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Designing National Indoor Radon Surveys According to IAEA Guidance

Charles Fitzpatrick

DESIGNING NATIONAL INDOOR RADON SURVEYS ACCORDING TO IAEA GUIDANCE

By

Charles Fitzpatrick

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University of Tulsa
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Department of Health Physics and Diagnostic Sciences
School of Allied Health Sciences
Division of Health Sciences
The Graduate College

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Charles Fitzpatrick

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Master of Science – Health Physics
Department of Health Physics and Diagnostic Sciences

Steen Madsen, Ph.D.
Examination Committee Chair

Carson Riland, Ph.D.
Examination Committee Member

Francis Cucinotta, Ph.D.
Examination Committee Member

William Culbreth, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Interim Dean

ABSTRACT

Radon is a radioactive gas that can accumulate indoors, typically in buildings with unfinished basements, poor ventilation, and/or cracks in walls or floors that lead to underlying soil, from which radon emanates. Radon is estimated to be the second most prevalent cause of lung cancer worldwide and is a threat to public health, which is a concern for national health authorities in many countries. Fortunately, radon can be measured and controlled. In order to know if radon poses a threat on a national level, studies must be performed that allow these authorities to extrapolate data from a relatively small amount of indoor radon measurements and apply them nationwide. This will allow countries to identify potential health risks due to radon and take actions that will reduce exposure.

The International Atomic Energy Agency (IAEA) will publish a Safety Report in 2018 entitled *Design and Conduct of Indoor Radon Surveys*, which will provide guidance for how to conduct indoor radon surveys on a national or regional scale. The main body of the text describes specific methods of creating and conducting a radon survey. This is followed by 12 annexes that contain examples of previous indoor radon surveys, along with input from the national health authorities that conducted those surveys.

The main purpose of the report is to ensure that national/regional radon surveys are as representative as possible. A representative survey means that the data taken from a comparatively small sample group can be extrapolated to represent the entire target country or region. A major concern is that biases can creep into such surveys and compromise their accuracy. By following the guidelines of the 2018 IAEA Safety Report, however, countries that

have little or no previous data on indoor radon can be straightforward and systematic in conducting their own representative surveys.

Many nations have not yet performed large-scale, representative indoor radon surveys. Cyprus and Slovenia both have previous radon data but have not followed through with broad surveys that are representative of the larger populations. This thesis will develop a theoretical radon measurement program for Cyprus and Slovenia, by using the IAEA guidelines in the Safety Report along with an analysis of methods utilized by the United States and Austria as templates.

The IAEA document strictly covers radon in homes[1], and correspondingly so will this thesis. It is important to be aware of radon risks in schools, workplaces and public buildings, but there are fewer of these and they can differ widely in construction. Homes are more widespread, are occupied for a longer average time during the day and tend to share similar construction characteristics across areas and regions, making extrapolation of results more reliable.

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[1] In this thesis and many of the references, the terms "home" and "dwelling" are used interchangeably.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

IAEA	International Atomic Energy Agency
WHO	World Health Organization
IARC	International Agency for Research on Cancer
EPA	Environmental Protection Agency
ES	Ever smokers
NS	Never smokers
SR	Safety report
BSS/GSR pt. 3	IAEA General Safety Requirements
SSG-32	Specific Safety Guide No. 32
SSNTD	Solid state nuclear track detector
SCF	Seasonal corrective factor
QA	Quality assurance
QC	Quality control
NRRS	National Residential Radon Survey
PSU	Primary Sampling Unit
SSU	Secondary Sampling Unit
pCi/L	Picocuries per liter
Bq/m^3	Becquerels per meter cubed
ANSI	American National Standards Institute
ICRP	International Commission on Radiation Protection
IJS	Jožef Stefan Institute
EU	European Union
CYSTAT	Statistical Service of Cyprus
GDN	Government Data Network
GIS	Geographical information system

1 INTRODUCTION AND BACKGROUND

1.1 Physical and chemical properties of radon

Radon is a radioactive gas that is undetectable by human senses; one cannot see, smell, or taste it. Radon is a noble gas, an atom of which has an entirely filled valence electron shell and is therefore nonreactive. It is found in the uranium decay series, uranium being nearly ubiquitous in the earth's crust and seawater. A diagram of the decay chain can be seen in Figure 1 below.

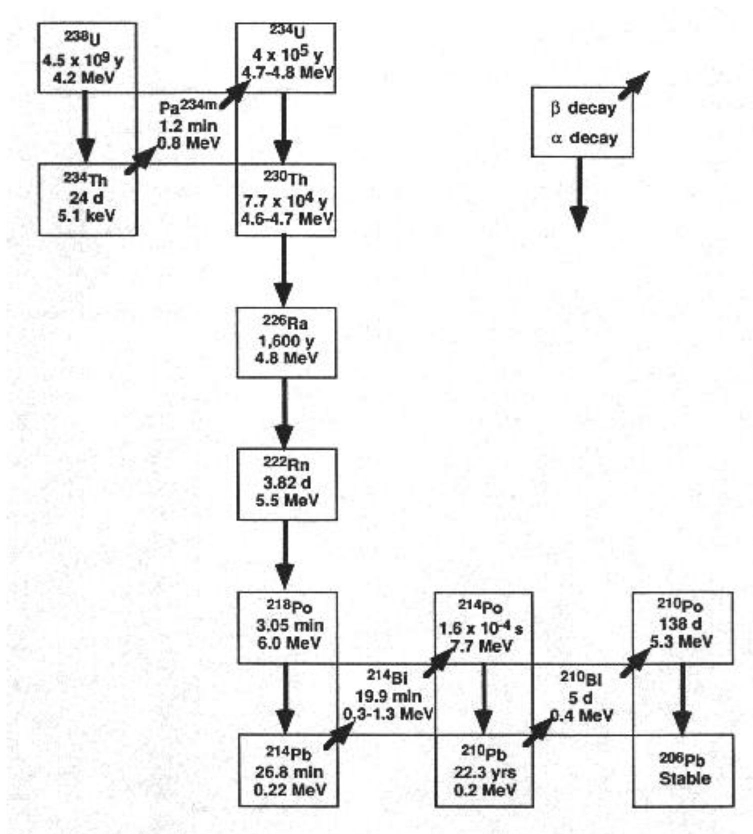

Figure 1. Uranium decay chain and energy of emitted particles. (New Jersey Society of Amateur Scientists, n.d.)

Radon is produced directly from decaying radium and then *itself* decays into isotopes of polonium, lead, and bismuth, often releasing a relatively high energy particle through alpha decay. This can cause damage if exposed to unprotected tissue.

1.2 Radon transport

The fact that radon is a gas makes it highly mobile, and as it decays from solid radium in soil it will mix with air and travel along free paths such as in permeable rocks and fissures. Through these pathways radon can find its way into the atmosphere or indoors. Buildings can have various ingress routes through which radon can enter, such as cracks in solid floors, construction joints, cracks in walls above and below ground level, gaps in suspended floors, gaps around service pipes, in groundwater, and cavities in walls (International Atomic Energy Agency, 2015). Figure 2 illustrates different ways radon can enter a house. The amount of radon entering a building is increased by a natural phenomenon called the stack effect, where heat in the building escapes through the upper floors, drawing in more soil air through ingress routes and pulling in more radon with it. This effect is exacerbated in the colder months, when the building is more sealed off to outside air and the temperature differential between inside and outside is more pronounced.

There are many ways that radon can enter a building, but the amount of radon found indoors depends on many factors. Some of the most significant are meteorological conditions (temperature, humidity, wind speed, barometric pressure, etc.), geology, building materials (radon can emanate from certain materials), construction type and the degree of ventilation (International Atomic Energy Agency, 2015). This makes it difficult to predict where radon levels may be elevated without performing measurements.

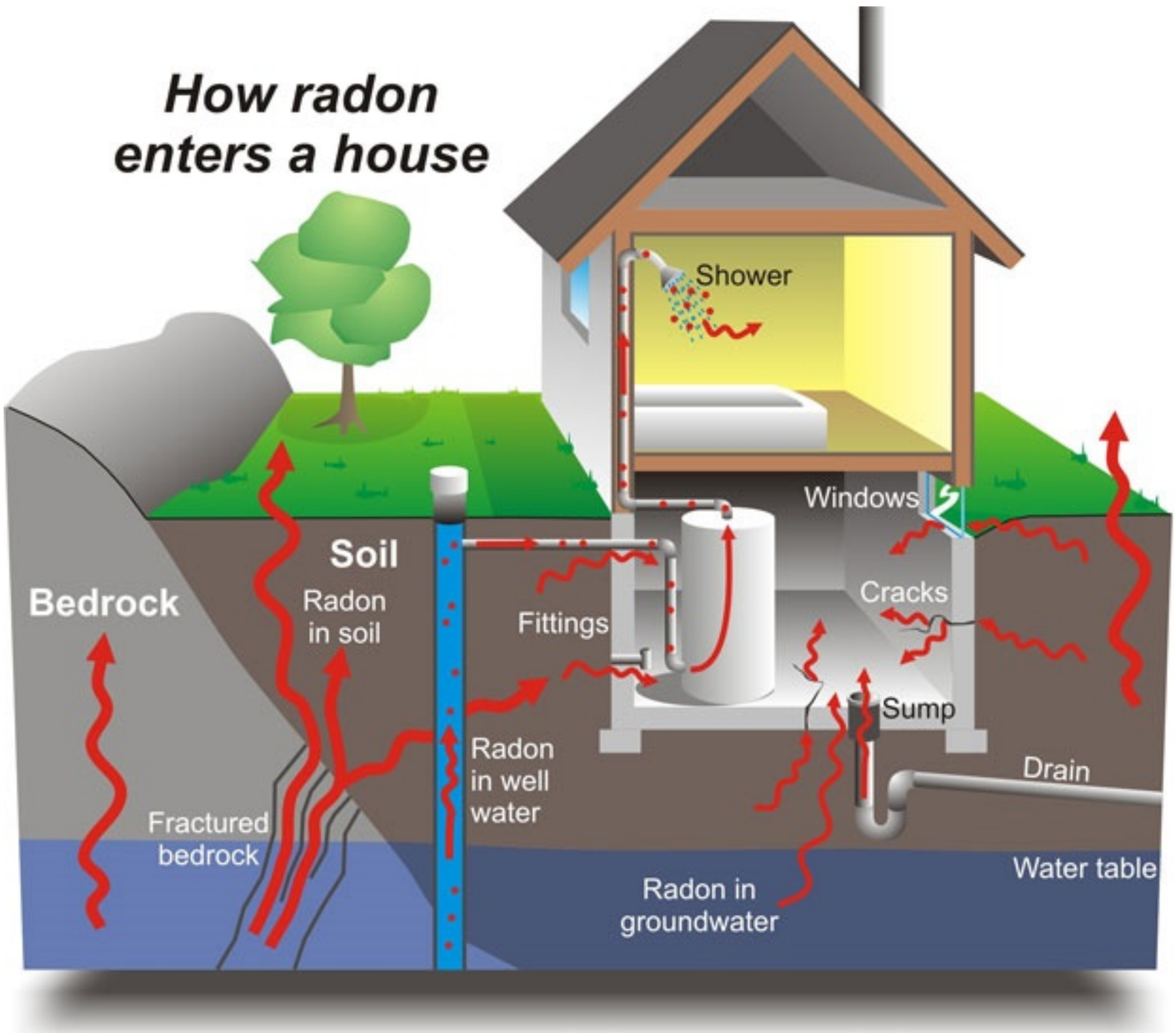

Figure 2. How radon enters a house (Government of Canada, 2012).

1.3 Health effects of radon

Long-term exposure to elevated concentrations of radon can be detrimental to one's health. People spend more time at home on average than anywhere else, and if radon in the home is at dangerous levels, it could have negative health effects. According to the World Health Organization (WHO) Handbook on Indoor Radon, "Epidemiological studies confirm that radon in homes increases the risk of lung cancer in the general population." (The handbook contains more information on the health effects associated with radon exposure.) The International Agency for Research on Cancer (IARC) has classified radon as carcinogenic to humans based on a thorough review of epidemiological studies of workers and residential radon studies (World Health Organization, 2009).

As mentioned before and illustrated in Figure 1, radon is a product of a decay chain, but the chain doesn't end at radon. The radon progeny, often referred to as daughters, continue to decay, and release a series of high energy alpha particles in the process (5.5 – 7.7 MeV) until the stable ^{206}Pb is reached. The decay progeny of radon can become attached to particles in the air, such as dust. Radon itself usually does not stay in the lung for very long, however these *particles* can be inhaled and become stuck in the lung, while the decaying radon daughters are attached to them. Then the daughters can release alpha particles into the surrounding unprotected lung tissue. This can result in damage to the DNA in the cells (or other biological damage), and lung cancer can develop as a result.

1.3.1 Radon and tobacco smoking

Radon and its progeny are estimated to be the second leading cause of lung cancer in the world next to cigarette smoke (World Health Organization, 2009). There is a synergistic effect between radon and tobacco smoking on lung cancer rates (Lee, Lichtenstein, Andrews, Glasgow, & Hampson, 1999). According to the U.S. Environmental Protection Agency (EPA), "Based on an assumed average equilibrium fraction of 40% between radon and its decay products and an indoor occupancy of 70%, the estimated risks from lifetime exposure at the 4 pCi/L action level are: 2.3% (all), 4.1% (ES) [ever-smokers], and 0.73% (NS)[never-smokers]." (US EPA, 2003). However, this includes the baseline risk, which is higher for smokers. The *relative* risk due to radon is higher for never-smokers, for whom an estimated 26% of lung cancers are due to radon compared to 12% for ever-smokers.

This EPA report was based on U.S. studies, so some generalizations may be made in applying it to other countries. Taking into account the national tobacco smoking rate of a specific country compared to the U.S. may give an indication of the risk of lung cancer and the estimated relative risk of developing lung cancer due to radon. This will be covered in subsequent chapters.

1.4 Representativeness of a survey

The basis of a representative survey is the chosen sample population. A representative sample population should fairly reflect the factors on which the survey will focus. For instance, in a radon survey for homes, some important factors will be housing characteristics, geology around the home, and weather conditions, to name a few. Because these will differ widely between countries, the methods used in one country's national survey may not be directly applicable to another's. But this is the purpose of the IAEA Safety Report – to gather together a wide variety of examples of radon surveys and provide a guide that will help *any* country create its own representative survey.

Representativeness is not a black and white issue, but at each step of the radon survey biases should be assessed and dealt with accordingly. Some biases are unavoidable and should be accounted for in the results. It should be noted that for all of the radon surveys mentioned in the guidance document and this thesis, when considering representativeness, the methods used are more important than the results.

1.5 Sampling methods

The World Health Organization's Handbook on Indoor Radon outlines multiple devices to measure indoor radon. The choice of detector in a study is important, because "it influences the cost of measurement per dwelling and therefore the cost of a radon program on a national level" (World Health Organization, 2009). Each type of detector has different characteristics that are best suited for different tasks and can be seen in Table 1.

The types of detectors fall into two categories: active and passive. Active detectors require power, but they can show fluctuations in radon concentration over time. These are generally used over shorter time periods to identify trends in radon concentrations. Passive detectors do not require power but are generally cheaper to operate and will show long-term averages. Table 2 identifies situations in which each detector would best be used for residential measurements.

Detector Type (Abbreviation)	**Passive/Active**	**Typical Uncertainty* [%]**	**Typical Sampling Period**	**Cost**
Alpha-track Detector (ATD)	Passive	10 - 25	1 - 12 months	low
Activated Charcoal Detector (ACD)	Passive	10 - 30	2 - 7 days	low
Electret Ion Chamber (EIC)	Passive	8 - 15	5 days - 1 year	medium
Electronic Integrating Device (EID)	Active	~ 25	2 days - year(s)	medium
Continuous Radon Monitor (CRM)	Active	~10	1 hour - year(s)	high

*Uncertainty expressed for optimal exposure durations and for exposures ~ 200 Bq/m^3.

Table 1. Radon gas measurement devices and their characteristics (World Health Organization, 2009)

Method	Measurement Type	Device
Preliminary Test for Radon	Short-term Sampling	CRM, EIC, ACD
Assessment of Exposure	Time Integrating	ATD, EIC, CRM, EID
Remediation Testing	Continuous Monitoring	CRM

Table 2. Primary methods and devices for residential radon measurements (World Health Organization, 2009)

1.6 Radon assessment strategy

Additionally, there are many factors that influence a specific country's approach to assessing its radon situation. The act of planning a study, carrying it out, and taking into account any possible remediation/preventative actions takes precise coordination. It relies on the cooperation of the participants, politics, the cost of the study or how much money is available in the budget, and the public health situation (e.g., if there is not a more pressing public health problem that requires more energy and resources), to name a few. This is why planning a national radon measurement program requires the coordinated effort of a radon authority, namely the lead organization or organizations responsible for radiation protection in the country.

1.7 Overview of the IAEA Safety Report

The forthcoming IAEA/WHO sponsored Safety Report (SR) – *Design and Conduct of Indoor Radon Surveys* – was written to help satisfy requirement 50 in the IAEA General Safety Requirements Part 3 (GSR part 3, also referred to as the International Basic Safety Standards, or BSS). This requirement states that for a given country, "The government shall provide information on levels of radon indoors and the associated health risks and, if appropriate, shall establish and implement an action plan for controlling public exposure due to radon indoors." It also further states that the government or national authority is required to ensure that "information is gathered on activity concentrations of radon in dwellings…through appropriate means, such as representative radon surveys" (International Atomic Energy Agency, 2014).

The SR contains five main sections, two appendices, and 12 annexes containing summaries of past national radon surveys, and the following is a summary of the information found in the report.

1.7.1 Introduction to the SR

This section states the objective, scope, and structure of the document. The end goal of the IAEA radon requirements is to reduce exposure to the public due to indoor radon. In order to do this, measurements must be taken and the data analyzed to estimate where radon may be a threat in a country. According to the document itself: "This Safety Report discusses the factors that need to be taken into account in designing and carrying out representative radon surveys. The SR will be of assistance to those national authorities that are considering whether they need to undertake a radon survey and, if so, how the survey can best be designed and conducted." And although the SR directly addresses radon in dwellings, many of the considerations may be applied to other buildings as well. It also specifically does not address: surveys of public buildings or workplaces; thoron (^{220}Rn) surveys; remediation of buildings or amending new building codes; or design of a national action plan to reduce radon exposure indoors.

1.7.2 Scientific and regulatory background

This covers the physical and chemical properties of radon, accumulation in buildings, health effects, along with a section discussing compliance with existing IAEA safety standards.

In this section the definition of 'national authority' is explained, as mentioned previously in section 1.6 of this thesis.

1.7.3 Assessment for the need for a survey

This section begins with a brief overview of the extent to which past documents have covered large-scale radon surveys. Three are specifically mentioned: the GSR Part 3, Specific Safety Guide No. 32 (SSG-32) which discusses the approach to undertaking radon surveys in a more general way, and the World Health Organization Handbook on Indoor Radon (WHO Handbook) which provides a breadth of specific radon-related information.

There is a forewarning here stating that undertaking a national radon survey will be time consuming and will require considerable resources. Therefore, the purpose, scale, and scope of the survey should be clearly defined when starting out.

The SR then suggests nominating a specific technical working group, consisting of scientists, statisticians, public health specialists, etc. to gather any existing data relating to radon in the country. The information of interest falls into two categories: public health information, such as tobacco smoking habits, and data pertaining to radon in the country, which could include university radon studies, geologic data, information on building materials, and other data such as characteristics of the housing stock.

1.7.3.1 Pilot surveys

This section is about pilot surveys, or smaller, preliminary surveys. The SR stresses that a pilot survey requires much care and consideration, because if a larger-scale study is conducted, many of the planning and data analysis procedures will either be used, amended, or omitted in the large-scale survey depending on their efficacy. It is essentially a test of the logistics of a survey, e.g. recruitment participation, detector distribution and collection methods, questionnaire usability, etc.

1.7.4 Design of an indoor radon survey

This section expounds upon aspects of the *planning* stages of a survey prior to carrying it out. It explains that measurements in dwellings are preferred because people in non-domestic buildings may not be representative of the entire population due to various factors, such as varying occupancy factors. Also, the importance of selecting or developing a database is stressed, to securely house and manage the radon data.

1.7.4.1 Sample basis

Here, positives and negatives of the type of survey (population vs. geological) are discussed. A survey based on population will be more representative in areas with higher population density like major cities, whereas a geographically based survey might underrepresent them, but a well-designed study will address both simultaneously. Regardless of the type of survey, it is important to define a spatial sampling unit (e.g. regions, municipalities, grid squares) such that the data can be easily compared to other spatial data, such as public health data. This section also includes a discussion of whether to measure the upper levels of apartment buildings.

1.7.4.2 Sample size

In this section the SR states that, "the most straightforward approach is to sample a fixed number of dwellings in each sampling unit," which, from the experiences of different countries, is typically less than 1% of homes nationwide. Alternatively, it says that a stratified approach may be necessary, where the sampling units are not equivalent (in regard to population density, geology, etc.). A few other sampling strategies are mentioned, such as a stepwise approach, which uses as small number of measurements made in a given area to decide if it can be labelled a 'radon priority area,' and a phased approach, which would spread the cost of the survey over a number of years. Many of these different strategies may be overlapped, such as a stratified approach that ends up measuring 1% of homes over a number of years is perfectly reasonable. This number was chosen based on a number of previously conducted radon surveys worldwide.

A study is briefly described that investigates sample sizes for community radon surveys. The results show that with only 100 samples, the percentage of dwellings with radon concentrations exceeding a reference level can be determined with an accuracy of 25%. The report concludes by stating that, "A large sample size, such as 1,000 samples in a community of several tens of thousands of homes, can definitely provide high quality results with a very small uncertainty" (Chen, Tracy, Zielinski, & Moir, 2008).

1.7.4.3 Additional options

Since a large-scale radon survey is resource intensive, it is prudent to perform other measurements at the same time to maximize the benefits. This includes using a questionnaire to gather as much information about the home as possible, such as if the home is on the ground floor, has a basement, means of ventilation, etc. and also to gather information of tobacco smoking habits of participants. A resource is also provided that describes a 'check for representativeness.' This method compares the housing characteristics of the participants with those provided in the most recent Census (or the soonest one after the survey). Therefore, it may be desirable for the radon survey questionnaire to contain the same questions as the Census to optimize this comparison. It may also be beneficial to measure gamma radiation with simple dosimeters at the same time as radon, especially in buildings that are suspected of having elevated levels of radionuclides.

1.7.4.4 Recruitment of participants

Usually recruitment is done by mail, telephone, in person, or by use of citizen groups. Contact by land line may increase bias, depending on the extent to which the population has switched to mobile phones. Experiences from a few countries show that in-person contact improves participation and completion rates.

In the case of renters, the conducting authority needs to decide beforehand whether to contact the tenants or the landlords. Landlords may have less interest in participating because a finding of elevated radon levels could involve additional expense for them. However, tenants have the right to know about the radon situation in their residences, so national legislation that defines the responsibilities between landlords and tenants would help determine the most appropriate way of measuring rental properties.

Anticipated non-participation and non-completion rates should be accounted for when planning the survey. These can be estimated from a pilot survey, and enough invitations can be extended so that the target participation rate is met by the end of the survey. Also, because some follow-up studies may need to be performed, the participants should be asked if they would be willing to be contacted or participate in any future studies.

Good communication can increase participation and ensure that the study runs smoothly. Advertising ahead of time can be useful in raising public awareness and can be done through print, radio, television, etc. In addition to communication before the survey, broad dissemination of results is also very important. Participants should be notified of their results and be assured that the results would be held in confidence. Depending on the results, they should also be provided with information on how to reduce the radon concentration in their residences, along with information on where to obtain expert advice.

1.7.4.5 Choice of radon detector

The SR states that for long-term measurements, i.e. longer than two months, solid state nuclear track detectors (SSNTDs – also called Alpha Track Detectors, or ATDs) are most often utilized. These are small solid materials, typically plastic, and when exposed to radiation, the nuclear particles leave tracks on the surface. When chemically etched, the tracks can be seen microscopically and measured to find specific information about the particles, such as energy and mass. These detectors are small and affordable and allow for a high rate of sample processing. The SR refers to the WHO Handbook for more information on radon detectors.

1.7.4.6 Duration and location of measurements

Twelve-month measurements are considered optimal due to the fluctuation of radon levels throughout the year, but six-month and three-month measurements are common. For the sake of obtaining conservative results, measurements are conducted during the 'heating season' – when radon concentrations are higher. Using seasonal corrective factors (SCFs) is discouraged because in order to calculate them, a large number of measurements need to be taken. Therefore, it is best to take conservative or year-long measurements.

Typically, two detectors are used for each dwelling – one for an occupied bedroom and one for the main living room. This ensures a measurement in two rooms where the inhabitants spend most of their time. Many guidance publications that deal with measuring radon in homes recommend placing the detectors away from windows and heat sources, as they may affect detector performance.

1.7.4.7 QA/QC during measurements

Some quality assurance/control (QA/QC) actions may be taken during the measurement process. Some steps can be taken to ensure the accuracy of results, including reducing the amount of storage time of detectors before and after exposure, and properly sealing detectors after exposure. These QA/QC methods differ from the QA/QC practices used by a radon laboratory, which occur in the laboratory as opposed to during measurements of radon in homes.

1.7.4.8 Sources of bias

The last section in this chapter refers to the Annexes of the report, which contain some examples of when biases occur and how to account for them. It states that some biases cannot be completely avoided and that it is better to know what the likely biases will be and to account for them as much as possible.

1.7.5 Conduct of a radon survey

1.7.5.1 Detector distribution and collection

In this section, specific information on how to securely and consistently deliver detector to the measurement laboratory is discussed. Many countries do this entirely with the postal service but in-person placement and collection are also possible, however this is more time consuming. It is helpful to send participants reminders when the test period is finished, so they remember to return the detectors.

1.7.5.2 Data validation and analysis

Each measurement needs to be validated, and if an essential piece of information is missing, such as the start or end date of the measurement, then that measurement will not be valid. Data will also need to be checked for log-normality, and a reference for how to do this is provided in the SR's references. Any outliers will need to be reviewed at this point as well, a check for representativeness (as mentioned earlier) can be performed, and the arithmetic and/or geometric mean can be calculated for the entire area of the survey and for the individual sampling units. The data can then be used to identify homes that may be in excess of a reference level, and any 'radon prone areas' can be pinpointed. Census data may be used to find any correlations in the data, such as to identify the number of people exposed, or if a certain type of home has a higher radon concentration.

1.7.5.3 Data management and mapping

With a large set of spatially distributed data, a radon map can be created to give a visual of the radon concentration trends across the measurement area. A radon map can be useful when communicating data to decision makers and the public and can also help experts develop a graded approach to reducing elevated radon levels. A graded approach means giving higher priority to dwellings with high radon concentrations.

Radon maps can have some downsides. Many times, the area is only represented by the average concentrations, and concentrations on the extreme ends are not well represented. Also, they often show a hard line between areas of differing average radon risks, which is usually not the case. This section provides references to studies that contain maps displaying results other than just averages, such as median, percentage of homes above a reference level, or as a risk index.

1.7.5.4 Reporting results to participants

After the data has been collected and verified, the results of each home can be sent to the respective participants, along with information on what the results mean. For homes with high radon, this could include references for day-to-day practices for radon reduction, and also provide resources for what to do or whom to contact to get further help.

1.7.6 Appendixes and annexes

Appendix 1 contains information on quality management for radon measurement laboratories. This section contains information on the QA/QC procedures for radon laboratories and will be helpful for a national authority that wants to start its own, but is not imperative if using an existing laboratory.

Appendix 2 contains an example of a questionnaire that was used in a Canadian study.

Annexes 1-12 are summaries of the radon surveys that were conducted in Argentina, Australia, Austria, Bulgaria, Canada, Iceland, the Islamic Republic of Iran, Ireland, Italy, Montenegro, the Netherlands, and the United States. Each summary was created or finalized by the radon authorities of each respective country and includes their own perspectives on what follow-up actions have been performed since the survey, as well as post-survey considerations, including what they would have done differently with the benefit of hindsight.

2 MATERIALS AND METHODS

2.1 Methodology

The first step has already been completed: two countries will be chosen as example countries (U.S. and Austria) that have conducted large-scale indoor radon surveys, and two countries will be chosen that have not but that may already have some radon data (Cyprus and Slovenia). Then, following the IAEA safety report and using the example countries' radon studies as in-depth models, a theoretical representative indoor radon survey can be created for each objective country. The United States and Austria have been chosen as the example countries because they have surveys that are largely representative of the greater population. These surveys will be compared with the SR and aspects that contributed to their representativeness will be identified. Next, available radon data for the objective countries will be reviewed. This includes the aforementioned surveys, university studies, geological data, and also general information pertaining to radon measurement in homes, such as population, number of homes, general housing type, other census data, etc. During this, the key factors pertaining to the representativeness of each country's survey will be identified, and an approach based on these factors will be developed.

Then, following the guidelines in the SR, theoretical large-scale radon surveys for these countries can be planned. Large-scale radon surveys can be resource intensive, so the cost of the surveys will also be considered during the planning process.

A final important point will be deciding what follow-up actions will be taken. Depending on the results, certain actions should be taken to ensure any future radon problems do not go undetected. This may include performing a specific number of radon measurements each year after the study or planning for another survey in five to ten years, depending on the cost/benefit analysis and the public health situation.

2.2 Completed Research

Research has been completed for the four aforementioned countries. For each, the goal will be to identify the following: What data pertaining to radon exists; what radon projects are currently underway; and any plans for future radon data collection.

2.2.1 United States

The EPA conducted a National Residential Radon Survey (NRRS) (United States Environmental Protection Agency, 1992), on which the following sections are based and published the results. The planning took three years; data collection took over one year; and editing and statistical analysis took about two years. In the end, 5,694 homes were measured, and results were based on national and regional estimates of radon concentrations and housing characteristics. The survey was conducted because elevated radon concentrations had been measured in areas of the U.S., namely in New York, New Jersey, and Pennsylvania. No grid system was used, but the survey was based on counties.

2.2.1.1 Sampling approach

The survey was designed to target housing units, and questionnaires were to be completed by permanent residents who had no plans to move in the next 12 months and who would be occupying the space for at least nine months during measurement. Included in the survey were single-family, detached homes, and multi-unit structures like apartments and mobile homes. The EPA partitioned the U.S. into 22 strata based on the results of previous limited testing, in which 125 primary sampling units (PSUs) approximately the size of one or more counties were chosen across the country. Then, a random sampling of secondary sampling units (SSUs) was chosen on the basis of small areas, such as Census Blocks. A random sample of homes within these SSUs were selected for the sample.

The number of homes the EPA initially aimed to measure was 5,000. The initial number of homes contacted was 11,423, and in the end measurements in 5,964 homes were validated.

2.2.1.2 Data Collection

Instead of using a questionnaire, the EPA gathered information about the participants' dwelling, smoking habits and other information through personal interviews. They also helped the inhabitants place the detectors – one on each floor or two if the home only had one level. Alpha track detectors were used for the year-long measurements.

2.2.1.3 Quality Assurance

Steps were taken to ensure that legitimate data was recorded during the sampling process. The procedures for placing detectors and the questionnaire usability were tested on 60 respondents, and the final questionnaire was decided upon based on this trial. Questionnaire responses were carefully reviewed, as there are some participants who did not provide adequate information about their housing characteristics or how much time they spent in the home. This data was used cautiously in the analysis.

2.2.1.4 Results and analysis

Three types of results were obtained: national and regional estimates of mean annual radon concentrations; statistics on housing characteristics, living habits, and the percentage of homes that tested for radon; and housing characteristics and other factors that may correlate with radon levels.

The EPA estimates that 64% of dwellings had annual radon concentrations below 1 pCi/L (37 Bq/m^3), 20% had between 1 and 2 pCi/L, and the remaining 16% were greater than 2 pCi/L. The annual average concentration was found to be 1.25 pCi/L and from this it was estimated that radon causes approximately 14,000 lung cancer deaths each year with an uncertainty range of 7,000 – 30,000 (US EPA, 1992). This estimate was based on a modified BEIR IV model, but a later report based on a modified BEIR VI model estimates that in 1995 the lung cancer deaths were due to radon was 21,100 [2] (US EPA, 2003). This later model is currently accepted for estimating risk due to radon in homes.

Six percent of homes had annual radon concentrations greater than 4 pCi/L, which is the level at which the EPA recommends action be taken to reduce the amount of radon indoors. More detailed results can be found in the NRRS.

2.2.1.5 Housing Characteristics

Part of the data analysis was to identify housing characteristics that may affect radon levels. Fifty characteristics (independent variables) were analyzed along with radon levels (dependent variables) to find the strongest correlations. Some of the important factors that could be used to predict radon levels were geographic location, housing construction, radon potential of the area, whether the home had a basement entrance inside, and the number of gas appliances within the residence.

2.2.1.6 Follow-up actions

Many follow-up actions have been taken since the report was published in 1992, including:

- New standards of radon testing and mitigation have been established by the American National Standards Institute (ANSI);
- Progress has been made on adding building codes addressing radon;
- According to the EPA, millions of homes with elevated radon concentrations have been remediated and new homes have been built with radon-reducing features.

[2] Out of the total lung cancer deaths for that year, this is the number that could be radon related (US EPA, 2003).

2.2.2 Austria

Austria conducted a population-based survey from 1992 to 2001 to identify high radon areas, so these areas could be targeted for reducing the exposure to radon (Friedmann, 2005). The survey consisted of 40,000 measurements in 8,000 homes, which covered roughly 0.25% of homes across the country. At the beginning of the survey the Austrian Radiation Protection Commission set a reference level of 400 Bq/m^3 for existing buildings and 200 Bq/m^3 for newly constructed buildings. The sample units were based on municipalities, of which there are a total of 2,358 in Austria.

2.2.2.1 Survey design

Only passive, ^{222}Rn detectors were used in this survey due to availability. The number of dwellings selected was proportional to the number of inhabitants in each municipality. One in every 200 dwellings was selected, and in larger cities the sample size was reduced because only ground-floor dwellings were chosen.

The survey took a three-step approach. First, all relevant radon data was collected and reviewed. Then, a pilot study was conducted in a test area – one rural and one urban environment. Then, procedures were adjusted based on the pilot study, tested again in an extended pilot phase, and the full national survey commenced in 1994.

Three types of detectors were used – SSNTDs, electrets, and charcoal liquid scintillation detectors. Two detectors were placed in each home, in the most frequently used rooms, typically the main bedroom and living room. They were placed one to two meters off the ground and away from doors and windows. Questionnaires were distributed along with detectors, either by interviewers or through the mail. SSNTDs and electrets measured for three-month periods, and the charcoal detectors measured in three-day periods, and all measurements were made in spring and autumn under the occupants' regular living conditions.

2.2.2.2 Results and analysis

Results were based on 'radon potential.' This was defined in the survey report as the mean radon concentration in a standard situation, as a base level from which mean conversion factors could be calculated. The standard situation is a single-family dwelling – with the living room on the ground floor, no basement or just a partial basement, no natural stone construction or single-paned windows – the inhabitants of which were two adults and no more than one child. Data analysis was performed (a more detailed description can be seen in the *Final Results of the Austrian Radon Project* (Friedmann, 2005), and radon potential was calculated for each municipality.

The rate of retrieval was about 85%. Based on the fact that 8,000 dwellings were measured in roughly 2,300 municipalities, this means that three to four dwellings were measured on average in each municipality.

The mean radon concentration was 99 Bq/m^3, thus a radon potential map was produced showing three groups – mean concentration below 200 Bq/m^3, between 200 and 400 Bq/m^3, and above 400 Bq/m^3. Some high-radon concentrations were found in areas where higher concentrations of uranium are found in crystalline rocks.

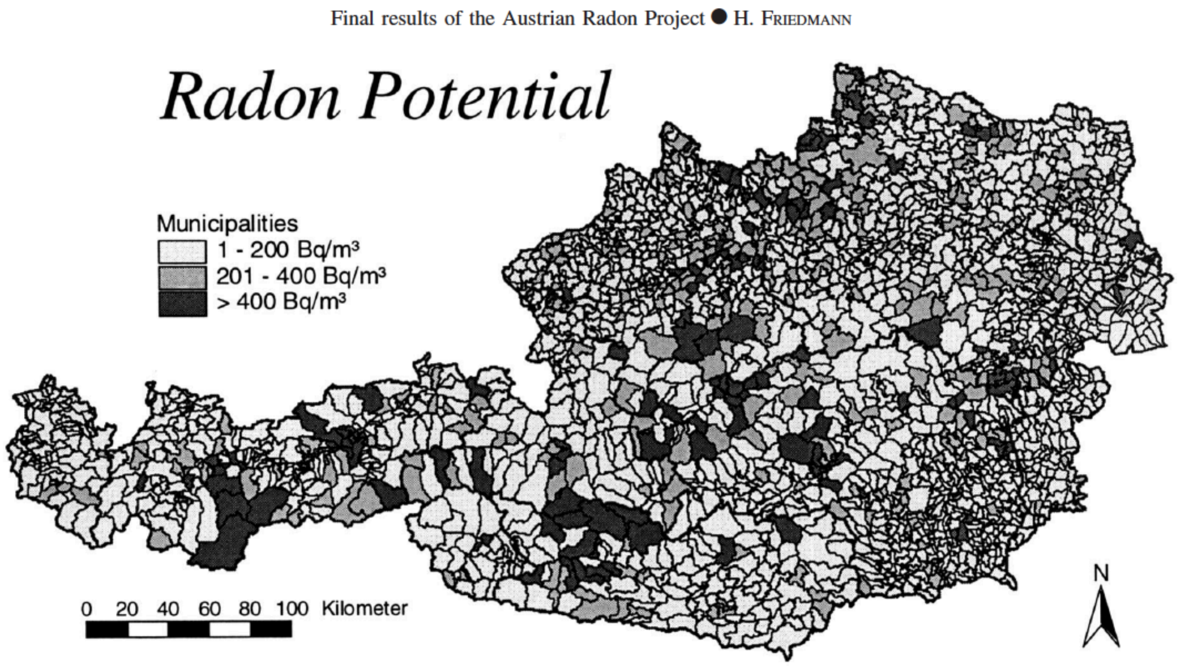

Figure 3. Radon potential map of Austria (Friedmann, 2005)

2.2.2.3 Follow-up actions

A more current study is underway. This is a geographically based survey and will improve the reliability of the Austrian radon map, measuring 35,000 more homes in a 2 x 2 km geographical grid. This should be completed by 2019. A minimum of 12 dwellings per grid square is required, which is a compromise between cost feasibility and meeting the requirement for acceptable uncertainty in the radon risk. An interesting part of the current study is that the measurements and distribution of collectors is carried out by volunteer fire brigades – a motivated, hierarchical corps of around 300,000 that helps improve the return rate of detectors.

2.2.3 The Republic of Cyprus

There have been at least five studies published that report indoor radon measurements in Cyprus:

1. Christofides and Christodoulides, 1993, reported passive measurements in 89 homes in a pilot survey. Measurements were taken over three- to four-month periods with CR-39 SSNTDs.

2. Anastasiou et al., 2003, reported 84 active measurements to the first study.
3. Sarrou and Pashalidis, 2003, reported 33 active measurements.
4. Theodoulou, Parpottas, and Tsertos, 2012, reported 108 active measurements, 2 each in a total of 54 km^2.
5. Soteriades et al., 2016, reported 240 passive measurements in schools, public buildings, private buildings, and other premises within four areas (Nisou area, Nicosia District, Famagusta District, and Paphos District).

The studies of primary interest are the first and the last, due to the fact that they used long-term, passive measurements. The other studies will not be ignored, because active measurements can be helpful, and they will be considered later in this thesis.

2.2.3.1 Airborne ^{222}Rn concentrations in Cypriot houses

The Christofides and Christodoulides study contained measurements that were sparse, spread out over the entire Greek-occupied area of Cyprus, and no measurements were made in the Turkish area (see Figure 6). This may have been due to disagreement between the areas at the time.

Although relatively low concentrations were measured in this study, the measurement density could be improved, because the homes probably differ in aspects that affect radon levels. Also, the IAEA SR recommends pilot studies be conducted in smaller areas. Such a sparse data set likely means that areas are underrepresented in the survey.

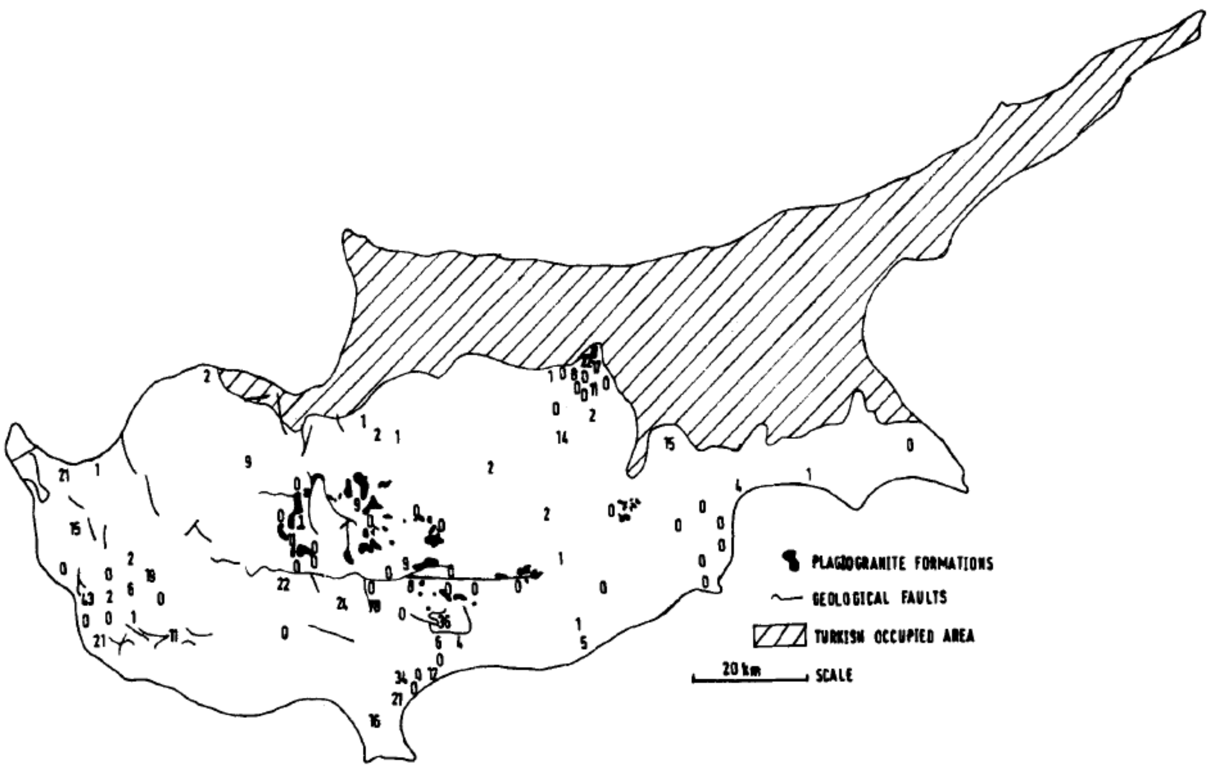

Figure 4. Map of Cyprus indicating the location of the detectors (the numbers indicate the measured radon concentration) from the first survey (Christophides & Christodoulides, 1993)

2.2.3.2 Environmental assessment of radon levels in Cyprus

The most recent study by Soteriades et al. was conducted because the previous studies were limited in number and in geographical coverage on Cyprus, and were lacking in passive, long-term measurements (Soteriades, et al., 2016). The aim was to evaluate the potential presence of radon and assess its levels in comparison with international standards. However, with 248 of the 435 measurements done in private buildings (there is no mention what type of private buildings they were) at an average of two detectors in each, this means that only 74 private buildings were measured across four different areas. These measurements were slightly more clustered than the 1993 pilot survey and included the Famagusta region in the Turkish area. A map of the data points can be seen in Figure 5.

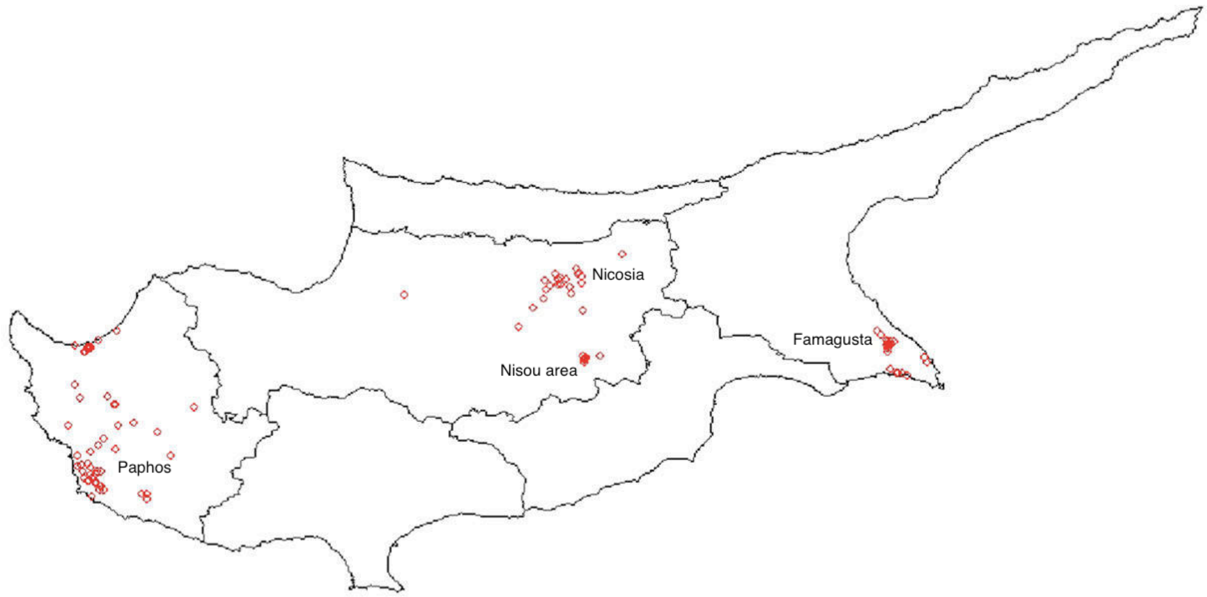

Figure 5. Map of indoor radon measurements from the 2015 Cyprus study. Data points include both public, private, and other buildings (Soteriades, et al., 2016).

With 303,242 private households across Cyprus according to the 2011 census, this study could also be improved to adhere more strongly to the suggestions found in the IAEA SR.

A new indoor radon study will be planned by using the current data from these past studies and by following the SR, as outlined in the methodology in section three of this thesis. The end goal is to have a dedicated, thorough, representative indoor radon survey for dwellings covering adequately diverse areas across Cyprus so that any possible public health threat due to radon will be identified. This way, the question of whether or not to commence with a radon action plan can be answered with certainty.

2.2.4 Slovenia

A paper by Janja Vaupotič published in 2003 titled *Indoor Radon in Slovenia* summarizes the history of the Slovene radon program (Vaupotič, 2003). Since 1990, measurements have been made in 730 kindergartens, 890 schools, 892 homes (Križman, Ilič, Skvarč, & Jeran, 1996), and other buildings such as spas, hospitals, wineries, and water supply plants. The two-step program began with measuring the schools, kindergartens, and homes, but in the second step the focus was turned toward schools, kindergartens, and workplaces (i.e. the spas, hospitals, wineries, and water supply plants), and the radon risk in homes was somewhat ignored.

The survey published in 1996 was purely for measurements in Slovene dwellings (Križman, Ilič, Skvarč, & Jeran, 1996). Long-term measurements were made during the winter using CR-39 SSNTDs uniformly over the country (approximately every 520th home was measured). The distribution of sample points can be seen in Figure 6. The results were seasonally corrected and analyzed to show a lognormal distribution.

Figure 6. Map of Slovenia showing the uniform distribution of sample points (Križman, Ilič, Skvarč, & Jeran, 1996)

The results showed an arithmetic mean of 86.9 Bq/m^3 and a median of 54 Bq/m^3 across the country (Figure 7 below shows the map of indoor radon concentrations). There was also a correlation between the natural geologic radiation in the country and enhanced indoor radon. This is especially the case in southern Slovenia, most notably the Karst region. As an example, this was tested in rural towns located in Dinaric regions where the soil is rich in uranium and radium, and the mean values were shown to be two to three times higher than the overall national level.

At the end of the survey, according to ICRP 65 recommendations, an action level of 400 Bq/m^3 was decided upon for existing buildings and 200 Bq/m^3 in new buildings in Slovenia.

About 1% of the data from this survey exceeded the 400 Bq/m^3 level, and it was estimated that radon concentrations in 4,000 – 5,000 homes exceed this recommendation.

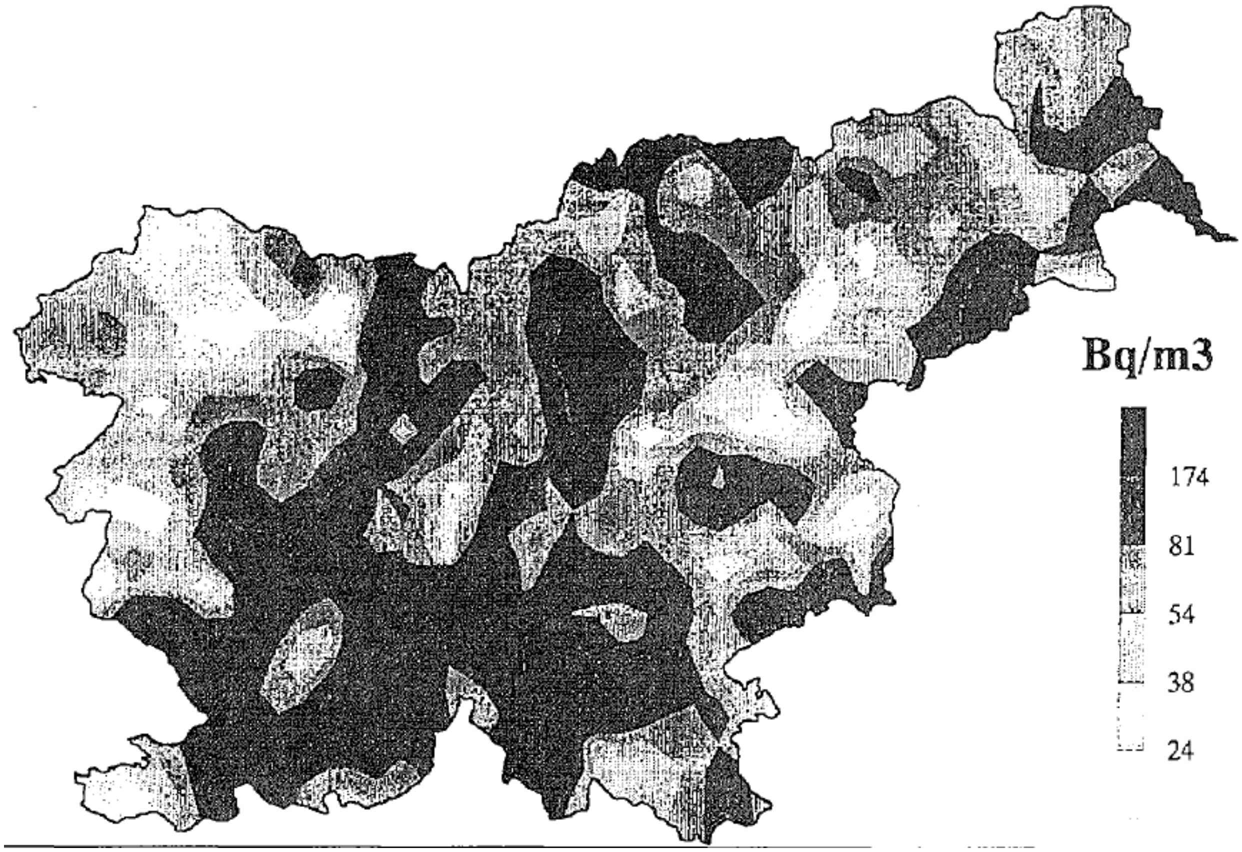

Figure 7. Map of indoor radon concentrations in Slovenia (Križman, Ilič, Skvarč, & Jeran, 1996)

The conclusion that this many homes may have radon levels in excess of the action level and the fact that this is the last extensive study of radon in homes is relatively concerning. It seems like radon in homes would be a priority since most people spend the major part of their days at home.

In the Vaupotič paper, a section describes the Slovene Radon Center, a joint coalition between experts in radiation and dosimetry from Jožef Stefan Institute (IJS) and the Nova Gorica

Polytechnic (now the University of Nova Gorica) working jointly with experts in building engineering from the National Institute of Construction and Building Engineering. This Radon Center can perform fast radon screenings using alpha scintillation cells and also measure annual exposure using etched track detectors for a whole year, and they possess a wealth of other devices for radon monitoring, dosimetry, and gamma spectroscopy. Yet, as of the year of publication (2003), only 35 buildings have been modified to reduce radon concentrations, all of them schools and kindergartens. The article states:

> "All people concerned about radon levels in their home or working place can ask the Slovene Radon Centre to carry out measurement at their expense. In the last five years about 250 measurements were performed." (Vaupotič, 2003)

Research has shown that no significant indoor radon surveys in Slovene homes have been published since the first publication in 1996 (Cindro, 2016). In other words, a significant, far-reaching attempt to reduce exposure to radon in Slovene homes is overdue. This thesis will use the methods described in section three to develop a modern, more detailed indoor radon measurement program for homes in Slovenia. The goal will be to provide a survey thorough enough to find specific areas and homes with elevated radon concentrations so that they can be reduced for the sake of public health.

The Austrian radon study would be a good beginning template for achieving this goal, since Slovenia shares a border with Austria. This means characteristics of the countries such as geology, housing type, etc. may be similar.

2.3 Country-specific considerations

As mentioned before, indoor radon concentrations will vary depending on numerous factors, including geology, climate, and housing type, which may also fluctuate on a regional scale. In this section, the factors that should be considered when planning a radon survey will be discussed for both Cyprus and Slovenia. Other country-specific data will also be taken into account, such as population statistics and prevalence of tobacco smoking habits.

2.3.1 Republic of Cypress

2.3.1.1 Climate

Cyprus has a warm climate compared to the rest of the Mediterranean part of the European Union (EU). It has very mild winters and warm to hot summers on average, with rain occurring typically in winter and summers being usually dry. Mild climates tend to lead to better ventilation in homes if air conditioning is not widespread, which usually results in lower radon concentrations.

2.3.1.2 Geology

The geology of Cyprus also does not give evidence of a great radon threat, with the only rock formation containing large quantities of uranium being the plagiogranites in the mountainous central part of the country. The plagiogranites are small areas grouped around the Troodos Ophiolite geological region. This region also contains several deep faults, which increases the amount of radon reaching the surface – and several villages are built on top of such faults (Anastasiou, Tsertos, Christofides, & Christodoulides, 2003).

2.3.1.3 Housing types/characteristics

Cypriot houses are normally composed of a concrete frame, brick walls covered with plaster, concrete roof, and concrete floor covered with tiles. The doors are usually wooden, and windows are glass, and the temperature conditions allow for long periods of ventilation, even during the winter (Anastasiou, Tsertos, Christofides, & Christodoulides, 2003).

2.3.1.4 Tobacco smoking habits

Thirty-one percent of adults (ages 15+, 44% male, 19% female) in Cyprus smoke tobacco as of 2016 (World Health Organization, 2017) compared with 15.5% in the United States (Centers for Disease Control and Prevention, 2018). A study on geographic trends of tobacco related cancers in Cyprus shows a map of the proportion of smokers in the general population grouped by areas (figure 8). This could potentially identify areas in need of more radon focus in a national survey, due to the synergy between tobacco smoke and indoor radon.

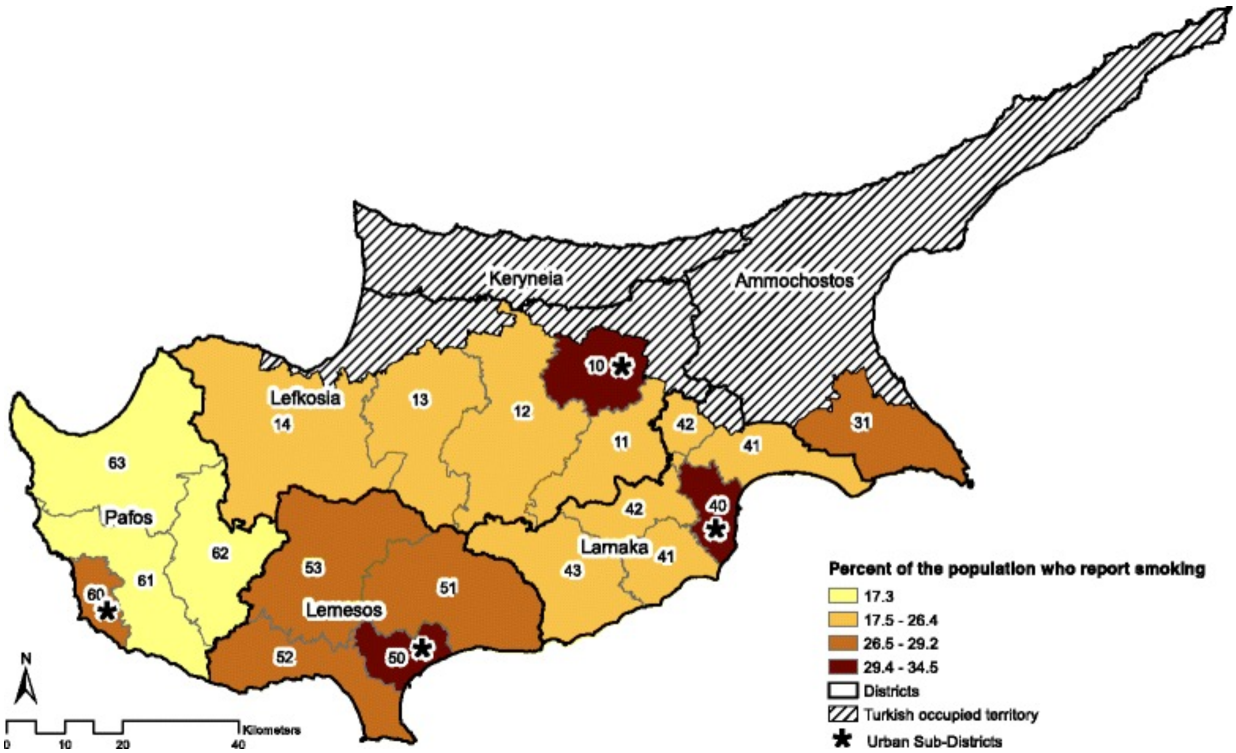

Figure 8. Proportion of smokers in the general Cypriot population by urban and rural areas of sub-districts (Farazi, et al., 2015).

2

2.3.2 Slovenia

2.3.2.1 Climate

The weather in Slovenia is diverse. In the northeast is a continental climate, and in the mountains an alpine climate, while the coastal regions have a sub-Mediterranean climate. In January, the average temperature across the country is 28° F, and in July it is 70° F, with snow cover very common in winter (Slovenia.si, 2013). The longer heating season may affect average indoor radon concentrations.

2.3.2.2 Geology

Similar to the climate, the geology and lithology vary greatly in Slovenia. Evidence from a past study shows that average indoor radon concentrations are highest in areas with limestone and dolomite (see figure 9). The areas containing the greatest amount of limestone are the karstic regions, which have shown the greatest potential for radon presence due to its high permeability.

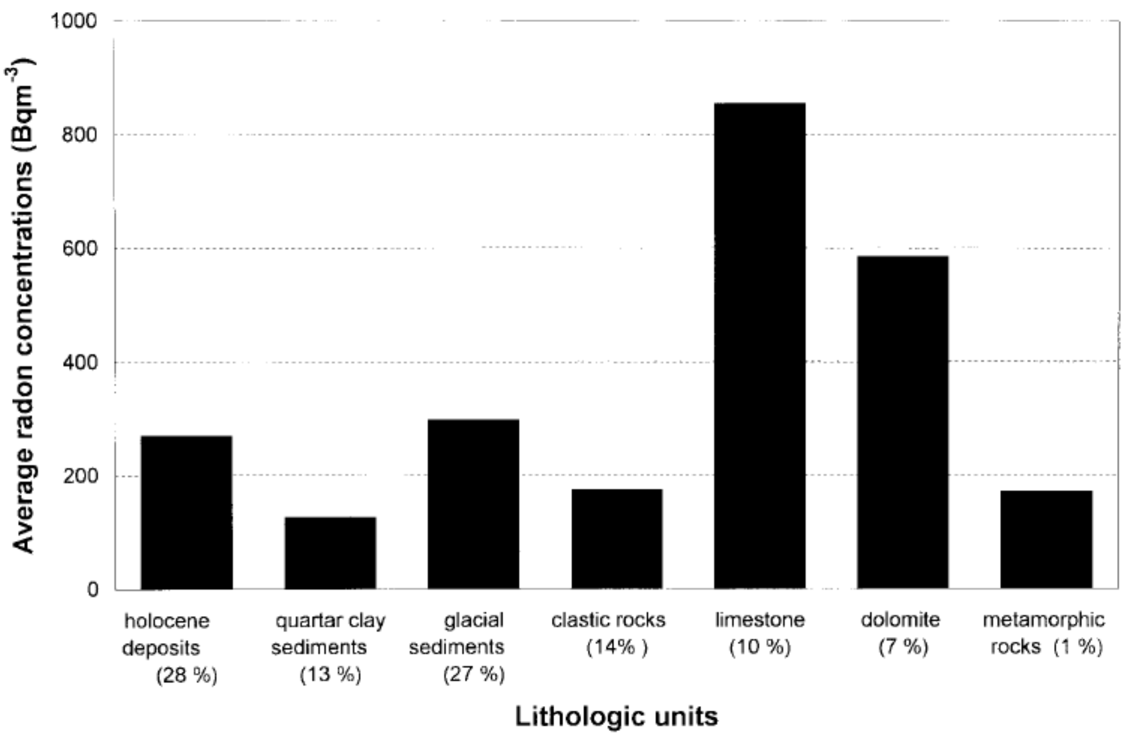

Figure 9. Average radon concentration in each lithological unit in Slovenia. The number under each lithological unit indicates the percentage of buildings (Popit & Vaupotič, 2002).

2.3.2.3 Housing types

Specific housing type information about Slovenia is less available than Cyprus, but the results of the first radon study show that higher radon concentrations were found in older detached houses, most likely due to the lack of concrete slabs and poor ventilation (Križman, Ilič, Skvarč, & Jeran, 1996). Newer houses are likely built on concrete slabs and have better ventilation, except during the heating season.

2.3.2.4 Tobacco smoking habits

A reported 24% of adults (ages 15+, 27% of males, 21% of females) in Slovenia smoke tobacco as of 2016 (World Health Organization, 2017). No studies have been conducted on the regional or geographic distribution of tobacco use in Slovenia.

3 RESULTS

This results section will be comprised of the two radon surveys for each country, Cyprus and Slovenia. These will be based off of the recommendations found in the IAEA Safety Report and on considerations previously mentioned in this thesis, namely the previous studies conducted by Cyprus and Slovenia, along with the completed United States and Austrian surveys used as examples.

3.1 Cyprus Radon Survey

3.1.1 Assessing the need for a radon survey

3.1.1.1 Purpose of the survey

The purpose of a representative Cypriot radon survey would be to follow up on past reports, most notably the one from 1993, and verify the conclusion that Cyprus in general does not have a tendency toward elevated radon concentrations. If elevated radon concentrations are found, then suggestions will be offered to help reduce the radon in those dwellings.

3.1.1.2 Scope of the survey

The scope will not necessarily be to thoroughly cover dwellings across the entire country, but to sample a few targeted areas where a denser sample population can be taken. The locations would ideally be in two heavily populated areas and one or two areas where the geological profile indicates that radon should accumulate. This would give an indication of radon concentration variance within smaller concentrated areas, as opposed to the sparse, scattered data that currently exists for Cyprus. The two heavily populated areas that will be the target for the survey are the two most populous cities in Cyprus, Nicosia and Limassol.[3] The two towns where the geological profile suggests radon may be an issue are Pedulous and Lemithou.

3.1.1.3 Existing information

Existing radon data suggests that there is no radon problem in Cyprus. An excerpt from the IAEA SR states,

> "If analysis of available data indicates that radon is unlikely to pose a health risk, there may be no need to conduct a full national survey. However, this hypothesis would need to be tested with a small-scale survey and this would need to be repeated in the future (e.g. every 10 years) to ensure that conditions affecting the ingress and accumulation of radon into buildings remain unchanged."

And that, precisely, is justification for revisiting the issue. If the results of the new survey are similar, plans can be made to reproduce the survey every ten or so years in different areas, and if they suggest radon could be an issue, then the survey can be reproduced in different areas and grow until the data is representative of the whole country over time.

Public health information for the country of Cyprus indicates that the tobacco smoking rates are higher than the average of the rest of the European Union (EU) and United States. This information alone is enough to warrant an investigation into the radon situation in the country, because of the established link between radon, smoking, and the risk of lung cancer.

[3] From here on out, unless otherwise mentioned, "Nicosia" will only apply to South Nicosia, since the city is divided into northern (Turkish) and southern (Greek) parts. These two parts of the country, Turkish and Greek, are essentially treated as two different countries due to conflict. This causes difficulty for data comparison and coordination among the two parts of the city.

Geologic data shows that the Troodos Ophiolite geological region contains areas with high uranium content, along several deep faults, which enhances the amount of radon reaching the surface – and several villages are built on top of such faults. Two villages that lie near these plagiogranites/fault lines are Pedoulas and Lemithou and will be areas of interest for this radon survey. Figure 10 shows these villages' location in Cyprus on a geological map.

In addition, due to the low expected concentration, the reference level for this survey will be set at the WHO recommended 100 Bq/m^3. Wherever concentrations exceed that level recommendations would be made to remedy it.

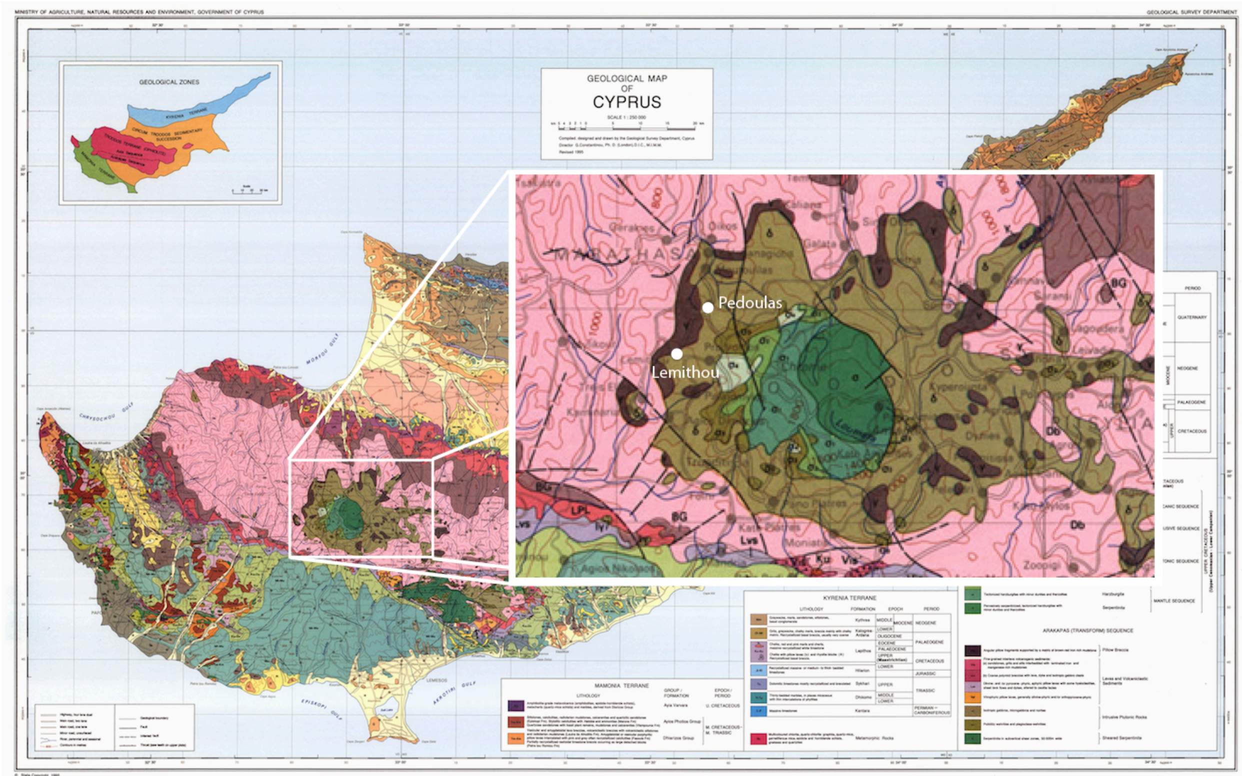

Figure 10. Location of Pedoulas and Lemithou near uranium containing plagiogranites (dark brown spots) and fault lines (dashed and solid lines) (Republic of Cyprus Geological Survey Department, 1995).

3.1.1.4 Pilot survey

The main question when starting out is, can the prior Cypriot radon surveys be used as pilot surveys? Some of the goals of pilot surveys are to test logistics of a survey, such as choice of detector, participant recruitment, rate of response, method of distribution, etc. Many of these aspects have been covered in the previous surveys and will lend useful information when designing a modern survey. However, some of them may need to be re-tested, such as rate of response or communication with participants, which may have changed now that communications technology is more advanced. Thus, it will be beneficial to perform a small-scale pilot survey in the test areas before the full survey is undertaken.

Specific logistics about the pilot survey will be suggested based on previous examples of radon surveys, but there will not be any physical data on which to base the rest of the survey. So, for this thesis, example data may be used based on these previous surveys when continuing to create the larger-scale surveys.

The number of measurements made during the pilot survey will be proportional to the target number of measurements required for that area. There is not an exact number to use here, as it will depend on the size of the survey but based on a previous Australian study which has been summarized in Annex II of the SR, about 200 pilot measurements worked well. So, for Limassol, 50 participants will be contacted; for Nicosia, 100 will be contacted; and for the villages of Pedoulas and Lemithou, since there are so few occupied dwellings, the entire target population (68 and 51 homes, respectively) will be contacted and the full study can commence for these towns.

3.1.2 Designing the radon survey

3.1.2.1 Assemble a working group

The first step to designing a radon survey is to assign a group or organization(s) that will be in charge of designing and carrying out the survey. According to the SR, the group will ideally be a mix of technical experts such as geologists, public health specialists, and statisticians. For the country of Cyprus, this group would start with the Ministry of Labour, Welfare and Social Insurance, acting through the Radiation Inspection and Control Service of the Department of Labour Inspection. They are the regulatory authority in Cyprus for radiation safety and security, including occupational and public exposure to radiation due to radon. Also, the University of Cyprus Department of Physics should be a part of the working group, as it was involved with the 2003 indoor radon study (Anastasiou, Tsertos, Christofides, &

Christodoulides, 2003). Help with managing the data gathering/processing, statistics, and storage could be done by the Statistical Service of Cyprus (CYSTAT), the organization that performs the Cyprus census.

3.1.2.2 Develop a database

An important step at the onset of the survey is to decide how and where the radon information will be stored. It should be easily retrievable and should be in the same or similar format as census information to aid comparison. The census information for Cyprus is stored in the Statistical Service of Cyprus main offices in Nicosia, and it would be ideal for the radon data to be sent there via the Government Data Network (GDN), a fast and secure method of data exchange within Cyprus (Diamantides & Hofman, 2012).

Also, at this stage, the decision will be made as to whether the survey will be geographically based, or population based. For Cyprus, as mentioned before, the measurements will be focused on two populated cities and two villages located in a geographic region where radon levels are expected to be elevated – so, a blend of rural and urban. But in the major cities, the survey will be population based.

3.1.2.3 Sample size

For a national survey, a good sample will cover 0.1% to 1% of the housing stock. So, this survey will aim for that level of completion in the target areas. Achieving this sample rate (or higher) in every step of the survey, if continued in the long term, will satisfy the suggestions proposed in the IAEA Safety Report for national surveys. A graded approach may be taken, with a higher percentage taken in less densely populated areas to obtain a more accurate view of the radon situation. The number of apartment blocks will affect the number of homes measured, as some will be located in apartment buildings above the ground floor, where radon is less likely to accumulate. So, only ground-floor apartment blocks will be included in the study, which may cause the end result of the study to overestimate the average risk of radon on the general public. But this study's purpose is to find areas where radon might be a problem and measuring the ground-floor apartments is a good way to do this.

In Austria's national survey, they ended up measuring a total of about 0.25% of the total housing stock, so this number will be a good starting point. In the two small villages, the target will be 75%, since the towns are small enough that it will be possible to attempt to measure every occupied dwelling, but we must allow for non-response and non-completion rates. Table 3 below shows the number of homes in the target areas and how many homes would be proposed for sampling.

City/Municipality	Total number of households (occupied and used as usual residence)	Target number of dwellings measured	Target percent (%)
Limassol	37,281	932	0.25
Nicosia	22,071	552	0.25
Pedoulas	68	51	75
Lemithou	51	38	75

Table 3. Target number of measurements for cities in Cyprus. North Nicosia is not included because its population data is in the Turkish census of Northern Cyprus. The data used is from the 2011 Census of Cyprus (Statistical Service of Cyprus, 2011).

To achieve these target numbers, the response and completion rates calculated from the pilot surveys will be used. So, if half of the participants who were contacted ended up sending in usable data for the pilot survey, then for Limassol, for example, about 1,864 participants would be contacted. Of course, overshooting the target number is preferable to undershooting, so rounding up to an even 2,000 would work as well if time and funds permit.

3.1.2.4 Questionnaire

The questionnaire data should contain similar questions as the most recent census. This will make it possible to perform a “check for representativeness” as mentioned in the safety report and previously in this thesis. CYSTAT will have access to all questions used in the 2011 census, and by using these along with a modified version of the example questionnaire provided in the SR and/or a questionnaire used in the previous surveys, an up-to-date questionnaire will be created. The most important information to gather will be:

- Detector location in the dwelling (floor and room)
- Measurement duration
- Type of dwelling (single detached house, apartment, etc.)
- Age of the dwelling
- Presence of a basement
- Type of foundation
- Smoking habits of inhabitants
- Information on possible previous radon measurements

An example questionnaire is provided in the SR appendix II and provides more details, but the questionnaire may vary from country to country based on the need for the questions to match census questions.

If the internet is prevalent in the locations of the surveys, it could be beneficial to give the participants the option to fill out the questionnaire online. This would be CYSTAT’s prerogative, as the cost and time required to set up an online form might not be worth the trouble but could be in place for future use for censuses and/or other radon surveys.

3.1.2.5 Communication with prospective participants

Educating the general public and making them aware of the radon survey is important. This could prime the prospective participants into having an interest so that they are more responsive when contacted by survey officials. This public awareness can be done through advertisements such as radio and TV commercials, billboards, and print ads. The information conveyed should cover the basics of radon and its health risks, the benefits of the survey, and should explain that it is being conducted by the government along with a competent organization rather than a private company, and that all information gathered will be strictly confidential (besides summary information on radon, such as radon concentration averages).

3.1.2.6 Recruitment of participants

Many past surveys have relied on land-line telephones, post, or face-to-face interactions to recruit participants. As mentioned above, if the internet is widely used, online contact should be considered as well. Participation rates are known to increase with face-to-face contact, however. These methods will be tested in the pilot survey, but it seems logical that the first contact should be by phone to arrange to send the detectors by post or set up an appointment for a volunteer to come and place them.

3.1.2.7 Choice of radon detector

The IAEA recommends longer-term measurements for radon surveys (three months to one year), and seemingly the best option is the use of SSNTDs. These were originally used in the

1993 Cyprus survey and are easy to use, so they will be used for this survey. They will be purchased from an accredited laboratory, perhaps Radonova Laboratories in Sweden.

3.1.2.8 Duration and location of measurements

A measurement period of at least three months will be recommended. This will be long enough to account for short-term fluctuations but short enough that possible detector fading won't be an issue, and if the measurement is performed during the fall or winter months it will provide a conservative estimate of the radon concentrations. Three-month measurements, as compared with one-year measurements, will also reduce the likelihood of any detector tampering occurring.

Two detectors will be placed in each dwelling – one in the master bedroom and one in the main living area. Locations near windows, drafts, and heating and cooling vents will be avoided.

3.1.2.9 QA/QC of measurements

To ensure quality assurance and quality control during the measurement process, certain practices will be used. The detectors will be sealed before and immediately after exposure to minimize exposure during shipping, and storage times before and after will be kept to a minimum. Also, double detectors will be placed in 1 of 10 dwellings. That is, two detectors will be placed next to each other in each room to ensure that the measurements between the two are accurate. "Blanks" will also be sent at a rate of five percent. The purpose of these is to measure the background exposure and ensure that there is no contamination during the shipping process.

Details on QA/QC of radon laboratories can be found in Appendix I of the SR. Since the detectors will be purchased from an already accredited laboratory, this will not be in the control of the radon authorities conducting the survey but are still important for the accreditation of any radon laboratory.

3.1.2.10 Sources of bias

Some sources of bias are hard to account for, and those that are unavoidable during the process should be reported. Those include measuring during the winter months and measuring only ground-floor dwellings, which will help locate any areas of concern but will overestimate the average radiation exposure per person due to radon.

3.1.3 Conducting the radon survey

3.1.3.1 Detector distribution and collection

For the populous cities of Nicosia and Limassol, detector distribution and collection will be done by post since there are many more measurements that should be taken in these cities and going door to door would be time consuming unless there is a large cohort of volunteers. In line with SR recommendations for using the postal service for detector distribution, the following steps will be taken:

1. The laboratory will send the detectors in radon-proof bags, and the participants will be given clear instructions that they should stay in the bags until they are ready for use.

2. Simple instructions will be included with pictures and a link to a website with an instructional video for how to place the detectors. An example of a detector information form is located in Appendix 1, and this could be used as a basis for creating a new instruction sheet.

3. A pre-paid return package will also be provided (may be in the form of a sealable bag or container) either at the beginning of the test or when the measurement time has lapsed. (Sending it after the measurement is complete would be a good way to remind the participants to send the detectors back.)

4. A reminder will be included that stresses the importance of correctly documenting the start and end dates of the survey, as that is one of the most important elements in correctly measuring the radon concentration.

5. The questionnaire or link to an online questionnaire will be included with the detectors.

6. A checklist will be provided to ensure that all the pieces of the package have been included.

7. Pictures of what the detectors should look like might be included as well, along with instructions that they should not be opened or tampered with in any way.

Follow-up calls can be made to the participants after the detectors are sent to assist with any or all of these steps.

At this point it will be beneficial to gain further information, such as if the participants would be willing to be contacted in the future for possible follow-up studies, and if they would prefer a different method of communication (e.g. paperless via email or phone). The phone number to an information hotline will be included, so if the participants have any questions during the process or about their results they can speak to someone directly. And as previously mentioned, at the end of the survey, a phone call or return package/envelope will be sent to remind the participants to send the detectors back.

For the small villages of Pedoulas and Lemithou, the door-to-door approach will work better. Response rates have been shown to be higher with the door-to-door method, and since an attempt will be made to measure every home, a high response rate is necessary. An appointment may be made online or via phone call, and a trained volunteer can go meet the participant, explain the details of the survey and walk them through the questionnaire and personally place the detectors in the proper locations. Instructions for what to do with the detectors after the measurement period has ended will be included and explained – otherwise phone calls will be made to the participants and/or prepaid envelopes/packages with instructions included will be sent to the participants at the end of this period.

3.1.3.2 Validation and analysis of data

Before the data can be processed, the measurement results will be checked to make sure that all necessary information is included and that the measurements were made according to the protocol. If an essential piece of information is missing for a measurement, it cannot be confirmed as valid. In addition, if any other information is missing, such as housing data, it will make it more difficult to draw conclusions from the data later. The completion rate can be calculated by dividing the number of dwellings successfully measured by the number of dwellings detectors were placed in/sent to.

The data will be tested for log-normality, and any outliers will be double checked. Also, the measurements will be corrected to account for background radon levels. Then, a check for representativeness can be performed.

Both the arithmetic mean and geometric mean will be calculated, but since the geometric mean tends to downplay the presence of very low or very high samples, the arithmetic mean will be more valuable to this study.

Finally, the data can be combined with questionnaire data to find other information, such as the number of persons exposed to concentrations of radon above the reference level or identify features of homes that tend to correlate with radon levels, similar to what the U.S. did in its National Residential Radon Survey.

3.1.3.3 Management and mapping of data

If enough concentrations of radon above the reference level are found, a map can be generated showing any areas with averages above this level. CYSTAT could use a geographical information system (GIS) to develop such a map. This would be used to help experts begin to target the areas with the highest radon concentrations and make efforts to reduce these levels. The map would not be made public, because when the general public sees that they are in an area that has been calculated to have average elevated radon concentrations, they will be more interested in participating in future radon surveys. The opposite is also true: When people see that they live in an area with low average radon concentrations, they assume there is nothing to worry about. This could lead to bias in future follow-up surveys, resulting in more measurements made in “radon risk areas.”

The results would be displayed as a predicted number of dwellings in each area over the reference level. And instead of showing areas with solid line boundaries, a smooth gradient map could be generated to avoid breaking the sample area into smaller areas.

3.1.3.4 Reporting results to participants

After the survey participants will be informed of their results by mail (or email if they opted to do so). Included with their results will be: the average concentration found in their home; information to allay concerns if it is higher than the reference level; and information on simple practices to reduce radon levels. The information will be presented in a very clear, concise, and easy to understand so as to not cause confusion. The graphic design of the results package will be similar to the information included in the first package sent to the participants.

3.2 Slovenia Radon Survey

Some of the methods in both the Cypriot and Slovenian surveys will be similar, such as the type of detectors and detector placement in homes. Below, greater emphasis will be placed on the methods that would be implemented in Slovenia that are different from the ones used in Cyprus.

3.2.1 Assessing the need for a radon survey

3.2.1.1 Purpose of the survey

The last indoor radon survey for dwellings in Slovenia was conducted in 1996. The goal of this survey will be to develop a modern survey thorough enough to find specific areas and homes across the entire country with elevated radon concentrations, so levels can be reduced for the sake of public health.

3.2.1.2 Scope of the survey

The scope of the survey will largely track the Austrian survey. The expected radon concentrations in Slovenia are not expected to be low, like Cyprus, due to the colder climate of Slovenia and the known presence of uranium and radium in the Dinaric regions, which showed higher concentrations of radon in the 1996 survey. So, for this study, measurements will be taken uniformly across the country. The aim will be to measure one in every 200 dwellings in each of the 212 municipalities, with a minimum of ten measurements made in each municipality. This will result in 4,617 households[4] measured out of the total of 820,541 (Stastical Office of the Republic of Slovenia, 2015), giving a coverage of 0.56%. This population-based approach will allow for adequate coverage in both populous cities and rural towns alike, with a denser sample distribution than the 1996 survey.

Similar to the Cyprus and Austrian surveys, only ground-floor dwellings will be taken into account.

3.2.1.3 Existing information

Existing previous radon data shows that there may be 4,000 to 5,000 homes in excess of the 400 Bq/m^3 reference level. The same data also shows that the geological profile of Slovenia might also cause excess radon concentrations in homes in certain geographical areas.

Public health information indicates 24% of adults in Slovenia smoke tobacco compared with 27% in Austria (World Health Organization, 2017). This means that the relative risk for smokers between the two countries should be roughly the same.

The geological profile of Slovenia shows that the Karstic region of the southwest is high in uranium and radium concentrations, which should indicate higher radon levels for homes built

[4] Here, "households" is used interchangeably with "homes" and "dwellings" since it refers to occupied dwellings of one or more persons at the time of the census.

in this area. Special attention will be paid to this area when analyzing the data at the end of the survey, with possible follow-up studies recommended.

The current reference level for Slovenia is 400 Bq/m^3 for existing buildings and 200 Bq/m^3 for new buildings and will be kept the same for the modern survey.

All other data pertaining to radon in Slovenia will be gathered prior to the survey as an initial step.

3.2.1.4 Pilot survey

A new pilot study will be conducted to test the new sampling methods. In the Austrian survey, a large city and a rural region were tested in the pilot survey, so for the Slovenian study two similar municipalities will be tested. The municipality of Maribor, containing the city of Maribor, the second most populous city in Slovenia, will aim for 258 measurements, and the municipality of Tolmin (essentially chosen at random) will aim for 23 measurements (see Figure 11). The sample density will be proportional to cities/areas with higher population density. The number of participants contacted will be higher than the target numbers to try and find an accurate rate of completion. Besides this, the pilot survey will resemble the full survey for these two municipalities. After the pilot survey, an extended pilot phase may be carried out, to re-test what was learned during the first pilot phase, and after this the full survey will commence.

Figure 11. Locations of Municipalities Maribor and Tolmin in Slovenia.

3.2.2 Designing the radon survey

3.2.2.1 Assemble a working group

The main organization that will be involved with the planning of the radon survey will ideally be the Center for Radon in the Department of Environmental Sciences at the Jožef Stefan Institute (IJS) in Ljubljana. The center has authored many papers related to radon in the past and will provide much insight to the new radon survey. The office in charge of statistics and database management will be the Statistical Office of the Republic of Slovenia, the organization responsible for conducting the Slovenian census.

3.2.2.2 Develop a database

The database used will ideally be connected to the census database. This way, the codes used to reference each dwelling can match and make data comparison relatively easy. It also will make random confirmation of census as a check for representativeness simpler. This database of course will be private and secure.

3.2.2.3 Sample size

As previously mentioned, the sample size will be roughly one out of every 200 dwellings measured, with a minimum of ten samples for each municipality, resulting in 4,617 dwellings measured out of 820,541 and a coverage rate of 0.56%. And for more populated areas, the sample density will be proportional to population density. And in cities with apartments, only ground-floor samples will be taken. If funds are not available to conduct this survey in one stage, then a graded approach may be taken, splitting the measurements into two parts to be done consecutively or with a gap in between.

3.2.2.4 Questionnaire

Many questions in the questionnaire will be identical to the most recent census. The most important information required will be similar to the Cyprus survey, such as detector location in the dwelling, type of dwelling, age of the dwelling, presence of a basement, type of foundation, smoking habits of inhabitants and information on possible previous radon measurement. It is important that the questionnaire questions match recent census questions in order to conduct a check for representativeness.

Similar to the Cyprus survey, there will be an option to opt for an online questionnaire and to receive future notifications via email.

3.2.2.5 Communication with prospective participants

Communication to prospective participants to raise awareness will be done in several ways. Use of advertisements on TV, radio, and print ads will be useful, along with perhaps an interview with a radon authority from the IJS on TV or the radio. One thing that helped awareness for Austria was the involvement of local and regional politicians, and the involvement of volunteer firefighters as the sample group, which is discussed in the next section.

3.2.2.6 Recruitment of participants

In the original Austrian radon survey, homes were chosen at random from the telephone directory. But now, land lines are sparser and most mobile phones are not listed in the directory. The way around this was by contacting volunteer firefighters and recruiting them for the survey. Slovenia could similarly recruit based on volunteer firefighters. A check of various online sources indicates Slovenia has more than 40,000 active volunteer firefighters – more than enough to conduct a representative survey. Austria checked for representativeness and found there were no biases in using this method. The Fire Brigade of Slovenia could cooperate with the other radon authorities to make this possible.

3.2.2.7 Choice of radon detector

One measurement system will be used for consistency – ideally long-term SSNTDs. An accredited laboratory will be contacted about providing these in bulk for the survey.

3.2.2.8 Duration and location of measurements

Measurements will be taken in seven-month measurements, partly during the winter and going into summer. The seven-month time frame was chosen because January is the coldest month in Slovenia and July the warmest. This will eliminate the need for a seasonal corrective factor and should give a good indication of the yearly average radon concentration without having to measure for an entire year.

The location of measurements will be two in each dwelling, one in the main bedroom and one in the main living area. The detectors will be placed away from windows, doors, and heating and cooling vents.

3.2.2.9 QA/QC of measurements

QA/QC can be done during measurement in a similar way to the Cyprus survey. Ensuring that the detectors are sealed in radon-proof bags before and immediately after the survey – along with minimizing storage times of detectors – will increase the accuracy of results. Double detectors will be placed in one out of every ten dwellings.

3.2.2.10 Sources of bias

As before, taking note of any biases that may occur during the survey is imperative. It is important to try and eliminate them but sometimes biases are unavoidable. The possible biases for this survey could arise in calculating the average exposure to the population from only ground-floor dwelling measurements, and it is possible that only measuring the residences of volunteer firefighters could introduce some bias, but this will be checked in the pilot survey.

3.2.3 Conducting the radon survey

3.2.3.1 Detector distribution and collection

Distribution and collection of detectors can be performed both by post and by individual interviews. It has been determined, as previously noted that the response rate rises and quality of completed questionnaires improves when using a personal interviewer, so this method is preferred. If the budget for the survey allows, then paid interviewers will be used to distribute as many detectors as possible. If not, then detectors can be distributed mainly by post. If interviewers are used, they will be thoroughly informed about radon and the project itself to ensure competency. In instances where detectors are distributed through post, follow-up calls may be placed to help participants place the detectors and fill out the questionnaire.

When the measurement period has ended, calls will be placed to the participants to remind them to send their detectors back, as well as to help make sure the detectors are sealed properly for shipment and that the start and end dates have been accurately recorded.

3.2.3.2 Validation and analysis of data

After the detectors have been sent back, the data points need to be validated to make sure all the required information is present. The completion rate will be calculated, a test for log-normality will be performed, and any outliers will be reviewed. The data will be corrected for background radon levels and then the geometric mean can be calculated since it reduces the effect of very low or very high values. (extreme values also will be examined).

Next, the mean of each municipality can be calculated, and using this, the number of estimated dwellings above the reference level can be determined for each municipality and used for mapping.

3.2.3.3 Management and mapping of data

A map can be created using the data with a GIS. Then, as mentioned in the last section, results can be shown as municipalities with estimated number of homes over the reference level, with a gradient map overlay showing the smaller variations within municipalities. This will give authorities a basic map to see which areas should be given attention to begin remediating dwellings in a graded approach. This map will be used for administrative purposes and not published for public use.

3.2.3.4 Reporting results to participants

Participants will be informed of the results by post or by email, if they opted for that earlier. Included will be information explaining what the results mean in the context of the mean concentrations in their area/municipality. Advice can be given on simple practices that can help reduce radon concentrations. Also, it will be explained that a graded approach to remediating high radon levels will be undertaken, and the participants will be given the contact information of the relevant authority if they have any more questions or concerns.

4 DISCUSSION AND CONCLUSION

Naturally, these example reports are not as thorough as if they had been planned by the government or radon authorities in Cyprus or Slovenia, as these authorities would have access to their specific resources. However, these are solid, well-considered examples of how different countries could use this specific IAEA Safety Report, "Design and Conduct of Indoor Radon Surveys," to tailor their own surveys to their specific needs based on previous data. These examples follow each step of the SR, containing tried-and-true methods along with modern methods, such as using the internet to provide information to the participants.

If a country has opted to perform a radon survey using the SR but there is no previous radon data available, the best option would be to err on the side of thoroughness, especially because the decision to take on a radon survey means there is a need to dedicate a good amount of time and resources in planning and executing it. Ensuring thoroughness at the beginning means less work will have to be done in the future to correct any mistakes or any issues that may have caused the survey to be less representative. However, the SR is not exclusively aimed at nations that have little or no radon data. As seen from examples in the annexes of the report, no nation is considered to be completely finished when it comes to measuring radon in homes. There is extensive work continuing around the world to expand the breadth of surveys so that they are as representative of the entire population as possible.

The best way to find and mitigate high radon concentrations in homes is to measure as many homes as possible, but it is not usually cost feasible to perform them all simultaneously. Instead, representative surveys are conducted over a number of years to reduce the amount of measurements and to spread out the cost. In this thesis, two countries in need of thorough representative surveys were chosen, along with two countries with thorough indoor radon reports to be used as examples. Then, the IAEA Safety Report was followed step-by-step to develop the basis of theoretical large-scale radon surveys for the countries using the example countries as templates. Even though the surveys created in this thesis will not be utilized by Cyprus or Slovenia, this would be a good starting point if they decided to continue performing indoor radon measurements in homes.

Amidst all the facts, figures, and planning, it is easy to lose sight of the main objective behind the IAEA report. Ultimately, the goal is to assist countries in preventing premature deaths that come as a result of radon exposure. Hopefully, by demonstrating how the report can be used, this thesis will encourage nations to strive toward finding and mitigating homes with radon levels that are threatening to health and educating the public on the dangers of radon, thus reducing the number of lung cancer deaths worldwide.

4.1 Future Work

This section contains some examples of any future research that could be done to follow up on this thesis. More theoretical surveys could be planned for different countries with more varied or extreme climates. On a more experimental basis, a follow up thesis about new radon testing methodologies could be physically tested in a small area. This could include methodologies such as new ways to send and receive detectors, use of the internet in surveys, or how to improve the efficiency of surveys, since they require much time and resources. Some factors affecting response/participation rates could also be considered. A study could be performed testing two small areas, one with publicly disseminated radon information and one without, and the response rates could be compared. Another program that could be tested would be an educational program for children in grade school – they could learn about radon and have a competition to see who could distribute the most detectors, or just have them take detectors home and measure their homes. This would have the two-pronged effect of educating the children and their parents as well as acquiring more radon data. Finally, a more detailed analysis of calculating sample sizes for radon surveys may be insightful. This could make use of Bayesian statistics, since many countries have performed radon studies before and Bayesian sample size determination depends on prior distributions, such as existing radon data.

Alpha-track Radon Detector Form

Record 6 digit Detector Number Here

______

A. When did you do your test?

Start: Month Day Year End: Month Day Year

B. Where did you place your detector?

First Name

Last Name

Street Address

City

State

Zip Code

County / Parish / District

Room Type

Structure/Foundation Type

____Slab at grade level
____Crawl space
____Full basement
____Bi-level or half basement/ half crawl
____Commercial / Public Building
____School / Daycare
____Other________________________

Test Level or Floor

____Basement or below grade
____1st floor or grade level
____2nd floor
____3rd floor or above
____Other________________

C. Where should we send the results? ___Send to above name & address

First Name

Last Name

Company / Organization

Street Address

City

State

Zip Code

D. How should we send the results?

Via: ____e-mail - (quickest option) or ____US Postal Service

E-mail address

Phone Number - (In case we have a question.)

Figure 12. Example radon detector form (RSSI, 2015).

Georgia State University Radon Test Information Sheet

Home Owner ID____________________

Research Staff Name____________________**Panther ID** ____________________

Sampling Address___________________________________City________State/Zip____

Homeowner Address (if different) _____________________City________State/Zip____

House Type:
Ranch () Split-Level () Multi-Story () Other__________ Construction Year_____

Building:
Frame () Brick () Block () Other_________

Foundation:
Slab () Crawl Space () Basement () Other_____________

Number of Smokers ______ Number of Children (under 18) ____________

Homeowner Awareness: Newspaper () T.V. () Radio () Family ()
Friends () Neighbors () Other________

Monitor ID_____________Date Placed _________ Time Placed _____________
Date Removed_________ Time Removed ___________
Floor: ____________

Test Methods: Charcoal () Continuous Monitor ()

Room Tested: Living () Bedroom () Den () Hallway () Office () Basement ()
Other_____

Figure 13. Example questionnaire from a Georgia State University radon study. This contains similar information as the previous form but contains more information that could be used in a census comparison to ensure representativeness (Chan, 2016).

REFERENCES

Anastasiou, T., Tsertos, H., Christofides, S., & Christodoulides, G. (2003). *Indoor radon (Rn-222) concentration measurements in Cyprus using high–sensitivity portable detectors.* Lefkosia: University of Cyprus.

Centers for Disease Control and Prevention. (2018, February 15). *Current Cigarette Smoking Among Adults in the United States* . Retrieved from CDC: https://www.cdc.gov/tobacco/data_statistics/fact_sheets/adult_data/cig_smoking/index.htm

Chan, S. (2016). *Analysis of Data Collected in Pilot Study of Residential Radon in DeKalb County in 2015.* Atlanta: Georgia State University.

Chen, J., Tracy, B. L., Zielinski, J. M., & Moir, D. (2008). Determining the sample size required for a community radon survey. *Health Physics*, 362-365.

Christophides, S., & Christodoulides, G. (1993). Airborne Rn-222 concentrations in Cypriot houses. *Health Physics, 64*(4), 392-396.

Cindro, M. (2016). *Slovenia Country presentation.* Vienna: International Atomic Energy Agency.

Diamantides, C. K., & Hofman, L. (2012). *Cyprus Blaise Integrated Census System (CY-BICS).* Nicosia: Statistical Service of Cyprus.

Farazi, P., Lander, L., Pavlou, P., Watkins, K., Le, L., & Soliman, A. (2015). Geographic trends of tobacco-related cancers in Cyprus. *Tobacco Induced Diseases*.

Friedmann, H. (2005). Final results of the Austrian radon project. *Health Physics, 89*(4), 339-348.

Government of Canada. (2012, October 25). *What is radon?* Retrieved from Health Canada: https://www.canada.ca/en/health-canada/services/environmental-workplace-health/radiation/radon/what-radon.html

International Atomic Energy Agency. (2014). *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3.* Vienna: International Atomic Energy Agency.

International Atomic Energy Agency. (2015). *Protection of the Public against Exposure Indoors due to Radon and Other Natural Sources of Radiation, Specific Safety Guide No. SSG-32.* Vienna: International Atomic Energy Agency.

Križman, M., Ilič, R., Skvarč, J., & Jeran, Z. (1996). *A survey of indoor radon concentrations in dwellings in Slovenia.* Ljubljana: Jožef Stefan Institute.

Lee, M. E., Lichtenstein, E., Andrews, J. A., Glasgow, R. E., & Hampson, S. E. (1999). Radon-smoking synergy: a population-based behavioral risk reduction approach. *Preventive Medicine*, 222-227.

New Jersey Society of Amateur Scientists. (n.d.). *NJSAS*. Retrieved from Geiger Counter: http://njsas.org/projects/atoms/geiger_counter/index.php

Popit, A., & Vaupotič, J. (2002). Indoor radon concentrations in relation to geology in Slovenia. *Environmental Geology*, 330-337.

Republic of Cyprus Geological Survey Department. (1995). *Geology of Cyprus*. Retrieved from Geological Survey Department: http://www.moa.gov.cy/moa/gsd/gsd.nsf/dmlGeoMap_en/dmlGeoMap_en?OpenDocument#

RSSI. (2015). *Instructions for testing your home*. Retrieved from Radon: https://www.rssi.us/radon-instructions-home-test.htm

Slovenia.si. (2013). *Facts about climate*. Retrieved from Slovenia.si: http://www.slovenia.si/slovenia/country/climate/facts-about-climate/

Soteriades, E., Petrokokkinos, L., Talias, M. A., Zissimos, A., Kolovou, M., Potiriadis, C., . . . Georgiou, E. (2016). Environmental assessment of radon levels in Cyprus. *Management of Environmental Quality: An International Journal, Vol. 27 Issue: 4*, 407-418.

Stastical Office of the Republic of Slovenia. (2015). *Population, households and families, municipalities, Slovenia, multiannually.* Retrieved from Slovenian register-based census: http://pxweb.stat.si/pxweb/Dialog/varval.asp?ma=05F3005E&ti=&path=../Database/Demographics/05_population/17_Households/15_05F30_Households_OBC/&lang=1

Statistical Service of Cyprus. (2011). *Population Census: Living Quarters (Total) - Geographical Distribution.* Nicosia: CYSTAT.

US EPA. (1992). *National Residential Radon Survey: Summary Report.* Washington, DC: EPA.

US EPA. (1992). *Technical support document for the 1992 citizen's guide to radon.* Washington, D.C.: Environmental Protection Agency.

US EPA. (2003). *EPA assessment of risks from radon in homes.* Washington, DC: United States Environmental Protection Agency.

Vaupotič, J. (2003). Indoor Radon in Slovenia. *Nuclear Technology and Radiation Protection*, 36-43.

World Health Organization. (2009). *WHO Handbook on Indoor Radon.* Geneva: WHO.

World Health Organization. (2017). *WHO report on the global tobacco epidemic: country profile Austria.* Geneva: WHO.

World Health Organization. (2017). *WHO report on the global tobacco epidemic: country profile Cyprus.* Geneva: WHO.

World Health Organization. (2017). *WHO report on the global tobacco epidemic: country profile Slovenia.* Geneva: WHO.

CURRICULUM VITAE

Charles Fitzpatrick

fitzpcharles@gmail.com

Education

University of Nevada, Las Vegas: Fall 2014 – Summer 2018 Las Vegas, NV

- M.S. Health Physics

University of Tulsa: Fall 2008 – Spring 2012 Tulsa, OK

- Graduated with B.S. Physics

Professional Experience

International Atomic Energy Agency (IAEA): August 2016 – August 2017 Vienna, Austria

- Intern: I helped organize consultant's meetings and created a safety report co-sponsored by the IAEA and World Health Organization titled "Design and conduct of indoor radon surveys" that assists countries in conducting representative radon surveys. I attended organizational meetings, worked with teams, and presented my work at the June 2017 Radiation Safety Standards Committee meeting.

Graduate Assistant: August 2015 – May 2016 Las Vegas, NV

- Graduate Assistant for UNLV: I assisted the professor of the class HSC 100 by grading papers and homework assignments online through blackboard for 50 students. I made three presentations to the class over two semesters on effective ways to conduct research and the importance of finding legitimate sources to cite.

NSI Technologies: August 2013 – July 2014 Tulsa, OK

- Assistant engineer: I helped model geologic terrain in an in-depth hydraulic fracturing software system. I also spent a large amount of time editing the help function of said software, making sure the help system was up to date with the latest version of the program. In this job I became familiar with taking directions from a supervisor in a professional job setting and accomplishing projects he assigned me. I also learned to always ask questions if I am unsure about the next step to take when accomplishing a task.