2006 – 06

Proceedings of the 2006 International Radon Symposium
September 17 – 20, 2006

RELATIVE HEALTH RISK FACTOR COMPARISONS THAT INCLUDE ULTRAFINE RDP FRACTION MEASUREMENTS

L. Moorman, Ph.D.
Radon Home Measurement and Mitigation, Inc.
Fort Collins, CO
USA

ABSTRACT

Simultaneous measurements of total, ultrafine, short-lived radon progeny and radon concentrations have been made in homes that indicate situations can be encountered where the usual risk interpretation based on measurements of radon or radon decay products alone can underestimate health risks. The health risk interpretation used in this analysis takes into account the difference in exposure-to-dose conversion factors in the lungs for the ultrafine progeny compared to the larger aerosols with progeny attached. A diagrammatic method will be discussed in which the relevant parameters are presented in a single graph comparing these relative health risks. Relative health risk improvements accomplished by radon mitigation systems can be presented in a transparent way with help of the proposed diagrammatic technique provided a full set of parameters was measured before and after the mitigation. The equipment used and assumptions made will be discussed and supporting examples will be presented.

INTRODUCTION

Equipment that can distinguish between short term Radon Decay Products (RDP's) attached to ultrafine particles compared to those attached to larger aerosols has made it possible to calculate differences in relative excess health risks based on known differences in exposure-to-dose conversion factors. The name "ultrafine RDP" will be used here for any short-lived radon decay atom (RDP's) that is embedded into an ultrafine particle, including the possibility of having formed a semi-stable cluster with water molecules of nanoscopic size, meaning a particle which size falls in the interval 1 to 10 nm. The name "microscopic RDP" will be used for all larger size aerosols that have RDP's attached, with special interest to aerosols with sizes in the interval 0.3 to 0.5 mm.

Published results of calculations based on physical models of the lungs arriving at exposure to dose conversion factors were reported for ultrafine aerosols to be a factor 25 higher than for the larger aerosols depending on which assumptions were used for the model.[i] Included in these calculations were assumptions based on individual breathing patterns and filtering effects of entry pathways, which as was reported may have substantial effects.

www.aarst.org

Radon gas measurements as opposed to radon decay product measurements often seem to be the preferred measurement method in the residential testing environment to determine exposure of occupants. The underlying assumption for the equivalence of these measurements is that there is a self compensation effect by which with increase of the aerosol concentration the attached fraction of PAEC and the equilibrium factor increase while the unattached fraction of PAEC decreases. The result would be that the total radiation dose is constant and thus independent of unattached fraction as well as equilibrium factor so that the risk can be parametrized by the radon gas concentration alone. In a recent publication Nikezic and Yu have examined this assumption and found that self-compensation between the radiation doses of unattached and attached fractions was not fully realized and the resulting dose conversion factor can vary approximately a factor 2 for the same radon gas concentration.[ii]

More than a decade earlier, in the period 1990-1993 an activity weighted size distribution study in homes, using an epidemiological normalization factor Hopke et al. derived an overall mean value of the conversion factor that was approximately double the value assumed by the ICRP, that the ICRP had used recommending a range for the action level in dwellings.'[iii]

These factors of two uncertainty exemplify the difficulty to accurately define a guidance criterium for humans occupying their residences in terms of overall radon gas or radon decay products based on a well defined health effect for occupants. As a consequence I will simplify this discussion by confining myself to the following task under the assumptions that will be stated: In this paper assuming a linear relationship of the health risk with fixed ratio between the two dose conversion ratio's of the two modes of a bimodal RDP-aerosol distribution I want to investigate the consequence for occurrences of false negative measurements assuming a guidance criterium set in terms of exposure to total radon decay products.[iv] Using equipment that is able to make these bi-modal measurements I also want to test the frequency of occurrences for false negatives and present a diagrammatic method in order to facilitate with the final interpretation.

THEORY

There are three important observations from BEIR IV that need to be implemented in the model in order to derive at a relationship between health risk in the form of lung cancer mortality and exposure to radon decay products. First, even without radon exposure there will be a background or baseline of lung cancer mortality risk rate. Secondly, the lung cancer mortality risk rate increases but lags behind in time after the exposure occurred, and this time-lag or latency period is taken to be five years. Thirdly, the lung cancer mortality rate increases linearly with the accumulated dose during the exposure interval before the latency period allowing for time sensitive exposure (TSE) models. Implementing all three components in a single model a linear relationship between the health risk rate five years in the future, $H(t+5)$, and the cumulative exposure, $W(t)$, is thus assumed that includes a background health risk rate, B, which exists at zero progeny exposure.

It is useful to define a measure of environmental exposure for the occupant of a residence as the potential alpha energy concentration, C, (PAEC), which is the total energy density per unit volume released by all alpha particles of the short lived radon decay products of radon after they have naturally disintegrated to the metastable (long lived) ^{210}Pb isotope. The unit in which PAEC commonly is expressed is Working Level (or MeV/m^3), but we will use here the unit mWL which is one thousands of a working level (0.001WL), and which will be a more useful magnitude when dealing with homes.

Assuming in our model a constant exposure rate since time t_0, the model is a constant relative risk (CRR) model, and the cumulative exposure can be expressed in the PAEC by:

$$W(t,t_0) = \int_{t_0}^{t} C dt = C\tau$$

In which $\tau = t - t_0$ is the time duration over which the health risk increase was acquired, which itself is more than five years before the lung cancer mortality risk increases. A linear expression for the relative health risk rate five years in the future as a function of the current value of the PAEC and the exposure time interval can then be given by dividing the health risk by the background as:

$$R(t+5) = \frac{H(t+5)}{B} = \beta C\tau + 1$$

In the expression the proportionality constant β is the relative health risk rate per unit dose and unit time. This rate is assumed proportional to the slope between exposure to environmental PAEC and the absorbed energy dose from the alpha particles of the short lived radon decay products deposited directly into the sensitive lung tissue. This slope will be referred to as the exposure-to-dose ratio and is sometimes referred to as the dose conversion factor, D_β. Thus:

$$\beta \propto D_\beta .$$

The excess relative health risk rate (five years in the future) is defined as the additional contribution above unity, $E = \beta C\tau$, and can be given as a percentage of the background health risk rate.

Next we assume the Aerosol particles are separated in a bi-modal size distribution, and distinguish the ultrafine particles from the larger microscopic particles while assuming further that each of the two modes contributes to the excess relative health risk with their own rate. This can be expressed as:

$$E_U = UC_U\tau$$

and for the fraction of larger aerosols the excess relative health risk rate is:

$$E_A = AC_A\tau .$$

Here we used U as the relative health risk rate per unit dose and unit time for the ultrafine aerosols and A as the same rate for the larger, yet microscopic, aerosols.

The ratio of the two relative health risk rates per unit dose and time due to ultrafine aerosols, and due to the larger microscopic aerosols can now be defined as:

$$\alpha = \frac{U}{A}$$

Due to the definitions of U and A as the relative health risk rates per unit dose and time and their respective proportionality to the exposure to dose conversion factors for their respective particle diameters, the resulting health risk rate ratio is also proportional to the ratio of the two exposure-to-dose conversion factors for the RDP-aerosols for the respective sizes:

$$\alpha = \frac{D_U}{D_A}$$

Next we define the combined exposure rate as the sum of the two PAEC components:

$$C = C_U + C_A$$

and define the fraction of the activity of ultrafine aerosols with RDP's attached compared to the total:

$$F = \frac{C_U}{C_U + C_A}$$

Finally we define the equilibrium ratio, ε, as an inverse parameterization of the "radon concentration" ρ, which is more correctly called the "radon activity density", expressed in pCi/L, by:

$$\varepsilon = \frac{C}{10\rho}$$

Expressing the individual excess relative health risk contributions as a function of the combined exposure rate we can derive the excess relative health risks in terms of the combined exposure rate:

$$E_U = UC_U\tau = \alpha FAC\tau$$

and:

$$E_A = AC_A\tau = (1-F)AC\tau$$

This leads for the combined excess relative health risk defined as the sum of the individual contributions to the following expression:

$$E = E_U + E_A = [1 + (\alpha - 1)F]AC\tau$$

We apply this to a reference home that we choose to be a home with potential alpha energy concentration (PAEC) at the EPA guidance, C = 20 mWL, and with an equilibrium ratio of 0.5 (i.e. with a Radon Activity Concentration of 4.0 pCi/L) and for which we assume in addition that a fraction of 5% (F_0 = 0.05) of the RDP's are attached to ultrafine aerosols while the rest of the short lived RDP atoms are attached to larger microscopic aerosols. When expressing from now on in this manuscript C in mWL, as was introduced before, we can express the excess relative health risk rate for this home at the guidance condition C_0=20 mWL as:

$$E_G = [19 + \alpha]A\tau$$

We can choose this expression for a home at the guidance condition as a measure of excess relative health risk. The excess relative health risk factor for any other home can be

expressed in units E_G by taking the following ratio:

$$J = \frac{E}{E_G} = \left[\frac{1+(\alpha-1)F}{19+\alpha}\right]C$$

Notice the cancellation of the common health risk rate A and exposure duration τ by expressing the excess relative health risk relative to that of the value for a Guidance home.[v] While F_0 and C_0 are known, F and C can be measured for a particular home which leaves α as the only unknown parameter in this expression.

As an example,[vi] by taking a fixed excess relative health risk factor J, an expression for C as a function of F can be derived and these are shown in Fig. 1, where various curves are shown for fixed values of α and the vertical line marks the ultrafine fraction of 5% for a Guidance home: This figure shows the importance of knowing and implementing the value of α for the health risk interpretation. As an example it shows that for an ultrafine fraction equal to 25% and α=20 in a home having RDP's test at the guidance level (20 mWL) an increase of the health risk rate by approximately three times is predicted compared to that of a guidance home.

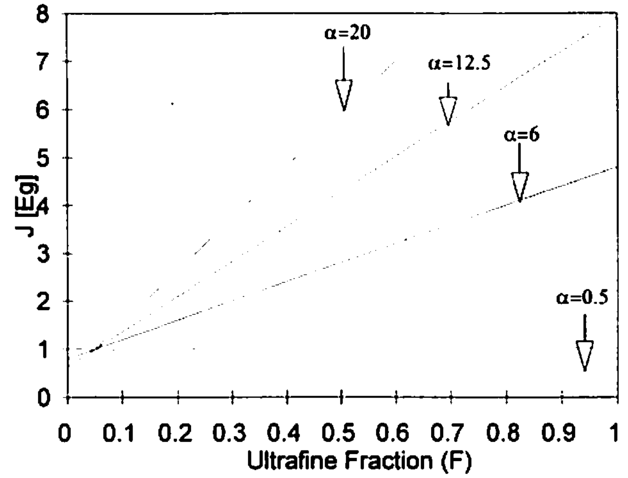

Fig 1: Dependence of the excess relative health risk factor J on the Ultrafine Fraction for C=20 mWL and for various values of the health risk rate ratio's α.

As a practical measure for this increased health risk a Risk Adjusted PAEC and Risk Adjusted radon activity can be defined based on the measured excess relative health risk factor, J, by recalculating the health effect increase in terms of the currently more familiar activity quantities. This can be done by linear scaling relationship with respect to the measured level using the risk rate $R_0 = 27\%$:[vii]

Risk Adjusted PAEC: $C_{adj} = \{1+(J-1)R_0\}C$ $[\mathrm{mWL}]_{adj}$

Risk Adjusted radon activity: $\rho_{adj} = \{1+(J-1)R_0\}\rho$ $[\mathrm{pCi/L}]_{adj}$

EQUIPMENT

Ultrafine progeny aerosol measurements (<10 nm) were made with E-RPISU equipment manufactured by Rad Elec, Inc. Such aerosols have in the past often been named "unattached fraction" to distinguish them from the "attached fraction" within the RDP aerosol distribution of which the decay products are attached to aerosol particles with larger (microscopic) diameters.

These ultrafine progeny aerosol measurements use an experimental filter and mesh comparison method by Raghavayya and Jones. Based on measurements they have used a diffusion theoretical calculation to arrive at the ultrafine progeny aerosol fraction.[viii] Their calculation was subsequently improvement by others.[ix]

The E-RPISU equipment consists of three E-PERM chambers with a single shared pump for two of the three chambers. The equipment is thus capable of measuring simultaneously radon gas concentration via a passive method and total potential alpha energy concentration (PAEC) of the short lived radon decay products and its unattached fraction via an active method. The resulting data can be processed by using an interactive communication with a website[x]. maintained by the distributor.

Simultaneous measurements of CRM (femtotech) and continuous working level monitors (TN-WL-02) have been made in all cases to verify consistency with radon and WL measurements obtained by the E-RPISU equipment. However no alternative simultaneous double measurement for the unattached fraction was available for comparison.

EXPOSURE-TO-DOSE CONVERSION FACTORS

Exposure-to-dose conversion coefficients to convert exposure to Radon Progeny potential alpha energy into the averaged dose to basal Cell nuclei in the bronchi of different subjects have been published based on dosimetric model calculations. In these it was noted that the dose per unit exposure in the "lobar/segmental" and "all bronchi" is approximately 25 fold higher for unattached progeny (AMTD approx. 0.001 µm) than it is for attached progeny with equilibrium AMTD in the range 0.3-0.5 um.[xi] Assumed nasal deposits were taken into account as well as different levels of physical exertion to arrive at these results. It was also noted that this ratio is somewhat lower for targets in the bronchioles and that for ultrafine progeny aerosols (<0.01 µm) the dose per unit exposure is strongly influenced by the assumed nasal filtration efficiency. Furthermore it was shown that the degree of clearance behavior for radon progeny has a small effect on doses calculated for secretory cell targets. Finally if basal cells were instead assumed to be the primary targets two-fold lower exposure-dose conversion coefficients were calculated for ultrafine aerosols compared to secretory cells with expected greater impact of uncertainty in clearance.

SIMULTANEOUS MEASUREMENTS OF EQUILIBRIUM RATIO AND UNATTACHED FRACTION

Measurements of unattached fractions with the equipment discussed is capable of simultaneously measuring RDP in WL and radon concentration. Measurements have been made in homes with various conventional radon mitigation systems installed as well as in a single home with various mitigation systems installed. Comparisons are made between mitigation systems on and off.

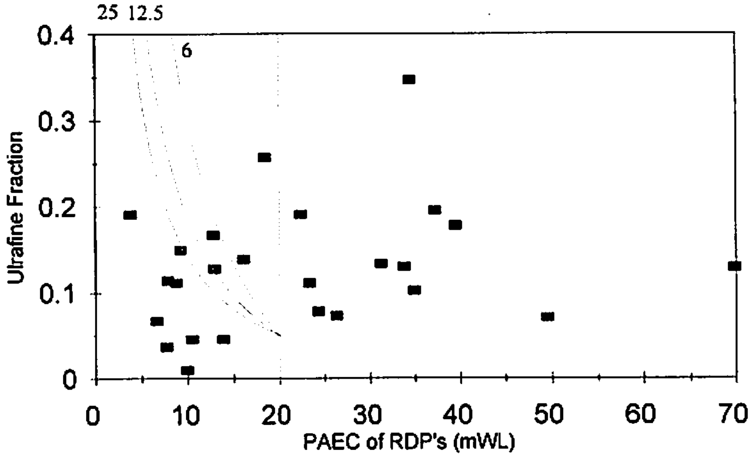

Fig 2: Measured ultrafine Fraction versus potential alpha energy of radon decay products. Purple lines mark the parameter values for a guidance home. Red curves mark positions of equal health risk to a guidance home when various values of alpha (25, 12.5, 6) are assumed.

Fig. 2 shows that the spread of data is consistent with a wide covering range of RDP's from 3 to 70 mWL and Ultrafine Fractions from 2% to 35%. The vertical line marks a guidance home with a PAEC of 20 mWL, whereas the horizontal line represents conditions of homes with an ultrafine fraction at an assumed average value of 5%. The three continuous curves represent the same excess health risk under the assumptions of the ratio of the two excess health risk rates α=25, 12.5 and 6 times respectively.
The area above the three curves and to the left of the 20 mWL mark is the area in which the excess relative health risk is predicted to be larger than the relative health risk for a guidance home despite the fact that the measured working level is below 20 mWL. The indicated area above the curve and below 20 mWL is substantial and several data points are located inside it. These are homes whose excess relative health risk is underestimated compared to the actual health risk if the increased health risk effect for ultrafine aerosols was taken into account. In this sense these homes represent "false negative" measurements.

Since radon levels as well as RDP WL measurements are known, equilibrium ratio's can be calculated and in Fig. 3 we give the values for the parameters measured. The average equilibrium ratio for these data was 31% and the spread seemed larger for the data below 20 mWL, than above it.

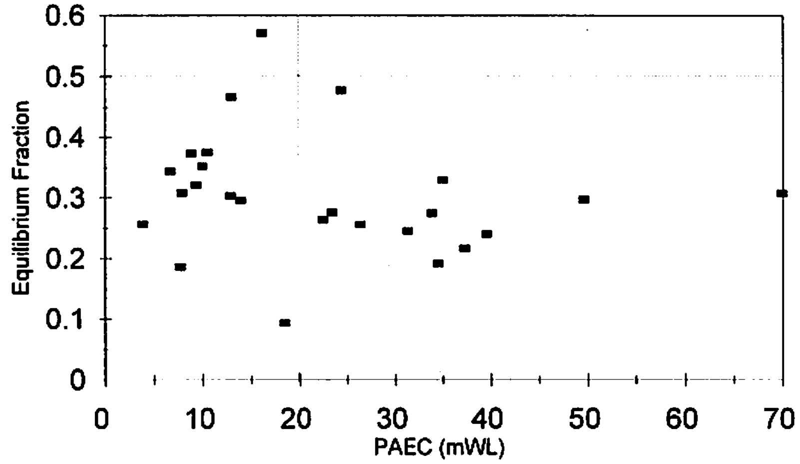

Fig 3: Measured Equilibrium Ratio versus potential alpha energy of radon decay products.

Attempts have been made to probe the relationship between ultrafine fraction and equilibrium ratio by fitting the data with a double logaritmic graph method for mines and residences. Both reported power laws for residences are indicated in Fig. 4 below as well a suggestive curve which is a fit with the same power law F~$\varepsilon^{-5/2}$ but with a different linearity factor. No theory is known that describes this behavior.

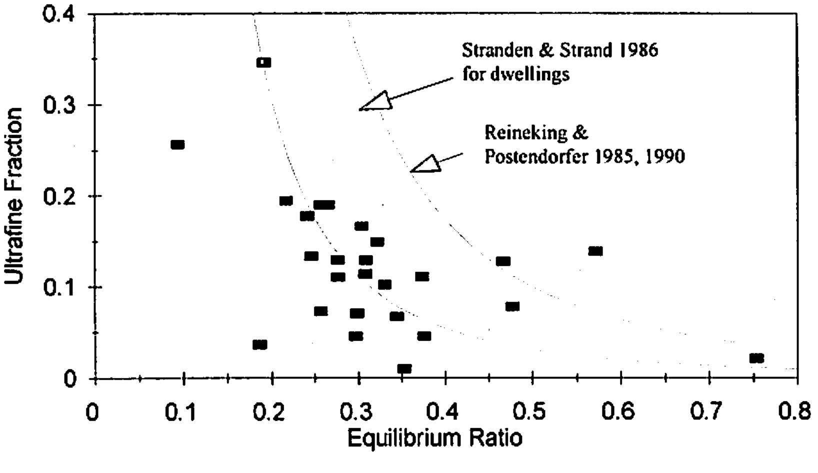

Fig 4: Simultaneous measurement of equilibrium ratio and ultrafine fraction.

A RELATIVE HEALTH RISK FACTOR DIAGRAM

The excess relative radon risk per home can be graphed diagrammatically showing the relevant measured variables at once.
We will first give the example of a guideline home which is a residence that is at the radon concentration above where the USEPA Radon Mitigation Standards recommend mitigation (Buyer's guide). It will also be our reference unit for the Relative Health measure. Such a house is modeled to have an equilibrium factor of 0.50 (ER=50%), and an ultrafine radon progeny aerosol factor of 0.05. In the figure the potential alpha energy concentration of the radon decay products is measured on the left ordinate. For reference on the right ordinate the equivalent radon activity level under ER=50% assumption is shown. The horizontal axis show the relative health risk of the total and of the two components that go into the total. The small open circle indicates that for the reference house based on the calculation discussed just over half of the health risk of the Guideline house is originating from the ultrafine aerosol fraction and almost half is from the larger particulates (solid circle). The two data points are connected by a line and the resulting total excess relative health risk is depicted at 0.02 WL and a relative health risk factor equal unity (E_g).

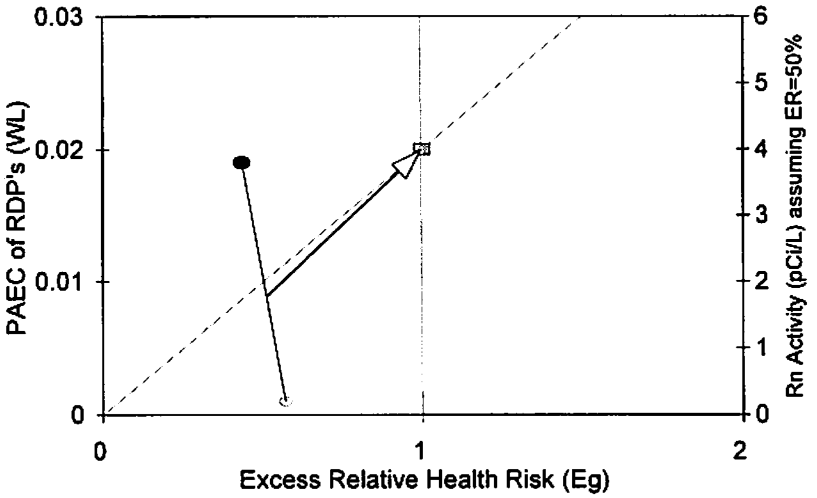

Fig 5. The Relative Health Risk as a function of PAEC of RDP's

In this diagram the diagonal line through the origin and the data point for the Guideline conditions represents the Relative Health Risk as a function of PAEC of RDP's under the EPA assumptions where no difference between ultrafine and larger aerosols is made. The line is also the demarcation line indicating that all measurements (squares) located below this diagonal line have relative health risks that are underestimated by the health risk assessment based on an RDP measurement only and vice versa. Thus under the assumptions used by the EPA all data points would always lie on this diagonal line.

We show the relative health risk diagrams comparing the situation before and after mitigation for two examples here. A factor α=25 for the exposure to dose conversion factor between "ultrafine" and "attached" RDP aerosols is assumed in the subsequent diagrams. These relative health risks will be normalized to a standard home that has a radon level at the action level, assumes an equilibrium of 50% (consistent with EPA assumption before 2001) and that has an ultrafine progeny fraction of 5%.

An example here is a special solar home that was built in the 1980's whose air exchange rate with the outside was reportedly an order of magnitude less than most other homes. The house has a solar heat storage system of 200 ton 6 inch diameter boulders completely filling a 4-foot crawl space that was located under it with intake and exhaust plenums that are two narrow crawl ducts on the two sides of this heat storage volume. Radon may have come from the soil or from the boulders. The combined surface area of the boulders in the crawl space was calculated to be very large. The estimated surface area of the boulders is equivalent to the surface area of the crawl space if it had 400 feet high walls and at the radon emanation rates of the boulder samples measured by us the a significant contribution to the measured radon concentrations in the house could not be ruled out. The heat storage volume is enclosed and no remediation of the material below the boulders seemed possible using normal active soil depressurization unless reached from the outside under the footings. Since the house was built in the mountains (at 8,500 ft altitude) this was also impractical because the house was reportedly built directly on the mountain rock. As a special feature the solar home had an internal 3000 cfm fan that could draw air through the bed of heat storage boulders as part of the solar heating system which is designed to warm the rocks up during the day and warm the house, while cooling the rocks down, at night. We performed tests with the Progeny measurement equipment in the unattached fraction mode, the E-RPISU-system, a Thomson Nielsen (TN-WL-02) and a Continuous Radon Monitor (Femtotech-510) and also with a set of two extra E-PERM's.

Results are summarized in Fig. 6. In the figure the standard guideline home is indicated with A, the solar home under normal closed conditions is B. When the 3000 cfm internal fan was used to draw air through the heat storage bed of rocks the RDP's went dramatically down and the house would have passed the RDP-criterion as it tested at 16 mWL, which is 20% below 20 mWL. However the current criterion used by us based on unattached measurements and assuming α=25 shows the house is still a factor 2.5 above the Health Risk of a Guideline home.

An Energy Recovery and Ventilation (ERV) system was installed to dilute the air lowering both radon and RDP's in the living sections of the home. The resulting value of the relevant parameters are given as D in the diagram. This house now has a relative health risk a factor two below a guidance home, as well as a factor two below 0.02 WL and with a measured radon concentration of 2.3 pCi/L is below 4.0 pCi/L, this is the case despite the fact that the equilibrium ratio has increased to 32%.

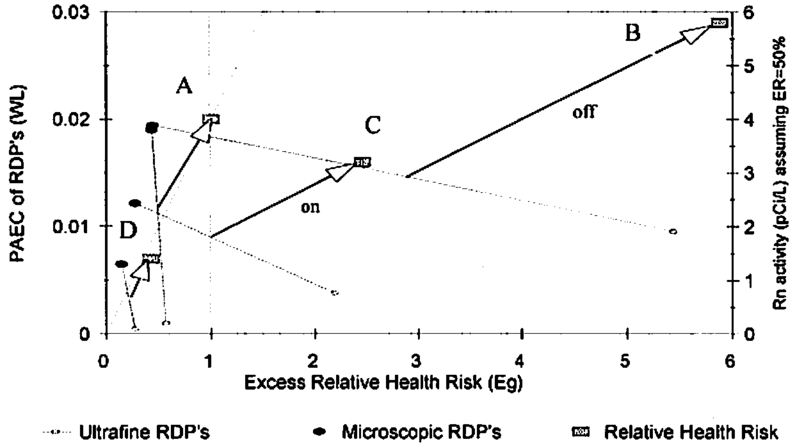

Fig 6. Solar home with full set of measurements (for α=U/A=25) . A: Guidance home for comparison, B: Solar home before mitigation, C: Solar home before mitigation with large solar fan operating, D: Solar home after mitigation with ERV system, with solar fan off.

Several relative health risk factor diagrams for measurements for sub-slab depressurization (SSD), sub-slab pressurization (SSP), energy recovery ventilation (ERV) systems installed by

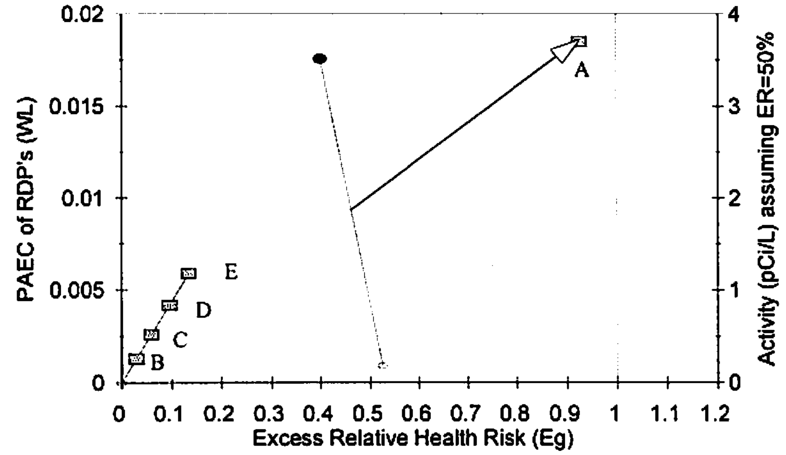

Fig. 7: Excess Relative Risk for a Home with close to guidance risk level before mitigation (A),
SSD was used with ventilators of various powers (B-E). (for α=U/A=25)

RHMM have been produced. The sensitivity of the method was probed on a home that tested close to guidance before mitigation and that tested very low after mitigation no matter which ventilator was used. The resulting diagram is presented in Fig. 7.

SUMMARY

By including ultrafine fraction measurements and a bimodal size distribution a health risk calculation can estimate excess health risks in homes relative to the health risk of a home with radon concentration at the EPA guidance level. In addition such measurements can determine more precisely the excess relative health risk reductions accomplished by radon mitigations.

In this manuscript we showed the existence of homes with excess health risks above that of an EPA-guidance home which have RDP levels below 20 mWL. A method is proposed to show the relevant set of parameters in a single diagram that built up the excess relative health risk. Measurements were done in homes before and after mitigation and the proposed diagrammatic method was used in order to display simultaneously the excess relative health risk changes accomplished by the mitigation and their relevant components.

ENDNOTES

1. Comparative Dosimetry of Radon in Homes and Mines (companion to Health Risk of Radon and Other Internally Deposited Alpha Emitters, BEIR IV), National Research Council, National Academy of Science, 1991. Panel of dosimetric assumptions affecting the applications of Radon Risk Estimates. p. 230

2. D. Nikezic, K.N. Yu, Rad. Prot. Dosim. (2005) Vol 113, No 2, pp.233-235

3. P.K. Hopke, B. Jensen, C-S Li, N. Montassier, P. Wasiolek, A.J. Cavallo, K Gatsby. R.H. Socolow, and A.C. James, Environment. Sci. Techn., 1995, 29 1359-1364

4. In our discussion we will use 20 mWL (and 50% equilibrium ratio as an example), unless otherwise stated, which was the EPA guidance level until 2002. Adjustments to the newly adopted 40% equilibrium ratio resulting in a new primary standard of 28 mWL based on the secondary standard of 4.0 pCi/L will not change the overall conclusions of this discussion.

5. If a=1 we find J=C/20 and for a 20 mWL home we would find J=1 indicating a health risk similar to the health risk of a home at the EPA Guidance level.

6. To give a scale to this excess risk a person at C0 = 20 mWL will have a yearly dose of 0.77 WLM when 75% occupancy is assumed. For this yearly dose BEIR IV p. 56 table 2.4 attributes an excess health risk over a lifetime of 40% for a non-smoking and 36% for a smoking male, and 41% for a nonsmoking and 37% for a smoking female, compared to persons of the same sex and smoking status. More recently "A Combined Analysis of North American Case Control Studies of Residential Radon and Lung Cancer", D. Krewski et al. Journal of Toxicology and Environmental Health, Part A, 69: 533-597 (2006), Taylor and Francis Group LLC, results for subjects who had resided in only one or two houses during a 25 year period in 18% at 100 Bq/m3(Exposure time window 5-30 year, Confidence Interval 2%-43%). This value can be recalculated to 27% at 4.0 pCi/L (CI: 3%-64%).

7. An excess relative health risk factor J=4 at a PAEC of 15 mWL with radon activity of pCi/L would result in a Risk Adjusted PAEC of 27 [mWL]adj and a radon activity of 5.4 [pCi/L]adj., which is larger than the EPA guideline value.

8. M. Raghavayya and J.H. Jones, Health Physics (1974) Vol 26, p 417-429

9. Kotrappa P., and Y.S. Mayya, Health Physics (1976) Vol 31, p 380-382

10. Distributor: Progeny Group Ltd. Calculations for total and ultrafine RDP's via website: www.progenygrp.com

11. "Comparative dosimetry of radon in homes and mines" a companion to Health Risk of Radon and other internally deposited alpha emitters BEIR IV. p 227-233 T Influence of Aerosol size , clearance behavior, and target cells.