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PC4199 REPORT

Measuring Radon Level in Singapore

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Abstract

Radon, a radioactive noble gas, is extensively researched upon in other countries due to her potential to increase the risk of lung cancer. Based on the World Health Organisation (WHO), radon is estimated to cause between 3 – 14 % of all lung cancers in a country. The main isotope, $^{222}$Rn, could be exhaled from the ground containing traces of $^{238}$U. Compared to the inert $^{222}$Rn, her progenies ($^{218}$Po and $^{214}$Po) are more likely to be lodged into the lung tissues. In addition, while $^{222}$Rn have a relatively long half-life of 3.8232 days, her progenies have much shorter half-lives. Hence, the decay progenies have the potential of undergoing $\alpha$ decay in the lungs before it is breathed out, increasing the risk of lung cancer. In spite of these dangers, there are no published data on radon levels in Singapore. Using RAD7, an instrument capable of resolving the energies of $\alpha$ particles emitted by the radon progenies, we performed the first study to measure the time variation of $^{222}$Rn level in various residential homes and workplaces in Singapore. We also computed the annual effective dose absorbed by Singaporeans in each location. From these results, we observed that air exchanges is a prominent factor in the variation of $^{222}$Rn level in the indoors. Finally, we evaluated other factors which could potentially affect the $^{222}$Rn level.
Acknowledgements

I would like to express my deepest gratitude towards my supervisors, Professor Chung Keng Yeow and Dr Pong Boon Kin for providing me with continuous guidance for the project. I would also like to thank my friends and family who have helped me in one way or another. In particular, I am extremely grateful to Dr Diane Tiong for assisting me in some data collections as well as the participants who warmly opened their homes for radon measurements.
Contents

Abstract i

Acknowledgements ii

1 Introduction 1

2 Origin and Health Risks of Radon 2

2.1 Decay Chain of Radon 3

2.2 Exhalation of Radon Isotopes 4

2.2.1 Emanating Power of the Grains 5

2.2.2 Transport Characteristic in Interstitial Pores 6

2.3 Behaviour of Isotopes in the Air 7

2.4 Health Risks of Radon 8

3 Measuring Radon Level with RAD7 10

3.1 Choice of RAD7 as the Detector 11

3.2 Working Principle of RAD7 12

3.3 Protocol in RAD7 Placement 16

4 Preliminary Results on Radon Level 17

4.1 Some Measurements 18

4.1.1 Offices 18

4.1.2 Homes 18
4.1.3 Physics Radiation Store in National University of Singapore . . . . 19
4.1.4 SNRSI Lab ............................................................. 20
4.1.5 DSO Storeroom .......................................................... 20
4.2 Effects of Air Ventilation .................................................. 21
4.2.1 Office Buildings .......................................................... 21
4.2.2 Homes ................................................................. 22
4.3 Outdoors ................................................................. 26
4.4 Homes ................................................................. 27
4.5 Offices ................................................................. 27
4.6 Dosimetry ................................................................. 28
4.6.1 Dose in Homes .......................................................... 29
4.6.2 Dose in Offices .......................................................... 29
4.6.3 Implications of Dose .................................................. 30

5 Future Study ................................................................. 32
5.1 Correlation with Temperature ............................................ 32
5.2 Radon Exhalation of Building Materials .................................. 34
5.3 Weather Conditions ....................................................... 36
5.4 Introducing a Second Detector .......................................... 37
5.4.1 Space Variation Within Homes ....................................... 37
5.4.2 Eliminating Other Factors ............................................ 37
Chapter 1

Introduction

Radon is a naturally occurring radioactive noble gas in the environment. Exposure to radon is the second leading cause of lung cancer. According to the United States Environmental Protection Agency (EPA), radon exposure contributes to 21,000 lung cancer death annually in the United States of America alone. In spite of these health risks, there is no published data on radon levels in Singapore.

This report aims to initiate the first studies of radon concentration in Singapore. In chapter 2, we provided a general background information on radon and the associated health risks. In chapter 3, we shortlisted a solid state detector (RAD7). The working principle of RAD7 and the experimental protocols were explained as well. The first measurement of radon concentration across various locations in Singapore were shown in chapter 4. Based on these results, we proposed that air ventilation could play a crucial role in the regulation of radon concentration. Given the preliminary data, we gave insights on the factors influencing radon concentrations in Singapore in chapter 5. We hope that this project would open new avenues for research in the field of radon exposure in Singapore.
Chapter 2

Origin and Health Risks of Radon

The three naturally occurring radon isotopes are $^{222}\text{Rn}$, $^{220}\text{Rn}$ and $^{219}\text{Rn}$. Table 2.1 summarises the half-life and decay constant of these three isotopes.

Table 2.1: Summary table for the three isotopes of radon [1].

<table>
<thead>
<tr>
<th></th>
<th>$^{222}\text{Rn}$</th>
<th>$^{220}\text{Rn}$</th>
<th>$^{219}\text{Rn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>3.8232 days</td>
<td>55.8 s</td>
<td>3.98 s</td>
</tr>
<tr>
<td>Decay constant [s$^{-1}$]</td>
<td>2.0984×10$^{-6}$</td>
<td>1.24×10$^{-2}$</td>
<td>1.74×10$^{-1}$</td>
</tr>
</tbody>
</table>

Among the three isotopes, $^{222}\text{Rn}$ is the most significant in terms of radiation exposure risks. Due to the long half-life of 3.8232 days, $^{222}\text{Rn}$ has the potential to travel through some depth of soil and building materials upon formation and accumulate in indoor air. On the other hand, the shorter half-life of $^{220}\text{Rn}$ (55.8 s) limits the distance it can travel through the soil or building materials before it decays, rendering it less significant. $^{219}\text{Rn}$ is considered the least significant. This could be attributed by the low natural abundance of $^{219}\text{Rn}$.

In consideration of the risk exposures posed by the different radon isotopes, the main focus of this report would be to study the concentration of $^{222}\text{Rn}$ with some marginal discussion on $^{220}\text{Rn}$. We would not be discussing the concentration of $^{219}\text{Rn}$ in this report.
2.1 Decay Chain of Radon

$^{222}\text{Rn}$ and $^{220}\text{Rn}$ are intermediate products of the decay of $^{238}\text{U}$ and $^{232}\text{Th}$ respectively. These $^{238}\text{U}$ and $^{232}\text{Th}$ isotopes are found in the soil or building materials. After undergoing a series of radioactive decay to the gaseous $^{222}\text{Rn}$ and $^{220}\text{Rn}$ isotopes, they would eventually be exhaled to the surrounding environment. Figure 2.1 shows the decay chain of $^{222}\text{Rn}$ and $^{220}\text{Rn}$.

![Decay chain of Radon](image)

Figure 2.1: Decay chain of $^{222}\text{Rn}$ and $^{220}\text{Rn}$.

Small but significant quantities of $^{238}\text{U}$, $^{232}\text{Th}$ and their corresponding progenies could be found in the ground and many building materials. Table 2.2 shows the activity concentration of $^{226}\text{Ra}$ and $^{228}\text{Ra}$ in different types of rocks. From the table, we observed that radium activity concentration differs for each materials. For example, granite has the largest average radium activity concentration. These data suggest that building materials could be an important contributor to environmental radon.

Besides radium activity concentration, another factor of concern would be the exhalation
rate of radon. Not all the radon decayed from the radium would be released into the surrounding atmosphere. In the next section, we would elaborate on the radon exhalation mechanism from building materials and some of the factors affecting exhalation.

Table 2.2: Activity concentration of $^{226}\text{Ra}$ and $^{228}\text{Ra}$ in different types of rocks [2].

<table>
<thead>
<tr>
<th>Type of Rock</th>
<th>Example</th>
<th>$^{226}\text{Ra}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid Intrusive Granite</td>
<td>78</td>
<td>1 – 370</td>
</tr>
<tr>
<td>Basic Extrusive Basalt</td>
<td>11</td>
<td>0.4 – 41</td>
</tr>
<tr>
<td>Chemical Sedimentary Limestone</td>
<td>45</td>
<td>0.4 – 340</td>
</tr>
<tr>
<td>Detrital Sedimentary Clay, Shale, Sandstone</td>
<td>60</td>
<td>1 – 990</td>
</tr>
<tr>
<td>Metamorphosed Igneous Gneiss</td>
<td>50</td>
<td>1 – 1800</td>
</tr>
<tr>
<td>Metamorphosed Sedimentary Schist</td>
<td>37</td>
<td>1 – 660</td>
</tr>
</tbody>
</table>

2.2 Exhalation of Radon Isotopes

When radium decays into radon, the radon atom would emanate from the grains into the air-filled pores. This emanation is mainly due to the recoil of radon during the $\alpha$ decay of radium. Through the $\alpha$ decay, the radon atom gains sufficient kinetic energy to move from the site of its generation. After which, the emanated radon atom would be transported through the air-filled pores. There are two mechanisms governing the transport of radon. They are molecular diffusion and forced advection [2].

In molecular diffusion, radon flows in the direction of a decreasing concentration gradient. This process could be described by Fick’s law applied to a slab of concrete experiencing one-dimensional $^{222}\text{Rn}$ concentration gradient of $\frac{dC}{dx}$ with isobaric and isothermal conditions [3],

$$J_D = -D_e \frac{dC}{dx}$$  \hspace{0.5cm} \text{(2.1)}

where $J_D$ is the $^{222}\text{Rn}$ fluence rate [Bq m$^{-2}$ s$^{-1}$] and $D_e$ is the effective diffusion coefficient of the material [m$^2$ s$^{-1}$].

On the other hand, forced advection allows radon to move into a building due to a negative pressure difference existing between indoor and outdoor atmospheres. This difference arises from external wind blowing on the building or heating inside the building.
The two step process for radon exhalation in a building material-air interface, emanation and transportation, is illustrated in figure 2.2. From the two step process, we observed that factors affecting the $^{222}$Rn exhalation rate could be classified into two categories, namely factors affecting emanating power of the grains and factors affecting the transport characteristics in the interstitial pores.

![Mechanism for exhalation of radon from porous building materials or soil.](image)

**Figure 2.2:** Mechanism for exhalation of radon from porous building materials or soil. (1) Emanation: Radon enters the interstitial pores from the grains; (2) Transport: Radon is transported out of material via the air-filled pores.

### 2.2.1 Emanating Power of the Grains

For the radon atom to successfully undergo emanation, the radon atom must be stopped in the pores (figure 2.2). A main factor governing the emanating power would be the size of the grains and the pores in the material [4].

When the grain size is larger than the recoil range of the radon atom, most of the radon atoms would not be able to reach the pores. Therefore, the emanation power is reduced. Likewise, when the pore size is smaller than the recoil range of the radon atom, most of the radon atoms might not terminate in the pores. Instead, it will be buried in another grain, causing less radon to be entrapped in the pores.

Emanating power also increases with increasing moisture in the material. This could be explained by the lower recoil range of radon atoms in water than in air (the recoiling radon atom in water has a range 1000 times shorter than that of air). Radon atoms entering a
Chapter 2. Origin and Health Risks of Radon

...pore filled with water would have a higher probability of being stopped by the water in the pore.

Lastly, emanating power increases with rising temperature. This is due to the reduction in adsorption of radon on the grains [2].

2.2.2 Transport Characteristic in Interstitial Pores

Studies have shown that molecular diffusion mechanism is more significant than forced advection in intact concrete [5]. As a result, factors affecting forced advection, such as wind speed and air pressure, might not be as significant. In this study, we would focus on the factors affecting the diffusion mechanism.

To solve the Fick’s law for a building wall of thickness \( d \), we apply the following boundary conditions for the \(^{222}\text{Rn} \) concentration \( C \) [2, 5]:

\[
C = \begin{cases} 
C_{\text{Ra}}f\rho & \text{for } x = 0 \\
0 & \text{for } x = d 
\end{cases}
\] (2.2)

where \( C_{\text{Ra}} \) is the activity concentration of \(^{226}\text{Ra} \) [Bq kg\(^{-1}\)], \( f \) is the fraction of \(^{222}\text{Rn} \) which successfully emanates into the pores and \( \rho \) is the density of the material [kg m\(^{-3}\)].

After applying these boundary conditions to the steady state solution for molecular diffusion, we substitute the \(^{222}\text{Rn} \) concentration into the Fick’s law (equation 2.1). The resulting \(^{222}\text{Rn} \) fluence rate \( J_D \) is given by\(^1\),

\[
J_D = \frac{C_{\text{Ra}}\lambda_{\text{Rn}}f\rho l_d}{\sinh \left( \frac{d}{l_d} \right)}
\] (2.3)

where we define the diffusion length of \(^{222}\text{Rn} \) to be \( l_d = \sqrt{\frac{D_e}{\lambda_{\text{Rn}}}} \) which depends on the effective diffusion coefficient \( (D_e) \) and the decay constant of \(^{222}\text{Rn} \) \( (\lambda_{\text{Rn}}) \). From this equation, the most important factors affecting the fluence rate of \(^{222}\text{Rn} \) are the thickness

\(^1\)The detailed formalism for the fluence rate can be found in Appendix A.
of the walls as well as the diffusion length. The fluence rate decreases exponentially with thicker walls (increasing $d$) and increases with diffusion length. The diffusion length would in turn be affected by the properties of the building material such as the moisture content and porosity. Possible characterisation of these factors would be further discussed in chapter 5.

2.3 Behaviour of Isotopes in the Air

After the exhaled radon undergoes $\alpha$ decay to her progenies, there are several processes that govern the movement of these progenies. Figure 2.3 summarises the behaviour of the progenies after radon exhalation [2]. We could observe that the main processes removing the progenies from indoors are plateout and ventilation (outdoor flow).

![Figure 2.3: Mechanisms of regulation of radon decay progenies. The red arrows shows each process. The clusters are formed when the progenies react with trace gases and air vapours.](image)

The reactive progenies are able to attach to aerosol particulates within the size range of $0.05 - 0.5 \mu m$ [2]. According to studies by the World Health Organisation (WHO), particulates of diameter between $2 \mu m$ and $10 \mu m$ or below $0.5 \mu m$ can be effectively deposited in the lungs [6]. As a result, the progenies deposited in the lungs have sufficient time to undergo $\alpha$ decay in the lungs, increasing the risk of lung cancer. Therefore, the health risks due to exposure to the radon decay progenies warrant our attention.
2.4 Health Risks of Radon

Studies have shown that radon is the primary cause of lung cancer among non-smokers. In fact, epidemiology studies conducted by the WHO estimated that the proportion of all lung cancers linked to radon lies between 3% – 14%, depending on the average radon concentration in the country and on the method of calculation. WHO also reported that the risk of lung cancer rises 16% per 100 Bq/m$^3$ increase in radon exposure. Therefore, they recommended that countries should adopt a reference level$^2$ of 100 Bq/m$^3$ [8].

International governments also had imposed action level$^4$ within their own countries. Table 2.3 shows some of the action level imposed by various countries.

Table 2.3: Average and action radon level in some countries [9].

<table>
<thead>
<tr>
<th>Country</th>
<th>Average Radon Concentration in Homes [Bq/m$^3$]</th>
<th>Action Level [Bq/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>46</td>
<td>150</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>20</td>
<td>200</td>
</tr>
<tr>
<td>Germany</td>
<td>50</td>
<td>250</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>140</td>
<td>200</td>
</tr>
</tbody>
</table>

We observed that the average radon level is usually below the action level. However, it is possible for many locations in a country to have radon concentration exceeding the action level. For example, the map of radon concentration in the United States in figure 2.4 show that radon concentration can be very localised.

Comparing figure 2.4 with table 2.3, we note that it is not enough to measure a few locations to comment on the whole radon concentration of the country. Therefore, it would be paramount for us to measure radon levels across as many locations in Singapore.

$^2$Reference level is a radon concentration above which, specified action or decision should be taken [7].

$^3$WHO recommends that the reference level should not exceed 300 Bq/m$^3$ if 100 Bq/m$^3$ cannot be implemented.

$^4$An action level is a radon level above which, intervention is recommended to reduce the exposure in a building [7].
2.4. Health Risks of Radon

Figure 2.4: Map of radon concentration in the United States [10]. The locations demarcated by red has radon concentration which exceeds the action level.
Chapter 3

Measuring Radon Level with RAD7

In a bid to obtain preliminary results of radon concentration in residential homes and offices in Singapore, we came up with some selection criteria to shortlist a measurement technique that is most suitable. The three criteria are as follows:

1. Ability to measure the variation of radon level with time.
2. Ability to measure radon in different locations.
3. Ability to do alpha spectroscopy.

To study the radon level with variation of time, we would require the timescale of the measurement technique to be relatively short. The detector used should also be portable so that we could cover the radon measurement for different locations. Finally, it would be beneficial if the detector could differentiate the $\alpha$ particles from the decay of $^{222}$Rn, $^{218}$Po and $^{214}$Po. Therefore, the detector must be able to carry out alpha spectroscopy.

In the following segment, we will be covering the working principles of several radon measurement techniques before proceeding to select the most suitable one based on the three stated criteria. The protocol of detector placement will also be discussed in chapter 3.3.
### 3.1 Choice of RAD7 as the Detector

Table 3.1 shows a summary of the working principles and the timescale for different radon measurement techniques.

<table>
<thead>
<tr>
<th>Working Principles</th>
<th>Detection Time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lucas Cell</strong></td>
<td>2 hours</td>
</tr>
<tr>
<td>• Filtered grab sample of air is taken using lucas flask</td>
<td></td>
</tr>
<tr>
<td>• Gas left in flask for 3 hours to achieve secular equilibrium between radon and progenies</td>
<td></td>
</tr>
<tr>
<td>• $\alpha$ particles (due to the decay of $^{222}$Rn, $^{218}$Po and $^{214}$Po) interact with scintillator</td>
<td></td>
</tr>
<tr>
<td>• Counts are recorded by photomultiplier tube</td>
<td></td>
</tr>
<tr>
<td>• Filtered air is pumped into the ionisation chamber</td>
<td></td>
</tr>
<tr>
<td>• Ionisation due to $\alpha$ decay of $^{222}$Rn, $^{218}$Po and $^{214}$Po are measured in the chamber</td>
<td></td>
</tr>
<tr>
<td>• Total ionisation pulses caused by individual $\alpha$ particles can be counted separately</td>
<td></td>
</tr>
<tr>
<td><strong>Electret</strong></td>
<td>3 days – 12 months</td>
</tr>
<tr>
<td>• Electrets have a permanent surface charge resulting in surface potential of several kV</td>
<td></td>
</tr>
<tr>
<td>• A teflon electret is placed at bottom of conducting plastic chamber</td>
<td></td>
</tr>
<tr>
<td>• Ionisation (due to $\alpha$ decay of $^{222}$Rn, $^{218}$Po and $^{214}$Po) causes the electret to lose its charge</td>
<td></td>
</tr>
<tr>
<td>• Average radon concentration $C = \frac{V_f - V_i}{F \cdot t}$</td>
<td></td>
</tr>
<tr>
<td>where $V_f$ and $V_i$ is the final and initial exposure voltage, $F$ is the calibration factor and $t$ is the exposure time</td>
<td></td>
</tr>
<tr>
<td><strong>Solid State Detector</strong></td>
<td>1 hour</td>
</tr>
<tr>
<td>• The detector P-N junction contains a depletion region</td>
<td></td>
</tr>
<tr>
<td>• $\alpha$ particles (due to the decay of $^{222}$Rn, $^{218}$Po and $^{214}$Po) would generate electron-hole pairs in the depletion region</td>
<td></td>
</tr>
<tr>
<td>• Number of electron-hole pair is counted and attributed to the energy of the $\alpha$ particle</td>
<td></td>
</tr>
<tr>
<td><strong>Gamma Spectroscopy on Activated Charcoal</strong></td>
<td>2 – 7 days</td>
</tr>
<tr>
<td>• Activated charcoal has an affinity for radon gas</td>
<td></td>
</tr>
<tr>
<td>• Radon adsorbed on charcoal will decay, leaving behind the decay products</td>
<td></td>
</tr>
<tr>
<td>• The decay products ($^{214}$Pb and $^{214}$Bi) could be measured via gamma spectroscopy.</td>
<td></td>
</tr>
<tr>
<td><strong>Etched Track Detectors</strong></td>
<td>1 month – 1 year</td>
</tr>
<tr>
<td>• Plastic materials are used to record tracks of $\alpha$ particles (due to the decay of $^{222}$Rn, $^{218}$Po and $^{214}$Po)</td>
<td></td>
</tr>
<tr>
<td>• The tracks are revealed by etching the plastic in NaOH or KOH solution supplemented with ethanol</td>
<td></td>
</tr>
</tbody>
</table>

---

5Generally, the material utilised are LR-115 or CR-39.
Table 3.2 compares the above techniques by considering the three criteria — time variation of less than 1 day, portability (weight of less than 10 kg) and the ability to carry out alpha spectroscopy.

Table 3.2: Comparison of different radon measurement techniques.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Time Variation</th>
<th>Portability</th>
<th>Alpha Spectroscopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucas Cell</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Pulsed Ion Chamber</td>
<td>✓</td>
<td>x</td>
<td>✓</td>
</tr>
<tr>
<td>Electret</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Solid State Detector</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gamma Spectroscopy on Activated Charcoal</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
<tr>
<td>Etched Track Detectors</td>
<td>x</td>
<td>✓</td>
<td>x</td>
</tr>
</tbody>
</table>

We concluded that a solid state detector would be most appropriate for this study. We eventually chose DURRIDGE RAD7 (a solid state detector) for the measurements. The next section will elaborate on the specifics of RAD7.

### 3.2 Working Principle of RAD7

The setup of the RAD7 detector is illustrated in figure 3.1.

![Figure 3.1: Schematic diagram of the interior of RAD7. The arrows and numbers indicate the air flow in the detector.](image)

Moisture is removed from the air as it passes through the desiccant (drierite). After which, the inlet filter would filter out the progenies of radon which are attached to dust particles.
3.2. Working Principle of RAD7

Beyond the size of 0.45 μm. This process would ensure that the RAD7 only detects the progenies that decay directly from radon in the 0.7 L hemispherical chamber. Since the walls of the hemispherical chamber has a charge of +2200 V with respect to the detector, it would push the ionised polonium isotopes towards the detector. The solid state detector would then measure the energy level of the α particles emitted by the polonium isotopes (218Po and 214Po). The temperature and RH sensor would measure the temperature and relative humidity of the air before the air is released back into the atmosphere via the outlet.

RAD7 measures the energy level of the α particles emitted by the polonium isotopes using the depletion region as shown in figure 3.2. When the α particles move within the depletion region, it loses energy by generating electron-hole pairs. These electron-hole pairs are then separated and collected. Since the energy of the α particle is directly proportional to the number of electron-hole pairs, we can characterise the α particles based on their energy.

![Figure 3.2: Schematic diagram of the depletion region in the solid state detector. The arrows indicate the movement of α particles after the decay.](image)

Figure 3.2: Schematic diagram of the depletion region in the solid state detector. The arrows indicate the movement of α particles after the decay.

Most measurements of 222Rn assumes that the secular equilibrium between 222Rn and the respective polonium isotopes (218Po and 214Po) is achieved, that is, each of the product decays at the same rate as when they are produced. Figure 3.3 shows the modelled decay activities of 222Rn, 218Po and 214Po against time.\(^6\)

\(^6\)The details of obtaining the graph can be found in Appendix B.
From figure 3.3, we observed that $^{218}$Po reaches secular equilibrium with $^{222}$Rn at about 20 minutes while $^{214}$Po reaches secular equilibrium with $^{222}$Rn at about 3 hours. Taking this observation into account, RAD7 would calculate the $^{222}$Rn concentration based on the counts of $^{218}$Po $\alpha$ particles for the first three hours. Subsequently, both the counts of $^{214}$Po and $^{218}$Po $\alpha$ particles would be used to determine the $^{222}$Rn concentration.

To evaluate the radon concentration, we used the counts of the $\alpha$ particles from the polonium isotopes. Here we covered the method to obtain the counts of those $\alpha$ particles from the energy spectrum obtained by RAD7.

As mentioned previously, RAD7 is able to characterise the $\alpha$ particles based on their energy. As a result, we are able to distinguish the $\alpha$ particles produced by the different isotopes. Table 3.3 consolidates the energies of the different $\alpha$ particles. For ease of classification, we have also introduced 4 energy channels A (5.6 – 6.4 MeV), B (6.4 – 7.2 MeV), C (7.2 – 8.2 MeV) and D (8.2 – 9.3 MeV).

<table>
<thead>
<tr>
<th>Decay Chain</th>
<th>Decay Isotope</th>
<th>Energy [MeV]</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{222}$Rn</td>
<td>$^{218}$Po</td>
<td>6.11</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>$^{214}$Po</td>
<td>7.83</td>
<td>C</td>
</tr>
<tr>
<td>$^{220}$Rn</td>
<td>$^{214}$Bi</td>
<td>6.21</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>$^{216}$Po</td>
<td>6.91</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>$^{212}$Po</td>
<td>8.95</td>
<td>D</td>
</tr>
</tbody>
</table>

Two examples of the energy spectra obtained from the measurements by RAD7 are shown in figure 3.4.
3.2. Working Principle of RAD7

(a) Pure radon in secular equilibrium

(b) Mixture of radon and thoron

Figure 3.4: Plot of counts against energy for different samples. The energies are segmented into 4 channels (A, B, C and D).

Since most of the gas sample would contain traces of $^{220}\text{Rn}$ [figure 3.4(b)], the counts of $^{218}\text{Po}$ is not equivalent to the total counts in channel A. Therefore, the counts due to the decay of $^{212}\text{Bi}$ has to be subtracted from channel A. Ideally, the counts of $^{212}\text{Bi}$ is half of the counts of $^{212}\text{Po}$. This is because $^{212}\text{Bi}$ can undergo both an $\alpha$ decay (branching ratio 35.9%) or a $\beta$ decay (branching ratio 64.1%) to $^{212}\text{Po}$ while $^{212}\text{Po}$ only undergoes $\alpha$ decay. As a result, the $^{222}\text{Rn}$ concentration $C$ is given by,

$$ C = \begin{cases} \frac{(N_A - \frac{1}{2}N_D)\eta}{V \cdot t} & \text{for the first three hours} \\ \frac{(N_A - \frac{1}{2}N_D) + N_C\eta}{V \cdot t} & \text{beyond three hours} \end{cases} \quad (3.1) $$

where $N_i$ is the alpha counts in channel $i$ ($i = A, C, D$) measured by the RAD7 detector, $\eta$ is the efficiency of the detector, $V = 0.7\text{L}$ is the volume of the chamber and $t$ is the time interval.
3.3 Protocol in RAD7 Placement

For this study, we followed the protocol imposed by the United States Environmental Protection Agency (EPA) [13].

To ensure that the detector is not near to any drafts, it is placed at least 90 cm from the doors and windows. The detector is also placed at least 30 cm from walls of the building, at least 50 cm from the floor and at least 10 cm from other objects. Figure 3.5 shows a photograph of the detector placed in Office A.

![Photograph of the detector placed in Office A. The height from ground and shortest distance from nearest wall are labelled in the photograph.](image)

Figure 3.5: Photograph of the detector placed in Office A. The height from ground and shortest distance from nearest wall are labelled in the photograph.
Chapter 4

Preliminary Results on Radon Level

$^{222}$Rn levels in offices and homes were continuously monitored for 2 – 4 days using RAD7. Table 4.1 summarises all the locations measured in the course of this study.

Table 4.1: Locations of measurements and their descriptions.

<table>
<thead>
<tr>
<th>Locations</th>
<th>Annotations</th>
<th>Address</th>
<th>Additional Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Offices</strong></td>
<td></td>
<td></td>
<td>Air conditioner timings:</td>
</tr>
<tr>
<td>Office A</td>
<td></td>
<td>NUS S13-03-03</td>
<td>Weekdays: 7am – 9pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Saturday: 7am – 3pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sunday: 7am – 12pm</td>
</tr>
<tr>
<td>Office B</td>
<td></td>
<td>1 CREATE Way, #04-01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Office cubicles</td>
<td>Air conditioner timings:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weekdays: 6am – 8pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Saturday: 7am – 1pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sunday: Switched off</td>
</tr>
<tr>
<td>Office C</td>
<td></td>
<td>1 CREATE Way, #04-01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Meeting room</td>
<td>Air conditioner timings:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weekdays: 6am – 8pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Saturday: 7am – 1pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sunday: Switched off</td>
</tr>
<tr>
<td><strong>Homes</strong></td>
<td></td>
<td></td>
<td>Condominium level 10</td>
</tr>
<tr>
<td>Living Room A</td>
<td></td>
<td>Bishan</td>
<td>Doors and windows opened</td>
</tr>
<tr>
<td>Living Room B</td>
<td></td>
<td>Lorong Chuan</td>
<td>Condominium level 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Windows opened</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td></td>
<td>Pasir Ris</td>
<td>HDB estate level 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Doors opened</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td></td>
<td>Sembawang</td>
<td>HDB estate level 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Doors opened</td>
</tr>
<tr>
<td>Bedroom 3</td>
<td></td>
<td>Jurong</td>
<td>HDB estate level 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Night: Air conditioner on</td>
</tr>
<tr>
<td>Bedroom 4</td>
<td></td>
<td>Outram Park</td>
<td>Private level 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Night: Air conditioner on</td>
</tr>
<tr>
<td>Bedroom 5</td>
<td></td>
<td>Pasir Ris</td>
<td>Landed level 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Doors opened</td>
</tr>
<tr>
<td>Bedroom 6</td>
<td></td>
<td>Tampines</td>
<td>HDB estate level 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Night: Air conditioner on</td>
</tr>
<tr>
<td><strong>Outdoors</strong></td>
<td></td>
<td>Utown Field</td>
<td>Soil as ground</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NUS S16 Lobby</td>
<td>Near to building</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pasir Ris</td>
<td>Tiles as ground</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td></td>
<td>NUS Radiation Store</td>
<td>Radium source present</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SNRSI lab</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DSO store</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SPS storeroom</td>
<td>Air conditioner on</td>
</tr>
</tbody>
</table>

17
4.1 Some Measurements

Here we show examples of the measurements obtained from an office, a residential room and other specific locations.

4.1.1 Offices

Figure 4.1 shows the variation of $^{222}\text{Rn}$ in Office A. We observed that there exist a periodic fluctuation which was consistent over a few days. In fact, all three offices have demonstrated the similar pattern, albeit different range of values. Section 4.2 would explain the main factor contributing to this pattern. Subsequently, section 4.5 would consolidate some data from all three offices into one graph.

![Figure 4.1: Variation of $^{222}\text{Rn}$ concentration in NUS S13-03-03 office, with air exchanges when aircon is operating. Annotation: Office A](image)

4.1.2 Homes

On the other hand, most of the measured homes did not show any meaningful fluctuations. The main fluctuations were probably due to background and statistical noise. One such example could be found in figure 4.2. However, there was one exception (Bedroom 3)

---

7 All the other measurements for the offices are in Appendix C.
8 All the other measurements for the homes are in Appendix D.
which contained a periodic fluctuation that was consistent over a few days. This exception
would also be discussed in section 4.2. Section 4.4 would consolidate some data from all
eight homes into one graph.

Figure 4.2: Variation of $^{222}\text{Rn}$ concentration in a living room in Bishan. Type of house:
Condominium level 10; Annotation: Living room A

In addition to measuring offices and homes, we have also measured the $^{222}\text{Rn}$ levels in
several other locations. We would show some of the results and comment on the safety of
the well-ventilated radiation facilities in the National University of Singapore.

4.1.3 Physics Radiation Store in National University of Singapore

Figure 4.3: Variation of $^{222}\text{Rn}$ concentration in the Physics Radiation Store containing a
radium sample. Detector is placed 94 cm from the radium source.
4.1.4 SNRSI Lab

Figure 4.4: Variation of $^{222}\text{Rn}$ concentration in the SNRSI lab in CREATE level B1. We noted that the $^{222}\text{Rn}$ concentration found in the radiation store and SNRSI lab (figure 4.3 and 4.4) are below the WHO first reference level of $100\,\text{Bq/m}^3$. These results indicated that these locations are safe due to efficient constant ventilation.

4.1.5 DSO Storeroom

In addition to the radiation store and SNRSI lab, we have measured the DSO storeroom. The consistent high value of $^{222}\text{Rn}$ concentration in figure 4.5 is expected as there is little to no ventilation in the storeroom.

Figure 4.5: Variation of $^{222}\text{Rn}$ concentration in the DSO Storeroom.

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9 Another measurement for the SNRSI lab is in Appendix E.
4.2 Effects of Air Ventilation

One notable observation was that air ventilation is one of the most prominent factors in regulating $^{222}$Rn concentration.

4.2.1 Office Buildings

An example of the variation of $^{222}$Rn in a commercial building can be found in figure 4.6.

![Figure 4.6: Variation of $^{222}$Rn concentration in a level 4 office meeting room in 1 CREATE Way #04-01 with air exchanges when the air conditioner is in operation. Annotation: Office C](image)

We observed that the $^{222}$Rn concentration increased when the air conditioner is switched off. A possible explanation would be that the commercial buildings contain an Air Handling Unit (AHU) which exchanges the indoor air with the outdoor air. Switching on the air conditioner would thus facilitate the ventilation of commercial buildings.

To understand the accumulation rate and the rate of decrease of $^{222}$Rn, we have obtained the slope of the graph with a linear fit. The fitting parameters for Office C slopes are consolidated in table 4.2.\textsuperscript{10} We observe that the rate of decrease in $^{222}$Rn is higher than

\textsuperscript{10}The fitting parameters for Office A and B are found in Appendix C
the rate of accumulation of $^{222}\text{Rn}$ (table 4.2). Moreover, most of the slopes fall around the same range for the accumulation and decreasing of $^{222}\text{Rn}$ respectively. The rate of accumulation falls within the range of $18.3 - 33 \text{ Bq m}^{-3} \text{ h}^{-1}$ while the rate of decrease falls within the range of $48 - 71 \text{ Bq m}^{-3} \text{ h}^{-1}$.

Table 4.2: Gradient and coefficient of determination of the linear fit for each slope for the measurements in Office C.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Time</th>
<th>Gradient $[\text{Bq m}^{-3} \text{ h}^{-1}]$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>31/01/2018 – 01/02/2018</td>
<td>9pm – 5am</td>
<td>$33 \pm 1$</td>
<td>0.993</td>
</tr>
<tr>
<td></td>
<td>7am – 11am</td>
<td>$-65 \pm 4$</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td>8pm – 2am</td>
<td>$26 \pm 2$</td>
<td>0.978</td>
</tr>
<tr>
<td></td>
<td>8am – 11am</td>
<td>$-48 \pm 8$</td>
<td>0.950</td>
</tr>
<tr>
<td>15/02/2018 – 19/02/2018</td>
<td>8pm – 1am</td>
<td>$28 \pm 3$</td>
<td>0.955</td>
</tr>
<tr>
<td></td>
<td>8am – 11am</td>
<td>$-70 \pm 10$</td>
<td>0.932</td>
</tr>
<tr>
<td></td>
<td>2pm – 12pm</td>
<td>$18.3 \pm 0.7$</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>6am – 11am</td>
<td>$-71 \pm 4$</td>
<td>0.988</td>
</tr>
</tbody>
</table>

4.2.2 Homes

An example of the variation of $^{222}\text{Rn}$ concentration in a residential bedroom is shown in figure 4.7. We note that the trend is opposite of the commercial building in figure 4.6. Instead, the $^{222}\text{Rn}$ concentration increased when the air conditioner is switched on.

![Figure 4.7: Variation of $^{222}\text{Rn}$ concentration in a bedroom in Jurong. Type of house: HDB estate level 3; Annotation: Bedroom 3](image-url)
We hypothesised that this might be due to the difference in air conditioner mechanisms between residential and commercial buildings. Contrary to the AHU in commercial buildings, the air conditioner in residential homes recirculates the indoor air. Generally, switching on the air conditioner of a bedroom results in lesser air exchanges as both the doors and windows are usually closed. To test our hypothesis, we repeated the measurements in the same bedroom while recording the air exchange conditions. Figure 4.8 shows the results of the repeated measurement.

Figure 4.8: Variation of $^{222}\text{Rn}$ concentration in the same bedroom (Bedroom 3).

The sharp drop in $^{222}\text{Rn}$ concentration during 23/03/2018 (12pm – 6pm) agrees with our hypothesis that the variation in $^{222}\text{Rn}$ concentration is due to the air exchanges by the doors (figure 4.8). From the figure, the lower $^{222}\text{Rn}$ concentrations coincide with the time that the doors are opened.

Similar to the method carried out for Office C, we have obtained the slope of the graph. The fitting parameters for Bedroom 3 slopes are consolidated in table 4.3. The rate of accumulation falls within the range of $10.9 – 17\text{ Bq m}^{-3}\text{ h}^{-1}$. In contrast to the case in Office C, the rate of decrease of $^{222}\text{Rn}$ seems to fall within two different ranges ($13 – 15\text{ Bq m}^{-3}\text{ h}^{-1}$ and $38 – 41\text{ Bq m}^{-3}\text{ h}^{-1}$ respectively). One possible explanation could be that the variations of $^{222}\text{Rn}$ concentration are influenced by other factors besides air...
ventilation. This possibility is supported by the results shown in figure 4.8. The steeper slope (23/03/2018 12pm – 2pm) corresponds to the opening of doors while the gentler slope (23/03/2018 9am – 11am and 24/03/2018 9am – 12pm) corresponds to the condition when the air conditioner is switched off with doors closed. One possible factor that might explain this observation could be the temperature of the air, which would be further discussed in chapter 5.

Table 4.3: Gradient and coefficient of determination of the linear fit for each slope for the measurements in Bedroom 3.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Time</th>
<th>Gradient [Bq m$^{-3}$ h$^{-1}$]</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>28/12/2017 – 30/12/2017</td>
<td>7pm – 1am</td>
<td>17±1</td>
<td>0.982</td>
</tr>
<tr>
<td></td>
<td>9am – 1pm</td>
<td>-15±3</td>
<td>0.910</td>
</tr>
<tr>
<td></td>
<td>9pm – 5am</td>
<td>10.9±0.4</td>
<td>0.990</td>
</tr>
<tr>
<td></td>
<td>10am – 2pm</td>
<td>-38±7</td>
<td>0.916</td>
</tr>
<tr>
<td>22/03/2018 – 24/03/2018</td>
<td>1am – 4am</td>
<td>15.7±0.7</td>
<td>0.996</td>
</tr>
<tr>
<td></td>
<td>9am – 11am</td>
<td>-13±2</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>12pm – 2pm</td>
<td>-41±3</td>
<td>0.995</td>
</tr>
<tr>
<td></td>
<td>7pm – 3am</td>
<td>12±1</td>
<td>0.937</td>
</tr>
<tr>
<td></td>
<td>9am – 12pm</td>
<td>-13±1</td>
<td>0.978</td>
</tr>
</tbody>
</table>

However, not all bedrooms share a similar pattern in their variation of $^{222}$Rn level. Figure 4.9 shows the measurement of another residential bedroom with similar conditions.

![Figure 4.9: Variation of $^{222}$Rn concentration in a bedroom in Outram Pearl Complex. Type of house: Private level 26; Annotation: Bedroom 4](image)
There are no visible trends in the figure. This is due to the low absolute concentration of $^{222}\text{Rn}$ with respect to the uncertainty. This low concentration could be attributed to the fact that the room is not air tight, thus allowing for air exchanges between the indoor and outdoor air. Figure 4.10 shows the photograph of the door connecting the bedroom with the toilet. The sliding door contributes to a larger drafts than a typical door. The drafts might lead to more extensive ventilation in the residential bedroom.

Figure 4.10: Photograph of the toilet door in the bedroom. From the photograph, one can deduce that the door is not air tight. Since the windows in the toilet are constantly opened, there could be a possibility of air exchanges between the indoor and outdoor air.
4.3 Outdoors

The $^{222}\text{Rn}$ concentrations for three different outdoor locations were measured for 6 hours. These three locations were selected to test the $^{222}\text{Rn}$ concentration in different conditions. The photographs and characteristics of each location are shown in figure 4.11.

![Photographs of different locations](image)

(a) Utown field  
(b) NUS S16 lobby  
(c) Pasir Ris condominium

Figure 4.11: Photograph of the different locations. Utown field has soil as the ground material. NUS S16 lobby is near to a building (nearest building wall is 5 m away). Pasir Ris condominium has flooring tiles as the ground material.

Figure 4.12 consolidates the graph for these three measurements. Generally, the outdoor $^{222}\text{Rn}$ concentration in Singapore is on the lower spectrum of the international values. According to the WHO, the average outdoor radon level varies from 5 – 15 Bq/m$^3$ [14].

![Graph of $^{222}\text{Rn}$ concentration](image)

Figure 4.12: Consolidation of $^{222}\text{Rn}$ concentration in the three outdoor venues.
4.4 Homes

In addition to Bedroom 3 and 4, there are six other residential rooms measured. Figure 4.13 consolidates 6 hours of data for these locations.

![Graph](image.png)

Figure 4.13: Consolidation of $^{222}$Rn concentration in several homes with either the doors or windows opened. Bedroom 3 (air conditioner switched on) is not in this graph.

Similar to the outdoor readings, the residential $^{222}$Rn concentration in Singapore is on the lower spectrum of the international values. However, this observation is only applicable for homes with sufficient air ventilation. Based on a survey by the WHO on 32 countries, the average indoor radon concentration ranges from $15.5 - 280 \text{ Bq/m}^3$. Out of these 32 countries, only 4 of these countries have an average concentration below $40 \text{ Bq/m}^3$ [15].

4.5 Offices

Figure 4.14 consolidates 6 hours of data for the three offices measured. Although the air ventilation could explain the difference in values with and without air exchanges (figure 4.14), it is unable to explain the different concentration gaps for individual locations. For example, the gap between office A with and without air exchanges are much smaller than office B and C. As a result, we noted that there are many other factors which would be interesting to consider in this project. Some notable parameters would be the air temperature and the building materials. These parameters would be further elaborated in chapter 5.
4.6 Dosimetry

To assess the health impact of the $^{222}\text{Rn}$ radiation on the residents in the measured homes, we have estimated the annual effective dose using the average $^{222}\text{Rn}$ concentration obtained in the measurements.

The annual effective dose $E$ [mSv a$^{-1}$] absorbed by the residents from $^{222}\text{Rn}$ and her progenies is given by,

$$E = 0.4 \cdot 0.8 \cdot 8,760 \cdot 9.0 \cdot 10^{-6} \cdot \bar{C}$$ (4.1)

where 0.4 is the equilibrium factor, 0.8 is the occupancy rate, 8,760 is the number of hours in a year, $9.0 \cdot 10^{-6}$ is the dose conversion factor and $\bar{C}$ is the average $^{222}\text{Rn}$ concentration in the location [16].

Similarly, we assessed the health impact of the $^{222}\text{Rn}$ radiation on workers in the measured offices by estimating the annual effective dose. Since there are periodic fluctuations of $^{222}\text{Rn}$ concentration for offices (figure 4.1 and 4.6), extra care has to be taken in the computation of occupancy rate and the average $^{222}\text{Rn}$ concentration. We also intend to compare the annual effective dose absorbed with and without overtime work. The following contexts of Singapore are taken into consideration.

Singapore has a total of 11 gazetted public holidays. Taking into account 52 weeks worth of weekend breaks and assuming that the worker did not take any leave, there are a total of 280 working days annually. We take the normal office hours to be 9am – 6pm and the
overtime office hours to be 8am – 8pm. The occupancy rate $R$ is thus given by,

$$R = \begin{cases} \frac{280}{24 \cdot 365} = 0.288 & \text{for normal office hours} \\ \frac{12 \cdot 280}{24 \cdot 365} = 0.384 & \text{for overtime office hours}. \end{cases} \quad (4.2)$$

Applying $R$ to the annual effective dose $E$, we obtain the the formula,

$$E = \begin{cases} 0.4 \cdot 0.288 \cdot 8 \cdot 760 \cdot 9.0 \cdot 10^{-6} \cdot \overline{C}_{NT} & \text{for normal office hours} \\ 0.4 \cdot 0.384 \cdot 8 \cdot 760 \cdot 9.0 \cdot 10^{-6} \cdot \overline{C}_{OT} & \text{for overtime office hours} \end{cases} \quad (4.3)$$

where $\overline{C}_{NT}$ and $\overline{C}_{OT}$ are the average $^{222}$Rn concentrations for the normal office hours (9am – 6pm) and the overtime office hours (8am – 8pm) respectively.

### 4.6.1 Dose in Homes

Table 4.4 shows the annual effective dose estimated for all eight of the residential homes using equation 4.1.

<table>
<thead>
<tr>
<th>Annotated Location</th>
<th>$C$ [Bq/m$^3$]</th>
<th>$E$ [mSv a$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room A</td>
<td>7±3</td>
<td>0.17±0.08</td>
</tr>
<tr>
<td>Living room B</td>
<td>13±5</td>
<td>0.3±0.1</td>
</tr>
<tr>
<td>Bedroom 1</td>
<td>8±5</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>Bedroom 2</td>
<td>14±6</td>
<td>0.4±0.2</td>
</tr>
<tr>
<td>Bedroom 3</td>
<td>80±40</td>
<td>2±1</td>
</tr>
<tr>
<td>Bedroom 4</td>
<td>4±3</td>
<td>0.11±0.08</td>
</tr>
<tr>
<td>Bedroom 5</td>
<td>7±3</td>
<td>0.18±0.08</td>
</tr>
<tr>
<td>Bedroom 6</td>
<td>12±7</td>
<td>0.3±0.2</td>
</tr>
</tbody>
</table>

### 4.6.2 Dose in Offices

Table 4.5 shows the annual effective dose estimated for all three offices using equation 4.3. We noted that despite the large variation of $^{222}$Rn concentration in offices, there were not much increase in annual effective dose for the overtime workers from the workers fulfilling the normal office hours.
Table 4.5: Estimated annual effective dose $E$ for the offices.

<table>
<thead>
<tr>
<th>Annotated Location</th>
<th>$C_{NT}$ [Bq/m$^3$]</th>
<th>$E$ [mSv a$^{-1}$]</th>
<th>$C_{OT}$ [Bq/m$^3$]</th>
<th>$E$ [mSv a$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office A</td>
<td>$24 \pm 8$</td>
<td>$0.22 \pm 0.07$</td>
<td>$30 \pm 10$</td>
<td>$0.3 \pm 0.2$</td>
</tr>
<tr>
<td>Office B</td>
<td>$40 \pm 10$</td>
<td>$0.4 \pm 0.1$</td>
<td>$40 \pm 20$</td>
<td>$0.5 \pm 0.3$</td>
</tr>
<tr>
<td>Office C</td>
<td>$40 \pm 20$</td>
<td>$0.4 \pm 0.2$</td>
<td>$50 \pm 30$</td>
<td>$0.6 \pm 0.4$</td>
</tr>
</tbody>
</table>

4.6.3 Implications of Dose

Based on the report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the worldwide annual average dose for radon gas is 1.26 mSv a$^{-1}$ and the typical range is 0.2 – 10 mSv a$^{-1}$ [17]. Comparing our annual effective dose calculated in table 4.4 and 4.5 with these values, we noted that our values are at the lower end of the range. However, it is still necessary to sample more locations to assess the health risk of $^{222}$Rn in Singapore.

That being said, there is little scientific evidence of any measurable adverse health effects below 100 mSv. For radiation dosage below 100 mSv, the natural incidence of cancer might mask any effects that may have been caused by radiation. There are a few models proposed to account for the cancer effect at low radiation dose. The relationship between the risk of cancer and radiation exposure for each models are illustrated in figure 4.15.

![Figure 4.15: The relation between excess relative risk and low dose radiation for three different risk models. The diagram is not drawn to scale. 100 mSv is the lowest dose where excess cancers have been conclusively observed.](image)

The linear-no-threshold (LNT) model is used internationally by most health agencies and
4.6. Dosimetry

nuclear regulators. Epidemiology studies carried out for radiation doses above 100 mSv shows that the cancer risk is linear to the radiation dose. The LNT model assumes that at low dose radiation, the same direct and proportional relationship between the radiation exposure and cancer risk holds true. Most of the effective dose limits set by regulatory bodies followed from this model to reduce the number of cancer cases in a large population. On the other hand, the threshold model implies that there is no risk of cancer due to radiation below a certain threshold dose [18].

The hormesis model proposed that low dose radiation might be beneficial to health. This is suggested by studies on adaptive protective mechanisms which could be stimulated by low dose radiation. For example, after human fibroblasts cultures were exposed to low radiation doses and allowed to undergo cell proliferation, the level of DNA double-strand breaks decreases to that of unirradiated cell cultures [19].

For the purpose of this report, we would not be commenting on the validity of the proposed models. While the reported preliminary values fall within the lower spectrum of the worldwide annual effective dose, we do not have sufficient data to make a conclusive remark on the typical dose absorbed by Singaporeans.

That being said, we chose to consider the effective dose limit set by the LNT model for our future studies as it is the most conservative model among the three.
Chapter 5

Future Study

In this segment, we will be proposing some possible modifications to the original test to obtain more information on different factors contributing to the $^{222}$Rn level in Singapore.

5.1 Correlation with Temperature

To assess the relationship between $^{222}$Rn concentration and temperature without much influence by the effects of air ventilation, we measured the $^{222}$Rn variation in a room when the air conditioner is always switched on with some changes in temperature. Figure 5.1 show the plot of temperature variation together with the variation of $^{222}$Rn concentration.

![Figure 5.1: Variation of $^{222}$Rn concentration and variation of air temperature in a store-room in NUS Special Programme in Science. From the trend, there seem to be a negative correlation between $^{222}$Rn concentration and temperature.]

To quantify this trend, a scatter plot of $^{222}$Rn concentration and temperature is done for the data above as shown in figure 5.2.
5.1. Correlation with Temperature

Figure 5.2: Scatter plot of $^{222}\text{Rn}$ concentration and temperature for NUS Special Programme in Science storeroom.

While it appears to indicate a negative correlation between temperature and concentration, the trend is not very strong with a coefficient of determination of $R^2 = 0.438$. The data points for each temperature fall within a large range of uncertainty. However, this may be due to the fact that the temperature variations in this context are too minute for us to observe any notable relationship. Hence, we plotted a scatter plot of $^{222}\text{Rn}$ and temperature for Bedroom 3 (figure 5.3).

Figure 5.3: Scatter plot of $^{222}\text{Rn}$ concentration and temperature in Bedroom 3.

The scatter plot in figure 5.3 also implies a negative correlation between the $^{222}\text{Rn}$ concentration and air temperature with a coefficient of determination of $R^2 = 0.819$. Despite the decent coefficient of determination, we are unable to confidently conclude on the correlation between the $^{222}\text{Rn}$ concentration and air temperature. This is because the test
does not clearly separate the influence by temperature and ventilation effects (which have a stronger influence on the concentration). Therefore, it would be meaningful to carry a future study with methods to eliminate influence by air ventilation.

One suggestion would be to enclose the RAD7 detector and a temperature data logger in a chamber made with concrete obtained from a local construction company. The temperature could be varied by heating or cooling the chamber. Since the chamber is a closed system, there is little to no ventilation. Hence, this setup allows us to study the effects of air temperature only.

5.2 Radon Exhalation of Building Materials

As discussed in chapter 2, the exhalation rate of $^{222}\text{Rn}$ plays an important role in determining the concentration of $^{222}\text{Rn}$. The subsequent results from chapter 4.1 and 4.4 strongly suggest that $^{222}\text{Rn}$ could originate from Singapore’s building materials. As a result, it would be beneficial to study the exhalation of $^{222}\text{Rn}$ in those materials.

In an attempt, we filled a cartridge with building materials from a local construction company as shown in figure 5.4.

![Figure 5.4: Photograph of the sample of construction materials. The bottom would be connected to the inlet of the desiccant while the top would be connected to the outlet of the detector, thus forming a closed system.](image)
5.2. Radon Exhalation of Building Materials

The $^{222}\text{Rn}$ concentration was monitored over the course of 2 days. Figure 5.5 shows the variation of $^{222}\text{Rn}$ concentration over time. The concentration of $^{222}\text{Rn}$ increases with a decreasing rate. Eventually, the graph seem to suggest that it has almost reached a steady state.

![Figure 5.5: Variation of $^{222}\text{Rn}$ concentration when the RAD7 is connected to the building materials.](image)

The $^{220}\text{Rn}$ concentration reached an extremely high value of 1,800 Bq/m$^3$, in contrast to the typical $^{220}\text{Rn}$ concentration of $\leq 40$ Bq/m$^3$ we have measured in all the other locations (figure 5.6). The high concentration might be due to the presence of large amounts of thorium. In addition, since the grains size are extremely small, the $^{220}\text{Rn}$ has sufficient time to reach the RAD7 before it decays. Besides the high concentration, we also observed that the $^{220}\text{Rn}$ concentration decreases over time (opposite trend with $^{222}\text{Rn}$). We wish to find a reasonable explanation for this opposing trend in the future.

In hindsight, calculating the absolute exhalation rates might not be feasible as the shapes and sizes of the material differs. Also, this setup might not be a good indicator of the exhalation rate in Singapore’s building materials. As mentioned in chapter 2, parameters such as humidity and air pressure affect the $^{222}\text{Rn}$ exhalation rates. Hence, the imposed conditions during the test should ideally match the typical conditions experienced in Singapore. However, since this setup uses a desiccant in a closed chamber, the humidity
Figure 5.6: Variation of $^{220}$Rn concentration when the RAD7 is connected to the building materials.

of the rocks would be much lower than the humidity in Singapore. Given that the RAD7 detector actively pumps air through the sample, the air pressure would be greater than the atmospheric pressure. To account for these parameters in this test, we propose using a passive detector which can work in high humidity. Among the detection techniques listed in chapter 3, the etched track detector is most suited for this test.

Nonetheless, this setup can be explored as a potential calibration tool for RAD7 to identify any drifting of the detector. Moving forward, we could assess the reproducibility of these results and study the outcome of the test when the construction materials are halved.

### 5.3 Weather Conditions

Outdoor $^{222}$Rn concentrations are predicted to increase slightly when there is rainfall. We could use this observation to test RAD7 sensitivity (resolution of the $^{222}$Rn concentration). Currently, we are unable to carry out the measurement of outdoor $^{222}$Rn concentrations under rainy conditions. This is because RAD7 cannot be exposed to water due to the electronics.

One suggestion would be to introduce longer tubing to connect the desiccant and the detector. With this, the RAD7 equipment could remain in the shelter while we measure
the outdoor levels.

5.4 Introducing a Second Detector

Having a second RAD7 would benefit the project as it could be used to measure space variation within homes and eliminate other factors affecting the $^{222}$Rn concentration.

5.4.1 Space Variation Within Homes

With two or more detectors, simultaneous measurements at different positions could be used to determine the concentration gradient of $^{222}$Rn. Using the concentration gradient, we could evaluate the effectiveness of different protocols of detector placement.

5.4.2 Eliminating Other Factors

Since most of the people in Singapore live in high rise buildings, it would be meaningful to study the variation of $^{222}$Rn concentration with building height. However, this study cannot be done with one detector alone. $^{222}$Rn concentration may vary from different times of the day (diurnal variation) and even different days (due to wind speed and other conditions). By introducing multiple detectors to measure $^{222}$Rn concentrations at the same time, we could eliminate the factor of time.

One of our concern regarding the RAD7 would be the accumulation of old decay progenies in the detector. If the old decay progenies are not purged out of the detector, the $^{222}$Rn concentration in the given time would be an overstatement of the actual concentration. By introducing a second detector, we would be able to test if the increase in $^{222}$Rn concentration is due to the progenies accumulation or due to actual fluctuation in environment. This could be done by starting the second detector a few hours after the first detector is running.
Chapter 6

Conclusion

In the report, we established our objectives to carry out the first studies of $^{222}\text{Rn}$ concentration in Singapore. Using RAD7, we measured several locations in Singapore and found out that the $^{222}\text{Rn}$ concentration rose to high values when there were little ventilation. Whenever there were good ventilation, our measurements would fall within the lower spectrum of the average international values of $^{222}\text{Rn}$ concentration. Upon computing the annual effective dose due to each of the location, we noted that all of the doses (except Bedroom 3) were lower than the worldwide annual average dose for radon gas of 1.26 mSv a$^{-1}$. This result holds true even for the offices which $^{222}\text{Rn}$ concentrations occasionally exceed the USA action level. This is because the periods of high $^{222}\text{Rn}$ concentration coincides with after office hours. However, we would require a larger sample size to conclude on the typical $^{222}\text{Rn}$ concentration in Singapore. In addition, we proposed future investigations of other factors affecting $^{222}\text{Rn}$ concentration — such as weather conditions, air temperature and the building materials. Regardless, our preliminary results have provided some insights on $^{222}\text{Rn}$ concentration across various locations in our nation. We believed that our study would assist future researchers in embarking on an island wide data collection in Singapore.
Bibliography


Appendices
Appendix A: Deriving the Fluence Rate for $^{222}$Rn

Assuming that we only consider the molecular diffusion transport mechanism, the steady state equation for $^{222}$Rn concentration is given by,

$$D_e \frac{\partial^2 C}{\partial x^2} - \lambda_{Rn} C = 0 \quad (1)$$

where $x$ is the one-dimensional spatial component, $D_e$ is the effective radon diffusion coefficient, $C$ and $\lambda_{Rn}$ are the concentration and the decay constant of $^{222}$Rn respectively. The first term of the equation represents the diffusion of $^{222}$Rn while the second term represents the natural decay of $^{222}$Rn.

By applying the boundary conditions in equation 2.2 to the solution for equation 1, we obtain the solution:

$$C(x) = -\frac{C_{Ra} f \rho \sinh \left( (x - d) \sqrt{\frac{\lambda_{Rn}}{D_e}} \right)}{\sinh \left( d \sqrt{\frac{\lambda_{Rn}}{D_e}} \right)}$$

$$= -\frac{C_{Ra} f \rho \sinh \left( \frac{x - d}{l_d} \right)}{\sinh \left( \frac{d}{l_d} \right)} \quad (2)$$

where $C_{Ra}$ is the activity concentration of $^{226}$Ra, $f$ is the fraction of $^{222}$Rn which successfully emanates into the pores, $\rho$ is the density of the material and $l_d = \sqrt{\frac{D_e}{\lambda_{Rn}}}$ is the diffusion length of $^{222}$Rn.

Substituting equation 2 into the Fick’s law in equation 2.1 enables us to obtain the fluence rate for position $x = d$,

$$J_D = -D_e \frac{\partial}{\partial x} \left( -\frac{C_{Ra} f \rho \sinh \left( \frac{x - d}{l_d} \right)}{\sinh \left( \frac{d}{l_d} \right)} \right)$$

$$= -D_e \left( -\frac{C_{Ra} f \rho \cosh \left( \frac{x - d}{l_d} \right)}{\sinh \left( \frac{d}{l_d} \right)} \right) \sqrt{\frac{\lambda_{Rn}}{D_e}}$$

$$= \frac{C_{Ra} \lambda_{Rn} f \rho l_d}{\sinh \left( \frac{d}{l_d} \right)} \quad (3)$$
Appendix B: Obtaining Decay Graph

To plot the decay curves of $^{222}$Rn, $^{218}$Po and $^{214}$Po, we solved the following differential equations analytically:

\[
\frac{dN_{222\text{Rn}}}{dt} = -\lambda_{222\text{Rn}} N_{222\text{Rn}}(t)
\]

\[N_{\text{Rn}}(0) = 10^5\]

\[
\frac{dN_{218\text{Po}}}{dt} = -\lambda_{218\text{Po}} N_{218\text{Po}}(t) + \lambda_{222\text{Rn}} N_{222\text{Rn}}(t)
\]

\[N_{218\text{Po}}(0) = 0\]

\[
\frac{dN_{214\text{Pb}}}{dt} = -\lambda_{214\text{Pb}} N_{214\text{Pb}}(t) + \lambda_{218\text{Po}} N_{218\text{Po}}(t)
\]

\[N_{214\text{Pb}}(0) = 0\]

\[
\frac{dN_{214\text{Bi}}}{dt} = -\lambda_{214\text{Bi}} N_{214\text{Bi}}(t) + \lambda_{214\text{Pb}} N_{214\text{Pb}}(t)
\]

\[N_{214\text{Bi}}(0) = 0\]

\[
\frac{dN_{214\text{Po}}}{dt} = -\lambda_{214\text{Po}} N_{214\text{Po}}(t) + \lambda_{214\text{Bi}} N_{214\text{Bi}}(t)
\]

\[N_{214\text{Po}}(0) = 0\]
Appendix C: Measurements for all Office

Figure 1: A second measurement on the variation of $^{222}$Rn concentration in NUS S13-03-03 office, with air exchanges when aircon is operating. Annotation: Office A

Table 1: Gradient and coefficient of determination of the linear fit for each slope for the measurements in Office A.

<table>
<thead>
<tr>
<th>Dates</th>
<th>Time</th>
<th>Gradient [Bq m$^{-3}$ h$^{-1}$]</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/11/2017 – 16/11/2017</td>
<td>11pm – 5am</td>
<td>11±2</td>
<td>0.905</td>
</tr>
<tr>
<td></td>
<td>7am – 1pm</td>
<td>-9±2</td>
<td>0.742</td>
</tr>
<tr>
<td></td>
<td>11pm – 5am</td>
<td>8±2</td>
<td>0.814</td>
</tr>
<tr>
<td></td>
<td>7am – 1pm</td>
<td>-10±3</td>
<td>0.738</td>
</tr>
<tr>
<td></td>
<td>11pm – 4am</td>
<td>7±1</td>
<td>0.823</td>
</tr>
<tr>
<td></td>
<td>5am – 11am</td>
<td>-9.0±0.9</td>
<td>0.950</td>
</tr>
<tr>
<td>17/11/2017 – 20/11/2017</td>
<td>10pm – 4am</td>
<td>13±2</td>
<td>0.904</td>
</tr>
<tr>
<td></td>
<td>5am – 10am</td>
<td>-13±1</td>
<td>0.949</td>
</tr>
<tr>
<td></td>
<td>7pm – 2am</td>
<td>9±2</td>
<td>0.836</td>
</tr>
<tr>
<td></td>
<td>7am – 11am</td>
<td>-18±3</td>
<td>0.961</td>
</tr>
<tr>
<td></td>
<td>12pm – 6am</td>
<td>3.2±0.3</td>
<td>0.879</td>
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<tr>
<td></td>
<td>7am – 1pm</td>
<td>-16±4</td>
<td>0.774</td>
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</table>
Figure 2: Variation of $^{222}$Rn concentration in the level 4 office cubicles in 1 CREATE Way #04-01, with air exchanges when aircon is operating. Annotation: Office B

Table 2: Gradient and coefficient of determination of the linear fit for each slope for the measurements in Office B.

<table>
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<tr>
<th>Dates</th>
<th>Time</th>
<th>Gradient [Bq m$^{-3}$ h$^{-1}$]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>18/12/2017 – 20/12/2017</td>
<td>8pm – 5am</td>
<td>21.0±0.7</td>
<td>0.991</td>
</tr>
<tr>
<td></td>
<td>6am – 10am</td>
<td>-39±4</td>
<td>0.971</td>
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<tr>
<td></td>
<td>8pm – 5am</td>
<td>24±1</td>
<td>0.980</td>
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<tr>
<td></td>
<td>6am – 10am</td>
<td>-45±7</td>
<td>0.955</td>
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</tbody>
</table>

Figure 3: Variation of $^{222}$Rn concentration in a level 4 office meeting room in 1 CREATE Way #04-01, with air exchanges when aircon is operating. Annotation: Office C
Appendix D: Measurements for all Homes

Figure 4: Variation of $^{222}\text{Rn}$ concentration in a living room in Lorong Chuan. Type of house: Condominium level 8; Annotation: Living room B

Figure 5: Variation of $^{222}\text{Rn}$ concentration in a bedroom in Pasir Ris. Type of house: HDB estate level 4; Annotation: Bedroom 1
Figure 6: Variation of $^{222}\text{Rn}$ concentration in a bedroom in Sembawang. Type of house: HDB estate level 8; Annotation: Bedroom 2

Figure 7: Variation of $^{222}\text{Rn}$ concentration in a bedroom in Pasir Ris. Type of house: Landed property level 2; Annotation: Bedroom 5
Figure 8: Variation of $^{222}\text{Rn}$ concentration in a bedroom in Tampines. Type of house: HDB estate level 8; Annotation: Bedroom 6.
Appendix E: Another measurement for the SNRSI lab

Figure 9: Variation of $^{222}$Rn concentration in the SNRSI lab in 1 CREATE Way level B1.