GEOLOGICAL INFLUENCES ON RADON IN HOUSES IN NOTTINGHAMSHIRE

by

A.C. Waltham

Summary

In the Gedling area, northeast of Nottingham, 85 houses were monitored for indoor radon levels. No value exceeded the Notification Level of 100 Bq/m^3. House construction and room ventilation are important influences on the radon levels. There are local radon concentrations in houses on fissured Permian limestones and on some horizons within the Triassic mudstones. High radon levels also occur in some of the artificial caves in the Triassic sandstones of Nottingham.

Introduction

Radioactivity is the emission of particles generated by the atomic disintegrations of the unstable isotopes of certain elements. It is a natural phenomenon of the world in which we live. Sources of radioactivity include outer space and various nuclear industries (contributing less than 1% of the total), but most originates within the ground. The major primary source is uranium-238 which is widely distributed, generally in small proportions, in some granites, some hydrothermal veins and some shales, and may also be present, but less abundant, in almost any other rock. Uranium-238 is an unstable isotope which decays through a chain of daughters until it eventually stabilises as lead (Fig. 1). This decay chain is dominated by solid, and hence generally immobile, elements, but radon-222 is a gas. Even though its half-life is short, radon can easily seep from the ground. Most radon diffuses into the atmosphere where it is diluted to irrelevantly low levels, but it can accumulate in poorly ventilated spaces—such as caves, house basements and even the living rooms of houses with leaky floors and sealed, double-glazed windows.

Radiation presents a threat to all forms of life, including man. The decay of radon-222 produces highly destructive alpha particles, which are only capable of travelling a few millimetres or centimetres; the danger to man from atmospheric radon is therefore infinitely small. But, the radon decays rapidly to polonium-218 and a chain of other daughters (Fig. 1). These solid particles attach to aerosols and dust particles and may get breathed in by man. They then may lodge in the lung lining. From there, the few milimetres travel of newly generated alpha particles is enough to let them enter the body tissue. The hazard is that these particles can fracture the DNA chains within cell nuclei, to a point beyond effective enzyme repair, so that cell mutations are produced—and these are the starting points for malignant cancer growth.

The absolute scale of radiation hazard to health—by radon or by any other factor—is open to medical debate, and many long-term effects remain unassessed. It is however beyond dispute that significantly improved health prospects are gained by reducing the total dose of radiation received from any source; this includes the unavoidable, natural, outdoors radiation dose, any dose received at work (limited to a small proportion of occupations, all tightly controlled by industrial regulations), and the dose received at home. The importance of house radiation levels was emphasized by the case of the Pennsylvania nuclear power plant worker who set off the site radiation detectors, not as he left work, but when he arrived from home in the morning (Brenner, 1989). His house proved to be unusually radioactive, due to radon migration, and since then house radon levels have been recognised as the source of a significant component of most peoples' radiation dose.

The standard unit of radiation measurement is the Becquerel, which is equal to one radioactive disintegration per second. Atmospheric radon can produce radioactivity levels of tens, hundreds or thousands of Becquerels per cubic metre of air—and this is how radon levels are expressed. The numbers may sound high, but a typical jar of coffee will have an activity level of 100 Bq. Alternative units of radon measurement are Working

Mercian Geologist, vol. 12, no. 2,
1991, pp. 79-86

Levels (based on a concept of what is acceptable) and Curies (the older unit, still used in America). The approximate conversion factors are:- 370 Bq/m^3 = 0.1 WL = 10 pCi/l.

Man is affected not just by the level of radiation, but by the accumulated dose gained from all sources. The dose is the product of radiation level and time, and is measured in either Sieverts or Working Level Hours.

Geological distribution of radon

The two primary factors influencing radon emissions from the ground are the concentration of parental uranium and the rock or soil permeability. Uranium content is normally high in granite, though there are considerable variations in level between different granites. Uranium characteristically migrates into the hydrothermal environment with consequent concentrations in mineralised veins, locally to the level where it may be economically mined. In the sedimentary environment, uranium is precipitated under reducing conditions, and is consequently enriched in some shale horizons and phosphatic limestones. The national surveys of house radon in Britain have identified the high radon levels in Cornwall and Devon, with the highest values on some of the granites, their mineralised peripheral zones and some areas of mine waste (Wrixon *et al*, 1988; O'Riordan, 1990). The same surveys have revealed other areas of high radon levels, on the mineralised limestones of Derbyshire, around some of the Scottish granites and on some Jurassic phosphatic sediments in Somerset and Northamptonshire; in all these areas radon levels are above the national average but are still orders of magnitude lower than those on the granites of Cornwall and Devon. The relationships of radon with granite and black shales is also clearly recognised in America (Hand and Banikowski, 1988; Brenner, 1989; Wilson, 1984).

Highly permeable rocks permit radon to migrate more rapidly from its rock source either into the atmosphere or into the confinement of a house. The greater fracturing of the Cornish granites may be partly responsible for radon levels being higher in houses on them than in houses on the less fractured Scottish granites. Any karst limestone may permit rapid radon migration through its fissures, to create anomolously high levels in overlying houses (Hawthorne *et al.*, 1984; Hand and Banikowski, 1988). This role is further demonstrated by the very high radon levels found in some sections of poorly ventilated limestone caves (Yarborough *et al.*, 1976). In part of one cave in the Derbyshire Peak District a radon level of over 80,000 Bq/m^3 has been recorded (Gunn *et al.*, 1989); the cave is the radon carrier, while the source may be either hydrothermal mineralisation, black shale horizons or interbedded phosphatic limestone. Soil permeability also has a significant influence on radon migration (Nazaroff and Nero, 1984), though the relationship between soil radon levels and house radon levels is complex (Nason and Cohen, 1987).

Even though bedrock properties have a clear influence on radon production and emission, household radon levels cannot simply be predicted from a geological map, because equal or greater influences are imposed by a wide range of other parameters, notably those related to house construction.

Radon in houses

Radon levels in household air depend on a range of factors including the bedrock sources of radon and the construction and ventilation of the house. The highest radon levels may be anticipated where radon may diffuse through a porous floor and then become trapped in poorly ventilated rooms. A multitude of factors within the house construction have very complex influences on the ultimate radon levels. Nationwide surveys within Britain have recognised that higher radon levels are more likely in houses with solid floors, double glazing, draught proofing and a lack of open windows (Wrixon *et al.*, 1988; Courtis, 1988). Also, radon levels are significantly lower in upper floors of houses, so that inhaling radon while asleep is usually less of a hazard than while awake. Conversely, radon levels are usually higher in basements, especially those cut into solid rock and left unlined, such as the sandstone 'caves' of Nottingham. House radon levels vary with the season, normally being reduced by open window summer ventilation, and are also influenced by pressure variations, set up by wind or forced heating, which can cause more radon to be drawn from the ground.

With respect to the hazard to human health, the main concern is with radon levels in the ground floor living areas. These are therefore the normal sites for measurement. If the radon level is high, remedial action may be appropriate. This may range from the sealing of floors and points of soil air entry, to forced, underfloor ventilation (DoE, 1990; Brenner, 1989). Such work can cost over £1000 per house; government grant aid is discretionary, with rather poorly defined limits (O'Riordan, 1990; Chevin, 1990).

The Action Level in Britain is 200 Bq/m^3 (reduced in 1990 to half its previous level in response to clearer perceptions of radiation hazards to health). This figure is based on 6 hours per day spent in the house ground floor living area giving an annual dose of 10 mSv, which is regarded as undesirable. A Notification Level of 100 Bq/m^3 warrants further monitoring, and a Priority Action Level of 800 Bq/m^3 warrants remedial action within one year. Less than 1% of houses in Britain exceed this Action Level, though their distribution is not uniform and rises to 12% of the houses in Devon and Cornwall (O'Riordan, 1990). Remedial action will involve substantial total costs, and modification of house construction methods is highly appropriate in certain parts of the country.

It is important to put the risks of household radon into a wider context. It may be estimated that the average dose of normal, unavoidable, natural radiation, of which about 40% is from radon, causes cancers which kill about 60 people per year out of a population of one million (ICRP, 1987; O'Riordan, 1990). The additional radiation dose received in a house with a radon level of 100 Bq/m^3 roughly trebles this death rate. In comparison, this risk is about equivalent to that of driving a car; and cigarette smoking increases the cancer hazard more than a hundred-fold. (The radon level in the house of Pennsylvania worker referred to above was over 100,000 Bq/m^3).

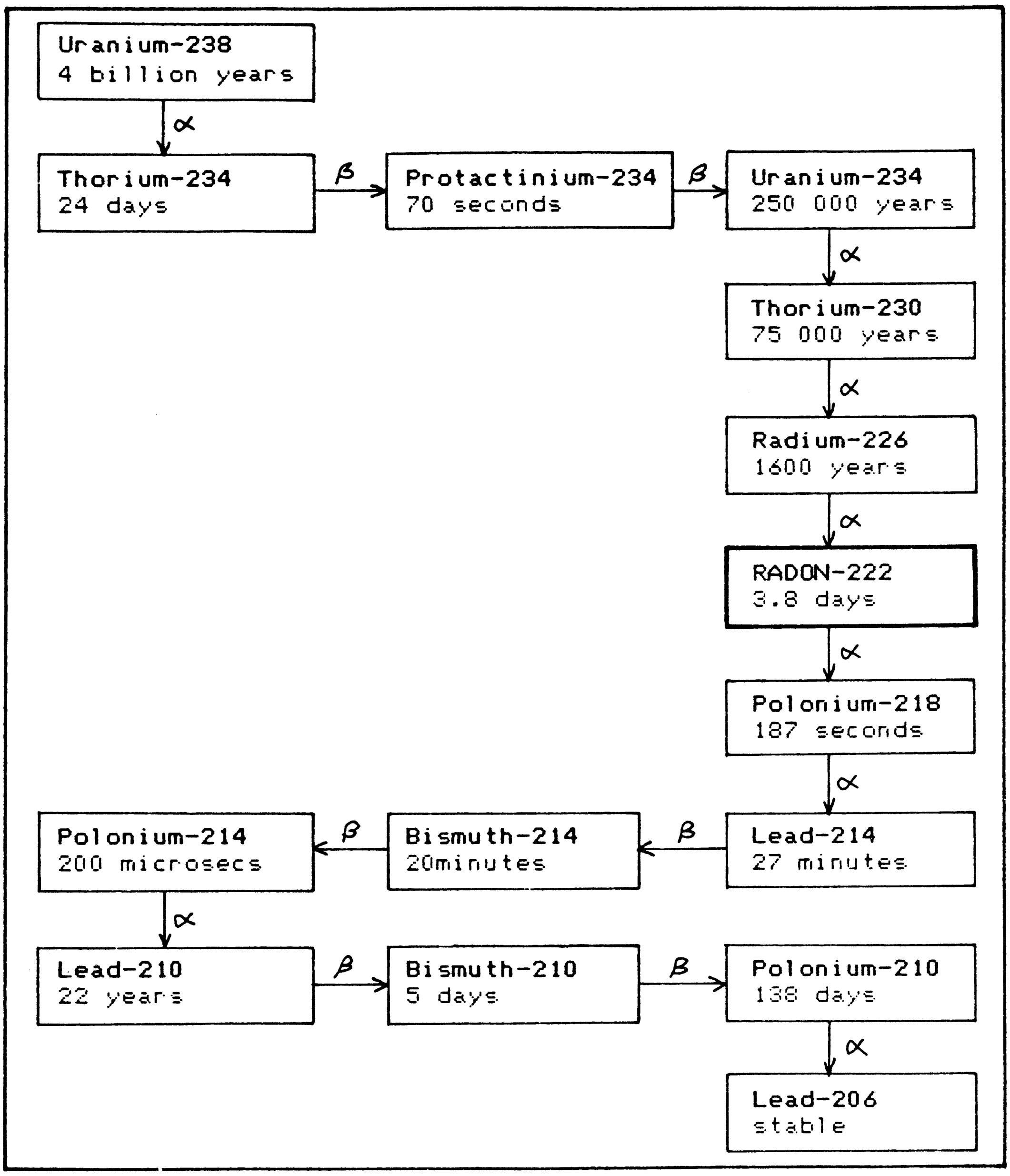

Fig. 1. The radioactive decay chain starting from naturally occurring uranium-238 and including radon-222 and its daughters (after Brenner, 1989). The half-life of each isotope is the period of time necessary for half the surviving mass to decay to its daughter. An alpha decay produces a free helium nucleus consisting of two protons and two neutrons. A beta decay produces a single free electron.

The limited local data from the national surveys showed that mean house radon levels in Nottinghamshire were low, and slightly below the national average. However, appreciable local variations do exist. The Environmental Protection Officer of Gedling Borough Council recognised his responsibility to monitor radon levels in a larger sample of houses in the borough, to better ascertain the potential of any health hazard. A pilot survey in 18 houses was carried out in 1989, followed by a main survey of 70 houses in 1990. After accidental losses these gave a total of 85 results.

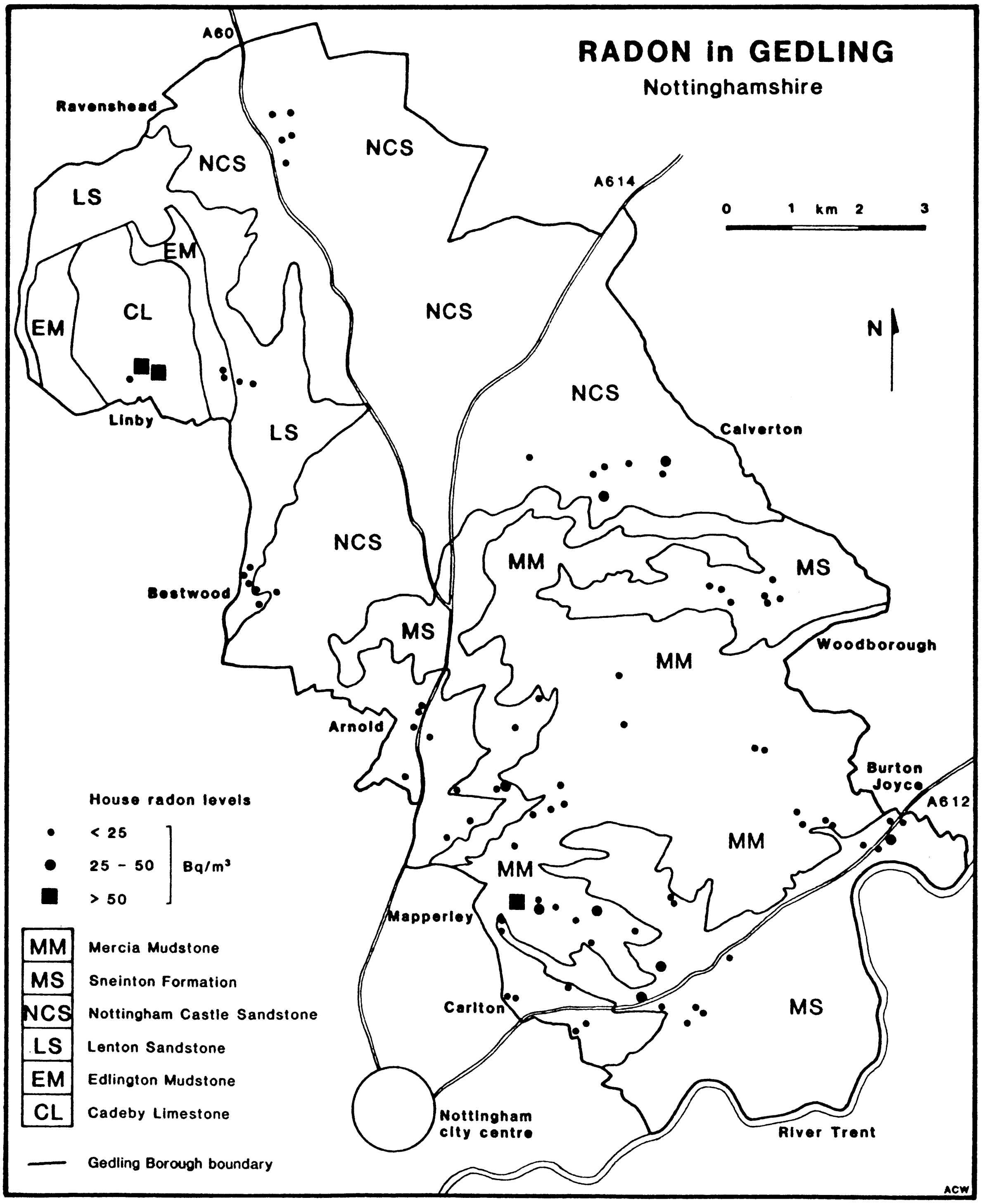

Fig. 2. Simplified map of solid geology and house radon levels in the Gedling Borough area (geology based on published B.G.S. 1:10,000 maps). Mercia Mudstone includes those formations above the Sneinton Formation; the stratigraphy and lithology are summarised in table 1.

Both surveys used passive detectors (Wrixon *et al.*, 1988). These record alpha particle impacts on prepared samples of plastic; after being in place for three months, they can, by calibration, yield the mean radon level in becquerels per cubic metre of air over that period. All the detectors were placed in ground floor living rooms of the sample houses. The pilot survey samples were random, using the houses of available council staff. The main survey was designed to sample a cross section of the geology of the borough, with a weighted distribution reflecting the spread of population (Gibbs, 1990). Small areas to be sampled were identified from the geological base map; within these areas the sample selection was random, except that houses with double glazing and without basements were chosen, where apparent, when a simple choice had to be made. This procedure was designed to encompass a "worst case scenario" within the limited available sample size, and may have produced a very small bias towards higher recorded levels in the overall survey results. Houses were identified only by approximate grid reference, and are only crudely located on Fig. 2, to respect the confidentiality of the data concerning householders who cooperated in the survey. Only summary statistics are published, while the full data remain in an unpublished report (Gibbs, 1990) which can be made available, through the writer of this paper, for any future research.

Both surveys covered three winter months between November and March. The measured radon levels are therefore enhanced due to the usual reduction of house ventilation through the colder months (Wrixon *et al.*, 1988). The raw values have been multiplied by a factor of 0.8 to approximate to the more meaningful annual average radon levels—and these deduced annual figures are considered in this paper.

The mean radon level in the samples houses of Gedling is 17.0 Bq/m^3. This compares with mean values of 20.0 and 24.2 Bq/m^3 obtained by two national surveys (Courtis, 1988; O'Riordan, 1990) each based on a sample of over 2000 houses. The Gedling area therefore has generally normal radon levels in its houses, just below the national averages which are elevated by the inclusion of data from localised hot spots such as on the Cornish granites. However the Gedling mean value does encompass three house radon levels in the 50–100 Bq/m^3 range, though none has yet been recorded which reaches even the Notification Level of 100 Bq/m^3. These higher values are of some interest, but they are fortunately of no real concern with respect to any potential health hazard.

Correlations of the survey results with details of the house construction and room conditions were limited by the sample size, which was small in comparison to the number of parameters involved, but revealed patterns which could be anticipated from the data obtained by the national surveys. Room ventilation was described as good or poor, based on an overall subjective assessment which covered draught levels, open windows and doors, and the presence of chimneys and double glazing. Radon levels were nearly 30% higher in the poorly ventilated rooms; mean values were 16.7 and 12.9 Bq/m^3 in poorly and well ventilated rooms respectively, in the sample of 82 houses on all rocks except the Cadeby Formation limestones. There was no significant difference between the mean radon levels in rooms with solid or suspended floors. Only the degree of room ventilation, or conversely the extent to which the house was sealed against the weather, provided a recognisably consistent factor which had to be taken into account during the further considerations of the parameters relating to ground conditions and geology.

House radon and the Gedling geology

Bedrock outcrops within the Gedling borough area comprise a sequence of Permian and Triassic rocks mostly dipping very gently to the southeast (Fig. 2). The Permian rocks are divided into the Cadeby Formation which approximates to what is better known as the Lower Magnesian Limestone, and the overlying largely argillaceous Edlington Formation, previously known as the Middle Permian Marl. The Sherwood Sandstone Group is divided into the underlying mottled sandstones of the Lenton Sandstone Formation, and the thicker, massive sandstones of the Nottingham Castle Sandstone Formation, which includes pebble beds in its wide but thinly populated outcrop. The exposed Mercia Mudstone Group is divided into the Sneinton, Radcliffe and Gunthorpe formations; the Sneinton Formation is a sequence of micaceous siltstones and mudstones (the old waterstones) and interbedded sandstones, while the Radcliffe and Gunthorpe formations are lithologically similar red mudstones with thin siltstone and sandstone skerries (Dean, 1989; Lowe, 1989). Drift is thin and patchy except for the Trent alluvium which covers much of the southern outcrop of the Sneinton Formation siltstones. Coal Measures underlie the whole area at depth, and have been extensively mined, but nowhere do they come to outcrop.

The variations in house radon levels across the main lithological units are summarized in table 1, and the distribution of sample sites is shown in Fig. 2. Except for the few high radon levels in houses on the Cadeby limestones, the contrasts between mean house radon levels on different rock units are small, and the limited sample size reduces their statistical significance. The lower three rock units have few samples as they have very few houses on them, and one detector was unfortunately lost in a house fire on the predictably significant limestone outcrop.

Table 1. Stratigraphical column of the main lithological units at outcrop in the Gedling Borough area, correlated with the means and ranges of radon levels recorded in houses.

Rock type at outcrop	House radon concentrations		
	Mean Bq/m^3	Range Bq/m^3	No. samples
TRIASSIC			
Mercia Mudstone Group			
Radcliffe and Gunthorpe formations	17.9	0–83.6	25
(mudstones with skerries)			
Sneinton Formation	16.7	4.6–43.8	28
(siltstone, sandstone and mudstone)			
Sherwood Sandstone Group			
Nottingham Castle Sandstone Formation	11.8	0–31.4	21
(sandstone with pebble beds)			
Lenton Sandstone Formation	13.4	6.2–3.3	6
(sandstone and clayey sandstone)			
PERMIAN			
Edlington Formation	10.9	3.5, 18.3	2
(mainly mudstone)			
Cadeby Formation	58.9	9.7, 70.7, 96.3	3
(mainly dolomitic limestone)			

Cadeby Formation limestones

Erratic house radon levels on the dolomitic limestones of the Cadeby Formation are compatible with those on any fissured limestone. Open fissures in the sub-soil bedrock permit rapid migration of radon and create the potential for high house radon levels, whereas a house sited wholly on a single block of limestone, or over clay-filled fissures is likely to have a low radon level. While there is no indication that the Cadeby limestones are a significantly high density source of radon, these results show the importance of fissures in permitting migration of radon from a larger mass of rock.

Nottingham Castle Sandstone Formation

The Nottingham Castle sandstones have a low mean value of house radon, even though they are very permeable rocks. Both they and the Sneinton Formation have log normal distributions of house radon levels, which suggest that open fissures are not significant in radon migration. The many artificially-cut 'caves' in the Nottingham Castle sandstones, mostly beneath the older parts of the Nottingham city centre (Owen and Walsby, 1989), are almost ideal radon traps. They are unlined, cut in the permeable bedrock, and most are poorly ventilated since they have only a single entry, commonly serving as the sub-basement of a single building. Spot samples of air from a number of the less well ventilated and rarely visited caves have been tested for radon; measurements were made with a radon decay products monitor (Wrixon *et al.*, 1988). Radon levels in the caves ranged between 160 and 900 Bq/m^3. Contrasts within the ten samples can be related to differences in ventilation, both between separate caves and between different parts of the same cave systems. Buildings over any of the caves have not yet been monitored for radon; there are few caves in the Gedling Borough area, and none lies beneath the houses tested in this survey.

Mercia Mudstone Group

The mudstones of the Radcliffe and Gunthorpe formations have a mean house radon level only slightly above the means of the other main rock units, but the mean hides a slightly skewed distribution with a small number of higher values. It is likely that the highest values are, at least in part, due to greater emissions of radon from the ground, as opposed to being purely a function of house parameters. A widespread marker horizon of high gamma radiation has been identified in borehole surveys at the stratigraphic level of the Radcliffe/Gunthorpe formational boundary (Balchin and Ridd, 1970). This may be a source of radon. Through the Mapperley area, this thin band of rock has a long winding outcrop which does correlate with the distribution of some of the higher recorded house radon levels, including the single highest level of 83.6 Bq/m^3. A second lithological contrast is provided within the mudstones by the sandstone and siltstone skerries, which may act as radon pathways due to their highest permeability. Table 2 summarizes the survey data from houses on the Radcliffe and Gunthorpe Formations of the Mercia Mudstone. Though the sample numbers are small, poorly ventilated houses on or close to either the Radcliffe/Gunthorpe boundary marker horizon of one of the skerries do appear likely to have higher radon levels.

The Sneinton Formation consists of a more varied sequence of siltstones, sandstones and mudstones; this could be expected to produce stratigraphically guided variations of radon distribution, as a function of bed permeabilities and perhaps with respect to the distribution of detrital mica. These factors may partly account for the range of house radon levels on this formation (table 1), but they have not been identified sufficiently for any correlation with the survey data.

Table 2. Mean radon levels in well and poorly ventilated houses correlated with their locations on or close to stratigraphical horizons within the Radcliffe and Gunthorpe formations of the Mercia Mudstone Group.

Room ventilation	Mean house radon concentrations (Bq/m^3) (Number of samples)		
	Good	Poor	All
On or close to the Radcliffe/Gunthorpe gamma marker horizon	5.0 (4)	32.6 (5)	20.2 (9)
On or close to any skerry band	7.4 (2)	48.2 (6)	22.3 (8)
Close to neither	11.6 (4)	10.1 (4)	10.8 (8)

Other geological factors

Alluvium is only extensive along the Trent valley where it covers part of the Sneinton Formation outcrop. The seven houses on it had a mean radon level of 15.5 Bq/m^3, while the mean level of those houses on the same rock without any alluvial cover was 17.1 Bq/m^3; the difference is not significant. Garden soils were subjectively described as either clayey or sandy, with a consequent contrast in permeability, but the survey revealed no clear correlation with house radon levels.

Deep coal mining has taken place beneath most of the Gedling borough area. Ground strains developed within the subsidence profiles over longwall mines include an inner zone of compression and a peripheral zone of extension (Waltham, 1989); these are known to affect rock permeability in many situations, and so could influence radon migration. The Gedling survey therefore included subsidence data, as interpreted from the British Coal plans of mine workings. The results were not conclusive. Table 3 summarizes the data for the 35 houses monitored on undermined areas of outcrops of the two major rock units. The high mean value on the Mercian mudstone suggests that more radon may emerge not from a rock of increased permeability, but may be squeezed out of a rock of reduced porosity. In nearly all cases, the ground strain is residual, and not active, as mining beneath has ceased more than 5 years previously; monitoring of houses in areas of active subsidence may reveal more useful data.

Other geological influences could not be recognised from the limited data available. Faults may be radon sources or pathways, but too few were identified for sampling. Enhanced radon emission could occur from the margin of a permeable, valley floor, inlier, beneath an impermeable caprock. However this effect is likely to be very limited, as most radon will only travel a few metres in soil or unfissued rock. Survey data was inconclusive, and differences could have been masked by the lower radon levels in more windswept hilltop houses.

Conclusion

In conclusion, the Gedling survey demonstrates that some features within the bedrock geology have significant influence on the amounts of radon in houses, and can be responsible for undesirably enhanced levels in poorly ventilated rooms. Though no recorded radon levels are high enough to provide any significant health hazard, further monitoring on the fissured limestones may be appropriate.

Mining ground strain	Mean house radon concentrations (Bq/m^3)	
	Mercian mudstone (Radcliffe and Gunthorpe formations)	Sherwood Sandstone (Nottingham Castle formation)
Extension	14.7	13.5
Neutral	8.2	7.2
Compression	29.5	10.7

Table 3. Mean radon levels in houses on Mercian mudstones and Nottingham Castle Sandstone subjected to tensile or compressive ground strain induced by mining subsidence. Based on sample of 35 houses, evenly distributed across the six fields, and with no significant bias created by the states of house ventilation.

Acknowledgements

The author gratefully acknowledges support and assistance from Gedling Borough Council for funding the radon survey of the houses using passive detectors supplied by Track Analysis Systems; Robert Crowder, Environmental Health Officer for Gedling Borough, who initiated and supervised the survey; Suzie Gibbs of Nottingham Polytechnic, who analysed much of the survey data as part of her undergraduate project; John Gunn of Manchester Polytechnic, who sampled the radon levels in the Nottingham sandstone caves; and David Lowe who constructively reviewed the manuscript.

References

Balchin, D.A. and Ridd., M.F., 1970. Correlation of the younger Triassic rocks across eastern England. *Q. J. Geol. Soc. London*, 126, 91–101.

Brenner, D.J., 1989. *Radon, risk and remedy*. Freeman, New York, 225pp.

Chevin, D., 1990. Radon, the grim seeper. *Building*, 255 (7652), 62–65.

Courtis, M., 1988. *Radon: report of the IEHO survey on radon in homes* 1987/8. Inst. Environ. Health Officers, London, 26pp.

Dean, M.T., 1989. Geological notes and local details for 1:10,000 sheet SK54SE Nottingham South. *Brit. Geol. Surv. Tech. Rep.* WA/89/8.

DoE, 1990. *The householders' guide to radon*. HMSO, London, 18pp.

Gibbs, S., 1990. *Radon in Gedling*. Unpubl. thesis, Nottingham Polytechnic, 102pp.

Gunn, J., Fletcher, S., Middleton, T. and Prime, D., 1989. Radon daughter concentrations in British caves: a progress report (Abstract). *Trans. Brit. Cave Res. Assoc.*, 16, 113.

Hand, B.M. and Banikowski, J.E., 1988. Radon in Onondaga County, New York: paleohydrogeology and redistribution of uranium in Paleozoic sedimentary rocks. *Geology*, 16, 775–778.

Hawthorne, A.R., Gammage, R.B. and Dudney, C.S., 1984. Effect of local geology on indoor radon levels: a case study. *Proc. 3rd Int. Conf. Indoor Air Quality and Climate, Stockholm*, 2, 137–140.

ICRP, 1987. Lung cancer risk from indoor exposures to radon daughters. *Ann. Int. Comm. Radiological Protection*, 17 (1).

Lowe, D.J., 1989. Geology of the Calverton district. *Brit. Geol. Surv. Tech. Rep.* WA/89/13.

Nason, R. and Cohen, B.L., 1987. Correlation between Radium-226 in soil, Radon-222 in soil gas, and Radon-222 inside adjacent houses. *Health Physics*, 52 (1), 73–77.

Nazaroff, W.W. and Nero, A.V., 1984. Transport of radon from soil into residences. *Proc. 3rd Int. Conf. Indoor Air Quality and Climate, Stockholm*, 2, 15–20.

O'Riordan, M.C., 1990. Human exposure to radon in homes. *Doc. Nat. Radiol. Prot. Bd.*, 1 (1), 17–32.

Owen, J.F. and Walsby, J.C., 1989. A register of Nottingham's caves. *Brit. Geol. Surv. Tech. Rep.* WA/89/27.

Waltham, A.C., 1989. *Ground subsidence*. Blackie, Glasgow, 202pp.

Wilson, C., 1984. Mapping the radon risk of our environment. *Proc. 3rd Int. Conf. Indoor Air Quality and Climate, Stockholm*, 2, 85–92.

Wrixon, A.D., Green, B.M.R., Lomas, P.R., Miles, J.C.H., Cliff, K.D., Francis, E.A., Driscoll, C.M.H., James, A.C. and O'Riordan, M.C., 1988. *Natural radiation exposure in UK dwellings*. Rep. Nat. Radiol. Prot. Bd. NRPB-R190, 188pp.

Yarborough, K.A., Ahlstrand, G.M. and Fletcher, M.R., 1976. Radiation study done in NPS caves. *Nat. Spel. Soc. News*, 34, 146–148.

Dr. A.C. Waltham,
Civil Engineering Department,
Nottingham Polytechnic,
Nottingham, NG1 4BU.