An Energy Efficient Approach for Radon Management
Part II: Radon Modelling and Evaluation

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ABSTRACT

This paper reports on the experimental results using a standard room chamber to evaluate the impact of various parameters on indoor radon concentrations. The paper assesses the suitability of using pre-existing mathematical models for the prediction of indoor Volatile Organic Compounds (VOC) to estimate radon concentrations in the heating, ventilating and air-conditioning (HVAC) environment. A test chamber study was conducted to thoroughly evaluate and validate parameters considered in these models. A modification factor to account for the indoor sinks was determined and was utilised to enhance the accuracy in applicability of the pre-existing models. The results indicates the modified radon prediction model is capable of correlating well with field data and appears to be applicable to other HVAC environments.

INTRODUCTION

The project involved development and formulation of a radon level predictive model in a HVAC environment. Initially, it focused on locating different models commonly used in assessing indoor air quality (IAQ), from the simplest to the more complex models. Two models which are generally used for indoor VOC and radon researches were finally identified. However, the VOC model was subsequently selected since it appeared to be more compatible under our research condition in better correlation with the field data. Modification of this model was undertaken to accurately reflect the environment under study. The process of model identification and verification also employed computer simulation techniques. The developed radon level predictive model was found statistically fit for used in other similar facilities in future. Other researches may further explore the capability of model.

MODELLING

Radon Level Predictive Model during Ventilation-off-hours

By considering the inert gas characteristics during the period of indoor radon accumulation, the radon emission rate (R) from the surrounding surfaces of the experimental room chamber can be estimated by using the commonly adopted mathematical model introduced by Nancy F. Roache, et. al. in 1996[1][2]:

$$R_{(t)} = (dC_{(t)}/dt + NC_{(t)})/L \qquad ...(1)$$

Where,

t	*Elapsed time (variable) during experiment*	*(hrs)*
$C_{(t)}$	*Indoor Air concentration measured at any time t during experiment*	*(Bq/m^3)*
S	*Surface area of room chamber selected for experiment*	*(m^2)*
V	*Volume of above room chamber*	*(m^3)*
L	*Loading factor of room chamber, $L = S/V$*	*(m^2/m^3, /m)*
A	*Fresh air volume per hr, $A = 360U*F$*	*m^3/hr*
$R_{(t)}$	*Emission rate from chamber surfaces at t*	*($Bq/m^2/hr$)*
N	*Fresh air exchange rate, $N = A/V$*	*(ACH, /hr)*
k	*Source decay rate*	*(/hr, per hr)*

Assuming $N = 0$, $NC_{(t)} = 0$, the mathematical model was transformed into:

$$R_{(t)} = (dC_{(t)}/dt)/L \text{ and } R = (C_{(t)}-C_o)/Lt$$

$$\text{So, } C_{(t)} = C_o + RLt \qquad ...(2)$$

$C_{(t)}$	*is also the accumulation concentration exhaled from walls at any time t;*	*(Bq/m^3)*
R	*Source emission rate*	*($Bq/m^2/hr$)*
C_o	*is the initial air concentration in the room chamber*	*(Bq/m^3)*

This mathematical model (2) was used to calculate the R in our experiments.

Radon Level Prediction Model during Ventilation-on-hours

After a series of model investigation exercises in conjunction with dilution of indoor pollutants within a single room environment, two models appeared to be applicable:

(A) *MODEL "A"*

Mathematical model introduced by P.A. Lawless (1996)[3] was presented in Figure 1. By estimating $\underline{RS}_{(t)}$ of VOC was in the climate chamber:

$$\underline{RS}_{(t)} = \underline{RS}_o \exp(-kt) \qquad ...(3)$$

Where:

$\underline{RS}_{(t)}$ is source strength as a function of time (mg/hr),
$\underline{RS}_o$ is the initial source strength (mg/hr), and
k is the source decay rate of VOC (/hr).

The model which predicts a corresponding time-dependent chamber concentration $C_{(t)}$ is:

$$C_{(t)} = \frac{RS_o}{V(N-k)}[\exp(-kt)-\exp(-Nt)]+C_o\exp(-Nt) \qquad ...(4)$$

V *is the room chamber volume (m^3),*
N *is air exchange rate (/hr), and*
C_o *is the initial chamber concentration (mg/m^3).*

As $\underline{RS} = R*S$ and $L = S/V$, , the C_{in} existed and the mathematical model (4) was adjusted to reflect our experimental conditions:

$$C_{(t)} = \frac{RL}{N-k}[\exp(-kt)-\exp(-Nt)]+(C_o-C_{in})\exp(-Nt) \quad +C_{in} \qquad ...(5)$$

C_{in}: is the background concentration of incoming outdoor air (Bq/m^3);
k: Source decay rate (/hr).

The adjusted model (5) was used to analyse our field data for evaluation.

(B) *MODEL "B"*

Similarly, another mathematical model, introduced by D. Capra et.al. in 1994, was used to evaluate the radon concentrations, $C_{(t)}$ in a test chamber[4]. The result is presented in Figure 1. This mathematical model was adjusted to account for same parameters as in model A for comparison purpose.

$$C_{(t)} = \frac{RL + NC_{in}}{N+k}\{1-\exp[-(N+k)t]\}+C_o\exp[-(N+k)t] \qquad ...(5a)$$

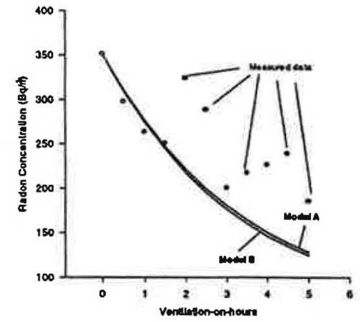

Figure 1. Comparing Models A and B (N = 0.30)

From the result of comparison, it was observed that Model A matches better than B.

MATERIALS AND METHODS

The Room Chamber

The experimental room chamber selected for this study was a typical office with HVAC service, located one floor above ground level of the HKUST campus building. Its dimensions measured 4.95m long, 2.77m wide and 2.85m high. With floor coverings and sealed windows, the effective surface area, S, was computed as 70.8 m^2 and the loading factor, L (S/V ratio) at 1.81 m^2/m^3. A fresh air supply duct was adjustable both in outflow velocity U (m/sec) and area F (m^2), the fresh air exchange rate N (ACH or Air Change/Hour) can be varied from 0.25 to 4 ACH. With this typical room set-up, radon emission rates ($Bq/m^2/hr$) obtained during the experiment can be used to simulate other HVAC environments of HKUST.

Measurements for Indoor Radon Concentrations

The measurement instrument was the time-integrated continuous monitoring device known as "RAD7 professional continuous radon gas monitor (RAD7)" made by the U.S. Niton

Corporation. The RAD7 was set up at the centre of room chamber, about one meter from floor and one meter away from walls, HVAC inlets and exhausts. Measurement frequency is 30 minutes a cycle, 48 cycles a day.

Investigated Items and Indicators

Parameter	*Description of items and Indicators*	*Units*
C	*Radon concentration taken during experiment*	*Bq/m³*
t	*Elapsed time (variable) during experiment*	*hrs*
S	*Surface area of room chamber for experiment*	*m²*
V	*Volume of room chamber*	*m³*
L	*Loading factor of room chamber, L = S/V*	*m²/m³, /m*
R	*Radon emission rate from chamber surface*	*Bq/m²/hr*
U	*Flow velocity of HVAC inlet*	*m/sec*
F	*Cross-sectional area of HVAC inlet ducting*	*m²*
A	*Fresh air volume per hour, A = 3600 U*F;*	*m³/hr*
N	*Fresh air exchange rate, N = A/V*	*ACH, /hr*
k	*Source decay rate*	*/hr, per hr*
T	*Air temperature in room chamber*	*°C*
H	*Humidity in room chamber*	*%*
P	*Air pressure*	*mm Hg.*

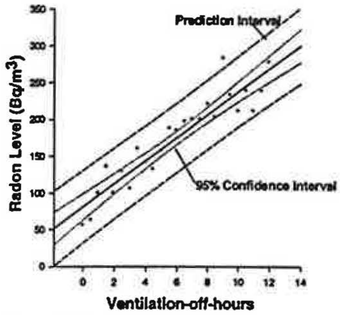

Figure 2. Regression for an individual period

Measurements for Other Indicators

Fresh air exchange rate (N) was measured by the U*F/V method. Flow velocity was measured by the U.S. VeloclCalc Model 8350-1 anemometer. Temperature and humidity were measured by thermo-hygrometer (Model RS 212-540). Atmospheric pressure was measured by Gischard Barometer, made in Germany. In these experiments, room temperature was 22.41 +/- 1.40 °C, room humidity 57.2 +/- 5.98 % and atmospheric pressure 756.4 +/- 1.1 mmHg etc.

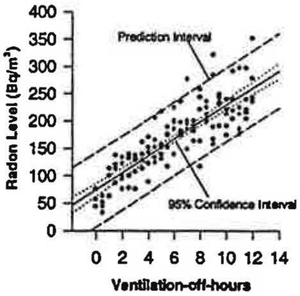

Figure 3. Regression for All Periods

Experimental Schedules for Vent-off-hrs

Experiments for ventilation-off-hours were conducted for 12 hours either from 17:00 pm to 5:00 am or 19:00 pm to 7:00 am. Ventilation parameters included 12 vent-off-hrs and 12 vent-on-hrs. The measurements for C, t and T were continuously measured and recorded according to RAD7 instructions. Final measurements were recorded for those successful experiments conducted in 5 consecutive nights.

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RESULTS

Experimental Results for the period of Ventilation-off-hours

The regression model for the experiments fit the observed data very well ($r^2 = 0.74$, $r = 0.86$, $p<0.01$). Figures 2 & 3 show the data plots for a selected period and all periods resp. As $Y = a + bX$, so $Y = C_{(t)}$ and $X = t$. The data was found to be in linear regression, so, $C_o = a = 73.82$ (Bq/m3), $R=b/L=15.57/1.81=8.6$ (Bq/m^2/hr). If t=12(hours),$C_{(12\,hrs)} = 260.61$ (Bq/m^3).

Experimental Results for the period of Ventilation on-hours

The result of these experiments are summarised in Figure 4 and Table 1.

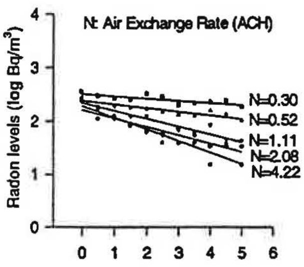

Figure 4. The Measured Data for All Experiments

Table 1. The Measured (M) & Calculated (C) Data of Radon Concentration at HKUST

V-on	*N=0.30*		*N=0.52*		*N=1.12*		*N=2.08*		*N=4.22*	
-hrs	*M*	*C*	*M*	*C*	*M*	*C*	*M*	*C*	*M*	*C*
0.0	*351.0*	*351.0*	*278.0*	*278.0*	*242.0*	*242.0*	*236.0*	*236.0*	*242.0*	*242.0*
0.5	*297.0*	*328.4*	*185.0*	*246.4*	*185.0*	*191.8*	*112.0*	*158.3*	*170.0*	*160.0*
1.0	*263.0*	*307.8*	*263.0*	*219.5*	*191.0*	*154.1*	*124.0*	*110.1*	*112.0*	*109.0*
1.5	*251.0*	*289.1*	*179.0*	*196.5*	*121.0*	*125.9*	*90.0*	*80.1*	*81.6*	*79.1*
2.0	*324.0*	*271.9*	*170.0*	*176.8*	*124.0*	*104.7*	*63.0*	*61.5*	*66.5*	*60.3*
2.5	*288.0*	*256.3*	*148.0*	*160.0*	*54.4*	*88.8*	*57.0*	*49.9*	*39.3*	*48.7*
3.0	*200.0*	*242.0*	*130.0*	*133.4*	*69.5*	*76.9*	*39.0*	*42.7*	*39.3*	*41.6*
3.5	*218.0*	*228.9*	*124.0*	*122.9*	*60.5*	*67.9*	*54.0*	*38.2*	*39.3*	*37.2*
4.0	*227.0*	*217.0*	*157.0*	*122.9*	*84.7*	*61.1*	*33.3*	*35.3*	*15.1*	*34.5*
4.5	*239.0*	*206.1*	*133.0*	*113.9*	*45.4*	*56.0*	*33.3*	*33.5*	*36.3*	*32.8*
5.0	*185.0*	*196.1*	*103.0*	*106.2*	*42.3*	*52.2*	*33.3*	*32.4*	*15.1*	*31.8*

DISCUSSION

Room Chamber Condition during Ventilation-off-hours

During HVAC was OFF at night, natural ventilation inside the room chamber was so small that the air exchange rate, N could be neglected. In fact, N inside the indoor environment of our room chamber could never be exactly 0. Some latest IAQ researches confirmed the common accumulation pattern of an indoor air pollutant reaching a plateau over time required high N as well as pollutant decay rate, such as, for the VOC[5]. So, in our experiment, radon accumulation at the 12 Vent-off-hrs can be estimated in linear progression.

Consideration of Emission Sources in Radon Predictive Modelling

Sources of radon emission are important parameters to determine the amount of air pollutant indoors. In this experiment, radon level was predicted by using the emission rate, R which was computed using model (2) with $C_{(t)}$ and t obtained during ventilation-off-hours. R can reflect radon emissions given off from building materials and surrounding soil through walls into the room chamber. They are the main sources of radon emission in an indoor environment.

Consideration of Indoor Sinks in Radon Predictive Modelling

Indoor sinks occur due to the adsorption/desorption behaviour of indoor room surfaces and materials. Some latest IAQ researches provided good evidences in confirming these properties[6]. Indoor sinks interact so tightly with the radon emission sources so that the behaviour of indoor sources and sinks is important and has to be identified properly. In this experiment, this sink effect can be realised through the inaccurate data fitting of the mathematical model (5) during analysis. To include this sink effect, a modification factor was applied into the model (5) which was transformed into another model (6) as indicated below:

$$C_{(t)} = \frac{RL}{MN-k}[\exp(-kt)-\exp(-MNt)]+(C_o-C_{in})\exp(-MNt)+C_{in} \quad ...(6)$$

Where,

$C_{(t)}$	*is concentration as a function of time (mg/m^3)*
R	*is 8.60 Bq/m^2/hr (radon emission rate from room chamber surfaces)*
L	*is 1.81 m^2/m^3 (loading factor), L = S/V*
N	*is 0.30, 0.52, 1.11, 2.08 and 4.22 /hr (air exchange rates)*
k	*is 0.01 /hr (radon decay rate)*[7]
t	*is 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 hr (vent-on-hrs)*
$C_{o'}$	*is 351 (N=0.30), 278 (N=0.52), 242 (N=1.11), 236 (N=2.08) and 242 (N=4.22) Bq/m^3 (initial room concentration)*
C_{in}	*is 15 Bq/m^3 (background air concentration)*
M	*is the modification factor to account for sinks.*

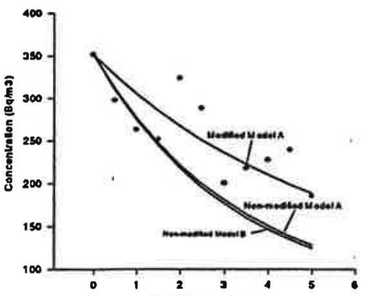

Figure 5. Comparing modified & non-modified models (when N=0.3031 ACH)

Using the simulation function of a powerful software simulator,[8] M was identified:

Parameter	*Value*	*StdErr*	*CV(%)*	*Dependencies*
Z	*1.869e-1*	*1.855e-2*	*9.927e+0*	*0.0000000*

Table 2. Computing Modified Factor (M)

N (1/hr)	*MN (1/hr)*	*M=(MN/N)*
0.3031	*0.1869*	*0.6166*
0.5178	*0.3187*	*0.6155*
1.1147	*0.5779*	*0.5184*
2.0819	*0.9545*	*0.4585*
4.2229	*0.9824*	*0.2326*

Where, for simulation, Z = MN

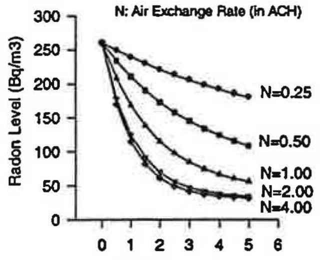

Figure 6. The Calculated Data of All Experiments

Figures 5 shows the simulated results of radon levels using the mathematical model (6) after application of the modification factors, M. From the figures, it was noticed that the curves fit the experimental data extremely well. The simulation was undertaken throughout the model verification process.

To further validate the model, a linear relationship between the air exchange rate (N) and the modification factors (M) was confirmed. The model for this linear regression is:

$$M = 0.6507 - 0.0985 * N \qquad ...(7)$$

Or $M = 0.65 - 0.1N \quad (r^2=0.99, p<0.01)$

With mathematical model (7), it becomes simple to calculate the modification factors with air exchange rates varying between 0.25 and 4.0 ACH. Figure 6 shows the ventilation-on-hours pattern for characterising indoor radon concentration. For different ACH with the same initial room radon concentration (C_o=260 Bq/m^3), the following results were found: If N=1.0, it takes only half an hour for $C_{(t)}$ to arrive at 208 Bq/m3; If N=0.5, it takes one hour for $C_{(t)}$ to arrive at 210 Bq/m3. Both these values are very close to the WHO Action level of 200 Bq/m^3.

Representative, Validation & Limitation of the predictive model

1. *Representative of the developed ventilation-off-hours model*

Using the modified model $C_{(t)} = C_o + Rlt$, as derived previously, with a 12 Vent-off-hrs of HVAC services, we find that $C_{(12hrs)}$ = 73.82 (Bq/m^3)+8.60(Bq/m^2/hr)*1.81(m^2/m^3)*12 (hrs)= 260.62 (Bq/m^3). This computed figure was found very close to our previously-sampled of average peak result[9] of 264.39 Bq/m^3 (Average Vent-off-hrs at HKUST is 12 hours). We can so confirm the radon predictive model developed is a good representative in HKUST condition.

2. *Preliminary validation of the ventilation-on-hours model developed*

The model was regarded to have successfully validated in a preliminary way during the processing of experiment with N parameters in variation, the results were observed to be smooth matching one and other. Table 1 confirms the statement. The model was further validated by the variation of the R parameters, from 8.60 to 4.85 Bq/m^3, as presented in our room chamber study[10]. This involves the evaluation of different Polyurethane-based surface covering effects to prevent radon emission from walls. Figure 7 summarises the results which confirms the modified radon predictive model with same modification factors is capable of matching the data well.

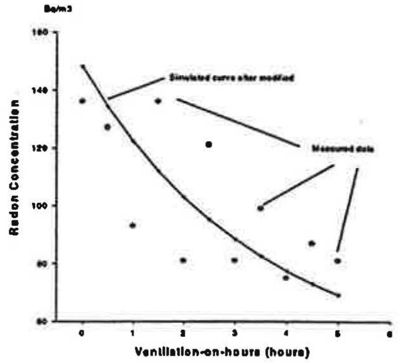

Figure 7 Effect of P-u Covering; N=0.48 ACH; M=0.60

3. *Limitation of the modified radon predictive models*

More studies might be required to validate the models in a more thorough sense especially the model modification part due to different environment configurations may yield different modification factors. This study contributes the method in arriving the essential parameters whereas future researchers can apply into their own situation whenever required.

CONCLUSION

The set of experiments yield the following conclusions:

1. Indoor radon was found accumulated in linear progression during the HVAC system was switched off, a model was formulated successfully to predict its concentrations;
2. With the inclusion of modification factor to account for the radon sink effect, a pre-existing VOC concentration predictive model can be successfully modified to predict indoor radon concentrations;
3. This radon level predictive model correlates well with the field measured data; and,
4. More intensive validation of the model to account for more complicated environments etc. in promoting its applicability may be required in future.

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