ATOMIC ENERGY CONTROL BOARD

ELLiot Lake Technical Note No. 2

Radon diffusion through concrete

Dilworth, Secord, Meagher and Associates Limited
Acres Consulting Services Limited

February 1978

DSMA Report No. 1012/975
"The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication and neither the Board nor the author(s) assume(s) liability with respect to any damage or loss incurred as a result of the use made of the information contained in this publication."
# TABLE OF CONTENTS

1. INTRODUCTION
   1.1 Previous Work ........................................... 1
   1.2 Experimental Work at Elliot Lake ......................... 1

2. THEORETICAL WORK ........................................... 2

3. DISCUSSION .................................................... 2
   3.1 Radon Diffusion Through Concrete ......................... 2
   3.2 Radon Diffusion from Concrete ............................. 3
   3.3 Total Radon Flux from Concrete ............................ 3
   3.4 Radium Content of Building Materials ..................... 3
   3.5 Expected Radon Flux from Elliot Lake Concretes ........... 4
   3.6 Significance of Radon Flux ................................ 4

REFERENCES ................................................................

APPENDIX 1 ................................................................

Page No.

1

2

2

2

3

3

4

4
1. **INTRODUCTION**

1.1 **Previous Work**

The radon diffusion constant for concrete has been estimated from flux measurements by Culo et al (Ref. 1) as part of the radon barrier development program for Grand Junction, Colorado. In these experiments the radon source was uranium mill tailings, which were placed as backfill against the poured concrete walls of an experimental basement. The radon concentration in the gas space of the porous tailings was approximately 40,000 pCi/L. The radon flux through the 20 cm thick concrete wall was measured repeatedly and found to lie between 2.1 and 2.6 x 10^{-5} pCi/cm²s (760 - 940 pCi/m²h). Treating the wall as a passive porous barrier, the diffusion constant for radon was calculated to lie between extremes of 1.7 - 3.1 x 10^{-5} cm²s, depending on the porosity of the concrete. These values are close to that (2.4 x 10^{-5}) calculated from the observed rates of oxygen-nitrogen diffusion in concrete (Ref. 2).

1.2 **Experimental Work at Elliot Lake**

A route of radon entry survey made in 20 houses with higher than average concentrations of radon included radon flux measurements using sealed accumulators on basement walls and floors. Over 100 measurements were made and the values ranged from essentially zero to 1000 pCi/m²h with a large number of wall measurements averaging 450 pCi/m²h, about half of the flux rate measured by Culo. However, measurements of the radon concentration in the gas spaces of the backfill adjacent to the walls, taken at the same time as the flux measurements, showed that the radon concentration was 50 - 1000 pCi/L. This is nearly two orders of magnitude less than that measured in the tailings, and so the flux should also be approximately a factor of 100 less, rather than a factor of 2. In addition, the radon flux from the concrete floors was generally lower than from the walls, despite the floors being less than half the thickness.
2. THEORETICAL WORK

A resolution of these apparent contradictions was suggested when it was realized that the radon flux from a concrete surface was composed not only of the flux from the radon diffusing through the concrete from an exterior source, but also of the flux from radon produced in the concrete by the decay of the small amounts of radium present in all building materials. At low external concentrations, the flux from the concrete could be a considerable portion of the total flux.

As Culot treated the concrete as a passive barrier, containing no radium, his calculations cannot be used to estimate the flux at low external radon calculations. Accordingly, the diffusion equation was solved for a porous medium containing sources, and the fluxes calculated for a number of wall thicknesses and radium contents. The results are shown in Figures 1 to 5, and discussed in Section 3. Details of the equations and the parameters used are given in Appendix 1.

3. DISCUSSION

To reduce the number of graphs and tables, unless otherwise stated, results are presented for one of the extreme values suggested by Culot of \( D = 1.7 \times 10^{-5} \text{ cm}^2 \text{s} \) and \( \rho = 0.05 \), and an internal radon concentration of 0 pCi/L (referred to as Case 1). The effect of changing these assumptions is shown separately.

3.1 Radon Diffusion Through Concrete

The flux produced by radon diffusion through concrete is shown in Figure 1 for Case 1. From this, for a standard poured concrete basement wall 20 cm thick, exterior radon concentrations of 5000 to 50,000 pCi/L are required to produce interior fluxes of 100 - 1000 pCi/m²h. These concentrations would also produce interior fluxes of 300 - 3000 pCi/m²h through 10 cm thick concrete block walls, and 300 - 6000 pCi/m²h through concrete floors, which vary in thickness from 5 - 10 cm.

Figure 2 shows the change in flux at different concrete thicknesses produced by using the other extreme value suggested by Culot of \( D = 3.1 \times 10^{-5} \text{ cm}^2 \text{s} \), \( \rho = 0.25 \) and an internal radon concentration
of 0 pCi/L (Case 2). The increase in flux is negligible at 20 cm and is about 60% at 5 and 10 cm thickness.

Figure 3 shows the effect on flux of increasing the internal radon concentration, calculated for concrete thicknesses of 5 and 20 cm. Radon flux is virtually independent of internal concentration, as long as the flux is over 100 pCi/m²h. Changing the internal concentration from 0 to 300 pCi/L changes the flux rate by only a few percent.

3.2 Radon Diffusion from Concrete

The normalized flux (pCi/m²h/pCi Ra) from a slab of concrete containing emanating radium is shown in Figure 4 against thickness for both Case 1 and Case 2. If the emanating radium content is as high as 1 pCi/g, then radon fluxes of about 1300 pCi/m²h would be produced at the surfaces of a 20 cm thick slab. This is equivalent to the flux produced by an exterior concentration of 65,000 pCi/L.

3.3 Total Radon Flux from Concrete

The total radon flux is the sum of the radon flux produced by the diffusion of exterior radon through the concrete, and the flux produced by the diffusion of radon produced in the interior of the concrete from radium in the building materials.

Figure 5 shows the total flux as a function of external radon concentration and emanating radium content.

3.4 Radium Content of Building Materials

Building materials in Elliot Lake are derived mainly from local alluvial deposits of sand and gravel, with only the cement imported. As sand and gravel make up over 80% of the mass of concrete, the radium content will depend mainly on the radium content of the aggregate. Local alluvial deposits and aggregates currently in use at the local 'ready mix' plant have been sampled, and their total radium content measured by high resolution gamma spectroscopy, and their emanating radium content estimated from their rate of radon production. These estimates are not very precise for alluvial deposits are very heterogeneous, so there can be large differences between samples, and the
counting errors tend to be large at these low levels of radioactivity. However, the total radium content of building aggregates is 0.5 - 1.0 pCi Ra/g, and the emanating radium content is 0.1 - 0.6 pCi em Ra/g. Depending on the exact location of the source of aggregates, local concrete can be expected to contain between 0.2 - 0.3 pCi em Ra/g.

3.5 Expected Radon Flux from Elliot Lake Concretes

From Figure 3, emanating radium concentrations of 0.2 - 0.3 pCi/g will produce fluxes of 240 - 450 pCi/m²h from a 20 cm thick concrete wall, and 90 - 250 pCi/m²h from a 5 - 10 cm thick concrete floor, which are very close to the mean values of radon flux from walls and floors obtained in most houses. If the concrete contained no radium, external radon concentrations of 20,000 pCi/L against the walls and 1000 - 5000 pCi/L against the floor would be required to produce these fluxes. In those few houses where lower fluxes were measured, the radon concentration was relatively high at the time of measurement, which decreases the sensitivity of the accumulator method of measuring flux. In addition, the mix used for basement floors may be different from that used in walls, and the floors are heavily troweled to produce a smooth surface. This produces a surface layer of low porosity and activity which will reduce the flux rate below that calculated on the basis of uniform porosity.

3.6 Significance of Radon Flux

Simultaneous measurements of radon and radon daughter concentrations in houses show that the daughters are not in equilibrium with radon. Consequently, the ventilation rate in the house must be greater than 1 air change in 2 hours. Taking a typical house as 350 m³ volume, and a typical ventilation rate of 1 air change/h, if a constant 4 pCi/L radon (approximately 0.02 WL) is maintained in the house, then every hour 1.4 x 10⁶ pCi of radon must leave the house. To supply this radon by diffusion through the 100 m² of basement wall and floor in contact with the soil would require a flux of 1.4 x 10⁴ pCi/m²h or about 40 times higher than found. To produce fluxes of this magnitude would require external radon concentrations of 80,000 - 800,000 pCi/L, or emanating
radium content in the concrete of 8 - 10 pCi/g. Neither of these conditions apply at Elliot Lake, so radon diffusion from or through concrete cannot be a significant source of radon at Elliot Lake.

REFERENCES


APPENDIX 1

1. **INTRODUCTION**

The one dimensional diffusion equation for an infinite slab representing a concrete basement wall, was solved for diffusion in a media with sources, and radon fluxes from the internal surface were calculated for a number of external and internal radon concentrations, wall thicknesses, porosities, and emanating radium contents.

2. **DIFFUSION EQUATION**

From Ref. 2, the diffusion equation with radon generation in a concrete wall is:

\[
\frac{D}{P} \frac{d^2C}{dx^2} - \lambda C + \frac{E}{P} = 0 \quad \text{or} \quad \frac{d^2C}{dx^2} - \frac{\lambda PC}{D} + \frac{E}{D} = 0
\]

where:
- \( D \) is the effective diffusion coefficient - cm\(^2\)/s
- \( P \) is the porosity of the concrete - cm\(^3\)/cm\(^3\)
- \( \lambda \) is the radon gas decay constant - 1/s
- \( C \) is the radon gas concentration in the concrete pores - pCi/litre
- \( E \) is the rate at which radon is produced - evaluated per unit volume of concrete - pCi/litre-s

and \( x \) is the distance into the concrete from the outside surface - cm

The solution to this equation is of the form:

\[
C = C_1 e^{rx} + C_2 e^{-rx} + C_3
\]

where:
- \( r = \sqrt{\frac{\lambda P}{D}} \)

and \( C_3 = \frac{E}{\lambda P} \)

\( C_1 \) and \( C_2 \) are defined by the boundary conditions.
The radon concentration at the outside surface of the wall is taken as equal to the radon concentration $C_s$ in the soil gas adjacent to the wall, and the concentration at the inside surface of the wall is equal to the radon gas concentration $C_i$ in the air of the building. For a wall, thickness $T$ cm, then:

$$C_1 = C_s - C_2 - C_3$$

and

$$C_2 = \frac{C_s e^{rT} - C_3(e^{rT} - 1) - C_1}{e^{rT} - e^{-rT}}$$

The radon flux across a surface at distance $x$ from the outer surface is given by:

$$F = -D \frac{dC}{dx} = -Dr (C_1 e^{rx} - C_2 e^{-rx})$$

The flux at the outside of the wall is:

$$F_0 = -Dr (C_1 - C_2)$$

and the flux on the inside is:

$$F_I = -Dr (C_1 e^{rT} - C_2 e^{-rT})$$

3. **CALCULATIONS**

The calculations were carried out by computer and consist of calculation of the flux at the outside and inside surface of a concrete wall for a given set of values for the parameters. The values used are described in the following sections.

3.1 **Radon Concentration at the Outside Surface**

The radon concentration of the outside surface of the wall is assumed to be equal to the radon concentration in the gas phase of the soil and backfill on the outside of the wall. Values used in the calculations were:
The higher concentrations are included so that the results can be compared with those of Culot.

3.2 Radon Concentration at the Inside Surface

The radon concentration at the inside surface is assumed to be equal to the radon concentration in the air inside the building. Values used (in pCi/litre) were:

0
10
100
500
1,000
2,500
5,000
10,000
40,000
100,000

3.3 Effective Diffusion Coefficient of Radon in Concrete

The value of the effective diffusion coefficient of radon in the gas phase of concrete as determined by Culot (Ref. 1 of main report) depends on the unknown porosity of the concrete used in the experimental building. Culot estimated extreme values of the concrete porosity, and so obtained correspondingly extreme values of the effective diffusion coefficient. These values were:

5% porosity gives $D = 1.7 \times 10^{-5}$ cm$^2$s
25% porosity gives $D = 3.1 \times 10^{-5}$ cm$^2$s

Calculations were carried out using both values of effective diffusion coefficient and porosity.

3.4 Radon Decay Constant

The half life of radon is taken to be 3.824 days and so

$\lambda = 2.1 \times 10^{-6}$ s$^{-1}$
3.5 Concrete Thicknesses

Walls in single family dwellings vary from 10 cm thickness (concrete block) to 20 - 25 cm thickness in poured concrete basement walls. Floors are generally 5 - 10 cm thick. Calculations were carried out for 5, 10, and 20 cm concrete thickness.

3.6 Radium Concentration in Concrete

The escape fraction of radon gas from the emanating radium in the building materials to the gas phase of the concrete was assumed to be 1.0. The radon production rate per litre of concrete is:

\[ E = \text{em Ra} \times p \times \lambda \text{pCi/Ls} \]

where:
- \( \text{em Ra} \) = emanating radium in concrete (pCi/g)
- \( p \) = concrete density 2350 g/L - typical
- \( \lambda \) = decay constant of radon (s\(^{-1}\))

Therefore:

\[ E = 4.93 \times 10^{-3} \ \text{em Ra} \ \text{pCi/Ls} \]

The analysis was carried out for values of \( \text{em Ra} \) (in pCi/g) of:

0
0.1
0.2
0.3
0.5
0.7
1.0
VARIATION OF FLUX WITH EXTERNAL RADON CONCENTRATION

FIG. 1
EXTERNAL RADON CONCENTRATION IN GAS SPACE (pCi/L): EFFECT OF INTERNAL RADON CONCENTRATION ON FLUX

FIG 3
Fig. 4

Normalized radon flux from emanating radium in concrete versus thickness.
Variation of flux with external radon concentration and radium content of concrete

**FIG 5**

**CONCRETE THICKNESS**
20 CM

**CASE 1**
Effect of small grab sample sizes on requirements for demonstration of noncompliance. Three different data geometric standard deviations (GSD) are shown which reflect the amount of variability in the environment.