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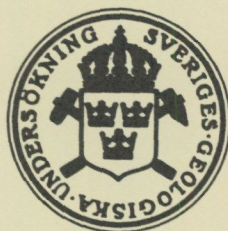
AVHANDLINGAR OCH UPPSATSER

ÅRSBOK 78 NR 1

ÅKE HESSELBOM

RADON IN SOIL GAS

A STUDY OF METHODS AND INSTRUMENTS FOR
DETERMINING RADON CONCENTRATIONS
IN THE GROUND



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ABSTRACT

Hesselbom, Åke, 1984: Radon in soil gas: A study of methods and instruments for determining radon concentrations in the ground. Sveriges geologiska undersökning, Ser. C, No. 803, pp. 1-58, Uppsala 1985.

This account presents a study of some of the commercially available detectors for field measurements of radon concentrations in soil gas and of radon flux from the ground surface. Most of the methods for measuring radon are based on detection of alpha particles or gamma radiation which are produced during radioactive decay of radon and radon daughter isotopes. The methods used can be described as active or passive. The active methods involve pumping of soil gas into or through a detector whereas the passive methods register radon concentrations in the ground under natural conditions.

Calibrations were made experimentally by exposing detectors in a controlled radon/radon daughter environment at the National Institute of Radiation Protection (SSI) in Stockholm, Sweden.

The method used have been compared with regard to:

- ability to detect variations in radon concentrations
- reproduceability
- depth effects
- meteorological effects

The results show that all methods and detectors used in the study have established the presence of radon in the soil gas. The accuracy of the results obtained, whatever the method or detector used and whatever purpose at the measurements, depends very much upon the physiographic and geological environment (e.g. types of soil, moisture content etc.) in which the detectors are placed.

INTRODUCTION

This account presents a study of some of the commercially available detectors for field measurements of radon concentrations in soil gas and of radon flux from the ground surface. The study was initiated by the Swedish Radon Commission and financed from a special government grant for research into radon problems. The aim of the study was to evaluate the various methods and instruments available, in order to give recommendations as to the most suitable radon measuring techniques for use in geotechnical investigations.

The study has been carried out at the Geological Survey of Sweden (SGU) and in collaboration with the National Institute of Radiation Protection (SSI), Studsvik Energiteknik AB (Hans Tovedal) and the Institute of Meteorology, University of Uppsala (Sven Israelsson).

The present account is based upon a report in Swedish (Hesselbom *et al.* 1981). Certain sections of the report have been excluded or shortened here, while others, such as that on calibration, have been extended. This account also includes new results and observations from investigations carried out during 1981.

Administration of the research grant and publication of the Swedish report were carried out by the Swedish Council of building Research, Stockholm (Statens råd för Byggforskning-grant 800504-1).

METHODS

GAMMA RADIATION

Measurements of uranium and thorium contents in the bedrock and soils were made using a gamma spectrometer (GAD-6, Scintrex) which is calibrated for use both on bedrock surfaces and in pits dug in the drift cover. Measurements were made in pits and at several points on every bedrock outcrop. The results of spectrometer measurements indicate whether soil gas measurements have registered radon only (Rn-222) or both radon and thoron (Rn-220). Furthermore, spectrometer measurements can indicate whether the source of radon and/or thoron lies within the vicinity of the radon detector or whether these gases have been transported from some distant source. In areas where radon is produced directly from the soil material, gamma spectrometry gives an indication of the homogeneity or otherwise of the soil; an important fact when comparing results from different detectors at different points in an area. Gamma radiation from the ground surface was measured with a scintillometer instrument (BGS-4, Scintrex).

PRINCIPLES FOR MEASURING RADON

Most of the methods for measuring radon are based on detection of alpha particles or gamma radiation which are produced during radioactive decay of radon and radon daughter isotopes.

The methods used can be described as active or passive. The active methods involve pumping of soil gas into or through a detector instrument whereas the passive methods register radon concentrations in the ground under natural conditions. Most of the active methods register radon concentrations directly and the results are simultaneously displayed on the detector instrument. The passive methods register radon concentrations over longer periods. Exposure time for the passive methods varies according to the type of detector used, and the radon concentrations to which it is exposed.

The active methods used in this study were soil gas emanometry and grab sampling. Two different emanometers were tested: Bondar-Clegg, Model RE 279, and EDA Instruments, Model RD-200. Both instruments were developed for field use in prospecting for uranium.



Fig. 1. Drilling a hole for an emanometer measurement.

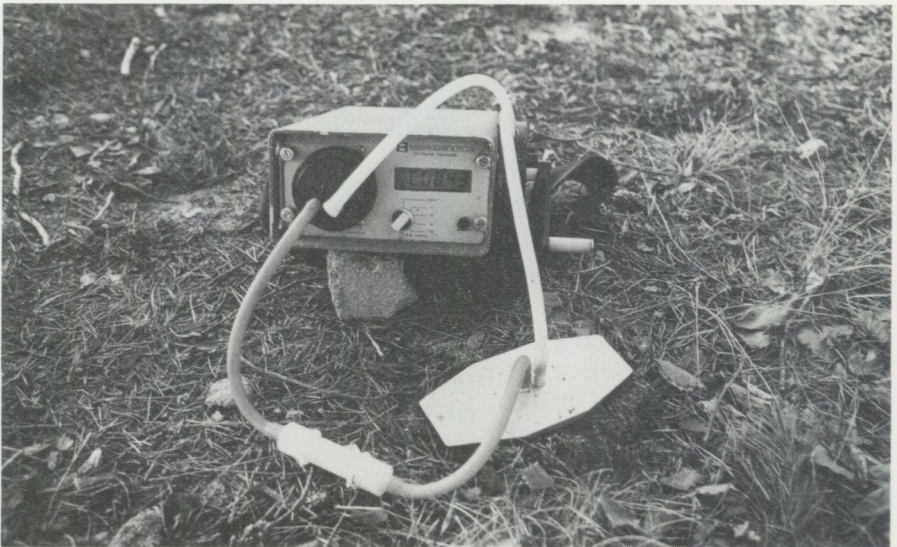


Fig. 2. Emanometer RE 279, Bondar-Clegg.



Fig. 3. Sampling with an emanometer from an accumulator.

Four passive methods were tested:

1. Alpha sensitive film, Track-Etch, Terradex Corporation and LR 115 type II, Kodak-Pathé.
2. Activated charcoal, ROAC (Radon On Activated Charcoal), Inter-Science R & D Services.
3. TLD, PRM (passive radon monitor), Studsvik Energiteknik AB.
4. Solid state detector, alphaMETER, Alpha Nuclear Co.

SOIL-GAS EMANOMETRY

The principle of the method is that soil gas is pumped up from a narrow hole drilled in the ground and passed through the detector instrument. The instrument is called an emanometer, zinc sulphide scintillator or Lucas chamber. The emanometer consists of a detector unit with a counter, a pump with connecting tubes and particle filter, and a probe (Figs. 1, 2 and 3). A hand drill or motor driven drill is also necessary for preparing the holes.

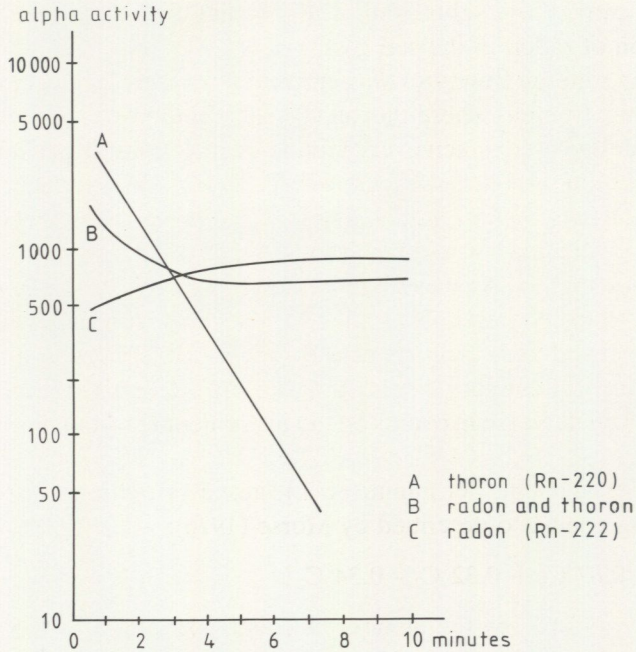


Fig. 4. Effect of time on alpha activity in a ZnS-cell. After Dyck (1969).

Emanometers are equipped with scintillation cells which are attached to a photomultiplier. The walls of the scintillation cells are coated with silver-activated zinc sulphide, ZnS (Ag). Radon in the soil-gas sample which is pumped into the scintillation cell decays to Plutonium-218 giving off alpha particles. When the alpha particles are absorbed by the zinc-sulphide surface, they give rise to light impulses (scintillations) which are amplified by the photomultiplier to give a measurable charge.

The following procedure has been used for measurements using an emanometer. A hole of about 20 mm diameter was drilled to a depth of 0.6–0.8 metres. Two probes of different lengths were placed into the hole. The probes were attached to a metal plate at ground level. Soil gas was pumped up via the shorter probe, through the instrument and back into the hole through the longer probe. The amount of soil gas circulated through the system was identical for all measurements made, and the procedure followed instructions from the manufacturer.

A clean (decontaminated) zinc-sulphide cell was inserted into the instrument before each measurement. Background activity in the cell was measured over one minute.

After pumping, the alpha activity was counted over a given time interval. The result was displayed as counts per minute (c/m) from which the

background activity was subtracted. The resulting figure is a measure of the concentration of radon in the soil gas.

A counting time of 5 minutes was employed for most of the emanometer measurements. In areas where thoron (Rn-220) could be expected to occur, however, readings were taken every minute over a 5-minute period. Thoron, with a half life of 54.5 seconds can only be detected if readings are taken immediately after sampling. Fig. 4 (Dyck 1969) shows the alpha activity in a ZnS cell during the first few minutes after sampling. Alpha activity is caused by both radon and thoron. Alpha activity caused by radon first becomes apparent as a slight rise in the curve. This soon levels off as equilibrium is attained between radon and its first daughter isotope (Po-218). Thoron, on the other hand, together with its daughter isotope (Po-216) decays very rapidly which causes a marked decrease in counts on the instrument read-out during the first few minutes.

The number of counts per minute (c/m) caused by radon can be estimated roughly using a method described by Morse (1976):

$$C_{Rn} = 0.87 C_3 + 0.32 C_2 - 0.34 C_1$$

where C_1 , C_2 and C_3 are the number of counts after each of the first three minutes. C_{Tn} (thoron) is taken to be the difference between the total number of counts per minute and C_{Rn} . The values used for C are corrected for background.

Both instruments used in this study are similar in function, weight and practicality for field use. EDA RD-200 has a larger ZnS cell than Bondar-Clegg Re 279, 170 cm³ and 140 cm³, respectively. The EDA instrument gives therefore more counts per minute than Bondar-Clegg for directly comparable measurements. Re 279 has one great advantage over RD-200 in that it corrects automatically for daylight, with the result that background activity in the ZnS cell for Re 279 rapidly goes down to an acceptable level and the waiting time between measurements is therefore considerably less than for RD-200. Most of the emanometer measurements made during the course of this study were therefore carried out using Re 279.

Detailed comparisons of the performances of the two instruments by means of test measurements in the radon room have not been made.

ALPHA SENSITIVE FILM

Two types of alpha polyester or cellulose nitrate (CN) film have been used and compared: Track-Etch, manufactured and analysed by Terradex, USA, and Kodak-Pathe LR 115 type II, analysed by Studsvik Energiteknik AB (see Fig. 5).

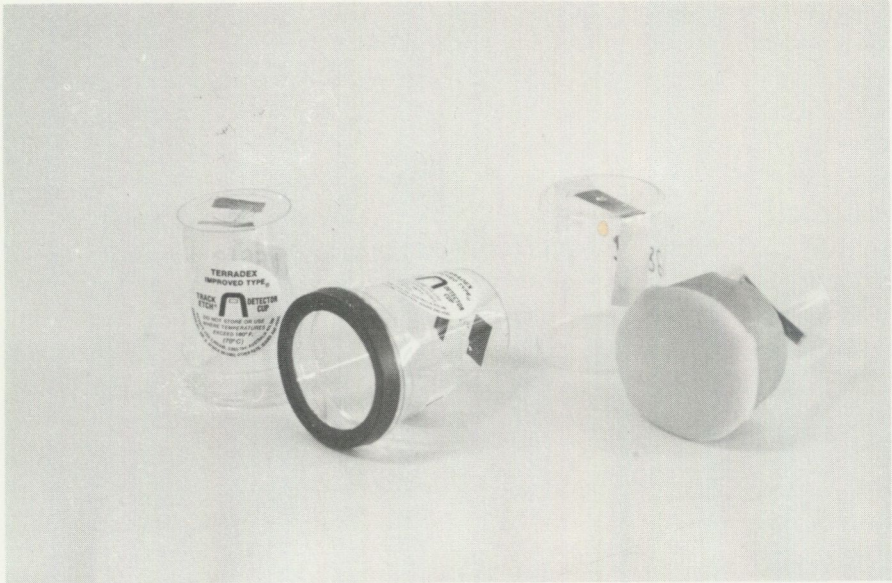


Fig. 5. Alpha sensitive film detectors. Left: Track-Etch with and without membrane. Right: Kodak LR 115 with and without filter.

Alpha particles which are adsorbed on the surface of these films leave a mark or track. After chemical etching, the tracks on the films are visible under an optical microscope. The number of tracks per given area (tracks/mm²) is proportional to the concentration of the alpha emitting isotope (radon, thoron) in the air within the range for alpha particles.

The detector consists of a film strip which is attached to the base (inside) of a plastic cup. The cups were placed, inverted, in holes in the ground (Fig. 6a) and covered with plastic bags. The holes were then refilled with soil. The depth of measurement has varied between 0.3 and 0.9 m. The detector units were exposed for 3 to 4 weeks. Then they were dug up, cleaned and sent for analysis.

SGU now mounts the detector cups (and ROAC detectors) at the bases of 75 mm diameter PVC tubes. The tubes are inserted into holes drilled down to a depth of about one metre using a drilling machine or auger (Fig. 6b). This method often saves time and effort.

Alpha sensitive films respond in the soil air to alpha radiation from radon (Rn-222) and thoron (Rn-220) and their daughter isotopes. In order to distinguish between radon and thoron when measuring in thoron-rich areas (e.g. granites and granite-rich tills), detectors fitted with thoron filters or membranes were used in addition to the open detectors. The Track-Etch detectors were fitted with semi-permeable plastic membranes supplied by Terradex,

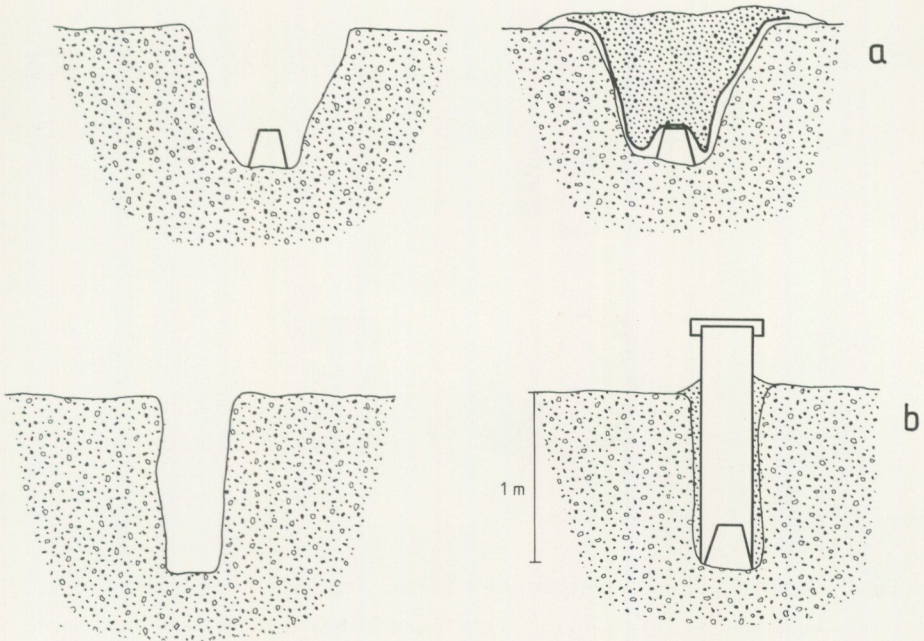


Fig. 6. Alternative methods of setting out Track-Etch, Kodak and ROAC detectors.

whereas the Kodak detectors were fitted with 5 mm thick foam rubber filters.

The Track-Etch thoron-membrane, which was specially developed for its purpose, functioned well in most cases. The filters which were attached to the Kodak detectors however appeared to have little beneficiary effect.

The results of the Terradex films are given as number of tracks per mm^2 normalised to 30 days exposure. Terradex have published the results of calibrations of their films (detectors both with and without membranes). These calibrations were carried out in the USA and at SSI in Stockholm.

Studsvik presents the results from the Kodak films used for soil gas measurements as number of tracks per mm^2 and day. They have also calculated the absolute radon content for the films which were exposed in the surface accumulators. These values are expressed as becquerels per cubic metre of radon and daughters, that is $\text{RN} + \text{RaA} + \text{RaC}$. The calculations are based on calibrations carried out at SSI.

The use of cellulose-nitrate film for measuring alpha particles from radon and radon daughter isotopes in air is covered by an American patent from 1972. The corresponding patent for Sweden is dated 1968. This implies that only cellulose-nitrate film which has been manufactured and supplied by Terradex may be used in Sweden for commercial radon measurements. The Kodak-Pathe film used in this study was used for research purposes only.



Fig. 7. Activated charcoal detector, type ROAC, Inter-Science R & D Services.

ACTIVATED CHARCOAL

It is well known that radon is adsorbed onto activated charcoal. ROAC detectors (Radon On Activated Charcoal), manufactured by Inter-Science R & D Services (Fig. 7), are based on this principle.

A ROAC detector consists of two parts: a small plastic cartridge filled with activated charcoal and a plastic cup. Radon is adsorbed onto the charcoal in the cartridge. The radon decays to its daughter isotopes of which Bi-214 and Pb-214 emit gamma rays during decay. This gamma activity can be measured by a NaI-scintillometer. Radon contents are calculated from the measured gamma activity by means of correcting the results for growth of radon during exposure of the detector and correcting for decay after exposure.

The ROAC detector are placed in the ground in exactly the same way as the alpha sensitive films (see Fig. 6a and 6b). The cartridge is opened, inserted into the cup and placed in an inverted position in the ground, either in a hole or in a PVC-tube. The detector can also be suspended freely inside the PVC-tube. Exposure time is 5–8 days. The detector is then taken up and the lid closed. Gamma radiation from the detector should be measured within a week from exposure. The detectors should be placed inside a lead box during measurement in order to reduce the effects of background radiation.

The instrument used in this study for measuring gamma radiation from the



Fig. 8. Thermoluminescence dosimeter (TLD), type PRM, Studsvik Energiteknik AB and Kodak film type LR 115.

detectors has been developed and constructed by SGU. The suppliers of ROAC sell similar instruments.

Activated charcoal can also adsorb large quantities of water which reduces its ability to adsorb radon. To prevent this, silica gel is placed in the detector together with the activated charcoal.

Thoron ($Rn-220$) is also adsorbed onto activated charcoal. The detectors must therefore be measured at two different times after retrieval in order to distinguish between gamma radiation from the radon and the thoron daughter isotopes which are present in the detector. The first measurement is made within 24 hours of retrieval whereby both radon and thoron activities are determined. The second measurement is made after about three days. By this time most of the gamma emitting daughter isotopes of thoron have decayed, and the gamma activity measured is that produced by radon daughter isotopes only.

THERMOLUMINESCENCE DOSIMETER (TLD)

A dosimeter has been used to record radon concentrations in surface accumulators. The instrument (type PRM, passive radon monitor) is manufactured by Studsvik Energiteknik AB (Fig. 8).

Radon diffuses into a measuring chamber in the instrument through a filter of foam rubber. The radon daughters produced in the chamber are collected on an electrically charged small piece of foil which lies in close proximity to a TLD-chip. The daughter isotopes on the foil decay, emitting alpha particles. The TLD-chip absorbs the energy produced when the alpha particles hit the chip. When the measuring period is completed, the TLD-chip is removed and analysed in a special instrument. The result obtained gives, after conversion, an average value for the concentration of radon in the accumulator during the period of exposure.

The dosimeter was placed on the ground, inside an accumulator for a period of 3–4 weeks.

SOLID STATE DETECTOR

A solid state detector for detection of alpha particles is, in principle, a reversely charged pn-diode of lithium-activated silicon, Si (Li), (silicon diffused junction). When an alpha particle enters the junction, a minute amount of current flows, or a number of electron-hole pairs is generated, the number of which is proportional to the energy of the alpha particle when it enters the junction. The flow of current is sensed and amplified to produce a pulse which can be counted.

The alphamETER manufactured by Alpha Nuclear Company, Canada (Warren 1977) has been used in this study. The instrument is cylindrical, 51 mm in diameter and 350 mm long. It consists of a detector and counter unit and batteries. One end of the cylinder is open to allow radon to reach the detector. All alpha particles with energies exceeding 1 meV are registered on a surface of 400 mm².

For field use, the alphameter is dug down into the ground to a depth of about 0.3 m (Fig. 9). Soil is packed carefully around the instrument in order to prevent leakages of radon along the sides. Exposure time can vary from a few hours to several days depending upon the radon concentration in the ground and the capacity of the counter. The instrument can also be mounted on an accumulator as shown in Fig. 10.

The results are displayed directly on the instrument while it is in situ. With this instrument it is therefore possible to study variations in radon concentrations with time at one and the same place. The instrument stores all the electronic pulses which are registered. The number of pulses, and exposure

time can be displayed digitally by connecting a battery to two contact heads on the outside of the instrument.

The solid state detector has great potential for future use in measuring radon, thoron and their daughter isotopes. The method can be developed further as it is technically possible, with this instrument, to study different energy frequencies in alpha radiation in the same way that a gamma spectrometer registers different energy frequencies in gamma radiation. It will then be possible to distinguish between alpha particles produced from radon, thoron and even from their respective alpha emitting daughter isotopes.

GRAB SAMPLES

Air samples were taken using 4.8 litre calcour-gas containers under vacuum. The samples were analysed in an ionisation chamber at SSI in Stockholm. The containers were connected to tubes on the upper surfaces of the accumulators. When the containers were opened, air from inside the accumulators was sucked into the containers.

At SSI the containers with the radon-grab samples are attached one by one to an 18 litre ionisation chamber which is under vacuum. The chamber is a sealed unit with two charged electrodes. When an alpha particle enters the chamber, ions are produced giving rise to a current of ions which is measurable. When properly calibrated, this method gives a measure of the radon content of the sample. Normally two samples can be analysed per hour.

RADON-FLUX METHOD

The radon emanation or flux was determined by measuring the radon concentration in accumulators which were placed on the ground surface (Fig. 10).

The accumulators are simple plastic containers with the following dimensions:

radius, open end	0.18 m
radius, closed end	0.14 m
height	0.40 m
volume (V)	0.032 m ³
effective height (H)	0.32 m

The accumulators were placed on the surface of the ground with the rim dug down to 0.1 m, and sealed around the contact with soil. Radon emanating from the ground (flux) was allowed to build up in the accumulators until equilibrium was reached. Equilibrium is controlled by



Fig. 9. Soil-gas measurement using an AlphaMETER, Alpha Nuclear Company.

radon emanation
 re-diffusion into the ground
 possible leakage
 decay rate
 ratio between the volume of the accumulator and the area of the open
 end.

Calculations of radon flux are based on a method described in Tovedal (1980). Flux is calculated by the following equation:

$$Q = \lambda H C_{\infty} \quad (1)$$

where

Q = radon flux, $\text{Bq m}^{-2} \text{s}^{-1}$

λ = relative changes in accumulated radon content, s^{-1}

H = effective height of the accumulator, m

C_{∞} = equilibrium value, Bq m^{-3}

The radon content in the accumulator is measured at a number of short time intervals during which flux can be regarded to be constant. λ and C_{∞} are calculated from the results and from H by "best fit least squares method".



Fig. 10. Flux measurement in an accumulator. Instrument, AlphaMETER, Alpha Nuclear Company.

An alphaMETER and emanometer Re 279 were used at various times to measure the radon content in the accumulators. Measurements were taken every 2 hours during the first 8–10 hours after the accumulator was placed on the ground, followed by one measurement the following day. Measurements were made on the 4, 5 and 7th days.

The results of the measurements taken during the first day were used to determine λ and C . The relationship between these and the measured concentration at time t , C_t is given in Tovedal (in prep.).

$$C_t = C_\infty (1 - e^{-\lambda t}) \quad (2)$$

$$\text{or } \lambda = 1/t \ln (1 - C_t/C_\infty) \quad (3)$$

TABLE 1. Measurements of flux in a surface accumulator using an alphaMETER.

Measurement	Time of measurement Date	Time	Time interval t , in hours	Radon concentration C_t kBq m^{-3}
Accumulator set out	80-07-10	09.00	0	-
1	"	11.00	2	7.3
2	"	13.00	4	19.7
3	"	15.00	6	28.0
4	"	20.00	11	39.5
5	80-07-11	10.00	25	56.2
6	80-07-14	10.00	97	53.9
7	80-07-15	11.00	122	54.2
8	"	15.00	126	59.8
9	80-07-17	10.00	169	70.3

For each series of measurements, a study was made of which C_∞ gave the best value. That combination of λ and C_∞ is then used in equation (1) for determining radon flux.

The following describes in one example how the method suggested by Tovedal (Tovedal in prep.) was used.

Results from one accumulator measured with an alphaMETER are shown in Table 1.

The accumulator was set out at 09.00 h on 10 July 1980 and nine measurements were made. Measurements 5-8 gave very similar results and as these relate to a period of 6 days, the average of these measurements is taken to be equilibrium C_∞ for radon.

$$C_\infty = 56.0 \pm 2.7 \text{ kBq m}^{-3}$$

The ninth value is much higher which is thought to be due to greater flux between 15 and 17 July. The same tendency was noted for other measurements made during this period.

If one considers only measurements 1-4 (Table 1), these give a best λ -value which corresponds to $C \approx 56$, if conditions during the measuring period were acceptably stable. The results are shown in Table 2.

Measurement 1 has been disregarded because it differs markedly from the others. The first measurements is always the most uncertain, partly because the radon concentration is lowest, but mainly because the relative error in

TABLE 2. Results obtained for measurements 1-4 (Table 1) for different equilibrium values.

Measurement	$\lambda \times 10^4, \text{ h}^{-1}$				
	$C_\infty = 52$	54	56	58	60
1	756	726	698	673	649
2	1190	1135	1084	1037	995
3	1289	1218	1155	1099	1048
4	1296	1195	1111	1039	976
Average for nos. 2-4	1258 + 4.7%	1183 + 3.6%	1117 + 3.2%	1058 + 3.3%	1006 + 3.7%

registering time is greatest here. A small time error of even 10 minutes can have a very marked effect upon the result.

Measurements 2-4 apparently give the best λ -value, $\lambda=0.11 \approx 3.2\%$ for equilibrium $C_\infty=56 \text{ kBq m}^{-3}$ which verifies stability during the measuring period.

Radon flux is calculated using these values:

$$\begin{aligned}\lambda &= 0.11 \text{ h}^{-1} = 3.1 \times 10.5^{-5} \text{ s}^{-1} \\ C_\infty &= 56 \text{ kBq m}^{-3} = 5.6 \times 10^4 \text{ Bq m}^{-3} \\ H &= 0.32 \text{ m}\end{aligned}$$

which when inserted into equation (1) give

$$\begin{aligned}Q &= 3.1 \times 10^{-5} \times 0.32 \times 5.6 \times 10^4 \\ Q &= 0.56 \text{ Bq m}^{-2} \text{ s}^{-1}\end{aligned}$$

Using the λ -value, the time at which equilibrium was reached can be calculated. The sequence is, however, exponential and therefore theoretically only a certain degree of equilibrium can be attained.

In this case 95% of the final value has been attained after

$$\begin{aligned}t_{95} &= -(1/0.11 \ln 0.05) \\ t_{95} &= 27 \text{ h}\end{aligned}$$

Regardless of radon flux, the measuring arrangement studied has a time function expressed by

$$C_t = C_\infty (1 - e^{-0.11 t})$$

Time is given in hours.

Value no 9, 70.3 kBq m^{-3} , which was obtained after 169 hours, should indicate that radon flux had increased from $0.56 \text{ Bq m}^{-2} \text{ s}^{-1}$ to

$$Q = 3.1 \times 10^{-5} \times 0.32 \times 7.0 \times 10^{-4}$$

$$Q = 0.69 \text{ Bq m}^{-2} \text{ s}^{-1}$$

under the assumption that stability had prevailed since the previous day.

CALIBRATION

The results of radon measurements are usually expressed as relative values in units such as counts/hour or tracks/ mm^2 , because absolute values of soil-gas radon concentrations are difficult to obtain and has usually not been important previously. In uranium prospecting the aim has only been to distinguish areas with enhanced radon concentrations in relation to background levels. More recently, however, radon has come to be regarded as an environmental problem, for example in Sweden, and the interest has increased for obtaining absolute values for radon concentrations in soil gas, as well as for radon emanation from the ground and from building materials.

Many articles have been published quoting absolute values but the instruments used have in all cases been technically advanced, expensive and with low measuring capacity. Only a few articles have been published which quote absolute values for soil-gas radon concentrations for methods and instruments of the type used in uranium prospecting (Alter 1980, Pacer and Czarnecki 1980).

Calibrations can be made experimentally by exposing instruments or detectors in a controlled radon/radon daughter environment. The radon source can be produced in several ways. A common method is to de-gas radon from a known radium solution. Another method is to allow radon to emanate from a radium-rich rock. The National Institute of Radiation Protection (SSI) in Stockholm have a controlled radon environment in a specially constructed radon room. The radon source is uranium ore (pitchblende) which is stored in the room. Continuous measurements are made of radon and radon daughter concentrations, temperature, humidity, ventilation, air pressure and particle content of the air. All of these factors can be varied. Extensive calibrations are in progress at SSI of detectors for indoor measurements of radon and radon daughter concentrations. As yet, no standardised calibration procedure has been developed in Sweden or elsewhere.

Most of the methods used by SGU in this study have been briefly tested in the radon room at SSI. In most cases, however, the radon concentration in the room was too low, and the number of measurements too few to allow for a real calibration. Hence, the results quoted in this report, expressed in the SI-unit Bq/m^3 (Becquerels per cubic metre), should not be regarded as absolute and

TABLE 3. Results of calibrations in the radon room at SSI.

Method	Unit	Calibration factors	
		Bq m ⁻³	pCi/l
ROAC	c/s	145	3.9
Track Etch (open)	tracks/mm ²	33	0.9
Track Etch (membrane)	tracks/mm ²	55	1.5
AlphaMETER	c/h	30	0.8
Emanometer RE 279	c/m	118	3.2

exact values based on determination calibration factors. The aim of the calibration tests have rather been to permit a rough calculation of the range of soil-gas radon concentrations measured in the field, and furthermore, by using a common reference unit, to be able to compare the results obtained by the different methods and instruments.

In this study the grab-sample method of measuring the radon flux (p. 15) is considered to produce the most accurate values, as the samples are analysed in the ionisation chamber at SSI, which is calibrated in conjunction with the radon room. For this reason grab-sample results have been used as reference for measurements by other methods.

When comparing the various methods used, precaution must be taken as to what the measurements represent. In some cases only radon is measured, in others both radon and thoron and/or their daughter isotopes. The soil-gas sample taken is not directly comparable for the various methods, nor is it comparable with the calibration environment (radon room) to which the calibration factors apply. This problem is exemplified by comparing the results of emanometer readings with those of other methods for soil-gas measurements and flux measurements. When sampling soil gas with an emanometer one cannot avoid atmospheric air mixing with soil gas. The extent of mixing varies with varying soil conditions. When sampling with an emanometer from an accumulator, no mixing of atmospheric air occurs, and such results compare favourably with those from other methods.

Measurements carried out in a thorium-rich environment (e.g. granites) are strongly affected by thoron (Rn-220). If corrections are not made for thoron at the time of measuring, the calibration factors shown here cannot be used.

Table 3 gives a summary of the results obtained from the various calibrations which, in some cases, are used by SGU to express the results of soil gas radon measurements as Bq/m³. The results quoted for Track-Etch are taken from Alter (1980).

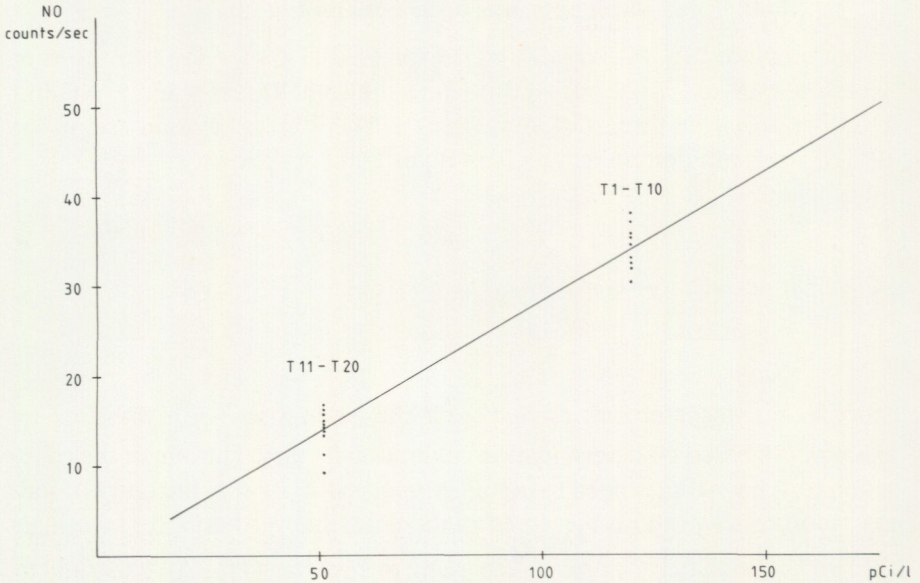


Fig. 11. Results of the test measurements using ROAC detectors, radon room at SSI.

TEST MEASUREMENTS IN THE RADON ROOM ROAC

ROAC detectors were exposed in the radon room at SSI on two occasions (10 detectors on each occasion). The time of exposure was one week. The average radon concentration in the room during exposure was $4\,440\text{ Bq/m}^3$ (120 pCi/l), and $1\,850\text{ Bq/m}^3$ (50 pCi/l) respectively.

Fig. 11 shows the calculated ROAC value plotted against the average radon concentration in the room during exposure. The ROAC value is calculated according to the following equation (Hambleton-Jones and Smith 1980):

$$\text{ROAC value} = \text{NO} = \text{NT}/(\text{FA} \times \text{FD})$$

where

$$\text{NT} = \text{NB} - \text{BG}$$

NB = measured impulses per time unit from the detector

BG = measured impulses per time unit, background

FA = correction factor for RnD growth (adsorption)

FD = correction factor for RnD decay

FA and FD are given by the equations

$$\text{FA} = 1 - e^{-\lambda t} \quad (1) \quad \text{and} \quad \text{FD} = e^{-\lambda t} \quad (2)$$

where $\lambda = 0.00755 \text{ (h}^{-1}\text{)}$ and t is the time of growth (TA) respectively time of decay (TD) expressed in hours.

The measured ROAC values (NO) expressed as c/s for the two series of detectors 1-10 and 11-20, respectively, are shown in Tables 4 and 5. NO has been measured at three different times (TD). The calibration factor for ROAC has been determined to 145 (Bq/m³)/NO as follows:

Series	radon content	NO	(Bq/m ³)	(pCi/l)/NO
1-10	4440	30.41	146	3.9
11-20	1880	13.13	143	3.9
		average value:145		3.9

More recent measurements carried out in the radon room verify these results (Per Andersson, pers. comm.).

Example: A ROAC detector is exposed in the ground for 5 days and 21 hours (TA = 139 hours). Gamma radiation is measured 2 days and 19 hours (TD=67 hours) after exposure. According to equation (1), FA=0.650 and to equation (2), FD=0.603. Background gamma radiation (BG) was measured to 21.28 c/s. Gamma radiation from the detector (NB) was measured to 105.66 c/s. Net radiation (NT) is therefore NB-BG = 84.38 c/s. The ROAC value (NO) can thus be calculated as follows:

$$\text{NO} = \text{NT}/(\text{FA} \times \text{FD}) = 84.38/(0.650 \times 0.603) = 215.28$$

which gives a radon content of

$$\begin{aligned} 215.28 \times 145 &= 31\,216 \text{ Bq/m}^3 \\ \text{or } 215.28 \times 3.9 &= 840 \text{ pCi/l} \end{aligned}$$

TRACK-ETCH

Track-Etch film has been calibrated by the manufacturer Terradex Corporation. The calibrations have been carried out both in the USA and at SSI in Stockholm. The calibration factors quoted here are taken from Alter (1980), and refer to calibrations made in two radon chambers at the Environmental Measurements Laboratory (EML) in New York. The conditions for nine separate test measurements are shown in Table 6. Table 7 gives the results in track density obtained for 4 different types of detectors: open, with thoron membrane (MEMB), with radon daughter filter (FILT), and with film without cup (BARE).

The open detectors used for field measurements in a thoron free environment (e.g. alum shale) correspond to the filter (FILT) measurements made

TABLE 4. ROAC values (NO) expressed as c/s for the series of detectors 1-10.

Detector	TA	FA	TD	FD	c/s · 10 ⁻²		NT	NO · 10 ⁻²
					NB	BG		
1	6 16	0.701	5 8	0.380	2338	1630	708	2658.
2	6 16	0.701	5 8	0.380	2395	1630	765	2872.
3	6 16	0.701	5 8	0.380	2458	1630	828	3108.
4	6 16	0.701	5 8	0.380	2398	1630	768	2883.
5	6 16	0.701	5 8	0.380	2543	1630	913	3427.
6	6 16	0.701	5 8	0.380	2517	1630	887	3330.
7	6 16	0.701	5 8	0.380	2411	1630	781	2932.
8	6 16	0.701	5 8	0.380	2475	1630	845	3172.
9	6 16	0.701	5 8	0.380	2485	1630	855	3210.
10	6 16	0.701	5 8	0.380	2392	1630	762	2861.

 $\overline{\text{NO}} = 30.45$

1	6 16	0.701	6 1	0.334	2385	1630	755	3225.
2	6 16	0.701	6 1	0.334	2377	1630	747	3190.
3	6 16	0.701	6 1	0.334	2309	1630	679	2900.
4	6 16	0.701	6 1	0.334	2358	1630	728	3109.
5	6 16	0.701	6 1	0.334	2358	1630	728	3109.
6	6 16	0.701	6 1	0.334	2302	1630	672	2870.
7	6 16	0.701	6 1	0.334	2312	1630	682	2913.
8	6 16	0.701	6 1	0.334	2363	1630	733	3131.
9	6 16	0.701	6 1	0.334	2337	1630	707	3020.
10	6 16	0.701	6 1	0.334	2284	1630	654	2793.

 $\overline{\text{NO}} = 30.26$

1	6 16	0.701	8 1	0.233	2216	1630	586	3588.
2	6 16	0.701	8 1	0.233	2191	1630	561	3435.
3	6 16	0.701	8 1	0.233	2023	1630	393	2406.
4	6 16	0.701	8 1	0.233	2144	1630	514	3147.
5	6 16	0.701	8 1	0.233	2052	1630	422	2584.
6	6 16	0.701	8 1	0.233	2149	1630	519	3178.
7	6 16	0.701	8 1	0.233	2150	1630	520	3184.
8	6 16	0.701	8 1	0.233	2066	1630	436	2669.
9	6 16	0.701	8 1	0.233	2141	1630	511	3129.
10	6 16	0.701	8 1	0.233	2150	1630	520	3184.

 $\overline{\text{NO}} = 30.51$

average 30.41
 stand. dev. 2.63
 -"-% 8.6

Average radon concentration during exposure (TA): 4440 Bq m⁻³Calculated calibration factor (Bq m⁻³/ NO): 146

TABLE 5. ROAC values (NO) expressed as c/s for the series of detectors 11-20.

Detector	TA	FA	TD	FD	c/s · 10 ⁻²			NO · 10 ⁻²
					NB	BG	NT	
11	5 6	0.614	5 19	0.350	2030	1698	332	1545.
12	5 6	0.614	5 19	0.350	1964	1698	266	1238.
13	5 6	0.614	5 19	0.350	2023	1698	325	1512.
14	5 6	0.614	5 19	0.350	2004	1698	306	1424.
15	5 6	0.614	5 19	0.350	1912	1698	214	996.
16	5 6	0.614	5 19	0.350	1969	1698	271	1261.
17	5 6	0.614	5 19	0.350	1987	1698	289	1345.
18	5 6	0.614	5 19	0.350	1871	1698	173	805.
19	5 6	0.614	5 19	0.350	1987	1698	289	1345.
20	5 6	0.614	5 19	0.350	1980	1698	282	1312.
$\overline{NO} = 1278$								
11	5 6	0.614	6 16	0.299	1910	1699	211	1149.
12	5 6	0.614	6 16	0.299	1933	1699	234	1275.
13	5 6	0.614	6 16	0.299	1994	1699	295	1607.
14	5 6	0.614	6 16	0.299	2003	1699	304	1636.
15	5 6	0.614	6 16	0.299	1935	1699	236	1286.
16	5 6	0.614	6 16	0.299	1967	1699	268	1460.
17	5 6	0.614	6 16	0.299	1949	1699	250	1362.
18	5 6	0.614	6 16	0.299	2013	1699	314	1710.
19	5 6	0.614	6 16	0.299	2004	1699	305	1661.
20	5 6	0.614	6 16	0.299	1944	1699	245	1335.
$\overline{NO} = 1450$								
11	5 6	0.614	7 17	0.247	1847	1635	212	1398.
12	5 6	0.614	7 17	0.247	1803	1635	173	1141.
13	5 6	0.614	7 17	0.247	1813	1635	178	1174.
14	5 6	0.614	7 17	0.247	1813	1635	178	1174.
15	5 6	0.614	7 17	0.247	1870	1635	235	1550.
16	5 6	0.614	7 17	0.247	1870	1635	235	1550.
17	5 6	0.614	7 17	0.247	1790	1635	155	1022.
18	5 6	0.614	7 17	0.247	1773	1635	138	910.
19	5 6	0.614	7 17	0.247	1815	1635	180	1187.
20	5 6	0.614	7 17	0.247	1785	1635	150	989.
$\overline{NO} = 1209$								
average								13.13
stand. dev.								2.33
- " - %								17.7

Average radon concentration during exposure (TA): 1880 Bq m⁻³

Calculated calibration factor (Bq m⁻³/ NO): 143

TABLE 6. Exposure conditions for Track-Etch calibration at EML. After Alter (1980).

Run	Chamber	Duration (days)	Average radon exposure rate (pCi/l)	Number of configurations	Replicates per configuration	Detectors
A	2m ³	14	1085	1	5	5
B	20m ³	120	38	1	3	3
C	2m ³	21	350	3	5	15
3-79	20m ³	79	25.6	4	5	20
3-36	20m ³	36	11.6	4	5	20
3-115	20m ³	115	21.2	4	5	20
4-30	20m ³	30	33.2	4	20	80
4-93	20m ³	93	32.6	4	20	80
4-63	20m ³	63	32.1	4	20	80
Total detectors						323

TABLE 7. Radon exposure *versus* mean track density. After Alter (1980).

Run	Chamber	Duration (days)	Radon exposure ((pCi/l)-days)	Detector reading (mean tracks/mm ²)			
				OPEN	MEMB	FILT	BARE
A	2m ³	14	15190	-	-	-	1608
B	20m ³	120	4660	-	-	-	638
C	2m ³	21	7350	556	259	-	851
3-79	20m ³	79	2020	90.6	31.9	55.6	115.1
3-36	20m ³	36	418	25.7	9.7	17.0	23.5
3-115	20m ³	115	2440	125.0	41.8	78.2	137.2
4-30	20m ³	30	996	45.2	19.2	34.2	73.2
4-93	20m ³	93	3030	200.9	73.8	126.5	297.6
4-63	20m ³	63	2020	110.9	45.8	77.5	206.0

during calibration. The filter prevents free radon daughters in the air of the calibration chamber from reaching the detector. The open detector in the radon chamber, however, measures both radon and free radon daughters, which is not the case for open detectors used in the ground where radon daughter isotopes are adsorbed onto soil particles.

In areas where thoron is present (thorium-rich granites), thoron can be prevented from reaching the detector to a very considerable extent by the use of a plastic membrane (MEMB). In these cases, the calibration factor used is the same as for MEMB in the radon chamber. It is assumed that the membrane prevents all thoron from reaching the detector.

TABLE 8. Calibration factors for Track-Etch. After Alter (1980).

Run	(Tracks/mm ²) / (pCi/l)-day			
	OPEN	MEMB	FILT	BARE
A	-	-	-	0.1068
B	-	-	-	0.1369
C	0.0756	0.0352	-	0.1158
3-79	0.0448	0.0158	0.0275	0.0570
3-36	0.0615	0.0232	0.0407	0.0562
3-115	0.0512	0.0171	0.0320	0.0562
4-30	0.0454	0.0193	0.0343	0.0735
4-93	0.0663	0.0244	0.0417	0.0982
4-63	0.0549	0.0227	0.0384	0.1020
Weighted mean	0.0562	0.0223	0.0372	0.0891
Weighted stand. dev.	0.0115	0.0050	0.0060	0.0229
Relative stand. dev. (%)	20	22	16	26

Table 8 gives the calibration factors calculated for the respective detectors from the measurements made during the nine test series. Terradex usually quote the measured track density as tracks per mm² normalised to 30 days. On the basis of the weighted averages given in Table 8, the following calibration factors are obtained:

	(Bq/m ³)/(tracks/mm ²)-day	(Bq/m ³)/(tracks/mm ²)-30 days
FILT:	995	33
MEMB:	1 660	55
	(pCi/l)/(tracks/mm ²)-day	(pCi/l)/(tracks/mm ²)-30 days
FILT:	27	0.9
MEMB:	45	1.5

Example: Terradex quote the results for an open cup which has been exposed in the ground for three weeks at a depth of 0.5 metres as 4 750 track/mm². The result is normalised to 30 days exposure time (in reality exposure was 3 weeks). The radon content of the soil gas is calculated as follows:

$$4\,750 \times 33 = 157\,700 \text{ Bq/m}^3$$

or

$$4\,750 \times 0.9 = 4\,275 \text{ pCi/l}$$

TABLE 9. Calibration of alphaMETERS in the radon room at SSI.

Instrument	Counts	Hours	c/h	(Bq m ⁻³) / (c/h)	(pCi/l) / (c/h)
78	345	4.87	70.8	25.9	0.70
79	339	4.87	69.6	26.6	0.72
80	308	4.89	63.0	29.2	0.97
81	283	4.88	58.0	31.8	0.86
82	249	4.89	50.9	36.3	0.98

$$Rn = 1850 \text{ Bq m}^{-3} \text{ (50 pCi/l)}$$

ALPHAMETER

Five alphaMETER instruments manufactured by AlphaNUCLEAR were exposed for just less than 5 hours in the radon room at SSI. The average radon concentration in the room was 1 850 Bq/m³ during the time of exposure. Table 9 shows the results obtained for each of the instruments. This test measurement was far from adequate to use as a basis for calculating soil gas radon concentrations expressed as Bq/m³. Further measurements in the radon room are planned. For the time being a factor of 30 (Bq/m³)/(c/h), or the factors quoted in Table 9 for each instrument, can be used to give a rough idea of the range of radon concentration. These factors only apply to the five instruments owned and tested by SGU.

Example: An alphaMETER (no. 78) was exposed in an accumulator for 10 hours at the end of which time the instrument displayed 4000 counts. The average radon concentration during those 10 hours can roughly be estimated as follows:

$$Rn = 4000/10 \times 30 = 12000 \text{ Bq/m}^3$$

alternatively

$$Rn = 4000/10 \times 25.9 = 10350 \text{ Bq/m}^3$$

or

$$Rn = 4000/10 \times 0.70 = 280 \text{ pCi/l}$$

EMANOMETER

An emanometer RE 279 (ser no. 0023) was tested in the radon room at SSI. The radon concentration in the room during the test period was 1 850 Bq/m³.

TABLE 10. Test measurements made with emanometer RE 279 in the radon room at SSI. Average radon content in the room 1850 Bq m^{-3} .

cell	background	0-5 min	5-15 min	c/m netto	$(\text{Bq m}^{-3}) / (\text{c/m})$
1	1	80	173	15.84	115.6
2	2	81	194	16.33	112.1
3	2	86	175	15.40	119.3
4	1	85	197	17.80	102.8
5	3	84	174	14.20	132.1
6	3	66	201	14.80	123.3
1	2	66	214	16.67	112.1
6	4	96	196	14.47	127.6
				average	118.1 $\approx 3.2 \text{ (pCi/l)}/(\text{c/m})$
				stand. dev.	9.5
				"- %	8

The procedure was as follows. A scintillation cell was inserted in the instrument and background measured over 1 minute. The instrument was taken into the radon room, and an air sample circulated through the instrument by pumping 100 revolutions. The instrument was taken out of the radon room, and counting commenced immediately. The counting periods was 0-5 minutes and 6-15 minutes. The results of the test measurements are shown in Table 10. A calibration factor of $118 (\text{Bq/m}^3)/(\text{c/m})$ was determined for the RE 279 instrument from the measurements made with cells 1-6. Further measurements made in the radon room verify these results (Per Andersson, per. comm.).

Each scintillation cell is unique with its own calibration constant which varies within the scope of statistical probability for radioactive decay. This constant probably changes with constant use of the cell. Dust and dirt collect on the sides of the cell, and the zinc sulphide coating can flake off. For the field measurements made by SGU, one calibration constant has been used for all the cells belonging to the respective emanometers, for example, the average value as shown in Table 10 for emanometer no. 0023. This is of course a considerable simplification permitting large errors. However, the aim has been to express radon concentrations in a unit which allows comparisons with other measuring procedures. The method employed is judged to be satisfactory from this point of view.

Example: A sample was taken from a hole which had been drilled in the ground in a thoron free geological environment. During the first 5 minutes of

counting, 103 counts were registered for cell 1. Background in the cell was 3 c/m. The radon concentration of the sample can be determined as follows:

$$R_n = (103/5-3) \times 118 = 2100 \text{ Bq/m}^3$$

or

$$R_n = (103/5-3) \times 3.2 = 56 \text{ pCi/l}$$

KODAK AND TLD

Calibrations and analyses of the Kodak films and TLD-instruments used in the study have been carried out by Studsvik Energiteknik AB, Sweden. SGU do not normally use Kodak films because its use for commercial purposes is prohibited in Sweden by a Track-Etch patent. The films have however, been tested in this study and compared with Track-Etch in both the radon room and in field studies. The calibrations of Kodak film have been carried out in a radon room by both Studsvik and SSI (Bäverstam 1980). Moreover, the calibrations were made on films without filters and so the effects of the free radon-daughters are not known.

For this reason it is not possible in this study to even roughly convert Kodak values to Bq/m^3 for measurements of radon concentrations in soil gas.

TLD have also been calibrated in the radon room at SSI by Studsvik. The results of these tests are not published.

GRAB SAMPLES

The grab samples taken from the accumulators and analysed in an ionisation chamber at SSI were intended as reference measurements to other measurements. The ionisation chamber at SSI is calibrated in conjunction with the radon room.

EXPERIENCE FROM FIELD APPLICATIONS

Transport of radon gas in soil air and radon flux from the ground surface are controlled by many parameters such as mineral composition of a rock, porosity, occurrence of fractures, degree of weathering, water content. Radon concentrations in the upper soil layers are also affected by fluctuations in groundwater level.

On basis of a large number of soil-gas measurements made by SGU, the following general rule can be applied for calculating absolute concentrations that are comparable with Track-Etch and ROAC for measurements made in the same geological environment.

For measurements made in till, sand or gravel, which is covered by 30–50 cm clayey topsoil (this applies to many gardens), the emanometer results are generally the same as those given by ROAC and also Track-Etch where concentrations are low. The same applies for emanometer measurements made under the foundations of houses, from the accumulators or from plastic tubes in the ground.

For measurements made in till, sand or gravel, which is not covered by a layer of material with low permeability, the emanometer results should be multiplied by a factor of between 3 and 7 to obtain similar Bq/m^3 values to those obtained from ROAC or Track-Etch. The more sandy or gravelly the till is the higher the factor.

For radon concentrations of about 1 million Bq/m^3 or higher, ROAC gives results which are 2–3 times lower than those given by Track-Etch. This may be due to the fact that activated charcoal becomes successively saturated with radon, or that Track-Etch films at such high concentrations become very difficult to analyse due to the very large numbers of tracks on the films.

It should be noted that calibrations have not been made in a thoron environment comparable to the radon environment of the radon room. The determinations made using instruments or detectors which measure radon plus thoron are therefore debatable.

The measurements made in this study indicate that determinations of absolute radon concentrations in soil gas and calibration of instruments for these measurements are greater problems than the corresponding measurements and calibrations for radon flux using surface accumulators. This is due to the fact that many more factors, which are difficult to measure, affect the results of soil-gas measurements. Correcting for these factors cannot be made during calibrations in a radon room. Even in cases where many of the effects of these factors can be corrected for, or ignored, the main question remains concerning the extent to which the measured radon concentrations are representative of the whole area being measured. The experience from the present study show that large variations in radon concentrations occur over very short distances, even in geologically homogeneous areas. It is always necessary to judge the soil-gas radon concentration of an area from a large number of measurements.

In general, experience is lacking in absolute calibrations of instruments for soil-gas measurements. This applies both to Sweden and elsewhere. Most of the instruments sold for soil-gas measurements have, in some way or other, been tested against known radon concentrations, but none have been subjected to extensive calibration in a radon or thoron room, or in field experiments. Of the methods used, only Track-Etch has been calibrated to a fairly satisfactory extent, and the results published (Alter 1980). Similar more

extensive calibrations under Swedish conditions are necessary in order to make it possible to express measured radon concentrations in soil gas as Bq/m³ or pCi/l.

RESULTS OF SOIL-GAS MEASUREMENTS IN THE FIELD

Results are presented of the measurements made during the study described in Hesselbom *et al.* (1980) and of measurements made during the course of various site investigations carried out by SGU during recent years. The methods studied can be used either for uranium prospecting (Smith and Baretto 1976, Gingrich and Fisher 1976) or for environmental investigations (Tanner 1964, 1978.)

The field studies were carried out in two geologically different environments: alum shale and granite. Both rock types often have high concentrations of uranium (radium) which may give rise to high concentrations of radon in soil gas. Moreover, as these rocks cover large areas of the more densely populated parts of Sweden, it was desirable, to acquire better information on soil-gas radon concentrations for these environments. The areas investigated were Ranstad, south of Skövde (alum shale) and Balltorp, Mölndal, south of Gothenburg (granite).

The methods used have been compared with regard to

ability to detect variations in radon concentrations
reproduceability
depth effects
meteorological effects

The many hundreds of measurements made by SGU indicate that radon concentrations in the soil gas in the overburden vary both locally and regionally by a factor of one to 3000 depending upon the radium content, moisture content and permeability in the soil.

A summary of the measurements of soil gas in Sweden is given in Table 11.

COMPARISON OF MEASUREMENTS IN TWO DIFFERENT GEOLOGICAL ENVIRONMENTS

Radon flux was determined by measuring the concentration of radon which had built up in the surface accumulators. Measurements were made at various time intervals using an emanometer, a solid state detector (alphaMETER) and simultaneous grab samples. Average concentrations of radon in the accumulators over longer periods were made using TLD dosimeters, film- and

TABLE 11. Calculated absolute concentrations (kBq m⁻³) in the surface accumulators. After Hesselbom *et al.* (1981).

Area	Measuring station	SSI	Emanometer	TLD	Kodak	ROAC	AlphaMETER
ALUM SHALE							
Area A	70 W	1.3	2			1	
	70 W	3.8	2	2.1	8.0		
	135 E	1.7	3				
	135 E	4.1	5	2.5	6.5		
Area B	3	146	93			104	
	4	145	97	58.5	158		
Ranstad		18.7	14				29
GRANITE							
Area C:1	6		107			110	
	7	107	64	288	186		
	8	59.8	43				56
Area C:2	6		21			34	
	7	25.5	20	78.3	75.8		
Granite outcrop X (area C)	X	15.6	18			16	
	Y			91.7	99.9		
Area D:1	6	7.1	6	15.3	17.5		
	7					6	
Area D:3	1	16.5	18			20	
	5		25	55.3	36.6		
Area D:2	4			13.4	14.9		
Granite outcrop W (area D)	W	0.7	1			1	
	Z			3.7	5.1		

NB. The values quoted for SSI, emanometer and ROAC refer only to radon. AlphaMETER and TLD refer to radon + thoron and Kodak refer to radon + thoron + radon and thoron daughter isotopes.

ROAC detectors. The exposure time for TLD and the film detectors was 3–4 weeks and for ROAC 5–8 days

The accumulators were placed, if not otherwise stated, on the ground dug down to about 0.1 m in the till. The till overlay either alum shale or granite bedrock. In the areas of alum shale, thoron (Rn-220) contents were negligible but in the granite areas, they varied considerably. The amounts of thoron in the granite areas were always sufficient to affect the results of measurements.

TABLE 12. Results of measurements made at varying depths in two of the areas studied. Radon concentrations are expressed as kBq m⁻³.

Method	Isotope	Surface accumulator	Depth (m)		
			0.3	0.6	0.9
Area B ALUM SHALE					
Track Etch (open)	Rn		503	1440	2110
Track Etch (memb)	Rn		665	619	2552
ROAC	Rn	104	511	796	904
Emanometer	Rn	94	92	182	
Kodak (open)	Rn + RnD	158			
TLD	Rn	58			
Grab sample SSI	Rn	145			
AlphaMETER	Rn		350		
Area C:2 GRANITE					
Track Etch (open)	Rn + Tn		(131)	(241)	(372)
Track Etch (memb)	Rn		97	265	573
ROAC	Rn	34	52	188	278
Emanometer	Rn + Tn	20		(20)	
Emanometer	Rn			14	
Kodak (open)	Rn + Tn + D	(76)			
TLD	Rn + Tn	(25)			
AlphaMETER	Rn + Tn	30	29		

The results (Tables 12 and 13) are given as kBq/m³ and based on information from analyses of grab samples carried out at SSI (ionisation chamber), Studsvik (TLD, Kodak) and from the comparative measurements made by SGU in the radon room at SSI.

The calculated radon concentrations correlate well for the various methods used. The grab-samples and emanometer measurements are directly comparable because they are both momentary measurements, the samples being taken at one and the same time. The other methods give the average concentration during exposure. The results from the Kodak films relate to radon and radon daughters which explains their often higher values. The poor correlation between the grab samples and TLD and the film detectors for the granite areas are due to the effects of thoron on the TLD instrument and the film detectors. The grab-sample measurements relate only to radon.

TABLE 13. Normal soil-gas radon concentrations in different soil types in Sweden. Depth of measurement, one metre.

Soil type	Uranium content ppm U	Radon concentrations Bq m ⁻³
Till (predominantly granite)	5 - 30	10 000 - 300 000
Till (alum shale)	10 - 100	100 000 - >1 000 000
Eskers	4 - 10	10 000 - 200 000
Other soil types	1 - 8	5 000 - 30 000

COMPARISON OF MEASUREMENTS MADE ALONG A TEST PROFILE

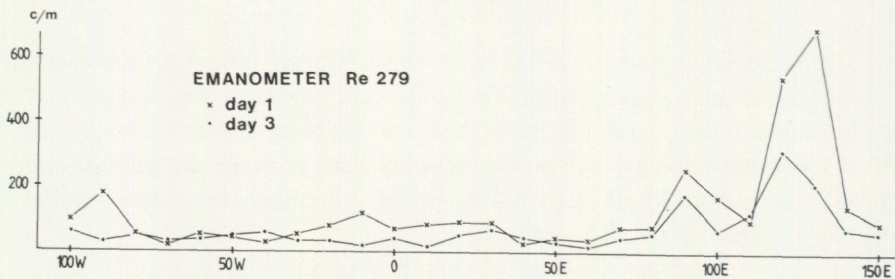
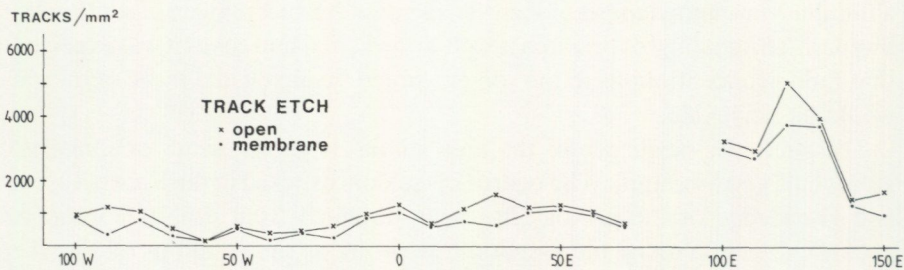
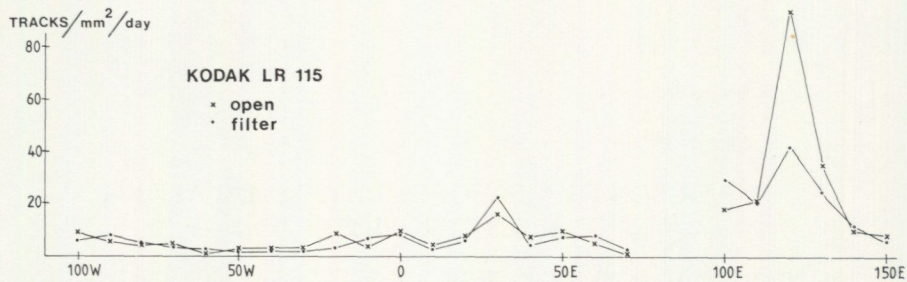
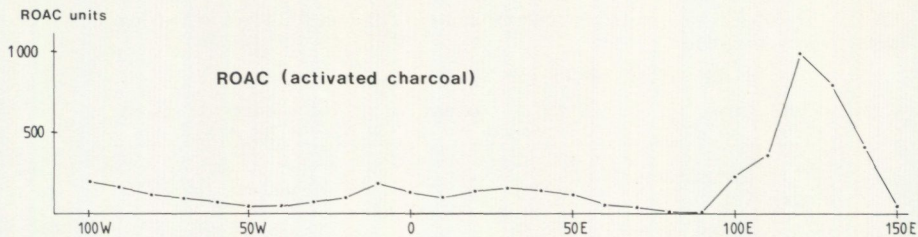
Measurements have been made, using a variety of methods and detectors, along a 250 m profile with the purpose of testing their ability to detect variations in soil-gas radon concentrations. The profile was selected over the alum shale uranium deposit of Ranstads Skiffer AB at Billingen in south-west Sweden. The geology of this area is well-known, and moreover it was expected that radon concentrations in the soil gas would be high while those of thoron would be negligible.

The geological sequence of the area studies is gneiss, sandstone, shales, alum shale and limestone. The bedrock is seldom exposed in the Ranstad area, and knowledge of the geology has been obtained from drill-hole data. A geological section along the length of the profile is shown in Fig. 12. At the western end of the profile, limestone occurs at the bedrock surface. The limestone horizon decreases in thickness eastwards along the profile to be replaced at the eastern end by alum shale with a uranium content of 200–330 ppm.

The overburden, which is 4–8 m thick, consists largely of sandy till with small boulders. At the western end of the profile these boulders are predominantly of limestone origin. At depth the till becomes more clayey in character and its boulder content decreases. Thick layers of clay occur in the central part of the profile. Along the whole length of the profile, the till is overlain by a humus-rich layer which is 0.1–0.5 m thick.

Groundwater lay at a depth of 0.5 m in the clayey part of the profile, and at a depth of 4.5 m at the eastern end.

Measurements of gamma radiation, uranium content (spectrometer) and radon were made at 10 m intervals along the profile. Gamma radiation,



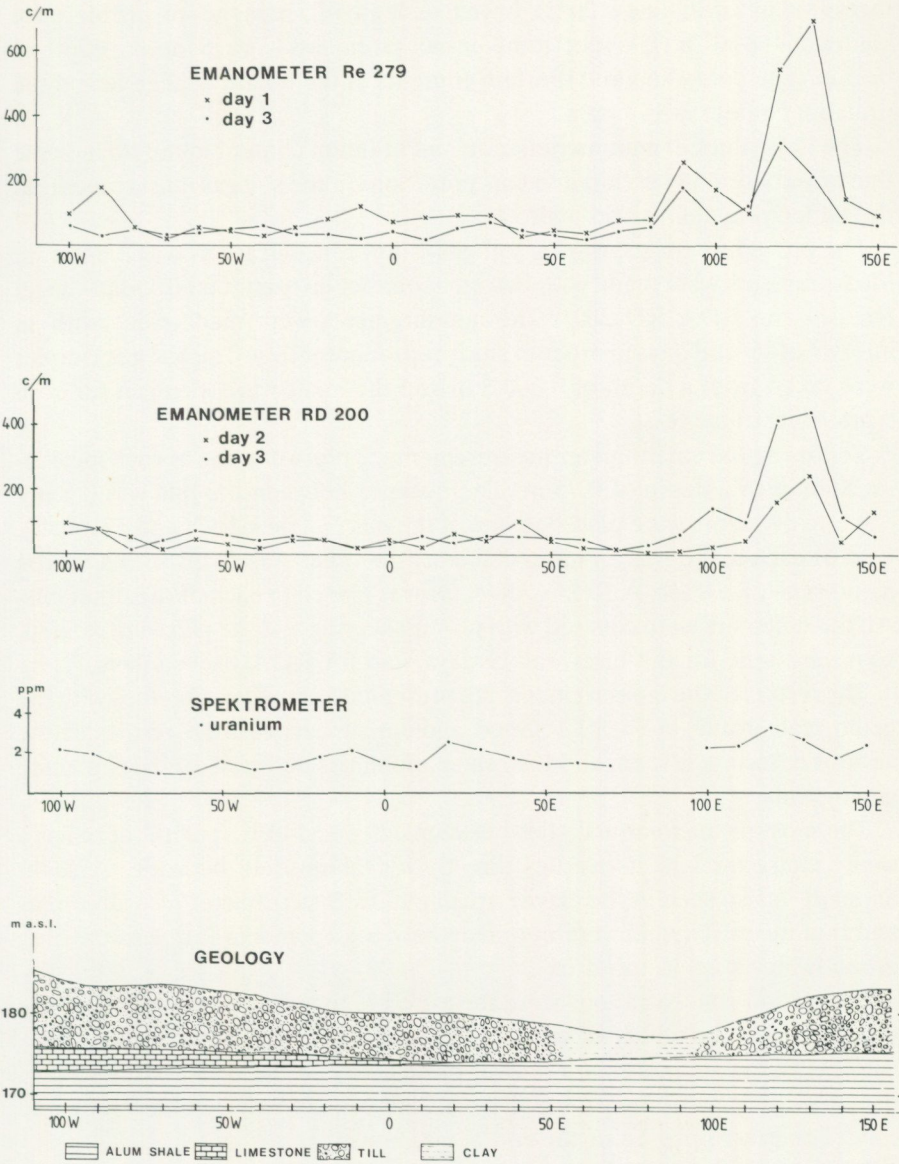


Fig.12 . Results of soil-gas radon measurements along a profile using a variety of detectors.

measured in a drill hole (130 E) down to a depth of 5 m in the soil profile, gave values of 4–8 $\mu\text{R/h}$. The spectrometer measurements were made at a depth of 0.75 m. The potassium and thorium contents of the till are negligible and the uranium content is 1–4 ppm.

The low values of gamma radiation and uranium content in the till indicate that any abnormally high radon concentrations in the soil gas must come from the underlying alum-shale bedrock.

The procedure for measuring soil-gas radon concentrations was as follows. Measurements were made with two emanometer instruments (Bondar-Clegg, RE 279 and EDA RD 200). The measurements were made twice with an interval of several days in order to study reproducibility. The soil gas samples were taken from a depth of 0.6–0.8 m and the holes were identical for both types of instrument.

Following the emanometer measurements, 2 pits were dug at each measuring station to a depth of 0.75 m. The distance between the pits was 0.5 m.

4 film detectors were placed in one of the pits (2 Track-Etch and 2 Kodak). One of each make was an open detector, the other was fitted with a thoron membrane or a filter. A ROAC detector was placed in each of the other pits. All the detectors were covered with plastic sheeting and the pits were refilled. Exposure time for the films was 19 days, and for ROAC seven days.

The results of the measurements are presented as profiles, together with the geological profile in Fig. 12. Good agreement between the results of the various detectors is seen, and the radon anomalies detected can be explained geologically.

The most distinct anomaly lies between 120 and 140 E. The till here has a sandy character and it overlies directly the alum-shale bedrock. A slight anomaly is also seen in the clayey area at 90 E. Spectrometer measurements and film measurements were not made between 80 and 90 E due to the high groundwater level in this area.

Low radon concentrations were measured in the clayey part of the profile which reflects the ability of clay soils to hinder diffusion of radon.

Slight radon anomalies are shown, particularly by the films, in the section 0–50 E. This part of the profile lies over the contact between limestone and clay. The exact position of the contact is, however, not known.

Radon concentrations are seen to be low at the western end of the profile over limestone bedrock. Here the limestone acts as a barrier to radon diffusion upwards from the alum shale. A slight radon anomaly occurs at the extreme western end of the profile for which there is no geological explanation.

A few weak anomalies in the uranium content as measured by gamma spectrometer coincide with radon anomalies. The radiation is probably caused by radon-daughter isotopes produced during the upward flow of radon from the underlying alum shale and detained on soil particles in the till.

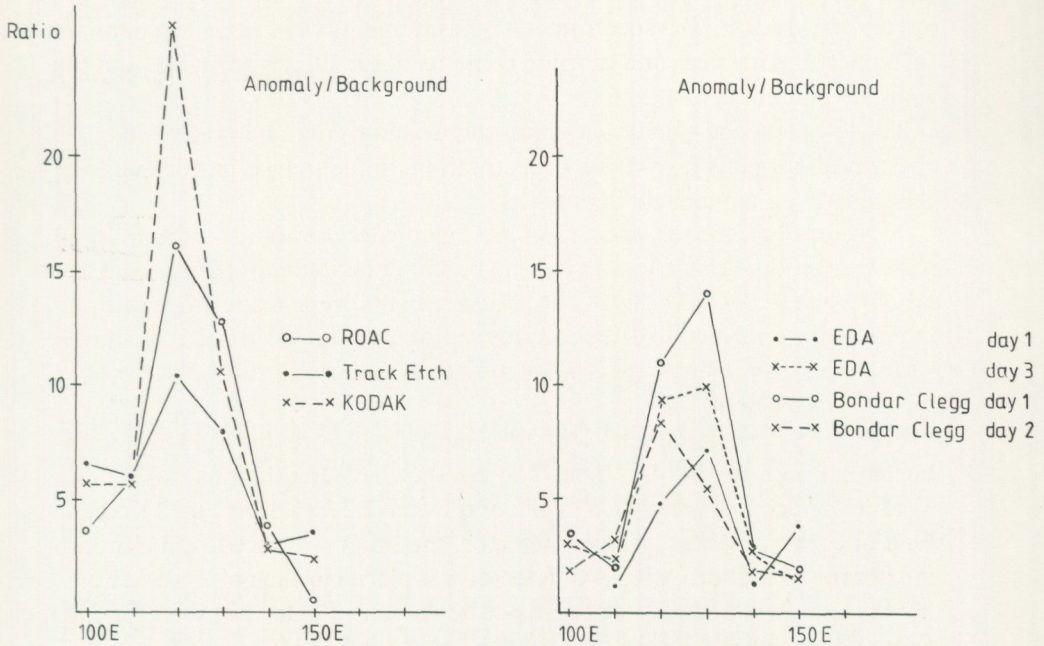


Fig. 13. Anomaly to background ratios for different radon detectors in soil gas. Depth of measurement 0.75 m.

The anomaly to background ratio for each of the different detectors is shown in Fig. 13. The example used is the anomaly between 100 E and 150 E compared with "relative" background measurements made around 50 W.

The largest anomaly to background ratios are shown by Kodak and ROAC (over 15 times) while the ratios for emanometer and Track-Etch vary between 5 and 10 times depending on the time of measurement.

A rough estimate has been made, from all the measurements, of the soil-gas radon concentrations using the calibration factors determined in the test measurements which were described earlier. Concentrations of 150 000 Bq/m³ are estimated for the Track-Etch and ROAC measurements over the anomaly between 120 and 140 E. The average radon concentration over the limestone is estimated to 15 000 Bq/m³.

One of the results shown by these measurements is that the plastic membranes used on the Track-Etch detectors reduced the radon signal by about 21 % compared with that of the open detectors. The filters used on the Kodak detectors, however, showed no such effect except where radon concentrations in the soil gas were exceptionally high.

TABLE 14. Maximum variation in relation to calculated average expressed in per cent.

Site	Track Etch		Kodak	
	OPEN	MEMB	OPEN	FILT
1	13	92	11	29
2	45	34	51	123
3	6	33	11	117

REPRODUCEABILITY

Radon detectors of various types have been tested for reproducibility. Unfortunately, the numbers of measurements made were not sufficient to allow a correct judgement of their precision. However they do show the extent to which variations occur when using the same detector (or type of detector) in the same place.

Track-Etch and Kodak detectors were tested on three different occasions. In each case, three detectors of each type were used, both with and without membranes or filters. The results of the measurements are shown in Table 14.

The extent to which variations occur between detectors of the same type probably depends on the soil conditions in which the detectors are used. For example, large variations between any two detectors can be explained if one of the detectors is inadvertently placed over a boulder or fragment with high emanation (Table 14, No. 2).

In general it appears that open film detectors show less variation in measured concentration than detectors fitted with membranes or filters. The diffusion coefficients for membranes and filters appear to vary between different detectors of the same type, sometimes more than seems acceptable.

Two ROAC detectors were placed, at different depths, in each of 24 measuring stations which were situated in different geological environments. The difference between the two measured concentrations in relation to the average was less than 10 % for 18 of these measuring stations. Differences of 16–38 % were obtained from the same test area for which the film detectors gave large variations, or where radon concentrations in the soil gas were very high.

The reproducibility of emanometer measurements was tested by taking a number of soil-gas samples from the same hole but at intervals of several days. Fig. 13 shows that the reproducibility of these measurements is satisfactory with regard to detecting radon anomalies. However, the response of the signal given varied very considerably. This gives further weight to the argument that emanometer measurements should only be regarded as relative. Some of the

variations in response, however, will be due to actual variations in soil-gas radon concentrations caused by changes in temperature, pressure, wind speed and precipitation.

DEPTH EFFECTS

Soil-gas radon concentrations increase with increasing depth in the soil profile. The measurements made in this study have been made at depths down to one metre only. The results obtained cannot therefore be compared with the various theories concerning radon transport which have been published during recent years. Other factors which also make such a comparison difficult are the problems of determining to what extent other parameters affect each individual result, for example, precision of the detector and homogeneity in soil conditions.

The depth at which a measurement is made strongly controls the magnitude of the result. Therefore, all measurements within one and the same area should, if possible, be made at the same depth. This depth should be sufficient to eliminate most of the effects of short term variations caused by changes in atmospheric and meteorological conditions. Measurements at shallower depths than 0.5 m should be avoided. For practical and particularly economic reasons, measurements can often not be made at greater depths than one metre.

Of the many records obtained in this study, two examples of depths effects is presented.

Figs. 14 and 15 illustrate the first example. The measurements were made along a profile with eight measuring stations situated at one metre intervals along the profile. The measuring stations comprise 6 pits and 2 surface accumulators (Fig. 14 a).

The profile itself was situated in an area of alum shale, at southern Ranstad in south-west Sweden. A section through the soil profile is shown in Fig. 14 b. The profile lies across the contact zone between limestone and alum shale. The different soil horizons comprise

- 0-1.2 m Boulder clay, possibly washed, with fragments (up to 5 cm) of alum shale. Radioactivity at ground level is 30-50 $\mu\text{R/h}$.
- 1.2-2.2 m Fine sand to silt, water saturated. Radioactivity in the sand layer is about 35 $\mu\text{R/h}$. The highest activity of 55 $\mu\text{R/h}$ was measured at the upper contact of this horizon.
- 2.2-2.7 m Silt-clay. Radioactivity, 30 $\mu\text{R/h}$.
- 2.7-? Till with boulders and fragments of alum shale, limestone, gneiss, granite and gabbro. Radioactivity, 30-35 $\mu\text{R/h}$.

The geological sequence of the profile was established by means of three auger drill holes. These were drilled down to 3 m where they were stopped at the bedrock of alum shale.

The uranium content (25 ppm) of the boulder clay layer was determined by spectrometer measurements made in the pits. The upper 10–20 cm of the boulder-clay layer contained fewer fragments of alum shale than the underlying layers. The uranium content here is about 10 ppm. Thorium contents are negligible while the potassium content is about 4 %. The latter contributes about 6 $\mu\text{R/h}$ to the total measured gamma radiation.

The pits were dug to different depths, Fig. 14 c. Before each pit was dug, an emanometer was made to determine whether radon concentrations in the soil gas were normal or high. All the emanometer measurements indicated that the radon concentrations were very high. The types and numbers of detectors used in each pit are shown in Fig. 14 c.

The results of the measurements are presented in Fig. 15. The spectrometer measurements show that the uranium content of the till is 10 ppm at both 0.6 m and 0.9 m depth. The uranium content measured in the two very shallow holes was 7 ppm, probably as a result of fewer alum shale fragments and more humus in these layers.

The Track-Etch results show marked increases in concentration with depth. The results obtained from the membrane detectors should, after correcting for use of the membrane be comparable with the results from the open detectors because thoron is not present in this geological environment. The membrane detector at station 6 has, however, significantly reduced the radon signal.

The measurements made with Kodak film show similar increases with depth to those shown by Track-Etch. The open detector at station 8 however gives an unexpectedly high value. This may have been caused by close proximity to the detector of an alum-shale boulder. The filters used on the Kodak detectors do not reduce the radon signal to the same extent as the membranes on Track-Etch.

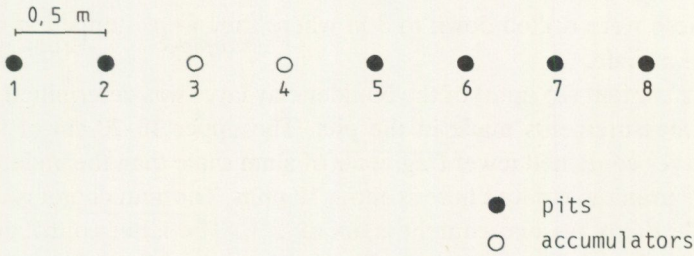
Increasing radon concentrations with depth were also obtained from ROAC measurements. The increase observed between 0.6 and 0.9 m depth, however, was not as great as that shown by both types of film detector. The largest standard deviation between two ROAC detectors was obtained in pit 1, 169 units at an average of 6 190.

Emanometer readings were made only at stations 1 and 5. The results obtained were 1 494 and 1 517 c/m, respectively. Both measurements were made at a depth of 0.7 m. The emanometer measurements indicate that radon concentrations in the soil gas are relatively constant at that depth.

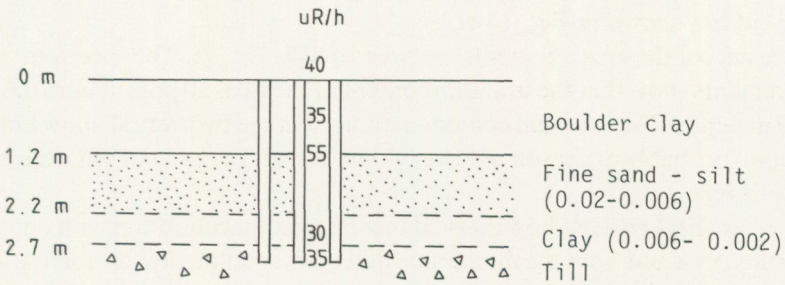
The Track-Etch result of 63 459 T/mm² (2×10^6 Bq/m³ or 57 000 pCi/l) is a very high value by world standards.

Some results of radon concentrations measured at varying depths are also

a.



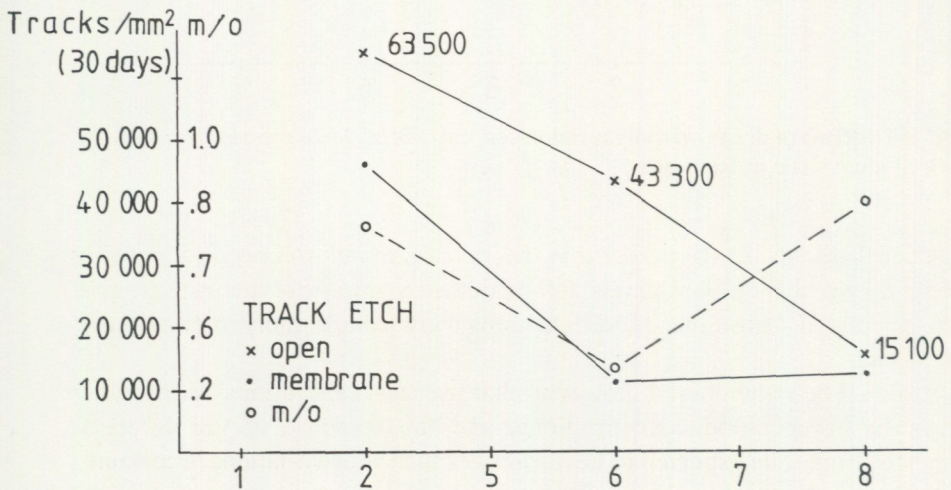
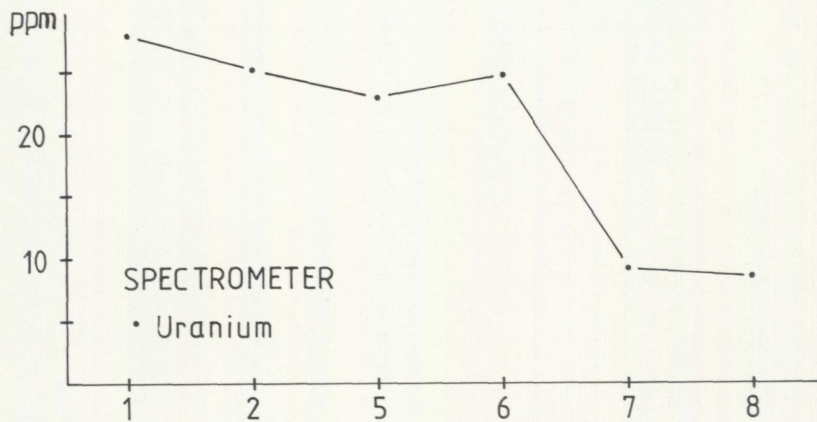
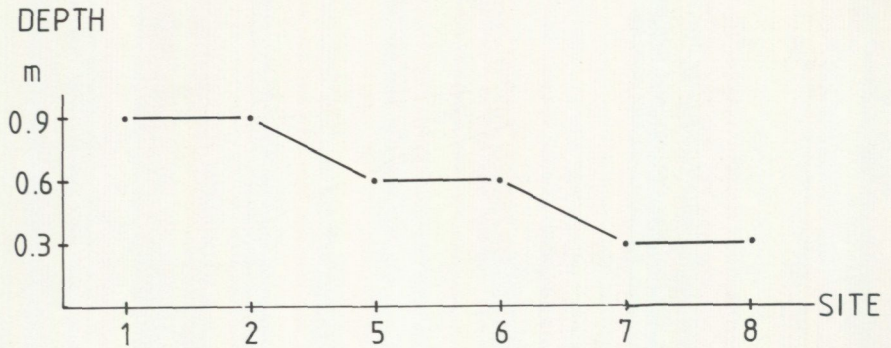
b.



c.

site	depth	Track-Etch		Kodak		ROAC		
		OPEN	MEMB	OPEN	MEMB			
1	0.9					2	Exposure times (days): films in pits - 20 ROAC in pits - 7 films and TLD in accumulator - 22 ROAC in accumulator - 7	
2	0.9	1	1	1	1			
5	0.6					2		
6	0.6	1	1	1	1			
7	0.3					2		
8	0.3	1	1	1	1			
3	TLD, Kodak films (5), emanometer, grab sample							
4	ROAC (3), emanometer, grab sample							

Fig. 14. Measurements to test the effects of depth on soil-gas radon concentrations. a. Plan of the measurements. b. Geological profile. c. Detectors used and depth of measurement.



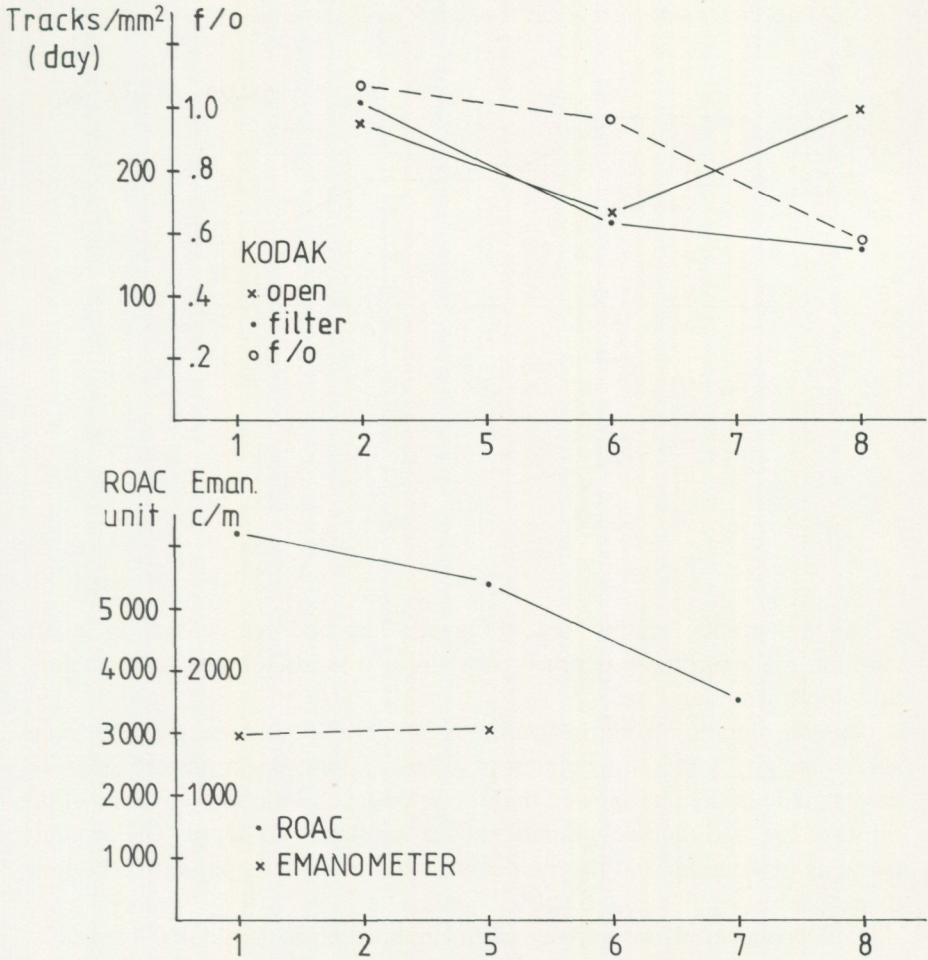


Fig. 15. Effects of depth on soil-gas radon concentrations. Measurements made in an area of alum shale at Ranstad.

given in Table 15. It is apparent that the increase in radon concentration with depth is recorded by all methods, although the magnitude of the increase and the calculated "absolute" concentrations vary considerably between the methods.

It should be remembered, however, that the "test calibrations" were made at much lower radon concentrations, and the response of the different methods cannot be expected to be linear over such wide variations in concentrations.

A test of the effects of depth on radon measurements was made in an area of granite overlain by till.

TABLE 15. Measurements of flux in a surface accumulator using an alphaMETER.

Measurement	Time of measurement		Time interval	Radon concentration C_t
	Date	Time	t, in hours	kBq m^{-3}
Accumulator set out	80-07-10	09.00	0	-
1	"	11.00	2	7.3
2	"	13.00	4	19.7
3	"	15.00	6	28.0
4	"	20.00	11	39.5
5	80-07-11	10.00	25	56.2
6	80-07-14	10.00	97	53.9
7	80-07-15	11.00	122	54.2
8	"	15.00	126	59.8
9	80-07-17	10.00	169	70.3

The topography of the area is rugged. The bedrock consists of a red, medium-grained granite which is overlain by a sandy till with few boulders. Soil depth is about 2 m.

Gamma radiation from the granite is 20–60 $\mu\text{R/h}$, and spectrometer measurements give a uranium content of about 30 ppm. Spectrometer measurements made in the pits showed that the uranium and thorium contents of the till were low and relatively homogeneous in relation to depth. The absolute contents of uranium and thorium in the till are 1.5–2.5 ppm and 7–10 ppm, respectively.

Radon concentrations were measured in three pits at depths of 0.3 m and 0.9 m. The distance between the pits was 0.5 m. Only Track-Etch and ROAC detectors were used. The Track-Etch detectors were exposed for 20 days, and ROAC for 6 days. The results of the measurements are shown in Fig. 16.

The Track-Etch detectors, both membrane and open types, clearly show increases in concentration with depth. The relationship between the open and membrane detectors in pit 2 indicates either a greater reduction in thoron concentration between 0.9 m and 0.6 m depth, or possibly the difference in diffusion coefficients between the two membranes used.

The ROAC detectors show an almost linear increase in radon concentration with increasing depth. The results shown in the diagram are averages for the two detectors used in each pit. The greatest difference between 2 detectors in relation to the average was 10 % for the detectors in pit 2.

The radon and thoron concentrations in the soil gas cannot be expressed in Bq/m^3 because calibrations of the detectors have not been made in a thoron

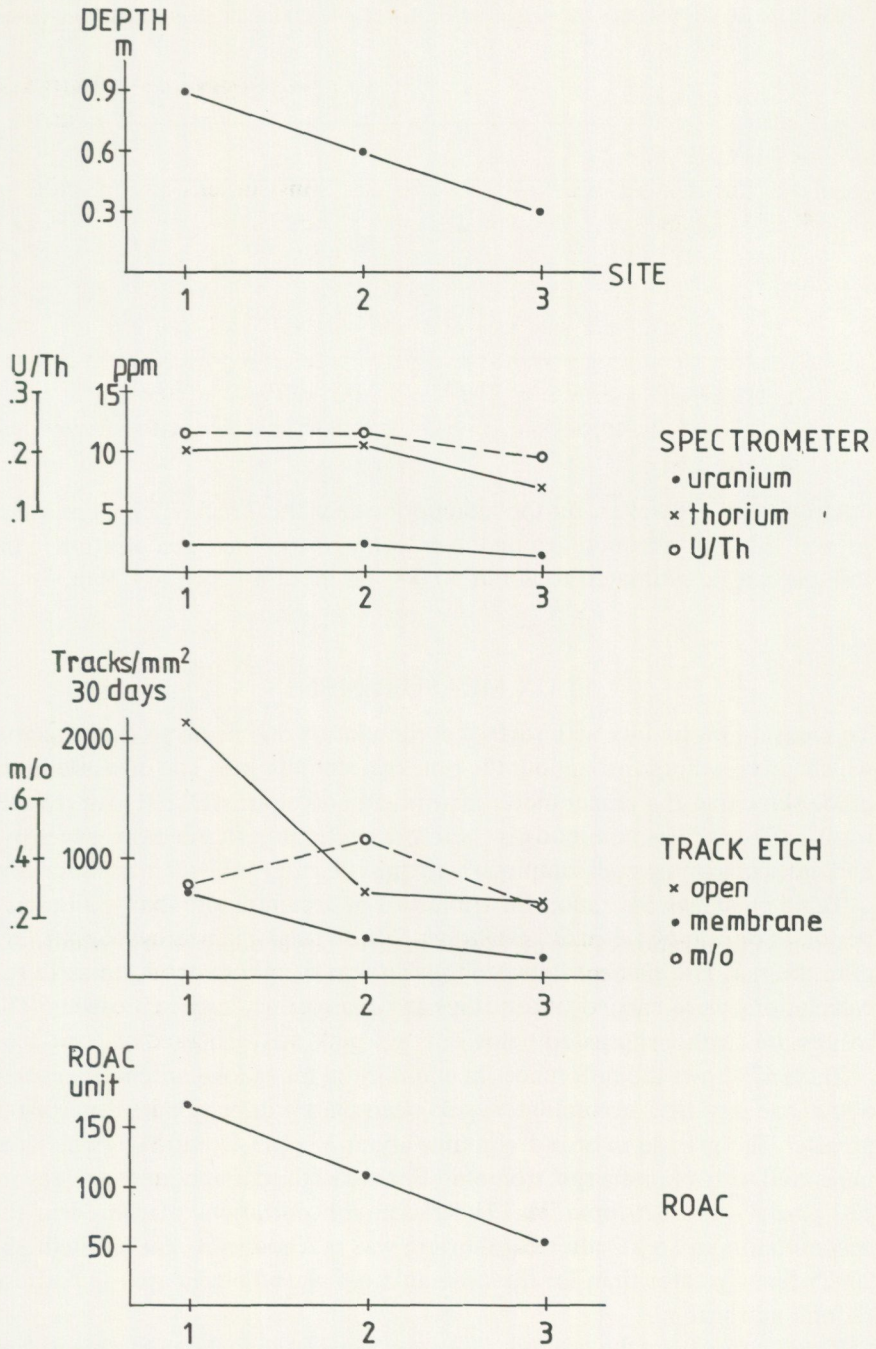


Fig. 16. Effects of depth on soil-gas radon concentrations. Measurements made in an area of granite in Mölndal, Gothenburg.

TABLE 16. Results obtained for measurements 1-4 (Table 15) for different equilibrium values.

Measurement	$\lambda \times 10^4, \text{h}^{-1}$				
	$C_\infty = 52$	54	56	58	60
1	756	726	698	673	649
2	1190	1135	1084	1037	995
3	1289	1218	1155	1099	1048
4	1296	1195	1111	1039	976
Average for nos. 2-4	1258 $\pm 4.7\%$	1183 $\pm 3.6\%$	1117 $\pm 3.2\%$	1058 $\pm 3.3\%$	1006 $\pm 3.7\%$

environment. However, on the assumption that the Track-Etch membranes prevent all thoron from reaching the detector, the radon concentration in the soil gas can be estimated to about 40 000 Bq/m³ at a depth of 0.9 m.

FLUX MEASUREMENTS

To measure radon flux with surface accumulators one needs to use detectors which give readings throughout the time of accumulation. The measurements made show that the emanometer instrument and alphaMETER give reliable results. Use of these methods is therefore preferable to the more expensive and time consuming grab samples which must be analysed later in a laboratory.

Table 16 shows the radon flux obtained in accumulators during the same period of time at two sites C:1 (station 6, 7 and 8) and C:2 (station 6 and 7) in a granitic area. The distance between the two sites was about one kilometre. The calculations were carried out in the same manner as described earlier. The results are further discussed below.

Table 17 shows the differences in equilibrium for radon contents measured about one day after accumulators had been placed directly onto outcrops of granite. The granite in area 1 contains about 30 ppm U and 100 ppm Th as measured with a gamma spectrometer. For area 2 the corresponding values are 130 ppm U and 320 ppm Th. The radon concentrations measured in the accumulators in area 2 after equilibrium was reached were, for all methods, 20-25 times greater than for the accumulators placed out in area 1, both for radon and thoron.

If radon flux from the ground is constant during the first day of a measuring period, the method gives acceptably reproduceable results. Sealing of the accumulators against the ground is not so critical because increased leakage

TABLE 17. Compilation of results of flux measurements from other accumulators.

Area, measurement	Detector	λ , h^{-1}	t_{95} , h	C_{∞} , $Bq\ m^{-3}$	Q , $Bq\ m^{-2}\ s^{-1}$	Q at later time
C:2 (6)	Re 279	0.25	12	19000	0.41	0.77
C:2 (7)	"	0.14	22	20000	0.25	0.52
C:1 (6)	"	0.30	10	42000	1.1	2.9
C:1 (7)	"	0.30	10	41000	1.1	3.3
C:1 (8)	AlphaMETER	0.11	27	56000	0.56	0.69

gives a higher Q value but lower C value and *vice versa*. Radon flux can therefore be determined with adequate accuracy even considering the variations which are caused by changes in air pressure, temperature etc.

The measurements made in this study indicate, that equilibrium is attained within the first day, that 4–5 measurements should be made within the first 10–15 hours and that the times for placing out the accumulators and taking the first measurement should be noted accurately.

For a complete assessment of the method, geological and meteorological data from the measured area and measured period should be taken into account along with the results of the measurements.

METEOROLOGICAL EFFECTS

Various meteorological parameters such as pressure, temperature, wind and humidity in the ground and in the atmosphere affect radon concentrations in the ground. In particular, they affect radon flux from the surface and radon concentrations in the upper soil layers (Kraner *et al.* 1964).

During the course of the study presented here, daily measurements were made of pressure, precipitation, temperature and wind speed.

Atmospheric pressure probably affects radon concentrations in the ground to quite considerable depths. Pressure gradients between the atmosphere and different depths in the soil profile give rise to movement of radon in the ground. When air pressure increases, atmospheric air with a low content of radon flows downwards in the upper soil layers. This flow penetrates successively down to greater depths. The opposite takes place when atmospheric pressure falls.

While the effect of wind speed on radon concentrations in the air above the ground is well-known, the effect on concentrations in the soil air is not so well-known. Earlier investigations (Israelsson 1978) show that wind speed can give rise to decreasing radon concentrations down to depths of more than one

TABLE 18. Radon and thoron concentrations in accumulators placed on granite outcrops. Results expressed in kBq m⁻³.

Detector	Isotope	Area 1	Area 2
		U 30 ppm Th 100 ppm	U 130 ppm Th 320 ppm
Grab sample (SSI)	Rn	0.7	16
Emanometer	Rn	0.8	18
ROAC	Rn	0.6	16
TLD	Rn + Tn	3.7	92
Kodak	Rn + Tn + D	5.1	100

metre. In order to study in detail the effects of wind speed on soil-gas radon concentrations, other parameters must not vary at all. The Bernoulli effect is thought to be insignificant because the average wind speed at ground level is effectively zero. However, turbulent fluctuations near to ground level can give rise to a pumping effect below ground level. The magnitude of the turbulent fluctuations increases strongly with increased wind speed. The roughness of the ground may also be important.

Annual variations over the same piece of ground also affect flux and radon concentrations in the soil gas, for example, snow cover, frozen ground, dry or wet ground etc.

All precipitation causes changes in the ground which affect radon diffusion. With excessive rainfall, up to 2.5 mm/hour or more, thoron flux is affected (Israelsson 1978). It is assumed that the same happens with radon in spite of the longer decay constant for radon.

Frozen ground or snow cover also affect soil-gas radon concentrations. Investigations in Uppsala, Sweden (Israelsson 1978) have shown that snow cover causes increases in soil-gas radon concentrations by a factor of 5. When the ground is frozen or covered by snow, flux is reduced to such an extent that soil-gas concentrations increase.

Water saturated ground also decreases the emanation of radioactive gases. With a soil humidity of about 15 %, thoron flux is reduced by about 90 %.

Meteorological effects on radon emanation were noted for the measurements made in an area of granite in south-west Sweden. Radon concentrations in relation to time for different accumulators are shown in Fig. 17. In the calculations of radon concentration in the accumulators it is assumed that radon flux is constant between sampling. After about one day, equilibrium was reached in all the accumulators. This remained constant over three days. During the following three days the radon concentration in the accumulators

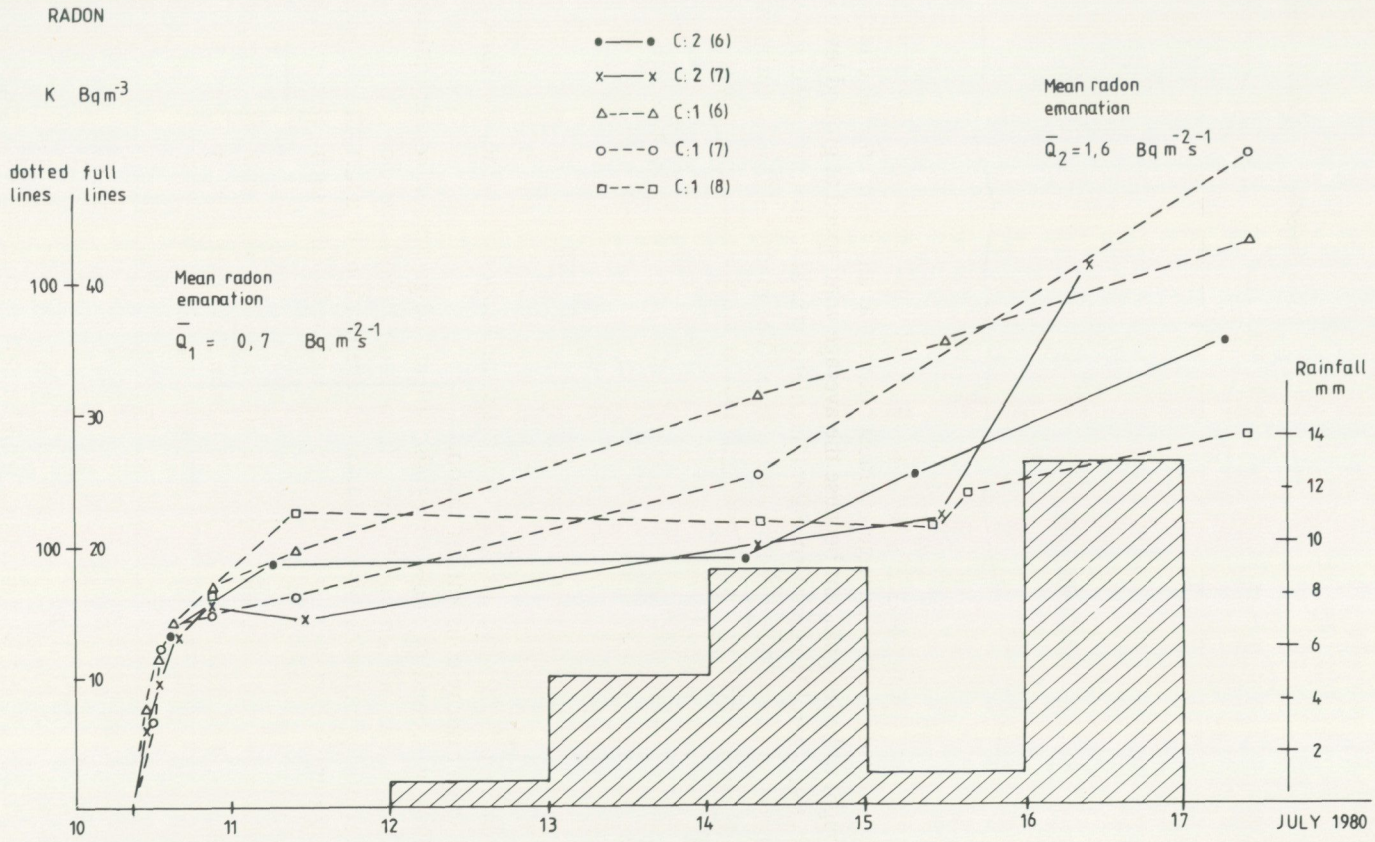


Fig. 17. Diagram showing how changes in rainfall affect radon flux.

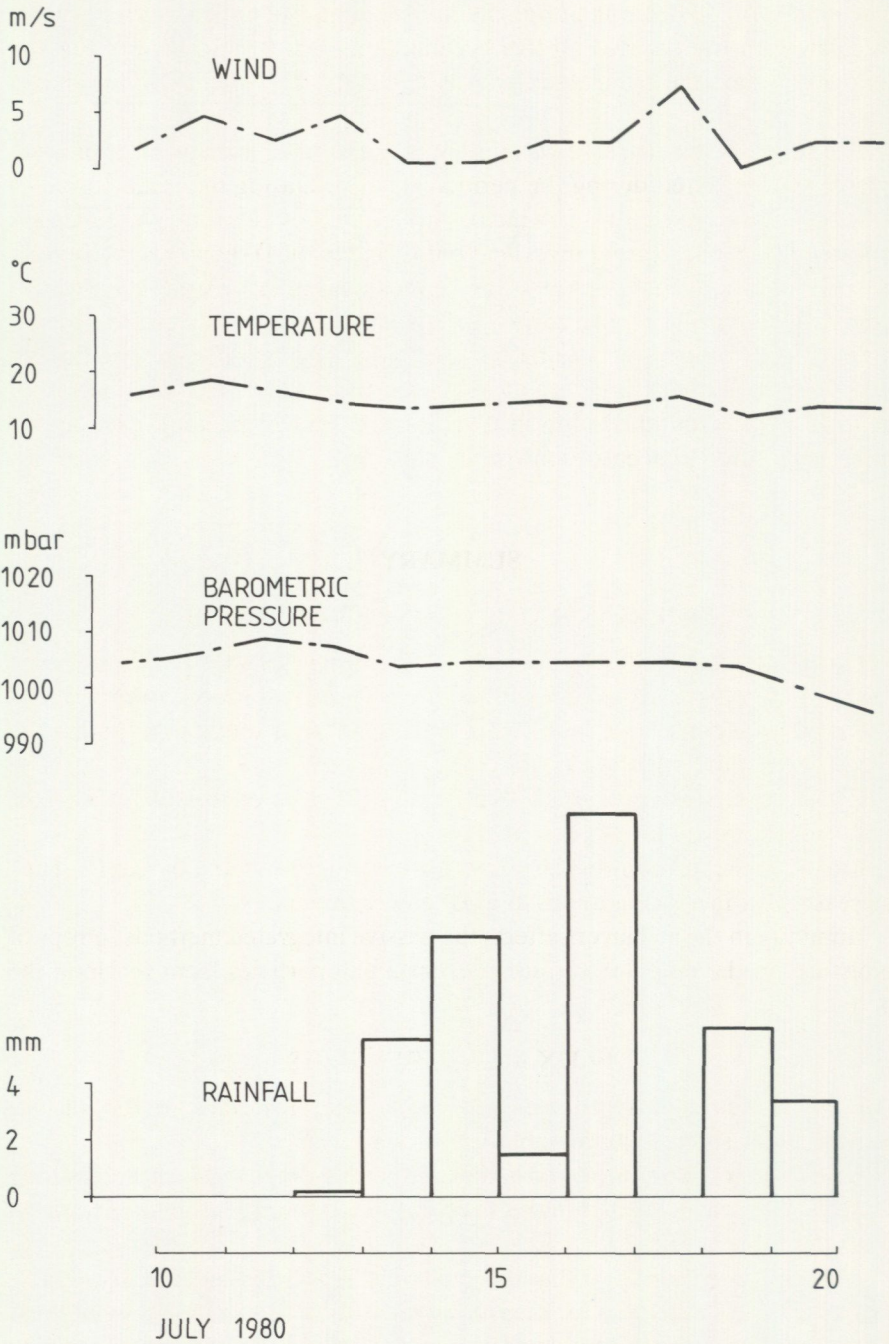


Fig. 18. The variation of wind, temperature, pressure and rainfall during the testing period.

rose markedly. Radon flux during the first three days of the measuring period, calculated on the basis of all five accumulators was $0.7 \text{ Bq m}^{-2} \text{ s}^{-1}$. For the following 3 days the calculated flux was $1.6 \text{ Bq m}^{-2} \text{ s}^{-1}$. (Mean Q values taken from Table 16).

The cause of this increase was probably due to the excessive precipitation which was measured during the period (Fig. 17). During the same period of time, no important changes in wind, temperature or barometric pressure were observed (Fig. 18). Earlier investigations (Tanner 1964) show that with excessive precipitation, soil gases near the surface tend to move upwards. This, of course, gives rise to increased radon flux at the surface. Afterwards, movement of radon in the soil is restricted due to diminishing diffusion coefficients and reduced permeability both of which are the result of increased moisture content in the ground. Radon flux then decreases which should give rise to increasing radon concentrations in the soil gas.

SUMMARY

SOIL-GAS RADON CONCENTRATIONS

All the methods and detectors used in the study have established the presence of radon in the soil gas. Moreover variations in soil-gas radon concentrations detected by one method were also detected by other methods although the magnitude of the variation could differ considerably.

Radon concentrations in the ground are directly related to geological conditions which prevail in the area measured.

Radon concentrations in the soil gas are strongly affected by depth. They increase with increasing depth in most environments.

Humidity in the soil layers affects the passive integrated methods. Drops of moisture on the detector surface prevent alpha particles from reaching the detector.

FLUX MEASUREMENTS

All the detectors used to measure radon concentrations in the surface accumulators showed comparable variations.

If radon flux from the ground is constant during the first day of a measuring period, the procedure used in this study for determining flux gives acceptably reproduceable results.

The measurements show that the emanometer and alphaMETER are sufficiently accurate detectors for measuring radon contents in the accumulators. They are therefore preferable to the more expensive and time consuming method of grab sampling followed by laboratory analysis. More detailed calibration of the instruments should, however, be carried out.

Meteorological variations affect radon flux. Measurements made, showed that flux increased from an average of $0.7 \text{ Bq m}^{-2} \text{ s}^{-1}$ to $1.6 \text{ Bq m}^{-2} \text{ s}^{-1}$ over two days due to heavy rainfall.

METHODS AND INSTRUMENTS

The choice of instrument or method depends upon the skill and experience of the operator and the purpose for which the measurements are made.

None of the methods or detectors used have proved to be so poor that one would not recommend their use. Some of the methods, for example soil-gas emanometry require greater experience of measuring radon and interpretation of results than does the use of alpha sensitive film.

EMANOMETERS

Emanometers have a high measuring capacity, 20–50 measurements per day, depending on the instrument used. The results are displayed directly on the instrument which allows for flexibility in the measuring programme. The method can differentiate between radon and thoron. Reproduceability is adequate. A disadvantage of soil-gas emanometry is that the determinations are only relative because the extent of dilution of the soil-gas sample varies according to the type of soil conditions in which measurements are made. For more accurate measuring, emanometers should be supplemented with an integrated passive method. Emanometer results can also be affected by rapid changes in meteorological conditions, in particular excessive precipitation. At high soil-gas radon concentrations, the scintillation cells become contaminated with daughter isotopes which have a negative effect on measuring capacity. Soil-gas emanometry requires experienced operators.

ALPHA SENSITIVE FILMS

Alpha sensitive films register radon concentrations over relatively long periods of time which minimises the effects of rapid changes in meteorological conditions. Correctly calibrated, this method can be used to determine absolute concentrations of radon in soil gas. The detectors can distinguish between radon and thoron if thoron membranes are used, although the diffusion coefficients of the different thoron membranes seem to vary considerably.

The method is relatively slow and it requires laboratory analysis of the film detectors. The investigated area must be visited twice, both for placing out the detectors and for removing them. Digging of pits can be very time consuming and laborious. The method has low measuring capacity and little flexibility. Precision is negatively affected by moisture.

ACTIVATED CHARCOAL

The activated charcoal method (ROAC) registers radon concentrations over longer time periods, but not as long as the film detectors (about one week as against 2–4 weeks). The detectors can be analysed by an operator with experience of carrying out radiometric measurements. Correctly calibrated, the method can be used to determine absolute radon concentrations in soil gas.

As with the alpha sensitive film method, the investigated area must be visited twice. Digging of pits can be very time consuming and laborious. The method has a low measuring capacity and little flexibility. Precision is negatively affected by moisture.

TLD METHOD

The TLD method has not been used sufficiently to permit a fair judgement of its advantages and disadvantages. Dosimeters have only been used to measure radon contents in the accumulators and here they gave acceptable results. Their construction and function is such that they are not suited to be used directly in site investigations.

ALPHAMETER

Only the alphaMETER type of solid state detectors has been used in this study. The comments that follow refer, therefore, only to this instrument. The method as such has great potential for measuring of soil-gas radon concentrations.

The results are displayed directly on the instrument and readings can be made at regular intervals without disturbing the instrument in place. The method is, therefore, very suitable for studying variations with time. Correctly calibrated the method can be used for making absolute determinations.

Disadvantages with the alphaMETER used in this study are the following ones. The instrument cannot be used in its present construction for making measurements at depths of more than 0.3 m; precision is negatively affected by moisture; and the method has low measuring capacity although relatively good flexibility.

GRAB SAMPLES

Grab samples have only been used for determining radon contents in the surface accumulators. They are the most accurate of all the methods used and are therefore a good control for all the other methods. Measuring capacity is however low, and the ionisation chamber measurements are expensive.

RECOMMENDATIONS

SOIL-GAS MEASUREMENTS

If the purpose of an investigation is to determine absolute concentrations, measurements of radon concentrations in soil gas should be based on an integrated passive method which measures over a specific time interval.

As a complement, direct measurements, for example soil-gas emanometry, can be used. Emanometer measurements give good reproduceability and the results give direct information about the relative concentration of radon in the ground. The method has, moreover, a high measuring capacity. Soil-gas emanometry is very suitable for increasing the number of measured points between passive detectors. One can therefore quickly determine whether radon concentrations in the soil gas vary within the area under investigation.

Interpretation of results must be based upon many measurements because large variations may occur between concentrations measured by adjacent detectors even in areas with homogeneous soil conditions. The distance between measurements is determined by the nature of the ground, and by the purpose of the investigation. For detailed site investigations the distance between measurements should not be greater than 10 m. A combination of passive and active methods can suitably be used for such investigations.

The depth at which measurements are made should be sufficient to eliminate short term variations caused by meteorological changes. At what depth the effects of such changes become negligible is not known, however, experience gained in this study suggests that soil-gas radon measurements should not be made at depths of less than 0.5 m. The greater the depth, the better the results, providing of course that the measurements are made above the level of the ground-water table. The depth at which measurements are made should always be taken into account when comparing results.

FLUX MEASUREMENTS USING SURFACE ACCUMULATORS

The method described here requires an experienced operator if it is to be used as a basis for judging radon risks in an area. The measurements must be complemented with measurements of gamma radiation or alternatively spectrometer determinations of uranium, thorium and potassium contents in areas of granite, and with geological studies.

A simple and very suitable detector for measuring radon contents in an accumulator is the direct reading emanometer. 1-5 measurements should be made during the first 10-15 hours followed by about 2 daily measurements until equilibrium has been attained in the accumulator. The actual times for

setting out the accumulation and sampling with the emanometer need to be noted accurately.

The method is very sensitive to meteorological variations such as changes in precipitation, air pressure, wind speed etc. which should be measured simultaneously with the emanometer measurements.

CONCLUSIONS

The accuracy of the results obtained, whatever the method or detector used and whatever the purpose of the measurements, depends very much upon the physiographic and geological environment (e.g. types of soil, moisture content etc.) in which the detectors are placed. The actual sites chosen for a series of measurements must be carefully selected and physiographic and geological parameters noted so that the results obtained can be compared and interpreted.

Placing of detectors in a fixed grid system is, for this reason, not always a suitable procedure.

For the interpretation of the results it is necessary to document the geology for each measured point and it is advisable to have a good knowledge of the uranium content of the soil. This is preferably determined by analyses with a gamma spectrometer in the pits or drill holes in which the detectors are to be placed.

In view of the many important parameters which control soil-gas radon concentrations, measurements need to be made by persons with good geological knowledge as well as experience in operating the instruments. This general conclusion applies to all of the methods described in this study.

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