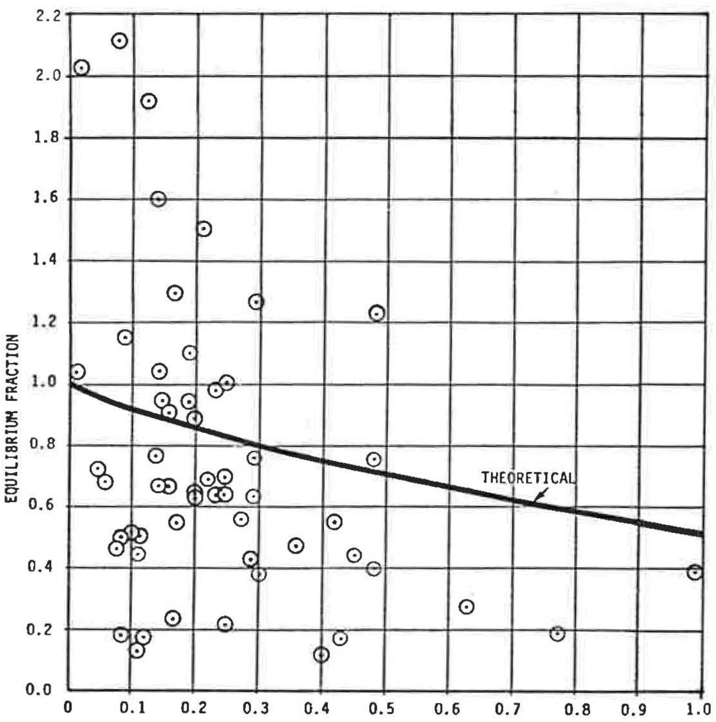

Figure 1 Equilibrium Fraction Versus Ventilation Rate

DETAILED FIELD TESTS OF RADON CONTROL TECHNIQUES IN NEW YORK STATE HOUSES

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Sixty houses with widely different construction practices and in different locations in upstate New York were monitored for integrated radon concentration. Four houses with the highest indoor air radon levels were then monitored using extensive real-time continuous instrumentation to evaluate temporary radon control techniques. Based on this experience, permanent controls were then installed and tested (using integrating monitors) in 14 houses. Among the results from real-time monitoring were insights into relationships between basement radon concentrations and basement pressure (relative to outside pressure). Of the several radon control techniques tested, whole house ventilation and basement ventilation (using air-to-air heat exchangers) were only marginally effective in reducing radon levels, while ventilation of unpaved crawl spaces and the combination of sealing below-grade openings and venting the sub-slab, provided the greatest reduction in indoor radon concentrations.

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INTRODUCTION

When elevated radon concentrations are discovered in a house, it is natural to ask if anything can be done to reduce the levels. In order to provide homeowners and contractors with practical, inexpensive radon control techniques, research must be done to determine the effectiveness of various methods of control.

As part of an extensive study of infiltration and indoor air quality, 60 houses with widely different construction practices that were located in different areas in central and northeast New York State were monitored for integrated radon concentrations using passive monitors. Four houses with the highest indoor air radon levels were then monitored using extensive real-time continuous instrumentation to evaluate a variety of radon control techniques. After the real-time evaluation of the various temporary control measures, permanent control techniques were installed in the original four houses and ten additional houses with radon levels above 2 pCi/l (the approximate ASHRAE guideline). Passive radon detectors were then deployed in each of the 14 houses, and seven houses without control techniques, for one to two months, to test the long-term effectiveness of the permanent controls.

REAL-TIME RADON MONITORING

The installation of radon control techniques in residential buildings has previously been carried out in the United States[1], Canada[2], and Sweden[3]. Although several researchers in the United States have conducted real-time radon monitoring in homes[4-7], only limited testing of radon control techniques using real-time monitoring equipment has been performed[7]. To better understand the mechanisms for reducing indoor radon concentrations, intensive testing of radon control techniques were conducted using a custom-built real-time monitoring system.

The detailed real-time radon monitoring part of this project was conducted from mid-October 1983 until January 1984 in houses numbered 05, 21, 31, and 37 which had some of the highest indoor air radon concentrations in the study. For each house, the total monitoring period ranged from two to four weeks. The primary purpose of this phase was to conduct intensive testing of radon control techniques using a real-time monitoring system to understand better the mechanisms for reducing indoor radon concentrations. Before control techniques were installed, the background radon and radon progeny concentrations were monitored in the basement. Radon control techniques were then temporarily installed and tested, both individually and in combination. Experiments with radon mitigation techniques usually lasted one to seven days. In order to differentiate between the natural variations in radon levels and those resulting from control techniques, weather, particulate, and infiltration variables were also monitored, along with radon and radon-progeny concentrations.

Temporary testing of radon techniques using real-time monitoring equipment greatly extended our understanding of the mechanisms of radon entry into basements. This knowledge aided significantly in the selection of permanent radon control measures for these four houses.

Pressure Difference Effects on Indoor Radon Levels

The difference in air pressure between the basement and outdoors was found to have the greatest effect on indoor radon concentrations. A

pressure difference can affect the indoor radon concentration through two different mechanisms. The first mechanism involves the rate at which radon from the surrounding soil enters the basement. The second mechanism relates to the basement air exchange rate caused by variations in pressure difference.

An example of the effect of pressure difference on the radon source rate can be seen in house 37, Figure 1. The differential pressure (dP) is defined as:

$$dP = P(\text{basement}) - P(\text{outside})$$

where P(basement) is the basement atmospheric pressure and P(outside) is the outside atmospheric pressure.

Referring to Figure 1, the differential pressure was large and negative during the first day of this experiment (between -13 and -25 Pa). This was caused by a 16 to 24 miles per hour (26 to 39 km/hr) westerly wind. (It should be noted that the house was on the top of a rise in a very exposed location which may explain the relatively large negative differential pressures encountered.) As the wind calmed after day 316, the negative pressure increased towards zero, which correlated with a decrease in the radon concentration. In this experiment, the large negative differential pressure caused an increase in the rate at which radon-laden soil gas entered the basement.

In house 05, Figure 2, the air exchange rate is the dominant mechanism affecting the indoor radon concentration. The radon concentration was the lowest during the first day of this experiment because of the negative differential pressure. The air exchange rate was found to be 1.1 hr^{-1} during the first day. When the differential pressure was reduced, the air exchange rate decreased to 0.28 hr^{-1}. This reduction resulted in a major increase in the indoor radon concentration.

One may ask why a negative differential pressure has an opposite effect in houses 05 and 37. The reason for this difference is that the basement of house 05 had a larger leakage area between the basement and the outside than house 37. In house 05, there were 4-inch (10-cm) and 1.5-inch (3.8-cm) PVC pipes leading from the basement to the outside. Whenever a negative differential pressure was induced in this basement, the path of least resistance to air flow to equalize the pressure was from the outside via the PVC pipes.

In house 37, there were no major openings from the basement to the outside. This condition caused the soil gas to be drawn into the basement whenever a large negative differential pressure was induced.

In summary, whenever a basement has a negative differential pressure (or more precisely, a negative pressure with respect to the outside), air is drawn into the basement to equalize the pressure difference. The major path of air into a basement will be from the source which has the lowest resistance to entry. If openings from the basement to the outside do not exist, or are minimal, then the primary source of make-up air into the negatively pressurized basement will be from the soil.

Effect of Control Measures on Indoor Radon Levels

Sump Venting and Sealing. Venting a basement sump opening to the outside was probably the simplest temporary control measure to install. This technique was tested in houses 05, 21, and 37. House 21, which had the highest radon concentration during the initial survey, was the first site for which sump ventilation was introduced and tested.

In Figure 3, the effect of venting the sump with a 50 cfm (25 l/s) centrifugal blower is shown. Prior to installing the blower on day 182, radon progeny concentrations averaged approximately 200 mWL and reached peaks over 500 mWL. During the second week of monitoring, the radon progeny levels were found to be below 10 mWL for most of the week. Toward the end of the second week, during cool weather, the effectiveness of the control technique appeared to decrease. At the time of the experiment, an explanation for this loss of effectiveness was not available so a second visit to house 21 was made in October 1984.

In October 1984, it was discovered that the sump ventilation system in house 21 had reduced effectiveness during periods of negative differential pressure. As shown in Figure 4, the loss of effectiveness during the first 20 hours of this experiment correlated with the period of greatest negative differential pressure. This pressure difference was caused by a 36°F (20°C) inside-outside temperature difference. As the differential pressure approached zero after the start of day 305, the radon progeny levels dropped by nearly a factor of three.

Negative differential pressure in the basement can reduce the effectiveness of the sump ventilation by drawing soil gas into the basement. The soil gas surrounding the basement migrates to regions of low air pressure. The sump and connecting drain pipes are held at a negative pressure with respect to the outside by the blower. The basement also may become negatively pressurized with respect to the outside due to winds or inside-outside temperature differences. A competition for soil gas can occur between the sump and a negatively pressurized basement, resulting in reduced effectiveness of the sump ventilation system.

In houses 05 and 21, sump ventilation was tested in combination with sealing cracks in the basement. The results of the testing in house 05 are shown in Figure 5. During the first three days, no significant reduction occurred when sump ventilation was the only radon control technique installed. On day 339, the floor/wall joint was sealed to supplement the sump ventilation. The combined effect of these two techniques reduced the radon progeny levels by nearly a factor of three. When the sump ventilation system was later turned off, it was found that sealing had minimal effectiveness without the sump ventilation.

In Figure 6, the effectiveness of sealing cracks and sump ventilation in house 37 is demonstrated. At the beginning of this four-day experiment, the sump and perimeter floor/wall cracks were sealed. The greatest reduction in radon concentration with the sealant-only technique occurred when there was a slight positive pressure in the basement with respect to the outside during the first part of day 319. Negative pressures in the basement towards the end of day 319 caused the sealing technique to lose effectiveness. In most types of sealing, there are always some entry routes present for soil gas. When a negative pressure developed in this basement, soil gas was drawn through the remaining openings between the basement and the soil.

On day 320, in Figure 6, a blower was installed to evacuate the sump to the outside. This technique, in combination with sealing cracks, reduced radon concentration below 1 pCi/l. This superior effectiveness remained even when the differential pressure was as low as -20 Pa. This result indicates that the resistance to soil gas entry into the basement was much greater than the resistance to soil gas entry into the sump. The amount of soil gas entering the sump was therefore much greater than the quantity entering the basement.

The testing of sump ventilation in houses 05, 21, and 37 showed that the effectiveness of this technique was highly dependent upon the resistance to soil gas entry into the basement. If this resistance was low, as in

house 21, then the basement will successfully compete with the sump ventilation system for soil gas. When sealing of basement openings was carried out as in houses 05 and 21, the resistance to soil gas entry into the basement increased which greatly enhanced the effectiveness of the sump ventilation system. It appears from our data that sump or sub-slab ventilation can have excellent effectiveness if the basement has a high resistance to soil gas entry.

<u>Air-to-Air Heat Exchanger</u>. House 31 had a finished basement, so sealing cracks and holes under the finished basement walls and floor was impractical as was any attempt to temporarily ventilate the sub-slab. The basement of this house was also fully open to the first floor so any attempt to ventilate only the basement was not possible. As a result, a whole-house air-to-air heat exchanger with a flow rate of approximately 70 l/s (140 cfm) was temporarily installed and tested.

In Figure 7, the effect of the air-to-air heat exchanger is shown. Due in part to the temporary nature of the installation, a draft was produced which caused discomfort to the homeowner. The air-to-air heat exchanger was turned off by the homeowner after only nine hours of operation. Even though the unit was tested for only nine hours, several interesting results were found.

Measurements of the air exchange rate before and after operation of the air-to-air heat exchanger showed the mean natural air exchange rate of this house to be $0.14 \pm 0.03\ hr^{-1}$. During the operation of the exchanger, the measured air exchange rate increased to $0.28\ hr^{-1}$ as predicted by calculations using the air flow of the heat exchanger. This factor of two increase in the air exchange rate caused a factor of two decrease in the indoor radon concentration.

Probably the most interesting finding in this experiment comes from observing the radon concentration after the air-to-air heat exchanger was turned off. It took nearly six hours for the radon levels to begin rising after the air-to-air heat exchanger was turned off. This lag time in radon build-up indicates that the radon source was partially depleted during the operation of the air-to-air heat exchanger. Unfortunately, time limitations did not allow us to test the repeatability of this observation.

<u>Summary of Techniques Tested</u>. In Table I, a summary of the results for temporary radon control testing is listed. The primary conclusion that can be drawn from these data is that the combination of sump ventilation and sealing was found to be highly effective in houses 05, 21, and 37. In house 05 radon progeny levels were reduced from 30 to 7 mWL (77% reduction) and radon levels decreased from 12 to 3 pCi/l (75% reduction); in house 21 radon progeny levels were reduced from 211 mWL to 15 mWL (93% reduction); and in house 37 radon progeny levels were reduced from 200 mWL to 4 mWL (98% reduction), while radon was reduced from 40 pCi/l to less than 1 pCi/l (a greater than 98% reduction).

The use of activated carbon filtration of basement air in houses 05 and 21 was found to be ineffective in reducing the radon levels, but was effective in reducing radon progeny concentrations in both houses. The activated carbon filtration unit had a flow rate of approximately 150 cfm (70 l/s). The filter consisted of nine kilograms of coconut shell carbon. The reductions in radon progeny levels were 60% and 43% in houses 05 and 21, respectively. The increased effectiveness of the carbon in house 05 as compared with house 21 was due primarily to the smaller basement volume in house 05. A smaller basement volume results in more air changes through the carbon filter per hour.

PERMANENT RADON CONTROL EVALUATION

Design Considerations

Source Identification. Areas in basements presenting the lowest resistance to soil gas entry are most likely to be strong sources of radon. Examples of such areas include unpaved floors, floor/wall joints and open sumps. To obtain a greater understanding of the radon entry routes, we installed several passive Track-Etch Type SF detectors near potential sources of radon in all homes which were scheduled to receive radon control techniques. The small size of the radon detectors made them ideal for placing in cracks and other small openings to the soil. A total of six to twelve detectors were placed in each house to help locate the strong sources of radon. In Table II, the locations of the highest measurements are listed for a few of the houses. Basement areas that were indicated to be strong sources of indoor radon included sumps, floor/wall cracks, unpaved crawl spaces, pipe penetrations, and floor drains. The highest radon concentration was 1026 pCi/l which occurred in the floor/wall crack of house 12. Generally, areas of high radon concentrations were found to have concentrations between 10 and 100 times higher than the average radon concentration in the house.

Cost Effectiveness. The number of radon control options available in each house was limited to one or two, mainly because of costs. (We had hoped to keep costs under $500 per house.) The cost-benefit analysis consisted of comparing the estimated installed cost of a technique with its probability of success. Techniques considered to have high probability were those that we had previously tested during the real-time follow-up monitoring phase. These high-probability techniques included sump ventilation, sealing cracks, basement ventilation and isolation, and ventilation of unpaved crawl spaces.

Homeowner Considerations. Whenever permanent modifications are to be made to the property of a homeowner, close cooperation between contractor and homeowner is essential. Most homeowners were very cooperative once they fully understood the reason for and scope of the modifications to be made. Our cooperation with the homeowners in this phase consisted of three parts. Intitally, a letter was sent to the homeowner explaining the proposed work in detail. After the homeowner received the letter, a follow-up phone call was made to further explain the proposed work. If, after the phone conversation, the homeowner still wanted further information, a visit was made to the house to show the homeowner exactly what was proposed. As a result of using this system of communication, all 14 homeowners agreed to participate in this phase of the project. A brief description of the permanent radon control techniques installed in the 14 houses, and the labor and material costs associated with the installation of the controls are given in Table III.

Types of Control Techniques

Sealing Cracks and Sub-Slab Ventilation. The first step is to seal cracks with caulk or closed-cell polyurethane foam. Polyurethane foam was used in cracks wider than about a half an inch (1 cm), such as perimeter floor/wall cracks in basements. After the foam hardened, it was cut and painted to blend in with the basement environs. Figure 8 indicates some of the areas that were sealed to prevent soil gas entry.

Introducing sub-slab ventilation is the next step. A sub-slab ventilation system was installed in five houses. There are two ways that sub-slab ventilation can be installed. One way is to utilize an

existing sump along with the sub-slab drainage pipes leading into the sump. If a sump opening is not present, then a hole is cut in the floor to provide access to the soil. Once a sump or hole is present, a fan is installed to evacuate sub-slab soilgas to the outside. Diagrams of these techniques are shown in Figure 9 and 10. These methods are consistent with more elaborate methods used in Canada[2] and Sweden[3].

Radon Isolation and Ventilation. This technique is used, for example, in an unpaved crawl space which is determined to be a source of indoor radon. It involves partitioning the crawl space from the heated space with wood framing, plywood, caulk, and insulation so that the radon-laden air of the crawl space will not readily migrate into the living space. The second component of this technique is the passive or active ventilation of the crawl space air to the outside. Figure 11 illustrates the method of radon isolation and ventilation from a crawl space.

Whole-House Ventilation. Whole house ventilation was performed in tight houses in which an existing air-to-air heat exchanger was present, or as a last resort, in very tight houses with relatively low levels of radon. It has been our experience that homeowners having air-to-air heat exchangers without automatic controls tend to utilitize their exchangers infrequently. In these houses, a simple radon mitigation technique consisted of installing a timer control which automatically cycled the exchanger on and off.

In houses where we installed an air-to-air heat exchanger, an attempt was made to minimize the volume which was ventilated. Houses with two compartments such as a basement and living space had only the basement ventilated. Diluting basement air with outside air can be an effective way of reducing living space radon concentrations.

RESULTS

Houses Without Controls. It is generally understood that radon concentrations in houses can vary widely from day to day or month to month. In order to properly evaluate the permanent control measures, a group of seven homes in which no controls were installed were monitored during the same period as the 14 houses receiving radon controls. The magnitude of the natural variation is shown in Table IV.

In these seven houses, the natural variation in radon concentrations between monitoring periods was a factor of two in many of the houses.

Houses with Low Reductions in Radon Concentration. In Table V the results of the permanent radon control evaluation are shown. Houses 16, 19, 41, 51,and 56 had the lowest reductions in radon concentration.

Analysis of why greater reductions were not found in these houses revealed two main reasons. The first and most important reason was the fact that these houses had relatively low radon concentrations prior to installation. Houses such as these have diffuse sources of radon which cannot be mitigated in a cost-effective manner. In addition, the natural variation in radon concentration in houses with low radon concentration tends to be on the order of the initial concentrations. Attempts to compare results from two different monitoring periods are therefore very difficult in these houses.

Sand Thermal Storage. Two solar houses with coupled sand thermal storage masses were studied in this phase of the project (houses 26 and 29). Both of these houses presented a similar problem. We suspected the sand thermal storage mass to be a source of radon, but could neither prove it nor seal it off from the living space. The sand storage mass in these two houses was extremely well coupled to the house by an air circulation system through the thermal storage mass.

At this point, it cannot be concluded that the sand mass is the primary source ofradon in these two houses. Three houses of similar construction with sand thermal storage did not have radon problems. However, it is difficult to conjecture how radon from the soil surrounding the houses with sand mass and elevated radon levels can enter these houses. This is because the thermal storage mass seems to be fairly well isolated from the surrounding soil by a heavy vapor barrier and rigid isocyanurate insulation. Further study is needed in these houses to settle these questions.

Houses with the Greatest Reductions in Radon Concentration. The greatest success in reducing radon concentration occurred in houses with high radon concentration. The reason for the large reductions in houses 05,12, 21, 31, and 37 can be attributed to two things. First, these houses had strongly concentrated sources of radon which could be effectively mitigated at low cost. Second, the high priority placed on these houses gave us greater time to analyze the dynamics of the radon entering the houses.

CONCLUSIONS

The use of real-time monitoring during radon mitigation testing is probably the single-most effective means of solving a radon problem. The immediate feedback obtained from the real-time monitors supplied valuable information. In house 21, for example, it allowed the determination that the induced negative pressures in the basement decreased the effectiveness of the sump ventilation system. Another example was house 31 in which it was learned that venting one opening in the basement slab was inadequate. By adding a second opening and venting it, adequate reductions in radon concentration were obtained.

In the analysis of real-time data, one of the most significant results was the relationship between basement pressure (relative to outside pressure) and basement radon concentrations. In houses with basements with large openings above grade, the relationship was direct (negative basement pressure brings in outside air and dilutes radon levels). In houses with basements with few openings above grade, the relationship was inverse (negative basement pressure brings in more radon increasing basement radon levels).

Of the several radon control techniques tested, whole house ventilation and basement ventilation (using air-to-air heat exchangers) were only marginally effective in reducing radon levels, while ventilation of unpaved crawl spaces and the combination of sealing below grade openings and venting the sub-slab, provided the greatest reduction in indoor radon concentrations.

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REFERENCES

1. M.V.J. Culot, K.J. Schiager, H.G. Olson, 1973, "Radon Progeny Control in Buildings", U.S. Atomic Energy Commission Report COO-22734, Fort Collins, Colorado.

2. DSMA ATCOM, Ltd., 1980, "Report on Investigation of Remedial Measures for the Radiation Reduction and Radioactive Decontamination of Elliot Lake, Ontario", Report AECB-1211-3 prepared for the Atomic Energy Control Board, Ottawa, Canada.

3. S. Ericson, H. Schmied, B. Clavensjo, "Modified Technology in New Constructions, and Cost Effective Remedial Action in Existing Structures, to Prevent Infiltration of Soil Gas Carrying Radon", Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, Stockholm, Sweden, August 1984.

4. C.T. Hess, C.V. Weiffenbach, S.A. Norton, 1983, "Environmental Radon and Cancer Correlations in Maine", Health Physics 45, 339-348

5. D.T. Grimsrud, W.W. Nazaroff, K.L. Revzan, A.V. Nero, 1983, "Continuous Measurements of Radon Entry in a Single Family House", paper presented at the 76th Meeting of the Air Pollution Control Association, 19-24 June, Atlanta, Georgia.

6. W.A. Goldsmith, J.W. Poston, P.T. Perdue, M.O. Gibson, 1983, "Radon -222 and Progeny Measurements in 'Typical' East Tennessee Residences", Health Physics 45, 81-88.

7. W.W. Nazaroff, M.L. Boegel, C.D. Hollowell, G.D. Roseme, "The Use of Mechanical Ventilation with Heat Recovery for Controlling Radon and Radon Daughter Concentrations in Houses", Atmospheric Environment 15, 263-270.

TABLE I. SUMMARY OF RADON REAL-TIME MONITORING RESULTS

			BASEMENT MEASUREMENTS				FIRST FLOOR MEASUREMENTS[b]	
HOUSE NUMBER	MONITORING PERIOD	CONTROL TECHNIQUE[a]	MEAN RADON[b] (pCi/l)	MEAN PROGENY[b] (mWL)	MEAN EQUILIBRIUM FACTOR	AIR EXCHANGE (/hr)	RADON (pCi/l)	PROGENY (mWL)
05	08/25/83-08/30/83	N	-	97	-	-	-	-
05	08/30/83-09/01/83	N	-	-	-	-	-	6
05	11/23/83-11/28/83	N	12	30	0.25	-	17*	-
05	11/28/83-12/02/83	F	12	12	0.10	1.1 - 0.28	10*	-
05	12/02/83-12/05/83	VS	11	26	0.24	0.76	6*	-
05	12/05/83-12/08/83	S, VS	5	8	0.27	1.8 - 1.0	-	-
05	12/12/83-12/14/83	S+, VS, VC	3	7	0.23	1.5	2*	-
05	12/14/83-12/16/83	S+, VS	6	16	0.27	0.89	< 1*	-
05	12/16/83-12/20/83	S+	11	25	0.23	1.00	-	-
21	06/24/83-07/01/83	N	-	211	-	-	-	-
21	10/18/83-10/20/83	VD, F	-	120	-	-	-	-
21	10/20/83-10/24/83	S, VD	34*	150	-	0.4 - 0.31	11	-
21	10/24/83-10/26/83	S, VD	35*	120	-	0.41 - 0.27	18	-
21	10/26/83-10/28/83	S, VD, F	36*	80	-	0.39	8	-
21	10/28/83-10/31/83	S, VD+	10*	60	-	0.40	4	-
21	11/02/83-11/04/83	S+, VD+	2*	15	-	0.39 - 0.37	3	-
31	02/02/84	N	-	34*	-	-	-	-
31	12/20/83-01/05/83	N	11	55	0.50	0.16	-	-
31	01/05/84-01/11/84	N	13	-	-	0.11	-	-
31	01/11/84	VW	5	19	0.38	0.28	-	-
31	01/11/84-01/17/84	N	9	-	-	0.11	-	-
37	08/17/83-08/22/83	N	-	54	-	-	-	-
37	08/22/83-08/24/83	N	-	-	-	-	-	10
37	11/14/83-11/16/83	S	15	65	0.43	0.30	-	-
37	11/16/83-11/18/83	S, VD+	< 1	4	-	-	-	-
37	11/18/83-11/21/83	S, VD	< 1	6	-	-	-	-

[a] F = FILTRATION USING ACTIVATED CARBON, N = NO CONTROL TECHNIQUE, S = SEALING OPENINGS BELOW GRADE, VC = VENTILATION OF CRAWLSPACE, VD = VENTILATION OF SUB-SLAB WITH SUB-SLAB DRAINPIPES, VS = VENTILATION OF SUB-SLAB WITHOUT SUB-SLAB DRAINPIPES, VW = VENTILATION OF WHOLE HOUSE WITH HEAT RECOVERY. THE SYMBOL + DENOTES ADDITIONAL SEALING OR VENTILATION USING A LARGER FAN.

[b] ASTERISK (*) DENOTES GRAB SAMPLES

TABLE II. SUMMARY OF HIGHEST DIAGNOSTIC RADON MEASUREMENTS

HOUSE NUMBER	MONITORING PERIOD	LOCATION	RADON CONCENTRATION (pCi/l)
02	07/19/83-11/15/83	UTILITY ROOM FLOOR/WALL GAP	70
05	07/18/83-11/15/83	SUMP OPENING	222
05	07/18/83-11/15/83	CRAWL SPACE	70
05	07/18/83-11/15/83	BASEMENT FLOOR/WALL GAP	30, 22
12	12/28/83-02/01/84	BASEMENT FLOOR/WALL GAP	1026, 404, 250
12	12/28/83-02/01/84	BURIED IN CRAWL SPACE	512
12	12/28/83-02/01/84	SUMP OPENING	476
19	02/03/84-03/13/84	PIPE PENETRATION	82
19	02/03/84-03/13/84	BASEMENT FLOOR/WALL GAP	69, 42
21	07/18/83-09/27/83	SUMP OPENING	66
26	07/22/83-02/09/84	SUMP OPENING	408
26	07/22/83-02/09/84	BASEMENT PIPE PENETRATION	76
28	08/01/83-02/08/84	BASEMENT PIPE PENETRATION	18
28	08/01/83-02/08/84	NEXT TO WATER METER	17
29	07/20/83-02/08/84	NEXT TO SAND MASS AIR CIRCULATION	10
31	12/28/83-01/17/84	DRAIN IN LAUNDRY	28
31	12/28/83-01/17/64	CAVITY BENEATH STAIRS	23
37	08/17/83-11/03/83	SUMP OPENING	913
37	08/17/83-11/03/83	BASEMENT FLOOR/WALL GAP	254, 240, 159, 127, 100
41	09/11/83-02/06/84	SUMP OPENING	137
51	02/09/84-03/29/84	FLOOR DRAIN	182

TABLE III. SUMMARY OF PERMANENT RADON CONTROL TECHNIQUES INSTALLED IN FOURTEEN HOUSES

HOUSE NUMBER	PERMANENT RADON CONTROL TECHNIQUE	LABOR COSTS[a] ($)	MATERIAL COSTS ($)	TOTAL COSTS ($)
02	VENTED SUB-SLAB	112.50	33.59	146.09
05	SEALED CRACKS, SEALED AND VENTED SUMP, ISOLATED AND VENTED UNPAVED CRAWL SPACE	287.00	270.00	557.00
12	SEALED FLOOR-WALL JOINT, SEALED AND VENTED SUMP, ISOLATED AND VENTED UNPAVED CRAWL SPACE	768.75	402.30	1171.05
16	INSTALLED AUTOMATIC TIMER ON EXISTING AIR TO AIR HEAT EXCHANGER	80.00	60.00	140.00
19	VENTED BASEMENT AIR WITH SMALL AIR-TO-AIR HEAT EXCHANGER	375.00	>79.19	954.19
21	SEALED FLOOR-WALL CRACK AND SILL, SEALED CINDERBLOCK WALL, SEALED AND VENTED SUMP	869.00	376.00	1245.00
26	SEALED CRACKS AND SUMP, MODIFIED AIR CIRCULATION SYSTEM	300.00	104.99	404.99
28	VENTED BASEMENT AIR WITH AIR-TO-AIR HEAT EXCHANGER	393.75	767.62	1161.37
29	WHOLE HOUSE VENTED WITH AIR-TO-AIR HEAT EXCHANGER	450.00	603.70	1053.70
31	VENTED SUB-SLAB IN TWO AREAS	310.00	125.00	435.00
37	SEALED AND VENTED SUMP, SEALED FLOOR WALL CRACK	273.75	235.76	609.51
41	SEALED BASEMENT OPENINGS	225.00	71.65	296.65
51	SEALED FLOOR DRAIN	10.00	5.00	15.00
56	ISOLATED CRAWL SPACE, VENTED BASEMENT AIR WITH SITE-BUILT AIR-TO-AIR HEAT EXCHANGER	553.13	223.86	776.99
MEAN COSTS ± STANDARD DEVIATION		358 ± 243	276 ± 239	640 ± 422

[a]LABOR COSTS ARE THOSE ASSOCIATED WITH THE INSTALLATION OF THE CONTROL TECHNIQUES AND DO NOT INCLUDE THE RESEARCH REQUIRED TO MONITOR AND DESIGN THE CONTROL TECHNIQUES.

TABLE IV. RADON PERMANENT CONTROL EVALUATION RESULTS FOR HOUSES WITH NO CONTROL TECHNIQUES

HOUSE NUMBER	PHASE	MONITORING PERIOD	INDOOR RADON CONCENTRATIONS (pCi/l) BASEMENT	FIRST FLOOR	SECOND FLOOR
07	I	07/19/82-04/28/83	1.2	0.5	-
07	I'	09/20/83-11/01/83	-	2.4	-
07	IV	02/03/84-05/07/84	8.3	0.6	-
09	I'	08/06/83-10/29/83	-	2.3	-
09	IV	02/03/84-05/07/84	2.3	0.6	-
22	I	08/17/82-02/22/83	2.2	0.9	-
22	I'	08/03/83-10/28/83	1.8	1.0	-
22	IV	02/02/84-05/01/84	4.1	2.2	-
30	I	08/27/82-04/09/83	4.5	2.5	-
30	I'	08/12/83-11/01/83	2.4	1.3	-
30	IV	02/10/84-05/14/84	3.3	3.5	
49	I	09/29/82-04/09/83	-	2.3	1.6
49	I'	08/20/83-11/01/83	-	1.5	1.4
49	IV	02/08/84-04/28/84	-	1.8	-
55	I	10/11/82-01/19/83	2.5	-	-
55	I'	08/13/83-11/10/83	0.9	-	-
55	IV	02/09/84-03/15/84	5.7	-	-
59	I	11/01/82-06/09/83	-	-	3.1
59	I'	08/21/83-11/20/83	3.0	1.7	2.1
59	IV	02/03/84-04/28/84	4.2	2.9	-

TABLE V. RADON PERMANENT CONTROL EVALUATION RESULTS FOR HOUSES WITH INSTALLED CONTROL TECHNIQUES

HOUSE NUMBER	PHASE	MONITORING PERIOD	INDOOR RADON CONCENTRATIONS (pCi/l)		
			BASEMENT	FIRST FLOOR	SECOND FLOOR
02	I	06/25/82-12/06/82	4.8	4.4	-
02	I'	09/09/83-11/15/83	9.0	11.7	-
02	IV	03/27/84-04/27/84	3.5	3.6	-
05	I	07/12/82-12/23/82	16.6	7.6	5.3
05	I'	08/24/83-11/15/83	16.2	8.6	8.4
05	IV	03/09/84-05/01/84	3.0	1.8	1.6
12	I'	09/18/83-11/19/83	18.3	5.4	12.9
12	IV	03/09/84-04/26/84	2.9	0.8	1.4
16	I	03/18/83-07/23/83	-	0.5	0.4
16	I'	09/05/83-11/09/83	-	2.4	2.7
16	IV	04/09/84-05/02/84	-	2.4	0.8
19	I	08/12/82-06/08/83	17.7	2.5	-
19	I'	08/06/83-11/01/83	19.9	1.6	1.4
19	IV	03/13/84-04/26/84	12.1	2.5	3.0
21	I	08/16/82-12/20/82	49.8	15.0	12.7
21	IV	03/12/84-04/26/84	1.4	0.9	0.6
26	I	08/24/82-04/08/83	11.3	8.6	6.4
26	I'	08/06/83-10/29/83	5.9	6.7	2.6
26	IV	03/06/84-05/05/84	9.1	4.1	4.2
28	I	08/25/82-04/09/83	9.3	5.9	3.6
28	I'	09/11/83-11/01/83	-	1.9	-
28	IV	03/29/84-04/30/84	4.8	1.4	1.5
29	I	08/26/82-04/19/83	7.4	7.6	-
29	I'	08/07/83-10/29/83	0.8	1.3	-
29	IV	03/07/84-04/30/84	2.3	3.7	-
31	I'	10/07/83-11/26/83	-	15.5	-
31	IV	03/26/84-04/26/84	2.0	1.3	-

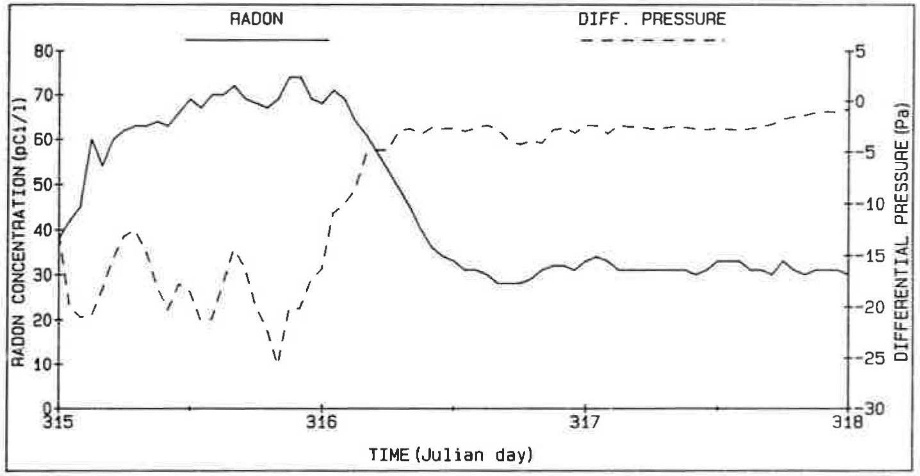

Figure 1. Effect of differential pressure on radon concentration (before control technique installed) in house 37.

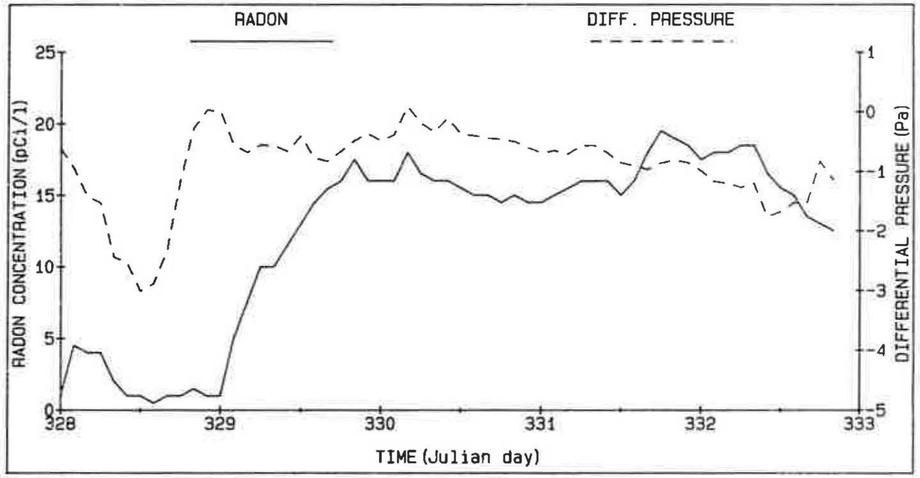

Figure 2. Effect of differential pressure on radon concentration (before control technique installed) in house 05.

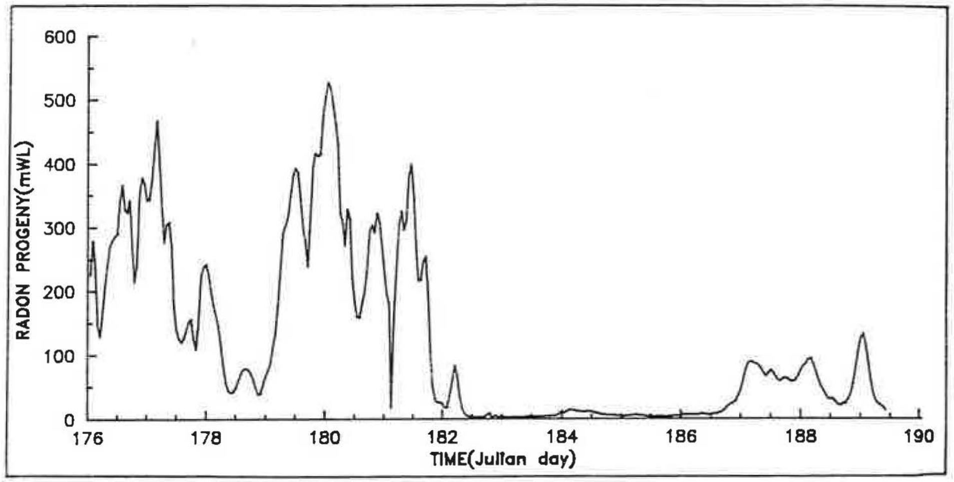

Figure 3. Effect of sump venting (Day 182 to 190) in house 21.

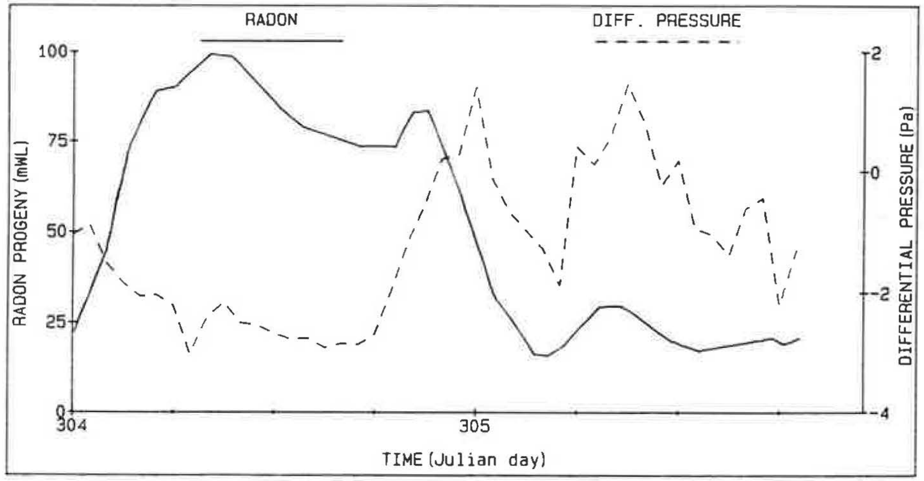

Figure 4. Effect of Differential Pressure on Radon Progen y in house 21 with sump venting.

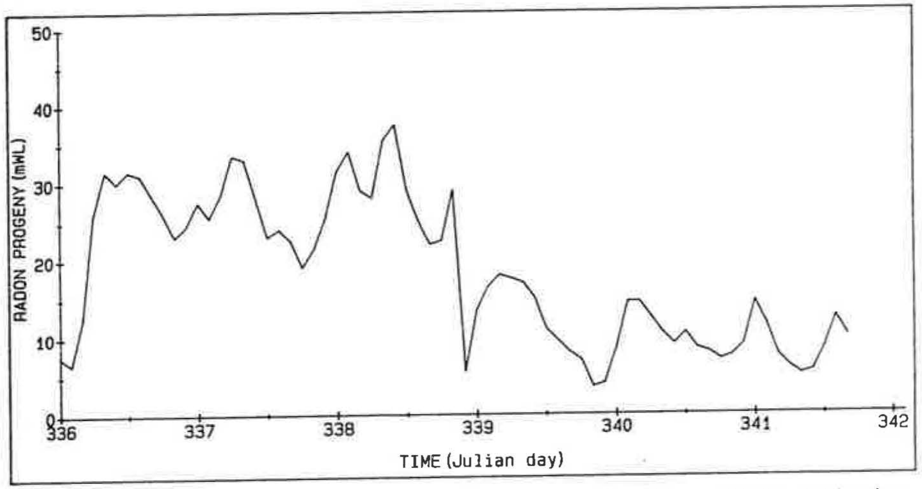

Figure 5. Comparison of the effect of sump venting (day 336 to 342) with sumping venting and sealing cracks and holes (day 339 to 342) in house 05.

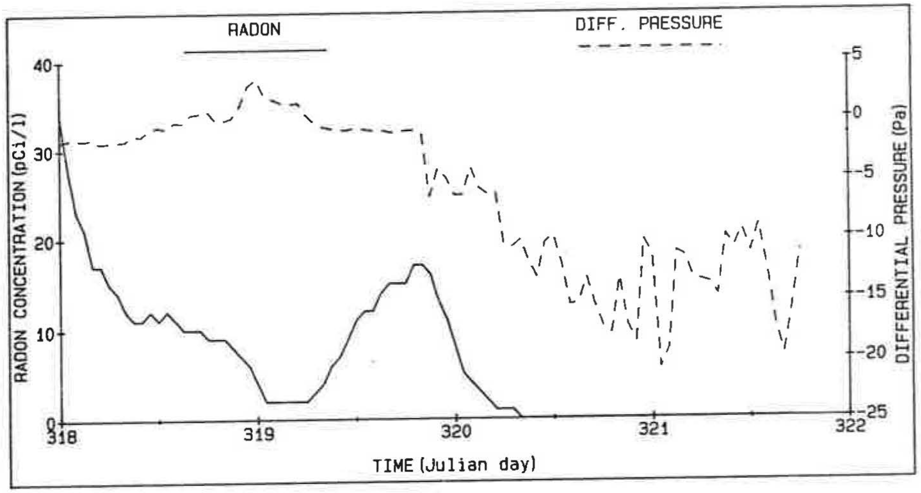

Figure 6. Effect of sealing cracks and holes (day 318 to 322) and venting sump (day 320 to 322) in house 37.

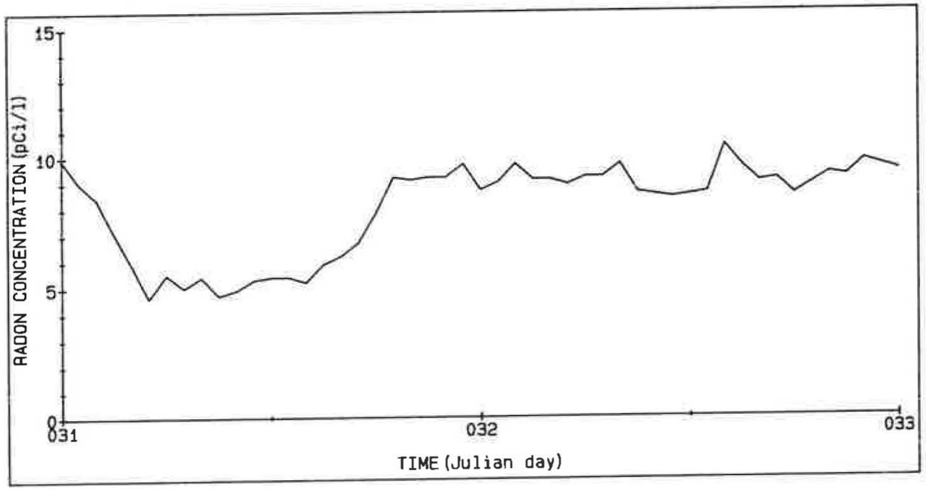

Figure 7. The effect of an air-to-air heat exchanger in house 31. The heat exchanger was on for the first nine hours in this graph.

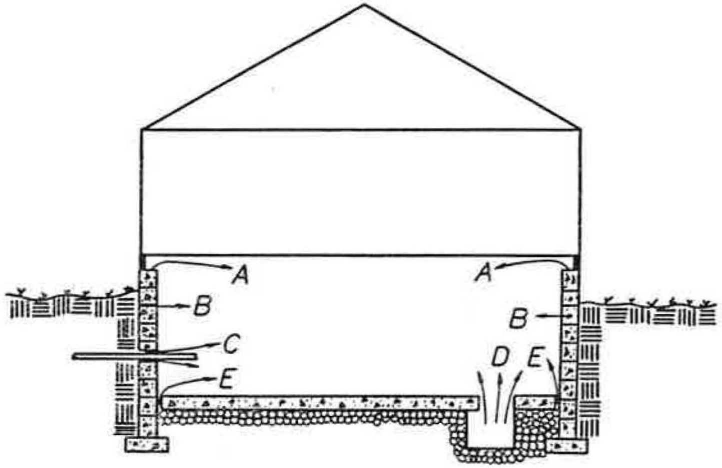

Figure 8 . Illustration of openings and cracks that need to be sealed to prevent radon entry and ensure the effectiveness of sub-slab ventilation. Radon entry points include unsealed concrete block tops (A), unsealed concrete block walls (B), around pipe penetrations (C), unpaved floor openings (D), and floor-wall drains or cracks (E).

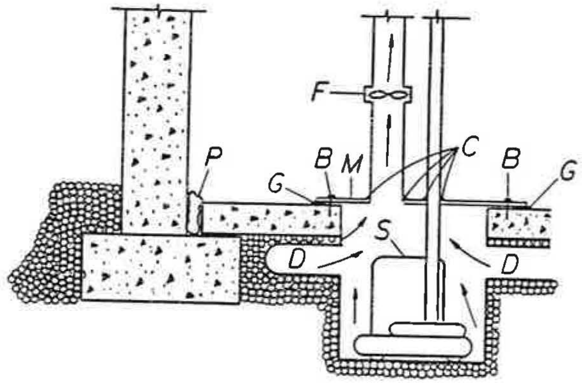

Figure 9 . Sub-slab ventilation using an existing sump and sub-slab drain-pipes. If the sump-pump is not submersible it is replaced by one (S). A negative pressure with respect to the basement (and the outside) is induced in the sub-slab by a fan (F) in a PCV pipe drawing radon from the sump and sub-slab via the drain pipes (D) to the outside. The plywood cover (M) is made removable by bolts (B). Gaskets (G) around the perimeter of the cover and caulking (C) at the PCV pipe and the sump pipe ensure air tightness. Also openings (P) from the sub-slab to the basement, are sealed with polyurethene foam to avoid short-circuiting of air directly from the basement to the outside.

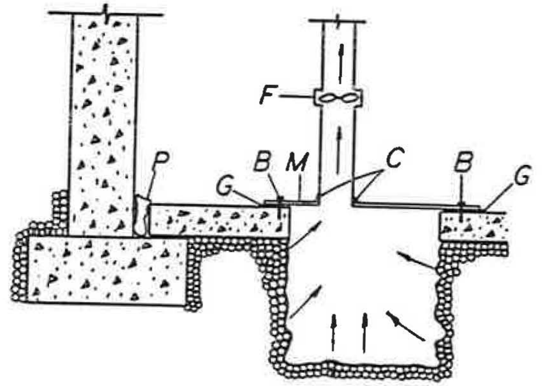

Figure 10 . Sub-slab ventilation using an opening cut through the slab and into the sub-slab gravel. This is simpler than the case of a sump in a sump opening but more than one opening may have to be made to ensure complete sub-slab ventilation without sub-slab drainpipes.

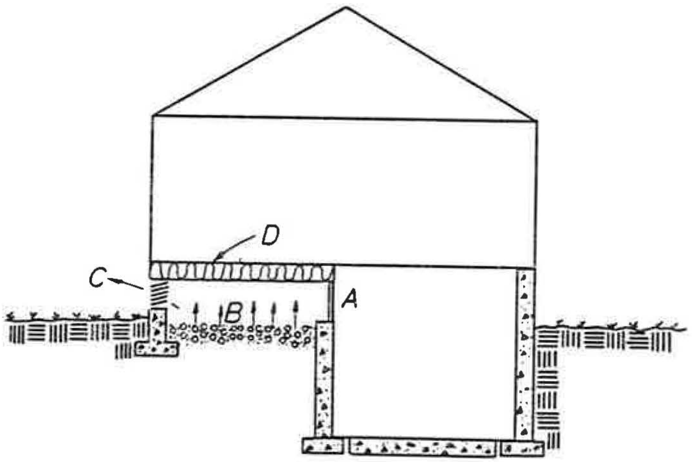

Figure 11 . Illustration of radon isolation and ventilation control technique. A partition (A) is constructed to isolate the crawl space from the basement. The radon (B) from the unpaved crawl space is then ventilated to the outside through an opening (C) constructed in the crawl space wall. To maintain energy efficiency the crawl space (D) is sealed with a vapor barrier and insulated.

PRELIMINARY EVALUATION OF FORMALDEHYDE MITIGATION STUDIES IN UNOCCUPIED RESEARCH HOMES

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The effectiveness of retrofit formaldehyde (CH_2O) mitigation measures for energy efficient homes is being investigated in unoccupied research houses constructed according to East Tennessee building codes. Formaldehyde emissions from carpet-covered, particleboard underlayment throughout these houses have frequently caused indoor CH_2O concentrations to exceed 0.1 ppm comfort guidelines, particularly during warm and humid seasons. The effectiveness of carpet and cushion, vinyl linoleum, and polyethylene vapor barriers over the underlayment have been compared with increased ventilation for reduction of indoor CH_2O concentrations under controlled 23°C and 50% relative humidity (RH) conditions. Approximate 2 to 2.5 fold reductions in CH_2O concentrations were achieved with the linoleum and polyethylene barriers. Simple steady-state models predict that sevenfold increases in air exchange rate would be required for comparable improvements in CH_2O levels. In contrast, common nylon carpet and urethane foam cushion flooring materials were ineffective in reducing CH_2O levels.