RADON FLUX MEASUREMENTS AS PREDICTOR FOR INDOOR RADON CONCENTRATIONS IN NEW HOME RESIDENTIAL STRUCTURES

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ABSTRACT

A method measuring vertical upwards total radon soilgas flow from the ground through building sites before construction is investigated as a predictor for the radon concentration inside a home after construction. The theory for this radon risk evaluation (RRE) is derived and simple analytical and more realistic numerical examples are given. Data obtained from short term radon tests inside homes are compared with numerical model calculations leading to additional insights that are validating empirically the derived connection between radon flux into the building and the radon concentrations. Special circumstances allowed the comparison of over two orders of magnitude of radon concentrations of finished homes with RRE radon concentrations that were obtained following a well defined protocol. Data are presented supporting the usefulness of this RRE-method as part of a radon resistant new home construction program. Conclusions are summarized.

MOTIVATION AND GOAL

If radon concentrations for indoor air in finished homes could be predicted before construction an informed decision could be made about the desirability of incorporating Radon Resistant New Home Construction (RRNC) methods during construction [1,2,3], In a few jurisdictions (e.g. Fort Collins, CO) codes have moved towards amending RRNC requirements via Appendix F of the newly adopted IRC-2000 code, or a modified version, independent of whether the house is proven to need RRNC within the framework of an accepted action level [4]. This approach, although understandable in the absence of a predictive method, is inefficient and unnecessary costly for those homes that do not need a radon system below the action level.

The proposed RRE tests can be done before the critical parts of the house are built so that RRNC methods can be incorporated to the appropriate level. If measurements are made with low results a minimum proposed RRNC method can be implemented. If measurements are made resulting in high values, maximum protection can be implemented during the construction of the building. This has the advantage that the highest efficiency for radon removal can be given to the building by a no-noise, passive,

radon mitigation system. It also means that buildings with little radon infiltration do not need to set aside extra costs for a radon system.
The goal of this research is to investigate if it is possible and if so determine the accuracy that can be achieved using a well defined protocol for the predictive nature of a Radon Risk Evaluation (RRE) based on in-situ measurements. Another goal is to develop the theoretical formalism resulting in practical graphical tools in which context these data can be understood.

CONSTANT PARAMETER THEORY

Consider a constant average entry flow rate density, which we will refer to as the radon flux density, of radon atoms, *F*, per unit of time and per unit footprint area entering a building through openings with the soil within the footprint or ground contact area, A, of the building. Consider furthermore a loss rate through natural radioactive decay by radon, Γ, into its daughter element polonium-218 with known decay time scale, τ,

$$\Gamma = \frac{1}{\tau}. \qquad (1)$$

and an average air exchange rate of inside air with outside air, G. Both loss terms will also be proportional to the number of radon atoms present inside the building, *N*. Absent other losses, a differential equation can be written down that describes the dynamic relationship between the number of radon atoms present in the building, N, its source and losses leading to the rate of change per time unit given by:

$$\frac{dN}{dt} = AF - (\Gamma + G)N \qquad (2)$$

Next we make the assumption that the air exchange rate G is determined by a time scale T during which a significant part of the air volume, say a fraction 1/e, from inside the home is exchanges with the outside air environment. Assuming furthermore that the radon in the outside air is negligible this leads to the model parameter's relationship:

$$G = \frac{1}{T}. \qquad (3)$$

The 'density of radioactivity' by radon measured in Bq/m^3, is the disintegration rate of radon nuclei and, although related, is not the same as the atomic density of radon. This radioactivity is often referred to as the 'average radon concentration' in the radon mitigation community.

$$R(t) = \Gamma \frac{N(t)}{V}. \qquad (4)$$

Similarly the "flux density of radioactivity" by radon through the footprint into the building is given by:

$$\varphi(t) = \Gamma F(t). \qquad (5)$$

In practical situations we often want to know the radon concentration on the lowest level of the building where it is frequently measured when the tester follows EPA guidelines. The relationship to the overall average concentration can be derived and can be described in terms of a simple multiplicative factor. In order to take into account appropriate weight factors for radon concentrations measured on different floors of the same building, μ_i, and the different volumes, V_i, on different floors, the radon concentration on the lowest floor compared to the average radon concentration for the total building is:

$$R_1 = MR \qquad (6)$$

with

$$M = \frac{V}{V_1 + \sum_{i=2}^{m} \mu_i V_i}. \qquad (7)$$

Depending on the type of home the described corrections can be as large as 53% for individual cases compared to other cases underscoring the significance to obtain the proper information from the blue prints of the home.

Another aspect that should be mentioned is that all equation so far have been expressed in SI-units where the radioactivity density or 'radon concentration' R_1 is expressed in Bq/m^3, all time units in seconds, all length units in meters and the radioactive flux into the building through the footprint in Bq/m^{2}s.

From a practical point of view we will often use different units that have become common place in the radon literature: R_1 is expressed in pCi/L, the time unit in hours (e.g. the inverse of the air exchange time scale G in 1/hr, e.g. "air changes per hour"), and the unit of distance in feet with the only exception that the radioactive flux into the building through the footprint is expressed in pCi/m^{2}s. These practical choices in units can be accomplished by inserting the dimensionless constant 'c' everywhere with the radiation flux, φ, in the equations, where:

$$c = \frac{3600}{305} \qquad (8)$$

When returning to the equations in SI units the constant c should simply be set to 1.

The behavior for absence of radon in the initial condition is obtained by solving equation (2) and using (4),(6) and (8) results in the familiar exponential saturation curve

$$R_1 = cM \frac{1}{(\Gamma + G)} \left(\frac{A}{V}\right) \varphi (1 - e^{-(\Gamma+G)t}) \qquad (9)$$

that can be measured in a house as the example given in Fig 1 with its initial transient time scale determined by the shorter time scale T rather than the larger time scale τ.

Eq. (9) shows that if the influx rate of radon through the footprint is known and if the time scale for the loss through the envelope of the building structure is known as well as the effective height of the building, the long term concentration in the building can be calculated. This is irrespective of whether the building has been constructed yet. This insight could make it possible to predict radon levels for buildings before their construction by measuring flux rates and deriving the other relevant parameters from architectural plans, even before the building is constructed.

The process of calculating the expected radon concentration will be named the radon risk evaluation (RRE) in this manuscript since it is an attempt to calculate the best predictor

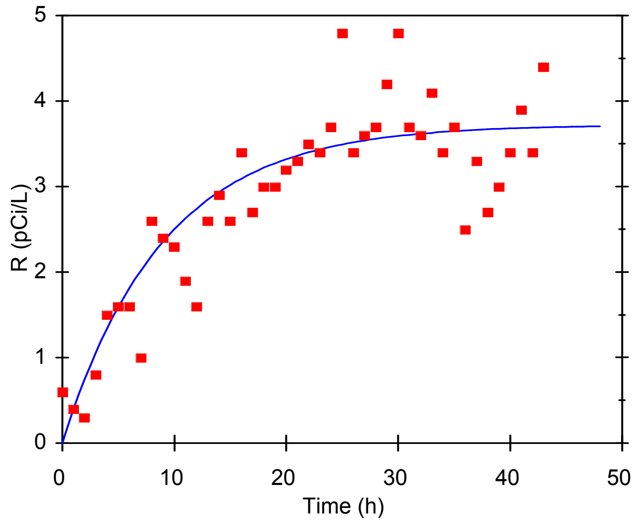

FIG 1: Data from a CRM compared with a numerically evaluated temporal behavior for an increasing radon concentration by radon trapped in a house with 1/G=T=10 hours and 1/Γ=τ=3.825 days=91.8 hours. Data taken in a house that was in open conditions before t=0 h and closed after t=0 h. Notice that the scatter of data is relatively large. This is because the radon levels are relatively low. (Data taken with femto-Tech CRM-510)

for the radon concentration in the finished building, before it is constructed. The concentration from this calculation will be referred to as the RRE concentration. The RRE concentration has the same unit as the radon concentration.

TIME DEPENDENT GENERALIZED THEORY

Generalizing the formalism for a time dependence of the radioactive entry flux through the footprint of the house, $\varphi(t) = \Gamma F(t)$, and an additional loss factor described by a strict positive function g(t) and other loss mechanisms, the differential equation governing the dynamics of the radon radioactivity measured in the lowest level of the home is:

$$\frac{dR_1}{dt} + \gamma(t) R_1 = c\alpha\varphi(t)\,, \qquad (10)$$

where

$$\gamma(t) = (\Gamma + G) + g(t) \qquad (11)$$

and where we introduced a parameter for the inverse of the effective height of the building:

$$\alpha = \frac{1}{H'} = \frac{MA}{V}, \qquad (12)$$

Equation (10) is an inhomogeneous, linear, first order differential equation that can be solved exactly yielding the general solution:

$$R_1(t) = R_1(0) + \frac{c\alpha}{f(t)} \int_0^t f(t')\varphi(t')dt \qquad (13)$$

with:

$$f(t) = f(0)e^{\int_0^t \gamma(t')dt'} = f(0)e^{\gamma + \int_0^t g(t')dt'} \qquad (14)$$

Using initial conditions N(0)=0 and f(0) =1 we will discuss a few characteristic analytical and more complicated numerical examples.

Complex looking real data can be well reproduced with a small number of degrees of freedom using this time dependent formalism. As an example we show here how we fitted a set of data that had a 24 hour cyclic behavior by using a sinusoidal behavior for the

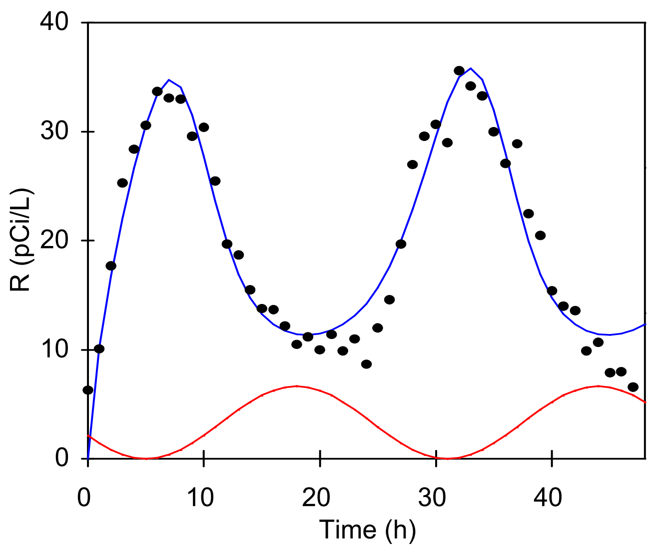

FIG. 2 Sinusoidal cyclic ventilation function (g(t), red curve) allows a good two-parameter fit with data of radon concentrations, R_1, measured with a CRM detector.

excess ventilation function, $g(t)$, and fitting the phase (time where maximum occurs) and amplitude (Strength of the ventilation rate). The resulting curve fits the data well as the resulting comparison shows in Fig. 2.

FLUX SAMPLE TEST EQUIPMENT

Measurements were made sampling the radon flux using a multiple set of H-chambers (960 ml) with short term electrets (HST) developed and produced by the manufacturer of the E-PERM system. (Rad-Elec, Inc., Frederick, MD). The half-sphere like chamber (H-chamber, hat chamber[1]) with a diameter of 6 inches has a Tyvek diffusion window instead of an open center half bottom. The chamber is vented to the sides so that it will not accumulate the radon concentration. When the H-chamber is placed on a radon emanating surface the radon enters through the bottom window and exits through the side vents. The semi- equilibrium radon concentration inside the chamber is representative of dynamic flux from the surface. The discharge rate of the electret is a measure of the radon flux. Flux monitors were calibrated by the manufacturer using well characterized radon flux beds at CANMET (Canada) using 7.7 ± 1.1 pCi/m^{2}s (Flux Units). The HST chamber-electret combinations have a sensitivity in 8 hours of 0.24 Flux Units.

A shovel and a ladder to be able to enter the space between the freshly built foundation walls were needed to set up the measurements. A carrying case was made to include all needed parts for 8 simultaneous measurements: 8 H-chambers, 8 electrets, one electret reader, roll of paper towels, one cross laminated radon shield and a writing supporting area (desk). This case was convenient in allowing us to efficiently make a single trip in and out of the building site with analysis performed in situ instead of the arduous process of multiple trips moving all attributes seperately in and out.

MEASUREMENT PROTOCOL

The *weather conditions* used for flux tests described in this manuscript are to be moderate, not wet and not extreme, See [2]. (1) We require absence of rain for at least 12 hours before the start of flux measurements. (2) We require absence of extreme temperatures for our region. (3) We require no frozen top soil conditions during the measurements (4) We require no extended period of severe wind conditions (> 20 mi/hr). (5) Tests are set up on undisturbed soil under the disturbed top layer inside the excavated basement, crawlspace or recently poured and hardened foundation walls, before the slab is poured and under the gravel fill, if possible. (6) Tests are not to be exposed during the early morning hours [5].

The *detection protocol* developed during these measurements includes: (α) Set up two tests for two hours side by side (2 inches apart), A, B, where the filter material of test A is shielded with 8-mil cross laminated radon barrier material to yield a background measurement. Test B is unshielded. Use a central location for consistent background testing and the initial scale measurement if multiple subsequent tests are done. The first set of two tests is to determine the order of magnitude of the flux density and whether the use of Short or Long term tests is advisable in the next step. Thus its function is to estimate the scale, to establish the optimal choice of the type of electrets and an estimated optimal time exposure for all subsequent measurements on this site. (β) Based on the outcome of (α) use all short or long term electrets in order to determine how much of the target area we can reach, and calculate the optimal exposure duration. Given the shape of the footprint choose a test location pattern that divides the total area in equal parts causing similar weights to the individual test results. (γ) In addition to (α) place 6 tests on a site with a footprint area up to 1500 sft and add 2 tests for every additional 500 sft footprint.

RESULTS OF RRE MEASUREMENTS

Nine residences have been investigated that resulted in RRE values of radon concentrations over a range of two orders of magnitude around the action level. The sites are named alphabetically from A to I in order to protect exact locations and home owners identities. All test locations were in three connected Counties in the Rocky Mountains and Plains area (i.e. Larimer County CO; Albany and Laramie County, WY). The Sites were chosen based on construction companies' and home owners' choice to be part of this experiment. No attempt was made in any other way to determine the radon content of the area prior to the RRE measurements except for site B and H due to special circumstances as will be explained below. Post construction radon tests were two-day, short term double simultaneous tests under closed house conditions with two E-PERM detectors identical to the EPA-protocol for real estate transactions for this device.

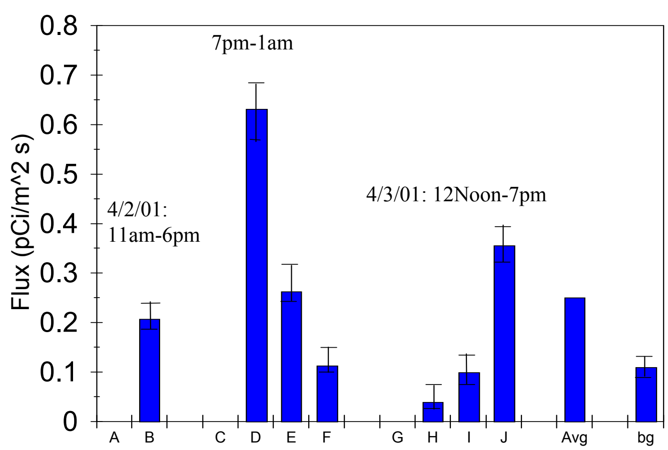

FIG 3 Radon Ground Flux measurements for site A.

As an example two residences out of the nine will here be discussed in more detail.
In residence A, a log home, (See Fig. 3) we placed the detectors on the site after foundation walls had been constructed and before the concrete slab was poured. Two detectors were used for the scale measurement (7 hours) and four detectors at one time (one background and three measurements during 5.7 hours) and the same four detectors were used the next day (6.75 hours) to avoid the early morning time period.

The results given in Fig. 3 shows a diagram with measured flux values based on standard handling of SST-electrets and manufacturers calibration of reader that is used to read the electrets. A flux measurement of this nature is based on manufacturers procedure as described in Ref. [5]. The variation among the measurements is significant as the values range from 0.038 to 0.63 pCi/m^{2}s with an average of 0.25 pCi/m^{2}s. The resulting RRE value is 1.9 pCi/L The radon concentration measured in the basement of this house later was found to be 4.05 pCi/L and above a crawlspace section 1.6 pCi/L. The bar diagram shows indeed a much lower influx of radon under the crawlspace which is measurement H. After the RRE test result was known the owner of this new home construction building opted not to install a radon system. Based on the post construction radon test the owner was satisfied with the final radon concentration and no further mitigation was requested.

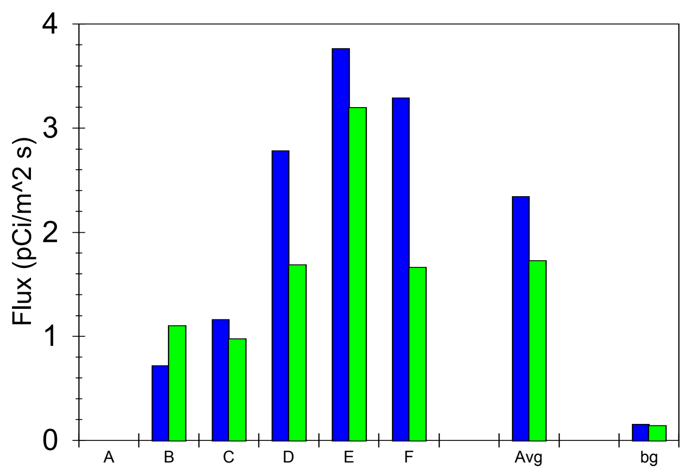

FIG 4 Example of Radon Ground Flux measurements with two sets of tests seperated by a week for site H.

Residence H provided a unique opportunity to test the RRE- radon concentration comparison. A Ranch style home without basement and sub-floor heating supply ducts built in the 1960's was tested for radon and came high (16.4 pCi/L). A radon mitigation system was proposed but its implementation was delayed. A year later the home owners decided to demolish the existing building and planned to build an entirely new residence with basement on the same Site. Flux measurements from the ground were obtained before the construction of the new building and these could be (a posteriori) compared with the measurements in the original ranch style building (that had no RRNC methods implemented). Two sets of flux measurements a week apart were performed in order to probe for the internal consistency of measurements at different times on the same site, the results are shown in Fig. 4. The first set of six flux measurements were 2.34 pCi/m^{2}s corresponding to an RRE value of 20.6 pCi/L. The second set of six measurements a week later were 1.78 pCi/m^{2}s corresponding to and RRE value of 15.2 pCi/L. Because the old home had a ranch style without basement the volume correction factor (M) was 1.00 since grade level was the lowest level.

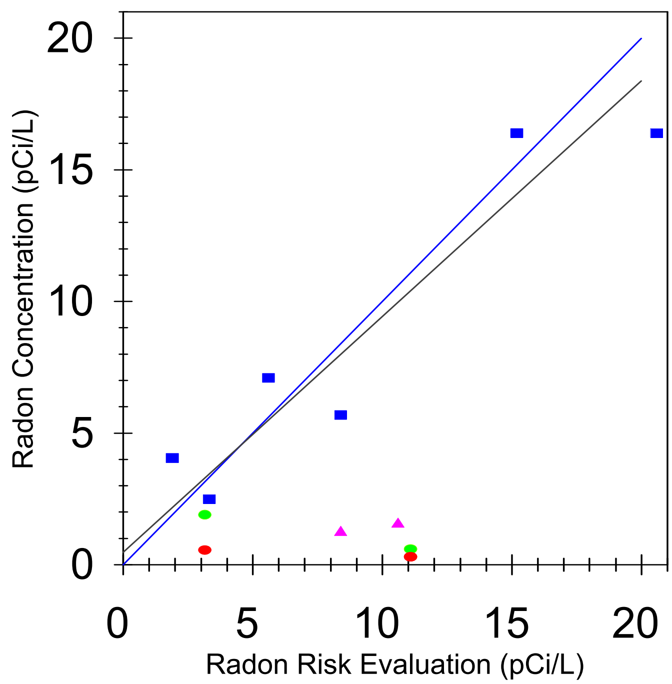

Fig. 5: Comparison via a correlation diagram for RRE measurements on sites and Radon test values in completed buildings (blue squares). Black line: best linear fit. Circles and triangles: various types of RRNC implemented.

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Fig. 5 summarizes the results in a correlation diagram comparing the predicted RRE and actual radon concentrations for homes with no mitigation installed. Only data below 20 pCi/L are shown. If the correlation had been perfect all blue squared data points would be located on the continuous line. Further analysis using the linear regression method shows that the best fit for the blue data points using the linear assumption is described by the black line (with an R-squared value of 0.89). This correlation diagram indicates a good correlation between RRE values and Radon concentrations within appropriate error bars.

In order to obtain a separation between the measured parameter, which is the average radon flux from the ground on the Site and a parameter that represents the building's construction characteristics we apply the steady state condition: $\frac{dR_1}{dt} = 0$ to Eq. (10) or by going to the long time limit of Eq. (9). The resulting linear relationship between average radon flux through footprint and average radon concentration for an individual home can be written as:

$$\varphi = XR_1 \qquad (15)$$

with X a parameter that characterizes the building dynamics under steady state radon flow:

$$X = \frac{(\Gamma + G)V}{cMA} = \frac{1}{c}\sum_{i=1}^{L} \mu_i [(\Gamma + G)H_i] \qquad (16)$$

in which the effective height of floor *i* compared to the footprint is defined by:

$$H_i = \frac{V_i}{A} \qquad (17)$$

The inclusion of the atomic decay rate Γ and ventilation rate G for closed building conditions G give X the unit of a length per time, i.e. a speed. Therefore X can be interpreted as a measure of the removal rate of radon from the building including transportation speed with which radon on the average moves through the building as well as the loss rate via decay to its daughter element, Po-218, inside the building.

This removal speed through the building thus contains the relevant building characteristics. Since the radon removal speed is specific to each building, indicated here with index *j*, we can make a graph of the measured fluxes φ_j before construction against the corresponding buildings' radon transportation speeds X_j.

In Fig. 6 we present this graph and have included all buildings (with fluxes less than 2.5 pCi/m^{2}s) for which RRE testing was done with the measured flux on the vertical axis and with the effective removal speed on the horizontal axis. In this diagram the blue squares are the data points corresponding to the various buildings discussed in the correlation diagram. Other buildings for which post-construction concentrations could not be compared with RRE values because Radon Resistant New Home Construction were applied can still be shown in this type of diagram.

At this point it is helpful to recognize from Eq. (15) that for a fixed radon concentration the relationship between flux and removal speeds is also a linear relationship:

$$\varphi_j = R_1 X_j \, . \qquad (18)$$

Thus this relationship is represented in the graph by a line through the origin with fixed slope. The red line starting in the origin marks for all transportation speeds the corresponding fluxes that result in a radon concentration of 4.0 pCi/L, i.e. it is the equi-concentration line for 4.0 pCi/L. The blue arrows mark the boundaries of the region within which the radon removal speeds of all nine buildings we studied fall, although it is not impossible for other buildings to be positioned outside these lines.

The grey arrow on the horizontal axis marks the value of the speed of radon due to diffusion through still air [5]. From the data one can conclude that the average radon removal speed for all buildings studied is larger than the radon diffusion speed and thus the vertical transportation of radon in these buildings must be of different origin. This origin is the pressure differences such as the stack effect and any other cause influencing the buildings air exchange rate with the outside environment. As an example for a ranch style home without basement the radon removal speed equals the diffusion speed when the air exchange time scale is 23 hours representing an extremely airtight home.

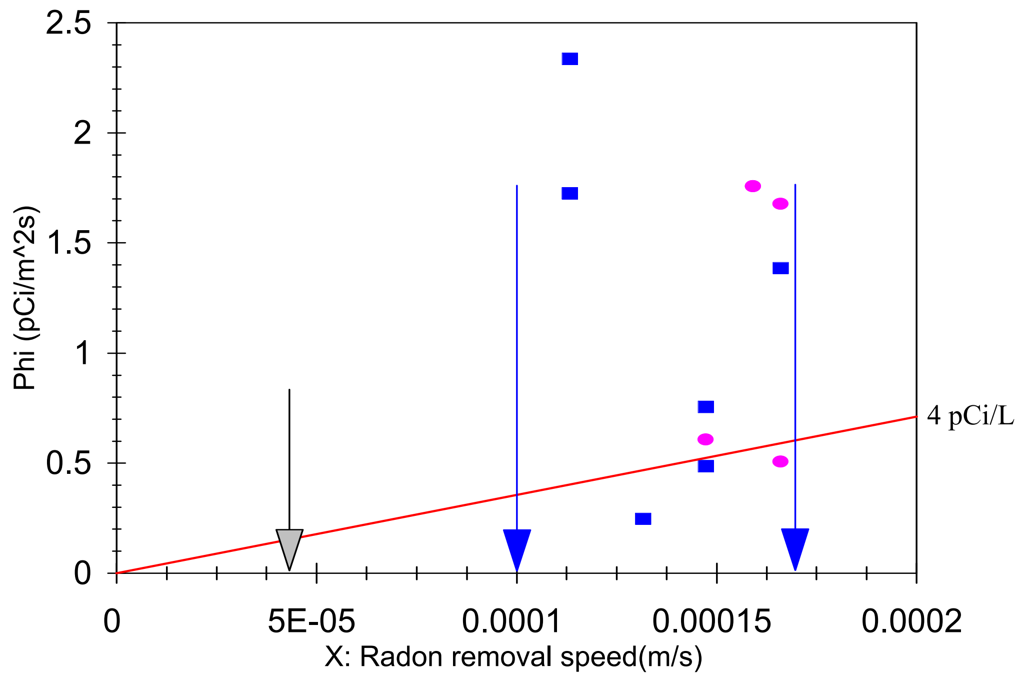

Fig. 6: Ground Flux (Radon Source) versus Radon Removal Speed (A Building Characteristic). Buildings above the line are predicted to be high after construction if no RRNC is applied.

Two (blue) data points have a flux value below the critical line of 4.0 pCi/L. These two data were buildings in which the radon concentrations were measured 4.05 pCi/L and lower. All pre-construction data points above the critical line resulted in finished buildings with radon levels well over 4.0 pCi/L, except in those cases when RRNC techniques were implemented.

The correlation diagram (Fig. 5) and the radon removal speed diagram (Fig. 6) are evidence that predictions can be made when the described method with adherence to the proposed conditions and protocol is followed, absent other abnormalities of the site not included in this study. It has been pointed out elsewhere that the gravel fill under the slab, when certain gravel pits are used, may add a substantial amount of radon to the final indoor radon concentration. Such an additional effect was not included, although it is possible to measure the radon emanation of the gravel ahead of time and apply a shift correction to the flux on the vertical axis in Fig. (6) in order to include such an effect. Other exceptions that are not included are results in KARST areas, where extremely large temporal variations can occur through naturally formed pipe and cavity structures underground.

CONCLUSIONS

In this presentation we have derived a theory that is shown to apply to radon risk evaluation concentrations of future buildings based on flux sample measurements on the pre-construction building sites. By comparing flux measurements with actual radon concentrations of constructed buildings on these sites via a correlation diagram we have investigated the practical appropriateness of this method. We conclude that in principle this is a valid method when appropriate steps are taken against extreme weather conditions that could interfere with the flux measurements. A proposed measurement protocol is given which is the protocol adhered to by us for most of the measurements presented in this manuscript. A graphical devise was analytically derived in which two independent parameters are used, the measured flux from the ground, and the radon removal speed that entirely depends on the building characteristics. It is shown that high and low predictions based on flux measurements can easily be discerned by using this diagram.

ACKNOWLEDGMENTS

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[6] *A user's guide to vacuum technology,* 2nd Ed.john F. O'Hanlon. using Table B-2 of Diffusion parameters for all other rare gasses, an extrapolation is made for Rn based on section 2.3. Based on this derived diffusion parameter a calculation of the speed of the diffusion front through still air is made following Section 2.3.3. The result is that the diffusive front through still air moves at a low speed of 4.4 10^{-5} m/s or 0.51 ft/hr.