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A VARIABLE AND DISCONTINUOUS SUBSLAB VENTILATION SYSTEM AND ITS IMPACT ON Rn MITIGATION

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Abstract- A house, with a high specific area in contact with earth materials, was chosen as the site for a long-term Rn mitigation study. Close to 30 000 Rn readings were collected and intensive use of statistics was made to determine locations, time periods and external parameters promoting high Rn activity. Several Rn mitigation methods were studied such as passive subslab ventilation, active subslab pressurization and active continuous and discontinuous subslab depressurization. Varying degrees of subslab depressurization were also combined with discontinuous fan activation to determine the most cost-effective method of Rn mitigation. Recommendations are for a -50 Pa subslab depressurization either on a full-time or a part-time basis. The most cost-effective method used for Rn mitigation was sealing of a slab opening. The minimum Rn concentrations were obtained, whether the opening was sealed or not, upon activation of the subslab depressurization system. The influence of cold weather and subsequent increased stack effect is clearly reflected in higher Rn concentration readings.

INTRODUCTION

Lack of adequate ventilation in a house may allow Rn and its decay products to reach levels well above the average outdoor levels. The potential primary sources of Rn in the house under study are the adjacent earth materials and existing building materials. The significant sources of Rn, as well as its primary pathways, will be examined, as will be the influence of subslab ventilation on indoor Rn concentration. Passive subslab ventilation, active subslab pressurization and depressurization will be examined as potential remediation. A simple analysis will be used to determine the potential role of each source. This will be derived from the efficiency with which a particular remedial system is controlling the Rn level in the house. Whereas in a typical house (including garage), an average volume of 500 m^3 has a 200 m^2 surface in contact with earth materials, with a subsequent specific contact surface of 0.4 m^{-1}, the house under study (including garage), has a volume of 500 m^3, with 300 m^2 in contact with earth materials and a subsequent specific contact surface of 0.6 m^{-1}. This high proportion of surface in contact with earth materials (50% higher than average) is due to the house under study being built into the side of a hill. The house design is one of slab over footing which eliminates the vertical floor/wall transition joint. It is noteworthy that the building has all its windows but one facing south, with the exception facing east. The building is to be considered very tight, with little or no cross-ventilation.

The purpose of this study is to examine the close to 30 000 Rn readings that were collected over a time period of two years ending in June 1990. Readings taken during the summer period, when windows were left open around the clock, were recorded but not incorporated in the study. The study ran from September 1988 to June 1989 and from September 1989 to June 1990.

RADON EMANATION AND EXHALATION

To study radon emanation from soils and its exhalation from building materials, a correct assessment of parent material and long-lived progeny present in these materials is necessary. The house is almost totally built of concrete. Polystyrene forms were used to shape the walls. These forms were then filled with concrete. The polystyrene remained subsequently in place and served as an internal and external insulation layer. Approximately 120 m^3 of concrete was used during construction. This includes the prestressed concrete roof of the garage which serves as floor to the kitchen but does not include patios, walkways, detached walls etc.. A concrete sample was taken every estimated 10 m^3. The twelve samples were collected, during construction, in Marinelli beakers for radiological assessment. With n=12, ^{226}Ra averaged 37.3 Bq kg^{-1}, with a standard deviation of 8.1 Bq kg^{-1}, while ^{238}U averaged 41.5 Bq kg^{-1}, with a standard deviation of 5.5 Bq kg^{-1} and ^{210}Pb was right at 80 Bq kg^{-1} with a standard deviation of 24.9 Bq kg^{-1}. Unrelated to ^{222}Rn but radiologically significant, ^{235}U averaged 1.7 Bq kg^{-1} while ^{212}Pb had a mean of 28 Bq kg^{-1}.

The highest calculated transmission fraction was for ^{214}Pb, a Rn progeny, with a photon energy of 351.9 keV. Fifty mm of concrete would have a transmission factor of 0.532 for ^{214}Pb, while ^{226}Ra would have one of 0.434 at 186 keV through 50 mm of concrete.

Soil samples taken around the house foundation revealed a ^{226}Ra concentration of 36 Bq kg^{-1}, while ^{238}U averaged 29 Bq kg^{-1} and ^{210}Pb equaled 44 Bq kg^{-1}. The ^{234}U mean was 26 Bq kg^{-1} and ^{230}Th averaged a concentration of 34 Bq kg^{-1}. The unrelated radioisotope of significance, ^{232}Th, measured 36 Bq kg^{-1}.

The slightly higher ^{226}Ra activity found in concrete does not make up for the much smaller emanation coefficient or escape to production ratio of ^{222}Rn found in concrete. It is unlikely that concrete will be found to be a major source of ^{222}Rn.

The assumption was made, subject to a revision based on observation, that the most important Rn entry process is the pressure driven flow of Rn through the substructural system (soil+slab). This is normally orders of magnitude higher than Rn entry rates from building materials, water and outdoor air. Entry rates by diffusion directly through the masonry substructure is even less (1). The Rn entry rate due to pressure-driven flow is primarily a function of a pressure differential driving this flow (2), soil Rn activity and substructural (soil+slab) permeability. Pressure differentials that activate Rn entry are, among others, the easily identifiable ones triggered by temperature differentials and combustion devices that draw indoor air needed for the combustion process.

INSTRUMENTS AND DESIGN

The ^{222}Rn activity was measured using charcoal canisters and the Working Level Reader (WLR) in conjunction with several Working Level Meters (WLM) from Eberline[1] for continuous sampling. The WLMs are really measuring the equilibrium equivalent concentration of Rn (EER), which is that activity concentration of Rn in radioactive equilibrium with its short-lived daughters which has the same potential alpha-energy concentration as the actual non-equilibrium mixture (3). This will be reported in this paper more simply as Rn activity.

The WLM provides the function of sample collection and data storage. These data points are stored in memory until retrieved by the WLR. The WLM microcomputer turns the pump on at the preset starting time, and the activity on the filter paper is counted for the total time period specified. Calibration of the WLM at the Technical Measurement Center, Grand Junction, Colorado , showed the instruments to be highly precise. Occuring inaccuracies were corrected through calibration. All the WLM readings were on the low side and had to be corrected by factors varying from 1.437 to 2.031. On the other hand, the repeatability of the measurements, no matter how originally inaccurate, yielded an average coefficient of variation of 3.19%, which is a measure of the precision of the instrument.

Subslab ventilation consisted of a network of perforated pipe installed horizontally underneath the existing slab. Such a comprehensive system is likely to provide a better performance than when a vertical pipe perforates the slab and a relatively strong pressure gradient with limited pressure field is induced.

In any case, good subslab communication is required. The subslab material consists of a 0.1 m layer of gravel with assumed high permeability. Ventilation could be passive or active. Active ventilation could result in subslab pressurization or

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[1] Eberline Instrument Corp, Airport Rd, Santa Fe, NM

depressurization and is produced by an on-line centrifugal fan well suited to conditions of moderate static pressures. The fan in use is a 90 Watt T-2 centrifugal fan from Kanalflakt[1] with a flow rate of 0.1275 m^3 s^{-1}.

STACK EFFECT

Temperature differentials produce pressure differentials across vertical walls. This pressure differential is directly proportional to the height of the walls. Making a few assumptions about temperature uniformity, the expression:

$$dp = (r*g*z*dT)/(T_i+273)$$

reflects the pressure difference at any distance z from the neutral pressure plane, with dT the temperature difference and T_i the indoor temperature. The soil gas density (in kg m^{-3}) is expressed by r while g is the acceleration due to gravity (in m s^{-2}). This expression can be simplified, after filling average values in for r and g, to reveal an average depressurization of 0.04 Pa °C^{-1} m^{-1}. In the house under study, this amounted to an average depressurization of 0.1 Pa °C^{-1}. The effect of soil temperature was considered separately.

The Rn entry rate in the bedroom, whose floor averages a depth of 2 m below the soil surface, is expressed by the equation (1):

$$E =((C*L*dp)/(V*P))*(G/(12W^3)+ACOSH((2Z)/W)/(PI*K))^{-1} \qquad (\text{in Bq m}^{-3}\ \text{s}^{-1})$$

where
V = volume of house (500 m^3)
C = soil gas concentration (40000 Bq m^{-3})
L = crack length (10 m)
G = slab thickness (0.15 m)
dp = pressure differential (1.873 Pa)
P = soil gas viscosity ($1.7*10^{-5}$ Pa s)
W = floor crack width (0.002 m)
K = soil permeability ($4.25*10^{-10}$ m^2)
Z = floor depth below soil surface (2 m)
E = Rn entry rate (Bq m^{-3} s^{-1})

The steady state mass balance equation for the corresponding indoor Rn concentration can consequently be calculated.

$$Rn = (E+(N-E/C)*Rn_0)/(N+d) \qquad (\text{in Bq m}^{-3})$$

where
N = ventilation rate (10^{-4} s^{-1})
Rn_0 = outdoor Rn concentration (4 Bq m^{-3})
d = decay constant of Rn ($2.1*10^{-6}$ s^{-1})

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[1] Kanalflakt, 1121 Lewis Ave., Sarasota, Fl.

The values in parentheses represent actual measurements, calculated averages, a derivation from measurements (such as the soil gas concentration derived from soil ^{226}Ra analyses) or a best guess (such as the ventilation rate). Accordingly, a soil would have to have a permeability of $4.25*10^{-10}$ m^2 to sustain a Rn entry rate of 0.0142 Bq m^{-3} s^{-1}, which in turn would lead to an indoor Rn concentration of 142.8 Bq m^{-3}, which is the average Rn concentration measured inside the bedroom in 1988-89. A permeability value of $4.25*10^{-10}$ m^2, although high, is indeed acceptable. Average soil permeabilities range anywhere from 10^{-16} to 10^{-7} m^2 but may be impermeable to the point of reaching values of 10^{-21} m^2, which are ideal for waste containment and are indeed the permeabilities evaluated to exist at the Waste Isolation Pilot Plant in the Salado formation in Carlsbad, New Mexico (4).

RESULTS (1988-1989)

When averaged, the Rn activity peak was found to be located at around 23.2 hrs (11.2 P.M.), while the minimum activity seemed to be centered around 10.8 hours (with standard deviations of 4.10 hours and 3.87 hours respectively). This seemed to correspond well with the computed timings of maximum and minimum depressurization. Maximum depressurization and consequent peak Rn activity seem to occur earlier than in the average home (5). This could be occuring because the heat is not controlled by thermostat and the house is mostly responding to solar heating patterns. The fact that the temperature is solely controlled by a solar heat sink could be at the origin of a maximum indoor-outdoor temperature difference occuring earlier than in a thermostat controlled home because of an early drop in indoor temperature and, consequently, earlier maximum temperature differential and the maximum depressurization that inevitably follows.

A computed depressurization of 1.87 Pa corresponded with a Rn activity of 142.7 Bq m^{-3}. The regression analysis of Rn activity on depressurization was run on the computed corresponding daily means. The correlation coefficient between depressurization and Rn activity is 0.32, which with 196 degrees of freedom (d.f.) is still highly significant (at the 1% level).

The correlation is significant at the 1% level because of the high degrees of freedom. The remarkable aspect of this regression analysis is that high depressurization was always associated with high Rn activity, although the reverse was not necessarily true. High Rn activities were also noticed at low depressurizations.

This would lead to the obvious conclusion that other factors besides thermally induced depressurization play a role in causing high Rn emanation rates into the house. Two of the factors, wind velocity and direction (6,7), and soil moisture (8), known to influence indoor Rn emanation, were not studied because of lack of equipment, although soil temperature was monitored. Because of the particular microclimate of a hillside topography, wind velocities and directions could not be assumed to be related to the ones measured at the airport, located on a plain on the other side of town. Acquisition of an anemometer and wind vane was not considered because of cost and dubious results originating from the warped topography. Cost was also a factor in not measuring soil moisture, although studies show that the emanation coefficient is strongly influenced by it. (9) show that the emanation coefficient increases nearly four times as the moisture content by mass increases from 0.2 to 5.7% to drop drastically as the soil becomes saturated.

Analysis of the Rn activity in the bedroom shows that in 64% of the cases, the nighttime average is significantly higher than the daytime readings, while in 28% of the cases daytime averages are significantly higher. In 8% of the instances there is no significant difference between daytime and nighttime averages. It is also noteworthy that in 46% of the instances, nighttime averages exceeded 150 Bq m^{-3}, while the 200 Bq m^{-3} level was exceeded 22% of the time, the 300 Bq m^{-3} level 6% of the time and the 400 Bq m^{-3} level was exceeded only once. A t-test of daytime vs nighttime means show a p-value of 0.0026 which demonstrates a very significant difference between those two averages. The maximum hourly average ever recorded was $1.33*10^3$ Bq m^{-3}.

A woodstove was ignited on 16 nights during the study period. Measurements show that Rn activity was 235 Bq m^{-3} or 164.4% of average during that period, which seems to indicate that woodstoves, or low outside temperatures, or cloudy days accompanied by snow on the ground (thereby additionally capping the soil and decreasing Rn exhalation) may be linked to an increased pressure differential.

Simultaneous depressurizations and Rn activity levels were measured or calculated simultaneously for the bedroom and the garage. Despite the fact that the garage floor was crisscrossed by shrinkage cracks, the Rn activity measured consistently lower in the garage. This could be due to a lower depressurization in the garage. If simultaneous depressurization and Rn activity readings were taken in the bedroom and the garage, time related uncertainty elements would be eliminated. In this case, the coefficient of correlation rose to 0.87 with 24 degrees of freedom (instead of 0.32 with 196 degrees of freedom where time and fluctuations thereof were a factor).

When the indoor Rn levels in the bedroom were compared to the indoor levels in the bathroom, a remarkable similarity emerged. Although the bathroom levels were consistently higher, the periods of maximum Rn activity in the bathroom and the bedroom show a high degree of concurrence with the maximum centered around 23.2 hours and r = 0.98, while the minimum centered around 10.8 hours and r = 0.95. The readings in both rooms are in almost perfect synchronization.

The Rn daughter activity, as measured with the WLM (W), is related to the Rn activity, measured with the charcoal canister (C), by the equation W = -65.8622 + 0.8439*C, with r = 0.57 and 54 degrees of freedom.

It is important to remember that even if readings were gathered every hour, all the above statistical analyses are based on computed daily averages. All the above experiments were performed with the venting system blocked off and inoperative. The subslab venting system was put in operation shortly before the annual deadline dictated by the arrival of summer (which meant a radical increase in room ventilation and subsequent Rn removal other than by quantitatively controlled means such as subslab ventilation controlled by a regulated fan).

The Rn activities, now measured by the hour because of the short study period remaining in 1988-1989, show a drastic drop when either convectional venting or active subslab pressurization was applied.

Table 1 shows the Rn activity in the bedroom before the system was in operation (I), when the system was convectionally venting or passive (P), and when the subslab was actively and continuously pressurized (A).

It is important to notice, that the data for P and A are statistically much less significant than the data for I because they cover a much shorter period of time (hours instead of days for I). It is also important to note the drastic drop in the standard deviation or the coefficient of variation (c.v.) when the system is activated.

When the subslab is pressurized, the trend of maximum and minimum activity seems to be curbed. This is reflected in the smaller standard deviation of the readings. House depressurization does not seem to influence Rn entry noticeably because of the overwhelming effect of subslab pressurization.

Four rooms were regularly checked and their Rn activity could be ranked as follows by decreasing order of activity: bathroom, bedroom, living room and kitchen. The fact that the remedial system equalizes the indoor Rn activity points the finger at the soil as the main source of Rn since the subslab pressurization only inhibits the soil gases entry but does nothing to prevent the Rn emanation from tap water and could only activate the emanation of Rn trapped in the slab. The subslab pressurization system affects Rn inhibition equally strongly in both bathroom and bedroom pointing again at the soil as the main source (water, available in the bathroom but not in the bedroom, does not seem to be a main source of Rn).

It is important to note that active subslab ventilation seems

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more effective in reducing Rn activity in the house than room ventilation.

Two remarks remain to be made. First, the effectiveness of the passive system was demonstrated by the appearance of an ice plume at the vent outlet. This can be explained by the fact that even a dry soil has a relative humidity of close to 100%. As the soil gases escape in winter, their saturation point is reached as the temperature drops. If the temperature is low enough, the condensate freezes to preserve the proof of the escape! Second, it is believed that for subslab pressurization to be effective, the system must create airflow to dilute the Rn in the subslab gas. The same problem is not faced when subslab depressurization takes place. This is why some authors believe subslab pressurization to be less effective than depressurization (10).

RESULTS (1989-1990)

NO SUBSLAB VENTILATION

During this period, the day-to-day correlation between Rn concentration and house depressurization due to temperature differential was poorer than during the previous season and was consequently found not to be significant. Only on a long-term basis could a trend be observed. The Radon concentration increased steadily from September 3 through January 12, as the average temperature continued to decrease. Figure 1 seems to indicate a strong relationship between average ambient temperature, and consequent room depressurization, and indoor Rn activity. More importantly, the Rn activity seems equally closely related to the soil temperature which plays a pivotal role in influencing the depressurization process since the house is built into the side of a hill and that differential pressure is consequently for a good part governed by soil temperature (The soil temperature underwent a steady drop during this period, which meant increased stack effect and consequent increased house depressurization followed by increased Rn intake). During the earlier part of the testing period, occasional opening of doors and windows took place as comfort requirements mandated.

To measure the impact of subslab depressurization on Rn infiltration, cyclical periods of high and low Rn concentration in the building had first to be established for that season. Daily t-tests were evaluated that showed a significant difference between nighttime and daytime Rn concentration. It was therefore determined to divide the 24 hour day (which is also a 24 readings day) into two uninterrupted halves respectively centered around a maximum and a minimum Rn concentration. Two WLMs were in uninterrupted use, out of a total of four for continuous rotation purpose. One WLM was again located in the bathroom, while the other was once more placed in the bedroom. Continuous rotation of the four WLMs took place to avoid bias. A concurrent intention was to check how well last seasons' results could be replicated.

Based on the various t-tests, it was decided to compare, in both the bathroom and the bedroom, the results obtained from 19:00 hrs to 6:00 hrs (night) against those obtained from 7:00 hrs to 18:00 hrs (day). The maximum readings (fig 2) occured around the same time period as the previous year (23.2 hrs). To check the effectiveness of subslab depressurization, it was determined to run a t-test of day vs. night on the Rn concentration obtained over a period of two and a half months in both the bathroom and the bedroom, without any ventilation taking place.

The Rn readings were again always higher in the bathroom. This was confirmed by readings obtained using Rn canisters located at regular interval in connecting rooms. The canisters were situated in the bathroom, the bedroom, the living room and the kitchen, with the bedroom, living room and kitchen canister located along an airway respectively 10 m, 20 m and 30 m from the canister in the bathroom. These readings were repeated ten times and, without any exception, the decreasing order of the activities remained unchanged: bathroom, bedroom, living room and kitchen. This seemed to indicate that the bathroom is the main entry route for Rn into the building. Although there is no ideal statistical method to express the existing relationships, some type of quantification of the strong path evidence can be demonstrated by applying a regression analysis which yielded:

$$Y = 263.9 - 5.06X \qquad \text{with } r = 0.999$$

where Y = Rn concentration in Bq m^{-3}
X = distance from the alleged source in m

Concurrent readings obtained from the WLMs showed that, without any single exception, and despite rotation of the WLMs, readings in the bathroom, which were taken during the day as well as during the night, were always higher than in the bedroom.
In both cases, day or night, the bathroom readings were more than 50% higher than in the bedroom (fig 3). Although the parallelism in the readings is as good as during the previous year, there is a greater discrepancy in the activity levels during the 1989-1990 season. This is mainly due to a strong drop in Rn levels in the bedroom.

Parallelism in the readings and, by extension, precision, can be concluded from a multiple regression analysis where one of the WLMs was chosen at random as the dependent variable whereas the three others were designated as independent variables. The adjusted coefficient of multiple determination, R^2, was found to be, after 106 consecutive measurements, equal to 0.985 (which is highly significant). The same test demonstrated further evidence of the precision through the low coefficients of variation (4.71%) existing between the various instruments in use.

A t-test performed on the Rn measurements taken in the bathroom demonstrated that for a nighttime average of 147.8 Bq m^{-3} and a daytime average of 85.6 Bq m^{-3}, the p-value was $7.6*10^{-6}$, which means that the chance that the two sets of samples (day and night) might belong to the same population (or not be different), is very slim indeed.

After applying the Behrens-Fisher correction where necessary, it was found that 80% of the bathroom readings were significantly higher at night than during the day (fig 4), while 14% of the readings did not show any significant difference and 6% of the measurements showed significantly higher daytime values (at the 5% significance level).

The t-test performed on the Rn measurements taken in the bedroom illustrate that for a nighttime average of 85.9 Bq m^{-3} and a daytime average of 56.4 Bq m^{-3}, the p-value was $4.2*10^{-5}$, which still demonstrated a very significant difference between nighttime and daytime means. The nighttime readings in the bedroom were significantly higher in 70% of the cases, not significantly different in 23% of the cases and 7% of the readings showed a significantly higher daytime reading. Table 2 compares the 1988-1989 with the 1989-1990 measurement period.

As can be seen, these Rn activities are quite a bit lower than the ones measured the year before. This is also confirmed by the Rn canister readings. One can only speculate about the effect of the sunny (and often warm) days that occured in the 1989-1990 fall and winter, causing lower room depressurization and consequent lower Rn concentrations (fig 5). Much more frequent use of the woodstove during the previous winter seemed to correspond to higher Rn activities in the house. The drop was also found to be much more drastic in the bedroom (which happens to be much closer to the stove).

The averaged daily coefficients of variation (CV) are significantly higher for daytime measurements in the bathroom (36.3% vs 25.5%) and the bedroom (35% vs 23.2%) with p-values of daytime vs. nighttime of $1.4*10^{-4}$ and $5*10^{-6}$ respectively. This shows daytime and nighttime CV to be significantly different, with daytime readings showing the highest variability, thereby indicating a higher variability in the spread of the readings recorded from one day to the next.

DISCONTINUOUS SUBSLAB VENTILATION

The active ventilation system was now used to depressurize the subslab. The depressurization time was gradually increased. The subslab depressurization was measured to be -175 Pa.

Depressurization time: 6 hours/day at -175 Pa.

The fan was activated from 0:00 hrs until 6:00 hrs. The decrease of Rn activity in the house was measured to be within one hour of start of activation, so that the time of maximum Rn activity remained at 23:00 hrs. Radon activity in the house bottomed out about 5 hours after fan activation to 35 Bq m^{-3} or less and remained near that level for about 10 hours, so that the period of lowest Rn activity did not correspond to the period of subslab depressurization.

Depressurization time: 12 hours/day at -175 Pa.

The daily subslab depressurization period lasted from 18:30 hrs until 6:30 hrs. The time of maximum activity in the house was now measured at 19:00 hrs, so that one could conclude that Rn abatement was measurable within one and a half hour of subslab depressurization. The half-day periods measuring the highest Rn activity were from 14:00 hrs until 1:00 hrs. Again, Rn activity bottomed out about 5 hours after fan activation. Although of questionable value, since the data sets are not independent, a t-test of "high" activity vs "low" activity showed that the difference was still significant.

Depressurization time: 24 hours/day at -175 Pa (from 6:00 hrs until 6:00 hrs).

Depressurization occurs from 6:00 hrs until 6:00 hrs the next morning, only to be deactivated for the next 24 hours and reactivated again the following day at 6:00 hrs. As was the case previously, fan activation caused an immediate lowering of the Rn activity with the readings again bottoming out after 5 hours and resulting further in a curve sharply reduced in amplitude. After the fan was deactivated the next morning at 6:00 hrs, a rather rapid rise in Rn activity occured at 16:00 hrs or about 10 hours after the fan was deactivated. The maximum readings obtained during the deactivation period were around 23:00 hrs. During depressurization of the subslab no trend at all was apparent.

Depressurization time: 24 hours/day at -175 Pa (from 18:00 hrs until 18:00 hrs).

Depressurization occurs now from 18:00 hrs until 18:00 hrs, ending consequently around the time that Rn activity normally starts to climb. Within a few hours after fan deactivation (at 18:00 hrs), a rapid rise in Rn activity is now witnessed (fig 6). While the subslab was depressurized, on the other hand, high Rn activity was inhibited, so that during this period, a flat curve appeared, contrasting sharply with the curve obtained after the fan was deactivated (before the diurnal peaks of Rn activity).

Since Rn levels remained low up to 10 hours after fan deactivation, it was concluded that activating the fan 12 hours/day during the period corresponding to that of highest indoor Rn activity was the most cost-effective way to use the discontinuous subslab depressurization system (at -175 Pa).

SUBSLAB DEPRESSURIZATION AT VARYING FAN SPEEDS.

It was obvious at this stage that, regardless of any remedial action taken, the bathroom measurements remained significantly higher than measurements taken in any other room. On investigation as to the probable cause,and removal of a trapdoor accessing the bathtub, a large slab opening was found. After sealing that opening with expanding polyurethane foam, only a sporadic and intermittent difference remained between the Rn concentration found in the bathroom and the rest of the house. The Rn levels now average 68 Bq m^{-3} throughout the house without any subslab ventilation taking place (average of the last 5 weeks in both the bathroom and the bedroom; table 3). Table 4 indicates the hourly maxima and minima obtained under varying circumstances. It is noteworthy that subslab depressurization results are not significantly different if measurements are taken before or after sealing of the slab opening.

Investigation of the influence of varying subslab depressurization on Rn concentration indicated that after sealing the slab opening, no drastic decrease in indoor Rn activity took place beyond -50 Pa depressurization, which is the smallest depressurization attainable through fan activation (Fig 7). The influence of warmer weather and subsequent decreased stack effect can be seen once more as time progresses. Weekly measurement cycles featuring daily increases in depressurization (from 0 to -175 Pa) show a trend of decreasing Rn concentrations as weeks (wk) progress towards springtime (table 3). Subslab depressurization appears to be effective if the fan is activated during the peak Rn activity hours (18:30 hrs until 6:30 hrs the next morning). Practically no activity occured until the fan was left deactivated during the peak Rn activity period (fig 8).

CONCLUSIONS

Probably the most cost-effective method used for Rn mitigation was the sealing of the slab opening under the bathtub. For research purposes, it was a boon that such action took place late in the study. Results show that indoor Rn activities were strongly dampened after sealing the slab opening and some relationships even disappeared totally thereafter (Such as the distance from "source" and Rn activity relationship).

The intermittent activation of the fan shows that the Rn mitigation is effective, in most cases, long after fan deactivation, showing a certain degree of "exhaustion" of Rn as a soil gas (probably replaced by atmospheric gases). This rule does not seem to apply if fan deactivation occurs around the time that indoor Rn activity normally starts to climb.

Equally low Rn concentrations could be obtained with the depressurization system in operation, regardless of whether the slab opening was sealed or not.

Before sealing the slab opening, decreases in Rn activity of 95% were obtained through subslab depressurization (at -175 Pa) because of the high initial Rn concentration. A noticeable drop in temperature (-2°C) was also experienced when the system was fully depressurized. After sealing the slab opening, it appears that the increased benefits obtained from running the fan at full speed are marginal and that an overall decrease in Rn activity of 85.3 % of maximum (obtained at a subslab depressurization of -175 Pa) can be obtained by running the fan at -50 Pa. Due to the much lower initial Rn concentration, this only amounts to a decrease of 51.6 % of the incipient Rn activity. A t-test shows no significant improvement to be obtained by depressurizing the subslab at -175 Pa instead of -50 Pa (p-value :0.033). A satisfactory reduction in Rn activity was obtained by depressurizing the subslab at -50 Pa for only 12 hours/day during the peak Rn activity hours (18:30 hrs until 6:30 hrs).

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REFERENCES

Journal 1. Mowris, R. J. and Fisk, W. J. Modeling the effects of exhaust ventilation on ^{222}Rn entry rates and indoor ^{222}Rn concentrations. Health Physics Vol. 54 No. 5 pp. 491-501, 1988.

2. Nazaroff, W. W. Entry by pressure-driven flow or molecular diffusion? A reassessment of Rn concentrations measured in an energy efficient house. Health Physics Vol 55: 1005-1014; 1988.

3. Swedjemark, G. A. and Makitalo A. Recent Swedish Experiences in ^{222}Rn Control. Health Physics Vol.

58 No 4 pp 453-460, 1990

Report 4. Lappin, A. R. and Hunter, R. L. Systems Analysis, Long-Term Radionuclide Transport and Dose Assessments; Waste Isolation Pilot Plant (WIPP), Southeastern New Mexico; 1989; SANDIA REPORT SAND89-0462*UC-70; DOE contract DE-AC04-76DP00789

5. Hall, A. Unpublished Rn data from New Mexico Environmental Improvement Division taken from over 250 houses in Northern New Mexico, 1986-1987.

Journal 6. Jonassen, N. On the effect of atmospheric pressure variations on the Rn concentrations of unventilated rooms. Health Physics Vol 29:216-220; 1975.

7. Stranden, E. and Berteig, L. Radon in dwellings and influencing factors. Health Physics Vol 39: 275-284; 1980.

8. Schery, S. D.; Gaeddert, D. H. and Wilkening, M. H. Factors affecting exhalation of Rn from a gravelly sandy loam. J. Geophys. Res. Vol 89: 7299-7309; 1984.

9. Strong, K. P. and Levins, D. M. Effect of moisture content on radon emanation from uranium ore and tailings. Health Physics Vol. 42 No 1 pp. 27-32,1982.

Symposium 10. Henschel, D. B.; Scott A. G.; Findlay, W. O. and Robertson, A. Testing of indoor radon reduction methods in 16 houses around Dayton, Ohio. 1988 symposium on radon reduction technology. Denver, Colorado.

Table 1: Rn activity (Bq m^{-3}) in 1988-1989

System	Mean	Std. Dev.	d. f.	c.v. (%)
Inactive	142.7	66.5	196	46.6
Passive	82.9	38.6	166	46.6
Active	30.6	6.66	200	21.7

Table 2: Comparison of Rn concentrations in bedroom (E) during 1988-89 and during 1989-90 and in bathroom (A) during 1989-90

	88-89(E)	89-90(E)	89-90(A)
Xn (Bq m^{-3})	155	85.9	147.8
Xd (Bq m^{-3})	129	56.4	85.6
p-value	$2.6*10^{-3}$	$4.2*10^{-5}$	$7.6*10^{-6}$
Xn > Xd (%)	64	70	80
Xd > Xn (%)	28	23	6
no difference (%)	8	7	14

Table 3: 0 to -175 Pa consecutive (8) weekly depressurization cycles and their influence on Rn (in Bq m^{-3}). (A refers to bathroom and E to bedroom)

Depress.(Pa)	0	-50	-75	-100	-125	-175
Rn (A)	138					25.0
" (E)	132					19.6
" (A)	122					36.5
" (E)	128					24.2
" (A)	190	43.5				
" (E)	167	35.0				
" (A)	92.9	35.0	40.1	38.2	35.6	36.4
" (E)	87.9	39.1	45.0	39.0	34.8	36.3
" (A)	51.0	36.0	32.7	40.5	38.7	31.0
" (E)	44.9	28.6	25.6	33.9	33.9	25.4
" (A)	65.2	43.0	35.9	43.7	40.7	26.9
" (E)	52.7	35.6	28.3	34.6	33.3	21.5
" (A)	83.3	31.6	34.7	37.7	29.2	25.6
" (E)	73.9	27.0	32.0	34.5	26.8	22.5
" (A)	73.1	28.4	30.6	29.5	38.9	31.0
" (E)	50.7	24.7	23.6	22.6	29.1	24.1

Table 4: Hourly extremes (in Bq m^{-3}):

	Max	Min
Before sealing	1330	37
After sealing	299	12.3
-175 Pa depressurization	50.8	2.73

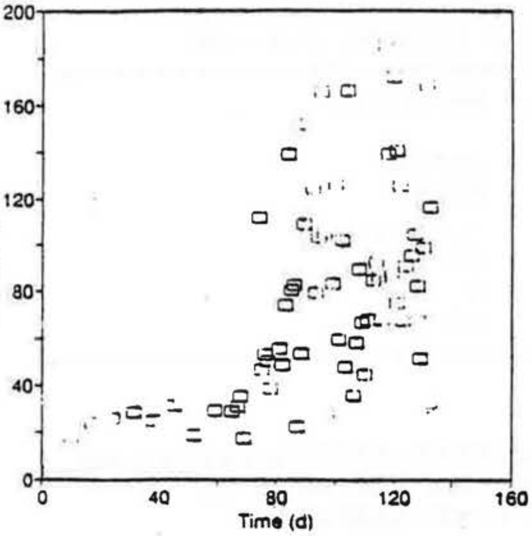

Fig. 1. Rn Levels as a Function of Time (Day 1 = 3 Sept 1989)

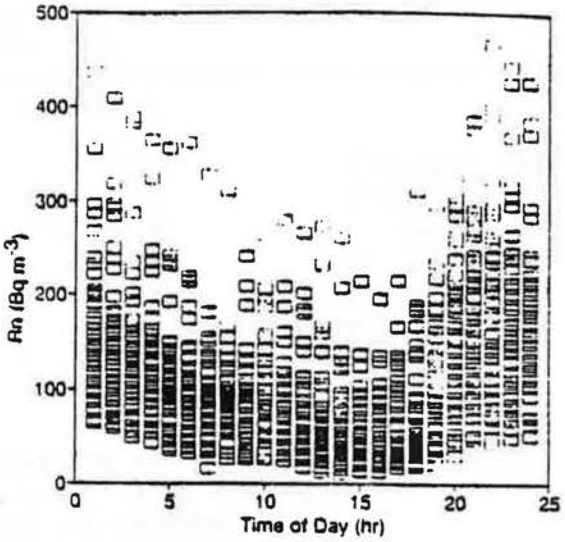

Fig. 2. Hourly Rn Levels (Winter 1989-90)

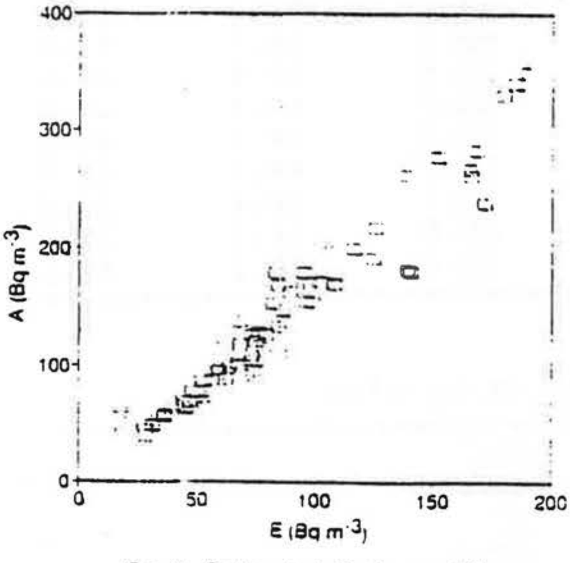

Fig. 3. Rn Levels in Bathroom (A) vs. Bedroom (E)

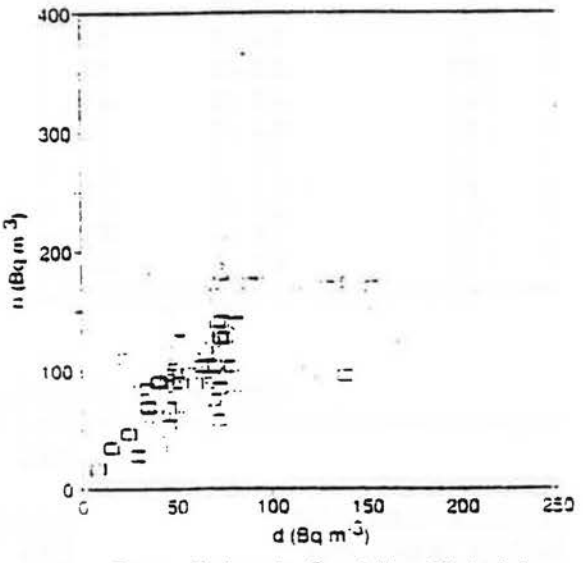

Fig. 4. Rn Levels, Day (d) vs. Night (n)