Technical University of Denmark

A pilot investigation of natural radiation in Danish houses

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A PILOT INVESTIGATION OF NATURAL RADIATION IN DANISH HOUSES

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Abstract. As a prelude to a nationwide survey a pilot study was carried out to establish techniques and procedures for the measurement of indoor radiation in Denmark. A passive cup dosemeter was designed containing CR39 track detectors and TLD's to measure radon and external radiation, respectively. The adequate performance of the dosemeter was verified in a radon intercalibration in 1984 carried out at the National Radiological Protection Board, UK.

A total of 82 dwellings were selected covering most regions of the country. The dwellings were monitored in two three-month periods, one in winter and the other in summer.

The average dose rate in air from external radiation was 0.09 μGy h^{-1}. In the winter the average radon concentrations were 88 Bq m^{-3} and 24 Bq m^{-3} for single-family houses and flats, respectively; and in the summer the corresponding values were 52 Bq m^{-3} and 19 Bq m^{-3}.

The study was partly financed by the Commission of the European Communities (contract No. BIO-F-555-DK(AD), 1983/84).

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CONTENTS

1. INTRODUCTION AND SUMMARY

The present study was conducted to investigate measurement techniques, establish procedures for a subsequent nationwide survey, and get a first impression of radiation levels in Danish dwellings. The study was partly financed by the Commission of the European Communities (contract No. BIO-F-555-DK(AD), 1983/84).

A passive cup dosemeter was designed to measure radon and external radiation. In this report the term "external radiation" includes the secondary cosmic radiation and the ambient gamma radiation. The dosemeter was used for integrating measurements in the pilot survey described below.

Active measurements of radon and radon daughters were made with scintillation flasks and gross alpha sequential counters, respectively. Active measurements of external radiation levels were made with a high-pressure ionization chamber and a plastic scintillator.

A 200 liter steel barrel with a $7 \cdot 10^3$ Bq RaCl source was used for calibration of the cup dosemeter. The radon concentration in the barrel was around 30 kBq m^{-3}. Furthermore, a 6 m^3 cellar room with a radon concentration around 2.5 kBq m^{-3} was used for calibration purposes.

Calibration of the instruments used to measure radon, and radon daughters was based upon the calibration of the scintillation flasks. The absolute calibration of this system was compared with the National Radiological Protection Board, UK, in 1982 and 1984 at CEC-organized intercalibration meetings. Comparisons have also been made with three Danish Laboratories. The calibration of radon daughter measurement equipment was carried out by comparing radon and RaA concentrations in the cellar room under conditions of equilibrium between the two.

The pilot survey of radiation levels in Danish houses comprised 82 dwellings distributed over most regions of the country. Of the dwellings 10 were flats and 72 were single-family houses with one or two floors. Integrating measurements were made in a three-month winter (1 Dec. 1983 to 29 Febr. 1984), and a three-month summer period (22 May to 13 Aug. 1984).

The dose rates from external radiation do not differ from winter to summer. The mean value for all dwellings is 0.09 μGy h^{-1}. Minimum and maximum values are 0.06 and 0.13 μGy h^{-1}, respectively. The mean dose rate for brick houses is 0.09 μGy h^{-1}. The corresponding values for concrete and wood houses are 0.08 μGy h^{-1} and 0.06 μGy h^{-1}, respectively. The active spot measurements of gamma radiation are in good agreement with the TLD results.

The results of the measurements of radon concentrations showed a marked difference between the winter and summer periods, and also between flats and single-family houses. The geometric mean values of Rn-222 for single-family houses were 88 Bq m^{-3} in winter and 52 Bq m^{-3} in summer. The corresponding values for flats were 24 and 19 Bq m^{-3}.

In single-family houses the parameters of importance for the radon concentration are ingress from the ground, air exchange and building materials. The ingress from the ground accounts for the generally higher concentrations in single-family houses than in flats. During the winter the rate of exchange between inside and outside air is kept rather low in Danish houses and the differences in radon concentrations between living-rooms, bedrooms and even basement rooms were found to be insignificant. On the other hand, significant differences were found in the summer period, where the mean values were 55 Bq m^{-3} in living-rooms, 43 Bq m^{-3} in bedrooms and 82 Bq m^{-3} in basement rooms.

The simultaneous active measurements of radon and radon daughters showed a wide variation in the value of the equilibrium factor F. In the winter period F ranges from 0.2 to 1.0 with a geometric mean value of 0.4. In the summer period the range is 0.1 to 0.8 with a geometric mean of 0.2.

The mean annual effective dose equivalent from radon was calculated to be H = 1.7 mSv. The corresponding value for external radiation was 0.8 mSv.

2. MATERIALS AND METHODS

2.1. The passive dosemeter

The passive dosemeter has been designed to measure radon as well as external radiation. It is a closed cup dosemeter. The sensitive elements are CR39 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. 1. The cup is a commercially available plastic container, 7.5 cm in diameter and 5.5 cm high (outer dimensions). It is provided with a perforated lid with 6 holes, (each having a diameter of 5 mm) and a glass fibre filter (Whatman GF/A). 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 two pieces of CR39, is placed on top of the TLD package. The 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. Generally, only one of the two pieces of CR39 is etched and counted. The other piece acts as a back-up detector.

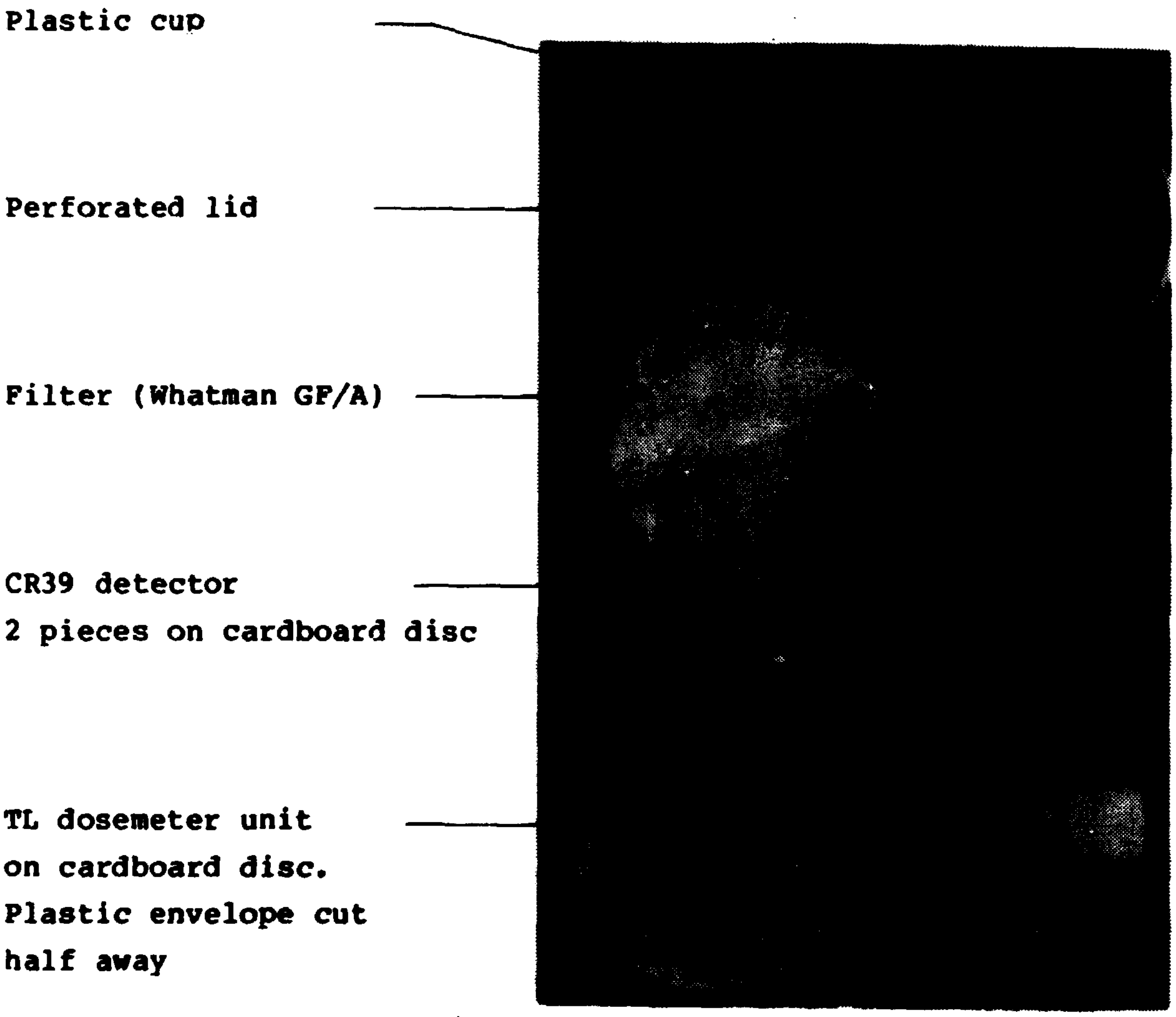


Fig. 1. Exploded view of the cup dosemeter.

2.2. CR39 and TLD procedures

The CR39 detectors were cut to a size of about 13 mm x 30 mm from sheets of a thickness of about 500 µm obtained from Pershore Mouldings Ltd., UK (grade PM355). After irradiation the detectors were etched in a 6.25 N NaOH solution at 70°C for 16 h. The etching was carried out in sealed test tubes in a thermostat-regulated oven. The tracks were counted at a magnification of 250x using a microscope equipped with a screen. The average number of tracks counted per detector was about 200 for the exposed detectors and about 40 for the unexposed background detectors.

The TLD unit contains a moulded plastic holder with an identification number and a binary hole code used for processing in an automated reader. A shielding of 1 mm aluminium is provided on both sides to obtain electronic equilibrium. In this work three Harshaw LiF TLD-700 discs (4.5 mm diameter x 0.9 mm) were used in each TLD unit. The TLD unit is shown in Fig. 2.

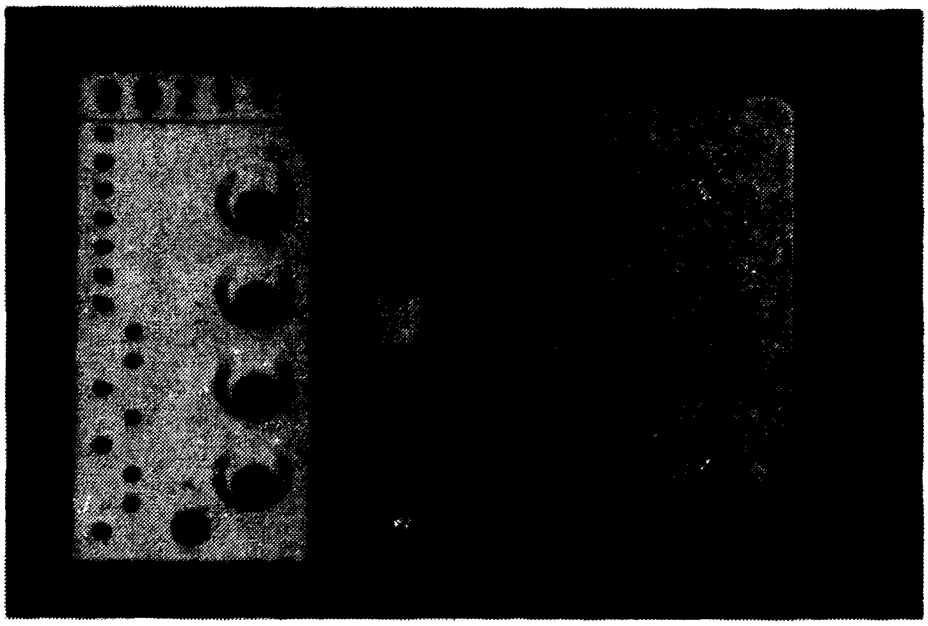


Fig. 2. Exploded view of the TLD unit.

The TLDs were read in an automated TL reader (Bøtter-Jensen et al., 1973) and each dose was determined from the mean value of the three individual TL disc responses.

The LiF discs were pre-irradiation annealed at 400°C for 1 hour followed by 100°C for 2 hours and post-irradiation annealed at 100°C for 20 minutes.

The dose received during mailing (transit dose) was determined in order to obtain the net value. 15 transit dosemeters were used to evaluate the mean transit dose. They were sent along with the site dosemeters and immediately returned to the laboratory.

Doses were determined by comparing them with the responses from dosemeters irradiated to known ^{60}Co radiation doses and then subtracting the mean transit dose. Dose rates were calculated by dividing the net doses with the integration times.

2.3. Instrumentation for active measurements

Measurements of radon daughter concentrations

Displacement pumps were used for sampling air at a flow rate of 18 liters per minute. The flow rate was calibrated against a gas-flow meter. Glass-fibre filters (Whatman GF/A) were used for collecting radon daughters for the gross alpha counting, which was done on standard alpha counters.

The concentration of each radon daughter was determined together with the total alpha-daughter concentration by counting through three periods. For that purpose a sequential counter was made, which controls the sequence of three preset counting periods and two intervals. The counts are printed out at the end of each counting period. The counting equipment is shown in Fig. 3.

The time sequence chosen and used for all the measurements was the one suggested by Busigin (Busigin and Philips, 1980) to yield a minimum of uncertainty: air sampling = 5 min, waiting time = 2 min, 1. counting period = 3 min, 1. interval = 2 min, 2. counting period = 8 min, 2. interval = 10 min, 3. counting period = 5 min.

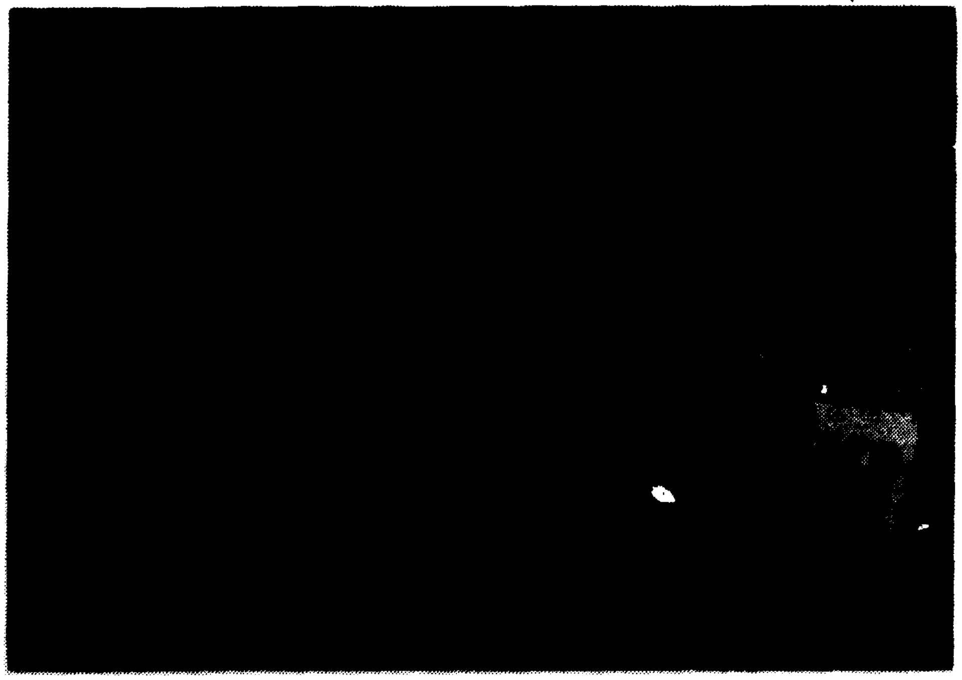


Fig. 3. Equipment for gross alpha measurement of radon daughters.

Measurements of radon concentrations

Spot measurements of radon concentrations were made using scintillation flasks. The flasks were made from brass tubing with a perspex end window and fitted with two Swagelok connectors. The inner surface was covered with alpha phosphor foil. The grab sampling of room air was done by flushing the flasks manually.

Semi-continuous measurements of radon concentrations

A semi-continuous radon monitor was designed to record the fluctuations in radon concentrations. The design was based on the idea suggested by Chittaporn, 1980. The monitor consists of a scintillation flask, 12 cm diameter by 12 cm high, mounted directly on a PM-tube. Radon in the ambient air can diffuse through filter-covered openings into the flask. The positively charged radon daughters formed inside the flask are collected on a central wire electrode, held at a negative potential of ~ 2000 V. The scintillation flask is fitted with a light trap. The counts corresponding to the decay of radon atoms in the flask are accumulated over a preset counting period, say one hour, and printed out. The count rate is converted to a mean concentration of radon in the counting period with a calibration constant found from simultaneous measurements of the radon concentration with scintillation flasks.

3. CALIBRATION AND INTERCOMPARISON OF INSTRUMENTS

3.1. Calibration facilities

A $7 \cdot 10^5$ Bq radium source (RaCl) was installed in a 6 m^3 cellar room. The floor and the lower part of the walls are covered with tiles, whereas the upper part of the walls and the ceiling are coated with a plastic paint. The ventilation ducts and all sanitary penetrations in the walls were carefully sealed off, and both the inner and outer entrance doors were sealed with rubber gaskets to form an airlock to the surrounding rooms.

By these precautions the ventilation rate was reduced to approximately 0.05 air changes per hour, and the radon concentration maintained at around 2500 Bq m^{-3}. An example of the fluctuations is shown in Fig. 4. The measurement was made with the semi-continuous radon monitor mentioned in section 2.3. The fluctuations are caused by the building ventilation system, which is shut down during night hours and week-ends.

A 200-liter steel barrel with a $7 \cdot 10^3$ Bq RaCl source was used for calibrating the cup dosemeter. The radon concentration in the barrel is around 30 kBq m^{-3}.

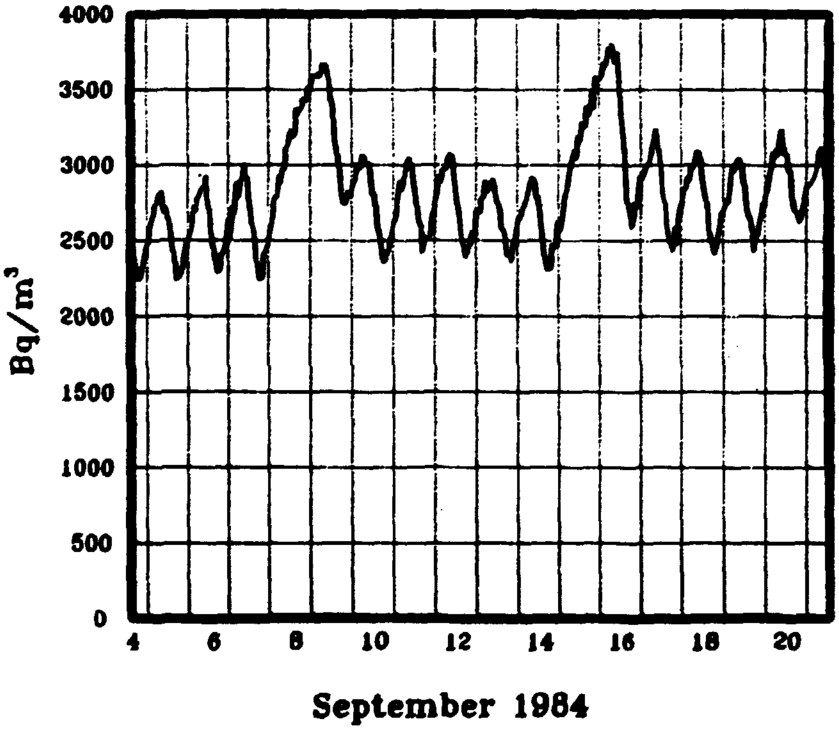


Fig. 4. Diurnal fluctuations of radon concentration in the calibration room due to changes of the ventilation in the building. The two pronounced peaks are caused by shut down of the ventilation during week-ends.

3.2. Calibration of instruments for radon and radon daughter measurements

Radon calibration

The calibration of all the instruments used to measure radon, thoron and their daughter products were ultimately based upon the calibration of the EDA scintillation flasks counted on the EDA radon detector, RD 200. The important factors in this context are the volume of the flasks (0.17 litres) and the counting efficiency (0.617 counts per disintegration). The stability of the equipment is frequently checked with a standard flask which gives a constant light output.

The absolute calibration of the EDA system has been compared with the National Radiological Protection Board, UK, in 1982 and 1984 at CEC-organized intercalibration meetings. Furthermore, comparisons have been made with three other Danish laboratories: The State Institute of Radiation Hygiene, the Laboratory of Applied Physics and the Department of Electrophysics, the two last named at the Technical University of Denmark. The results of these comparisons confirm that our standard systematic calibration uncertainty (standard deviation) of 10% is a conservative value.

Radon daughter calibration

The calibration of the radon daughter equipment was carried out as suggested by Jonassen, 1983. The volumes of the air samples are determined from knowledge of the constant flow rate and sampling time. The flow rate was determined from comparisons with calibrated gas meters. To determine the counting efficiency of the alpha probe a series of measurements of radon and radon daughters were made in the radon calibration room after a gas burner was lit. The gas burner produces very high aerosol concentrations in the room air, and since the radon daughters attach rapidly to these aerosols, the equilibrium factor approaches unity. This effect was observed from simultaneous measurements of radon and RaA. From these measurements the counting efficiency of one of the alpha probes was confirmed to be 0.34 counts per disintegration.

The radon daughter calibration is somewhat less accurate than that for radon gas due to the relatively large uncertainty of the RaA-figures because of the total-count technique.

<u>Radon dosemeter calibration</u>

The calibration of the cup dosemeters was performed by exposing them in the steel barrel. During exposures a fan inside the barrel ensured a thorough mixing of the air. The radon concentration in the barrel was determined as the mean of two scintillation-flask samples, one taken shortly after the exposure was started, and the other taken shortly before the exposure was ended. All exposures lasted a sufficiently long time to allow the radon concentration in the dosemeters to reach the same level as in the barrel. The lack of radon-daughter activity in the cup dosemeter during the initial exposure period was compensated for by not removing the CR39 detectors from the cup until a minimum of 3 hours had passed following termination of the exposure in the barrel.

The background track density and the sensitivity of CR39 track detectors may vary from one sheet of plastic to another. Therefore, the CR39 detectors used in this study were divided into groups, so that each group was composed of 1) detectors to be exposed in dwellings, 2) calibration detectors, and 3) background detectors. All detectors belonging to one group were cut from the same sheet of CR39 and were handled and etched together. The calibration and background detectors were taken out randomly from the sheet.

For the winter exposures the following procedure was used: The CR39 detectors were divided into 6 groups with about 38 detectors per group. In each group 3 detectors were given calibration exposures ranging from 45 to 491 kBq m^{-3}h, and 3 were used to determine the background track density.

For the summer exposures the CR39 detectors were divided into 4 groups with about 58 detectors per group. In each group 5 detectors were given calibration exposures ranging from 82 to 707 kBq m^{-3} h, and 4 were used to determine the background track density.

The results of the calibration exposures are shown in Figs. 5, 6, and 7.

For the winter exposures a χ^2-test has shown that the data from all the six groups can be pooled into one set (Fig. 5) corresponding to a background of 50 tracks per cm^2, and a sensitivity of 5.1 tracks per cm^2 per kBq m^{-3} h. The standard deviation of the reading of the 18 background detectors was 15.6 tracks per cm^2 corresponding to about 3 kBq m^{-3} h.

For the summer exposures analysis of the calibration data has led to pooling of the detectors into two sets, i.e. one set (Fig. 6) composed of the detectors from groups 1 and 2 (all from sheet No. 7), and another set (Fig. 7) composed of the detectors from groups 3 and 4 (all from sheet No. 9). The corresponding backgrounds and sensitivities are:

Groups 1 and 2:

Background: 58 cm^{-2} (standard deviation from 8 detectors: 11.5 cm^{-2})

Sensivity: 5.6 cm^{-2} per kBq m^{-3} h

Groups 3 and 4:

Background: 69 cm^{-2} (standard deviation from 8 detectors: 20.7 cm^{-2})

Sensitivity: 6.1 cm^{-2} per kBq m^{-3} h

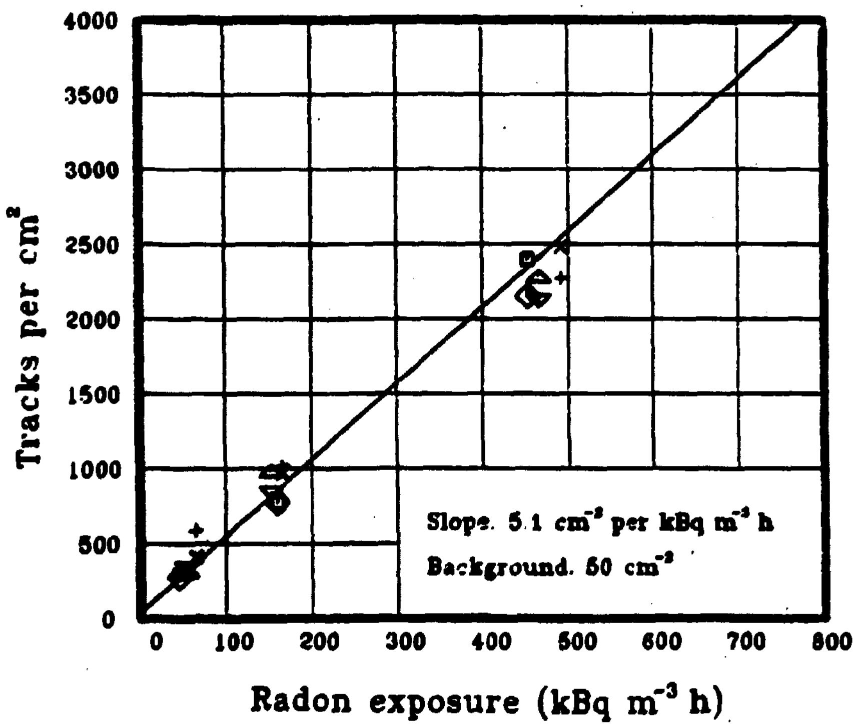
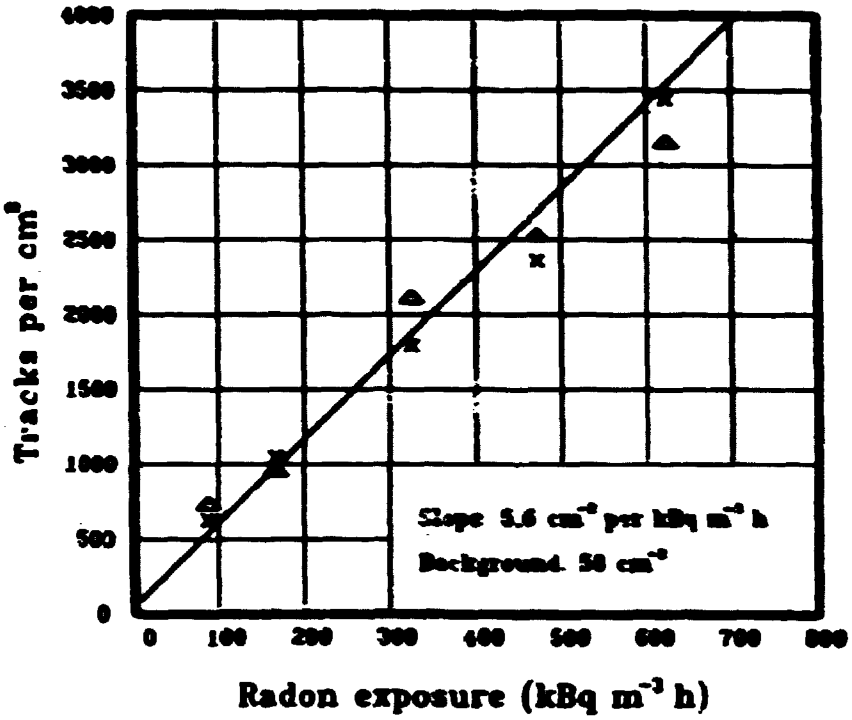
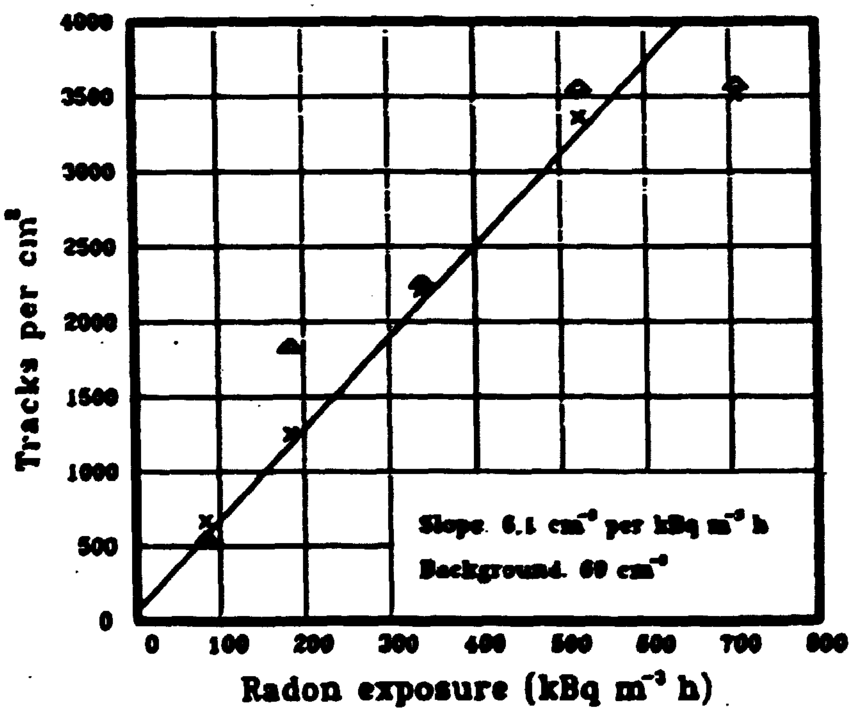


Fig. 5. Calibration data for the CR39 detectors used for the winter measurements. The six different symbols refer to the six separate groups of detectors mentioned in the text.



<u>Fig. 6.</u> Calibration data for the CR39 detectors from groups 1 (x) and 2(Δ) used for the summer measurements (cf. the text).



<u>Fig. 7.</u> Calibration data for CR39 detectors from groups 3 (x) and 4 (Δ) used for the summer measurements (cf. the text).

3.3. Calibration of instruments for measurement of external radiation

The calibration of the instruments used for active measurements was carried out by placing them in known gamma radiation fields produced by low-active ^{226}Ra, ^{137}Cs and ^{60}Co sources manufactured and certified by the Amersham Chemical Company, UK. Two calibration methods outlined and tested at Risø for routine control of environmental gamma rate meters were used. The methods are described elsewhere (Bøtter-Jensen, 1982).

4. MEASUREMENT PROGRAMME

Measurement periods

The choice of number and length of time periods for measurements with the cup dosemeter in dwellings was based on the following considerations:

- It is desirable to gather information on seasonal variations of radon concentrations in dwellings.

- It was important to gain experience with the cup dosemeter in field use at an early stage of the project, and to have ample time to implement possible improvements in the later stages.

For these reasons it was decided to select a three-month period in winter (1 December 1983 to 29. February 1984) and a three-month period in summer (22 May to 13 August 1984).

Selection of dwellings

One of the purposes of the present pilot study was to gather information on radiation levels in dwellings on a nationwide scale. Therefore, the dwellings were selected so that most regions of the country were represented. The study comprised 82 dwellings. Their locations are shown in Fig. 8.

Of the 82 dwellings, 10 were flats in multi-storeyed buildings and 72 were single-family houses with one or two floors. 27 of the single-family houses had a cellar. In each dwelling one dosemeter was placed in the main living-room and another in a bedroom. Houses with a cellar had a third dosemeter placed there.

The occupants of the dwellings were asked to fill in a questionnaire with information pertinent to the conditions that influence the radon concentration in a dwelling: type and age of the dwelling, building materials, ventilation conditions, etc.

Mailing of the dosemeters

The dosemeters were to large to be posted into letter boxes. Instead, the dosemeters had to be dispatched as small parcels. Apparently this did not cause any major nuisance to the participants although they had to return the dosemeters twice.

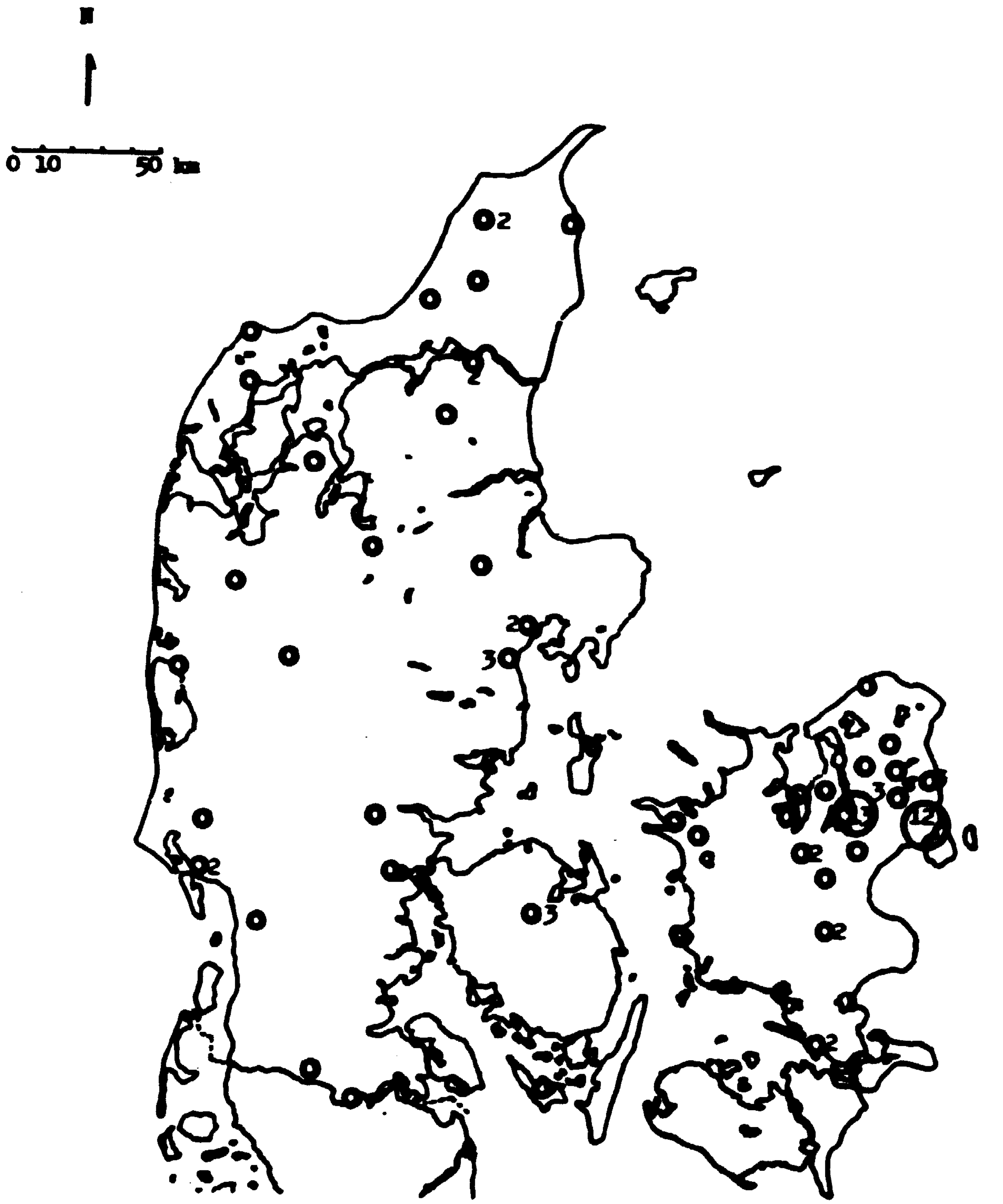


Fig. 8. Locations of the dwellings.

5. RESULTS OF MEASUREMENTS OF EXTERNAL RADIATION

5.1. Results of TLD-measurements

The TLD-results, corrected for transit dose, are listed in Table 1. The mean transit dose was found to be 9 µGy.

The results are shown in histograms in Figs. 9 and 10 as well as in cumulative distributions in Figs. 11 and 12. The mean value of the dose rate is 0.089 µGy h^{-1} in both winter and summer.

Analyses of variance showed no significant differences associated with the season, the type of house or the type of room. However, there was a significant difference (P>99%) between the building materials: wood 0.062 µGy h^{-1}, concrete 0.076 µGy h^{-1}, and brick 0.091 µGy h^{-1}.

Table 1. Results of TLD Measurements (µGy h^{-1})

Dwelling No.	Winter 1983/84 L	Winter 1983/84 B	Winter 1983/84 C	Summer 1984 L	Summer 1984 B	Summer 1984 C
1	[illegible]	0.110		[illegible]	0.110	
2	[illegible]	[illegible]		0.110	[illegible]	
3	[illegible]	[illegible]		[illegible]	[illegible]	
4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.071
5	[illegible]	[illegible]		[illegible]	0.071	
6	0.122	0.122		0.112	[illegible]	
7	0.117	[illegible]		0.117	[illegible]	
8	[illegible]	0.119	[illegible]	0.121	[illegible]	[illegible]
9	[illegible]	[illegible]		[illegible]	[illegible]	
10	[illegible]	0.071		0.072	[illegible]	
11	[illegible]	0.073		[illegible]	[illegible]	
12	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.072
13	[illegible]	0.077		[illegible]	[illegible]	
14	[illegible]	0.121	[illegible]	[illegible]	[illegible]	0.110
15	0.111	[illegible]	[illegible]	0.111	[illegible]	[illegible]
16	[illegible]	0.077		[illegible]	[illegible]	
17	0.072	0.071		0.072	[illegible]	
18	[illegible]	[illegible]		0.110	[illegible]	
19	[illegible]	0.072		0.073	[illegible]	
20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
21	[illegible]	[illegible]		[illegible]	[illegible]	
22	[illegible]	0.072		0.071	[illegible]	
23	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24	[illegible]	0.077		[illegible]	[illegible]	
25	[illegible]	0.072		[illegible]	[illegible]	
26	[illegible]	[illegible]		[illegible]	[illegible]	
27	[illegible]	[illegible]		[illegible]	[illegible]	
28	[illegible]	[illegible]		[illegible]	[illegible]	
29	[illegible]	[illegible]		[illegible]	[illegible]	
30	[illegible]	[illegible]		[illegible]	[illegible]	
31	[illegible]	[illegible]		[illegible]	[illegible]	
32	[illegible]	[illegible]		0.112	[illegible]	
33	[illegible]	[illegible]		[illegible]	[illegible]	
34	[illegible]	0.072	[illegible]	[illegible]	0.072	[illegible]
35	[illegible]	[illegible]		[illegible]	[illegible]	
36	0.110	[illegible]	[illegible]	[illegible]	0.110	[illegible]
37	[illegible]	[illegible]		0.072	[illegible]	
38	[illegible]	[illegible]		[illegible]	[illegible]	
39	[illegible]	[illegible]		[illegible]	[illegible]	
40	[illegible]	[illegible]		[illegible]	0.127	
41	[illegible]	[illegible]		[illegible]	[illegible]	
42	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
43	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
44	[illegible]	[illegible]		[illegible]	[illegible]	
45	[illegible]	[illegible]		[illegible]	[illegible]	
46	[illegible]	0.111	[illegible]	[illegible]	0.112	[illegible]
47	[illegible]	[illegible]		[illegible]	[illegible]	
48	[illegible]	[illegible]	0.114	[illegible]	[illegible]	0.114
49	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
51	[illegible]	[illegible]		[illegible]	[illegible]	
52	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
53	[illegible]	[illegible]		[illegible]	[illegible]	
54	[illegible]	[illegible]		[illegible]	[illegible]	
55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
56	[illegible]	[illegible]		[illegible]	[illegible]	
57	[illegible]	[illegible]		[illegible]	[illegible]	
58	[illegible]	[illegible]		[illegible]	[illegible]	
59	0.113	[illegible]		[illegible]	[illegible]	
60	[illegible]	[illegible]		[illegible]	[illegible]	
61	[illegible]	[illegible]		[illegible]	[illegible]	
62	[illegible]	[illegible]		[illegible]	[illegible]	
63	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
64	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.073
65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.112
66	[illegible]	[illegible]		[illegible]	[illegible]	
67	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
68	[illegible]	[illegible]		[illegible]	[illegible]	
69	[illegible]			[illegible]	[illegible]	
70	[illegible]	[illegible]		[illegible]	[illegible]	
71	[illegible]	[illegible]		[illegible]	[illegible]	
72	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
73	[illegible]	[illegible]				
74	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.077
75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
76	[illegible]	[illegible]		[illegible]	[illegible]	
77	[illegible]	0.071		[illegible]	[illegible]	
78	[illegible]	[illegible]		[illegible]	[illegible]	
79	[illegible]	[illegible]	[illegible]	0.077	[illegible]	[illegible]
80	[illegible]	0.112	[illegible]	[illegible]	[illegible]	0.113
81	[illegible]	[illegible]	0.117	0.071	[illegible]	[illegible]
82	[illegible]	[illegible]		[illegible]	[illegible]	
83	[illegible]	[illegible]		[illegible]	[illegible]	

L: Living-room, B: Bedroom, C: Cellar room

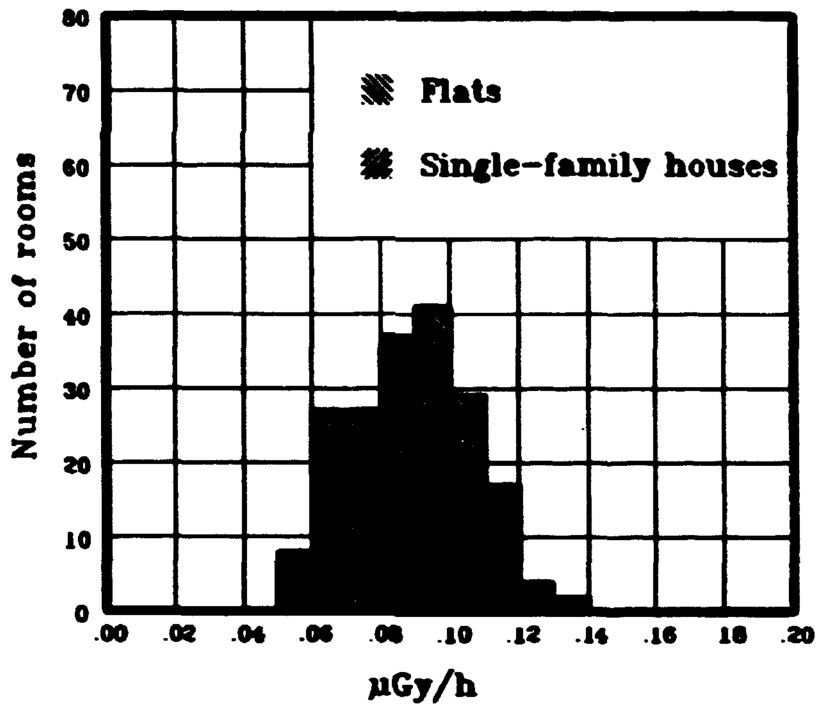


Fig. 9. Results of TLD measurements, winter 1983/84.

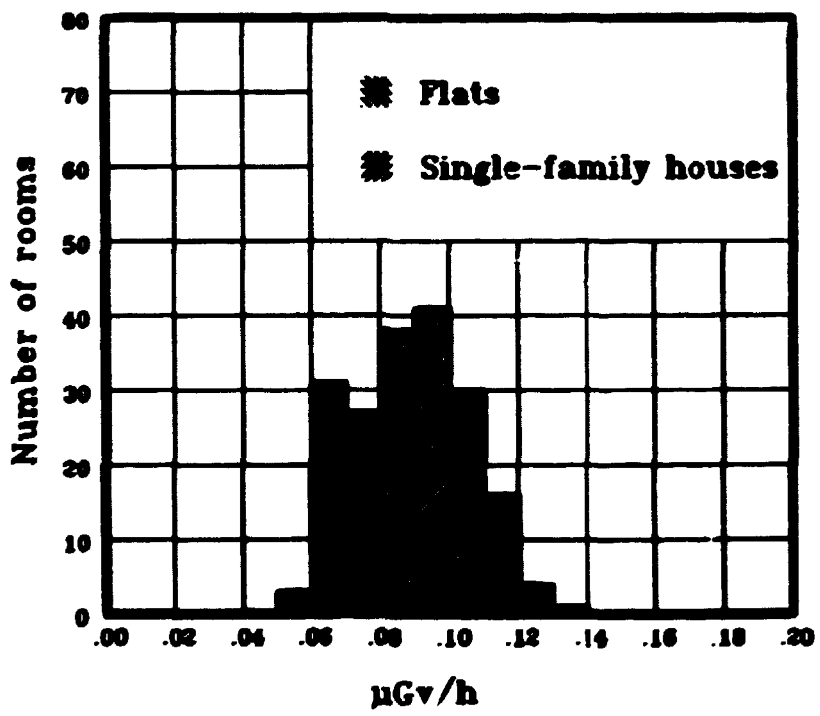


Fig. 10. Results of TLD measurements, summer 1984.

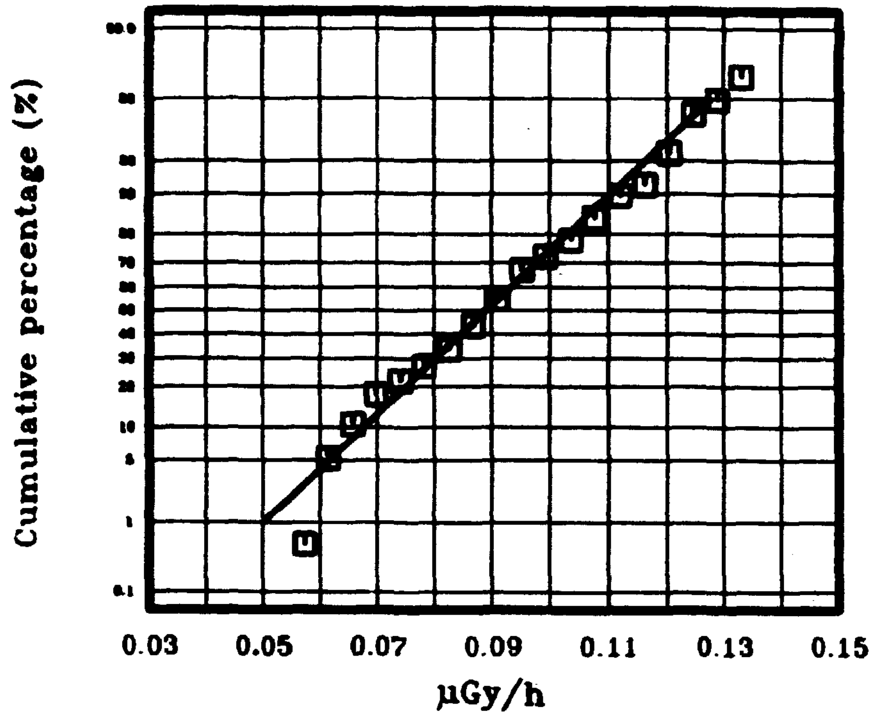


Fig. 11. Cumulative distribution of TLD results, winter 1983/84.

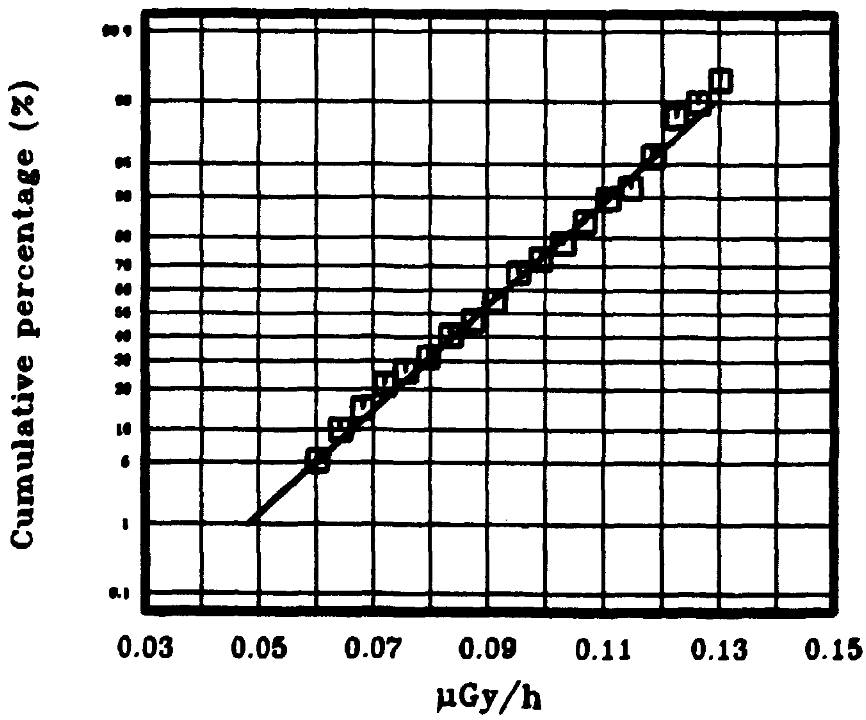


Fig. 12. Cumulative distribution of TLD results, summer 1984.

5.2. Results of active measurements

During the two three-month periods a number of active measurements of external radiation were carried out in selected dwellings.

The results are shown in Table 2, which also contains results of the corresponding passive measurements.

The agreement between the active and the passive measurements is good. This was to be expected as the dose rate from external radiation is not time dependent.

Table 2. Comparison of results of active and passive measurements of external radiation.

Dwelling No.	Room	Period	Active measurem. $\mu Gy\ h^{-1}$	Passive measurem. $\mu Gy\ h^{-1}$
1	L	Winter	0.104	0.105
1	B	"	0.113	0.110
2	L	"	0.104	0.104
2	L	"	0.106	0.104
2	B	"	0.105	0.108
2	B	"	0.105	0.108
4	L	"	0.070	0.061
4	B	"	0.076	0.070
4	C	"	0.076	0.070
41	L	"	0.067	0.066
41	B	"	0.070	0.062
2	L	Summer	0.103	0.110
32	L	"	0.086	0.112
34	L	"	0.084	0.078
36	L	"	0.098	0.106

6. RESULTS OF MEASUREMENTS OF RADON AND RADON DAUGHTER CONCENTRATIONS

6.1. Results of passive radon measurements

The results of the passive measurements of radon in living-rooms (L), bedrooms (B) and cellar rooms (C), are given in Table 3 and are also shown in histograms in Figs. 13 and 14 as well as in cumulative distributions in Figs. 15 and 16. The geometric means for the winter period are 24 Bq m^{-3} for flats and 88 Bq m^{-3} for single-family houses, and for the summer period they are 19 Bq m^{-3} and 52 Bq m^{-3} for flats and single-family houses, respectively.

The following observations are based upon analyses of variance of the mean radon concentrations using a 99% significance level.

Between winter and summer periods there was no difference for flats (geometric mean 21 Bq m^{-3}) and for wooden houses (geometric mean 23 Bq m^{-3}). For houses of bricks and concrete the geometric means were 90 Bq m^{-3} for the winter and 53 Bq m^{-3} for the summer. These houses also showed higher levels for the summer in cellars (geometric mean 82 Bq m^{-3}) than in living-rooms and bedrooms (geometric mean 49 Bq m^{-3}).

These observations agree with the observation that radon in the soil is a major contributor to radon levels in single-family houses. Furthermore, the results also clearly reflect the effect of increased ventilation rates in dwellings in summer compared with winter.

Table 3. Results of passive radon measurements (Bq m^{-3}).

	Winter 1983/84			Summer 1984		
Dwelling No.	L	B	C	L	B	C
1	144.	119.		70.	80.	
2	337.	161.		304.	201.	
3	164.	142.		81.	86.	
4	214.	202.	282.	84.	69.	187.
5	19.	13.		10.	10.	
6	14.	8.		17.	14.	
7	12.	16.		13.	10.	
8	65.	60.	89.	35.	34.	63.
9	10.	10.		8.	10.	
10	36.	27.		23.	19.	
11	10.	14.		17.	22.	
12	17.	8.	80.	41.	24.	80.
13	155.	103.		55.	53.	
14	43.	33.	171.	67.	55.	201.
15	7.	30.	69.	32.	26.	80.
16	203.	130.		254.	151.	
17	52.	30.		25.	22.	
18	75.	52.		30.	30.	
19	70.	60.		95.	69.	
20	50.	44.	180.	83.	59.	124.
21	100.	21.		46.	13.	
22	371.	261.		116.	82.	
23	21.	36.	47.	27.	22.	62.
24	99.	92.		61.	42.	
25	265.	85.		67.	28.	
26	81.	27.		42.	26.	
27	60.	40.		37.	34.	
28	155.	110.		98.	106.	
29	87.	48.		55.	26.	
30	140.	78.		43.	26.	
31	199.	184.		42.	71.	
32	70.	64.		37.	37.	
33	204.	217.		30.	26.	
34	341.	180.	108.	111.	107.	114.
35	271.	122.		210.	141.	
36	41.	41.	212.	70.	36.	290.
37	188.	142.		107.	119.	
38	104.	173.		155.	162.	
39	55.	96.		37.	53.	
40	141.	101.		122.	102.	
41	47.	33.		19.	19.	
42	110.	150.	346.	80.	92.	241.
43	24.	67.	44.	24.	24.	49.
44	323.	175.		46.	40.	
45	187.	95.		112.	72.	
46	345.	32.	114.	66.	28.	44.
47	119.	110.		55.	32.	
48	125.	110.	182.	59.	31.	93.
49	71.	60.	79.	48.	26.	50.
50	40.	85.	95.	35.	31.	20.
51	90.	104.		39.	46.	
52	142.	212.	150.	64.	53.	97.
53	169.	160.		56.	36.	
54	152.	301.		99.	89.	
55	151.	109.	98.	40.	59.	59.
56	96.	125.		30.	22.	
57	110.	107.		44.	25.	
58	72.	56.		39.	33.	
59	64.	15.		24.	25.	
60	97.	60.		26.	17.	
61	34.	19.		35.	10.	
62	57.	24.		41.	32.	
63	45.	83.	89.	31.	46.	83.
64	119.	126.	93.	60.	61.	47.
65	140.	60.	120.	54.	37.	62.
66	132.	87.		52.	53.	
67	146.	291.	470.	231.	115.	124.
68	20.	27.		29.	43.	
69	64.	44.		24.	30.	
70	93.	140.		65.	73.	
71	131.	242.		90.	100.	
72	21.	15.	147.	21.	11.	53.
73	133.	104.				
74	124.	56.	177.	27.	21.	60.
75	53.	43.	119.	30.	26.	57.
76	21.	10.		22.	17.	
77	82.	90.		24.	17.	
78	131.	135.		35.	31.	
79	111.	40.	96.	36.	19.	69.
80	51.	21.	51.	45.	36.	42.
81	56.	67.	82.	27.	30.	31.
82	90.	55.		59.	52.	
83	13.	20.		42.	30.	

L: Living-room, B: Bedroom, C: Cellar room

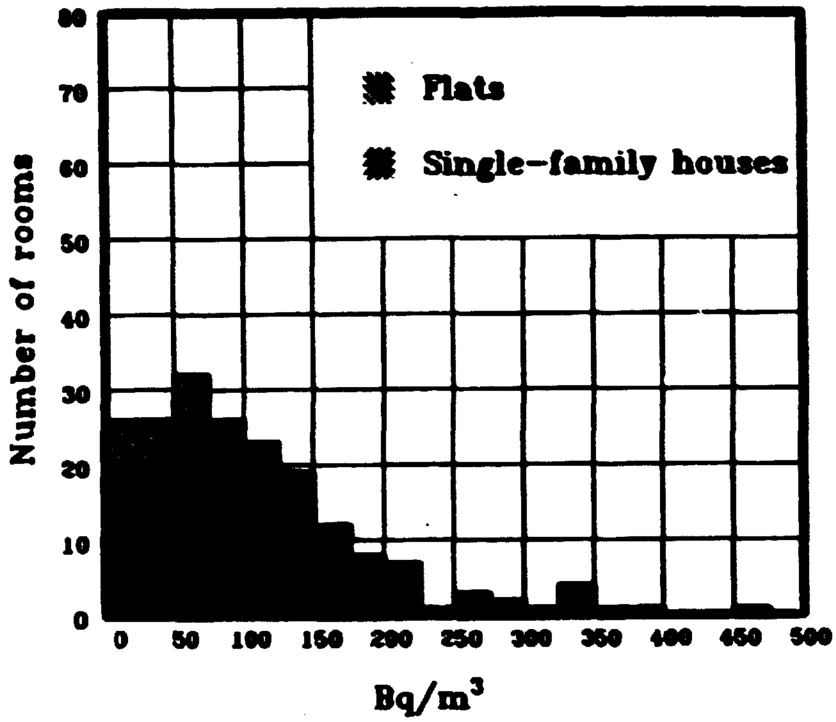


Fig. 13. Results of passive measurements of radon, winter 1983/84.

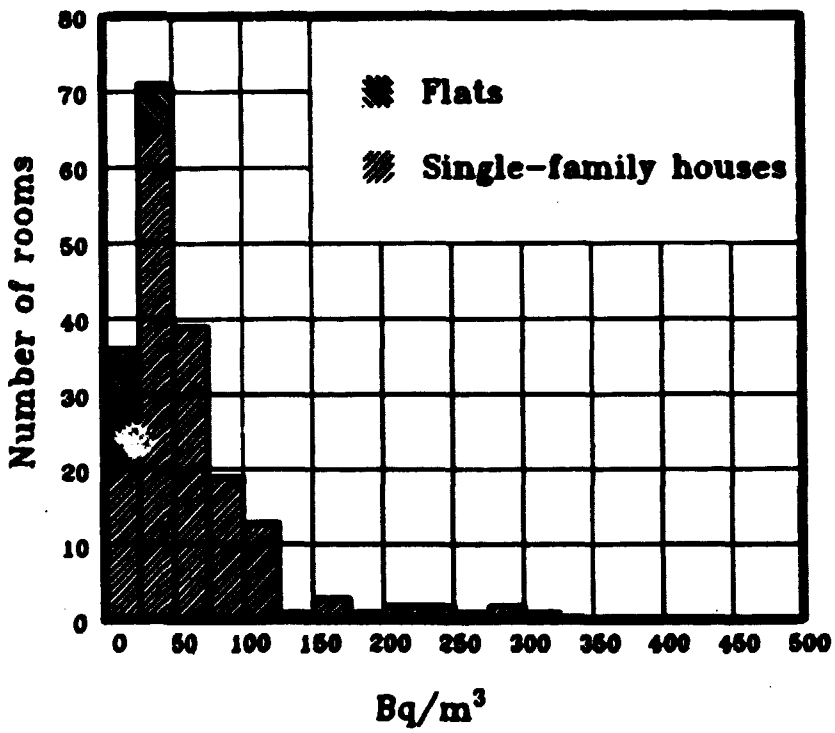


Fig. 14. Results of passive measurements of radon, summer 1984.

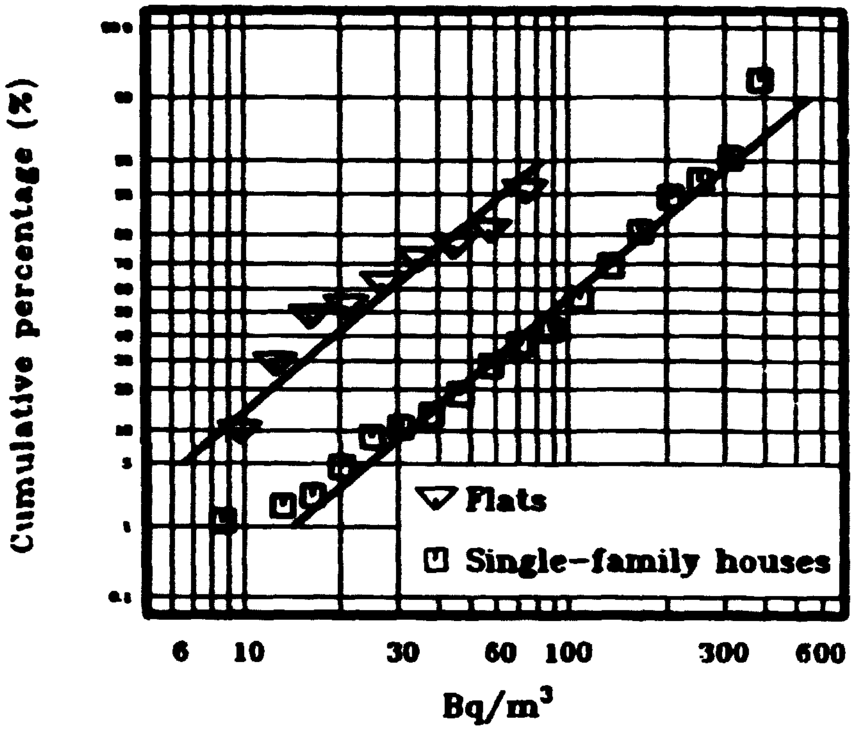


Fig. 15. Cumulative distributions of passive radon measurements, winter 1983/84.

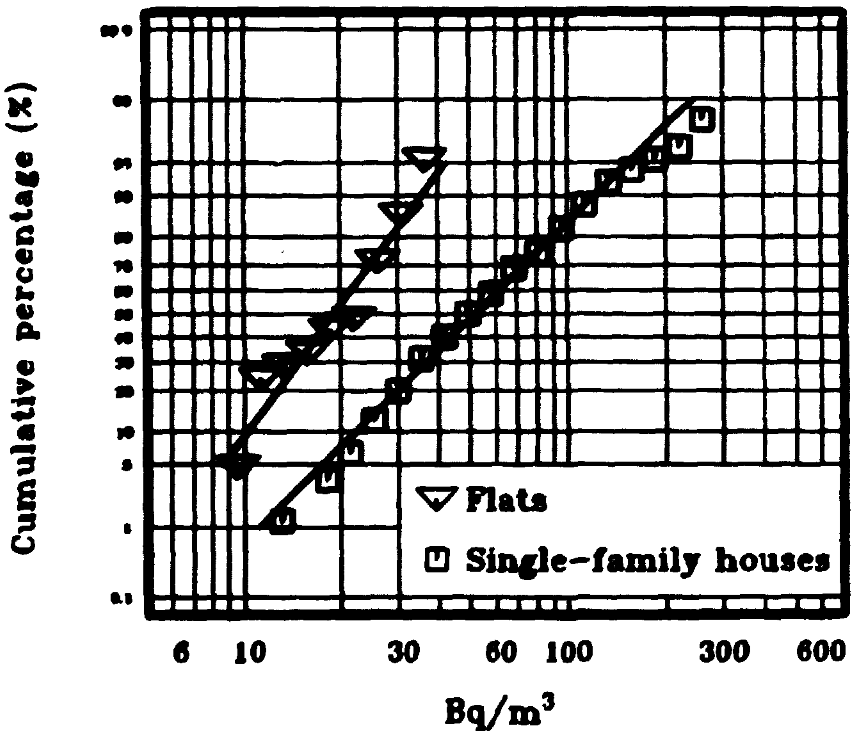


Fig. 16. Cumulative distributions of passive radon measurements, summer 1984.

6.2. Results of active radon and radon daughter measurements

A number of active measurements were made in some of the 82 dwellings. In most cases each measurement consisted of simultaneous determination of the concentrations of radon and the radon daughters. The results of measurements in the winter are listed in Table 4, and the results of the summer measurements are shown in Table 5. Table 5 includes a number of measurements made with the purpose of determining the contribution of thoron daughters to indoor lung exposure. These measurements do not include the determination of the radon concentration (Jensen, 1984).

For comparison, the corresponding results of the passive measurements (mean value over the respective periods) are shown in Tables 4 and 5. Taking into account the well-known variability of the radon concentration, one would not expect a close correlation between active and passive measurements. Yet one may get an idea of the general level of the radon concentration in a dwelling by means of grab sampling measurements if they are performed under conditions that are not too extreme. The observed ratio (F) between the equilibrium equivalent radon concentration (EER) and the radon concentration (C_R) is also listed in the tables. The F-values are shown in histograms, Figs. 17 and 18. In the winter period F ranges from 0.2 to 1.0 with a geometric mean of 0.4, and in the summer period F ranges from 0.1 to 0.8 with a geometric mean of 0.2. The lowest values are measured in rooms with open window(s).

Table 4. Results of active measurements of radon and radon daughter concentrations, winter 1983/84

Dwelling No.	Room	Active measurements C_R (Bq m^{-3})	EER (Bq m^{-3})	$F = \frac{EER}{C_R}$	Passive measurements C_R (Bq m^{-3})
1	L	261	95	0.36	144
1	L	243	181	0.74	144
1	B	158	61	0.39	119
1	B	214	137	0.64	119
2	L	525	321	0.61	337
2	L	893	428	0.48	337
2	L	373	155	0.42	337
2	L	530	232	0.44	337
2	L	357	151	0.42	337
2	L	359	138	0.38	337
2	B	483	326	0.67	161
2	B	416	166	0.40	161
2	B	424	156	0.37	161
2	B	539	236	0.44	161
2	B	464	210	0.45	161
2	B	389	165	0.42	161
3	L	165	65	0.39	164
3	B	130	65	0.50	162
4	L	49	19	0.39	214
4	L	111	34	0.31	214
4	L	122	54	0.44	214
4	L	209	62	0.30	214
4	B	37	21	0.57	202
4	B	80	42	0.53	202
4	B	49	47	0.96	202
4	B	132	50	0.38	202
12	L	67	30	0.45	17
12	B	82	18	0.22	8
28	L/B	38	5	0.21	155/110

Table 5. Results of active measurements of radon and radon daughter concentratrions, summer 1984.

Dwelling No.	Room	Active measurements C_R ($Bq\ m^{-3}$)	EER ($Bq\ m^{-3}$)	$F=\frac{EER}{C_R}$	Passive measurements C_R ($Bq\ m^{-3}$)
1	L	10.4	2	0.19	70
1	L	nm	18		70
1	B	7.7	1	0.13	80
1	B	9.5	10		80
2	L	147.0	94	0.64	306
2	L	371.0	241	0.65	306
2	L	nm	210		306
2	B	15.3	12	0.78	201
2	B	119.3	46	0.39	201
2	B	nm	363		201
4	L	24.5	2	0.08	84
4	L	nm	1		84
4	B	28.8	3	0.10	69
10	L	nm	12		22
10	B	nm	10		19
11	L	nm	4		17
11	B	nm	3		22
13	L	nm	7		55
13	B	nm	4		53
15	B	nm	3		26
27	L	32.3	1	0.03	37
27	L	nm	26		37
27	B	14.0	0.3	0.02	34
27	B	nm	24		34
28	L	8.0	1	0.13	98
28	L	nm	31		98
28	B	21.0	1	0.05	106
28	B	nm	40		106
29	L	20.4	3	0.15	55
29	L	nm	32		55
29	B	19.8	1	0.05	26
29	B	nm	27		26
31	L	78.1	36	0.46	42
31	B	38.1	19	0.50	71
32	B	28.4	9	0.32	37
33	L	14.4	2	0.14	30
33	B	6.9	2	0.29	26
33	B	nm	1		26
34	L	138.6	78	0.56	111
34	B	93.3	39	0.42	107
36	L	21.2	10	0.47	70
36	B	32.3	3	0.09	70

nm: not measured

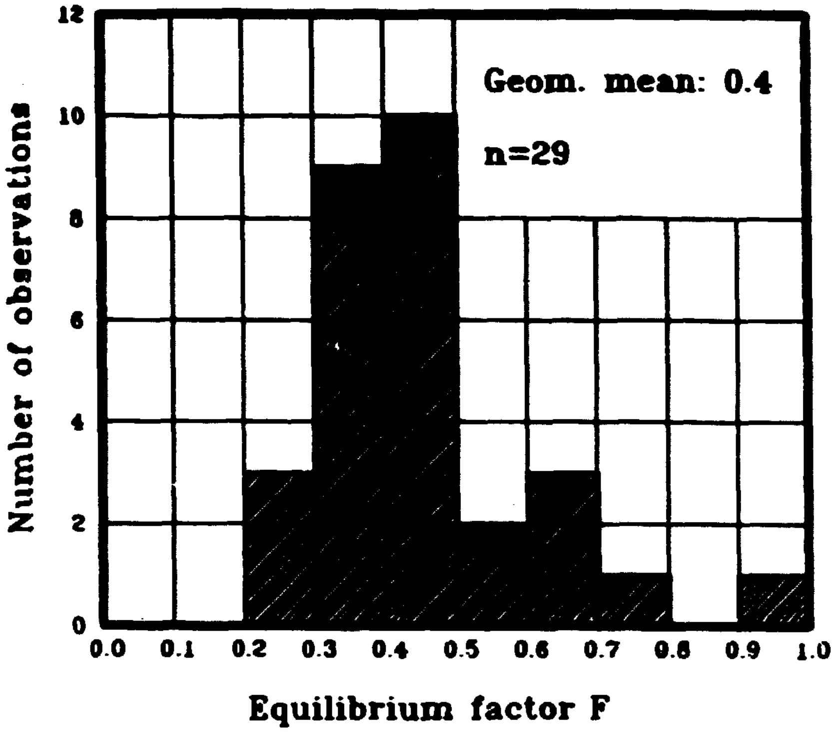


Fig. 17. Results of measurements of $F = \frac{EER}{C_R}$, winter 1983/84.

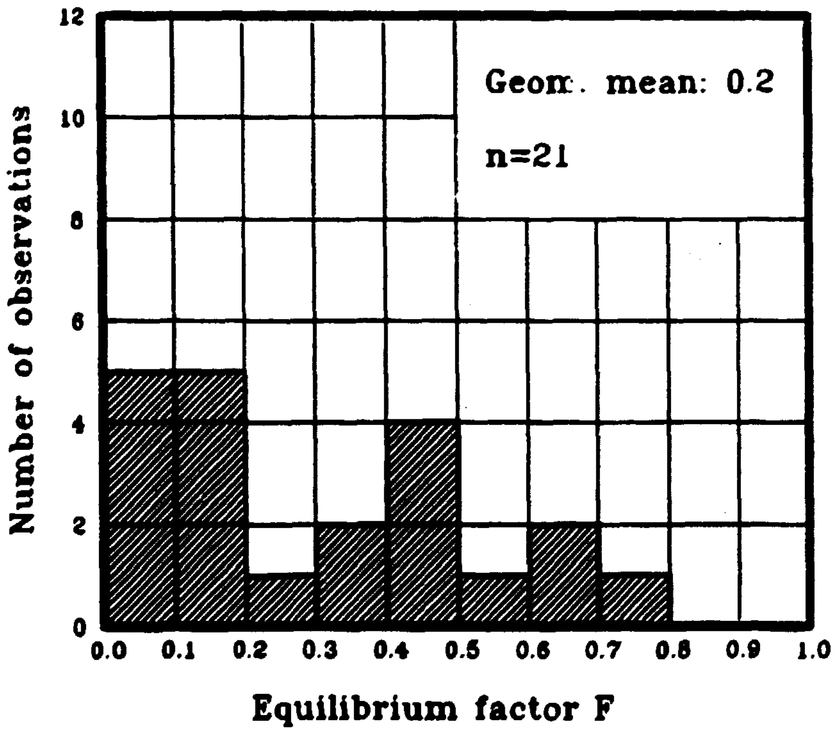


Fig. 18. Results of measurements of $F = \frac{EER}{C_R}$, summer 1984.

7. EFFECTIVE DOSE EQUIVALENT FROM RADON EXPOSURE

Although the sample of dwellings used in the pilot survey may not be statistically representative for the country as a whole, a calculation of the annual effective dose equivalent from the observed radiation levels may give a preliminary indication of the average dose to the Danish population from indoor radiation.

For the conversion from radon concentration to annual effective dose equivalent the following values from UNSCEAR 1982 are used:

- conversion factor from EER to H_{eff} = 0.061 $[mSv(Bq\ m^{-3})^{-1}]$
- equilibrium factor F = 0.5

The equilibrium factor F = 0.5 is used instead of the observed mean values due to the limited number of measurements.

In Denmark the fraction of people living in apartment houses is 0.31, and the fraction living in other types of dwellings is 0.69.

From these assumptions and values, and from the mean radon concentrations found in the pilot survey (section 6.1.) the mean annual effective dose equivalent can be calculated to be

$$\bar{H}_R = \left(\frac{88+52}{2} \cdot 0.69 + \frac{24+19}{2} \cdot 0.31\right)0.5 \cdot 0.061 \quad mSv$$

$$\bar{H}_R = 1.7\ mSv$$

The contribution from thoron daughters to the total annual effective dose equivalent has been found to be less than 10% of the contribution from radon daughters (Jensen 1984).

The mean dose rate from external radiation was found to be 0.09 μGy h^{-1} (section 5.1.), corresponding to a dose equivalent rate of 0.8 mSv y^{-1}. This value includes the contributions from cosmic radiation and ambient gamma radiation. In Denmark the mean outdoor dose equivalent rate from cosmic radiation and ambient gamma radiation is about 0.7 mSv y^{-1}.

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A Pilot Investigation of Natural Radiation in Danish Houses

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Abstract. As a prelude to a nationwide survey a pilot study was carried out to establish techniques and procedures for the measurement of indoor radiation in Denmark. A passive cup dosemeter was designed containing CR39 track detectors and TLD's to measure radon and external radiation, respectively. The adequate performance of the dosemeter was verified in a radon intercalibration in 1984 carried out at the National Radiological Protection Board, UK.

A total of 82 dwellings were selected covering most regions of the country. The dwellings were monitored in two three-month periods, one in winter and the other in summer.

The average dose rate in air from external radiation was 0.09 $\mu Gy\ h^{-1}$. In the winter the average radon concentrations were 88 $Bq\ m^{-3}$ and 24 $Bq\ m^{-3}$ for single-family houses and flats, respectively; and in the summer the corresponding values were 52 $Bq\ m^{-3}$ and 19 $Bq\ m^{-3}$.

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