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Modelling Multiple Radon Entry and Transport in a Domestic Dwelling

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With a commercial program, BREEZE, a model was developed to study the radon entry and migration in a domestic house with a cellar. Its robustness was tested by examining the model's function for a range of inputs and comparing calculated results with a set of data measured in a real house. Also modelled was a mechanical ventilation system in the cellar, hence the cellar ventilation was investigated as a radon remedial measure. The modelling carried out in the research suggests that careful attention is needed in radon mitigation in such houses due to the functional and structural characteristics of cellars. It reveals that cellar ventilation can be an effective solution to indoor radon problems in such houses. It also shows that a simple model can represent a complex problem with a certain degree of accuracy. © *1997 Elsevier Science Ltd.*

INTRODUCTION

A domestic radon problem normally involves radon entering into a house via multiple entry routes and transport between all rooms. Computer modelling therefore has two tasks: simulating radon entry from the soil and predicting concentration distribution in all rooms of the house. It is essential to address both the above tasks, particularly in modelling houses with cellars, which are common in older dwellings in the North of England (Fig. 1). The cellar in such a house is normally underneath a part of the house. Radon from the soil can enter the cellar and then pass to the upper part of the house. It can also enter directly into the upper part through the ground floor [1]. However, these two modelling tasks have not been implemented simultaneously in existing models using either CFD or nodal-network techniques. In CFD models, houses are simplified as a single space which can be specified as one of the boundary conditions in the computational domain. The main interest is in studying the mechanism of radon entry through certain substructures and impacts of various parameters on radon entry, such as those of environment and measurable properties of soil [2, 3]. Hence those models do not tackle problems which involve air movement in multiple nodes [4]. The nodal-network models, on the other hand, simplify the radon source and focus at radon migration, predicting the inter-node flow rates and radon concentrations in rooms of a building. A multi-cell model developed in the National Institute of Standards and Technology (NIST), Gaithersburg, U.S.A. is an example of this approach [5]. It simulates radon migrating within rooms in large multi-storey buildings. This model simplifies the radon entry, a complex phenomenon, by assuming that radon entry is linearly proportional to the differential pressure between the basement and outdoors [6]. This assumption, however, is not supported by measurements in two single-family houses with basements when the pressure is over 4 Pa [7]. Further, it is not supported by the computer simulation with high disturbance pressure and high soil permeability [8]. More importantly, in the NIST model the basement is the only source of indoor radon, which is very different from the cellar in a domestic house. A new model for such a house is therefore required.

Another motive to develop a new model was that there is a lack of knowledge on radon problems in such types of house. The particular interest is in the effectiveness and mechanism of cellar ventilation, a proposed radon reduction measure in such houses. The measure provides extra ventilation to the cellar by increasing natural ventilation, or installing a fan system in the cellar. This mechanical system can either depressurise the cellar and perform extract ventilation, or pressurise it and perform supply ventilation. Although a field study was conducted in an occupied house with a cellar to test this measure, the study has yielded a very limited number of reliable results owing to the restricted access to the house [1]. A new model that simulates the cellar ventilation can be used to explain and expand upon the limited number of experimental results. It can also be used to determine the mechanism behind the remedial measures and help to establish a good ventilation strategy.

This paper presents an attempt at developing the model of the house, which involves multiple radon entry through its substructure and transport to the rooms. The method and procedure applied in the model development are described in the next section of this paper. This is followed by the results of the model's performance as a part of the model's verification and a set of comparisons between the calculated results and the results measured in the real house. Simulation results of five typical ven-

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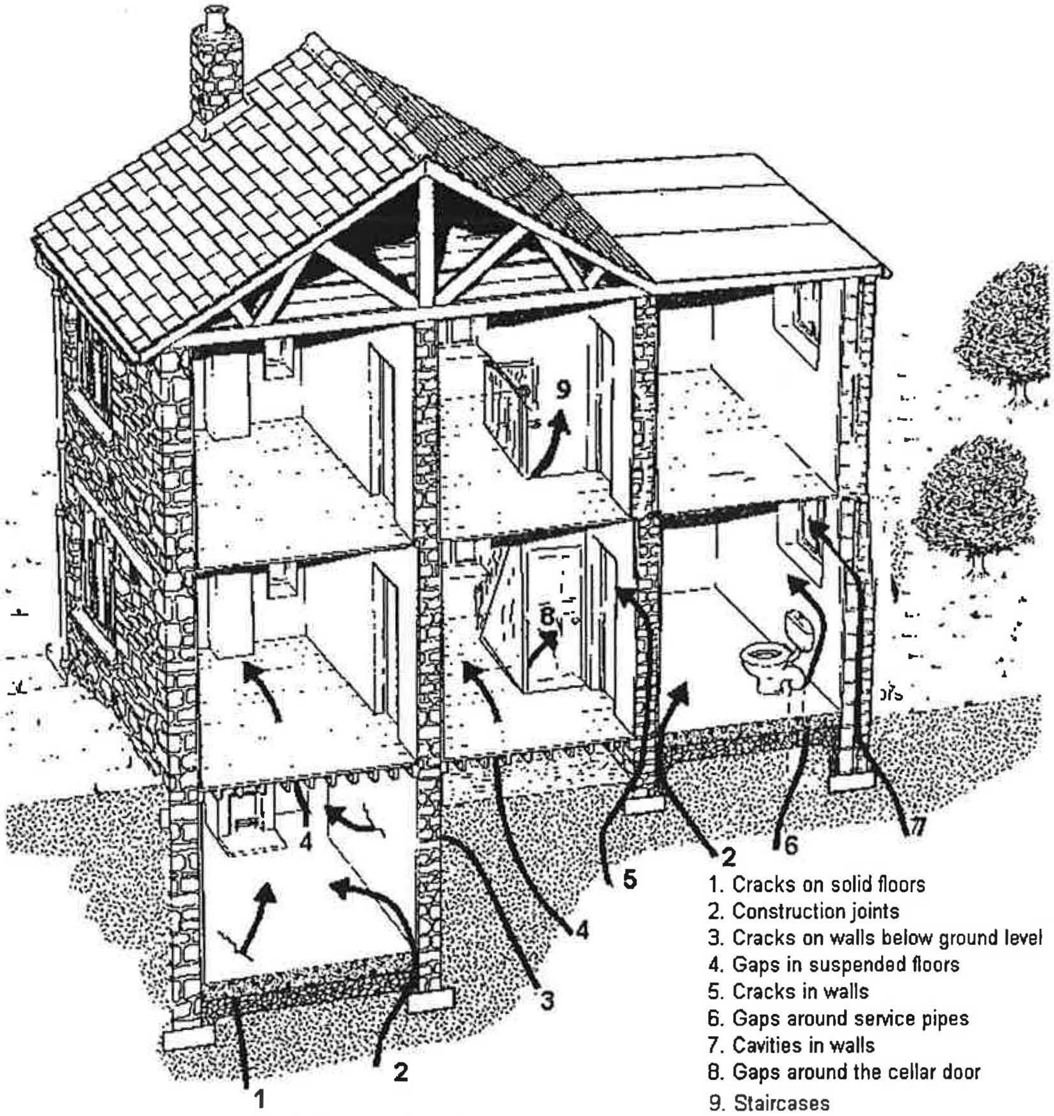


Fig. 1. Radon entry into a domestic house (courtesy of DOE).

tilation conditions are also presented. The conclusions are presented at the end.

METHOD

A commercial program, BREEZE [9], was used in the model development. On the basis of a nodal-network approach, the program calculates inter-zonal airflow and contaminant dispersal in multiple zones of a building and predicts the building's infiltration characteristics and contaminant distribution features. The model was set up according to the configuration of the real house, including all rooms, windows, doors and the fan system in the cellar. In addition to these basic calculations, the main effort in the model development was to enable it to simulate the following three processes that BREEZE cannot specify: (1) air flow and aerosol contaminant moving between two floors via staircases (Fig. 2); (2) air flow and contaminant travelling through vertical cracks on the ground floor; and (3) variable radon entry that depends on differential pressure and radon concentration in the soil.

The staircase was modelled by creating three separate shafts (S1, S2 and S3 in Fig. 3). Each one links two neighbouring floors only. Figure 2 shows a section through the staircase on one floor. Figure 2a shows the air movement in a real house. Figure 2b is a simple shaft defined in BREEZE, through which contaminant passes. Figure 2c shows two separate shafts created in the model. Radon gas enters from downstairs and, before it goes upstairs, it pollutes the landing and consequently the other rooms on the same floor either by wind disturbance or flow circulation created by a stack effect.

Vertical cracks on floors cannot be modelled in BREEZE. The cracks on the ground floor, the radon entry routes, were modelled by combinations of vertical shafts and horizontal cracks. Three small shafts were created between the ground floor and the cellar or the soil, linked by three pairs of cracks (C1, C2 and C3 in Fig. 3c and d). Then the air flow and radon movement via these paths could be calculated.

The most important part of the development was that it created a radon source in the model. The source provides variable entry rates to the cellar and the upper part of the

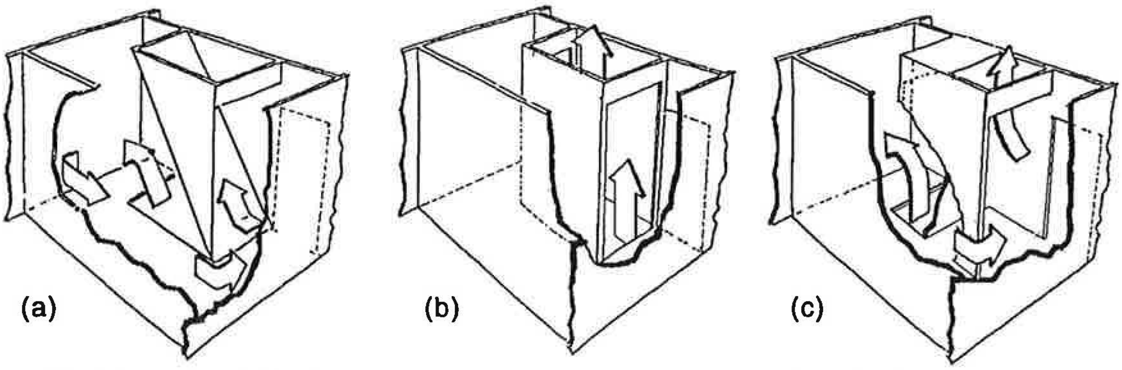


Fig. 2. One section of the staircase on the middle floor of the house. There is one single shaft in the old model, in which air flow passes through that floor. Two separate shafts link the upper and lower floors, respectively. (a) Staircase and landing; (b) single shaft in the old model; (c) two shafts in the new model.

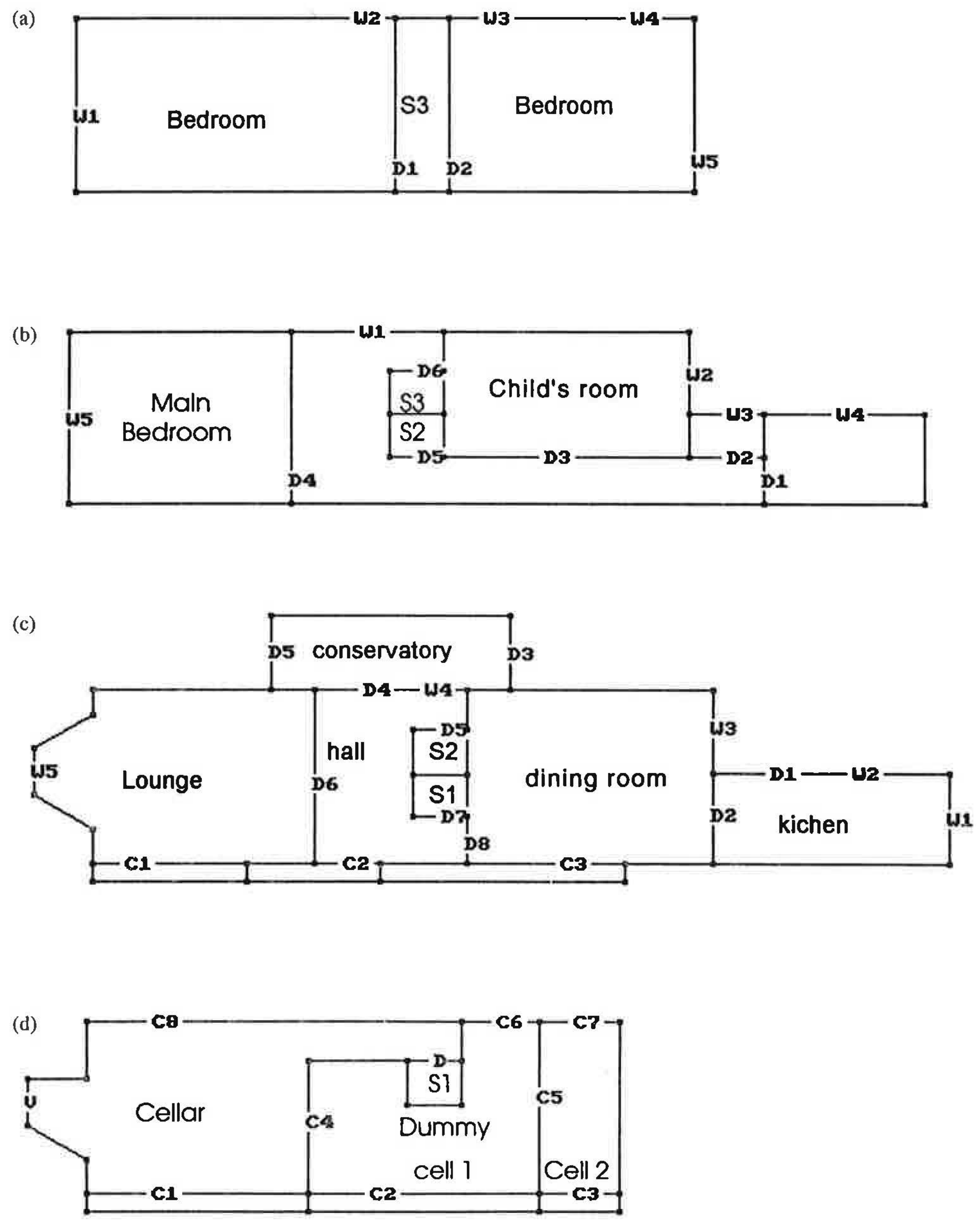


Fig. 3. The floor plans of the model with two dummy cells.

house whilst BREEZE only specifies constant pollutant feeding rates. The radon source is made of two dummy cells with different feeding rates and linked by cracks with the outdoors, the cellar and the living area. Dummy cell 1, next to the cellar, has a lower feeding rate and represents the soil adjacent to the substructure of the house. The cell plays a role as a buffer zone in the source, where concentration and pressure are affected directly by the conditions in the cellar. The other one, DC2, represents the soil, where the concentration is less influenced by the pressure in the cellar. A linking path, C5, keeps the concentration and pressure different in the two cells, which to some extent represents the concentration and pressure gradient in the soil. Two other cracks, C2 and C3, allow the source to release radon to the living area constantly as a result of the depressurisation of the house in all ventilation conditions. This part of entry is called direct entry in later discusion. Along with the variable feeding rates, a fixed feeding rate is set to the cellar to reflect the molecular diffusion on the surface of the walls and floors, which is relatively independent of the pressure [10].

The air flow rates through all closed external windows and doors and leakage of the roof and cellar were calculated to represent the infiltration characteristics of the house. The input data for these air paths were taken from the Air Infiltration Calculation Techniques Guide [11] or estimated visually. All wind pressure coefficients were from scale model tests carried out at the Building Research Establishment, Garston, U.K. [12]. The leakage of the cellar to the outdoors was via a crack, C8, on the cellar wall. The wind pressure coefficients at soil surfaces were assumed to be zero to minimise the influence of air flow near the ground.

Other input data were set according to the field study. The dominant direction of wind was from the southwest during the period of the field tests. Its speed for the modelling was set to 0.5 m/s to represent the average effect during the period. The ambient temperature was set at 5°C while indoor temperatures were 10, 18, 16 and 16°C in the cellar, the ground floor, the first floor and the top floor, respectively. Typical domestic heat gains were set to most rooms to create a two-way air change through large openings such as doors, hence the contaminant tends to be evenly distributed on both sides of each opening. All internal doors were fully open except the cellar door. The input data to the two dummy cells were calibrated with the results of the tests. This parameter adjustment was because of the fact that none of these data is available for this simplified representation of radon source. A range of ventilation conditions for the modelling was defined by the measured data from the field tests. In the field tests, the fan system created cellar ventilation from full flow extract to full flow supply. The air change rate in the cellar varied from −9.0 to 9.6 ACH accordingly. The negative means the fan extracts air out of the cellar whilst the positive means the fan draws air into it.

Model validation was carried out in two parts: testing the model's performance by varying some crucial input data, and comparing the predicted results with those measured in the field tests under the same conditions. In the performance test, the two input variables were the wind speed and the ventilation rate of the cellar. The physical function of the dummy cells was examined under these conditions. The output parameters being examined were radon concentration in the cellar, the average radon concentration in the living area (ACILA) and radon entry rate into the cellar. As the first two parameters were also measured in the field tests, the results from the two approaches were compared within the range of ventilation conditions.

Using the model, five typical ventilation conditions were simulated. The radon distribution and the mechanism of the system in reducing indoor radon could be examined. Hence the effectiveness of each ventilation mode was evaluated, which could be helpful to propose a ventilation strategy in such a house to reduce indoor radon levels. Specifically, the differential pressure between the cellar and the outdoors, ΔP_{cell}, was calculated, in order to study the impact of the ventilation system on this parameter, drawing soil gas into the cellar. Another differential pressure across the envelope of the house at ground floor level, ΔP_{house}, was also calculated under the ventilation conditions. It introduced radon from the soil underneath the floor into the living area.

RESULTS AND ANALYSIS

Model's performance test

This test was carried out within the range of ventilation conditions. The wind speed was 0.5 m/s according to the field tests. According to the modelling, the differential pressure between the cellar and outdoors (ΔP_{cell}) varied from −22 Pa to 18 Pa corresponding to the range. The radon concentration in the cellar and the average concentration in the living area (ACILA) were calculated. The curves of the concentrations are plotted against the differential pressure in Fig. 4. Within the range, there were some critical stages, as follows.

1. Deep depressurisation: $\Delta P_{cell} < -2.9$ Pa; it drew radon from the soil, air from the ground floor and a certain amount of outdoor fresh air owing to the leakage of the cellar. As ΔP_{cell} increased, radon entry did not drop significantly. The air change rate decreased. Hence radon level rose. When $\Delta P_{cell} = -2.9$ Pa, there was no air change in the cellar, and radon built up to an extremely high level.
2. Mild depressurisation: $-2.9 < \Delta P_{cell} < 0.0$; less radon was introduced, yet outdoor fresh air started to come into the cellar via the system. Hence radon was diluted and its level dropped.
3. Pressurisation stage: the fan system produced a positive pressure in the cellar which prevented soil gas entering the cellar. The concentration in the cellar was caused only by diffusion. The level was constantly low.

Also examined was the flow rate through the crack linking the cellar with the soil and the convective radon entry, which equals the multiple of flow rate through and radon concentration in the soil. Figure 5 shows a linear relationship between flow rate through the crack and the differential pressure, as defined in BREEZE. The curve of radon entry rate vs. differential pressure is plotted in Fig. 6. It reveals an exponential trend as other articles suggest

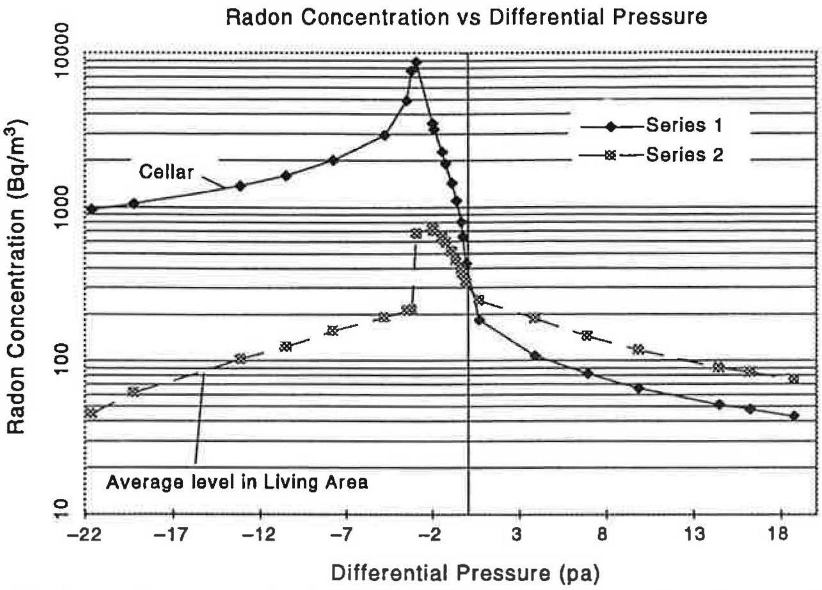


Fig. 4. Calculated radon concentration levels vs. differential pressure between the cellar and outdoors.

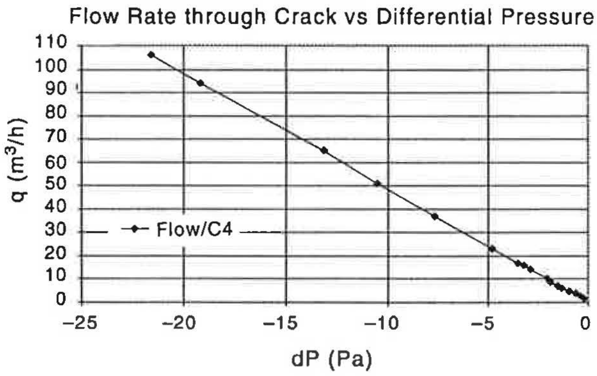


Fig. 5. Flow rate through crack 4 vs. differential pressure between the cellar and outdoors.

[4, 8]. These curves can be compared with those from CFD models for quantitative verification.

Another test was conducted to examine the behaviour of the model when the wind speed changed. The test shows the modelling results were also reasonably good when the wind speed was lower than 0.5 m/s but unacceptable when it was higher than 1.0 m/s. The reason might be the simplification of the radon source. The two empty cells were too simple to model accurately the ground soil, a porous medium with very low permeability.

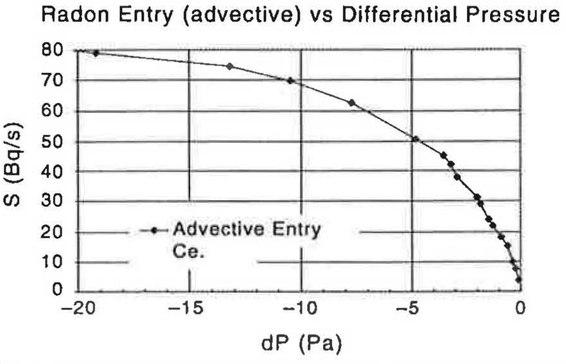


Fig. 6. Radon entry rate through crack 4 vs. differential pressure between the cellar and outdoors.

Comparison between calculated and measured results

Results from both the field tests and the modelling are compared again within the range of ventilation conditions and shown in Fig. 7. The comparison between the calculated radon levels in seven rooms with their measured correspondents shows that the consistency is generally good. Of 53 pairs of data, 10 standard deviations are less than 10%; 19 deviations are less than 20%: 27 less than 50%, and seven have extreme values. There is a good agreement between the measured and the calculated results on the side of negative air change rate and small positive air change rate. A discrepancy occurs at medium positive air change rate. Although the good agreement is due to the fact that the modelling input was calibrated by measured results, the simple radon source in the model, to some extent, presented the ground soil containing radon gas. For the discrepancy, there were four causes: the deviation of measured values; the estimation of parameters used in the model; the simplification of environment conditions; and the simple presentation of the radon source. In the field tests both radon and ventilation were not measured precisely; for example, the monitor gave between 10 and 50% variation to each reading. In the modelling, the data input were not accurate. The wind fluctuation in the field tests was ignored in the modelling. The most significant source should be again the simplified radon source. Obviously, the two dummy cells could not accurately represent the infinite nature of ground soil.

Although other reasons for the discrepancy are not yet clear, the generally good agreement indicates that the model had a good performance in extract ventilation, natural ventilation and even in full flow supply ventilation. The curves of concentration in the cellar indicate that there was a turning point representing a very critical stage. As discussed previously, the air change in the cellar was zero at the point, hence the radon level became very

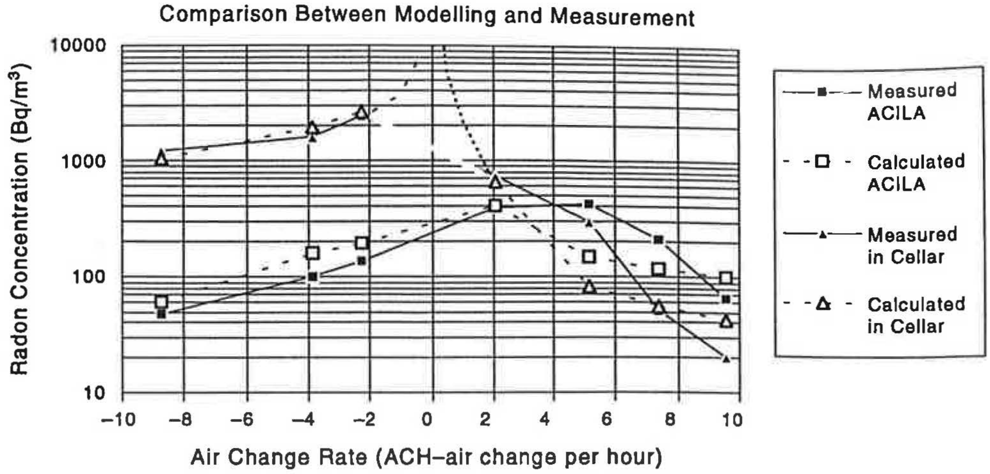


Fig. 7. Radon concentration in both the cellar and the living area under various air changes of supply and extract ventilation.

high. The extreme high concentration was calculated in modelling although not measured in the field testing (Fig. 7). Figure 5 also shows that at this stage the differential pressure, ΔP_{cell}, was about -2.9 Pa. Under this condition, no inter-zonal flow passed through cracks linking the cellar and the ground floor. Radon in the living area was only a consequence of direct entry from the soil through the cracks linking the ground floor and the soil.

Modelling radon distributions

The five typical ventilation conditions simulated were: extraction with high and low air change rates; natural ventilation with a small window in the cellar; and supply with high and low air change rates. Their results are presented in Fig. 8. The fresh air flow into the upper floors of the house is shown in the top right-hand corner under each condition. Above there is the air change rate of the whole house.

The diagrams show that the radon concentrations in all rooms above ground level tended to be at the same level in most conditions. Radon was evenly distributed, to some extent, except in full extract ventilation that reversed air flow in the staircase and resulted in zero concentration on the two top floors. On the other hand, in most simulations, the levels in the cellar were very different from those in the other rooms. This suggests that a single figure, ACILA, could describe the radon problem in the house and reflect the radon hazard to the residents, as the normally occupied place in such type of houses is the living area only. Therefore this parameter should be the crucial factor in radon mitigation rather than the level in the cellar, an intermittently or even seldom-used space. This could also be true in other houses of the same type.

These diagrams also show a leakage of the cellar to outdoors, which was a crucial air flow path in the house. It provided an easier air inlet for a depressurised cellar than the perimeter crack around the cellar door, because the pressure difference between the cellar and outdoors was larger than that across the cellar door. A proper amount of leakage in the cellar could prevent spillage if there was an open-flued appliance in the living area. Further study on this area can again be based on this model with some modification, such as creating another shaft to simulate a chimney.

The mechanism of cellar ventilation

The modelling also reveals how the mechanical system in the cellar reduced the radon in the living area. The differential pressure across the envelope of the house at ground floor level, ΔP_{house}, varied within a small range under all ventilation conditions. As the system extracted less and less flow, the pressure rose from -3.7 Pa to -3.2 Pa. In natural ventilation, it was about -3.0 Pa. When the system increased the air supply to the cellar from low flow to high flow, ΔP_{house} increased further from -3.0 Pa to -2.5 Pa. This reveals that the living area was constantly depressurised in all conditions. More radon was drawn into the living area in extract ventilation than in supply. The extract ventilation reduced the radon in the living area mainly by preventing radon going from the cellar into the living area. Additionally, it increased the air change rate in the living area by increasing the depressurisation in that area, although not significantly (Fig. 8b and c). The supply ventilation, on the other hand, reduced ACILA in another way. It reduced the pressure, ΔP_{house}, so that radon entry into the living area decreased. Also it pressurised the cellar and stopped radon gas coming into the cellar. Hence when it blew air from the cellar into the living area, the air carried much less radon, and yet it also increased air change rate in the living area.

Reversed radon concentration distribution

A reversed radon distribution in the house, observed in the field tests, was also found in the computer modelling. The radon levels in the living area were higher than that in the cellar under supply ventilation with medium air change in the cellar (when ACH>4 in Fig. 7). The same phenomenon was also found by Cavallo *et al.* in a house with full-sized basement [13]. They suggest that the basement wall could be an additional route for radon passing from the basement into the upper part of the house, although no further study has been done. In the house with a cellar, this reversed contribution was due to the direct radon entry, as discussed previously. This direct

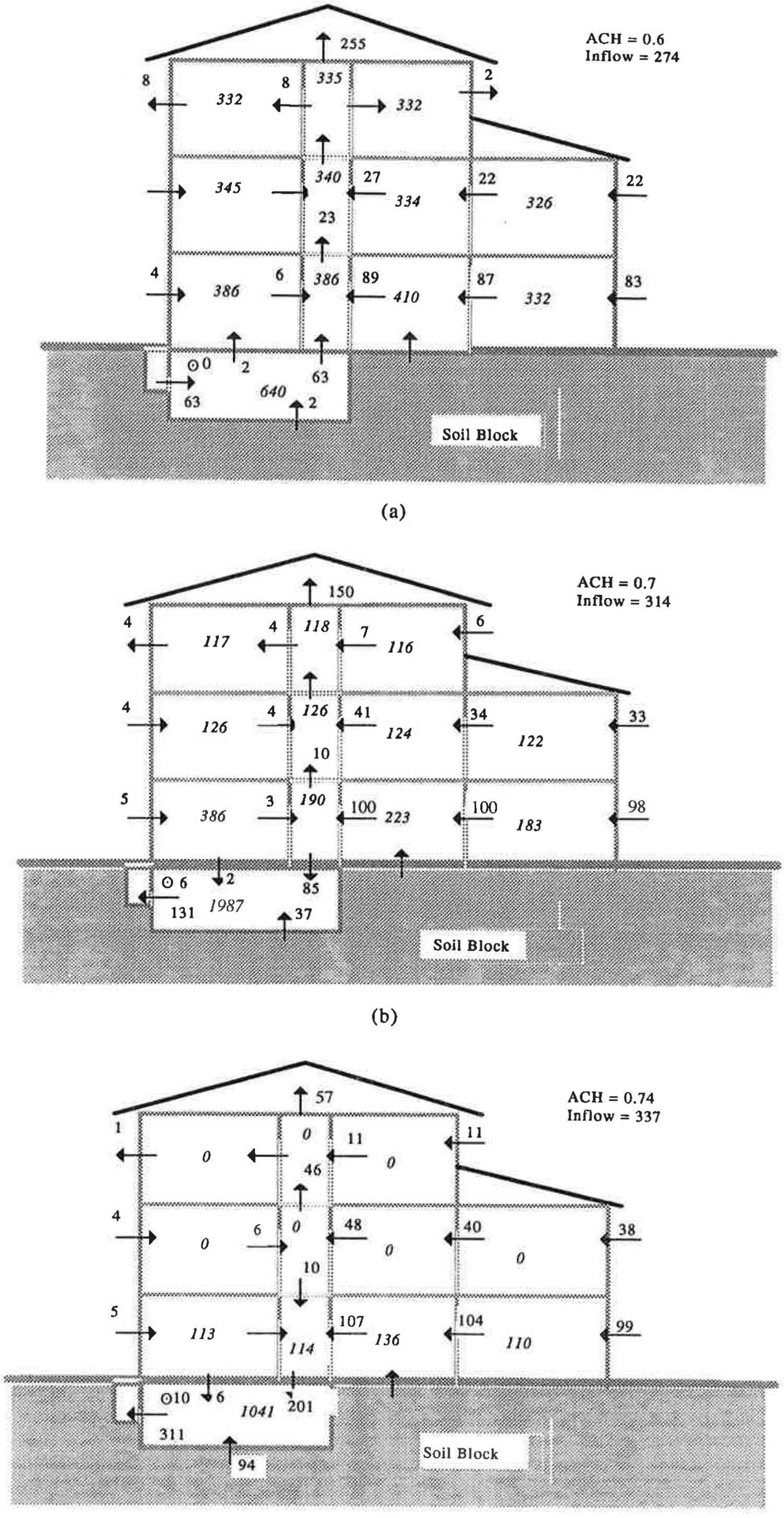
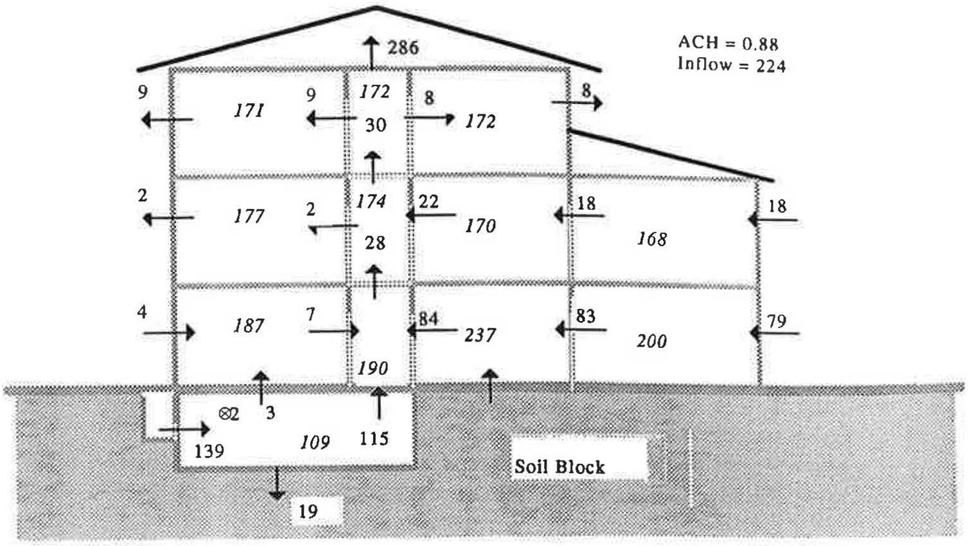
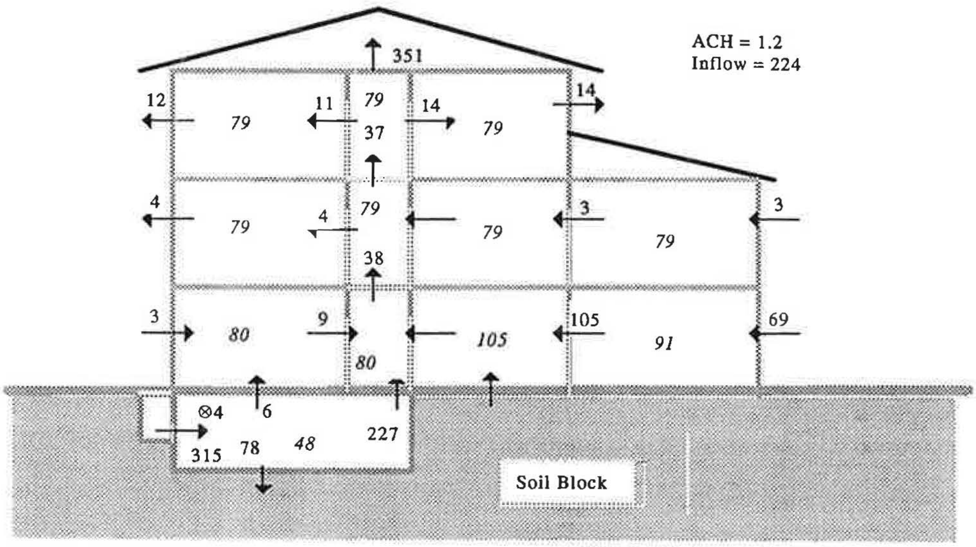


Fig. 8a–c. *Caption overleaf.*



(d)



(e)

Fig. 8. Modelling results—radon concentration and air flow rates in the house under various ventilation conditions: (a) natural ventilation; (b) low ACH extract ventilation; (c) high ACH extract ventilation; (d) low ACH supply ventilation; (e) high ACH supply ventilation. Italic numbers present the concentration levels (in Bq/m^3); arrows and numbers present the flow direction and value (in m^3/h), respectively; an arrow without a number means that the value is less than 1. In top right corner, the air change rates of the house (cellar excluded) and outdoor air into part of the house are given. ⊗ means the air flow is from the cellar to outdoors and ⊙ means the air flow is from outdoors into the cellar owing to the cellar's leakage to outdoors. The values are not balanced as some paths of flow are not shown on the diagrams.

entry was via the cracks on the ground floor linking the living area with the soil underneath and contributed a significant portion of radon to the living area. If there was no direct entry and the cellar was the only route for indoor radon, the level in the cellar should be higher than those in the living area. This was confirmed in computer modelling. The reversed distribution disappeared when C2 and C3 were closed in all ventilation conditions. The existence of the direct entry results in difficulty for those conventional remedial measures that solve the radon problem in the basement but not that in the living area.

Ventilation strategy

Initial assessment of the three ventilation modes—extract ventilation, natural ventilation and supply ventilation—in terms of efficiency has been discussed elsewhere [1]. In this study the ventilation modes were examined in another way. In Fig. 9, there are three curves representing the three modes. The radon levels dropped as air change rate (ACH) increased. The figure also shows that it required a higher ACH in the living area in order for supply ventilation to reduce radon to the same level as for extract ventilation. Hence it introduced more cold air, which might raise other side-effects. Natural cellar

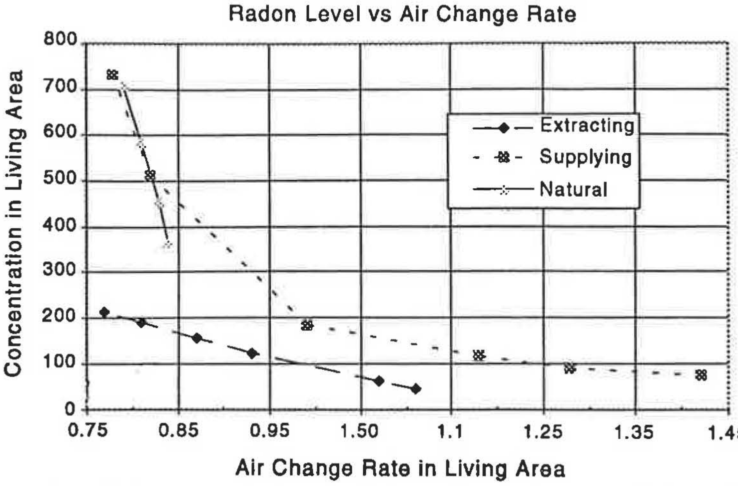


Fig. 9. Modelling various air change rates in three ventilation modes vs. radon concentration in the living area of the house.

ventilation again was found to be inappropriate in this type of house, although it did not increase the air change rate in the living area when the cellar window was fully opened. The additional infiltration in the living area owing to extract ventilation was the lowest. The impact of extract ventilation on the air change rate in the living area was the smallest. Therefore it was the most favoured solution.

CONCLUSIONS

Although the agreement between calculated and measured results did not give a robust physical validation and the agreement was due to the calibration with the experimental results, it shows that the performance of the model is acceptable and the dummy cells to some extent simulated the radon source. The expertise gained here could be used to develop models of other houses to carry out a qualitative study. It is hoped that the procedure and method in the model development could also be applied to handle other indoor pollution problems caused by soil gases, such as methane and other volatile organic compounds.

The modelling explained observations in the field tests and generalised, to some extent, the conclusions based on the limited number of measured results. It suggests that natural ventilation is not a effective mitigation solution in such houses and shows that both extract and supply ventilation are better solutions. Extract ventilation is more efficient than supply ventilation at low air change rates, hence is practically preferable owing to a low ventilation load. The modelling study also explains how the cellar ventilation reduces indoor radon and how the multiple radon entry routes cause difficulty for conventional radon remedial measures in such houses.

There are some other areas remaining for further research, such as the study on spillage. It could also be interesting to develop a more accurate radon source model using CFD approach and combine it with a multizonal house model to carry out a more realistic parametric study.

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