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Risø National Laboratory, DK-4000 Roskilde, Denmark
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AN INVESTIGATION OF FACTORS INFLUENCING INDOOR RADON CONCENTRATIONS

B. Majborn, A. Sørensen, S.P. Nielsen and L. Bøtter-Jensen

Abstract. Variations in indoor radon concentrations and some influencing factors have been studied during a two-year period (1986-1987) in 16 almost identical single-family houses. The annual average radon concentration in the houses varied from about 50 to about 400 Bq/m^3. Variations in soil characteristics and radon concentration in soil gas could not be directly related to the variations of the average indoor radon concentrations. Most of the houses showed a "normal" seasonal variation of the radon concentration with a maximum in the winter and minimum in the summer. A deviating seasonal variation was found in three of the houses. Hourly data obtained in one unoccupied house during a period of 2-1/2 months showed no or only weak correlations between the indoor radon concentration and meteorological factors. However, for most of the houses, the seasonal variation of the indoor radon concentration was well correlated with the average indoor-outdoor temperature difference on a 2-month basis. It was demonstrated that the radon concentration can be strongly reduced in the Risø houses if a district-heating duct, which is connected to all the houses, is ventilated, so that a slightly lowered pressure is maintained in the duct.

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1. Introduction and summary

A recent survey of natural radiation in a representative sample of Danish dwellings has shown that the distribution of the annual average radon concentration can be described by two log-normal distributions, one for single-family houses and the other for apartments (U187). For the single-family houses the distribution has a median of 52 Bq/m^3 and a standard deviation of 2.0, whereas for the apartments these numbers are 18 Bq/m^3 and 1.4 respectively. These results are in general agreement with previous observations (Sø85). For most of the single-family houses, the main source of radon is the soil below the house. Significant differences between the distributions of radon concentrations in single-family houses were found based on a classification of the subsoil. For areas characterised by mainly moraine clay the geometrical mean value is 58 Bq/m^3 compared to 39 Bq/m^3 for the rest of the country, characterised by mainly sand and gravel (U187).

The object of the investigations reported here is a cluster of 16 almost identical single-family houses built in 1956/57 as dwellings for Risø employees. The site of the houses forms an area of about 150 m by 300 m, and the subsoil is mainly moraine clay. Even though 14 of the houses have identical base constructions (slab on grade), the annual average radon concentrations in these houses vary from about 50 to about 400 Bq/m^3. 5 of the 16 houses (i.e. 31%) have an annual average radon concentration above 200 Bq/m^3. In comparison, only about 3% of all single-family houses in Denmark have an annual average radon concentration above 200 Bq/m^3, according to the national survey (U187). In view of the varying radon levels in the 16 Risø houses, and in view of the relatively high radon concentrations in these houses (i.e. high on a Danish scale), it was decided to use the houses in an investigation of some of the factors that influence indoor radon concentrations.

The investigations comprised:

1. A characterisation of the subsoil at a number of locations on the site.
2. Measurements of the radon concentration in the soil gas at a number of locations.
3. Integrating measurements of radon in the living-room and in a bedroom of all the houses on a 2-month basis for two full years (1986 and 1987).
4. Continuous measurements of a number of physical quantities inside and just outside one house for a period of about 2-1/2 months (April - June 1986) when the house was unoccupied. The measured quantities were: the radon concentration in the living-room, in a bedroom and in a district heating duct, the radon exhalation from the soil surface just outside the house, the radon concentration outdoors, the temperature indoors and outdoors, the outdoor atmospheric pressure, and the outdoor-indoor differential pressure. In addition, the air-exchange rate was measured a number of times during the period.
5. Continuous measurements of the radon concentration in 5 of the houses for a period of about 2-1/2 months (March-May 1987).
6. Investigations of the effect of maintaining a slightly lowered pressure in a district-heating duct which is connected to all the houses.

The main results and conclusions can be summarized as follows:

1. The soil in the investigated area is mainly composed of moraine clay. However, deposits with a more mixed and permeable composition were found in part of the area. 92 samples of soil from the bore holes showed radon emanations varying from 4 to 17 radon atoms$\cdot kg^{-1} \cdot s^{-1}$. Neither the soil samples nor the measurements carried out in the bore holes indicated the presence in the area of any layers with an unusually high radon emanation. Grab samples of soil gas taken at a depth of 50 cm at various locations within the area showed radon concentrations ranging from 4 to 82 kBq/m^3. The results of the soil investigations could not be directly related to the variations of the average indoor radon concen-

trations. However, the measured radon concentrations in soil gas did demonstrate that the soil in the area has the potential of acting as a source of relatively high indoor radon levels.

2. The integrating radon measurements showed annual average radon concentrations ranging from 57 to 407 Bq/m^3 in the living-rooms and 38 to 354 Bq/m^3 in the bedrooms. Most of the houses showed a "normal" seasonal variation of the radon concentration with a maximum in the winter and minimum in the summer. A deviating seasonal variation was found in three of the houses. Two of these have a foundation which differs from that of the other houses. In the five houses, where continuous radon measurements were made, the average diurnal variation of the radon concentration showed a maximum in the morning. The hourly data obtained in one unoccupied house during a period of 2-1/2 months showed no or only weak correlations between the indoor radon concentrations and meteorological factors. However, for most of the houses, the seasonal variations of the indoor radon concentrations were well correlated with the average indoor-outdoor temperature difference on a 2-month basis. This, and the observed diurnal variations of the indoor radon concentrations, indicate that pressure-difference-driven flow of soil gas into the houses is the predominant mechanism of radon entry.
3. It has been demonstrated that the radon concentration can be strongly reduced in the Risø houses if the district-heating duct is ventilated, so that a slightly lowered pressure is maintained in the duct.

2. Characteristics of site and houses

2.1. The site

The houses are situated next to Risø National Laboratory at the eastern shore of Roskilde Fjord. A plan of the site is shown in figure 2.1. The site is about 150 metres wide and 300 metres long. The ground level is between 15 and 19 metres above sea level. A small ground water pocket was found in the highest part of the site.

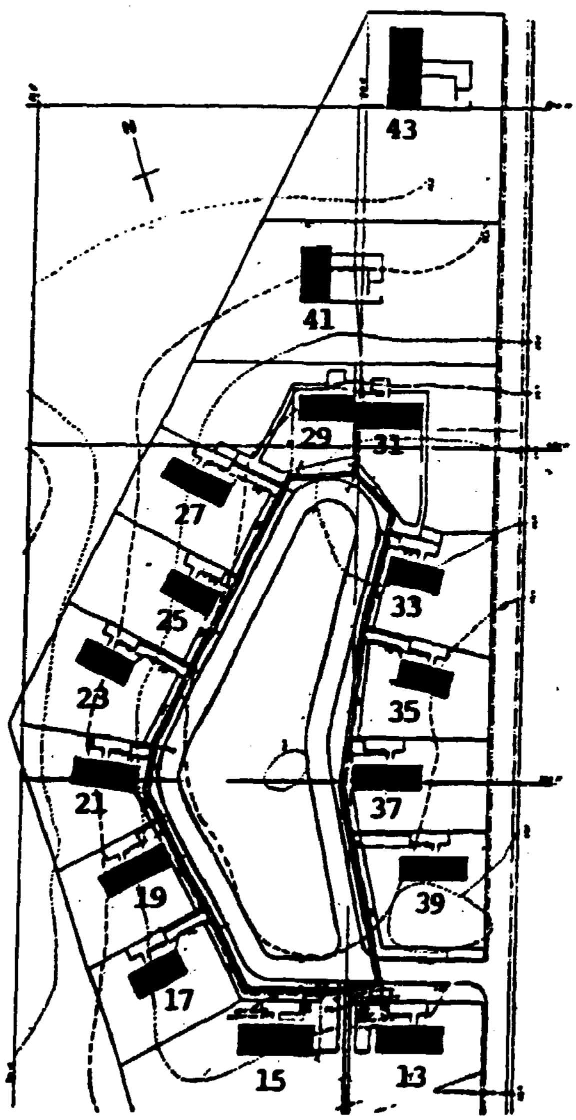


Figure 2.1. Plan of the site of the Risø houses

The area consists of glacial deposits on the underlying lime stone. The soil is characterized by quarternary moraine clay mixed with deposits of sand, gravel and small stones.

2.2. The houses

The houses are single-family houses built of bricks. They are all of the slab-on-grade type except the two northernmost houses, which have a crawl space (no. 43) and a crawl space and partly a cellar (no. 41). The other houses differ only in length, having one chamber more or less. An important feature is a district-heating duct which is extended into each house, where it proceeds circumferentially along the outer walls as an integrated part of the foundation.

Figure 2.2 shows a plan of the typical Risø house and figure 2.3 shows the cross section. The coarse concrete slab is covered with a layer of tarred felt, which is glued together to form a moisture barrier. The tarred felt is placed both underneath and above the district-heating duct.

The airing of the houses takes place by natural ventilation through air ducts in the kitchen and in the bathroom.

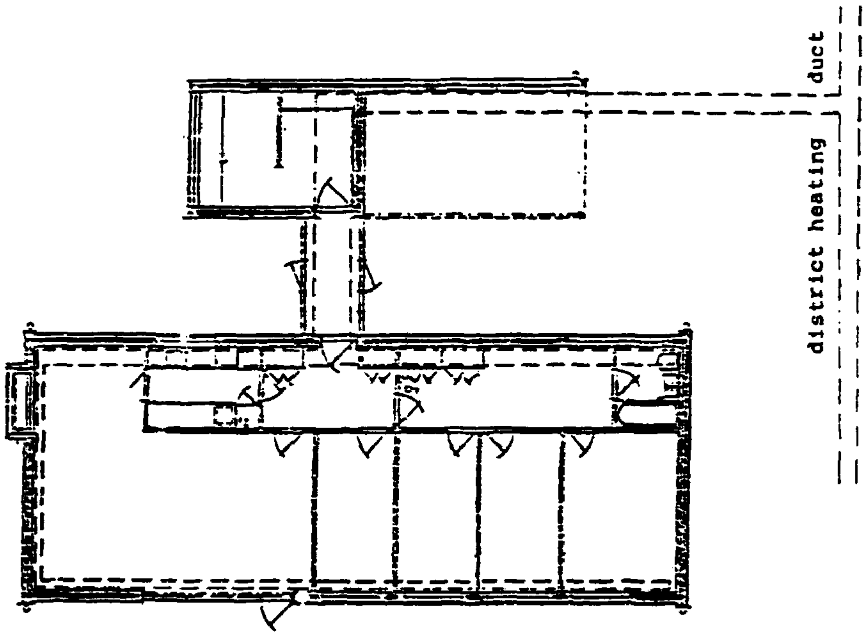


Figure 2.2. Plan of the Risø house

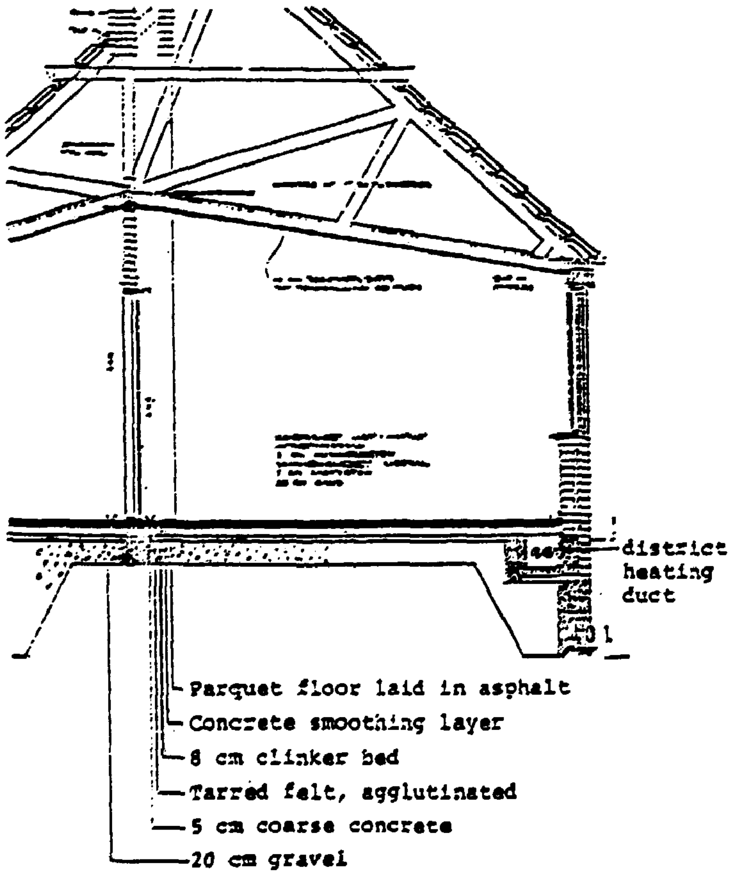


Figure 2.3. Cross section of the Risø house

3. Methods

3.1. Soil investigations

The soil investigations are described in Appendix I.

3.2. Measurements of radon in soil gas

Radon in soil gas was measured either by grab sampling or by integrating measurements using the passive radon dosemeter described in section 3.3.

The grab samples were taken at a depth of 50 cm below the ground surface by sucking soil gas through a tube with an inner diameter of 13 mm into scintillation flasks.

3.3. Passive radon dosemeter

Integrating radon measurements were made with a passive dosemeter designed to measure radon as well as external radiation (Sø85, Ma86). It is a closed cup dosemeter. The sensitive elements are CR-39 track detectors for the measurement of radon and thermoluminescence dosemeters (TLDs) for the measurement of external radiation.

The components of the dosemeter are shown in Fig. 3.1. The cup is a plastic container, 7.5 cm in diameter and 5.5 cm high (outer dimensions). It is provided with a perforated lid and a glass-fibre filter. This combination results in a characteristic diffusion time (λ^{-1}) of about 10 min for the diffusion of radon into or out of the cup. The TLD unit is sealed into a plastic envelope and taped onto a cardboard disc, which is placed in the bottom of the cup. Another cardboard disc, holding the CR-39 detector, is placed on top of the TLD package. The

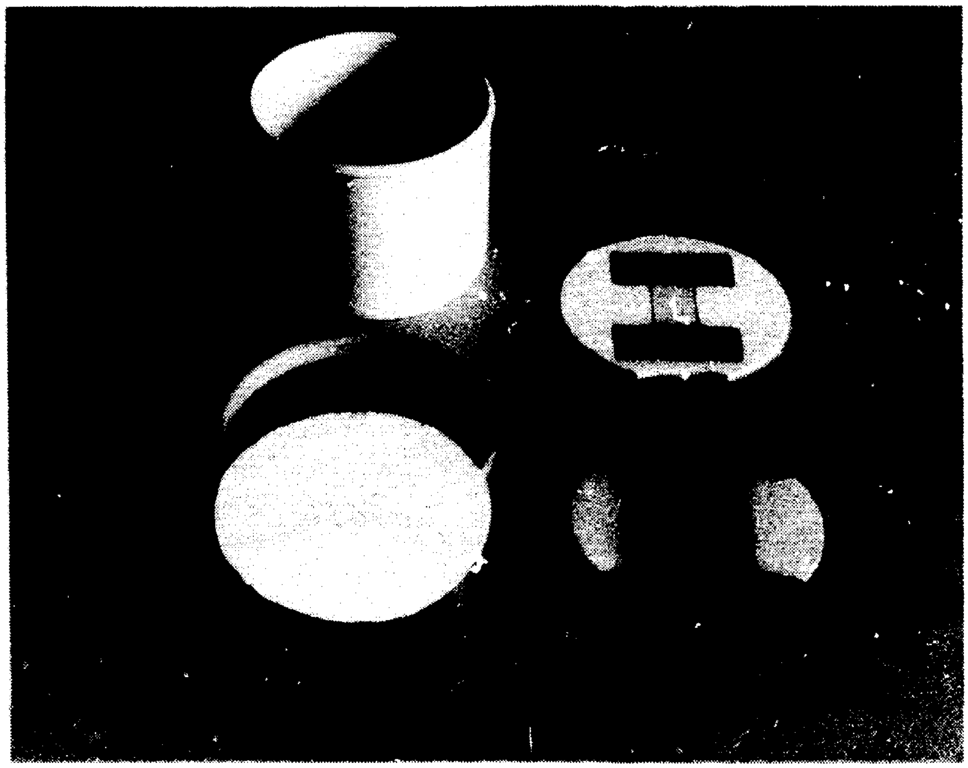


Figure 3.1. The components of the passive radon dosemeter
1. Plastic cup
2. Perforated lid
3. Glass-fibre filter
4. CR-39 track detector
5. TL detector unit

diameter of the upper cardboard disc is slightly greater than the inner diameter of the lower part of the cup, so that a firm press fitting is obtained. In the present work only radon was measured, so TLDs were not included in the dosemeter.

Track counting is performed manually using a microscope or semi-automatically using an image analysis system.

The performance of the dosemeter was tested in the second CEC radon dosimetry intercomparison in 1984 (Mi86) and again in the third CEC radon dosimetry intercomparison in 1987. In the 1984-intercomparison, the exposure estimates obtained with 3 groups of 10 dosemeters each deviated 4-9% from the nominal exposures, with standard deviations of 9-21%. In the 1987-intercomparison, the exposure estimates obtained with 4 groups of 10 dosemeters each deviated 3-6% from the nominal exposures, with standard deviations of 7-9%.

3.4. Continuous radon monitor

Variations in the radon concentration were measured with continuous radon monitors designed and built at Risø. Each monitor is composed of a cylindrical detector unit and an electronic counter system with print-out facilities as shown in figures 3.2. and 3.3. Five monitors of this design were built and used in the investigations.

The detector unit contains a scintillation chamber, 15 cm in diameter by 15 cm high, mounted with a photomultiplier tube. The inner wall of the chamber is covered with a teflon foil coated with a ZnS alpha scintillation phosphor. Radon in the ambient air passes into the chamber through a glass-fibre filter, which retains the radon daughters. Inside the chamber, a central wire electrode, held at a negative potential of about -1500 volts, partly collects the radon daughters formed in the chamber. The ambient air is purged through the chamber at a rate of 1 litre per minute by means of a small pump placed inside the detector unit.

The scintillations are counted over a preset time and accumulated counts are printed out after each time interval. The count rate, corrected for background, is converted to a mean concentration of radon in the counting period by means of an experimentally obtained calibration factor.

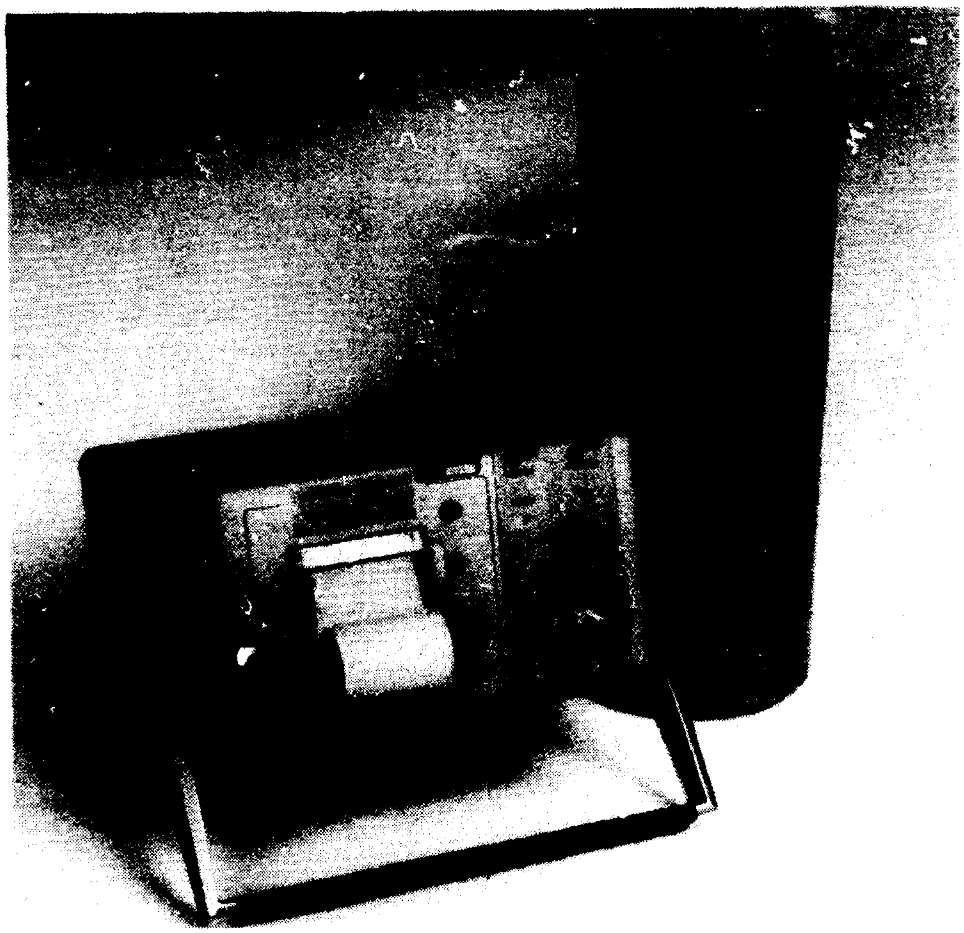


Figure 3.2. The continuous radon monitor. On the left: electronic counter system with printer. Right: detector unit containing scintillation chamber and PM tube.

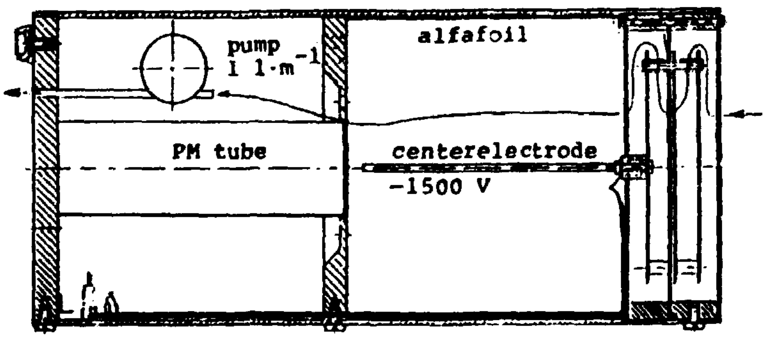


Figure 3.3. The continuous radon detector unit, schematically.

3.5. Collection of meteorological data

Measurement data were collected on a datalogger as either digital or analog signals from the instruments.

The temperatures were measured with thermocouples having their cold junctions at $0^{o}C$. The recorded values are the average values over the measurement period.

Atmospheric pressure was measured with a pressure transducer, which covered the range from zero to 1.2 bar. The collected data were later calibrated to the actual barometric reading from the nearby meteorological station at Risø National Laboratory.

Data on wind direction and wind speed were obtained from the meteorological mast at Risø National Laboratory.

3.6. Measurement of air-exchange rate

The air-exchange rate was measured by the tracer gas technique (rate of decline) using SF_6 as the tracer gas.

4. Results

4.1. Soil investigations

The soil investigations are described in Appendix I.

The results can be summarized as follows:

1. In most of the area the soil consists of moraine clay, i.e. clay with a content of sand and/or silt and/or gravel. The physical properties of the soil, e.g. the permeability, are dominated by the clay.
2. In a part of the area (cf. Figure 1 in Appendix I) sandy deposits with a high permeability for water have been found. In this part of the area ground water was found in the bore holes (holes no. M3, 27A, 27B, 33 and 35, cf. Figure 1, Appendix I). The water table was found at depths of between 2 and 3 metres.
3. 92 samples of soil from the bore holes showed radon emanations varying from 4 to 17 radon atoms$\cdot kg^{-1}\cdot s^{-1}$. 12 samples showed emanations above 10 atoms$\cdot kg^{-1}\cdot s^{-1}$, i.e. above typical emanations for Danish moraine clay (Da85).
4. Neither the soil samples nor the measurements carried out in the bore holes indicate the presence in the area of any layers with an unusually high radon emanation.

Figure 2 in Appendix I shows the geological profile revealed by the investigations along a line from bore hole no. 41 (north-east) to bore hole no. 17 (south-west).

Additional soil investigations were carried out in 1987 near house nos. 33 and 35. These investigations comprised 18 drillings of holes with a diameter of 22 mm down to depths of between 1.2 and 3.0 metres. The investigations showed that the soil around the two houses has a varying composition. Strong variations were found within distances of a few metres.

4.2. Radon in soil gas

The radon concentration in soil gas was measured at various locations on the site in different periods during 1986 and 1987.

1. In June and July 1986 integrating radon dosemeters were used to measure radon in soil gas at 8 locations around Risø house no. 27, and also at 8 locations around Risø house no. 17. Measurements were made June 2-9, June 9-16 and June 16-26 at house no. 27, and July 9-16 and July 16-23 at house no. 17. At house no. 27 the dosemeters were placed at distances between 65 and 147 cm from the wall of the house and at depths between 21 and 36 cm. The measured radon concentrations are given in Table 4.1. They vary from 1600 to 15000 Bq/m^3 with an overall average value for the 8 locations and 3 periods of about 6000 Bq/m^3. At house no. 17 the dosemeters were placed at distances between 60 and 125 cm from the wall of the house and at depths between 20 and 30 cm. The measured radon concentrations are given in Table 4.2. They vary from 400 to 17000 Bq/m^3 with an overall average value for the 8 locations and 2 weeks of about 7000 Bq/m^3.
2. On November 18-19, 1986, grab samples were taken at a depth of 50 cm at locations adjacent to 10 of the bore holes used for the soil investigations (cf. Appendix I). At each location two grab samples were taken. The results are shown in figure 4.1. The measured average radon concentrations range from 12000 to 82000 Bq/m^3.
3. During the period March 24 to May 13, 1987, grab samples were taken at 5 locations near the 5 houses which were continuously monitored for indoor radon during that period (cf. section 4.5). Each location was 3 metres from the wall of the respective house (Figure 4.2), and the samples were taken at a depth of 50 cm. All the samples were taken between 9 and 12 a.m. The results are shown in Figure 4.3 and summarized in Table 4.3.

Table 4.1. Radon concentration in soil gas around Rise house no. 27 measured with integrating dosemeters

Period (1986)	Exposure time (h)	Location: / Depth(cm):	1	2	3	4	5	6	7	8	Mean	S.d.
		Depth(cm):	30	29	29	33	31	30	36	21	30	4
June		Radon concentration (Bq/m^3)										
2-9	169		9490	6120	4790	5040	5980	7360	8730	3060	6320	2130
9-16	166		5100	6440	3800	4730	11290	15410	10650	1600	7500	4570
16-26	240		4980	4790	3390	3580	4390	4600	5850	2200	4220	1130
										Overall mean:	6010	

Table 4.2. Radon concentration in soil gas around Rise house no. 17 measured with integrating dosemeters

Period (1986)	Exposure time (h)	Location: / Depth(cm):	1	2	3	4	5	6	7	8	Mean	S.d.
		Depth(cm):	30	21	25	27	21	20	25	22	24	3
July		Radon concentration (Bq/m^3)										
9-16	169		9640	7080	5900	9240	3590	1690	17300	430	6860	5370
16-23	169		8050	5890	6830	15010	3680	3750	8560	5320	7140	3650
										Overall mean:	7000	

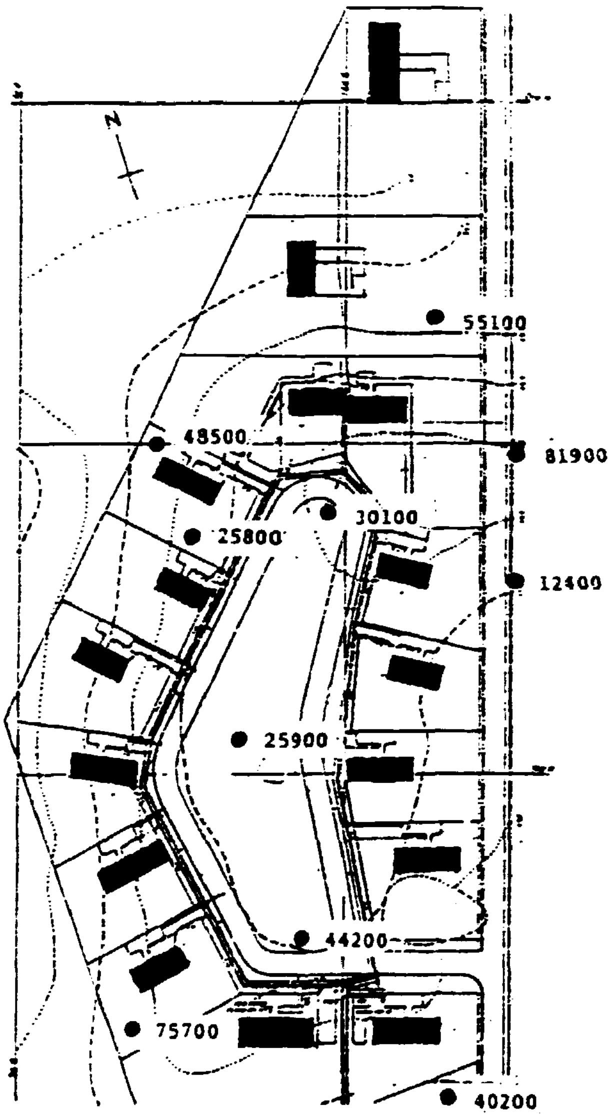


Figure 4.1. Results of grab sample measurements of radon in soil gas at a depth of 50 cm, November 18-19, 1986. The measured radon concentration (average of 2 grab samples) is given in Bq/m^3 at each location.

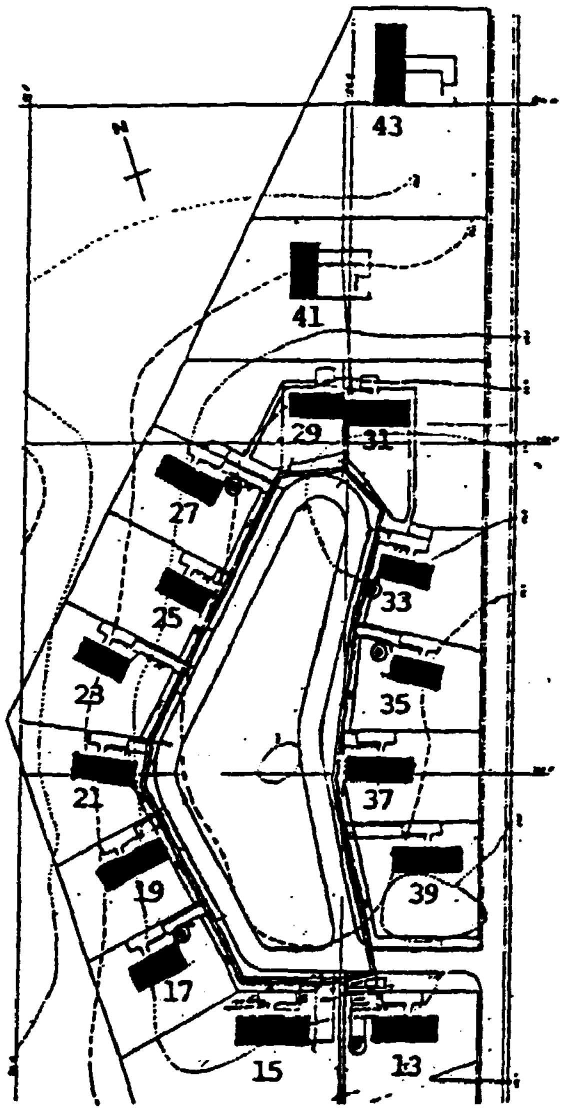


Figure 4.2. Locations for grab sampling of radon in soil gas March 24 - May 13, 1987. Each location is 3 m from the wall of the respective house (nos. 13, 17, 27, 33 and 35).

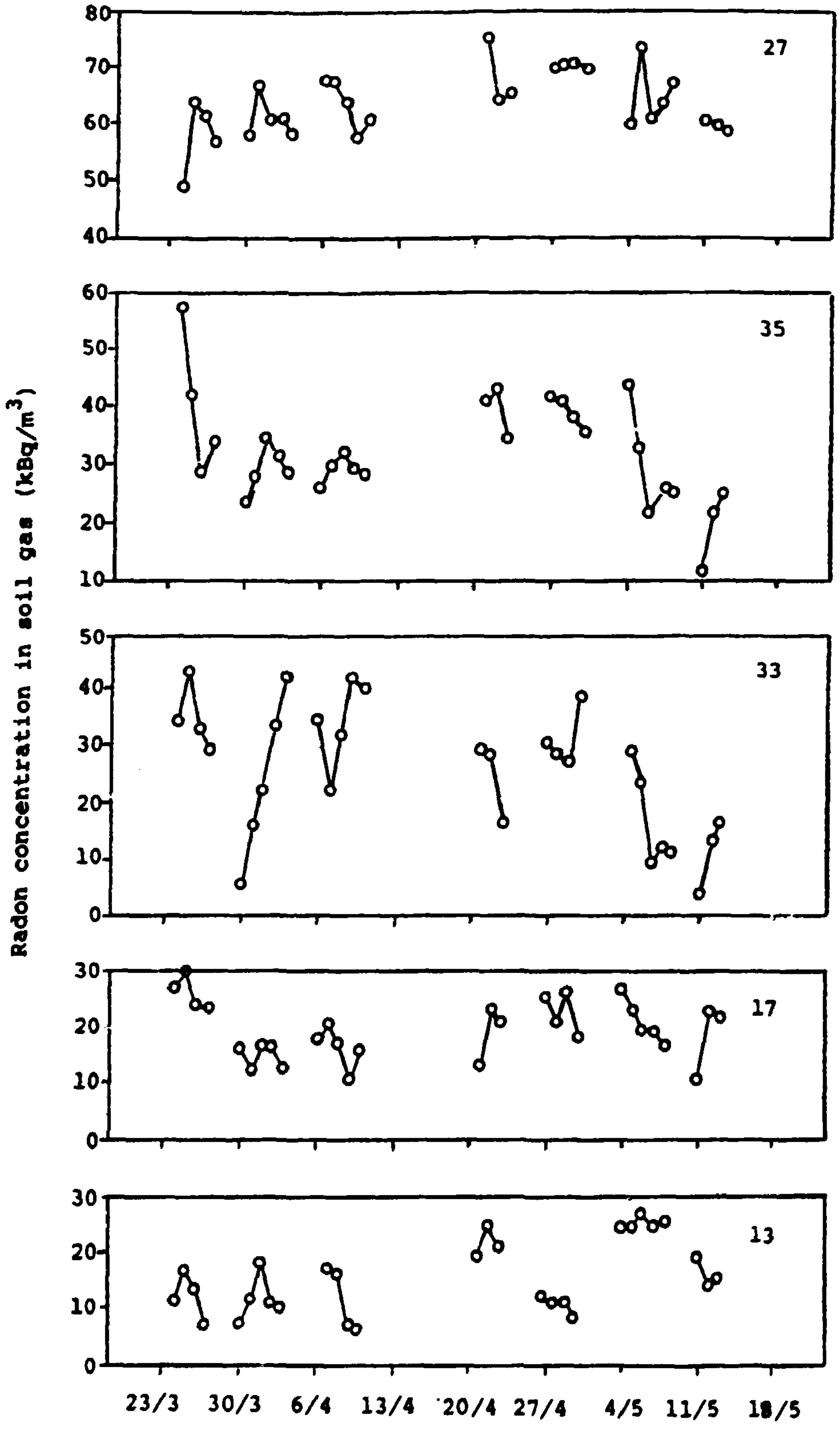


Figure 4.3. Results of grab sample measurements of radon in soil gas at a depth of 50 cm, March 24 - May 13, 1987. The samples were taken at the 5 locations shown in Figure 4.2, near house nos. 13, 17, 27, 33 and 35.

Table 4.3. Summary of the results of measurements of radon in soil gas at 5 of the Risø houses during the period March 24 - May 13, 1987. Grab samples were taken at a depth of 50 cm at locations 3 m from the wall of the respective house.

Location		Number of samples	Radon concentration (Bq/m^3) mean	s.d.
House no.	13	28	15900	6600
"	17	29	19500	5200
"	27	29	63400	5700
"	33	29	25900	11300
"	35	29	32200	8900

4.3. Integrating radon measurements

Integrating radon measurements were made in all 16 Risø houses on a 2-month basis throughout the two years 1986 and 1987. For each 2-month period each house was provided with two dosemeters of which one was placed in the living-room and the other in a bedroom. The results are given in Figures 4.4, 4.5, 4.6 and 4.7. For house no. 27, no results were obtained for November-December 1986, because the dosemeters were lost in connection with a change of inhabitants. Furthermore, the results have been discarded in a few further cases, because they were considered to be unreliable, due to inhomogeneous track distributions on the CR-39 detectors. This was observed in 11 out of 382 measurements, mostly in March-April 1986.

House no. 15 was not normally occupied during 1986 and 1987. Until June 1987, the living-room was used as an office during daytime on weekdays, and the bedroom was used occasionally as a guest room. From July 1987, the house was unoccupied, apart from another bedroom, which was used occasionally as a guest room.

House no. 27 was inhabited by one family until March 31, 1986, and by another family from December 1, 1986. In the intervening period it was unoccupied. Continuous measurements were made in the house during the period April 2 - June 16, 1986 (cf. section 4.4).

Change of inhabitants also occurred in house no. 17, which was unoccupied in an intervening period of 3 months (June 1 - August 31, 1986), and in house no. 39, where the change occurred per September 1, 1987.

The inhabitants of each house were asked to note all periods of one week or more, when the house was unoccupied. House no. 35 is inhabited by a single person, who spent a significant part of his time abroad during 1986 and 1987.

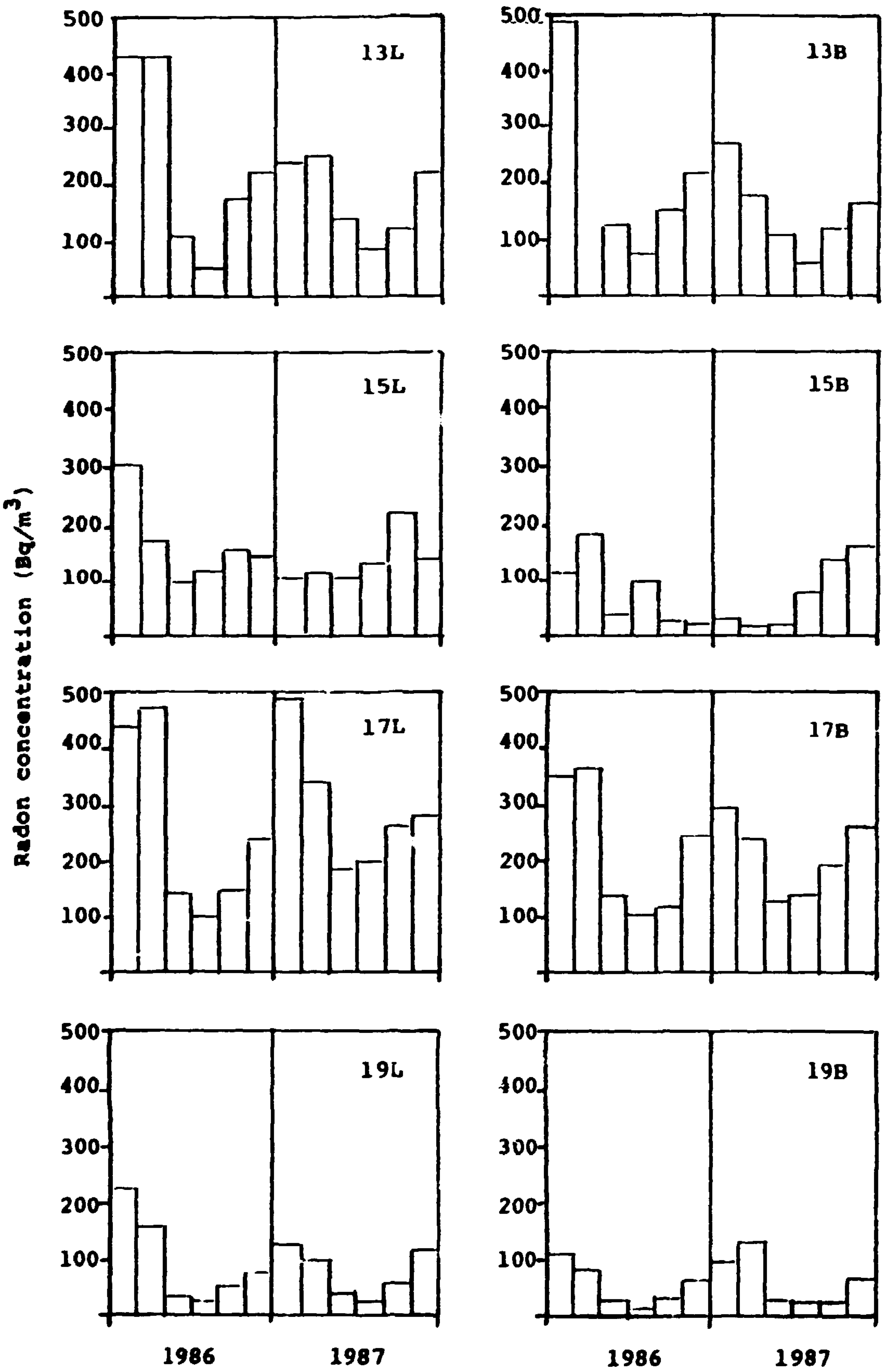


Figure 4.4. The average radon concentration per 2-month interval in 1986-1987 in the living-rooms (L) and bedrooms (B) of Risø house nos. 13, 15, 17 and 19.

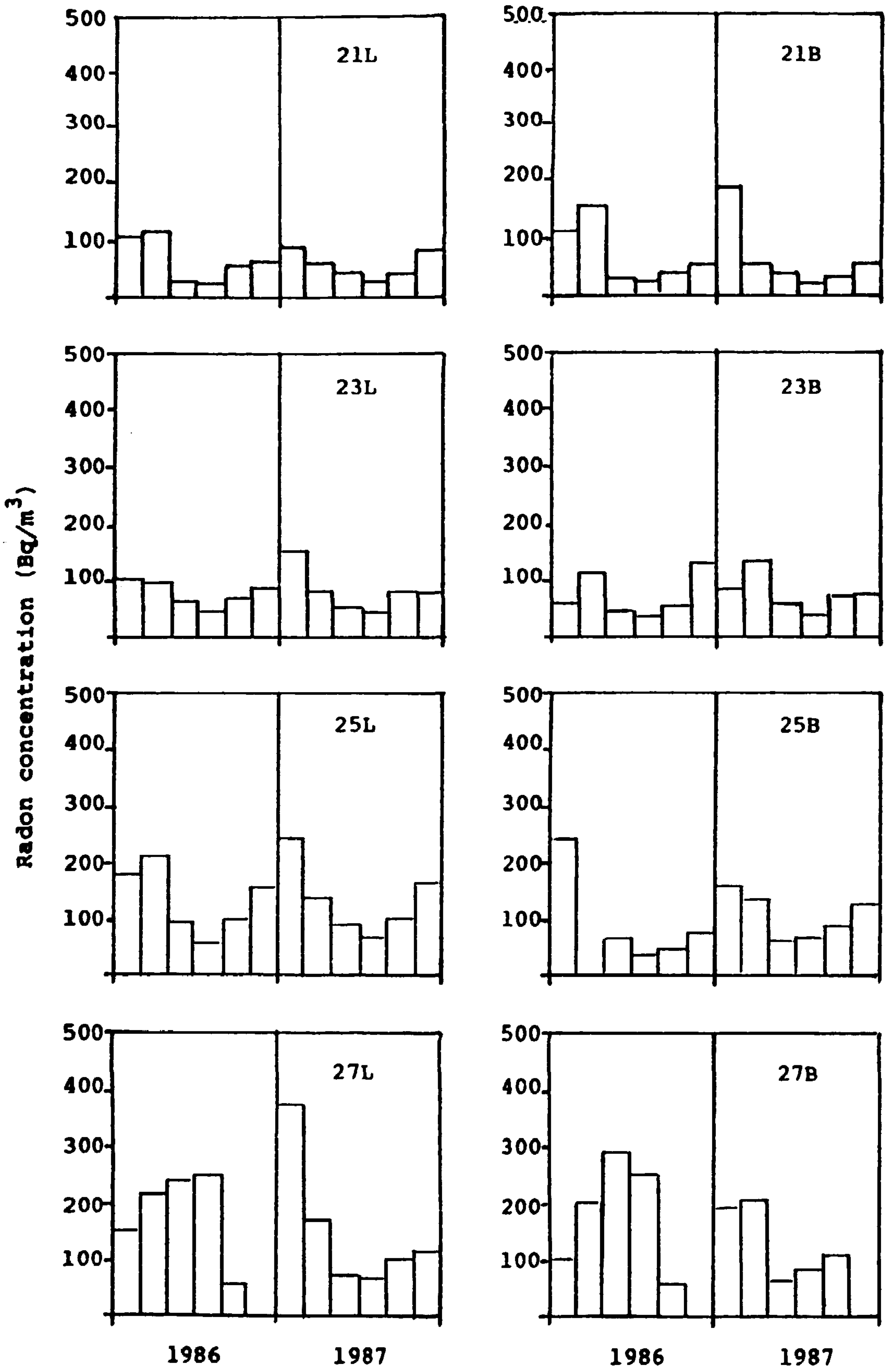


Figure 4.5. The average radon concentration per 2-month interval in 1986-1987 in the living-rooms (L) and bedrooms (B) of Risø house nos. 21, 23, 25 and 27.

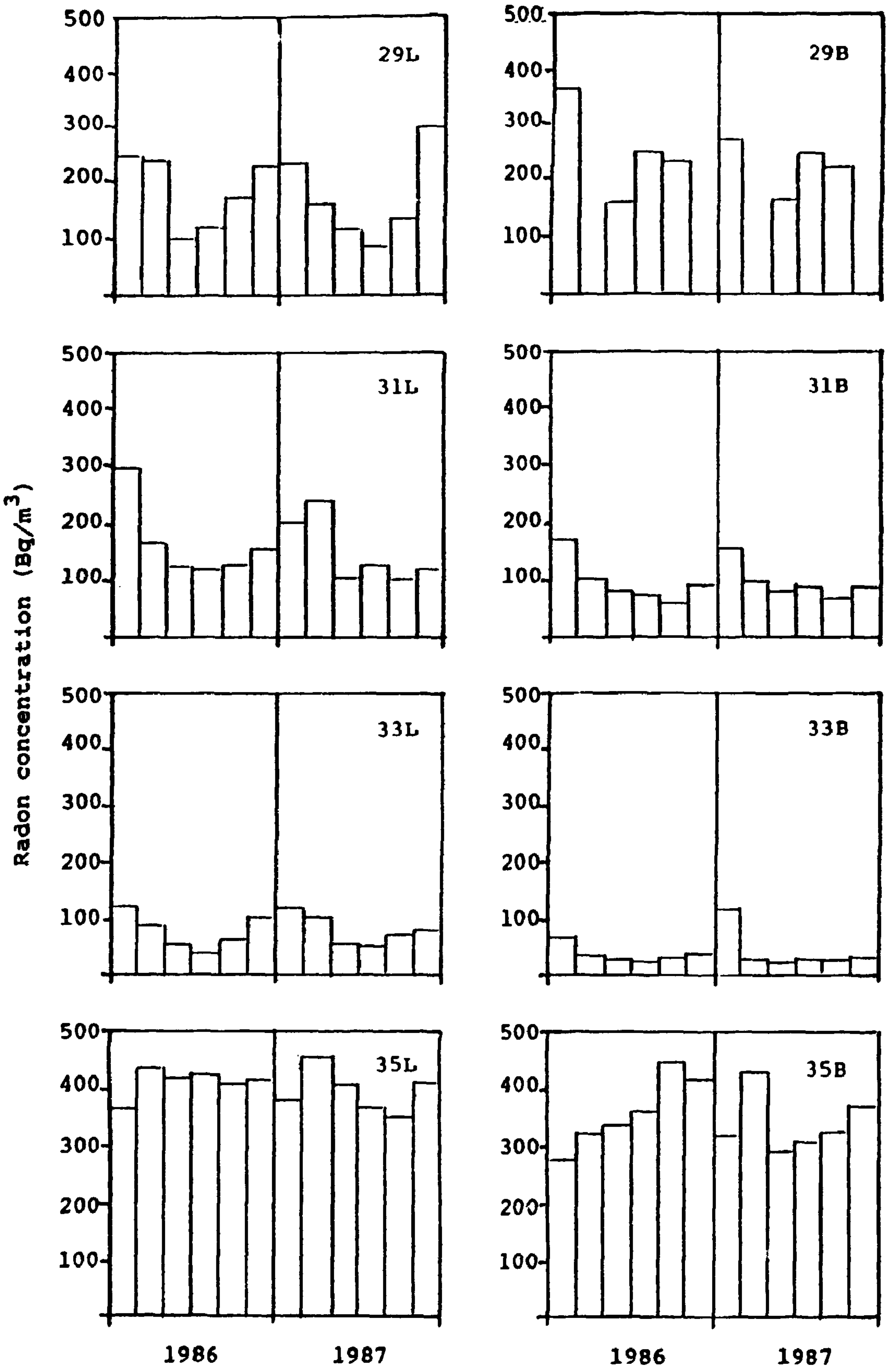


Figure 4.6. The average radon concentration per 2-month interval in 1986-1987 in the living-rooms (L) and bedrooms (B) of Risø house nos. 29, 31, 33 and 35.

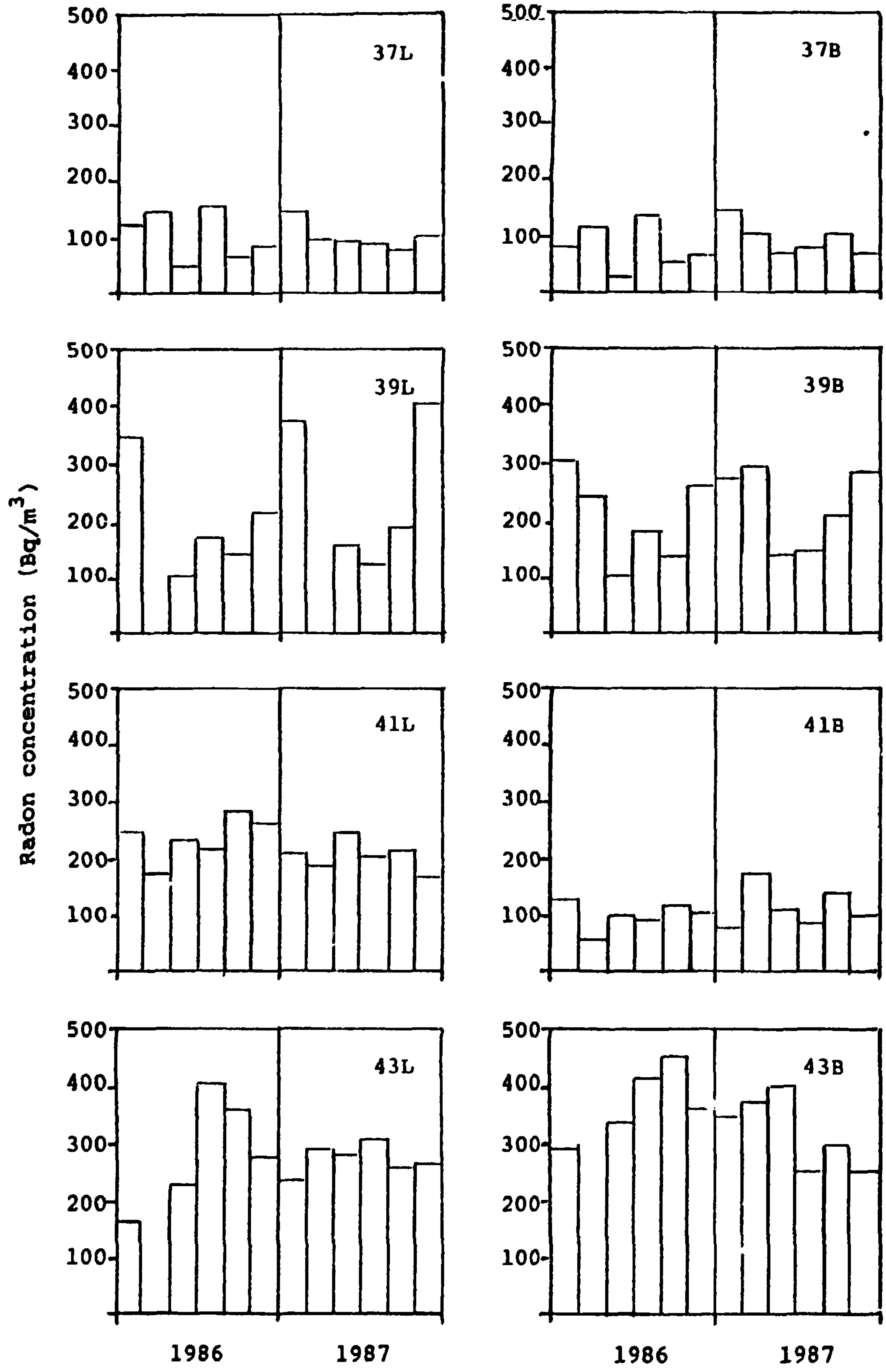


Figure 4.7. The average radon concentration per 2-month interval in 1986-1987 in the living-rooms (L) and bedrooms (B) of Risø house nos. 37, 39, 41 and 43.

In some cases an apparent increase in radon concentration occurred when a house was unoccupied for a period. This seems to be the case for house no. 27 during spring and summer 1986, and also for house nos. 37 and 39 during July-August 1986. On the other hand, house no. 17 was unoccupied during July-August 1986 without any apparent increase in the radon concentration.

Most of the houses exhibit a "normal" seasonal variation of radon concentration with a maximum during the winter and a minimum during the summer. Exceptions are house nos. 35, 41 and 43. For house nos. 41 and 43 this may be related to the difference in their type of foundation relative to that of the other houses (cf. section 2.2). The seasonal variations of the average radon concentration in the living-room, for two groups of four houses each, are shown in figures 4.8 and 4.9. The first group is composed of house nos. 19, 21, 23 and 33 (annual average 50-100 Bq/m^3), and the other of house nos. 13, 17, 29 and 31 (annual average 150-300 Bq/m^3). For both groups the average radon concentration is about a factor of 2 higher during the winter half-year (November-April) than during the summer half-year (May-October).

The annual average radon concentrations in 1986 and 1987 for the living-room and bedroom of the 16 houses are given in Table 4.4. For those living-rooms where results are available for all six 2-month periods in both years (13 houses), the average ratio of the radon concentration in 1987 to that 1986 is 0.93 with a standard deviation of 0.10. For the bedrooms, the corresponding ratio (for 11 houses) is 1.04 with a standard deviation of 0.10. For the living-rooms, the annual average radon concentrations (average for 1986 and 1987) range from 57 to 407 Bq/m^3. For the bedrooms they range from 38 to 354 Bq/m^3. The average radon concentrations for both rooms and both years range from 56 Bq/m^3 in house no. 33 to 380 Bq/m^3 in house no. 35.

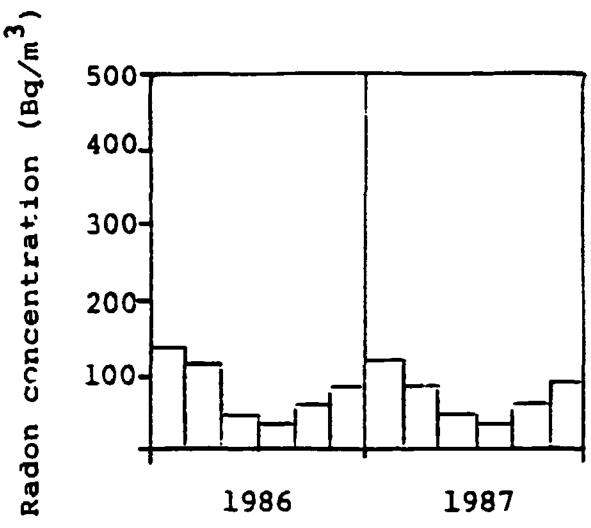


Figure 4.8. Seasonal variation (1986-1987) of the average radon concentration in the living-rooms of house nos. 19, 21, 23, and 33.

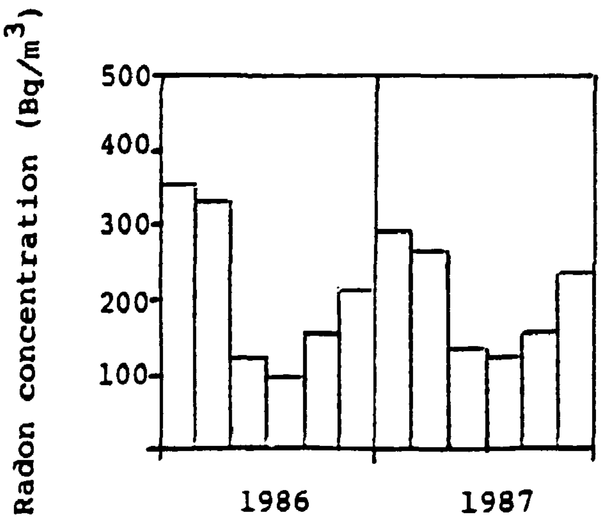


Figure 4.9. Seasonal variation (1986-1987) of the average radon concentration in the living-rooms of house nos. 13, 17, 29 and 31.

Table 4.4. Annual average radon concentrations (Bq/m^3) in the Risø houses for 1986 and 1987

House no.	1986 Living-room	1986 Bed-room	1986 Average	1987 Living-room	1987 Bed-room	1987 Average	Overall average$^{1)}$
13	233	208$^{2)}$	221	173	149	161	191
15	171	82	127	141	75	108	117
17	268	229	249	297	214	255	252
19	103	57	80	86.	64	75	78
21	60	65	63	53	59	56	59
23	79	75	77	82	79	81	79
25	130	90	110	132	106	119	115
27	192$^{2)}$	188$^{2)}$	190	153	132$^{2)}$	142	166
29	181	246$^{3)}$	213	168	224$^{3)}$	196	205
31	173	104	139	158	103	130	135
33	73	35	54	74	40	57	56
35	417	366	391	397	341	369	380
37	105	81	93	101	94	97	95
39	200$^{2)}$	214	207	254$^{2)}$	227	241	224
41	239	101	170	208	118	163	166
43	296$^{2)}$	378$^{2)}$	337	278	325	302	319

Notes: 1) Annual average for both rooms and both years

2) 10-month average

3) 8-month average

4.4. Continuous measurements at one house

Continuous measurements of a number of physical quantities were made inside and just outside Risø house no. 27 for a period of about 2-1/2 months (April 2 - June 16, 1986), when the house was unoccupied. All the inner doors in the house were kept open during the measurements, whereas the windows and outer doors were kept closed (except during the short times of entry or exit of persons).

The 5 continuous radon monitors were installed in the house as shown in Figure 4.10. The radon concentrations in the living-room and in a bedroom were monitored by monitor nos. 2 and 5, respectively. Monitor no. 3 monitored outdoor air, and monitor no. 4 the air in the district-heating duct. Monitor no. 1 monitored radon exhaled from the soil, yielding a relative measure of the exhalation rate as a function of time. The absolute exhalation rate was measured by grab sampling with scintillation flasks (ingrowth rate in an inverted drum).

The temperature indoors and outdoors, the atmospheric pressure and the differential pressure (outdoor - indoor pressure difference) were measured and logged into a datalogger as hourly mean values. The radon concentrations were also logged on an hourly basis. In addition, data on wind direction and wind speed at various heights above ground were obtained from the nearby Risø meteorological mast, and data on sunshine and rain during the period were obtained from Risø's department of meteorology and wind energy.

The air-exchange rate was measured by the tracer-gas technique. SF_6 was injected and mixed with the air in all rooms by means of small fans. The house was thus regarded as one compartment. The rate of decline of the SF_6 concentration was followed and the results converted to air-exchange rate. The air-exchange

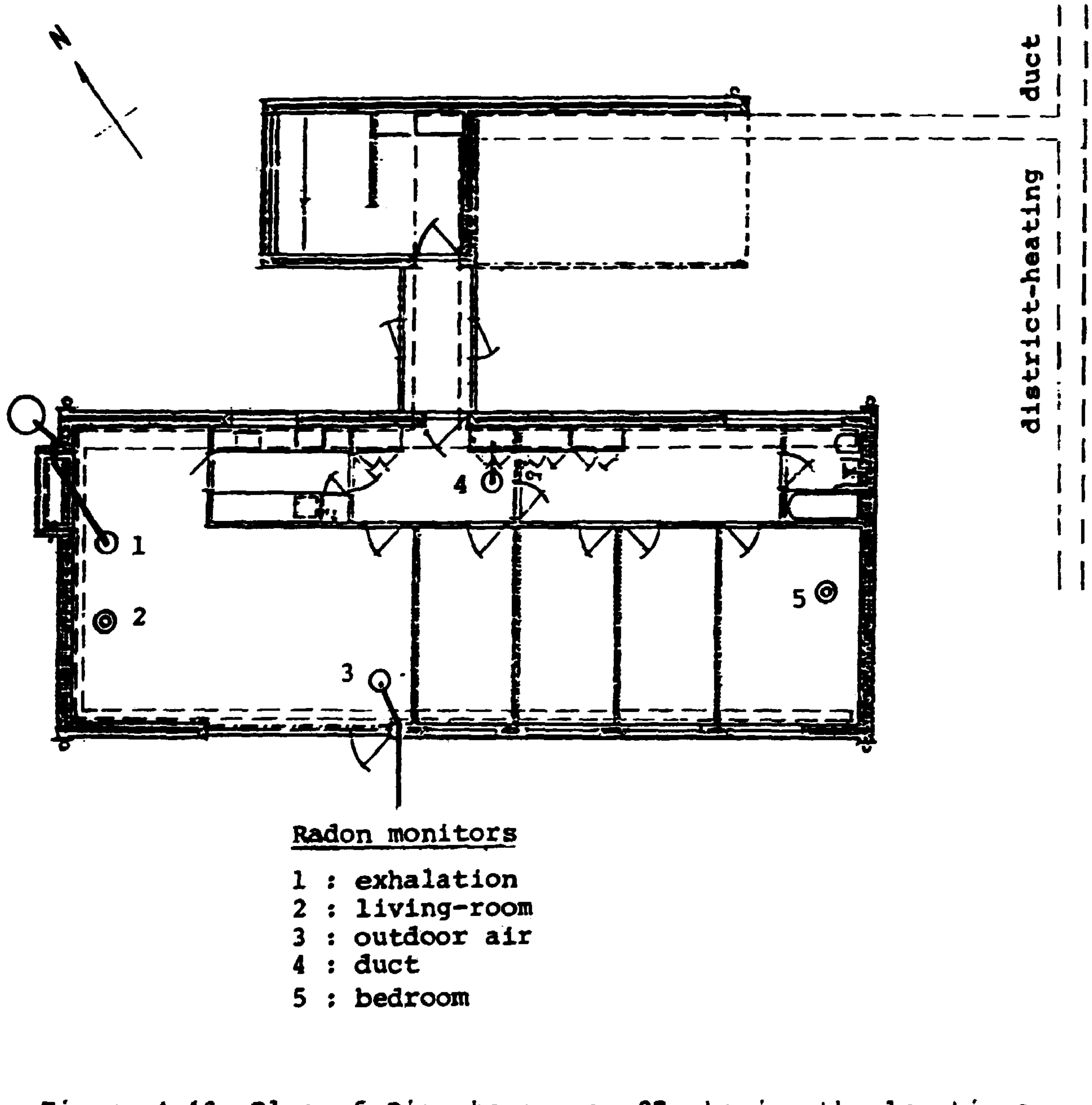


Figure 4.10. Plan of Risø house no. 27 showing the locations of the 5 continuous radon monitors, April 2 - June 16, 1986.

rate was measured 16 times during the period April 1-11. The results range from 0.24 to 0.41 air changes per hour with a mean value of 0.31 and standard deviation of 0.05. During the period April 14-24 a ventilator was blowing air out of the house in connection with another experiment. The ventilator yielded a depression of ΔP = 25 Pa and 3.8 air changes per hour which is unrealistic in an inhabited house. Nevertheless, the radon level did not change very much. From April 24 to 28 the air flow was reversed so that air was purged into the house. Not surprisingly, this caused the radon level to go down to low values in the house and also in the district-heating duct.

Figure 4.11 gives a general overview of the continuously measured radon concentrations and other quantities. The data obtained with monitor 3, which was monitoring outdoor air, have not been included, because they turned out to be erroneous, partly due to a leak of indoor air into the monitor and partly to an electronic failure. The collection of data on temperature and pressure was interrupted in two periods.

The collected data have been subjected to a number of correlation analyses. The data have been compared on an hourly basis and on other time bases, in full or in limited sub-periods. Furthermore, the wind speed, a directionally weighted wind speed, and the rate of change of atmospheric pressure have been included in the analyses.

For the data on an hourly basis, the highest correlation coefficient (0.96) was found for radon in the living-room and in the bedroom. This is not surprising as the inside doors in the house were kept open and the air was circulated with small fans. In the further analyses, the data on radon in the two rooms were combined to "radon in the house". Among the other parameters, only two sets had a correlation coefficient above 0.5: outdoor and indoor temperature (0.66), and radon in the house and in the district-heating duct (0.64).

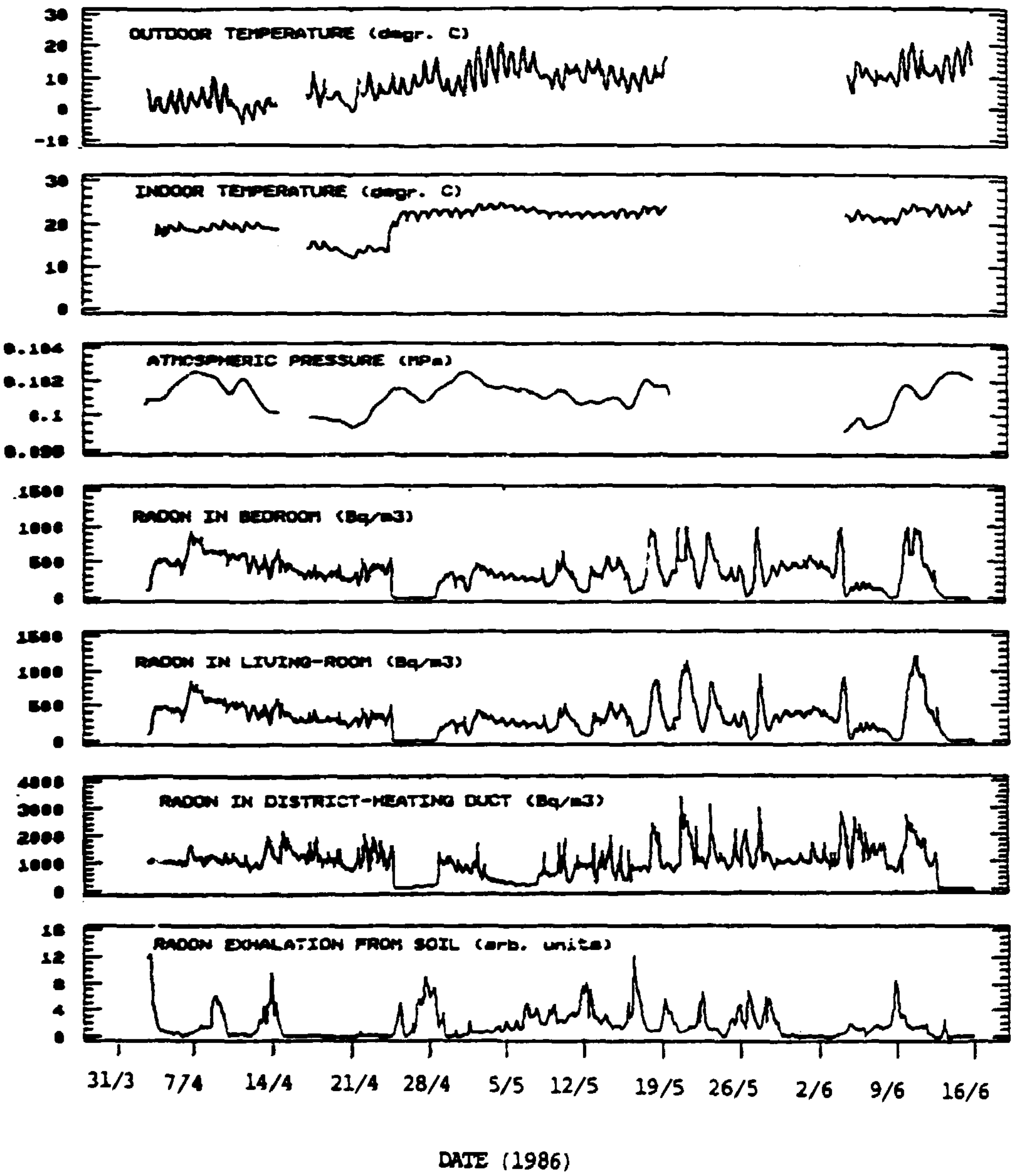


Figure 4.11. Continuously measured radon concentrations, temperatures and atmospheric pressure at Risø house no. 27, April 2 - June 16, 1986.

4.5. Continuous radon measurements in 5 houses

During the period March 4 - May 19, 1987, the radon concentration was monitored continuously in Risø house nos. 13, 17, 27, 33 and 35. House nos. 13 and 17 are situated in the part of the area characterised by a subsoil of mainly moraine clay, whereas the other 3 houses are situated in the part of the area that has a more mixed subsoil (cf. section 4.1). Moreover, nos. 13 and 17 have relatively high average indoor radon levels, whereas nos. 33, 27 and 35 have a low, medium and high average indoor radon level, respectively, compared with the other Risø houses (cf. section 4.3). Risø house nos. 33 and 35 are an example of two neighbouring houses, which have very different average indoor radon levels, but are otherwise identical.

The houses were occupied most of the time during the monitoring period, so, in order to limit the nuisance for the occupants, the continuous monitors were run as silently as reasonably achievable, i.e. with the pump disconnected and with stamping of data at 3-hour rather than hourly intervals. This implies that a 3-hour resolution was accepted in the registration of time variations in the radon concentration.

The variations of the radon concentration as a function of time are shown in figure 4.12 for the whole monitoring period. Diurnal variations are obvious in most of the houses during most of the monitoring period, although the radon concentration seems to vary in a different manner in house no. 35. The average diurnal variation of the radon concentration in each house normalized to the daily means is shown in figure 4.13.

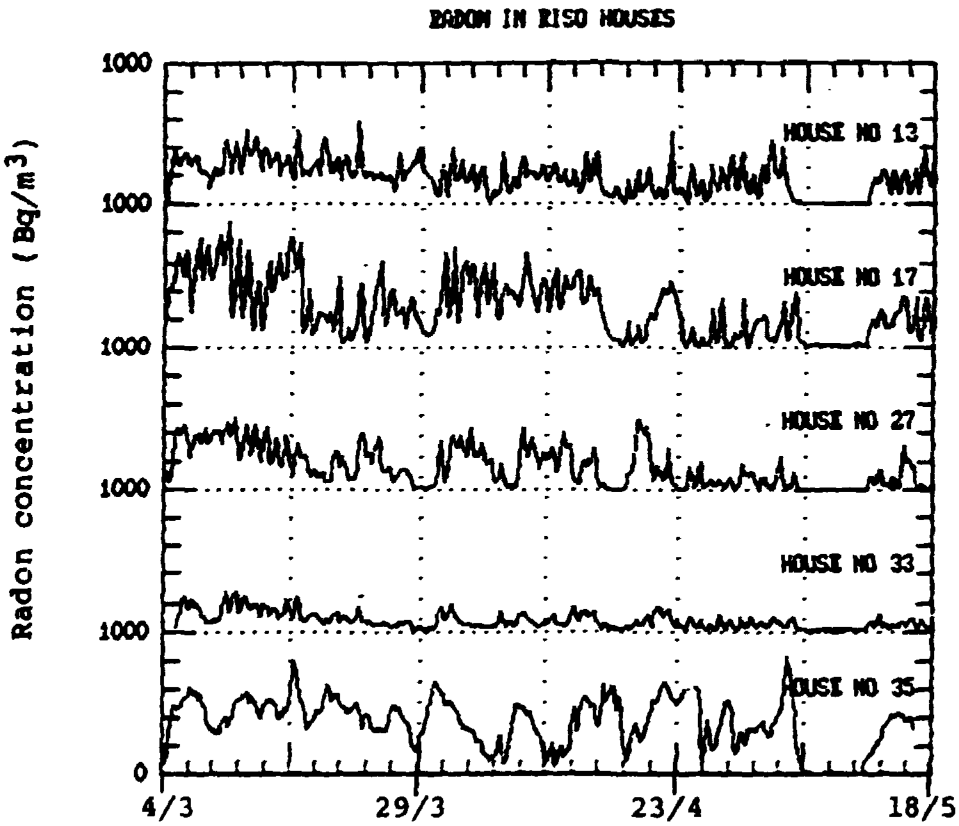


Figure 4.12. Continuously measured radon concentrations in 5 Risø houses during the period March 4 - May 18, 1987. From May 4 to May 11 a slightly lowered pressure was maintained in the district-heating duct (cf. section 4.6).

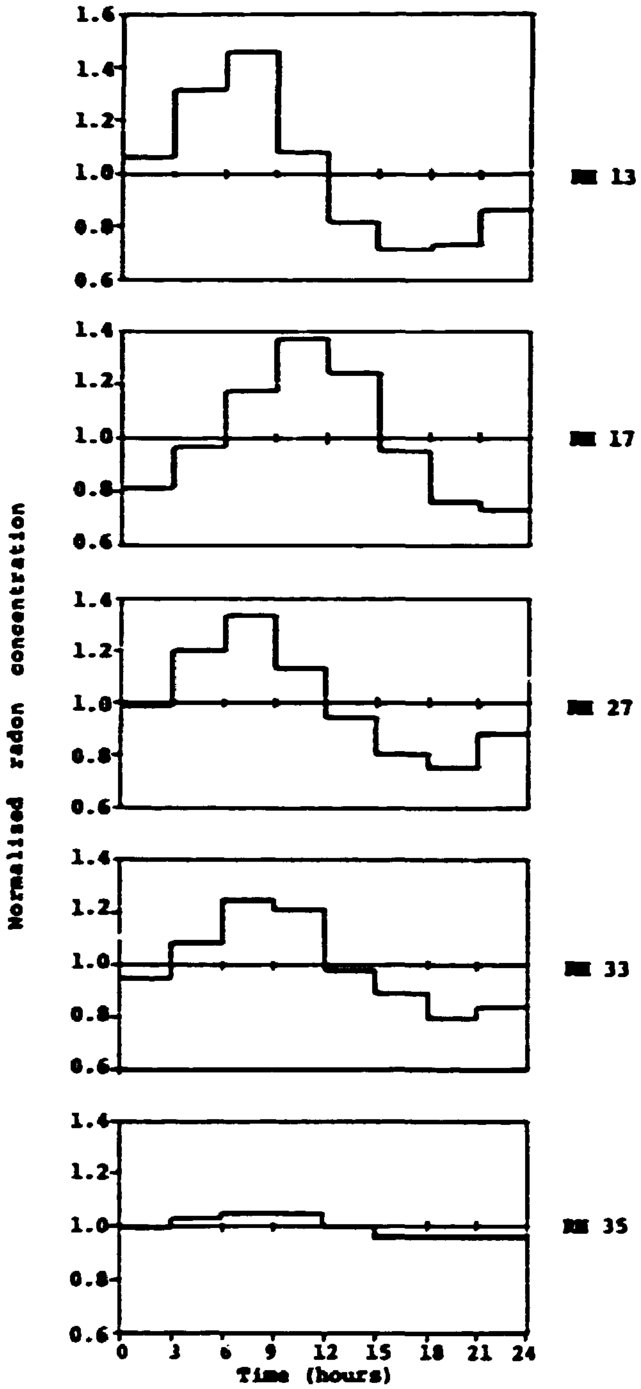


Figure 4.13. Average diurnal variation of the radon concentration for 5 Risø houses normalized to the daily means for the period March 4 - May 18, 1987. (Data from the period May 4-11, when a slightly lowered pressure was maintained in the district-heating duct, have not been included). The standard errors of the values are typically about 4%.

4.6. Effect of maintaining a slightly lowered pressure in the district-heating duct

During the period November 28 - December 8, 1986, an experiment was performed in order to investigate the effect of maintaining a slightly lowered pressure in the district-heating duct. Continuous radon monitors were installed in house nos. 13, 17, 31 and 43. The monitors were operated with the pump running and with stamping of data every hour. From December 3 at 10 a.m. to December 5 at 2 p.m. a ventilator was operated, so that a depression of about 5 Pa was maintained in the district-heating duct. The ventilator was replacing one of the lids covering an entry point to the district-heating duct (situated north of and near to house no. 15). The variations of the radon concentration in the houses are shown in figure 4.14. It is obvious that the radon concentration in the houses is strongly reduced during the period when the lowered pressure is maintained in the duct, although it is not kept as low in house no. 43 as it is in the other 3 houses. (No. 43 is situated at the farthest end of the duct (cf. figure 2.1)).

A similar experiment was carried out in connection with the continuous measurements of radon in 5 of the houses during March - May 1987 (cf. section 4.5). In this case the ventilator was operated for a week, i.e. from May 4 at 1 p.m. to May 11 at 1 p.m. The ventilator was installed at the same location as mentioned above, and the depression in the duct was maintained at about 5 Pa. The influence on the radon concentration in the houses is obvious from figure 4.15. The radon concentration is strongly reduced in all 5 houses during the period when the lowered pressure is maintained in the duct.

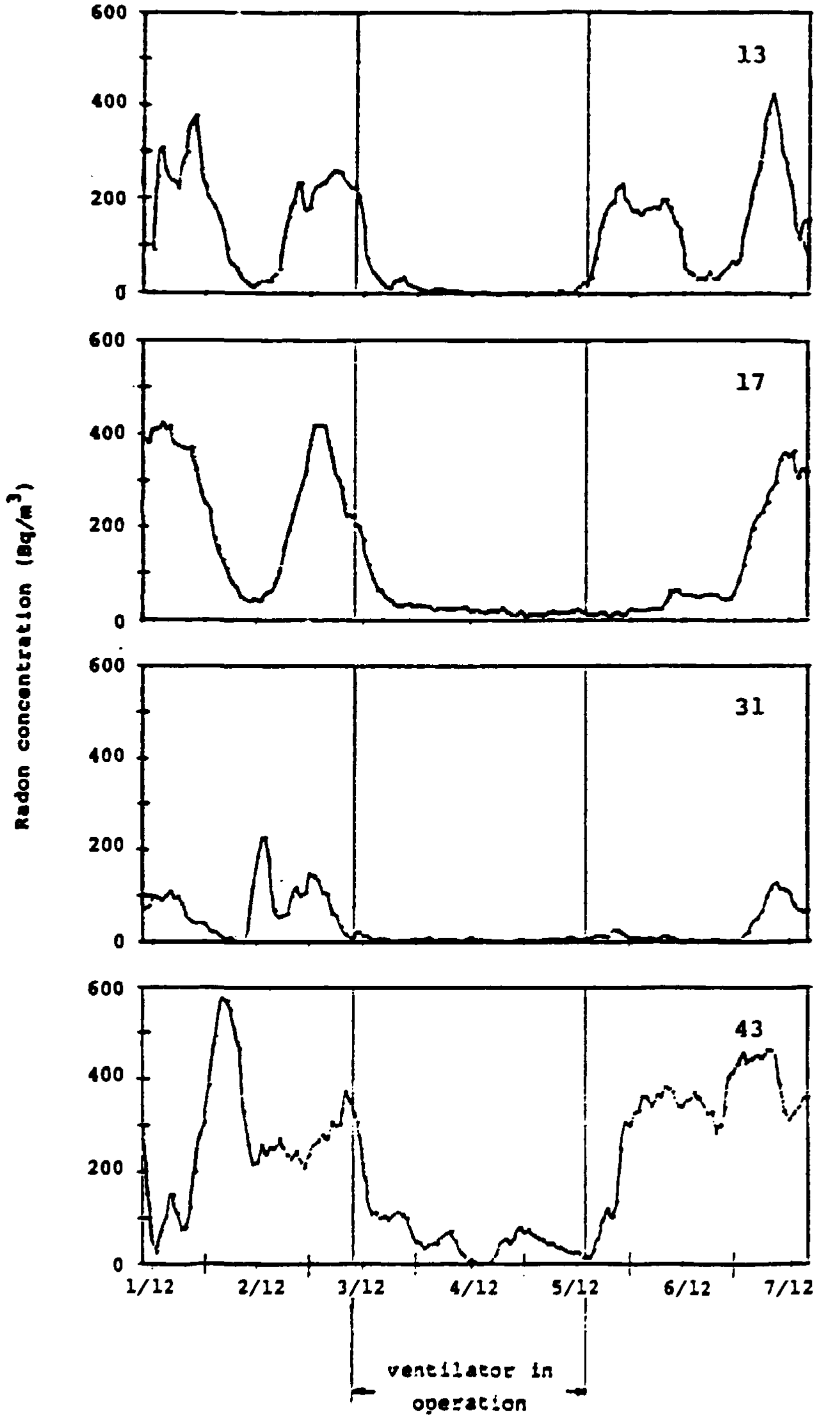
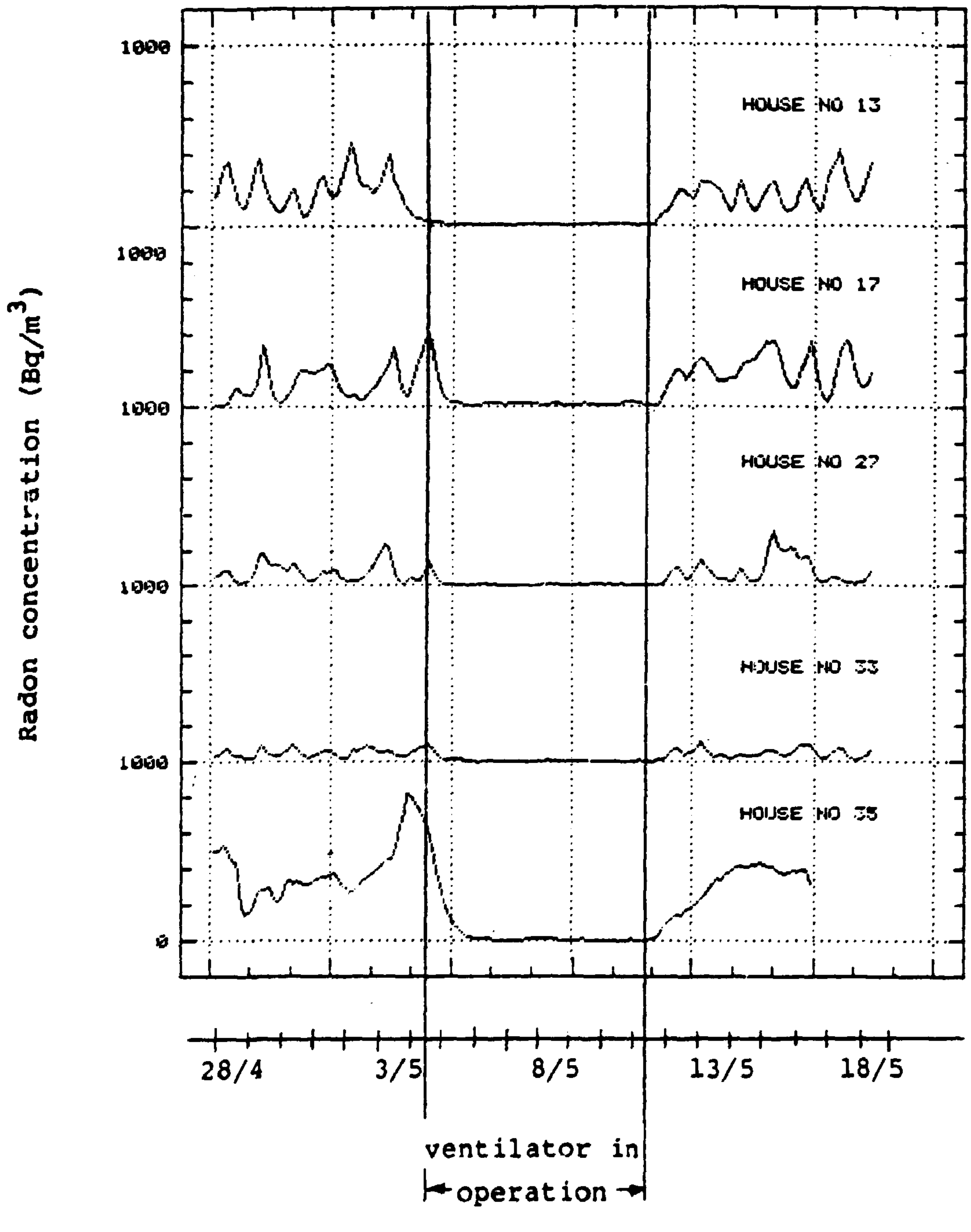


Figure 4.14. Radon concentrations in Risø house nos. 13, 17, 31 and 43 during the period December 1-7, 1986. From December 3 at 10 a.m. to December 5 at 2 p.m. a depression of about 5 Pa was maintained in the district-heating duct.



<u>Figure 4.15.</u> Radon concentrations in Risø house nos. 13, 17, 27, 33 and 35 during the period April 28 - May 18, 1987. From May 4 at 1 p.m. to May 11 at 1 p.m. a depression ot about 5 Pa was maintained in the district-heating duct.

5. Discussion

5.1. Relations between soil characteristics, radon in soil gas and indoor radon concentrations

The soil in the investigated area is composed mainly of moraine clay. However, deposits with a more mixed and permeable composition were found in a sub-area (cf. Appendix I). No geological deposits with an unusually high - or low - radon emanation were found.

House nos. 27, 29, 31, 33 and 35 are situated in the sub-area characterized by mixed deposits (cf. Figure 1 in Appendix I). In these 5 houses, the annual average radon concentrations range from 56 to 380 Bq/m^3 with an arithmetic mean of 188 Bq/m^3 and a standard deviation of 120 Bq/m^3 (cf. Table 4.4). In the remaining 11 houses, the annual average radon concentrations range from 59 to 319 Bq/m^3 with an arithmetic mean of 154 Bq/m^3 and a standard deviation of 84 Bq/m^3. Hence, the distribution of indoor radon concentrations within the sub-area does not seem to be significantly different from that in the rest of the area.

The grab samples of soil gas taken at a depth of 50 cm on November 18-19, 1986, showed radon concentrations from 12 to 82 kBq/m^3 (cf. Figure 4.1). The highest values were 76 kBq/m^3 adjacent to bore hole no. 17 and 82 kBq/m^3 adjacent to bore hole no. 31, i.e. both in the "moraine clay" part of the area (cf. Figure 1 in Appendix I).

The grab samples taken during the period March 24 - May 13, 1987, at house nos. 13, 17, 27, 33 and 35 showed radon concentrations from 4 to 75 kBq/m^3 (cf. Figure 4.3). The average soil-gas radon concentrations were higher at house nos. 27, 33 and 35 (situated in the sub-area with a mixed soil composition) than they were at house nos. 13 and 17 (situated in the "moraine clay" part of the area).

The indoor radon levels do not appear to be correlated with the radon levels in soil gas near the houses. However, the results of the soil gas measurements clearly demonstrate the potential of the soil to act as a source of high indoor radon levels.

In a Swedish proposal for classifying radon risks from the ground, quoted in the Nordic recommendations on naturally occurring radiation (RP86), the ground is classified as "high", "normal" or "low" radon ground, according to a number of criteria. "Normal" radon ground includes ground with soil-gas radon contents of 10 - 50 kBq/m^3 (for clay up to 100 kBq/m^3). Houses on "normal" radon ground should be built with a "radon protective" construction. According to this classification, the area of the Risø houses would be considered as an area with "normal" radon ground.

5.2. Relations between indoor radon concentrations and meteorological parameters

The analyses of the data collected at house no. 27 during April 2 - June 16, 1986, showed no or only weak correlations between the time variations of the radon concentrations and the meteorological parameters. The average diurnal variation of the radon concentration in the house showed a maximum in the morning, as did also the average diurnal variations in the 5 houses monitored during March 4 - May 18, 1987. This variation indicates that pressure-difference-driven flow of soil gas into the houses is the predominant mechanism of radon entry (Ar87).

The seasonal variations of the radon concentrations in 1986-1987 showed a maximum in the winter and minimum in the summer in most of the houses, which also indicates that the predominant mechanism of radon entry is pressure-difference-driven flow of soil gas (Ar87). Exceptions were house nos. 35, 41 and 43 (cf. Figures 4.6 and 4.7). For house nos. 41 and 43 this may be related to the difference of their type of foundation relative to the other houses. No. 43 has a crawl space and 41 has both a crawl space and cellar. Seasonal variations of the indoor radon concentration with winter/summer ratios around one or smaller than one have been observed previously in some Danish dwellings (Sø85), and in other countries as well, e.g. in Finland (Ar87).

For the majority of the houses, which showed a "normal" seasonal variation of the radon concentration, the variations are closely related to the indoor-outdoor temperature difference. Figure 5.1. shows the variation of the average outdoor temperature at Risø on a 2-month basis in 1986 and 1987. This variation has been compared with the variations of the average radon concentrations on a 2-month basis in the living-rooms of two groups of four houses each (cf. Figures 4.8 and 4.9). Linear regression analyses showed correlation coefficients between outdoor temperature and indoor radon for the two groups of

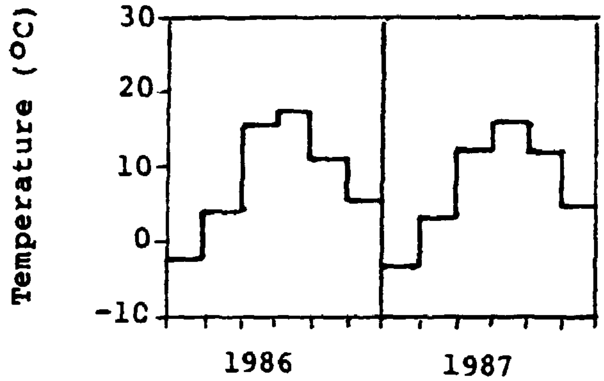


Figure 5.1. The average outdoor temperature at Risø per 2-month interval in 1986 and 1987.

houses of -0.98 and -0.95 for 1986, -0.98 and -0.98 for 1987, and -0.96 and -0.94 for 1986 + 1987. As the variations of the average indoor temperature are small compared with those of the outdoor temperature, the results indicate that a strong correlation exists between the average indoor radon concentrations and the average indoor-outdoor temperature difference.

5.3. Possible remedial measures

The International Commission on Radiological Protection (ICRP) has published principles for limiting exposure of the public to natural sources of radiation (IC84). For existing dwellings, the ICRP suggests an action level that corresponds to an annual average radon concentration of about 400 Bq/m^3 (200 Bq/m^3 equilibrium equivalent radon concentration (EER)). At this action level, simple action to reduce the radon exposure might be considered. In the Nordic recommendations on naturally occurring radiation (RP86), it is recommended that possibilities for remedial action should be considered, if the average radon concentration exceeds about 200 Bq/m^3 (100 Bq/m^3 EER).

In 1986 and 1987 the annual average radon concentration did exceed 200 Bq/m^3 in 5 of the Risø houses, cf. Table 4.4. However, the levels were not excessive, as they were all below the action level of about 400 Bq/m^3 suggested by the ICRP.

In this investigation it has been demonstrated that one possible remedial measure that could be taken against radon in the Risø houses would be to maintain a slightly lowered pressure in the district-heating duct, which is connected to all the houses (cf. section 4.6). This measure would have the advantage that it would apply to all the houses simultaneously.

Alternatively, passive remedial measures in the individual houses with the highest radon levels might be considered. In house nos. 43 and 41, increased ventilation of the crawl space might be applied. In the other houses, sealing of possible leakage paths might be applied, after identifying the main entry points of soil gas into each house.

6. Conclusion

In this work it has been shown that the annual average radon concentration in the 16 Risø houses varies from about 50 to about 400 Bq/m^3. The soil in the area has been characterized, and measurements of radon in soil gas have been carried out. The results of the soil investigations could not be directly related to the variations in the average indoor radon concentrations, but the potential of the soil in the area to act as a source of relatively high indoor radon levels was demonstrated.

The observed diurnal and seasonal variations of the indoor radon concentrations indicate that pressure-difference-driven flow of soil gas into the houses is the predominant mechanism of radon entry. For most of the houses, the variations of the average radon concentration on a 2-month basis were closely related to the variation of the average indoor-outdoor temperature difference. In three of the houses, deviating seasonal variations of the radon concentration were observed. Two of these houses have foundations which differ from those of the other Risø houses.

It has been demonstrated that the radon concentration can be strongly reduced in the Risø houses if the district-heating duct is ventilated, so that a slightly lowered pressure is maintained in the duct.

Acknowledgements

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Appendix I.

Summary of soil investigations at the Risø houses

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Geology and radon at Risø Huse

The Department of Electrophysics at the Technical University of Denmark has investigated the geology at Risø Huse in order to find a possible correlation between the indoor radon concentrations and the local geology. Three questions have been in focus:

1. Does the permeability of the geological deposits vary from one location to another inside the Risø Huse area?

2. Are there within the Risø Huse area geological deposits with unusual high - or low - radon emanation?

3. Are there other geological factors - e.g. the level of the ground water - that could influence the inflow of radon to the buildings.

....oooo....

In order to answer these questions the following investigations have been carried out:

A. 11 boreholes have been drilled to depths ranging from 2,70 m to 6,50 m. The diameter of the holes was app. 100 mm. During the drilling the lithology vs. depth was recorded.

B. During the drilling 113 samples were collected for examination in the laboratory. The lithology of the samples was investigated and their content of uranium/radium, thorium and potassium was measured.

C. The specific radon-emanation of 92 samples was measured in the laboratory.

D. Spectral Natural Gamma-ray logs were run in all 11 boreholes. The purpose of the logging was to check the lithological log and to assure that thin layers with a high content of radium had not been missed during the sampling.

E. The lithology/geology around the boreholes was further validated by measurements in the boreholes with a neutron-moisture probe and a gamma-density probe.

F. The geology around two neighbouring houses with very different radon content was investigated by drilling 18 holes to a maximum depth of 3,0 m (diameter = 20 mm).

GEOLOGY

The existing geological maps for the Risø Huse area indicated prior to the investigations that the area around Risø Huse was composed everywhere by moraine clay i.e. clay with a content of sand and/or silt and/or gravel. Thus a low permeability for both water and radon should be expected.

The investigations showed, however, a more complex situation. Within the North-eastern part of the Risø Huse area were found sandy deposits with a high permeability for water. A "water table" was found app. 2.5 m below the surface in 5 boreholes (100 mm diameter) whereas no water was found in the remaining 6 boreholes. The figures 1 and 2 show the distribution of the permeeble deposits.

Figure 1 shows a map of the Risø Huse area. The boreholes are indicated with their identification numbers e.g. #M3, and the buildings are identicated with their "street numbers". In the boreholes #27A, #27B, #M3, #33 and #35 ground water was found at a depth of app. 2.5 m below the surface. In the other boreholes no water was detected.

The position of the water table in the boreholes was measured twice - at the drilling time and 3-5 months later. Only minor variations in the depth of the water table were found. When water was taken from the boreholes, the water level returned to its original position within a few minutes. No pumptests were however performed, and it is not known whether the boreholes with water are interconnected.

The area with ground water is indicated in the map (figure 1). The permeable layer(s) may be due to diluvial deposits of sand and silt; the deposits have, however, been disturbed by later ice-age glaciers.

RADIOACTIVITY AND RADON EMANATION.

The laboratory measurements revealed no samples with unusual concentrations of natural radioactive elements, and the emanations of radon were within the range known from other Danish Quarternary deposits. Table 1 shows the measured values for borehole #M1. 11 samples were taken during the drilling (to a depth of 5.90 m.) The concentration of radium-226 varied from 20 to 26 Bq per kg - corresponding to 1.6-2.1 ppm eU. The emanation of radon-222 varied from 5.8 to 13.4 atoms per kg and sec. (Samples having the original moisture content).

The 92 samples (taken from all boreholes) showed radon emanations ranging from 4.1 to 17.3 atoms per kg and sec. 12 samples snowed emanations above 10 atoms per kg and sec. i.e. above typical emanations for Danish moraine clay. Almost all samples with emanations above 10 atoms per kg and sec. (10 out of 12) were taken from the uppermost app. 100 cm of the boreholes #M1, #13, #27A, #27B, #35 and #41. This distribution of samples with high radon emanations cannot easily be correlated to the distribution of the geological deposits.

EXAMINATION OF THE SOIL AROUND THE HOUSES NO.33 AND 35.

Measurements of the radon concentrations in the houses no. 33 and 35 had unveiled large differences. Therefore it was decided to perform a more detailed examination of the geology/lithology around those houses. 18 holes with a diameter of 22 mm vere drilled to a maximum depth of 300 cm. They showed large differences in the lithology within distances

of less than 1 meter - both vertical and horizontal.
At depths of more than 2 m the ground at house no.35 was very moist whereas only minor amount of moisture was detected at house no.33.

CONCLUSION.

The investigations have shown that the geology/lithology vary very much within the Risø Huse area. The main results are indicated in figure 2, which shows a vertical cross section of the area from North-East to South-West. Within the area named "Mixed deposits" were found deposits ranging from coarse sand to clayey sand and moraine clay. Outside that area was found moraine clay everywhere.

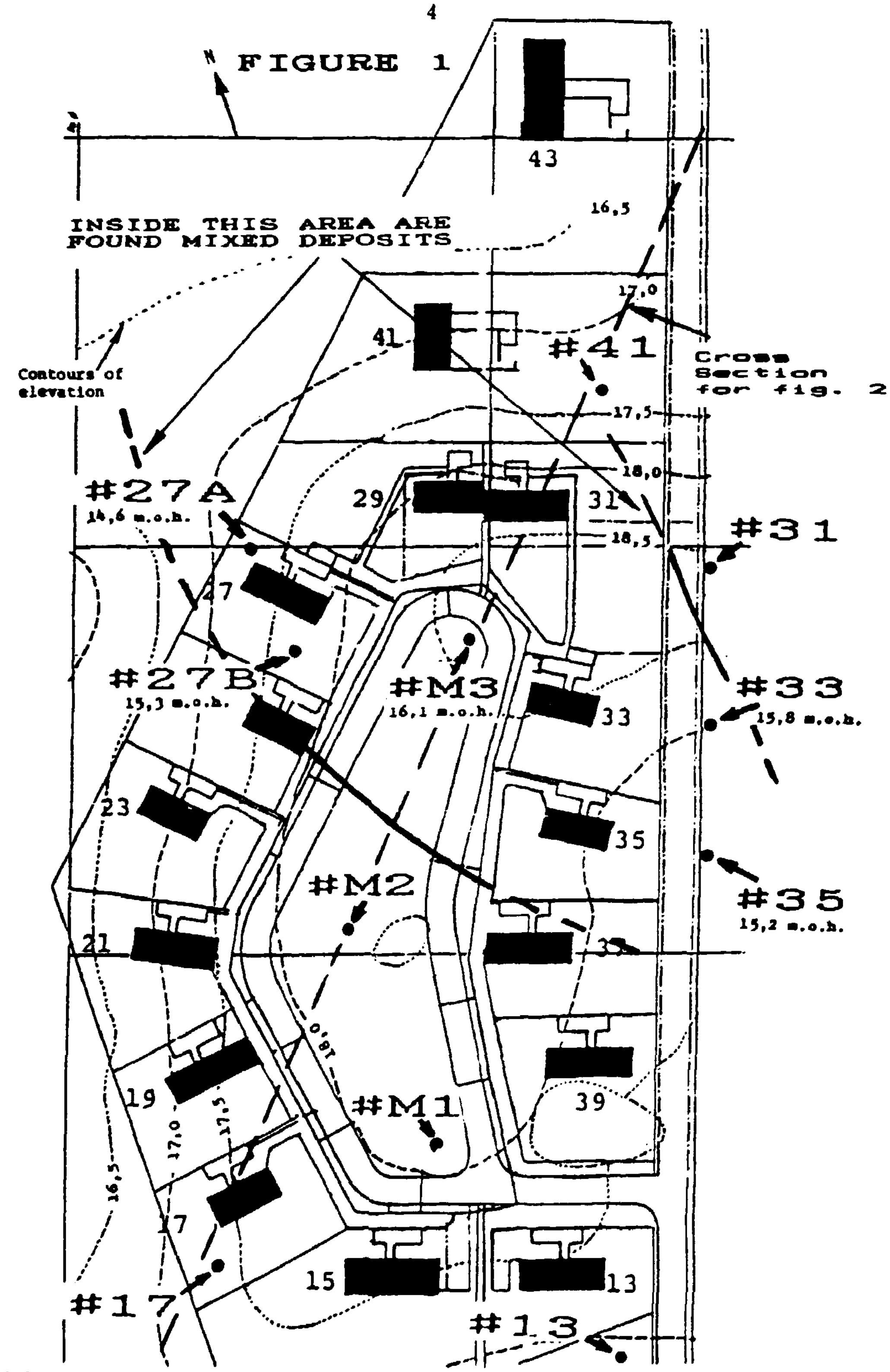
Measurements of samples taken at different depths in different boreholes unveiled radon emanations that varied from 3.8 to 17.3 atoms per kg and sec. 12 samples (moraine clay) had emanations above 10 atoms per kg and sec. which are above typical radon emanations of Danish moraine clay. Ten of those samples were collected from the uppermost app. 100 cm of the boreholes. However, no correlation was found between the geology and the ten samples.

It has not been possible to establish a connection between the geology/lithology of the area and the radon concentrations in the houses. The results of the investigations indicate that the geology/lithology might influence the radon concentrations in the houses in the following ways:

a. Permeable deposits were found, and they may act as a "flow channel" for soil gas with radon above the water table. Thus the answer to question no.1 is "yes"; the permeability of the geological deposits do vary within the Risø Huse area.

b. The radon emanation from samples taken at a depth of 0-100 cm from different boreholes vary from 4.9 to 17.3 atoms per kg and sec. The emanation from the samples of moraine clay are slightly higher than the average for Danish moraine clay, but the emanations are not exceptional. For question no.2 the answer is "no"; there have not been found unusual high - or low - radon emanations.

c. The mechanical integrity of the houses might have been threatened differently due to the large variation in the geology/lithology across the Risø Huse area - i.e. development of cracks in the membranes (bottom plates of the houses) between the soil and the inside of the houses might be more probable at some locations than in other locations. Thus the question no.3 should be answered with a "yes"; there have been found other geological factors that could influence the inflow of radon to the buildings.



MAP OF THE RISØ HUSE AREA
WITH POSITIONS OF THE BOREHOLES

In the boreholes M3, 27A, 27B, 33 and 35 was found ground water. The level of the water table is given in meters above sea level.

GEOLOGICAL PROFILE BETWEEN BOREHOLE #41 AND #17

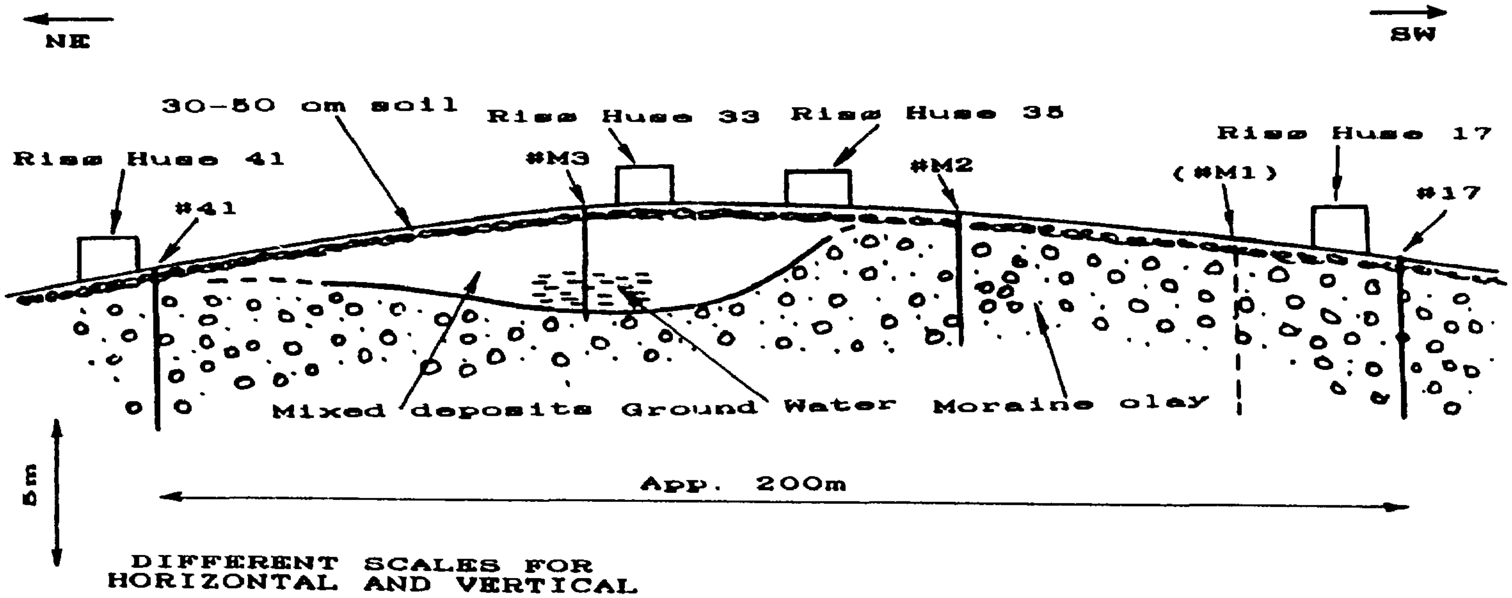


FIGURE 2

The mixed deposits with ground water extend (at least) 30-50 m towards South-East and towards North-West

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Table 1. DATA FOR SAMPLES FROM BOREHOLE #M1

Sample no.		Depth cm	Th ppm	U ppm	K %	Moisture %	Emanation atoms per (kg*sec.)
1	Soil, light brown	0-50	7.6	2.0	1.92	6.0	12.7
2	Soil, clayey, with gravel, brown	75-95	6.4	1.6	1.76	8.2	13.4
3	Clay, sandy with gravel, brown	140-170	5.5	1.6	1.47	6.4	7.2
4	Clay, sandy with gravel, brown/yellow	175-205	6.1	2.0	1.52	12.5	6.7
5	Similar to sample no. 4	225-250	6.1	2.0	1.57	11.4	7.5
6	Clay with gravel, sandy, olive-brown	295-315	5.7	2.1	1.51	14.4	6.7
7	Clay and gravel, light olive-brown	360-390	5.3	1.6	1.48	9.6	5.6
8	Similar to sample no. 7.	425-455	5.4	1.7	1.43	11.6	5.6
9	Clay. sandy with some gravel, light ol. br.	470-490	5.1	1.7	1.39	12.1	6.1
10	Clay and gravel light olive-brown	510-535	5.4	1.8	1.45	11.2	5.8
11	Similar to sample no. 10.	575-590	5.1	1.7	1.41	6.7	5.8

Risø National Laboratory **Risø - M - 2689**

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Abstract (Max. 2000 char.)

Variations in indoor radon concentrations and some influencing factors have been studied during a two-year period (1986-1987) in 16 almost identical single-family houses. The annual average radon concentration in the houses varied from about 50 to about 400 Bq/m^3. Variations in soil characteristics and radon concentration in soil gas could not be directly related to the variations of the average indoor radon concentrations. Most of the houses showed a "normal" seasonal variation of the radon concentration with a maximum in the winter and minimum in the summer. A deviating seasonal variation was found in three of the houses. Hourly data obtained in one unoccupied house during a period of 2-1/2 months showed no or only weak correlations between the indoor radon concentration and meteorological factors. However, for most of the houses, the seasonal variation of the indoor radon concentration was well correlated with the average indoor-outdoor temperature difference on a 2-month basis. It was demonstrated that the radon concentration can be strongly reduced in the Risø houses if a district-heating duct, which is connected to all the houses, is ventilated, so that a slightly lowered pressure is maintained in the duct.

Descriptors - INIS

DOSE RATES; HOUSES; RADIOECOLOGICAL CONCENTRATION; RADON; SEASONAL VARIATIONS; SOILS; VENTILATION

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