NISTIR 5135

SITE EXPLORATION FOR RADON SOURCE POTENTIAL

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December, 1992

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U.S. Department of Commerce
Ronald D. Brown, *Secretary*
National Institute of Standards and Technology
John W. Lyons, *Director*

Prepared for:
Department of Housing
and Urban Development
Washington, DC 20410

ABSTRACT

Proposed measurement methods and test procedures and tentative protocols for the assessment of the radon source potential of building sites and fill materials are presented. The proposed protocols are based on repeatable measurements of invariant soil properties, with corrections for typical prevailing environmental conditions. The measured or estimated soil properties are: the radium activity concentration per unit dry mass of the soil; the emanation coefficient; the in-place dry density; the porosity; and the dry gas permeability. Three specific field exploration methods are proposed: The "SPT" method, which utilizes the Standard Penetration Test (ASTM D 1586); a manual procedure, whereby a soil sample is extracted from an auger hole or excavation and saved for laboratory analysis; and a soil gas extraction test, where an in situ measurement of soil gas permeability and radon activity concentration is linked with measurements of in-place dry density and natural water content. The proposed test and site exploration procedures can be readily integrated with present geotechnical engineering practice. An empirically-based expression for a radon source potential index is proposed. The index is used to rate the radon source potential of building sites and fill materials.

Keywords: advection; building technology; diffusion; permeability; radium activity concentration; radon availability; radon source potential; soil exploration; soil testing.

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LIST OF SYMBOLS

A_{Ra} = radium activity concentration in soil (Bq kg^{-1})

C = radon activity concentration (Bq m^{-3})

C_{eq} = equivalent radon activity concentration (Markkanen, 1991) (Bq m^{-3})

C_m = measured (or moist) radon activity concentration (Bq m^{-3})

C_{max} = maximum possible radon activity concentration (Bq m^{-3})

d = arithmetic mean particle diameter according to Eq(17), (m)

d_i = average diameter of particle-size class i (m)

D = interstitial diffusion coefficient (m^2 s^{-1})

D_0 = diffusion coefficient in air ($1.1 \cdot 10^{-5}$ m^2 s^{-1})

D_m = measured (or moist) interstital diffusion coefficient (m^2 s^{-1})

D_R = relative density of sands (%)

D_w = depth to groundwater table (m)

$EF1$ = environmental factor for drainage (dimensionless)

$EF2$ = environmental factor for groundwater table (dimensionless)

$EF3$ = environmental factor for climatic conditions (dimensionless)

ERC = effective radium concentration (Bolch - Bq kg^{-1})

f = emanation coefficient (dimensionless)

G = volumetric radon generation in soil pores (Bq m^{-3} s^{-1})

G_s = specific gravity of soil grains (dimensionless)

H = depth at which radon concentration was measured (m)

J_d = diffusive flux density (flux rate) vector (Bq s^{-1} m^{-2})

J_{RAN} = radon flux density at the interface between the ground and a basement foundation, resulting from diffusive and advective transport under a 5-Pa suction.

k = coefficient of dry gas permeability (m^2)

k_w = water permeability coefficient (m s^{-1})

k_m = measured (or moist) coefficient of gas permeability (m^2)

k_{min} = minimum permeability coefficient (Eq(30)), (m^2)

l = diffusion length (m)

M = interstitial migration distance

M_a = interstitial migration distance for advective transport (m)

M_d = interstitial migration distance for diffusive transport (m)

m_d = dry mass of soil sample (kg)

m_i = mass of soil in particle-size class i, excluding +#4 mesh (kg)

n = porosity of soil (dimensionless)

n_{eq} = equivalent porosity (Markkanen - dimensionless)

N = SPT blow count from field data (blows/0.3 m)

$(N_1)_{60}$ = SPT blow count corrected for overburden pressure and 60% energy efficiency (blows/0.3 m)

N_0 = γ-activity extrapolated to sealing time in counts per second (s^{-1})

N_1 = first measurement (s^{-1})

N_2 = second measurement (s^{-1})

N_∞ = predicted γ-activity (s^{-1})

p = pressure (Pa)

RAN = radon availability number[1] (Tanner - kBq m^{-2})

RAN_a = radon availability number for advective transport (kBq m^{-2})

RAN_d = radon availability number for diffusive transport (kBq m^{-2})

S = volume fraction of water saturation (dimensionless)

t_0 = time of sealing container

t_1, t_2 = time of first and second measurement

v = seepage velocity vector (Darcy - m s^{-1})

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[1] In the literature *RAN* is referred to as a "number", even though it is not dimensionless.

v_i = interstitial seepage velocity vector (m s^{-1})

V = total volume of system (bottle + cell - net volume occupied by soil particles (Markkanen - m^3)

V_b = total volume of bottle (Markkanen - m^3)

V_L = total volume of Lucas cell + valves (Markkanen - m^3)

w = water content (% of dry unit weight)

W_i = weighing factor (Bolch - dimensionless)

Y = radon source potential index (Yokel - Bq m^{-2} - but dimensionless as interpreted)

γ_w = unit weight of water ($9.8 \cdot 10^3$ N m^{-3})

λ_{Rn} = decay constant of radon (2.1×10^{-6} s^{-1} for ^{222}Rn)

μ = dynamic viscosity of soil gas = 1.8×10^{-5} Pa s @ 18°C & 101.325 kPa

μ_w = dynamic viscosity of water ($1.053 \cdot 10^{-3}$ Pa s)

ρ_d = dry mass density of soil (kg m^{-3})

ρ_s = mass density of soil grains (typically 2,650-2,700 kg m^{-3})

∇ = gradient operator (m^{-1})

EXECUTIVE SUMMARY

Elevated radon in buildings has been recognized as a serious potential public health hazard and indoor radon mitigation has been legislated (EPA, 1992(1), Public Law 100-551, 1988). Substantial research efforts have been devoted to epidemiological studies to assess the effects of radon exposure, indoor radon surveys in various areas in the U.S, study of radon transport mechanisms, and geological mapping (for instance DOE, 1992). The purpose of this report is to propose exploration and test methods for the characterization of the radon source potential of individual building sites and fill materials.

In one of the most commonly used methods of assessing the radon source potential of building sites a volume of soil gas is extracted and the radon activity concentration in the extracted soil gas volume is measured in a scintillating cell. At the same time, the gas permeability of the soil is measured by a controlled soil gas extraction or air injection procedure, in which the required suction or pressure, and the flow rate of the extracted or injected gas are monitored. While this is an efficient procedure, the measured quantities are sensitive to transitory conditions, which include soil moisture content and pressure gradients in the soil mass during, and prior to, the time the measurements are taken. For this reason the measurements are not repeatable. In this report proposed test and site exploration procedures for the measurement of invariant soil properties are presented. A tentative protocol for the assessment of the radon source potential of building sites and fill materials is proposed, which is based on repeatable measurements of invariant soil properties, with corrections for typical prevailing environmental conditions.

The measured or estimated soil properties are: the radium activity concentration per unit dry mass of the soil; the emanation coefficient; the in-place dry density; the porosity; and the dry gas permeability. The radium activity concentration is measured by γ-spectrometry and the emanation coefficient is estimated. However, as an alternative, γ-spectrometry can be used to measure the emanation coefficient if a more accurate estimate is desired. The dry density is measured by retrieving a relatively undisturbed sample of known volume and establishing its dry weight. As alternatives, nuclear measurements or other established American Society for Testing and Materials (ASTM) procedures can be used to measure this quantity. The porosity can be calculated using an estimated value for soil particle density or, alternatively, a value determined by a measurement of the specific gravity of the soil particles by established ASTM procedures. The dry gas permeability can be determined by a particle size analysis and a recently developed correlation between gas permeability and particle size distribution. Alternatively, if the soil moisture content at the time of measurements is not too high, the dry gas permeability can be determined by a measurement of the moist gas permeability using the soil gas extraction method and a calculation of the dry permeability using a recently developed correlation between dry and moist permeabilities of granular soils.

Some of the test methods considered are more accurate than others. In order to provide a means for resolving uncertainties and potential disagreements in the interpretation of test results, the test methods are ranked in a hierarchical order. Results obtained by more accurate methods would supersede the results obtained by less accurate methods. Three specific field exploration methods are proposed; however, the required measurements can be performed by many other exploration methods. The three proposed methods are:

(1) The "SPT" method that utilizes the Standard Penetration Test (ASTM D 1586), which is presently the most commonly used method of performing soil borings. In addition to the standard procedure specified by ASTM, a relatively undisturbed core sample is retrieved for determining dry density, and additional undisturbed samples are saved to provide enough soil for spectrometry and particle size analysis. The SPT method is the preferred method in the case where a geotechnical soil exploration is planned for other purposes (such as foundation design or planning of cut and fill operations)

(2) A manual procedure, whereby a soil sample is extracted from an auger hole, or some other type of excavation and saved for laboratory analysis. A rapid and low cost version of the manual procedure would use field spectrometry to determine radium activity concentration and visual-manual soil identification procedures or utilization of the results of percolation tests to determine permeability.

(3) The soil gas extraction test, linked with measurements of in-place dry density and natural water content. The measured radon activity concentration in the soil gas and the measured soil gas permeability can then be interpreted on the basis of the soil saturation at the time the measurements were taken.

The proposed test and site exploration procedures can be readily integrated with soil exploration and testing procedures used in present geotechnical engineering practice, and wherever possible present ASTM methods are utilized. In this way, maximum economy is achieved, particularly if a soil exploration has to be conducted for other purposes.

An empirically based expression for radon source potential is proposed in which the radon source potential is estimated in terms of a "Radon Source Potential Index (Y)". This index is expressed in multiples of the present Environmental Protection Agency threshold of 150 $\mathrm{Bq/m^2}$ (4 pCi/L). The index is based on invariant soil properties, but can be adjusted for expected environmental conditions, such as characteristic soil water content, proximity of the groundwater table, and prevailing climatic conditions. On the basis of this index, radon potential is ranked as Low $(Y \leq 0.5)$, Moderate $(0.5 < Y \leq 1.5)$, High $(1.5 < Y \leq 7)$, and Very High $(Y > 7)$. Similarly, the use of borrow material is ranked as unrestricted use (UU-no restriction), fill material (FM - can be used as fill under buildings but requires evaluation), potential resource (PR - can be used if diluted to FM level), building site restricted (BR - cannot be used under buildings), and Restricted Use (RU - cannot be used near ground surface, even for landscaping).

A flow chart for the proposed field exploration procedures is provided in a summary in Section 7. The summary also contains an index of all the proposed testing procedures and examples of radon potential evaluations.

The expression for the radon potential index must be considered tentative since it is derived from a limited data base. It is recommended to assemble additional data in order to test, and possibly refine or modify, the proposed radon source potential index and to examine the practicality and cost effectiveness of the proposed testing procedures by trial applications. It is also recommended to conduct additional studies on the effect of anisotropy of permeability and the determination of permeability coefficients on the basis of the particle size distribution and water content of soils.

1. INTRODUCTION

Elevated radon in buildings has been recognized as a serious potential public health hazard and indoor radon mitigation has been legislated (EPA, 1992(1), Public Law 100-551, 1988). Substantial research efforts have been devoted to epidemiological studies to assess the effects of radon exposure, indoor radon surveys in various areas in the U.S, study of radon transport mechanisms, and geological mapping (for instance DOE, 1992). The purpose of this report is to propose exploration and test methods for the characterization of the radon source potential of individual building sites and fill materials.

Soil and rock have been identified as the most important source of indoor radon (Collé & McNall, 1980, DSMA Atcon Ltd., 1983, Åkerblom et al., 1984, Nero & Nazaroff, 1984). The actual indoor radon concentration in a building at any point in time depends on many variables, including pressure and radon activity concentration levels and gradients in the gas contained in the pore space of the soils surrounding the building foundation, pathways for the entry of radon into the building, pressure gradients from the foundation soil into the building, building configuration, and ventilation rates within the building. These latter parameters in turn are affected by barometric pressure and temperature gradients, wind velocities, and other factors. As a consequence of the seasonal, diurnal and temporal fluctuation of the many contributing factors, the indoor radon concentration fluctuates, and it is difficult to associate the source potential of a site with specific values of radon activity concentration. Indeed the source potential itself varies with soil moisture content and meteorological conditions (Nazaroff and Nero, 1988).

In a report published by the National Institute of Standards and Technology (NIST) (Yokel, 1989), it was recommended to develop a site characterization protocol which is based solely on measurable invariant site characteristics (characteristics which are not sensitive to transient conditions). The four site characteristics measured in this proposed protocol are radium activity concentration per unit mass of the soil surrounding the building foundations (a measure of the radium content per unit mass of the subsoil, which is the source of radon gas production), the dry gas permeability, and the dry density and porosity of the soil. An additional optional measurement would be the emanation coefficient, which is a measure of the fraction of radon atoms that recoil from disintegrating radium and come to rest in the soil pores. This latter measurement, however, is sensitive to the soil moisture content, which in turn represents a transient condition. The maximum emanation coefficient, however, is an invariant soil property.

In various versions of a currently used procedure, a sample of soil gas is extracted and the radon activity concentration in this sample is measured (Åkerblom et al.,1984, Eaton and Scott, 1984, Kunz, 1988, Tanner, 1988, Nazaroff and Sextro, 1989, Nielson et al., 1989). While extracting the sample, an in-situ measurement of the air permeability of the soil is performed. This latter procedure does not produce repeatable measurements because the measurements are sensitive to transitory conditions, including the moisture content of the soil and its variation within the soil mass, and meteorological conditions at, and prior to, the time of measurement. With additional measurements of in-place soil density and moisture content, this latter procedure can also be used to produce data on invariant soil properties.

The protocols discussed in this report cannot provide direct information on anticipated indoor radon activity levels, because there are many other contributing factors which vary with time or with the type of building and its heating ventilating and air conditioning system, the landscaping, and such factors as irrigation, drainage, and weather conditions. However, the resulting information will provide a measure of the **propensity** for supplying indoor radon. In other words, if other factors, such as building type, configuration, condition and ventilation rate are equal, the radon flux into houses at two different sites will differ if the source potential derived on the basis of the site characteristics identified differs for these sites. The information on radon source potential will be useful in the initial planning and design stages of buildings and subdivisions, and in real estate transactions, where information on radon source potential may be required.

The objective of this report is to propose site exploration and testing procedures. It is important to distinguish between measurements taken at a given site and protocols which include the interpretation of the measurements. The site exploration and testing procedures proposed produce quantitative estimates of variables associated with the radon source potential of sites. The interpretation of the measurements proposed in this report should be considered tentative. It is based on some model studies and on a very limited body of data which correlates measured indoor radon concentrations with certain measured site characteristics (because of the great number of variables and the temporal variation of indoor radon concentrations a very large quantity of data is needed to produce statistically significant results). The interpretation may change as more data correlating site characteristics with indoor radon concentrations become available.

Section 2 of the report provides background information on the test variables and their measurement; Section 3 deals with testing procedures; in Section 4 three different options for field exploration are proposed; a specific method for radon source potential assessment proposed in this report is presented in Section 5; and a proposed protocol for radon source potential assessment is presented in Section 6. Section 7 contains a summary of the proposed testing procedures, several examples of radon potential assessment, and recommendations for further research.

2. TEST VARIABLES

2.1 Introduction

In this section the test variables and their measurement, and site conditions which affect exploration methods and the interpretation of test results, are discussed, and some quantitative information is provided.

Two mechanisms need to be considered when radon source potential is evaluated: **radon generation** and **radon migration.**

The rate of volumetric **radon generation** in a mass of soil can be expressed by the following equation (Yokel, 1990):

$$G=(f\rho_d A_{Ra}\lambda_{Rn})\frac{1}{n} \qquad \ldots\mathbf{(1)}$$

where: G = volumetric radon generation in soil pores (Bq m^{-3} s^{-1})
f = emanation coefficient (dimensionless)
A_{Ra} = radium activity concentration in soil (Bq kg^{-1})
ρ_d = dry density of soil (kg m^{-3})
λ_{Rn} = decay constant of radon (2.1 x 10^{-6} s^{-1} for ^{222}Rn)
n = porosity of soil (dimensionless)

When radon generation is in equilibrium with radon decay (for instance in the absence of any radon flux) the maximum possible radon concentration in the pore space of the soil occurs:

$$C_{\max}=\frac{G}{\lambda_{Rn}}=(f\rho_d A_{Ra})\frac{1}{n} \qquad \ldots\mathbf{(2)}$$

where: C_{max} = maximum possible radon activity concentration in soil pores (Bq m^{-3})

The actual radon concentration measured at shallow depths is usually less than the maximum possible because of radon depletion by movement to the atmosphere.

The variables associated with radon generation are the radium activity concentration, A_{Ra}, the emanation coefficient, f, the dry density of the soil, ρ_d, and the porosity of the soil, n. While affect the accuracy of the overall estimate. However, as will be seen from the following discussion, there are test procedures which measure radon generation potential without separation of all the constituent variables.

There are three radon isotopes, ^{222}Rn, with a half life of 3.825 days, ^{220}Rn with a half life of 56 s, and ^{219}Rn with a half life of 4 s. They in turn are decay products of ^{226}Ra with a half life of 1,600 y, ^{224}Ra with a half life of 3.7 d, and ^{223}Ra with a half life of 11.4 d, respectively. The contribution of ^{219}Rn to the overall health risk is not significant (Nazaroff, 1992). Even though the ^{222}Rn and ^{220}Rn activities formed tend to be about equal, the contribution of ^{220}Rn to indoor exposure is presently estimated to be only about 25% of that of ^{222}Rn, in part because of the shorter half life of ^{220}Rn (EPA, 1992, Schery, 1990). It is therefore convenient to base the estimate of the source potential on measurements of ^{222}Rn activity concentration.

Radon transport is by two mechanisms: pressure driven flow of soil gas, and diffusion (radon flux due to concentration gradients). Pressure driven transport (advection) is thought to be governed by Darcy's law (because of the small pressure and temperature gradients soil gas flow is assumed to be laminar and incompressible) and thus by the following equation:

$$v = -\frac{k}{\mu} \nabla p \qquad \ldots(3)$$

where:
v = seepage velocity vector (m s^{-1}) (averaged over entire soil volume)
μ = dynamic viscosity of soil gas = 1.8×10^{-5} Pa s @ 18°C & 101.325 kPa
k = coefficient of gas permeability (m^2)
∇p = pressure gradient(Pa m^{-1})

Diffusive transport follows Fick's first law:

$$J_d = -D\, n\, \nabla C \qquad \ldots(4)$$

where:
J_d = diffusive flux vector (Bq s^{-1} m^{-2}) (averaged over entire soil volume)
D = interstitial diffusion coefficient (m^2 s^{-1})
C = radon activity concentration (Bq m^{-3})

The variables associated with radon transport are the coefficient of gas permeability, k, and the interstitial diffusion coefficient, D.

2.2 Test Site Conditions

2.2.1 Subsurface Conditions

Subsurface conditions tend to vary from site to site and are often difficult to characterize. The simplest case is a homogeneous, isotropic, relatively deep layer of foundation soil. This is the case most often considered in radon entry models; however, it seldom occurs in nature.

Another simple case which is quite common is a soil deposit which is orthotropic (horizontal and vertical permeabilities are not identical). Included in this category are soils which were deposited in horizontal layers. Such soils are often, but not always stratified, and they always exhibit orthotropic characteristics. In particular, the permeability of such soils in the horizontal direction tends to be significantly larger than that in the vertical direction. Such subsurface conditions tend to be characteristic for sedimentary soils, as well as man made fills. In some extreme cases, such as alternating layers of granular soils and clays, horizontal permeabilities may exceed vertical permeabilities by more than 2 orders of magnitude. In the case of layered sedimentary soils, radium activity concentrations may vary from layer to layer. Not all orthotropic soil deposits were necessarily deposited in horizontal layers. Many of these soils are orthotropic because they were pre-loaded in the vertical direction during their geological history. Most soil deposits in the northern U.S. were glaciated and supported ice layers which had thicknesses in excess of 300 m. Many other soil deposits were pre-loaded by soil layers which eroded over the years.

Another case of common interest occurs when conditions on a single site are not uniform. The question then arises whether the site can be adequately characterized by exploration at a single point, or even at several points.

Sites where the underlying bedrock is at a shallow depth may require special study. If the bedrock is fissured, soil gas may be supplied through fissures from a considerable depth. In these instances measurements on the soil surrounding the foundation may not provide relevant information. While the radium activity concentration in the bedrock can be measured, it seems unrealistic to evaluate the radon source potential of bedrock formations by standard test procedures because such an evaluation requires study by a geologist. Fortunately, many geological studies are under way or have been completed, and rock formations which carry a high radon source potential will often be mapped. Mapping protocols are currently being developed (DOE, 1991, pp 47-62,61-63). Whether the radium activity concentration of shallow soil deposits can be used to estimate the source potential of the site depends on their geologic origin. Residual soils, which were formed by decomposition of the underlying bedrock, generally provide good information on the source potential of the site as a whole and the underlying bedrock formation. However sedimentary soils, glacial deposits and man-made fills which did not form by weathering of the local rock formation may not provide useful information. In most instances, however, sedimentary and glacial deposits tend to be deep and therefore govern the rate of radon entry. In this instance, the soil gas extraction method is most appropriate.

The depth of the soil layer from which radon can be supplied to the interior of a building, and thus the depth to which the subsurface conditions need to be explored, depends on the dominant mode of radon transport. In general, diffusive migration will be affected by a soil depth of about 5 m or less (Bolch, 1987). The soil depth which contributes to advective transport increases with the gas permeability of the soil.

2.2.2 Climatological Conditions

Climatological conditions affect the source potential determination in two ways: Some of the variables are sensitive to weather and soil moisture conditions; and the source potential derived from the measurements is sensitive to general climatological conditions (Yokel, 1989).

In terms of their measurement, the variables discussed in 2.1 fall into two categories: the radium activity concentration (A_{Ra}), the dry density of the soil (ρ_d), the porosity (n), and the coefficient for dry gas permeability (k) are invariant, and their measurement is not affected by transient weather conditions; the emanation coefficient (f), the ambient radon activity concentration in the soil gas (C_m), and the ambient coefficient of permeability (k_m) are strongly affected by soil moisture (and in the case of C weather) conditions at the time of their measurement, and therefore their measurement is not repeatable and requires interpretation in terms of prevailing conditions (Yokel, 1989).

While the invariant properties can be measured independently of weather and soil moisture conditions at the time of their measurement, the resulting source potential is affected by climatological conditions. Generally, emanation coefficients will tend to be lower and gas permeabilities higher in arid regions, radon entry is sensitive to prevailing wind conditions and heating and cooling requirements, and radon activity concentrations in the soil gas (for the same radium activity concentration) are sensitive to ground freezing and rainfall intensities .

2.3 Variables

2.3.1 Radium Activity Concentration (A_{Ra})

The radium activity concentration in a soil volume can be determined by γ-spectrometry. Figure 1 shows the important components of the decay chain of ^{238}U, the uranium isotope of which ^{226}Ra and ^{222}Rn are decay products. The actual decay products measured in the recommended protocols for γ-spectroscopy are the lead isotope ^{214}Pb and the bismuth isotope ^{214}Bi. These have half lives of 26.8 min and 19.9 min, respectively. The laboratory measurement of A_{Ra} is accomplished by sealing a soil sample in an aluminum can. γ- ray emissions from this sample are subsequently counted after a specified period of sample confinement (for instance Austin and Droullard, 1978). Spectrometry is performed either by using a germanium detector (high purity germanium (HPGE) or lithium-drifted germanium (Ge(Li)) or by a thallium activated sodium iodide (Na(Tℓ)) detector - a sodium iodide crystal, activated with about 0.1% thallium iodide (ASTM E 181-82).

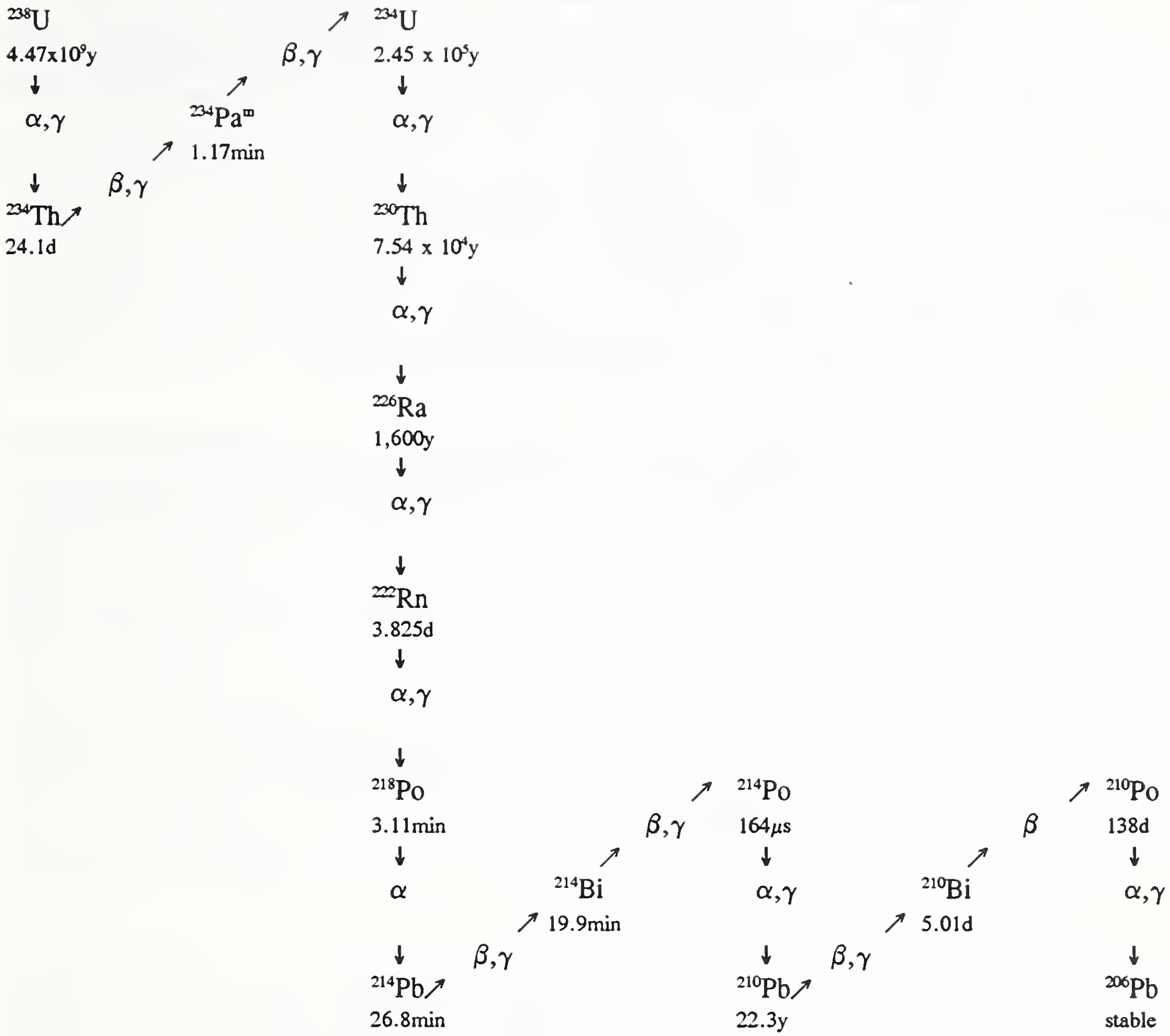

Figure 1: ^{238}U Decay Chain [^{234}Pa and minor branchings ($^{214}Bi \rightarrow {}^{210}T\ell$ and $^{210}Bi \rightarrow {}^{206}T\ell$) have been omitted].

Before containment in the aluminum can, the radon gas is allowed to escape from the sample. Since the count is performed on ^{214}Pb and ^{214}Bi, which are decay products of ^{222}Rn, the count will only provide accurate information on ^{226}Ra activity after the radon production is in equilibrium with the radon decay. This state is approached to within 1% after approximately 30 days (Austin and Droullard, 1978) and to within 2% after approximately 14 days (Williamson and Finkel, 1990). A shorter sample incubation period can also be used (about 4 to 5 days in accordance with Austin and Droullard, 1978), if two counts are executed. The first count should be performed soon after the sample is sealed, and the second count at the end of the incubation period. The minimum time that must elapse after sealing the can must be several half lives of ^{214}Pb so that there is approximate equilibrium between its production and decay. Williamson and Finkel, 1990, recommend a waiting period of not less than 4 h and not more than 1 d for the first count; however, they recommend a 2 week incubation period before the last count. Austin and Droullard, 1978, used waiting periods of at least 3 h.

The count associated with the predicted (or measured) radium activity concentration, N_∞, as well as a calculated emanation coefficient are given in Eqs.(5-7) below (Austin and Droullard, 1978).

$$N_\infty = N_1 + \frac{N_2 - N_1}{1 - \exp[-\lambda(t_2 - t_1)]} \qquad \ldots\mathbf{(5)}$$

where:

N_∞ = predicted γ-activity in counts per second (s^{-1})
N_1 = first measurement (s^{-1})
N_2 = second measurement (s^{-1})
t_1 = time of first measurement (s)
t_2 = time of second measurement (s)

$$N_0 = N_\infty - (N_\infty - N_1)\exp[\lambda(t_1 - t_0)] \qquad \ldots\mathbf{(6)}$$

where:

N_0 = γ-activity extrapolated to sealing time (s^{-1})
t_0 = time of sealing container (s)

$$f = 1 - \frac{N_0}{N_\infty} \qquad \ldots\mathbf{(7)}$$

where:

f = emanation coefficient (dimensionless)

An economical and efficient testing protocol proposed in Section 3.3.1 of this report is to seal an oven-dried soil sample in a can for 14 *d*, perform a count, assuming that $N_\infty \approx N/0.98$, where N is the count. The radium activity concentration of the soil sample, A_{Ra}, Bq kg^{-1}, can then be calculated:

$$A_{Ra}=\frac{N_\infty}{m_d} \qquad \ldots(8)$$

where: m_d = dry mass of soil sample (kg)

In this latter protocol, the emanation coefficient, *f*, is estimated.

γ-spectroscopy can also be performed in the field. Germanium, as well as sodium iodide detectors are being used (DSMA Atcon, Ltd., 1983). The advantage of the sodium iodide detectors is that they do not require cooling. Usually, the procedure is performed one meter above the ground surface. In this instance the radon gas, as well as some of the bismuth and lead isotopes are allowed to escape. This must be taken into consideration when the results are interpreted. There are also small detectors [25 mm (1 in.) diameter] which can be inserted in the drillhole, and special downhole instruments have also been developed. When measurements are performed in drillholes the question arises whether or not there is equilibrium between radon production and decay. This would depend on the depth of the measurement, as well as the length of time the drillhole was open and other parameters. Thus, even when the in-place measurements are calibrated against the laboratory procedure there is some degree of uncertainty in the interpretation of results.

The advantage of the in situ measurements is that a large mass of soil contributes to the γ-ray production. Thus the counting can be performed rapidly. This method can be very useful for rapid and inexpensive exploration, interpolation between results obtained by more rigorous procedures, downhole exploration to detect changes associated with stratified soil deposits, and detection of "hot spots". Available instruments are equipped with portable data acquisition and reduction systems which permit interpretation of the results of the count in the field. Rigorous calibration methods, such as those recommended in HASL - 300 (EPA, 1992) must be followed to ensure proper interpretation of the measurements.

2.3.2 Emanation Coefficient *(f)*

The mechanism associated with the fraction of radon gas emanated from the soil particles that remains in the soil pores is complex (Tanner, 1964, 1980, Semkow, 1991, Nazaroff, 1992). However, since the range of recoiling ^{222}Rn is 63 μm in air and only 0.1 μm in water, a much larger percentage of the radon atoms emitted from the soil grains into the pore space will remain in the pore space if it is filled with water. A large percentage of the radon dissolved in the pore water will subsequently escape into the pore space filled with air [the partition coefficient between water and air, κ, is 0.245 at 20°C (Boyle, 1922) and: $C_a = C_W / \kappa$ (Henry's Law), where C_a and C_W are the radon concentrations in air and water, respectively]. It may be argued that if a substantial portion of the pore space is filled with water the radon flux will be reduced with air permeability. However, particularly in well graded granular soils, the air permeability will not be much reduced when only a moderate fraction of the pore space is filled with water (narrow, capillary spaces will be filled first - refer to figures 4 and 5).

The measurement of the emanation coefficient is complicated by the fact that it is affected by the moisture content of the soil. It could be accomplished by the method described in equations 5 to 7, or by a similar procedure (the sample could also be de-emanated (flushed of mobile radon) after it was sealed for an extended time). However, if oven-dried soil is used, the measurement of f by the method described in equations 5 to 7 could underestimate the coefficient for dry soils (f_d) (Hahn, 1936) which in any case is likely to be smaller than the value of f for the same soil at its natural water content. However, the procedure described above can also be performed with a moist soil sample, either using a moist sample retrieved in the field, or by adding water which does not contain significant quantities of dissolved radon to an air dried soil sample. The best estimate would probably be obtained from a moist undisturbed sample (Schultz, 1981). However, undisturbed samples are difficult to obtain, particularly in granular soils. If the soil sample is not oven dried prior to spectrometry, the dry weight of the soil sample can be obtained after the test.

Substantial experimental data on emanation coefficients were generated for Finnish glacial tills (Markkanen and Arvela, 1991). The data indicate that emanation coefficients reached a maximum at water contents of 10 - 15% (of the dry weight of the soil) for clays, 2 - 10% for sands, and 2 - 5% for gravels. The authors suggested that for measurements of emanation coefficients, water contents for all soils could be standardized at 5%. A plot of the data obtained by Markkanen and Arvela for soils with 5% water content shows a range of f from 0.3 - 0.42 for clays, decreasing to a range from 0.2 to 0.3 for gravels (emanation coefficients decreased with increasing grain size). For air-dried samples, emanation coefficients ranged from 0.17 - 0.31 for clays, 0.11 - 0.24 for silts, 0.11 - 0.22 for sands, 0.15 - 0.23 for gravels, and 0.12 - 0.25 for tills. Thus the coefficients for samples with 5% water content were approximately 40% greater than those for air-dried samples. The difference may be even greater for oven-dried samples. Markkanen and Arvela's data also indicate that emanation coefficients at 0°C were similar to those at 20°C.

In addition to spectrometry on samples at equilibrium and de-emanated samples, Markkanen and Arvela used a procedure whereby a soil sample of approximately 0.5 kg dry mass is incubated in a tightly sealed glass bottle of 2.34 L volume. After an appropriate ingrowth period (3 weeks was normally used) an air sample was taken into an evacuated scintillation cell (Lucas cell) through a valve placed in the cap of the bottle. This is a direct measurement of the equilibrium ^{222}Rn activity concentration, C_{eq}, associated with the experimental ratio of void volume to total volume, n_{eq}, which is calculated by the following equations:

$$C = C_m\left(1 + \frac{V_L}{V}\right) \qquad \ldots(9)$$

where:
C = corrected radon activity concentration (Bq m^{-3})
C_m = measured radon concentration (Bq m^{-3})
V_L = total volume of Lucas cell + valves (m^3)
V = total volume of system (bottle + cell - net volume occupied by soil particles) (m^3)

$$C_{eq} = \frac{C}{1 - e^{-\lambda t}} \qquad \ldots(10)$$

where:
t = ingrowth time - no correction if $t > 1.8 \cdot 10^6$ s (3 weeks)

If this procedure is used, C_{eq} can be used to calculate the quantity $f\rho_d A_{Ra}$ directly by the following equations:

$$f\rho_d A_{Ra} = C_{eq} n_{eq}$$
$$n_{eq} = \frac{V_b - \dfrac{m_d}{\rho_s}}{V_b} \qquad \ldots(11)$$

where:
V_b = total volume of bottle (m^3)
m_d = dry mass of sample (kg)
ρ_s = mass density of soil grains (typically 2,650-2,700 kg m^{-3})

To determine C_{max}, the measured or estimated void ratio in the field, n, must be used in conjunction with Eq(2).

Markkanen and Arvela compared the above test with the results of spectrometry in which the radium activity concentration, as well as the emanation coefficient were measured for the same moisture content. A comparison of tests on 350 samples by both methods showed no systematic disagreement between the methods. However, there is considerable scatter for individual samples, particularly for low emission counts. The authors attribute the experimental scatter to probable differences in water content homogeneity (the way the water is filling the pores), statistical counting errors, and possibly slight leakage in the bottles and the aluminum cans used.

statistical counting errors, and possibly slight leakage in the bottles and the aluminum cans used. The data do not indicate that one of the methods is preferable to the other.

The authors indicate that, in order to prevent diffusion into the sample, the (air volume)/(sample volume) ratio must be much greater than 1.

The question arises whether the measurement on a disturbed sample will accurately measure the in situ emanation coefficient. There is no indication that Markkanen and Arvela attempted to either test undisturbed samples, or samples that were re-constituted to the in situ density. The authors are not aware of any available data specifically correlating density with emanation coefficients. However, there is evidence that disaggregation (which is associated with a decrease in density) increases the emanation coefficient (Schutz, 1981). Consequently, the measurement of emanation coefficients on disturbed samples, which usually are less dense than the in situ soil, would probably tend to somewhat overestimate the magnitude of f.

Markkanen and Arvela do not address the quantitative effect of A_{Ra} on the emanation coefficient. Nielson et al., 1992, tested 131 sample of Florida soils and proposed the following equations:

$$\begin{aligned} &For\ A_{Ra} \leq 300 Bqkg^{-1}: \\ &f = 0.004 A_{Ra} + 0.20 \leq 0.55 \\ &For\ A_{Ra} > 300 Bqkg^{-1}: f = 0.50 \end{aligned} \qquad \text{...}\mathbf{(12)}$$

In the proposed protocol, the emanation coefficient is estimated to be 0.25 for sands and gravels and 0.4 for silts and clays, or equal to the value obtained by Eq(12), whichever is greater. As an alternative, measured values at 5% water content can be used.

2.3.3 Dry Density (ρ_d)

In traditional geotechnical engineering practice the dry density is defined as a unit weight (γ_d, the weight of the solid particles per unit volume of soil). This is convenient for many engineering purposes. In this report dry density is defined as the mass of solid particles per *total* volume, ρ_d in kg m^{-3}. Conversion from one quantity to the other should not present a problem.

There are three methods by which in-place density can be measured: (1) non-destructive (nuclear) measurements; (2) measurements involving removal of a disturbed soil sample of known in-place volume (which is measured by various methods); and (3) removal of undisturbed (or relatively undisturbed) soil samples of known volume. All three methods require determination of the water content (usually by oven or microwave drying of the soil sample), and thereby provide information on in-place dry density and natural water content. Other than for the purpose of volume measurement, the proposed protocol does not require an undisturbed sample. However, an undisturbed sample may be useful for the accurate determination of f.

(1) **The nondestructive method** utilizes measurements of the transmission or back scatter of γ-radiation from a radioactive source (radium or a radioactive cesium isotope). This method measures the total in-place density (including the pore water). The dry density must then be calculated after determining the water content. This latter determination can be made by another nondestructive measurement of the scatter of neutrons emitted from a source (usually americium-beryllium isotopes) by the hydrogen atoms in the pore water.

A nuclear measurement method is specified in ASTM D 2922-91 for shallow-depth measurements. Downhole instruments are also available. The nuclear method is rapid and efficient. It is practical when many measurements are performed in rapid succession. It could also be practical in conjunction with manual exploration methods; however, a soil sample must still be retrieved for spectrometry. The use of these methods in conjunction with a routine geotechnical exploration by soil borings is practical with a down-hole instrument which is compatible with the drilling procedure used. Such an instrument, which combines density and moisture measurements, is commercially available and has been used in geotechnical exploration (Sully and Echezuria, 1988). A drawback in using this method is the need for strict safety precautions against radiation exposure.

(2) A variety of methods of **removing a disturbed sample of known volume** have been standardized by ASTM. These include: the Sand Replacement method (ASTM D 4914-89); the Rubber Balloon method (ASTM D 2167-84); and the Sleeve method; (ASTM D 4564-86). All three methods involve the removal of a soil volume in situ, the in-place measurement of the removed volume by different methods, and the weighing of the removed soil volume before and after oven drying. These methods are generally cumbersome and require a fairly large working area. They can be performed at the ground surface or in a pit, but not in a drillhole.

(3) **Removal of undisturbed, or slightly disturbed soil samples** is not always feasible. Generally, high quality relatively undisturbed samples can be obtained in moist cohesive soils (soft to medium clays and plastic and organic silts). High quality samples cannot be obtained from granular soils or desiccated cohesive soils. However, useable samples can be obtained in most instances from moist fine to medium sands and non plastic silts. In saturated soils pistons or valves are applied to prevent the escape of the wet sample. There are also a variety of retaining devices which keep the sample in the sampler (Hvorslev, 1949).

Samplers can be advanced by two methods: the more desirable method is pushing the sampler into the ground by a steady pressure. However this method generally does not work in granular soils or stiff clays (it may work in moist fine sands). The other method is to advance the sampler by hammer blows. This latter method results in greater disturbance.

Sampling devices and methods are described in ASTM D 4700-91 which is a guide for sampling in the vadose (unsaturated) zone, and ASTM D 1587-83, which is a standard practice for thin walled tube sampling. A very practical sampling method is also described by Williamson and Finkel, 1990, Procedure 1-2.

The density and moisture determination considered under (3) consists of the removal of a carefully measured and trimmed portion of a sample, which consequently has a known volume and determination of its dry density and water content by oven (or microwave) drying and weighing.

Of particular interest in conjunction with this method is the Standard Penetration Test (SPT) (ASTM D 1586-84): In the SPT a split barrel sampler is used, which is opened after it is retrieved. The standard sampler has an outer diameter of 50.8 mm (2.00 in.), an inner diameter (at the tip) of 34.925 mm (1.375 in.) and is driven 0.45 m (18 in.) into the ground[2]. The sample is not undisturbed (no drive sample is, particularly if the sample diameter is small), but in most instances a reasonable portion of the sample will contain a continuous soil core. From this core a measured length should be carefully removed and placed in a sealable moisture proof container, as specified by ASTM. The upper 50 mm (2 in.) of the core should not be used because they are likely to consist of material that was disturbed by the drilling operation. The lower 50 mm (2 in.) (near the tip) may also be disturbed. Because of the quantitative requirements for the γ-spectrometry and particle-size analysis samples, the rest of the split-spoon sample should also be saved in a separate moisture-proof container. The only record required for the in-place density sample, in addition to those required by ASTM D 1586, is the length of the soil sample removed. From the length of the core and the inside diameter of the sampler (dimension "C" in figure 2 of ASTM D 1586) the sample volume can be calculated. The dry density and water content can then be determined by standard methods (for instance ASTM D 2937-83). In conjunction with the SPT, it is also possible to take more undisturbed and larger samples than those associated with the split barrel (for instance thin wall samples). If such samples are taken, the quantity of soil retrieved can be larger. A 600+ mL sample is required by the recommended Williamson and Finkel spectrometry procedure, which uses Marinelli beakers.

In view of the uncertainty associated with the estimate of permeability and with other variables associated with radon entry, it is not unreasonable to estimate the in-place dry density. Some guidance can be derived from the following information.

Tables I and II show typical ranges of values for dry density of various soil types. These values were derived from a large data base. For granular soils (sands and silts) the variation is 25% or less from the average value. For cohesive and organic soil the variation can be much greater. If penetration test data are available for granular soils, an interpolation can be made assuming that the lower limit is for 0% relative density and the upper limit for 100%. Correlations with SPT blow counts, corrected for depth and efficiency, are given in Table III and in Eq(13). Thus use of Tables I and II and interpolation with the aid of SPT data should result in a reasonably good estimate of ρ_d for granular soils. Difficulties may arise in some glacial tills and gravels, where SPT blow counts can be erratically high because of the presence of large pebbles. However, if there is a subsurface investigation by soil borings there are usually sufficient data

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[2] Dimensions are given as specified by ASTM.

Table I: **TYPICAL SOIL PROPERTIES** (After Lamb and Whitman, 1969)

SOIL TYPE	POROSITY		DRY DENSITY, kg m^{-3}	
	n_{max}	n_{min}	ρ_{dmin}	ρ_{dmax}
Uniform Spheres	0.476	0.26		
Standard Ottawa Sand	0.44	0.33	1,470	1,760
Clean Uniform Sand	0.50	0.29	1,330	1,890
Uniform Inorganic Silt	0.52	0.29	1,280	1,890
Silty Sand	0.47	0.23	1,360	2,030
Fine to Coarse Sand	0.49	0.17	1,360	2,210
Micaceous Sand	0.55	0.29	1,220	1,920
Silty Sand and Gravel	0.46	0.12	1,430	2,340

Table II: **TYPICAL DRY DENSITIES OF SOIL**
(after Holtz and Kovacs, 1981)

SOIL TYPE	DRY DENSITY, kg m^{-3}	
	ρ_{dmin}	ρ_{dmax}
Sands and Gravels	1,500	2,300
Silts and Clays	600	1,800
Glacial Tills	1,700	2,300
Crushed Rock	1,500	2,000
Peat	100	300
Organic Silts and Clays	500	1,500

Table III: CORRELATION BETWEEN SPT BLOW COUNT AND RELATIVE DENSITY
(after Jamiolkowski et al., 1988)

IN-PLACE CONDITION	RELATIVE DENSITY, %	BLOW COUNT, $(N_1)_{60}$
Very Loose	0 - 15	0 - 3
Loose	15 - 35	3 - 8
Medium	35 - 65	8 - 25
Dense	65 - 85	25 - 42
Very Dense	85 - 100	42 - 58

$$\begin{aligned}&\textit{For}\quad D_R \geq 36\%: \quad \frac{(N_1)_{60}}{(0.01\,D_R)^2} \simeq 60\\ &\textit{for fine sands:}\quad \textit{multiply } N \textit{ by } \frac{55}{60}\\ &\textit{for coarse sands:}\quad \textit{multiply } N \textit{ by } \frac{65}{60}\end{aligned} \qquad \ldots\mathbf{(13)}$$

where:
N = SPT blow count from field data (blows/0.3 m)
$(N_1)_{60}$ = SPT blow count corrected for overburden effects and 60% energy efficiency (blows/0.3 m).

to establish whether the deposits are loose or dense. Many glacial tills were subjected to very high overburden pressures and their densities are near the upper limit of 2,300 kg m^{-3}. The in-place density of compacted fills can be rather closely estimated from Table IV.

Table IV: TYPICAL DRY DENSITIES OF SOILS COMPACTED TO 95% OF MODIFIED PROCTOR DENSITY (Holtz and Kovacs, 1981)

SOIL TYPE	DRY DENSITY, kg m^{-3}
Clean Uniform Sand (Fine to Medium)	1,770
Well Graded Silty Sand	1,880
Well Graded Fine to Course Sand	2,030

2.3.4 Porosity, n

When the dry density, ρ_d, and the mass density of the soil grains, ρ_s, are known, the porosity can be calculated by the following equation:

$$n=1-\frac{\rho_d}{\rho_s} \qquad \text{...(14)}$$

To use Eq(14), a specific value for ρ_s must be determined. This can be done in accordance with ASTM D 854 by determining the specific gravity of the soil grains, G_s, where $\rho_s = 1000\ G_s$. Table V shows typical values for G_s. These values can be used if n is estimated. The most commonly used value for ρ_s for granular soils is 2,650 kg m^{-3} which is appropriate for silica sands. Note from Eq(1) that the radon generation is a function of ρ_d/n. As the dry density increases, the porosity decreases, which has a cumulative effect on the volumetric radon generation in the pore space. This effect, however, is offset by a decrease in permeability with a decrease in porosity.

Porosity can also be estimated from Table I, interpolating between the lowest and highest values in a manner similar to that suggested for estimating dry densities.

It is of interest to note, that the emanation coefficient tends to decrease as the porosity decreases. Since C_{max} is a function of f/n (Eq(2)), a reasonable estimate can be made by assuming that the ratio f/n typically varies approximately from 0.8 to 0.9.

Table V: **SPECIFIC GRAVITIES OF MINERALS** (Lambe and Whitman, 1969, Means and Parcher, 1963)

MINERAL	G_s	MINERAL	G_s
Quartz	2.65	Augite	3.20 - 3.60
K-Feldspars	2.54 - 2.57	Olivine	3.27 - 3.37
Na-Ca-Feldspars	2.62 - 2.76	Gibbsite	2.30 - 2.40
Calcite	2.72	Talc	2.70 - 2.80
Dolomite	2.85	Anhydrite	3.00
Muscovite	2.7 - 3.1	Pyrophyllite	2.84
Biotite	2.8 - 3.2	Serpentine	2.2 - 2.7
Chlorite	2.6 - 2.9	Kaolinite	2.64
Magnetite	5.17 - 5.18	Halloysite ($2H_2O$)	2.55
Hematite	4.90 - 5.30	Montmorillonite	2.75 - 2.78
Siderite	3.83 - 3.88	Attapulgite	2.3
Gypsum	2.3	Ilite	2.60 - 2.86
Hornblende	3.00 - 3.47		

2.3.5 Permeability *(k)*

Typical water permeabilities for various saturated soils (converted into "equivalent" air permeabilities for dry soils) are shown in figures 2 and 3. Figure 2 was originally prepared by Terzaghi and Peck, 1976, and Tuma and Abdel-Hadi, 1973. Figure 3 was originally prepared by Casagrande and Fadum, 1944. Note that permeabilities of soils range from 10^{-7} m^2 for clean gravels to 10^{-18} m^2 for clays. Since radon entry is associated with soil gas permeability, the water permeabilities of saturated soils shown in figures 2 and 3 should be considered lower-bound values for dry gas permeabilities. For flow of water through soil pores, the flow velocity at the boundary between the soil grains and the pore space is zero. This is not the case for gas flow (Corey, 1988, p. 98). This phenomenon is referred to as "slip flow" or the Klinkenberg effect (Klinkenberg, 1941). The magnitude of the slip flow effect at atmospheric pressures and low flow velocities ranges from zero for coarse sands to 2 for silts (Corey, 1988).

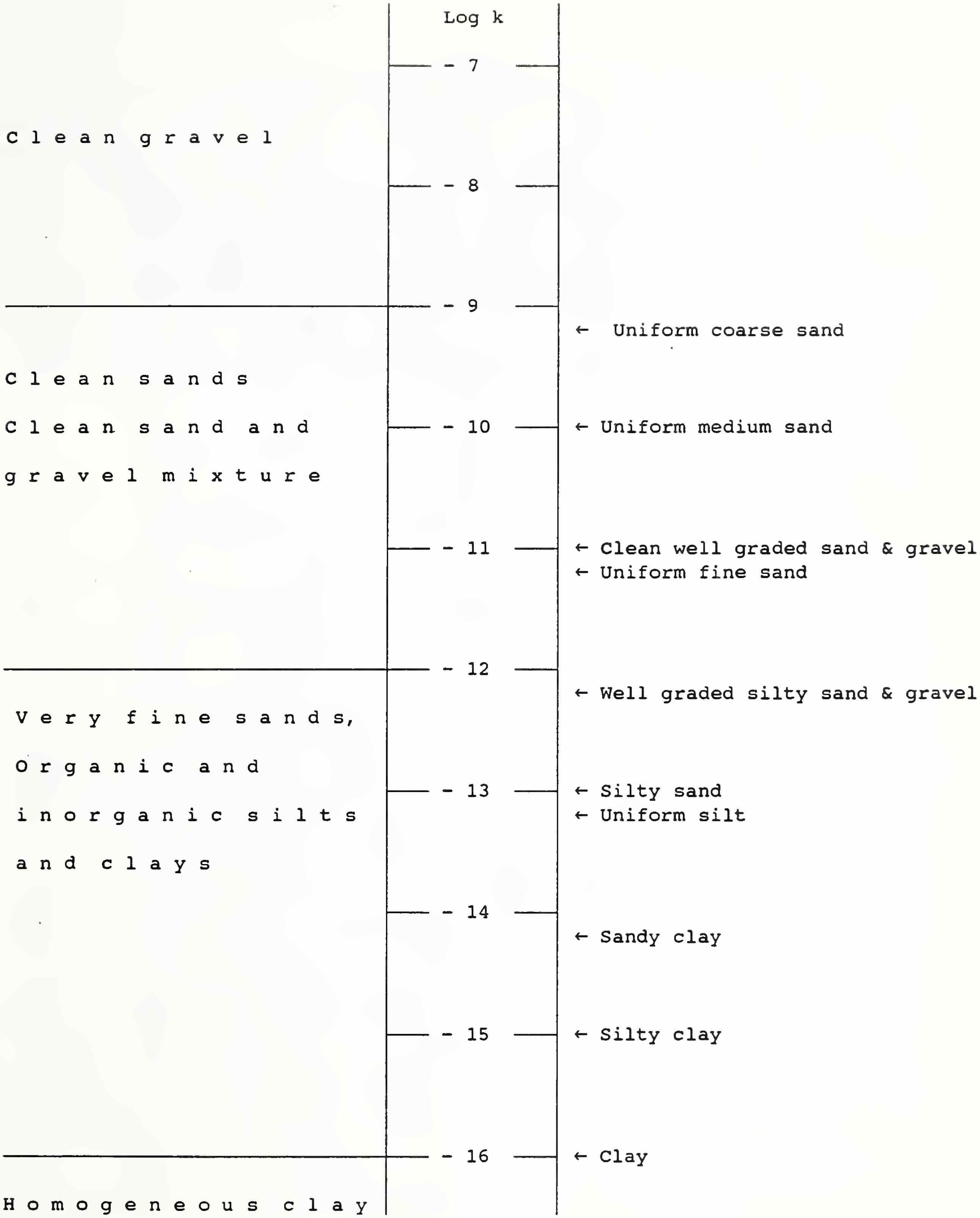

Figure 2: Typical Soil Permeability Values (after Nazaroff et al.,1988)

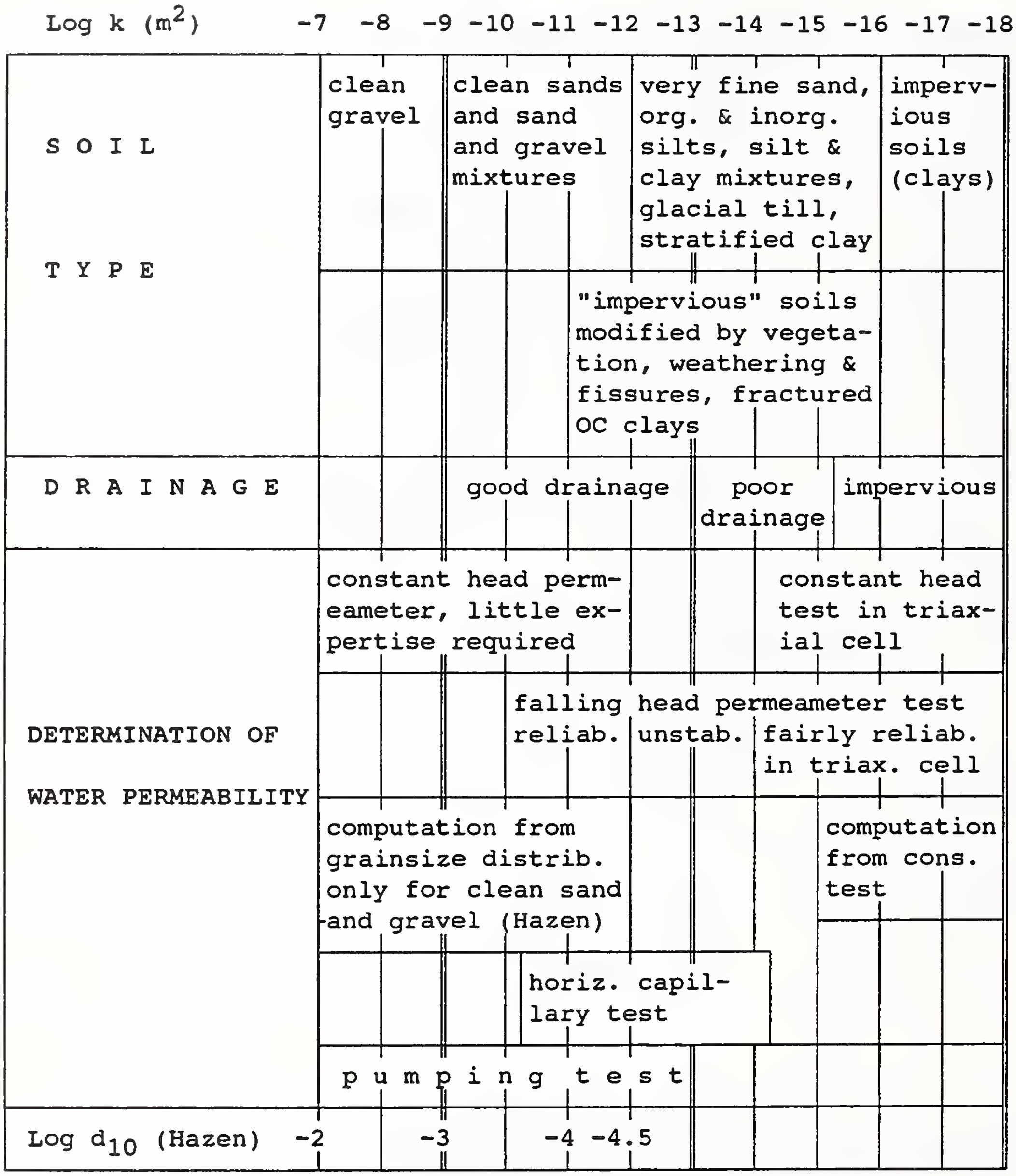

Figure 3: Soil Permeability and Drainage Characteristics (after Holtz and Kovacs, 1981, Peck et al., 1974).

Figure 3 also indicates tests by which water permeability may be determined and their range of applicability. It should be noted that laboratory tests should be performed on undisturbed samples, and that if the sample was taken vertically, the tests would measure permeability in the vertical direction. Since undisturbed samples are difficult to obtain for granular soils, a reasonable simulation may be obtained from a sample which is reconstituted to the in-place density. An accurate measurement of in-place density would be required for such a procedure. The only in situ measurement procedures mentioned in figure 3 are well pumping tests, which are quite common and tend to be reliable because they engage a large volume of soil. Water permeabilities of soils are usually given by a permeability coefficient which has the dimension of velocity and which is referenced to the gradient of the piezometric head, rather than directly to pressure gradients. A conversion can be obtained by the following equation:

$$\begin{aligned} & k \geq k_w \frac{\mu_w}{\gamma_w}; \\ & @\ 18\,^{\circ}C:\ \mu_w = 1.053 \cdot 10^{-3} Pa \cdot s;\ \gamma_w = 9.8 \cdot 10^{3}\ N \cdot m^{-3} \\ & \therefore\ k(m^2) \geq k_w(m \cdot s^{-1}) \cdot 1.07 \cdot 10^{-7} (m \cdot s) \end{aligned} \qquad \ldots\mathbf{(15)}$$

where:
k_w = water permeability coefficient (m s^{-1})
μ_w = dynamic viscosity of water (Pa s)
γ_w = unit weight of water (N m^{-3})

One item in figure 3 deserves special attention: "impervious" soils modified by vegetation, weathering and fissures, and fractured overconsolidated (OC) clays. There are two cases of interest: otherwise impervious soils made permeable by root systems; and fissured and fractured clays. In both cases, the dry gas permeability could be much higher than the water permeability, because clays shrink as they dry. Indeed, fissured or fractured clays in the dry state could be as permeable as gravels. Furthermore, under a fairly large building foundation there is no surface water supply and many clay deposits could eventually desiccate, or remain dry if the building foundation was constructed in the dry season. Thus some clays with a high swelling potential should be considered pervious, even if in situ tests indicate otherwise. Swelling clays with a surface layer which is overconsolidated from seasonal expansion abound in the U.S. These clays will develop fissures as a result of structural excavations and seasonal desiccation. It is therefore very important to identify clays with a high swelling potential. This can be accomplished by a 1-dimensional swelling test (ASTM D 4546-90). However, such clays can also be identified by simple routine classification tests which can be performed on disturbed soil samples (Atterberg Limits, ASTM D 4318-84). Guidance is provided in Table VI. All clays with a high or very high swelling potential should be considered pervious, unless substantial indoor radon data from houses in the vicinity indicate otherwise.

Table VI: ESTIMATE OF EXPANSION POTENTIAL OF CLAYS FROM CLASSIFICATION TESTS (after BUREC, 1974)

DEGREE OF EXPANSION	PROBABLE EXP. (% OF VOLUME, DRY - SAT.)*	COLLOIDAL CONTENT (% - 1μm)	PLASTICITY INDEX (PI) (D 4318)	SHRINKAGE LIMIT (SL) (D 4318)
Very High	> 30%	> 28%	> 35	< 11
High	20 - 30%	20 - 31%	25 - 41	7 - 12
Medium	10 - 20%	13 - 23%	15 - 28	10 - 16
Low	< 10%	< 15%	< 18	> 15

* Expansion data are for surcharge pressure of 6.89 kPa (1 psi)

For the protocols proposed in this report, three methods are considered for estimating the permeability coefficient: (1) a permeability estimate based on a particle size analysis of soil samples (ASTM D 422-72); (2) an air permeability measurement in the field; and (3) a permeability estimate based on a visual-manual soil classification (ASTM d 2488-90). Some guidance is also provided for interpreting the results of percolation tests which are routinely performed for construction sites which are not served by sanitary sewers. (This latter test is standardized in the 1965 edition of the "FHA Minimum Property Standards for One and Two Living Units" but the standard is not included in later editions of this document. This raises some questions about the quality control in the performance of the test).

(1) The permeability coefficient, k (m^2), can be estimated on the basis of **particle size distribution** by the following expression proposed by Rogers and Nielson, 1991.

$$k=\left[\frac{n}{500}\right]^2 d^{\frac{4}{3}} e^{-12S^4} \qquad \text{...(16)}$$

where: d = arithmetic mean particle diameter according to Eq(17), (m)

S = volume fraction of water saturation according to Eq(18)

$$d = \frac{\sum m_i d_i}{\sum m_i} \qquad \ldots(17)$$

where: m_i = mass of soil in particle-size class i, excluding +#4 (4.75 mm) mesh size (kg)

d_i = average diameter of particle-size class i (m)

$$S = \frac{w\rho_d}{1000n} = \frac{w\rho_d}{1000\left(1 - \frac{\rho_d}{\rho_s}\right)} \qquad \ldots(18)$$

Eq(16) was developed by empirical correlations with 137 air permeability measurements in Florida and Utah soils. The question still arises, however, whether two soils with different gradation curves and the same value of d would have identical permeabilities. For instance, in accordance with Eq(16), a uniform (poorly graded) sand with particle diameter d would have the same permeability as a well graded sand with the same mean value for d. In accordance with the Hazen equation (Hazen, 1892), however, the permeability of the well graded sand would be lower. This variable was not explored by Rogers and Nielson. Further research is therefore needed. Nevertheless, the expression worked well for 137 data points and is therefore recommended for the proposed protocol.

(2) **Air permeability measurements in the field** consist of the withdrawal or injection of air by negative or positive pressure, respectively. The pressure, as well as the rate of air flow are measured, and from these measurements the air permeability is calculated. Most probe measurements are interpreted assuming homogeneous isotropic soil. However one type of probe (Tanner, 1991) withdraws air with four different probe geometries, permitting an estimate of k in the horizontal and vertical direction. Isotropy was assumed for the case of the 137 measurements from which Eq(16) was developed. Several measuring devices were developed (Nielson et al., 1989, Tanner, 1988, Damkjœr and Korsbech, 1991, DSMA Atcon, 1983, Turk et al., 1987, and others). Most devices can be used to depths of 1-2 m, and combine a soil gas radon measurement with the permeability measurement. The greatest drawback of these measurement methods is that the gas permeability of soils is sensitive to the water content. Thus the field measurements are in most instances not repeatable. However, if this field measurement is combined with a determination of in situ water content at the time the measurement was taken, a correction can be made in accordance with Eq(16). An accurate determination of the degree of saturation, S, requires knowledge of in-place dry density, ρ_d, water content, w, and density of the soil particles, ρ_s. The measured gas permeability can then be used to calculate the dry gas permeability, which is an invariant quantity, by the following equation:

$$k=k_m e^{12S^4} \qquad \ldots(19)$$

where: k_m = the measured permeability coefficient (m^2)

(3) Permeability can be **estimated from a visual-manual soil classification**, using figures 2 and 3. This is the least accurate way of estimating permeability.

(4) The **FHA percolation test** (FHA, 1966) is performed in a 100-300 mm (4 to 12 in.) diameter borehole carried to the depth of a proposed disposal field (usually below the basement floor level). The hole is cleaned and the bottom and sides are roughened, and a 50 mm gravel layer is placed at the bottom of the hole to prevent scour. a 300 mm water level is maintained above the gravel layer for at least 4 h or overnight. Subsequently, 150 mm of water are placed in the hole and the water drop is measured at 30-min intervals, with water refilled if required. This procedure is continued for 4 h, and the level drop over the last 30 min interval is recorded. In very pervious soils, where the 150 mm of water seep in in less than 30 min, level readings are taken every 10 min, and the requirement of 4 h saturation is also relaxed.

The test results give some indication of permeability. In very permeable soils ($k > 10^{-10}$ m^2), the water level will drop at a rate of 10 mm/min or faster. In well drained soils ($k > 5 \cdot 10^{-12}$ m^2) the water level will drop at a rate of 5 mm/min or faster.

One problem that has been noted in section 2.2.1 is orthotropy of permeability. If the permeability in the horizontal direction is greater than that in the vertical direction, k becomes a vector quantity. The only practical method presently available to identify ortotropy is Tanner's probe (Tanner, 1987). Presently available information does not provide an adequate basis for considering this variable. However, it is recommended in section 7 to study the effect of orthotropy on radon entry and in situ permeability measurements and the feasibility of considering its effect on radon source potential.

2.3.6 Diffusion Coefficient *(D)*

The diffusion coefficient varies with the saturation. The following equation is proposed by Rogers and Nielson, 1991, for calculating the interstitial diffusion coefficient:

$$D=D_0 n \exp(-6Sn-6S^{14n}) \qquad \ldots(20)$$

where: D_0 = diffusion coefficient in air (1.1×10^{-5} m^2 s^{-1})

Eq(20) is based on many data. It indicates that the diffusion coefficient can be estimated if n and S are known. A measurement to determine the diffusion coefficient is therefore not needed.

3. TESTING PROCEDURES

3.1 Introduction

The primary aim of the proposed testing procedures is to facilitate the merger of exploration for radon source potential with present geotechnical soil exploration practice. The information produced by these procedures can be used in three different ways: (1) it can provide a basis for an overall rating of sites in terms of their propensity to produce elevated radon levels in buildings; (2) it can provide input data for radon transport and entry models (for instance Nielson et al., 1992), which are used for radon potential mapping or radon entry prediction. (3) it can provide boring log information that can be used to rate the radon potential of soils that are used as fill material under buildings (Bolch, 1987).

These procedures are designed to produce repeatable measurements of invariant soil properties (C_{max}, ρ_d, n, k). However, they also provide information on the natural water content of the soil at the time of sampling. When these data are used in models, assumptions will have to be made with respect to typical water contents and other climatological factors.

3.2 Summary and hierarchical rating of measurement methods

Each of the invariant soil properties can be estimated by different methods, ranging from estimates based on soil types and field spectrometry to accurate measurements. In most instances it is possible to determine which method will yield more reliable estimates. Thus more accurate methods can be used to revise estimates based on less accurate methods. In this summary the methods are listed in progressive order of accuracy. In each instance, the results obtained by more accurate methods should take preference over those obtained by less accurate methods.

3.2.1 Radium Activity Concentration (A_{Ra})[3]

LEVEL	TEST METHOD
I	Field γ - Spectrometry - aerial
II	Field γ - Spectrometry - detector 1 m above ground
III	Field γ - Spectrometry - downhole method
IV	γ - Spectrometry, NaI(Tℓ) detector, $\approx$ 90 mL sample (EML HASL 300, 7.21.1)
V	γ - Spectrometry HPGe detector, $\approx$ 90 mL sample
VI	γ - Spectrometry, NaI(Tℓ) detector $\approx$ 600 mL Marinelli beaker (EML HASL 33)
VII	γ - Spectrometry, HPGe detector, Marinelli beaker

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[3] A test method similar to that performed by Markkanen and Arvela, (p. 10) can be substituted for both the measurement of the radium activity concentration and the measurement of the emanation coefficient. Because there is no track record for this method in the U.S., the method is rated inferior to level IV for A_{Ra} and level II for f.

3.2.2 Emanation Coefficient (f)[3]

LEVEL	TEST METHOD
I	Estimate: granular soils: $f = 0.25$; cohesive soils: $f = 0.4$, or Eq(12)
II	Measured: 2 or more spectrometry counts at $w = 5\%$, disturbed sample
III	Measured: 2 or more spectrometry counts at $w = 5\%$, undisturbed sample

3.2.3 Dry Density (ρ_d)

LEVEL	TEST METHOD
I	Estimate, using tables I, II, III, and IV, and Eq(13)[4]
II	Removal of a slightly disturbed sample[5]
III	Removal of disturbed sample of known in-place volume
IV	Nuclear density and water content measurement

3.2.4 Porosity (n)[6]

LEVEL	TEST METHOD
I	Calculated porosity, using an estimated value for ρ_s
II	Calculated porosity, using a measured value for ρ_s (ASTM D 854)

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[4] An exception is the case of compacted fills, covered by table IV. For this case, an estimate is considered adequate and no in-situ density measurement is necessary for improved accuracy.

[5] Removal of a high-quality undisturbed sample in accordance with ASTM D 1587 is considered equivalent or superior to level III

[6] Ratings for determination of porosity are also subordinated to the rating of the dry density determination.

3.2.5 Dry Permeability *(k)*

LEVEL	TEST METHOD
I	Estimate based on visual-manual soil classification (ASTM D 2488)
II	Estimate based on particle - size analysis (ASTM D 422) and Eq(16)
III	Estimate based on in situ air permeability test, corrected for saturation.[7]

3.2.6 Diffusion Coefficient *(D)*

The dry interstitial diffusion coefficient can be assumed at $n \cdot 1.1 \cdot 10^{-5}$ m^2 s^{-1}. An assumed in-situ diffusion coefficient, if needed, can be calculated by Eq(20). The accuracy level of the calculated coefficient will depend on the accuracy levels of ρ_d, w, and n.

3.3 Test Methods

3.3.1 Radium Activity Concentration *(A_{Ra})*

References:

Chieco, N.A., Bogen, D.C.,Knutson, E.O., "EML Procedures Manual, 27th Ed. HASL-300," Environmental Measurement Laboratory (EML), Department of Energy, Nov. 1990 (rev. February, 1992); Sect. 3.3 - Field Gamma-Ray Spectrometry; Sect. 4.5.2.3 - Gamma; Sect. 7.21 -Aluminum Sample Cans for Gamma Counting.

A.D. Williamson and J.M. Finkel, "Standard Measurement Protocols, Florida Research Program," Report SRI-ENV-90-070-6411, U.S. Environmental Protection Agency, Research Triangle Park, NC, January, 1990. Procedure 1-6

Austin, S.R. and Droullard, R.F., "Radon Emanation from Domestic Uranium Ores Determined by Modifications of the Closed-Can, Gamma only Assay Method," Report 8274, U.S. Dept. of Int., Bureau of Mines, 1978.

Procedures:

Field spectroscopy: follow procedures recommended by the manufacturer and calibration procedures recommended in HASL 300. Allowance must be made for ^{214}Bi depletion. Must be calibrated against other measurements. Note that in downhole measurement the depletion will depend on length of time hole was open and atmospheric conditions.

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[7] If $S \geq 0.65$ an estimate from particle - size analysis may be more accurate.

Laboratory procedures: Seal soil volume of ~ 90 mL or ~ 600 mL in aluminum can, perform count after 2 weeks, divide result by 0.98. Use oven-dried sample and single count for determination of A_{Ra} only. Use sample with 5% water content and a minimum of 2 counts, one at least 4 h but no longer than 1 d after sealing the can, one 2 weeks after sealing and, optionally, an intermediate count for determination of A_{Ra} and f.

3.3.2 Emanation Coefficient *(f)*

References:

Austin, S.R. and Droullard, R.F., "Radon Emanation from Domestic Uranium Ores Determined by Modifications of the Closed-Can, Gamma only Assay Method," Report 8274, U.S. Dept. of Int., Bureau of Mines, 1978.

M. Markkanen and H. Arvela, "Radon Emanation from Soil," Paper No. 77, 5th Int. Conf. on Natural Radiation Environment, Salzburg, Austria,, September, 1991

A.D. Williamson and J.M. Finkel, "Standard Measurement Protocols, Florida Research Program," Report SRI-ENV-90-070-6411, U.S. Environmental Protection Agency, Research Triangle Park, NC, January, 1990

Procedures:

An allowance for a coefficient of 0.25 for granular soils and 0.4 for cohesive soils but not less than the coefficient calculated by Eq(12) is acceptable as a substitute for testing.

Test procedure must be performed on a soil sample with 5% or greater water content. γ-spectrometry can be performed in accordance with Austin and Droullard, 1978, or Williamson and Finkel, 1990. Use of the Markkanen-Arvela procedure (refer to 2.3.2 p 10), using a disturbed sample with 5% water content is acceptable, provided that the accuracy of the procedure has been previously verified against the results from γ-spectrometry for at least five different samples.

γ-spectrometry on undisturbed or re-constituted samples should be performed in accordance with Austin and Droullard, 1978, using an aluminum can without a well and trimming the sample carefully to fit the can. Water content determination should be made after completion of the test[8]. Water content should be 5% or more.

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[8] The sample should not be oven-dried before the test, since there is evidence that the elevated temperature could irreversibly decrease the emanation coefficient (Hahn, 1936).

3.3.3 Dry Density (ρ_d)

References:

ASTM D 2488-90 Standard Practice for Description and Identification of Soils (Visual-Manual Procedure

ASTM D 2487-90 Standard Test Method for Classification of Soils for Engineering Purposes

ASTM D 2216-90 Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil or Rock

ASTM D 4643-87 Standard Test Method for Determination of Water (Moisture) Content of Soil by the Microwave Method

ASTM D 2937-83 Standard Test Method for Density of Soil in Place by the Drive Cylinder Method

ASTM D 4914-89 Standard Test Method for Density of Soil or Rock in Place by the Sand Replacement Method in a Test Pit

ASTM D 2167-84 Standard Test Method for Density and Unit Weight of Soil In Place by the Rubber Balloon Method

ASTM D 4564-86 Standard Test Method for Density of Soil In Place by the Sleeve Method

ASTM D 2922-91 Standard Test Method for Density of Soil in Place by Nuclear Methods (Shallow Depth)

ASTM D 3017 - Test Method for Water Content of Soil and Rock in-Place by Nuclear Methods (Shallow Depth)

ASTM D 1586-84 Standard Method for Penetration Test and Split-Barrel Sampling of Soil

ASTM D 1452-80 Standard Practice for Soil Investigation and Sampling by Auger Borings

ASTM D 4700-91 Standard Guide for Soil Sampling in Vadose Zone

A.D. Williamson and J.M. Finkel, "Standard Measurement Protocols, Florida Research Program," Report SRI-ENV-90-070-6411, U.S. Environmental Protection Agency, Research Triangle Park, NC, January, 1990, Procedure 1-1.

Procedures:

Density Estimate: Use of estimated density is only recommended when the SPT (ASTM D 1586 is used and it is not possible to recover a relatively undisturbed portion of the soil sample retrieved. Identify soil by ASTM 2487 or 2488; use tables I and II to get upper and lower density limit; use corrected SPT blow count in conjunction with table III and Eq(13) to estimate relative density; estimate density by interpolation between upper and lower density limits in tables.

Removal of an undisturbed or slightly disturbed sample is practical in conjunction with the STP procedure, as well as exploration using hand operated or mechanical augers. In conjunction with the SPT method the soil sample should be no smaller than 100 mL (at least 150 mm (6 in.) long). Sampling by the SPT procedure can be improved by using a thin-wall tube sampler (ASTM D 1587-83). When appropriate samplers are used it is advantageous to retrieve a larger quantity (about 750 mL). For sampling in auger holes the method described by Williamson and Finkel, Procedure 1.1, is very convenient, However, any other method described in ASTM D 4700 is acceptable as long as the sample retrieved is reasonably undisturbed and its dimensions are accurately recorded. The water content and dry density of the sample can be determined in the laboratory (ASTM D 2216 or D 4643).

Removal of a disturbed sample of known volume is practical when the available working area is large enough (at the ground surface or in an excavation). Excavation safety regulation prescribed by OSHA should be observed in this case. Any of the ASTM methods specified for this purpose (ASTM D 4914, 2597 or 4564) will yield satisfactory results.

Nuclear density measurements near the surface can be performed in accordance ASTM D 2922. The method measures total density, and the water content needs to be determined separately. Either laboratory methods previously described or Nuclear methods (ASTM D 3017) can be used. As noted in 2.3.3, downhole instruments combining nuclear measurements of density and water content are commercially available. These latter instruments should be used in accordance with the manufacturer's instructions. When non-destructive methods are used, a soil sample still may have to be retrieved for spectrometry and in some instances for permeability estimates.

3.3.4 Porosity *(n)*

Reference:

ASTM D 854-83 Specific Gravity of Soils

Procedures:

The mass density of the soil particles may be estimated or measured.

Estimates can be performed using Eq(14) and table V to estimate ρ_s. The most common value used for particle density of silica soils is 2,650 kg m^{-3}.

Measurements of the particle density of soils should be performed in accordance with ASTM D 854, using Eq(14) to calculate n.

3.3.5 Permeability *(k)*

References:

A.D. Williamson and J.M. Finkel, "Standard Measurement Protocols, Florida Research Program," Report SRI-ENV-90-070-6411, U.S. Environmental Protection Agency, Research Triangle Park, NC, January, 1990, Procedure 1.1.

Nielson, K.K., M.K. Bollenbacher, V.C. Rogers, and G. Woodruff, "Users Guide for the MK-II Radon/Permeability Sampler", U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, DC, August, 1989.

Tanner, A.B., "A Tentative Protocol for Measurement of Radon Availability from the Ground," Radiation Protection Dosimetry, Vol. 24, pp 79 - 83, 1988.

Turk et al., "Radon Remedial Action in Spokane River Valley, Vol. 1, LBL-23430, Lawrence Berkeley Lab., Berkeley, CA, 1987.

Rogers, V.C. and Nielson, K.K., "Correlations for Predicting Air Permeabilities and ^{222}Rn Diffusion Coefficients for Soils," Health Physics, Vol. 61 No. 2, pp 225-230, August, 1991.

ASTM D 2488-90 Standard Practice for Description and Identification of Soils (Visual-Manual Procedure

ASTM D 2487-90 Standard Test Method for Classification of Soils for Engineering Purposes

ASTM D 422-72 Particle-Size Analysis of Soils

ASTM D 421-85 Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants

ASTM D 4318-84 Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils

ASTM E 11-81 Standard Specification for Wire-Cloth Sieves for Testing Purposes

ASTM D 4546-90 Test Methods for 1-Dimensional Swell or Settlement Potential of Cohesive Soils.

Procedures:

Estimates can be made on the basis of soil identification by ASTM D 2488-90 using figures 2 and 3. In case of uncertainty the classification yielding the highest permeability should be used.

Estimates on the basis of particle size analysis shall be performed as follows: (1) Secure sample of adequate size to perform the required tests in accordance with ASTM D 421. An SPT sample taken for dry density determination will not be adequate for this purpose. Therefore, after removal of a measured length of the SPT sample for determination of dry density, the rest of the sample shall be preserved in a separate container. After the determination of ρ_d and w, both samples should be combined for particle size analysis and optionally for spectrometry. (2) Perform particle-size analysis in accordance with ASTM D 422 as follows: Remove the portion of the sample retained in the #4 sieve. Use preferably five sieve sizes between the #10 and #200 sieves (#10, #20, #40, #60, # 80, #100, #200). (3) If the fraction of -#4 (smaller than #4) sieve material passing the #200 sieve is less than 70% by weight of the total -#4 sieve material, only the fraction of -#4 material retained by the sieves can be optionally used to calculate the arithmetic mean particle diameter (d). This should result in an overestimate of k by approximately 10%. If this error is not acceptable, a hydrometer analysis should be performed and all the measured particle fractions below the #4 mesh size should be used to calculate d. (4) Calculate k using Eqs.(16) and (17). The value of n used to calculate k should be derived from a Level II or better accuracy for the dry density determination.

Estimates on the basis of in-place air permeability measurements should be performed in accordance with Williamson and Finkel, 1991, Procedure 1.1. Methodologies used can be those specified by Nielson et al., 1989, Tanner, 1988 or Turk, 1987, or other methodologies acceptable to EPA. The measured permeability coefficient, k_m, should be converted to the dry permeability coefficient, k, using Eq(19). The value for saturation used in Eq(19) should be based on a Level II accuracy or better measurement of dry density. In-place air permeability measurements are considered superior to laboratory determinations for saturations of 0.65 or less, because they are made in undisturbed soil (also refer to figure 4).

Permeability of clays: Many clays fissure upon desiccation and become very permeable. Unless there is a preponderance of evidence that the clay deposit in question does not produce elevated radon levels in buildings, the following procedure can be used: (1) Secure disturbed soil sample of 220 g mass or more. (2) Determine liquid limit, plastic limit and plasticity index in accordance with ASTM D 4318. (3) Refer to table VI to determine swelling potential. If swelling potential is high or very high assume that $k \geq 10^{-10}$. If swelling potential is medium, assume that $k \geq 10^{-11}$. A more accurate measure of swelling potential can be obtained by a 1-dimensional swelling test (ASTM 4546), using a 6.89 kPa surcharge. For this latter procedure, an undisturbed sample should be used.

Another diagnostic test that gives an indication whether a clay may be fissured upon desiccation is the drying test (Tucker and Reese, 1979, Yokel et al., 1980). This test requires an undisturbed sample, 12 to 25 mm thick and approximately 150 mm in diameter. It may be expensive to obtain such a sample from a borehole, but samples could be taken at the ground surface or at the base of an accessible excavation. Undisturbed samples cannot be taken if the clay is desiccated. The sample is oven dried at 100°C for 24 hours. If significant pre-existing fissures are present, the sample will crack along these fissures when drying. If the dry sample is intact, it is grasped between the thumb and forefinger of each hand and broken. If the sample can be easily broken, it is either predominantly granular material or fissured clay. An attempt is then made to pulverize the sample with the fingers. If it breaks up into clumps which are hard to pulverize, the material is likely to be a fissured clay.

4. FIELD EXPLORATION METHODS

4.1 Introduction

The field exploration methods proposed in this section are designed to produce repeatable measurements or estimates of invariant soil properties which are related to the radon source potential of sites or fill materials. Three exploration methods are proposed: a method that utilizes present geotechnical soil exploration procedures with some modifications; a method which can be used with hand held or readily available mechanical equipment and which is suitable for exploration of single sites because of the low equipment mobilization cost; and a procedure which can be used together with present radon exploration methods to produce data on invariant soil properties. These methods are proposed because they are considered practical and economical. Any other method which produces the measurements specified in Section 3 is acceptable.

4.2 Number and Depth of Data Points

As discussed in Section 2.2.1, there are many factors which affect the characteristics of a site, among them are topography, variability of subsurface conditions, depth and characteristics of the underlying bedrock, origin of soil deposits, depth and variability of groundwater level, permeability and stratification of the soil deposits and climatological conditions. It is therefore impractical to make rules which apply to all sites. Bolch, 1987, used a radon diffusion transport model to define an "effective radium concentration" from a weighted average of measurements at different depths. His weighting factors (W_i) are given in the following table. The effective radium activity concentration is calculated by the following equation:

$$ERC = \frac{1}{0.75} \sum (W_i A_{Rai}) \qquad \textbf{...(21)}$$

where: ERC = effective radium concentration (Bq kg^{-1})
W_i = weighting factor (to 1.8 m depth)

The weighting factors are listed below:

DEPTH, m	W_i
0.0 - 0.3	0.16
0.3-0.6	0.15
0.6-0.9	0.14
0.9-1.2	0.12
1.2-1.5	0.10
1.5-1.8	0.08
below 1.8	0.25

Bolch's model indicates that an "infinite" thickness is about 5 m, and that 75% of the contribution is from a 1.8-m deep layer. This model was subsequently used for radon-potential mapping. While this model is useful for certain subsurface conditions, it is important to recognize several facts: (1) The model was developed for diffusive radon transport and may not be valid for advective transport; (2) The diffusion length is a function of the diffusion coefficient, which in turn is a function of soil saturation. As saturation increases, the diffusion coefficient and the diffusion length decrease. Thus these depth contributions are only valid for saturations of less than 50%. (3) Many buildings have basements, and radon migration occurs from the bottom slab as well as the basement walls. The concept of an "effective radon concentration" does not apply to these buildings. One important factor to keep in mind is orthotropy. If the horizontal permeability is much greater than the vertical permeability, the relative contribution of the soil immediately below the basement slab (and, if applicable, the soil adjacent to the basement walls), will increase.

As a practical matter, samples will rarely be collected at 300-mm intervals. For instance the SPT sampler is 450 mm long. In practice there will probably be a maximum of three, and often only one sample (except if the soil is stratified). For reasonably homogeneous conditions the most practical approach is to take one sample immediately below the basement slab, and in some instances another sample between 1 and 1.45 m below the slab, or alternately one single sample about 1 m below the subslab. If multiple samples are taken, the sample with the highest radon potential should be used (unless the soil is stratified).

For evaluation of fill material a sample should be taken every 1.5 m or whenever the material changes.

4.3 The SPT method

In the Standard Penetration Test (ASTM D 1586) a split spoon sampler of 50.8 mm (2.00 in.) outer diameter is driven into the ground with a 63.5-kg (140 lb) hammer dropped from a height of 0.76 m (30 in.). Before retrieval, the sampler is advanced 0.45 m (18 in.) and the number of hammer blows is counted for each 0.15-m (6-in.) increment of sampler advance. The sampler is then brought to the surface and opened (the sampler barrel is split longitudinally). ASTM specifies a visual description of the sample as to length (percent of recovery), color, stratification and condition, and placement of one or more representative portions of the sample in a moisture-proof container without ramming or distorting the apparent stratification. ASTM also describes the information to be included in the boring log.

In the proposed method, the ASTM procedure is modified as follows:

(1) Remove a relatively undisturbed portion of the sample of at least 150 mm (6 in.) length (Sample #1), cut to a precise length ($\pm$ 1 mm) using a spatula formed to fit the 38-mm inside diameter of the sample barrel. Place this latter sample in a sealed moisture proof container. Record the length of the retrieved sample to a 1-mm precision. Remove the rest of the 450-mm (28 in.) long sample and place in a sealed moisture-proof container (Sample #2).

(2) In the laboratory, oven-dry Sample #1 and determine w and ρ_d in accordance with ASTM D 2216 [for the purpose of calculating the sample volume, the diameter of the sample is assumed to equal the inside clearance of the sampler shoe - Dimension C in ASTM 1586, which is 34.925 mm (1.375 in.)]. Oven-dry Sample #2 and determine dry mass and w in accordance with ASTM D 2216. Combine Samples #1 and #2, mix thoroughly, perform particle-size analysis in accordance with ASTM D 422 and Section 3.3.5 of this report, and calculate k.

(3) If the portion of the sample retained in the # 4 sieve is less than 40% of the total dry mass of combined Samples #1 and #2, remove the portion of the sample retained in the #4 sieve from the sample used for spectrometry. Otherwise use the whole sample, removing only particles larger than 13 mm (0.5 in.). If a hydrometer analysis was performed, recover soil sample used for this purpose and oven-dry for 24 hours. Thoroughly mix the remaining soil sample [including the portion (if any) used for hydrometer analysis], place a portion of the sample in a suitable aluminum beaker (Chieco et al., HASL-300, 7.21), seal, store for 2 weeks, and perform spectrometry in accordance with Section 3.3.1 of this report.

(4) Prepare log: record measured quantities: A_{Ra}, ρ_d, w, k. Record calculated and estimated quantities: f, n, S, C_{max}. f is estimated at 0.3 for granular soils and 0.4 for cohesive soils; n and S are calculated assuming $\rho_s = 2{,}650$ kg m^{-3}, or any other value chosen from Table V.

Alternate options:

1. Less accurate estimates:

(1) Estimate ρ_d from visual-manual soil classification (ASTM D 2488) in accordance with Section 3.3.3.

(2) Estimate k from visual-manual soil classification or from available data on properties of the subsoil in accordance with Section 3.3.5.

(3) Estimate C_{max} from a measured ^{222}Rn activity concentration in the soil-gas with a Lucas cell using the following equation:

$$C_{\max} = \frac{C_m}{1-\exp\left[-H\left(\frac{\lambda}{D_m}\right)^{0.5}\right]} \qquad \ldots\textbf{(22)}$$

where:
H = depth at which radon concentration was measured (m)
C_m = measured ^{222}Rn activity concentration in soil gas (Bq m^{-3})
D_m = Diffusion coefficient for measured saturation (m^2 s^{-1})

2. More accurate options

(1) Measure ρ_s of the soil sample by ASTM D 854.

(2) Measure in-place air permeability in accordance with section 3.3.5 and correct for saturation using Eq(18).[9]

(3) Measure in-place ρ_d and w with downhole nuclear gage.

Modification of procedure for clay soils:

For clays a particle-size analysis is not needed. Instead, determine Atterberg limits in accordance with ASTM D 4318. Use Table VI to predict degree of expansion. Determine permeability in accordance with Section 3.3.5.

4.4 Manual Procedures

These procedures are designed to be used when a geotechnical exploration by soil borings is not planned for other purposes. It is practical for the exploration of individual sites. The manual methods specified in this section do not include presently used procedures for soil gas extraction which are covered in the next section. In this method a soil sample is obtained by manual procedures and tested in the laboratory. The following procedure is recommended:

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[9] This method is considered more accurate than the estimate based on particle-size analysis if $S \leq 0.65$. The soil gas permeability measurement is usually linked with an in-place ^{222}Rn activity concentration measurement. This combination of measurements is efficient because the need for spectrometry is eliminated.

(1) Use any convenient method of advancing an auger hole or excavation to the desired sampling depth.

(2) Use any convenient method (Section 3.3.3) to remove a sample of a known in-place volume (Sample #1) and save sample #1 in a moisture-proof sealed container (a properly-sealed plastic bag is acceptable) and label sample #1 as in-place density sample.

(3) Take a second disturbed sample (Sample #2) by any convenient method, such that the volume of sample #1 + sample #2 $\simeq$ 750 mL., place in moisture-proof sealed container, and label.

(4) In the laboratory, oven-dry Sample #1 and determine w and ρ_d in accordance with ASTM D 2216. Oven-dry Sample #2 and determine dry mass and w in accordance with ASTM D 2216. Combine Samples #1 and #2, mix thoroughly, perform particle-size analysis in accordance with ASTM D 422 and Section 3.3.5 of this report, and calculate k.

(4) If the portion of the sample retained in the #4 sieve is less than 40% of the total dry weight of combined Samples #1 and #2, remove the portion of the sample retained in the #4 sieve from the sample used for spectrometry. Otherwise use the whole sample, removing only particles larger than 13 mm (0.5 in.). If a hydrometer analysis was performed, recover soil sample used for this purpose and oven-dry for 24 hours. Thoroughly mix the remaining soil sample [including the portion (if any) used for hydrometer analysis], place a portion of the sample in a suitable aluminum beaker (Chieco et al., HASL-300, 7.21), seal, store for 2 weeks, and perform spectrometry in accordance with Section 3.3.1 of this report.

(6) For clays a particle-size analysis is not needed. There are two options for assessing potential permeability upon desiccation: (1) perform drying test in accordance with Section 3.3.5; (2) determine Atterberg limits in accordance with ASTM D 4318. Use Table VI to predict degree of expansion. Determine permeability in accordance with Section 3.3.5.

(7) Prepare log: record measured quantities: A_{Ra}, ρ_d, w, k. Record calculated and estimated quantities: f, n, S, C_{max}. f is estimated at 0.3 for granular soils and 0.4 for cohesive soils; n and S are calculated assuming ρ_s = 2,650 kg m^{-3}, or any other value chosen from Table V.

The test method specified in Williamson and Finkel, 1990, Section 1.2, devised by Rogers and Associates, in which a 100-mm (4-in.) diameter bucket auger is used together with a 50 mm diameter x 100 mm length thin wall tube drive sampler (ASTM D 2937) is considered practical for many applications because the auger is used to advance the initial hole as well as to retrieve the tube sampler after it is driven into the ground. However, a nuclear moisture and density measurement could also be used together with a disturbed sample for particle-size analysis.

Less accurate options:

(1) Estimate permeability on the basis of visual-manual soil classification, percolation tests, or information on the soil formation (refer to Section 3.3.5).

(2) Estimate volumetric radon generation on the basis of field spectroscopy.

(3) Estimate C_{max} on the basis of an ^{222}Rn activity concentration measurement in the soil gas.

More accurate options:

(1) Use nuclear moisture and density measurements.

(2) Use air permeability test and correct for water content.

(3) Measure ρ_s of the soil sample by ASTM D 854.

4.5 Soil-Gas Extraction Test

The soil-gas extraction test combines an air-permeability measurement with a radon activity concentration measurement in the soil gas. The instrumentation used is portable, and equipment mobilization cost is therefore low. The obvious advantage of this test is that it directly measures radon concentration and transport. The disadvantage of the test is that both quantities measured are very sensitive to saturation of the subsoil, and that radon concentration in the soil gas is also sensitive to prevailing temperature and pressure gradients. However, if the measurement is combined with an in-place density and water content determination, the measured gas permeability, which is a function of saturation, can be converted by Eq(18) to the dry gas permeability, which is an invariant soil property. The accuracy of the test decreases with increasing saturation. The test is not recommended for saturation levels in excess of 0.65. A correction can also be made to convert the measured radon activity concentration, C_m, to the maximum possible radon activity concentration, C_{max}, as a function of the depth of the measurement and the saturation of the soil (and thus the diffusion coefficient) at the time of the measurement using Eq(22). This latter correction, however, is based on the concentration profile that would result when diffusion is the sole radon transport mechanism and does not account for the potential effects of advective radon transport caused by transient pressure gradient changes. To minimize the potential error associated with the depth correction it is recommended to make the measurement at a minimum depth of 0.9 m. However, this may not be possible when the depth to bedrock or practical refusal is less than 0.9 m.

The following procedure is recommended:

(1) Make air permeability and radon activity concentration measurements in accordance with Williamson and Finkel, Section 1.1, or other procedures in accordance with sections 3.3.1 and

3.3.5 of this report.

(2) Make an in-place soil density measurement at the same location, or at a horizontal distance not to exceed 0.6 m from the gas permeability measurement location (if one density test serves more than one permeability test).

(3) Make a laboratory determination of ρ_d and w; calculate S. Follow the procedures specified in Sections 4.3 or 4.4 of this report.

(4) Calculate k, using Eq(19); calculate C_{max}, using Eqs.(20) and (22).

As a practical matter it is recommended to follow the procedure specified by Williamson and Finkel, Sections 1.1 and 1.2. However, other soil gas extraction tests can be substituted for the specific test recommended by Williamson and Finkel.

As previously noted, the soil gas extraction test can be combined with any of the other procedures recommended and its use could eliminate the need for the particle-size analysis and the spectrometry. For very moist soils ($S \geq 0.65$), the test is not recommended.

5. INTERPRETATION OF TEST RESULTS

As noted in the introduction, there are only limited data linking radon source potential with indoor radon levels. There are some mathematical models which will accept the soil properties measured in the testing protocols proposed herein and predict indoor radon potential (Kunz, 1988, Tanner, 1988, Nazaroff and Sextro, 1989, Nielson, 1992, Laureiro, 1987, and others). There are also expressions for radon source potential that were developed by various authors (refer to summary in Yokel, 1989, pp 33-35). In addition to the various soil properties measured in the testing protocols previously described, there are environmental variables which must be taken into consideration. The most important of these variables is the water content of the soil surrounding the structure. While the natural water content is measured in the previously-described tests, there is no assurance that the water content at the time of the test is indicative of the water content that should be considered for radon source potential assessment. Water contents change seasonally, they depend on the weather conditions just prior to the time of measurement, and they may drastically change as a result of drainage systems and landscaping associated with building construction. Figure 4 shows normalized plots of k_m/k, where k_m is the moist permeability coefficient in accordance with Eq(19), and $D/D_0\ n$, where D is the moist interstitial diffusion coefficient, calculated in accordance with Eq(20). The same plot is shown in figure 5 on a semi-logarithmic scale to provide more information on higher levels of saturation. Note that the decrease of both the coefficient of permeability and the diffusion coefficient with saturation has a cumulative effect on radon entry. It can also be deduced from figures 4 and 5 that saturated soils do not contribute significantly to radon transport. Thus the groundwater surface is an effective barrier to radon transport.

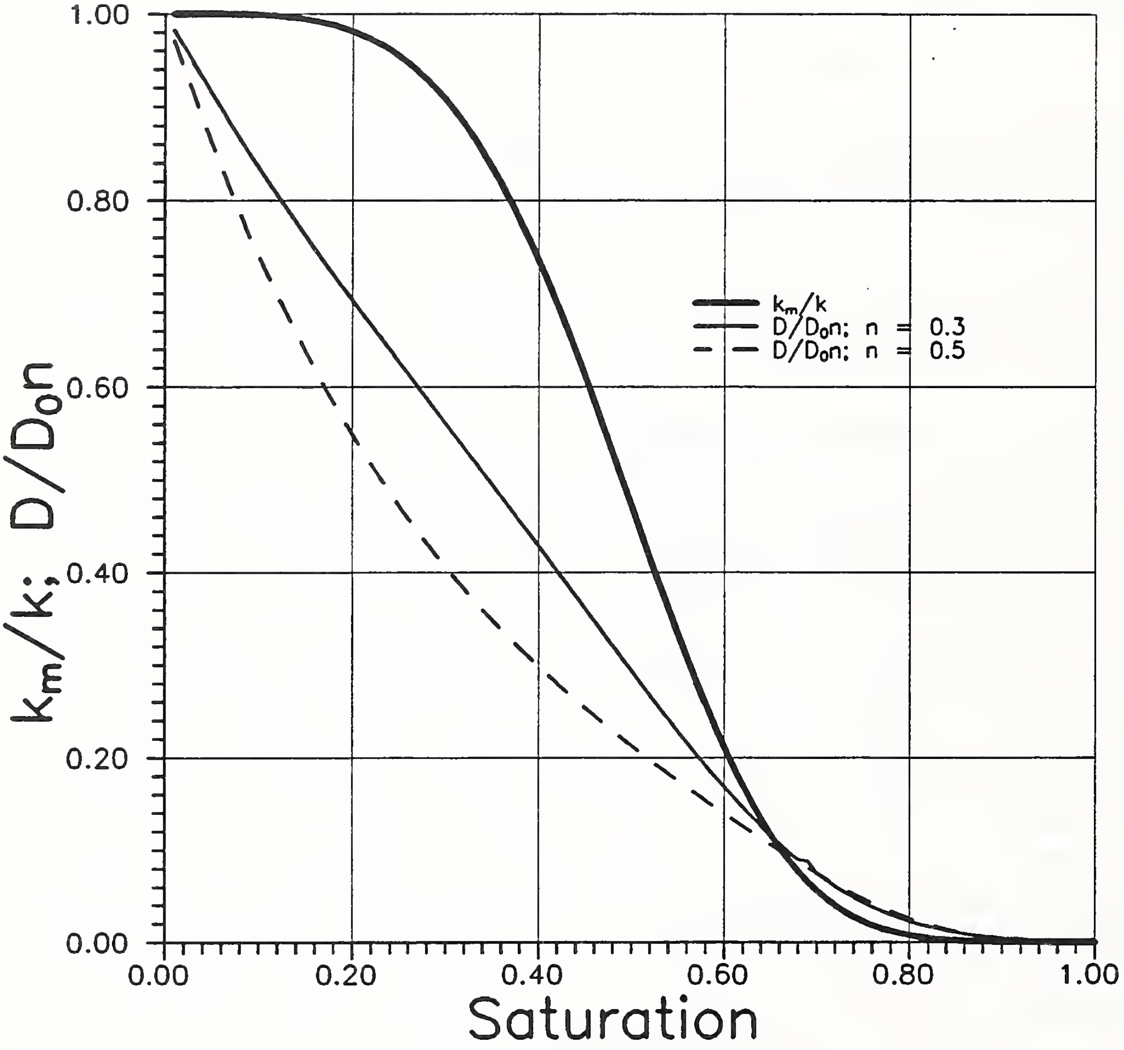


Figure 4: Effect of Saturation on Permeability and Diffusion Coefficients.

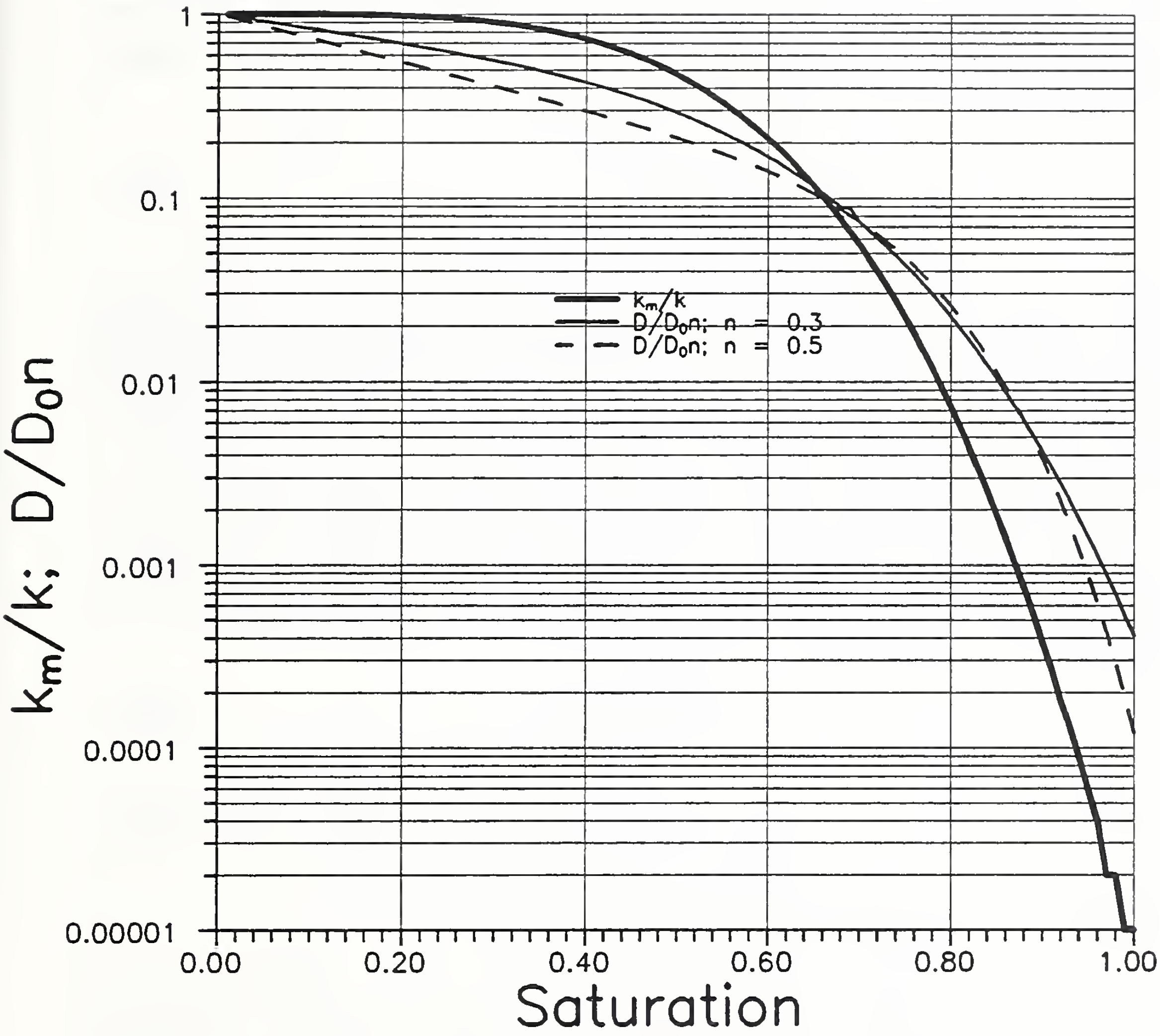


Figure 5: Effect of Saturation on Permeability and Diffusion Coefficients.

As noted in the introduction, the interpretation of the measurements of the variables contributing to radon transport is not clear cut, because of the additional variables affecting to radon entry into buildings. One model that considers advection and diffusion is the "Radon Availability Number", *RAN* (kBq m^{-2}) (Tanner, 1988), which is defined as the amount of radon per unit area that can be fed from soil and sustained external to its surface (such as the interface between the soil and a building foundation) by a combination of diffusion and advection under an assumed pressure gradient. Israël (1962) reasoned that the steady-state quantity of radon in the atmosphere must be balanced by a deficit of radon in the ground, lost to the atmosphere by the diffusion process, and showed that the deficit, on a unit area basis, is equal to the quantity of radon that would be contained in a soil layer equal to the diffusion length (l) if there were no loss other than decay, where:

$$l = \left[\frac{D}{\lambda_{Rn}} \right]^{0.5} \qquad \textbf{...(23)}$$

The *RAN* concept extended Israël's idea to include both diffusive and advective migration of radon, wherein the diffusion length is replaced by the "interstitial migration distance" M, and $M \cdot n \cdot C_{max}$ is the volume of soil gas of concentration C_{max} that can be supported externally to the soil. The assumed negative pressure gradient is obtained by dividing an arbitrary pressure of -5 Pa by the hundredfold diminution distance $(4.605\ M)$, and can be calculated by an iterative procedure. The *RAN,* equal to $\mathrm{M} \cdot \mathrm{n} \cdot C_{max}$, was originally obtained from a 1-dimensional equation by Clements, 1974, for radon flux density at the Earth's surface with a constant convective velocity in addition to diffusion. The *RAN* is the product of the flux density and the mean life of radon (λ^{-1}). Alternatively the flux density is:

$$J_{RAN} = 1000 \cdot RAN \cdot \lambda_{Rn} \qquad \textbf{...(24)}$$

where: J_{RAN} = radon flux density through a soil interface to a space maintained at -5 Pa relative to the atmosphere from which the radon is continually removed (Bq m^{-2} s^{-1})

RAN = radon availability number (kBq m^{-2})

The boundary condition of negligible radon concentration at the soil interface, although appropriate for a soil surface exposed to the atmosphere, is considered unrealistic at a building foundation interface. An equation for the interstitial migration distance, allowing for a radon concentration C_0 at the boundary is given by Tanner, 1990:

$$M = \frac{1}{2n\lambda}\left[1-\frac{C_0}{C_{\max}}\right]\left\{-\frac{k_m}{\mu}\frac{dp}{dz} + \left[\left(\frac{-k_m}{\mu}\frac{dp}{dz}\right)^2 + 4\lambda n^2 D\right]^{\frac{1}{2}}\right\} - \frac{C_0}{C_{\max}}\frac{1}{n\lambda}\frac{k_m}{\mu}\frac{dp}{dz} \qquad \ldots(25)$$

where: dp/dz = pressure gradient normal to interface (Pa m^{-1}); z is positive upward; thus, dp/dz is negative if advective flow is upward.

RAN = $M \cdot n \cdot C_{max}$

It is suggested that $C_0 = 0.5\ C_{max}$ would give a realistic RAN in many conditions.

If diffusive and advective transport modes are de-coupled, simple approximate expressions can be derived for the radon availability numbers associated with advective and diffusive radon transport. For advective radon transport:

$$\text{by definition: } \frac{dp}{dz} = \frac{5}{4.605 M_a}; \quad (z \text{ is positive downward})$$

$$\therefore v_i = \frac{k_m}{n\mu}\cdot\frac{dp}{dz} = \frac{k_m}{n\mu}\cdot\frac{5}{4.605\, M_a}$$

$$M_a = \frac{1}{\lambda_{Rn}}\cdot v_i = \frac{1}{\lambda_{Rn}}\cdot\frac{k_m}{n\mu}\cdot\frac{1.086}{M_a} \qquad \ldots(26)$$

$$\text{using: } \mu = 1.8\cdot10^{-5};\ \lambda_{Rn} = 2.1\cdot10^{-6}$$

$$M_a = 1.695\cdot10^5\cdot\left(\frac{k_m}{n}\right)^{0.5}$$

$$RAN_a = C_{\max}\cdot M_a\cdot n = 1.695\cdot10^5\cdot C_{\max}\cdot\sqrt{k_m n}$$

where: $v_i = v/n$ = interstitial seepage velocity (m s^{-1})

M_a = interstitial migration distance for advective transport (m)

RAN_a = radon availability number for advective transport (kBa m^{-2})

For diffusive radon transport:

$$M_d = \left[\frac{D_m}{\lambda_{Rn}}\right]^{0.5} = 690\sqrt{D_m} \qquad \ldots(27)$$

$$RAN_d = 690 \cdot (C_{\max} - C_0) \cdot n \cdot \sqrt{D_m}$$

where: D_m = diffusion coefficient for applicable saturation ($m^2\ s^{-1}$)

Thus:

$$RAN = 1.695 \cdot 10^5 \cdot C_{\max} \cdot \sqrt{k_m n} \geq 690 \cdot (C_{\max} - C_0) \cdot n \cdot \sqrt{D_m} \qquad \ldots(28)$$

Some data associating *RAN* with indoor radon levels are available (for instance Weston, 1989, proprietary data accessed by the authors, Nielson et al., 1992), but many of the data points do not contain information on water content and porosity. Generally, the data indicate that indoor radon levels increase with increasing radon availability numbers. Data are available for sites in Florida, where construction is mostly slab-on-grade, and sites in Colorado and Virginia, where radon entry is through basements.

The test procedures recommended in this report provide data from which C_{max}, *k, and n* can be determined. The question arises how these quantities affect radon entry. It can be shown that radon entry is directly proportional to C_{max} (Yokel, 1989). Advective flux is proportional to k if there is steady-state pressure-driven flow, and proportional to $k^{0.5}$ if the flow is caused by transient pressure gradients (or fluctuating pressures) (Yokel, 1989 p.6). Even though there may be both steady-state and fluctuating (transient) pressure gradients, it is reasoned that most of the pressure-driven flow of soil gas is of a cyclic or transient nature. Thus it is reasoned that radon source potential should be a function of $C_{max} \cdot k^{0.5}$, which has the dimension of *RAN*.

The following expression fits many available data for reasonably well drained granular soils. It is similar to an expression, derived for data for glacial soils by Kunz, 1988, (Yokel, 1989), and it has the same dimension as *RAN* as derived in Eq(26). In its present form it reasonably fits other available data. Thus it is proposed on an interim basis until more empirical data can be assembled:

$$Y = 6{,}600 \cdot C_{\max} \cdot \sqrt{k\, n} \qquad \ldots(29)$$

where: Y = an index estimating indoor radon levels in multiples of 150 Bq m^{-3} (4 pCi/L)

Eq(29) is for well drained (dry to moist) conditions $(S \leq 0.5)$. For poorly drained (moist to wet) conditions, the value of k in Eq(29) should be assumed to be 2 times the calculated or measured value of k_m (it would be calculated, if an average saturation value is assumed, and measured when the natural moisture content is considered representative). For dry (arid) conditions the value of k would increase and the value of f would be reduced. These latter effects tend to compensate for each other. For this reason, the potential index is held constant for saturation levels below 0.5. Since $k \approx 2\ km$ at $S = 0.5$, the value of $2k_m$ is used for assumed saturation levels in excess of 0.5.

Eq(29) does not account for diffusion. However, an estimate of diffusive effects using the radon availability number indicates that diffusion can be significant for soils with low water contents. Thus a clay, even if it is not fissured, could have a high radon potential if it is desiccated. So could a dry silt deposit, even if its permeability is very low. One way to account for this factor is by assigning a minimum value to k in Eq(29). The value of $k = 6.5 \cdot 10^{-12}$ is proposed for this purpose. This minimum value of k can be used in the same way as permeability. Namely, if the soil is well drained $(S \leq 0.5)$ the proposed value of k is used. If the saturation exceeds 0.5 the permeability coefficient can be decreased by the following equation:

$$k_{\min} = 2\,[6.5 \cdot 10^{-12} \exp(-12 S^4)] \qquad \textbf{...(30)}$$

where: k_{min} = minimum permeability coefficient (m^2)

At a saturation level of 0.5 the minimum permeability coefficient calculated by Eq(30) would be $6.5 \cdot 10^{-12}\ m^2$.

The permeability coefficient in Eq(26) also has an upper limit. When the permeability coefficient is very large, radon entry is usually limited by the entry mechanism into buildings, rather than the permeability of the soil, and the radon activity concentration in the soil gas is reduced by atmospheric dilution (Loureiro, 1987). Examination of the data previously referred to indicates that an approximate upper limit for effective permeability is $3 \cdot 10^{-10}\ m^2$. However, in some instances very high indoor radon concentrations were recorded for relatively moderate levels of A_{Ra} (proprietary data avalable to the authors).

6 RADON POTENTIAL ASSESSMENT

6.1 Assessment of Site Environment

Environmental Factors *EF1, EF2, and EF3*

(1) Drainage conditions *(EF1)*: For well-drained conditions $EF1 = 1$. For poorly drained sites or wherever $(S \geq 0.5)$, an estimated value for S is acceptable if it is properly documented. $EF1$ is then calculated by the following equation:

$$EF1 = \sqrt{2 \cdot e^{-12 S^4}} \qquad \text{...(31)}$$

(2) Groundwater conditions *(EF2)*: If the depth to the groundwater table [D_w (m)] is more than $5EF1$ (m), then $EF2 = 1$. If $D_w \leq 5EF1$ m, then:

$$EF2 = \frac{D_w}{5\,EF1} \qquad \text{...(32)}$$

(3) Unfavorable environmental conditions *(EF3)*: Environmental conditions are considered unfavorable if: 1. prevailing wind velocities at the site are high [Exposures C and D in accordance with ASCE Standard 7-88 (ASCE, 1990)]; or 2. the climate is cold [average annual frost penetration exceeds 0.75 m (refer to Figure 1302.1,p 251, Standard Building Code (SBCCI, 1988))]. Arid climates are not considered unfavorable, and high winds need not be considered if the climate is cold. If environmental conditions are unfavorable, use $EF3 = 1.5$ (the magnitude of $EF3$ is an estimate by the authors).

Shallow bedrock:

If bedrock is within 0.3 m of basement slab, and no information on the radon potential of the rock formation is available, use soil gas extraction measurements and assume that: $C_{max} \geq 2\ C_m$ and $EF1 = 1$. If gas extraction measurements are impractical assume that: $Y \geq 1.5$.

If information on the rock formation is available, use the available information to assess radon source potential.

6.2 Calculation of radon source potential index

The radon source potential index (Y) is calculated by the following equation:

$$Y = 6{,}600 \cdot EF1 \cdot EF2 \cdot EF3 \cdot C_{\max} \cdot \sqrt{k\,n} \leq 0.07 \cdot C_{\max}. \qquad \text{...(33)}$$
$$where:\ k \geq 6.5 \cdot 10^{-12}\,m^2$$

Calculate the source potential for each sample at a given site. If more than one sample is involved, use the worst sample or a weighted average (in which case a justification is required). If radon entry was limited by 0.07 C_{max}, indicate that radon potential could be higher.

The following rating is proposed:

Proposed Rating For Sites:

Index Y	Radon Source Potential
$Y \leq 0.5$	LOW
$0.5 < Y \leq 1.5$	MODERATE
$1.5 < Y \leq 7$	HIGH
$Y > 7$	VERY HIGH

Proposed Rating for Borrow Material (Based on Bolch, 1992):

Index Y	Allowable Use
$Y \leq 0.5$	UNRESTRICTED USE (UU)
$0.5 < Y \leq 1$	FILL MATERIAL (FM)
$1 < Y \leq 2.5$	POTENTIAL RESOURCE (PR)
$2.5 < Y \leq 5.5$	BUILDING SITE RESTRICTED (BR)
$Y > 5.5$	RESTRICTED USE (RU)

Notes:

UU: Use of material not restricted in any way
FM: Can be used as fill under buildings but potential effect must be evaluated
PR: Can be used if diluted with other materials to the FM level
BR: Cannot be used as fill under buildings
RU: Should not be used near ground surface (even for landscaping)

6.3 Test Report

The test report shall contain the following information:

Table VII: Measured Soil Properties
Sample No._______ Depth, m ________
Location

Measured Soil Property	Value	Test Method Used
Dry Density, ρ_d, kg m^{-3}		
Particle Density, ρ_s, kg m^{-3}		
Nat. Moisture Content, w, %		
Dry Permeability Coef., k, m^2		
Activity Conc., A_{Ra}, Bq kg^{-1}		
Emanation Coef., f		

Soil Type:
Method of Identification:

Calculated Soil Properties:

Porosity: ____________________________

C_{max}: ________________________________

Assumed Saturation (decimal, only if $S > 0.5$) ______________________________

Justification:

____

Radon Source Potential Index (Y):

Environmental Factor(s):

EF1 ______________________________

EF2 ______________________________

EF3 ______________________________

Justification for choice of environmental factors:

____

Calculated Radon Source Potential Index *(Y)*: ____________________________

Rating of Radon Source Potential: ____________________________________

Comments:

____

7 SUMMARY AND RECOMMENDATIONS

7.1 Introduction

This report contains proposed laboratory and field test procedures which can be used to estimate the radon source potential of sites and borrow materials. Most of the procedures recommended are well established. However, the combination of spectrometry and traditional geotechnical testing procedures may present some logistical problems, because most geotechnical testing laboratories do not have the equipment and trained personnel to perform spectrometry.

It is important to draw a distinction between the proposed field, laboratory, and exploration procedures, on the one hand, and the proposed interpretation of test results on the other. While the proposed tests can be readily performed, their interpretation is based on relatively recent research data and on a limited number of data points which link indoor radon in dwelling units with the characteristics of the sites on which they are located.

7.2 Testing and exploration procedures

7.2.1 Field Exploration methods

The report contains a menu of different testing procedures and exploration methods. The choice of the most appropriate method will depend in each instance on considerations of practicality, economy, and required accuracy. For example, if a geotechnical exploration is conducted for other purposes, it may be most practical and economical to use the SPT procedure (4.3), and incorporate the radon potential evaluation in the general geotechnical exploration program at relatively little additional cost. On the other hand, for small projects and isolated sites, the high mobilization cost associated with drilling equipment would render the SPT method uneconomical. In this case, the manual procedure would be most practical. A soil sample at the appropriate depth could be taken by a relatively unskilled workman and sent to a laboratory for evaluation. However, if a trained technician and soil gas extraction equipment are available, a soil gas extraction test could be used together with the manual procedure and the need for spectrometry could be eliminated. Soil gas extraction could also be used in conjunction with an SPT exploration. Finally, with proper calibration, field spectrometry could be very economical and yield acceptable results. Figure 6 contains a flow chart for the three recommended exploration methods.

7.2.2 Variables

All or part of the following properties need to be determined:

The **radium activity concentration** (A_{Ra}, Bq kg^{-1}) can be determined by spectrometry.

The **emanation coefficient** (f, dimensionless) can be estimated or determined by spectrometry.

The **dry density** (ρ_d, kg m^{-3}) can be determined by standard ASTM methods or estimated.

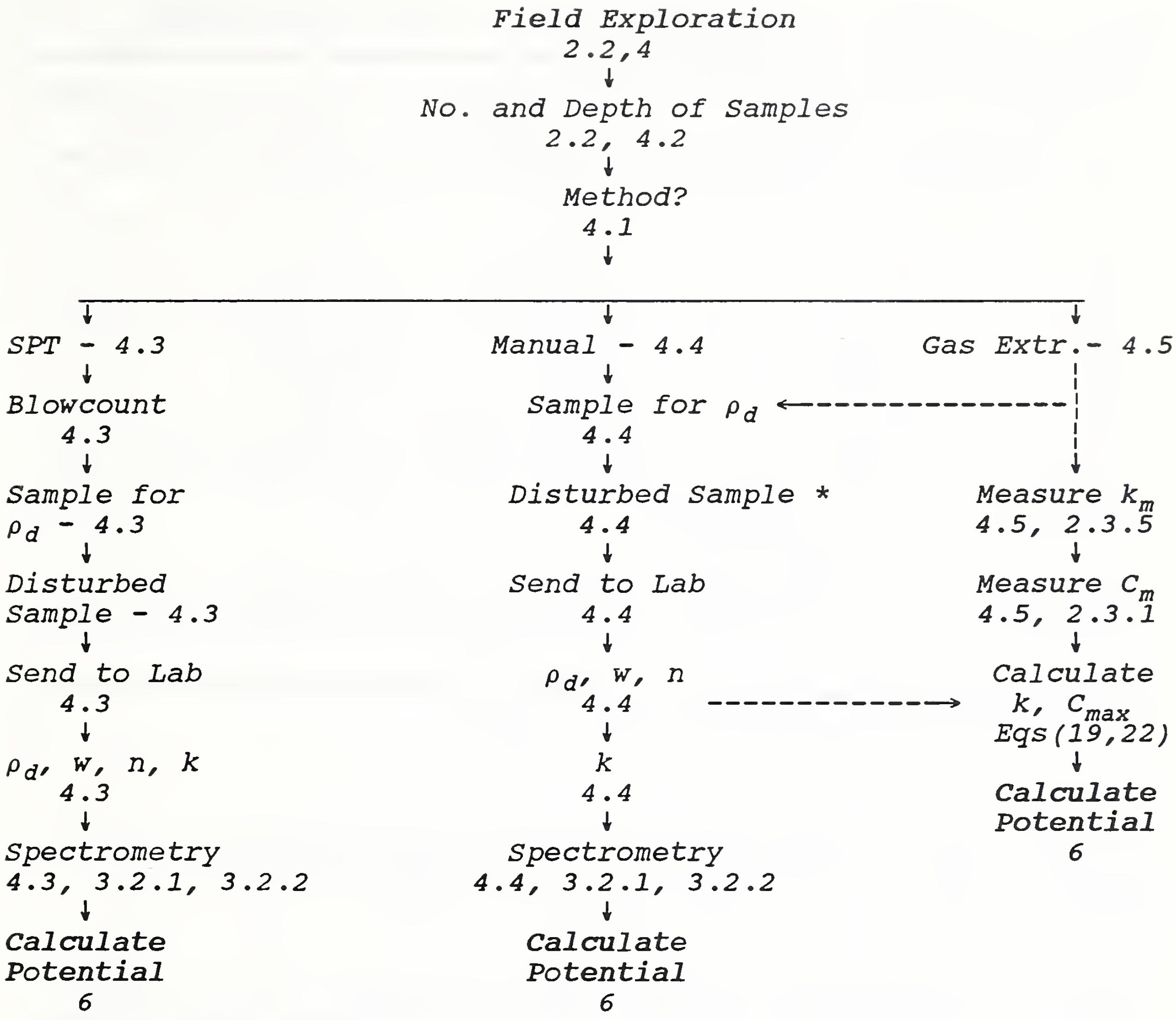
The **porosity** (n, dimensionless) can be determined by calculation based on estimated or measured soil particle density.

The **radon activity concentration in the soil pores** (C_{max}, C_m, kBq m^{-2}) can be determined from A_{Ra}, f, ρ_d, and n, or directly measured by the gas extraction or Markkanen methods.

The **permeability** (k, k_m, m^2) can be measured by soil gas extraction, calculated from particle-size distribution, or estimated from soil classification or FHA percolation tests.

The **interstitial diffusion coefficient** (D, D_m, m^2 s^{-1}) can calculated by Eq(20)

Table VIII provides a road map for the information on the variables provided in this report.



* Disturbed sample is not needed for gas extraction method

Figure 6: Flow Chart for Field Exploration

Table VIII: INDEX OF INFORMATION ON TEST VARIABLES

Test Variable	Background	Test Methods	Rating of Methods
A_{Ra}	2.3.1	3.3.1	3.2.1
f	2.3.2	3.3.2	3.2.2
ρ_d	2.3.4	3.3.3	3.2.3
n	2.3.4	3.3.4	3.2.4
C_{max}, C_m	2.1, Eq(2)	4.5, Eq(22)	see A_{Ra}, f, ρ_d, n
k, k_m	2.3.5, Figs. 2, 3. Eqs.(15,16,17,19)	3.3.5	3.2.5
D, D_m	2.3.6, Eq(20)		3.2.6

7.2.3 Radon Potential Assessment

A very simple empirical method for radon potential assessment of building sites and borrow material is presented in Section 6. The method permits consideration of environmental factors.

The empirical method presented in Section 6 is concise and requires no further summary. Graphical plots of environmental factor *EF1* on a linear and logarithmic scale are provided in Figures 7 and 8, respectively.

In addition, the exploration and test methods proposed in this report provide all the information required by other assessment protocols.

Some examples of potential assessment are presented below:

Example 1:

1. A well-drained wooded site (no exposure to high winds) has a groundwater table more than 5 m below basement level. The manual procedure was used to retrieve a relatively undisturbed sample from the bottom of a pit.

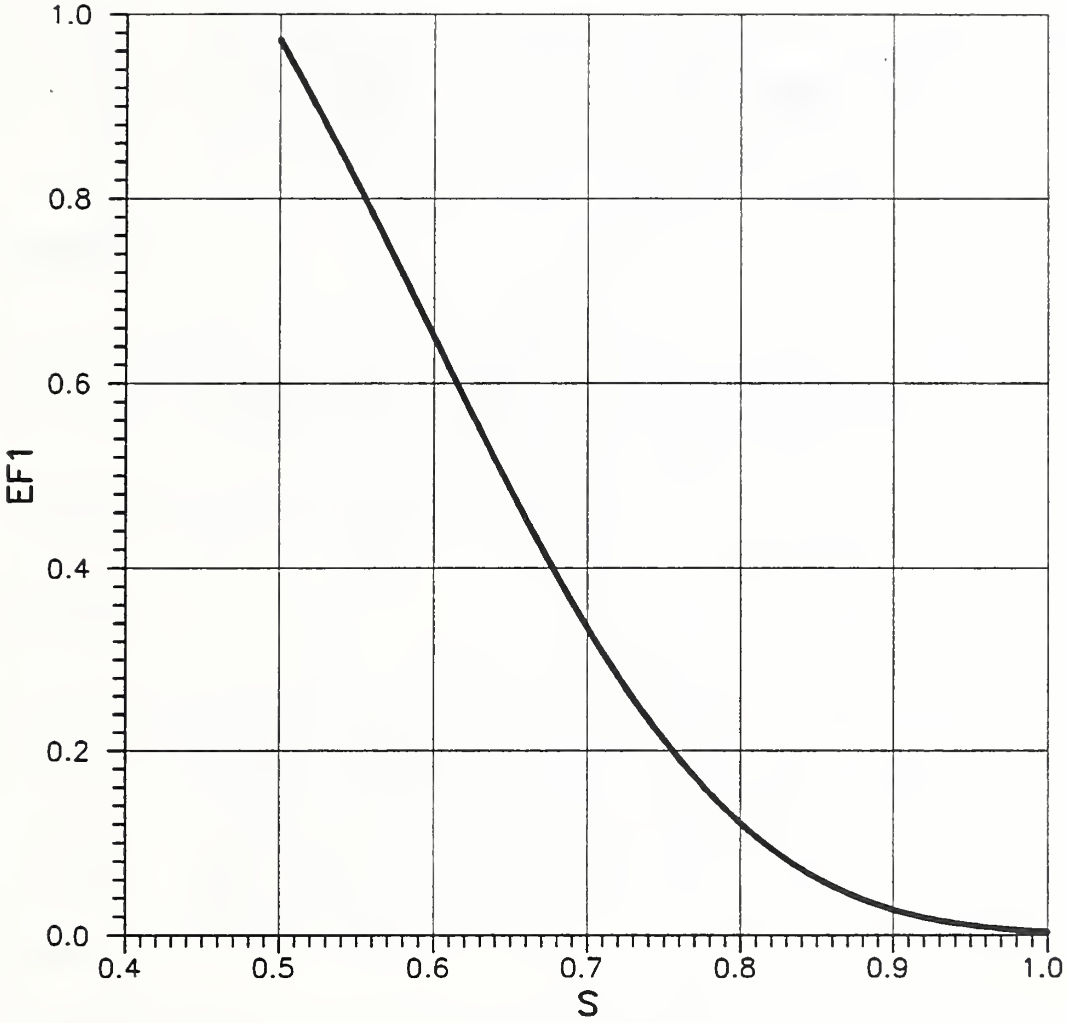


Figure 7: Plot of Environmental Factor *EF1*, Linear Scale

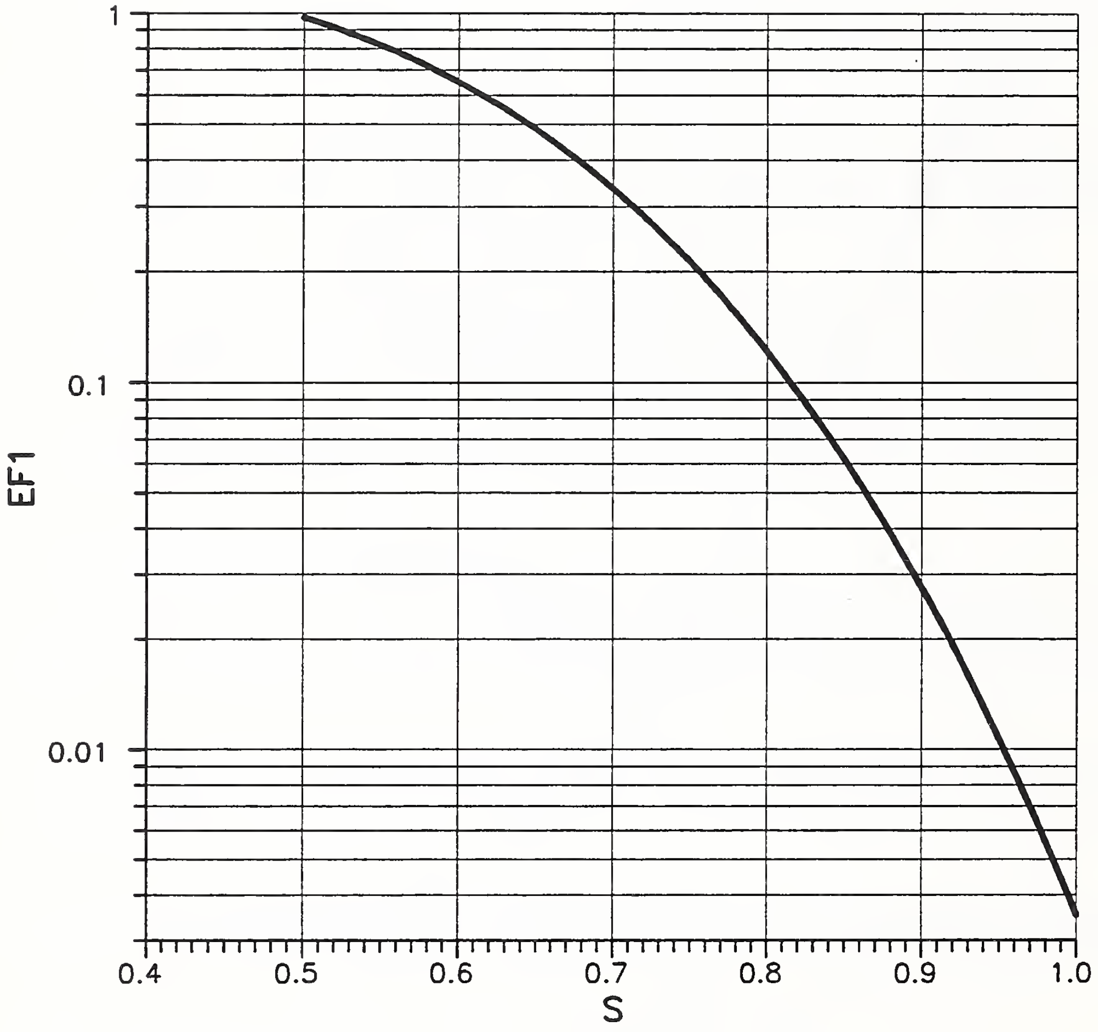


Figure 8: Plot of Environmental Factor *EF1*, Logarithmic Scale

A laboratory analysis of the sandy soil, including spectrometry and particle-size distribution provided the following data:

$A_{Ra} = 35$ Bq/kg
$\rho_d = 1{,}300$ kg/m^3
$\rho_s = 2{,}650$ kg/m^3 (estimated)
$k = 10^{-10}$ m^2
$f = 0.25$ (assumed)
$n = 1 - \rho_d/\rho_s = 1 - 1{,}300/2{,}650 = 0.509$
$C_{max} = (f\, A_{Ra}\, \rho_d)/n = (0.25 \times 35 \times 1{,}300)/(1000) \times n = 22.35$ kBq/m^3
$Y = 6{,}600 \times 22.35 \times (0.509 \times 10^{-10})^{0.5} = 1.05$
$0.5 < Y \leq 1.5$. **The radon source potential is moderate.**

Example 2:

A site has radium activity concentration and dry density equal to that of the site in example 1, but it is located on a desiccated silty clay with a k of 10^{-15} m^2. In this instance diffusion will control radon entry, so k is taken as $k_{min} = 6.5 \times 10^{-12}$ m^2.

Therefore: $Y = 6{,}600 \times 22.35 \times (0.509 \times 6.5 \times 10^{-12})^{0.5} = 0.27$.
$Y \leq 0.5$. **The radon source potential is low.**

Example 3:

A site has radium activity concentration and dry density equal to that of the site in example 1, but it is located on a well drained gravel soil with $k = 10^{-9}$ m^2. In this instance the upper limit for radon entry will control.

Therefore: $Y = 0.07\, C_{max} = 0.07 \times 22.35 = 1.56$.
$1.5 \leq Y < 7$. **The radon source potential is high.**

Example 4:

The site in example 1 is poorly drained (moist to wet). Accordingly, it is assumed that the soil is 75% saturated ($S = 0.75$).

Therefore: $EF1 = (2 \times \exp(-12\, S^4\,))^{0.5} = (2 \times .022)^{0.5} = 0.21$; $Y = 1.05 \times 0.21 = 0.22$.
The radon source potential is low.

7.3 Recommendations

It is recommended to further evaluate the practicality and cost effectiveness of the proposed testing procedures, and the validity of the proposed protocol for radon potential assessment. The following additional work is therefore recommended:

(1) Data acquisition:

Available data should be assembled, and further data should be acquired on the correlation between site characteristics and indoor radon levels. There are data which were assembled in the Florida radon study and in other EPA sponsored studies as well as data from other countries (i.e. Sweden and Finland). These should all be assembled in a data base which combines information on site characteristics which specifically addresses the variables identified in this report with information on indoor radon measurements. The radon potential assessment protocol proposed in section 6 can then be tested against the assembled data. It should be noted that many existing data points do not include information on soil water content and dry density.

(2) Study of permeability:

The data linking particle size characteristics and saturation with soil gas permeability are of recent origin (Rogers and Nielson, 1991), and are based on gas permeability tests conducted in the field, and soil tests conducted in the laboratory. Since all the data originated from in situ measurements of permeability on a limited number of sites, not all the variables could be explored. In particular, particle size distribution was not identified as a variable. The permeability coefficients were determined on the basis of soil gas extraction measurements. The accuracy of the determination of the permeability coefficients therefore entirely depends on the validity of the mathematical model used to interpret these test results. This latter model does not consider the possibility, that the permeability in the horizontal direction may be greater than that in the vertical direction. Since permeability is an important variable in the proposed protocol, it is proposed to conduct two additional studies:

1. Validation, and if necessary revision, of the correlation between particle size and permeability.

It is proposed to conduct a carefully controlled laboratory study of the following variables: arithmetic mean particle diameter; particle-size distribution (or percent fines); saturation (water content); and relative density (porosity). Particle sizes should range from gravel to silt. Permeability should be measured in the laboratory, using carefully prepared samples. Because of the many variables involved, a great number of samples will have to be tested.

2. Effects of orthotropy.

Mathematical modeling should be used to study the effect of orthotropy on (1) radon entry; and (2) air permeability measurement. In addition, Tanner's device (Tanner, 1991) or an equivalent system should be used to identify orthotropy in a number of pre-selected sites, in order to get an appreciation of the extent of orthotropy in some typical deposits (particularly those which were studied by Rogers and Nielson). It is important to develop an appreciation of the magnitude of the error introduced by assuming that orthotropic sites are isotropic. There are errors in both the permeability measurement and the assumed radon entry model. To some extent these errors may cancel each other. However, this would not be the case when permeability is calculated from particle size, porosity and saturation.

(3) Review of recommended testing and site exploration procedures.

In this study the proposed procedures should be used in the field and the laboratory in order to critically appraise their practicality and cost effectiveness. The experience gained in this way would also be used to refine, and possibly revise, some of the proposed procedures. This work can be merged with the data acquisition effort proposed in (1).

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