DEVELOPMENT PROGRAM FOR RADON REDUCTION

REPORT 6
VARIATION OF RADON CONCENTRATION IN SOIL GAS
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IN SOIL GAS

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ACRES CONSULTING SERVICES LIMITED

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FIGURES
1. **INTRODUCTION**

This report is to document the results of work being carried out on behalf of the Atomic Energy Control Board, under DSS contract, by DSMA ATCON LTD., in collaboration with Acres Consulting Services Ltd.

The work involves the reduction of radon and radon daughter concentrations in occupied buildings. This report documents the results of one investigation carried out as a part of the associated Development Program.

The gradient of radon concentration in soil gas as a function of depth has been examined theoretically and experimentally by a number of authors (Refs. 1, 2, 3), who all assumed that the controlling mechanism was diffusion, except in the upper few decimetres of soil where fluctuations of atmospheric pressure might lead to a more rapid decrease of radon concentration. Their measurements suggest that the relaxation length in moist glacial till with a grass cover is in the order of 1 m to 1.5 m. Therefore, the radon concentration at a depth of 60 to 90 cm should be between 25% to 60% of the equilibrium radon concentration in the soil at greater depths.

The Subsurface Investigation Program (Ref. 4) showed that the overburden at Elliot Lake was a sandy gravel till. Sufficient samples were taken to demonstrate that the radon production rate of the overburden did not vary significantly with depth or location of the sample. As measurements of the radon concentration in soil gas were made routinely by two different methods over the period of September 1977 to December 1978, we have an opportunity to compare theory with practice.

2. **ESTIMATED RADON CONCENTRATION IN SOIL GAS**

In order to calculate the expected radon concentration in soil gas, the essential parameters were measured. The sandy gravel till has an approximate bulk density of 1.7 gm/cm$^3$ and a porosity of about 38%. The emanating radium content lies between 0.15 and 0.25 pgRa/g, with an average of about 0.18 pgRa/g.

Assuming that a radium-radon concentration equilibrium exists in dry soil, a calculation using these parameters gives an estimated equilibrium radon concentration in the soil gas of 900 pCi/litre. Since
porosity is not uniform throughout the overburden, the estimated radon concentrations in soil gas were also calculated for the lowest and highest anticipated porosities. For a low porosity of 20%, the estimated radon concentration in soil gas is 1800 pCi/litre, and for a high porosity of 50%, 550 pCi/litre.

2.1 Effect of Soil Water

In reality, the soil is not absolutely dry, and the voids contain some water. During the summer and fall months, typically 35% of the voids are filled with water but the amount can vary between 10% to 90% depending on rainfall and location. If the average soil temperature at depth is assumed to be 10°C, then the ratio of radon concentrations in soil water and soil gas is 0.34 (Ref. 5). For soil with a porosity of 38% and a typical saturation of 35%, the predicted radon concentration is 1200 pCi/litre in soil gas and 420 pCi/litre in soil water. If the soil is dry, with only 10% of the void volume filled with water, the radon concentrations expected are 1000 pCi/litre in soil gas and 350 pCi/litre in soil water. For wet soil that is 90% saturated, the radon concentration expected is 2200 pCi/litre in soil gas and 750 pCi/litre in soil water. Fully saturated soil would have a radon concentration of 900 pCi/litre in the soil water. The lower the porosity, the higher the saturation is likely to be. Therefore, an extreme value would be 20% porosity and 90% saturation which would give a concentration of 5500 pCi/litre in soil gas and 1800 pCi/litre in soil water.

2.2 Expected Radon Concentrations Near the Surface

The expected equilibrium radon concentration at a depth of several metres in Elliot Lake overburden therefore lies between 500 and 6000 pCi/litre, depending on the radium content, porosity and moisture content of the soil with a nominal value of about 1200 pCi/litre. Applying a diffusion calculation, the estimated radon concentration in soil gas at a depth of 60 to 90 cm from the surface should lie between 180 to 3000 pCi/litre, with a nominal value of about 500 pCi/litre.
3. **SAMPLING METHODS**

Measurements of radon concentration in soil gas have been made by both soil probes and perforated plastic pipes inserted into 2 metre deep holes during the subsurface exploration program.

3.1 **Soil Probes**

The soil probe technique and equipment were originally developed for uranium prospecting.

A soil probe consists of a 95 cm \( \times \) 1 cm (diameter), thin walled, steel tube which is supported by a closely fitting mandrel passed down the centre. The tube and mandrel are driven into the soil as a unit until the end of the tube is about 60 to 90 cm deep; then the mandrel is removed. One litre of soil gas is withdrawn through the tube by means of a small hand pump, passing through a desiccator, an in-line filter and a flow-through scintillation cell. Since the soil adheres tightly to the exterior of the tube, the soil gas sample is drawn from the soil at the depth of the tube end with a negligible chance of dilution by atmospheric air drawn down the side of the tube.

3.2 **Boreholes**

During the Subsurface Investigation Program (Ref. 4), 99 augered holes on 72 house lots were lined with perforated plastic pipe, 7.5 cm in diameter. All of these holes were a minimum of 120 cm deep; the deepest being 300 cm. The pipes projected about 30 cm above ground, and were closed at the top by a tightly fitting plastic cap.

Samples were taken from these pipes by replacing the plastic cap with a temporary rubber cap which had a 1 m rubber tube inserted through it. A 1 litre sample of the borehole air was withdrawn by means of a small hand pump, passing through a desiccator, filter and flow-through scintillation cell.

3.3 **Measurement of Radon Concentration**

The flow-through scintillation cells which were used for this study have a volume of 153 cm\(^3\), and a nominal sensitivity of 4 counts/minute per pCi in the cell. Most of the cells were within 20% of the nominal
sensitivity. The cell background was always less than 5 count/minute, and often less than 2 count/minute. The standard counting period was 10 minutes after a delay of at least 2 hours. The minimum detectable activity was approximately 5 pCi/litre.

4. FREQUENCY OF MEASUREMENT

4.1 Soil Probes

Measurements were made over the period of September to November 1977 at 28 sites. The program was terminated when the soil probes could not penetrate the frozen ground.

4.2 Boreholes

Measurements were made over the period November 1977 to November 1978 in a limited number of boreholes. Although the original intention was to sample all holes at 6 to 8 week intervals, a number of holes filled with ice, or were buried by snowdrifts and could not be located. These holes were not sampled for several months. In the spring a number of owners requested that the pipes be removed from their lawns, which terminated sampling in a number of holes that had been sampled during the winter. A further reduction in sampling intensity was made in the summer as the result of higher priority demands on staff time. Measurements were made during the winter alone in 26 holes, during the summer alone in 7 holes, and during the whole year in 45 holes.

5. COMPARISON OF SOIL PROBES AND BOREHOLES

5.1 Soil Probes

Repeated measurements taken in quick succession from the same probe, and from probes inserted to the same depth close to each other show a variability of little more than the 20% variation expected in cell sensitivity. However, measurements taken from the same depths but at locations separated by 7 to 10 metres on a single house lot varied considerably. In some cases, the variations were as great as a factor of 10.
This wide range of values suggested that the distribution of the measurements might be log-normal. Therefore, the cumulative frequency distribution of the radon concentrations was plotted on log-probit graph paper, as shown in Figure 1.

The distribution is unusual in that two distinct straight lines can be fitted to the data with a marked knee occurring on the graph at about 500 pCi/litre. The lower line has an Apparent Geometric Standard Deviation (AGSD) of 7.7, while the upper line has an AGSD of 2.7. This shows a marked reduction in the variability of measurements greater than 500 pCi/litre in value.

5.2 Boreholes

Repeated measurements in quick succession from the same borehole do not vary more than would be expected by the 20% variation in cell sensitivity. Readings taken from separate boreholes on the same house lot on the same day varied by as much as two orders of magnitude. This wide variability suggested that the distribution of the measurements might be log-normal. Figure 1 also shows the cumulative frequency distribution of the radon concentration in the 45 associated boreholes at the same 28 sites on which the soil probe measurements described above were made. The distribution exhibits characteristics similar to those of the soil probe measurement distribution, i.e. two straight lines but with a knee at 350 pCi/litre. The variability is slightly less than that observed for the soil probes, as the lower line has an AGSD of 4.4 and the upper line has an AGSD of 2.1.

5.3 Comments

In comparing the soil probe and borehole distributions, the most interesting feature is that radon concentrations in the boreholes are lower than those determined by the soil probe. The median concentration for the borehole distribution is 200 pCi/litre as compared to the median concentration of 400 pCi/litre for the soil probe distribution. This discrepancy occurs despite the fact that the boreholes extend to an average depth of 1.7 metres compared with soil probe, depths of only 0.6 to 0.9 metres.
It is also interesting to note that 46% of the borehole readings are less than the estimated minimum concentration of 180 pCi/litre, as compared to 32% of the soil probe readings.

6. ANALYSIS OF THE BOREHOLE DATA

As measurements were made in boreholes throughout the year, the data was analyzed to see if seasonal and/or geographical effects might cause the unusual distributions. The seasons were defined as winter which extended from November 3, 1977 to March 16, 1978, the approximate limits of snow cover; and summer which extended from June 22, 1978 to October 31, 1978.

Zone 1 (Figure 2) shows the greatest degree of similarity between summer and winter, with the knees and median concentrations for both occurring at 200 pCi/litre. An AGSD of 8.3 (lower) and 3.3 (upper) for the summer lines as opposed to AGSD's of 5.2 and 2.1 for the lower and upper winter lines, indicates a slightly higher variability in the summer readings.

Zone 2 winter and summer distributions (Figure 3) are distinctly separated. Both the knee and median concentration values are 500 pCi/litre for the summer distribution. For the winter distribution, the knee is at 300 pCi/litre and the median concentration is 250 pCi/litre. The summer distribution variability is less than that of the winter distribution, as indicated by AGSD values of 5.0 and 1.8 for the summer lines, and 7.0 and 2.4 for the winter lines.

Zone 3 + 3A (Figure 4) also shows a distinct separation of the summer and winter distributions. Although the knee occurs at 300 pCi/litre in both distributions, the median concentration values are quite different, with 250 pCi/litre for the summer and 100 pCi/litre for the winter. For the summer the AGSD values are 6.7 for the lower line as compared to 12.5 for the winter lower line, and 3.2 for the upper summer line compared to 2.2 for the winter upper line.

6.1 Comments

The average emanating radium content of the overburden, as determined by the Subsurface Investigation Program, is 0.17 pgRa/g for Zone 1;
0.20 pgRa/g for Zone 2; and 0.14 pgRa/g for Zones 3 + 3A. These slight differences in radon production rate do not seem to be reflected in the distributions which differ by much larger factors. Since the same type of frequency distribution describes the measurements made in all the zones and for both winter and summer seasons, the conclusion which must be drawn is that neither a geographical nor a seasonal factor is the cause of the unusual distribution. The only observation which can be made is, on average, the radon concentration in soil gas is higher in the summer than in the winter.

7. CONCLUSIONS

The radon concentration in soil gas measured at the 60 to 90 cm depths by the soil probe method was found to be highly variable. Almost 40% of the measurements were less than the lower limit of the concentration which was predicted from diffusion theory using the known parameters of the overburden. The cumulative frequency distribution is unusual, in that it consists of two apparently log-normal portions with a distinct knee near the lower limit of the estimated radon concentration.

Measurements made on the same sites by both soil probes and boreholes showed similar frequency distributions. However, the borehole median value was 50% of the soil probe median value despite the fact that the boreholes penetrated deeper. This would indicate that the gas in the boreholes was not in equilibrium with the soil gas. This was verified by measuring the radon concentration in borehole air, applying suction to the tube for a minute to draw soil gas into the tube, and then measuring the concentration. Large changes in concentration were observed, the largest being from 120 to 800 pCi/litre.

The variability of measurements in an individual hole over a period of several months is so great that it is not possible to detect a seasonal effect in any one hole. The cumulative frequency distributions for groups of holes for summer and winter are similar in shape, but have differing AGSD and median concentration values. On average, the winter concentrations are less than the summer, and the variability at the higher concentrations is less in the winter season. This reduction in concentration and variability may be due to the decrease in soil moisture that occurs during the winter. However, it is surprising that the heavy
and continuous snow cover and frozen surface layer of the soil does not increase the radon concentration in soil gas nor significantly change the frequency distribution of measurements.

In summary, the radon concentration in soil gas, in at least the upper two metres of soil, is much more variable than predicted by simple diffusion theory. Part of the variability is due to changes in soil moisture, which is not accounted for by the theory. In areas of frequent precipitation, such as Northern Ontario, it is possible that the fluctuations of soil moisture are sufficiently large and rapid that a true equilibrium is never established between the soil radium and radon in soil gas and water.

Precipitation acts to displace soil gas by compressing the soil gas between the layer of water moving down through the soil and the water table, or by raising the water table which traps the soil gas as bubbles which then move with the soil water (Ref. 6). These mass-transfer mechanisms, plus the similar effects of atmospheric pressure fluctuations, may be an explanation of the extreme variability observed in the radon concentrations in soil gas at Elliot Lake.
REFERENCES


FIGURE 1
CUMULATIVE FREQUENCY DISTRIBUTION FOR ASSOCIATED BOREHOLES AND SOIL PROBES
CUMULATIVE FREQUENCY DISTRIBUTION FOR ZONE 1

FIGURE 2

CUMULATIVE FREQUENCY DISTRIBUTION FOR ZONE 1
FIGURE 3
CUMULATIVE FREQUENCY DISTRIBUTION FOR ZONE 2
FIGURE 4

CUMULATIVE FREQUENCY DISTRIBUTION FOR ZONE 3 + 3A