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Radon Monitoring in Air, Water and Soil

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1. INTRODUCTION

In ICRP 65 [1] W.Jacobi wrote, *"the radon saga is a scientific thriller with tragic features and political confounders".* The radon saga dates back to the mining industry, in around 1470 when extensive mining of silver began in Schneeberg southern Germany. Over the years radon issues have interested scientist, politicians, labour and the general public.

In this paper there are three broad issues that will be discussed. These will be a brief overview of radon, radon monitoring, and challenges in radon monitoring. In the brief overview the discussed points will be; what is radon, why the interest in radon, and brief history of radon. Radon monitoring will be discussed from a general perspective, and certain specific issues on radon monitoring in air, water and soil will be raised. In the last section challenges in radon monitoring will be presented.

2. RADON: A BRIEF OVERVIEW

2.1 A brief history (based on ICRP 65)

Radon remained a chemical curiosity for decades, even being promoted at times as a 'health giving' gas at various spas [2]

The history of radon dates back to the 15th century when a high mortality from lung disease was observed among young silver miners of Schneeberg region (a small city in Saxony /Germany). The disease was called 'Schneeberger Lungenkrankheit' (Schneeberger Lung disease). There were also mining activities in Jachymov. The mining techniques that were used in this region were described by Agricola (1494-1555) in his book *De Re Metallica*. A mining engineer Herbert C Hoover and his wife translated this book into English. Hoover later became the president of the United States of America. The occurrence of the disease increased in the 17th and 18th centuries due to increased mining.

After Marie and Pierre Curie had extracted Radium (Ra-226) from Jachymov ores (1898), the radium emanation (radon) was identified. The first radon measurements were then done in the mines of Schneeberger and Jachymov by Elster and Geitel (1901). Very high radon concentrations were found in the mines. The results of these measurements were used as the basis for assuming a relationship between radon and lung cancer. Although more radon measurements carried out in these mines seemed to support the hypothesis, it still was not generally accepted.

It was not until 1953 that it was understood that the radon progeny are the causative agents of lung cancer. This was after a proposal by William F. Bale who wrote that "*In these and other past evaluations of the hazard associated with radon, the vital fact seems to have been almost entirely neglected that the radiation dosage due to the disintegration products of radon, present in the air under most conditions where radon itself is present, conceivably and likely will far exceed the radiation dose due to radon itself and to disintegration products formed while the radon is in the bronchi*".

A probable influence of radon on lung cancer risk to members of the public was discovered very recently. The first published indoor radon measurements were done in Sweden (Hultqvist 1956) in a study initiated by Rolf Sievert. Years later, more radon surveys were made in several countries as reported in the UNSCEAR reports. The estimation of lung cancer risk from indoor progeny exposure is based on epidemiological data of radon exposure in underground mines.

Basically the history of radon dates back to the mining industry.

2.2 What is radon?

The radioactive gas produced in the decay of the uranium decay series has born several names. The name 'radon' was introduced by Schmidt in 1918 [2] and is now universally used as the name of this element.

Radon is a naturally occurring radioactive inert gas, which has no taste, smell or colour. It occurs in the radioactive decay of radium, which is formed in the radioactive decay series of natural uranium. Radium acts as a permanent source of radon and is found in small quantities in all soils, rocks and minerals although the amount varies from place to place.

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} + 4.60\ \mathrm{MeV} \quad \ldots \quad 2.1$$

$$^{224}_{88}\mathrm{Ra} \rightarrow {}^{220}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} + 5.69\ \mathrm{MeV} \quad \ldots \quad 2.2$$

$$^{223}_{88}\mathrm{Ra} \rightarrow {}^{219}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} + 5.50\ \mathrm{MeV} \quad \ldots \quad 2.3$$

The equations above illustrate the mode of the formation of the three naturally occurring isotopes of radon, Rn-222 (radon), Rn-220 (thoron) and Rn-219 (actinon). They occur in the decay chains of the three primordial radionuclides U-238, Th-232 and U-235 respectively as shown in the radioactive decay equations forming parts of the three decay series as illustrated in figure1 [3]

The radon isotope in the thorium decay series, originally known as thoron, was discovered by Soddy and Rutherford in 1900. That in the U-238 decay series, by Dorn in 1901 and that in the U-235 series, originally known as actinon, by Giesel in 1902 [4].

Actinon has a very short half-life of 3.96 s. Since it occurs in the decay chain of U-235 which is only present as 0.7% of natural uranium, the abundance of actinon in gases from most geological sources is very low. Thoron has a somewhat longer, but still very short, half-life of 55.6 s and is not usually important unless very large concentrations of thorium are present. Rn-222 having a relatively long half-life of 3.82 days can be distributed via air and water. It can travel long distances before it decays. In this paper, the term radon will be used to apply to the isotope Rn-222.

2.3 Why the interest in radon

Radon's unique properties as a naturally occurring radioactive gas have led to its use as a geophysical tracer for locating buried faults and geological structures, in exploring for uranium, and for predicting earthquakes [5,6]. Radon has also been used as a tracer in the study of atmospheric transport process [7,8]. There have been several other applications of radon in meteorology, water research and medicine [9].

Much attention, however, has been given to radon as a radiological health hazard. More recently, human exposure to radon decay products in buildings has emerged as an important issue

Lung cancer is the principal health concern associated with radon exposure. Radon itself is only partially responsible for the hazard. Being chemically inert, it does not accumulate to any great degree in the body. Rather, the primary concern is associated with the decay products of radon. These species are chemically reactive and so may be deposited on respiratory tract tissues when inhaled. Subsequently alpha particle decays may damage cells near the deposition site, contributing to an increased risk of lung cancer. Recent studies have also suggested that childhood leukaemia may be linked to radon exposure [10]. Radon progeny are a transient series within a major radioactive series (shown in figure 1). Only the short-lived daughters have significance as far as the release of alpha energy is concerned in relation to dosage. Decay beyond Pb-210 is not generally considered important as a health hazard because the total absorbed alpha energy is slowed drastically by the 22-year half-life of Pb-210.

Two main factors have led to much attention being given to radon exposure as a radiological health hazard [9].

- The establishment of a positive and significant correlation between lung cancer incidence rate and radon progeny exposure in mines, during the 1960s.

- The increased indoor radon levels as a result of the large-scale tendency towards energy saving in houses by lowering the air exchange rate.

The potential magnitude of the problem of human exposure to radon and its progeny can be summarised in the following statement.

Of the aggregate radiation dose received by human populations, the dominant portion is associated with inhalation of radon progeny. The relative magnitude of the natural source of radiation is summarised in table 1 and typical indoor radon concentrations are given in table 2. Table 2 shows values from a few countries, there are, however, many more countries that have conducted radon surveys indoors.

3. GENERAL ISSUES REGARDING RADON MONITORING

Designing and implementing a radon-monitoring program is very site specific. Although this section will be presented in general terms, the important issues in radon monitoring will still be addressed.

The Monitoring Plan

Using a plan, radon monitoring will be organised into steps that will ensure proper progression of the work and appropriate use of resources. The different steps in the plan development are indicated below:

RADON MONITORING PLAN

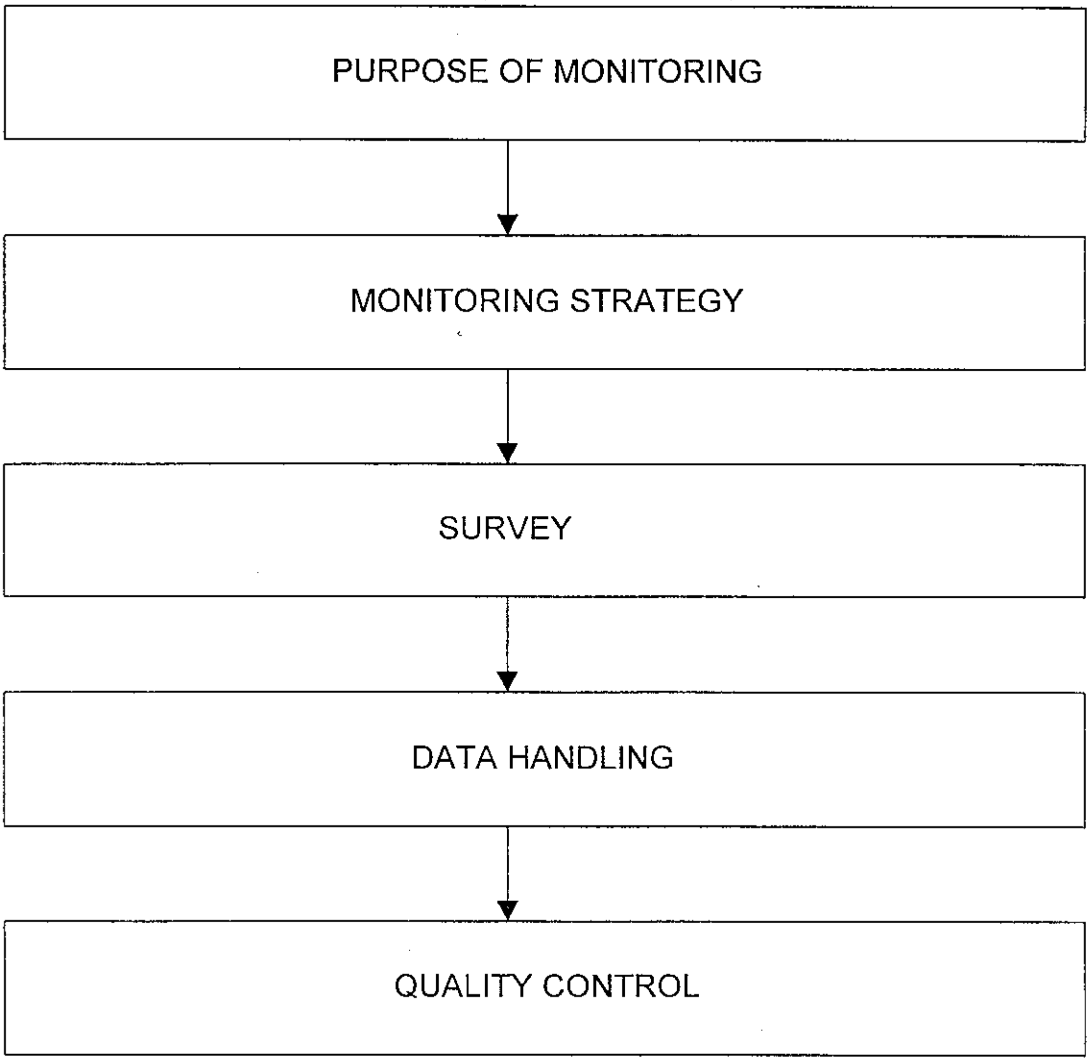

Figure 2. A radon monitoring plan

The figure shows the various steps in a radon-monitoring plan.

Certain generic factors can be used to decide on each of the steps in the monitoring plan. The generic factors include the following.

a. Meteorological conditions during the implementation of the program.

b. The environmental condition during the monitoring program. This refers to things like moisture content of tailings, wet or dry conditions in the underground environment.

c. Distribution of people in the area to be monitored and possible changes during the monitoring period.

d. Sampling (location, frequency, and number of samples).

e. Regulatory requirements (if applicable)

3.1 Purpose of monitoring

For a good monitoring program it is important to clearly define the purpose of monitoring in the forefront.

Generally monitoring is performed to detect, quantify, and compare results with goals. Monitoring must therefore be fit for purpose it must provide sufficient information to enable decision making.

If the purpose is not sufficiently understood, it is possible to spend huge resources on a monitoring program that is not appropriate, especially because the purpose will impose certain requirements and restrictions on a number of monitoring parameters in the monitoring plan.

Generally, purposes for radon monitoring can be classified under each of the following categories:

- Demonstrate compliance for
  - Public exposure
  - Worker exposure (including keeping doses ALARA)
- Research and development
- Public assurance and remediation/intervention.
  - identification of areas with high indoor radon levels

- diagnostic measurements for remedial actions

Each of these categories would have specific objectives for monitoring. In this discussion more focus will be given to monitoring for demonstrating compliance, although some of the issues discussed may also be applicable to monitoring for other purposes.

Monitoring to demonstrate compliance.

Monitoring to demonstrate compliance would be mostly applicable to authorised operations.

For compliance purposes monitoring can be divided into three stages namely; pre-operational monitoring, operational monitoring, and post-operational monitoring. The post operational could be long and short term. Each of the different stages has specific objectives.

Pre-operational monitoring is important to develop baseline data. The baseline data is used for comparison during the operational stage of a facility and for determining the adequacy of closeout activities.

The objective of operational monitoring includes the following: [13]

- Demonstrate compliance with safety standards for workers and members of the public and the environment.
- Evaluation of the adequacy of control measures
- Obtaining data for decision regarding post-operational remedial actions.

The objective of post-operational monitoring will be to: [13]

- Confirm pathways and measure long term dose commitments to critical groups following remedial actions; and
- Confirm, after the remedial actions have been completed, that releases are within acceptable levels.

Public assurance and remediation/intervention

Radon monitoring for public assurance is generally carried out with an objective to determine the remedial measures that must be done. In some countries radon monitoring is done to establish a nation-wide average value, or to identify areas and houses with high radon concentrations. The monitoring is usually done in homes, and office buildings where the safety requirements of authorised facilities do not necessarily apply.

Members of public are usually advised on the results of the monitoring and the necessary actions are taken. In some countries it is up to the member of public to do remedial measures, while in some countries there are government policies that have been established to assist people with houses that have high radon concentration.

3.2 Monitoring Strategy

In developing a monitoring strategy for radon, there are at least two issues that must be considered. The first issue is that the concentration of radon is influenced by seasonal and diurnal variations. The second issue is that the strategy must be influenced by the scale of the monitoring program. It is usual that in a large-scale program where thousands of dwellings are monitored, simple and inexpensive devices are used [14]. This also applies to a monitoring program in a large mining industry like in the Republic of South Africa where there are hundreds of thousand workers.

On the other hand, in-depth measurements would require a more extensive and complex instrumentation [14].

Under the monitoring strategy, three issues will be discussed.

3.2.1 *The measurand*

Radon monitoring can be done using measurement techniques that depend on the radioactive properties of the radon gas or its progeny. A decision must therefore be taken whether radon would be monitored by measuring the gas or the progeny. The choice of either measuring the progeny or the gas will depend on many variables including the resources, and purpose of monitoring program.

3.2.2 *The monitoring types*

There are three different categories of radon monitoring that may be identified. These are source monitoring, environmental monitoring, and individual monitoring. Sources of radon could include the soil, tailings, building material, water, ore body, worked out area, up cast shaft from underground mining, etc. If more than one type of monitoring is used, there needs to be reconciliation of data before decisions are made.

Source term monitoring is the detection and quantification of radon that is discharged from a source to the environment, which is common in the case of an authorised operation.

Environmental monitoring refer to detection and quantification of radon in the environment which includes air, soil and water. Regarding human exposure, environmental monitoring could be regarded as monitoring at the receptor point, which could include indoor environment, outdoor environment, area monitoring for underground working, etc. In the case of monitoring for the protection of members of the public, environmental monitoring can further be divided into single source, and multiple source monitoring.

Individual monitoring include detection and quantification of radon to which an individual person is exposure. This is common for dosimetry purposes in the case of workers especially when individual doses approaches the dose limit. This though is not common for members of the public, except for scientific purposes such as validation of models and development of certain techniques. Individual monitoring entail monitoring radon for each individual or monitoring a representative population of the workers based on some statistical sampling criteria.

During the development of the monitoring plan, the type of monitoring must be decided.

3.2.3 Monitoring techniques and methods

The basic theory for monitoring radon is common for all the techniques. The techniques rely mainly on the radioactive properties of the gas and its progeny. Radon and its progeny Po-218 and Po-214 are alpha emitters, while the other two, Pb-214, and Bi-214 are beta and gamma emitters. The various techniques measure the high-energy alphas or the gamma energies from these daughters, only a few techniques are based on the beta decays [15].

Two other characteristics distinguish the measurement techniques for radon. These are whether radon or its progeny is measured, and the time resolution of the technique. Regarding time resolution the techniques are grouped into three modes; grab-sample mode, continuous mode, and integrating mode.

In the grab sample mode, the radon concentration of air sample collected over a short time at a single point is determined. In the continuous mode, information is obtained on the time dependence of radon concentration. In the integrating mode, the technique gives the radon concentration integrated over the sampling period. The sampling period could vary from days to months. The modes may further be grouped into active and passive. The mode selected will depend on many factors like availability of resources, sensitivity, available time before decision-making, etc.

There are at least seven different techniques that have been used for radon measurements [13]. These techniques include Ionisation chambers, scintillation cells, activated charcoal detectors, solid state nuclear track detectors, solid state surface barrier detectors, thermoluminescent dosimeters, electret ion chambers, and electrostatic precipitation technique.

Radon concentrations in the environment are usually low therefore, accuracy and precision of measurement techniques are considered in selecting the technique to be used. Detector response is another parameter that must be considered. The advantages and disadvantages of these techniques are with regards precision, mode, and detector response. If data were required immediately, a grab technique would have an advantage over an integrating technique although there could be issues of representivity of the sample.

When the technique has been selected the measurement method to be followed in monitoring radon must be well documented to ensure that monitoring performed by different operators at different times are comparable and consistent. This will entail detailing the sampling protocol, which will include sampling procedure, sampling location, sampling frequency, and sample suite. Precaution must be taken regarding background determination, and calibration conditions.

3.3 Survey

When the technique and method for radon monitoring has been decided, the next step is the actual survey. In many countries that have done radon monitoring especially on a large-scale, the survey is usually carried out in two main phases.

The first phase is usually a preliminary or pilot survey. The essential elements of this phase are site characterisation and screening survey. The surveys in this first stage offer the initial experience to the experimentalist. Some screening criteria may be based on specific features that have an influence on radon emanation like, uranium deposits, granitic areas, type of material used for building etc. Some of the conclusions of this phase may be to re-define the objectives of the next stage of the survey.

The next stages of the monitoring usually involve a detailed survey. This phase may be designed based on the conclusions of the pilot work and the overall purpose of the monitoring. At this stage, one of the important issues is to make sure that quality data is obtained to enable good input to the decision-makers.

3.4 Data handling

Data handling will entail analysis of data, and records and reporting.

Analysis of data

The fundamental aim of data analysis is to be able to compare the results against the objective of the monitoring. If the objective was to demonstrate compliance, the analysis must be done according to regulatory requirements. Some regulatory requirements may relate to; exposure time, equilibrium factor, dose conversion factors, uncertainty analysis, laboratory capabilities, etc.

Uncertainty analysis is an important element of data analysis. It is an acceptable fact in science that with any measurement there is a certain degree of uncertainty associated with it. The user of the results must be given a certain confidence level against which to rely on the given results.

Records and reports

Recording and reporting the results of monitoring is very important. Certain recording and reporting formats may need to be used, but this depends on the purpose of the monitoring. A report is a summary of the monitoring.

3.5 Quality control

The monitoring program must be able to address the following three issues: calibration, standardisation, and quality assurance.

Calibration can be understood as the determination of a factor for converting a detector/instrument response into the required quantity, which is radon concentration in this case. The instrument is usually calibrated in a controlled condition where the activity concentration is sufficiently high to reduce measurement uncertainties. The calibration conditions must be documented.

Standardisation reflects the traceability to international standards. The standard used in calibrations must be traceable to national standards, which must be consistent with international standards. Regarding standardisation, it is also important that the measurement conditions are consistent with the calibration conditions otherwise, certain corrections must be made.

The basic objective of quality assurance is to provide confidence in the radon monitoring program (sampling, data handling, and interpretation of the data)[16]. Quality assurance activities should start from project design and be maintained through out until decision making. There must be a quality assurance program.

4. SPECIFIC ISSUES FOR RADON MONITORING IN AIR, WATER AND SOIL

4.1 Monitoring in air

Radon monitoring in air could be done indoor, outdoor and in underground mining environment. The sources of radon indoor could be internal, and external. The internal sources include building material, water, basement air, soil, etc [17]. The external source is mainly outdoor air. Radon levels indoors are usually a result of its generation and mobility in the various sources combined with openings into building [18].

The main factors that affect the variations of radon indoor are changes in ventilation rate, and temperature differences. The ventilation rate affects the air exchange rate between indoors and outdoors. When windows and doors are closed the radon level in the house increases from internal sources, and the reverse is true when the house is open. Differences in temperature result in pressure differences between indoors and outdoors. This creates a driving force for radon to enter indoors. When the indoor pressure is low, radon is sucked into the house [19]. The temperature differences are because outdoor temperatures vary widely during day and night, while indoor temperatures may not change greatly. Seasonal changes also results in temperature differences between indoors and outdoors.

Integrating techniques are usually the best for monitoring air. Using these techniques, the diurnal and seasonal variations can be accounted for. It is also a fact that radon concentration in outdoor air is usually low (see table 3). The use of integrating techniques and sampling over a long time can improve the quality of data even at these low concentrations. The solid state nuclear track detectors, charcoal canister detectors, and electret ion chambers are widely used for radon gas as integrating technique.

The levels of Radon and progeny are measured in units of Bqm^{-3} (Becquerel per cubic metre). 1 Bq of radon per cubic metre of air can be understood to mean one radon atom decay per second in every cubic metre of air. The concentration of progeny is presented as the Equilibrium Equivalent Concentration (EEC), where EEC is expressed in Bqm^{-3}.

4.2 Monitoring in water

Radon is soluble in water. Radon in water is due to the radium in the water, surrounding soil and bedrock. The concentration of radon in ground water is usually much higher than it is in surface water [20]. Typical values of radon in surface water are around 40 Bqm^{-3}, while in ground water it ranges from 4 to 40 $kBqm^{-3}$ [11] (see table 4).

When water is used indoors, the radon in the water outgasses and becomes airborne [21].

Radon monitoring in water has been done using various methods most of which are grab sample techniques. Some of the methods include degassing radon dissolved in the water and then using scintillation cells to measure the radon [22]. Other methods involve extracting radon from the liquid using liquid scintillation cocktail and then counting in a liquid scintillation spectrometry [23]. The electret ion chamber is also used for radon determination in water.

4.3 Monitoring in soil

Radon monitoring in soil involves either measuring the radon in soil air or measuring the radon flux from a soil. There are a number of in-situ and laboratory methods that have been developed for radon monitoring in soil gas. The in-situ methods used for radon flux can be grouped into three categories namely; accumulation, flow-through, and adsorption [13]. The accumulation involve placing a container over the test surface with the open end on the surface (see figure 3). This method measures the radon build-up within the container as a function of time. The flow-through method although resembling the accumulator configuration, it measures the radon concentration in the exhaust gas (see figure 4). The adsorption method measures the radon flux using an adsorption medium positioned close to the test surface. Activated charcoal is used as a typical adsorption medium. The accumulator is usually used as a grab method, while the adsorption method can be used as an integrating technique[24]

Laboratory methods for determining flux tend to rely on a combination of measurements and computational methods[26]. In the laboratory some of the input parameters and variables are measured, these would include radium content, emanation coefficient, and diffusion coefficient.

5. CHALLENGES IN RADON MONITORING

There are many challenges regarding radon monitoring, however, in this paper only a few are presented.

5.1 The monitoring plan

This is not a technical challenge, but a project management one. Often a technical person or a scientist is required to do a large-scale radon monitoring which may require huge resources. If indeed monitoring is performed to detect, quantify, and compare results with goals, then an aspect of project management comes into radon monitoring. The challenge is where do you start, (Do you buy a few equipment and then start measuring next to your mother's house?).

The approach that is proposed here is that start by developing a monitoring plan. If the monitoring plan is not properly design, resources can be wasted, and incorrect conclusions can easily be drawn. It is good to spend some time in the beginning to address the 4W+H (what, who, when, where, and how).

5.2 Dose estimation based on source and environmental monitoring

Doses to a critical group situated some distance from a source can be estimated using any of three monitoring types. Suppose Source monitoring and environmental monitoring are used in a particular situation. To estimate doses using results from source monitoring usually requires a combination of source term measurements and transport model. Using environmental monitoring, the measurements could be done at the receptor thus giving a more reliable value of the exposure received by the critical group.

In most cases, the dose estimates from these two monitoring types do not agree. Should the best option be to discard the results from source term monitoring in favour of those from environmental monitoring.

If the purpose of the monitoring was to demonstrate compliance from an authorised operation, the concern is usually with regards the incremental above background. If there had been no baseline data, should it still be appropriate to consider dose based on environmental monitoring which include exposure from background. How should the background be estimated if the source term covers vast areas and there has been in operation for decades, such that what was background then and what it is now cannot be clearly distinguished. Should one then measure background some distance away, what about the differences in geology.

5.3 The equilibrium factor

In most large-scale radon surveys, the radon gas is measured instead of the progeny. This is usually due to high costs of progeny measuring devices especially if the surveys are to be carried on over several months. In order to estimate the dose, one needs to know the equilibrium factor.
This factor (F factor), gives the relationship between the contents of radon progeny and radon [20]. The equilibrium factor may vary due to many changes indoors and in underground environment. In houses where wood fire is used (typical in Africa), and where smokers reside, there will be a lot

of smoke and the equilibrium factor may be increased. In underground mining, the ventilation conditions vary with districts and thus the residence time changes, which in turn changes the equilibrium factor.

How should the equilibrium factor be determined simultaneously with the radon survey, or should one just use average values.

5.4 Area monitoring and individual monitoring

For dosimetry it is expected that a certain dose value is assigned to individuals. This should entail personal monitoring of all the individuals or a representative fraction of the people. In many cases, area monitoring is done and then doses are estimated from the monitoring results. This is usually due to cost constraints.

There is a huge uncertainty that is introduced by trying to estimate individual doses based on area monitoring especially in underground workings when using grab techniques. The uncertainties are due to many factors including spatial and temporal representivity as a mine is a dynamic and continuously changing environment.

How should one balance the need to reduce uncertainty so as to assign reasonable accurate doses, with reducing costs to appreciable levels.

6. CONCLUSION

Indeed the field of radon is full of dilemmas, controversies and frustration [1], which still exist in many countries. If proper radon monitoring is done, the information obtained can go a long way in addressing some of these dilemmas, controversies and frustrations.

It is believed here, that a way forward towards providing useful information must begin with recognising that radon monitoring requires project management. Some elements of project management include the development of a plan, which is implementable, and should be regularly evaluated and improved. In the monitoring plan, technical issues and challenges can be addressed. Most importantly through the plan, the necessary budgetary constraints will be imposed and the required data quality achieved.

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Table 1 Human exposure to radiation [12]

Components of Exposure	Annual Effective Dose (mSv)
Radon	**1.28**
Cosmic Rays	0.38
Cosmogenic radionuclides	0.01
Terrestrial Radiation: external exposure	0.46
Terrestrial radiation: internal exposure	0.23
Total	**2.4**

Table 2 Indoor Radon Concentration [12]

Country	Type of sampling	Purpose of survey	Average value (Bqm-3)
Belgium	Radon, passive	Nation wide Population exposure (preliminary survey)	41(median)
Canada	Radon, radon progeny Grab samplings,	Nation-wide variability of exposure	33 (mean)
China		Population exposure	120 (mean)
Denmark	Radon, passive	Nation-wide Population exposure (pilot survey)	50 (median)
Germany	Radon, passive	Nation-wide Population exposure	49 (mean)
France	Radon, passive and Progeny active	Nation-wide Population exposure (preliminary results)	76 (mean)
Japan	Radon, electrostatic Integration	Nation-wide population exposure	10 (mean)
Sweden	Radon, passive	Nation-wide Population exposure	85 (mean)
South Africa*	Radon, passive	Identifying high radon houses	63 (average)
United Kingdom	Radon, passive	Nation-wide population exposure	17 (median) in living room
United States	Various	Nation-wide population exposure	61 (mean)

* Reference [25]

Table 3 Radon Concentration in outdoor air [11]

Location	Mean value (Bqm-3)
Austria	7.0
Bolivia	1.5
Finland	2.3
France	9.3
Germany Fed.Rep.of	2.6
India	3.7
Japan	2.1
Peru	1.5
Philippines	0.3
Poland	3.3
United kingdom	3.3
United States (Cincinnati)	9.6
Norwegian Sea	0.2

Table 4. Radon Concentration in water [11]

Location	Average concentration (kBqm-3)
Austria	
Salzburg	1.5
Finland	
Helsinki and Vantaa	1200
Other areas	280
Italy	80
Sweden	19
United States	
Aroostock, Maine	48
Cumberland, Maine	1000
Hancock, Maine	1400
Lincoln, Maine	560
Penobscut, Maine	540
Waldo, Maine	1100
York, Maine	670

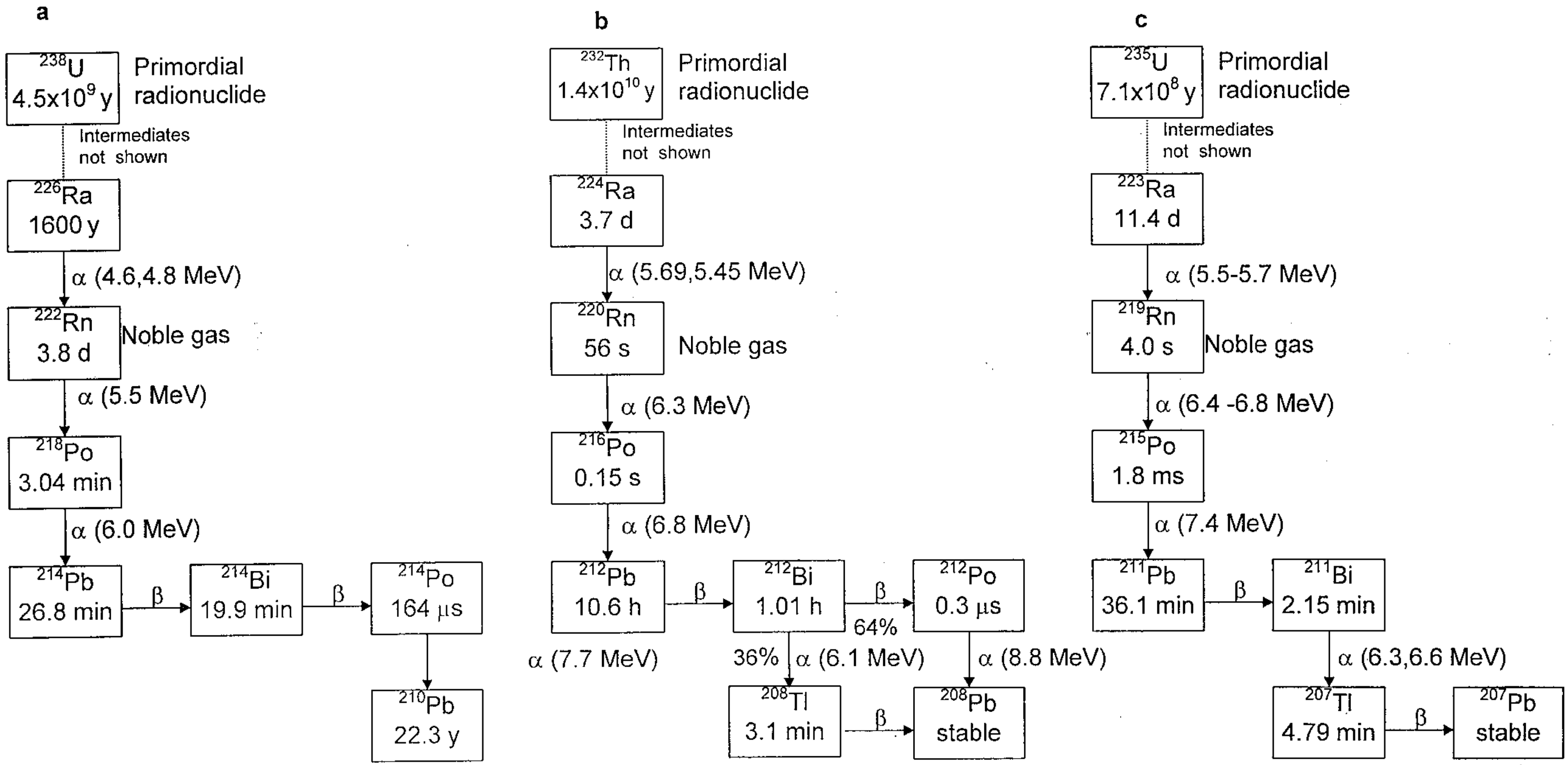
a
238U
4.5x10^9 y
Primordial radionuclide
Intermediates not shown
226Ra
1600 y
α (4.6,4.8 MeV)
222Rn
3.8 d
Noble gas
α (5.5 MeV)
218Po
3.04 min
α (6.0 MeV)
214Pb
26.8 min
β
214Bi
19.9 min
β
214Po
164 µs
210Pb
22.3 y
b
232Th
1.4x10^10 y
Primordial radionuclide
Intermediates not shown
224Ra
3.7 d
α (5.69,5.45 MeV)
220Rn
56 s
Noble gas
α (6.3 MeV)
216Po
0.15 s
α (6.8 MeV)
212Pb
10.6 h
α (7.7 MeV)
β
212Bi
1.01 h
β
64%
212Po
0.3 µs
36%
α (6.1 MeV)
α (8.8 MeV)
208Tl
3.1 min
β
208Pb
stable
c
235U
7.1x10^8 y
Primordial radionuclide
Intermediates not shown
223Ra
11.4 d
α (5.5-5.7 MeV)
219Rn
4.0 s
Noble gas
α (6.4 -6.8 MeV)
215Po
1.8 ms
α (7.4 MeV)
211Pb
36.1 min
β
211Bi
2.15 min
α (6.3,6.6 MeV)
207Tl
4.79 min
β
207Pb
stable

Figure 1

Figure 3 Typical accumulator [13]

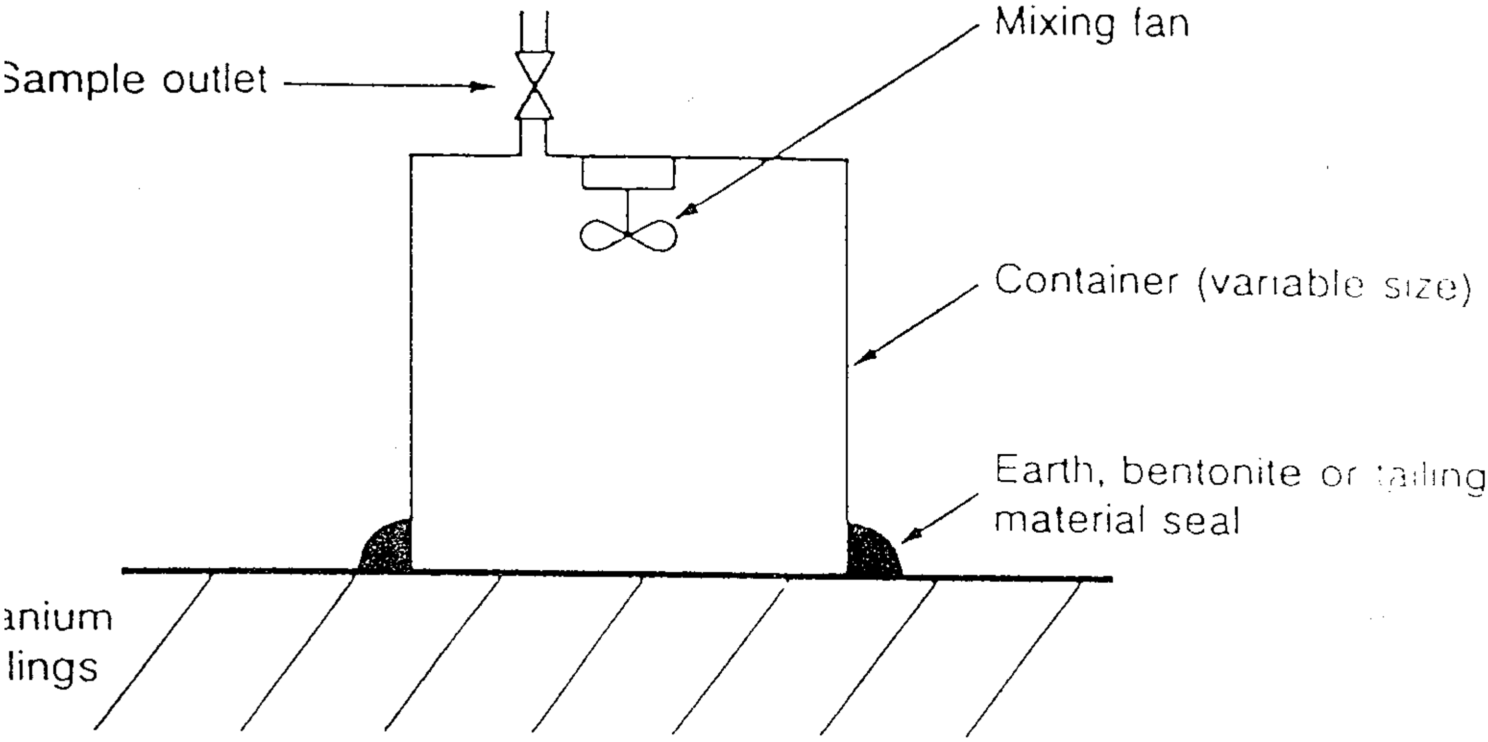

Figure 4 **Schematic diagram of a flow through method [13]**