UNIVERSITY OF NAIROBI

ASSESSMENT OF RADIOLOGICAL HAZARDS ASSOCIATED WITH INDOOR NORM DOSE EXPOSURE IN RESIDENTIAL HOUSES IN NAIROBI, KENYA

BY

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A Thesis Submitted for Examination in Partial Fulfillment of the Requirements for Award of the Degree of Master of Science in Nuclear Science of the University of Nairobi.

DECLARATION

This thesis is my original work and has not been submitted for examination and award of any degree at any other University or institution of higher learning. Where other people`s work has been used, it has been acknowledged and referenced in accordance with the University of Nairobi requirements.

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DEDICATION

Dedicated to my parents for their unending love and support, who taught me the value of hard work, patience and endurance in learning. Also dedicated to my brother Richard Sitati, who has been a constant source of encouragement and my family for steadfast support throughout these studies. Special tribute also goes to Joseph Njoroge, Senior Elder, Life Reformation Centre, Nairobi, for his insight and inspiration.

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LIST OF ABBREVIATIONS

AARST - The American Association of Radon Scientists and Technologists

ACH – Air exchange per hour

ALARA - As Low As Reasonable Achievable

ASHRAE - American Society of Heating, Refrigerating and Air-Conditioning Engineers

BEIR - Biological Effects of Ionizing Radiation

CEN - European Committee for Standardization

CLL – Chronic Lymphocytic Leukemia

DALYs - Disability-Adjusted Life-Years

DNA - Deoxyribonucleic Acid

EC – European Commission

EPA - Environmental Protection Agency

ERR – Excess Relative Risk

ETS - Environmental Tobacco Smoke

EU – European Union

IAEA –International Atomic Energy Agency

IARC – International Agency for Research on Cancer

IAQ- Indoor Air Quality

ICRP - International Commission on Radiological Protection

ICRU –International Commission on Radiation Units and Measurements

KNBS - Kenya National Bureau of Statistics

MCA - Multichannel Analyzer

NEA - Nuclear Energy Agency

NEMA - National Environmental Management Act

NORM - Natural Occurring Radioactive Materials

NRPP -The National Radon Proficiency Program

OECD - Organization for Economic Co-operation and Development–

OSHA - Occupational Safety and Health Administration

PHA - Public Health Act

RBM - Red Bone Marrow

UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation

VOC - Volatile Organic Compounds

WHO – World Health Organizations

DEFINITION OF TERMS

Building Material : Any construction material/product that is incorporated in a permanent manner in a building or parts**.**

Radon: refers to Radon-222 and its decay products; Polonium-218 and Polonium-214

Indoor Air quality: The physical and chemical nature of indoor air, as delivered to the breathing zone of building occupants, which produces a complete state of mental, physical and social well-being of the occupants, and not merely the absence of disease or infirmity.

Action Level: actions considered only in cases where levels are higher than recommended action levels.

Reference Level: represents the level of dose or risk , above which it is judged to be inappropriate to plan to allow exposures to occur , and below which optimization of protection should be implemented.

Indoor Exposure- is the sum of the inhalation doses due to radon and thoron and the external radiation dose from gamma radiation emitted by building materials excluding shielding effects.

Equivalent Gamma Dose Rate- Equivalent dose is a dose quantity *H* representing the stochastic health effects of low levels of ionizing radiation on human (millisieverts, mSv)).

Absorbed Dose - the amount of energy deposited by ionizing radiation per unit mass (Grays, Gy)

Effective Dose – The mmeasure of the biological effects of exposure to ionizing radiations (Sieverts, Sv).

Excess Lifetime Cancer Risks- Long-term effects of exposures to radioactivity and inhalation of radionuclides.

Ventilation opening area - means operable windows, doors although a dedicated non-window opening for ventilation is acceptable. Spaces that meet the local exhaust requirements are exempted from this requirement.

Ventilation rate- is the volume of fresh air introduced into the space per hour.

Air Change per Hour (ACH) is the volume fraction of ventilated air per hour that estimates infiltration of outdoor air pollution indoors and diluting indoor space emissions

Air change- The rate of airl entering or leaving a space by natural or mechanical means in terms of the volume of the space.

Minimum ventilation rate - minimum ventilation rate per person (m^3h^{-1} per person), minimum ventilation rate per area ($m^3h^{-1}m^{-2}$) or Air change rate h^{-1} (ACH)

Ventilation per area (*l*ps/m^2) estimates the dilution need of emissions from surfaces

DALYs – is the numbers of healthy years of life lost from death or disability**.**

Sick Building Syndrome (SBS) - A situation or condition in which building oocupants experince acute health and comfort effects that are linked to time spend in a building such actute discomfort include headaches; eye,nose or throat irritation; dry cough; dry or itchy skin; cizziness and nausea; inability to concentrate; and fatigue.

ABSTRACT

Indoor air quality has profound impact on health worldwide; effects on respiratory, circulatory and immune systems due to sick building syndrome. This study examined the radiological hazards associated with indoor air quality in selected residential houses in Nairobi City for exposure to NORM. In situ measurements were done using Gamma Spectroscopy Multichannel NaI (Tl) analyzer on the type of building materials (for floor, walls and ceiling), used in three hundred and thirty (330) residential houses. Indoor NORM radioactivity content, ambient gamma equivalent dose were measured and the ventilation rate of the main living rooms evaluated. The radiological hazards assessed were; absorbed dose, effective dose and excess life time cancer risks. The results indicate potential exposure associated with NORM within the type of building materials. The dominant radionuclide identified was ^{40}K; mean 107 kBq (103 -163) kBq (floor), mean 140 kBq (97 -344) kBq (walls) and mean 120 kBq (84 -167) kBq (ceiling) and dose rate of 0.32 mSv/yr (floor) and 0.34 mSv/yr for both walls and ceiling. Other NORMs were below their detection limits. For indoor ambient gamma dose rate, the ceiling was the dominant source of exposure for most residential houses and exceeds 2 mSv/yr. The indoor absorbed dose ranged from 60.34 - 272.73 nGy/h with a mean value of 113 nGy/h and varies with type of building material used with correlation significance of 26%. The results of mean absorbed dose rate show that residence within Kapiti Phonolites regions are relatively at risk of high exposure than those in Nairobi Phonolites. The indoor annual effective dose obtained from the floor, ceiling, and walls are 0.55 ± 0.18 mSv, 0.63 ± 0.21 mSv and 0.71 ± 0.24 mSv and are within the UNSCEAR indoor annual exposure of 0.41 mSv for adults, 0.45mSv for children and 0.53 mSv for infants, respectively. The findings of this study indicate potential exposure from tiled floors (1.34 mSv/a) and concrete roof (1.06 mSv/a). The estimated excess lifetime cancer risk ranges from 0.2 to 0.6 % with a mean value of 0.28%. The three parameters of ventilation namely; ventilation rate, air exchange rate per hour, and ventilation per area were studied. Most main living room residential houses had ventilation openings areas less than 5%, air change rate per hour ranges between 0.48 to 0.61 h^{-1} with mean value of 0.51 h^{-1}, and are not compliant to the local minimum requirement of 0.5 - 1 h^{-1}. This findings are in agreement with indoor air quality and exposure dependency on ventilation systems. However, there is indication of poor indoor air quality in some Nairobi residence whose exposure rate is dependent on; the type of building materials used, ventilation area opening, ventilation rate, the floor level, locations of residences, the size of the rooms, indoor occupancy and lifestyle. The study therefore recommends incorporation of radiation protection and safety standards of NORM in building materials of residential houses and indoor air quality standards, and policies for the building and construction industry of residential houses. Further investigations of the associations between indoor air quality and respiratory diseases or allergies and the air change rate in homes could be considered and public ventilation awareness campaigns.

CHAPTER 1 :

INTRODUCTION

1.1 Introduction

Section 1.2 introduces the background of the study; indoor air quality, housing situation in Kenya, sources of indoor NORM and radon exposure, effects of ionizing radiation and human cell effects. Section 1.3 defines the research problem , Section 1.4 highlights the objectives of the study while section 1.5 states the justification and significance of the study. Section 1.6 summaries the scope of the study.

1.2 Background

For many decades, much attention has focused on controlling air pollution in the ambient environment, industrial and transport emissions until late 1970s, when indoor air quality research were initiated, to mitigate against occupational health related diseases in industrial workplaces and the impact of indoor pollutants in buildings. In 2012, indoor exposure accounted for 1.6 million annual deaths, 3% of the global disease burden, which by far exceeded that by outdoor air pollutants (WHO, 2012). And by 2016, household air pollution mortality contributed 3.8 million deaths (WHO, 2018) and 77 million DALYs (Health Effects Institute, [HEI], 2018).

The first guidelines on air quality were published by the European Union in 1987, followed by the second edition in 2000 (WHO, 1987, 2000). In developing countries however, the 2005 global update of air quality guidelines drew attention of indoor air pollution for inclusion (WHO, 2006). In Kenya, control of ambient air pollutants started in 1999, with ambient air quality tolerance limits and indoor occupational air pollutant exposure limits NEMA L/N No.8/1999. In 2004, Kenya`s indoor air pollution was linked to high mobility especially for children below 5 years (MOH, 2009). Until recently, the Kenya 2014 air quality regulations have identifiable gaps in regards to residential indoor air exposures and control limits (The National Enviromental Management and Co-orddination [NEMA], 2014).

In general, most common indoor exposure pollutants include; benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons (especially benzopyrene), radon, trichloroethylene and tetrachloroethylene (WHO, 2009). Other indoor air pollutants sources include building materials, mould, home products, volatile organic compounds (VOCs) (WHO, 2009). These pollutants vary with house type, conditions, location and occupancy habits.

The impact of indoor air pollution consists of among others, health effects on the respiratory and circulatory system; sensation of chest tightness or difficulty in breathing, acute and chronic changes in pulmonary function; allergy and other effects on the immune system; cancer and effects on reproduction; on the skin, dryness and irritation of the mucous membranes of the eyes, nose and throat irritation.

An increased risk of developing lung cancer has been linked to exposure to environmental tobacco smoke (ETS) and to radon decay products. Besides, lung cancer high fatality rate is much lower than the number of people contracting respiratory disease and allergies experiencing irritative effects due to exposure to indoor pollution (WHO, 2009, 2018). The European "Commission Directive 93/67/EEC" indoor risk assessment encompasses; hazard identification, exposure assessment, dose-effect evaluation, and qualitative and quantitative risk assessment. It is achievable starting from substance, source, environment, target group, effect and pathway. For this study, NORM source such as type of building materials and the ventilation system were investigated (EU/C 93/67/EEC).

For indoor radon, changes in building design, equipment, climate and building materials are a significant source of indoor exposure (Mounir, El-Sersy, Nasser, & Hassan, 2012). Various studies still show evidence of health effects of indoor radon exposure in homes (Kendall & Smith, 2002; McCormack & Schuz, 2012; Torres-Duran, Barros-Dios, Ferndez-Villar, & Ruano-Ravina, 2014; WHO, 2009). Indoor radon concentration is influenced by the radon exhalation and ventilation rates (Abdallah, Mohery, Yaghmour, & Alddin, 2012) where poor ventilation increases radon exhalation and radon concentration levels. With the ongoing trends and shift in the nature of occupations and indoor occupancy of 90%, people spend more time indoors; as such the demand for indoor air quality is a necessary requirement in most countries.

Poor indoor environment has a consequence on productivity; high absenteeism, frequent sick offs and lowers efficiency. The U.S. Occupational Safety and Health Administration (OSHA) estimated that businesses loss 14 to 15 minutes for each employee per day due to poor indoor air quality; and is responsible for Sick Building Syndrome and Building Related Illnesses. (Jones, 1999) describes Sick Building Syndrome occupant’s health complaints whose symptoms include; irritation and itching of the eyes, nose and throat irritation, runny or congested nose, other flu-like symptoms, chest tightness, itchy skin occasioned with the development of rash, headaches, lethargy, poor concentration and irritability. While Building Related Illnesses (BRI); described by clinically diagnosed illnesses attributable to specific or well-established causes associated indoor air pollutants; e.g. long-term cancer risk from exposure to indoor radon, allergic reactions such as hypersensitivity, pneumonia and formaldehyde.

In principle, 85% of the public radiation dose exposure is due to natural radiation sources from members of the radioactive series; uranium (^{238}U), actinium (^{235}U), thorium (^{232}Th), and neptunium (^{237}Np). Each of which has a radioactive gas, radon that presents radiation health hazard (UNSCEAR, 2000, 2008; Cember & Thomas, 2006). The main external source of exposure is the gamma radiation emitted from natural occurring radioactive materials (NORM) radionuclides from the earth's crust, cosmogenic, building materials, air, water, foods, and in the human body (UNSCEAR, 2000, 2008).

Assessments of the different conditions of radon emanations, an ionizing gas, indicate that, absorbed dose in the lungs is similar to exposures experienced in mines and homes (WHO, 2009; ICRP, 2010). The risk level depends on its concentration, length of exposure, type of soil, location and building materials used in construction of houses (ICRP, 2014). Globally, radon is the second leading cause of lung cancer after tobacco smoking (WHO, 2009). It is emitted in varying quantities from rocks and soils. It can reach high concentrations in enclosed spaces such as caves, mines and buildings (UNSCEAR, 2000).

In the United Kingdom for example, radon in homes delivers larger doses to the public than any other natural source of ionizing radiation (WHO, 2009). On 17th September 2013, the IAEA hosted a forum to deliberate on radon exposure in the homes, where experts discussed the health risks associated with radon exposure as a matter of global concern, they developed plans to measure and control exposure levels for States to adopt. Public and stakeholder's education programs and governmental cooperation were highlighted as key components (International Atomic Energy Agency [IAEA] GC 57, 2013).

In addition, the Euratom Directive 59/2013 (Euratom, 2014), directs member states on regulation of indoor radon exposure, establishment of national reference levels of NORM and indoor radon concentrations to less than 300 Bqm^{-3} and action plan, which promotes action to identify dwellings with higher indoor exposures, and promote public awareness programs on indoor exposure and its associated health risks. Furthermore, (Euratom, 2014) treats the exposure to natural radiation in dwellings, workplaces and other buildings as an existing exposure situation. It pays attention to indoor exposure from natural radionuclides through three pathways namely: (i) gamma radiation emitted by building materials containing U-238 series, the Th-232 series and K-40, (ii) inhalation of thoron progeny exhaled from superficial layer of building materials on walls, ceilings and floors, such as phosphogypsum and, (iii) inhalation of radon progeny, emerging from the soil beneath the building and construction materials with Ra-226.

In summary, the Table 1.1 below shows the sources of annual average radiation dose exposure received by the general public in the four countries, with indoor exposure as leading sources (Smetsers & Tomas, 2019).

Table 1.1 : Sources of Annual Radiation Dose

Radiation Sources	**Country**			
	USA	**UK**	**Belgium**	**Netherlands**
Indoor	40%	61%	44%	38%
Medical	48%	16%	48%	40%
Natural	10%	22%	6%	21%
Reminder	2%	16%	2%	1%

1.2.1 Housing situation in Kenya

Kenya has been grappling with a housing demand that far surpasses supply. Currently, the country experiences an annual short fall exceeding 250,000 units of residential housing. The housing supply has been around 50,000 units annually, leaving a deficit of 200,000 units while cumulative backlog is 1.85 million units (UN Habitat, 2019). Furthermore, the country has a poor maintenance culture in both public and residential buildings which the Ministry of Land and Physical planning intervened by launching the maintenance policy in 2016 for buildings to be inspected in every 5 years (Ministry of Lands, 2016).

Indoor exposure is a global burden (Euratom, 2014; CEN, 2017; Smetsers & Tomas, 2019). Moreover, urban housing infrastructure development has been recognized as a major burden in developing countries and therefore assessment of radiation exposure in residential in Nairobi is essential, as different building materials are used (Kenya National Bureau of Statistics [KNBS], 2009);

1.2.2 Sources of Indoor NORM and Radon exposure

Potassium 40 has an isotopic abundance of 0.0118% has half-life of 1.248×10^{9} years and emits 1460.8 keV gamma-ray ray. Uranium ^{238}U (half-life of is 4.5×10^{9} years) is present in all rocks and soils, and is in high concentrations in acidic igneous rocks. Thorium, ^{232}Th concentration is 100% by weight and has half-life is 1.4×10^{10} years (Eisenbud & Gesell, 1997).

The contribution of building materials to indoor exposure has been investigated worldwide from naturally occurring raw building materials and processed products. The findings indicate presence of NORM concentrations and radon (Karangelos, Petropoulos, Anagnostakis, Hinis, & Simopoulos, 2004; Kumar, Chauhan, Joshi, & Sahoo, 2014; Moura, Artur, Bonotto, Guedes, & Mar-tinelli, 2001; Saad, Al-Awami, & Hussein, 2014; UNSCEAR, 2000)

The main sources of NORM residues reused in building materials are from; coal mining and combustion, metal mining and smelting, mineral sands, fertilizer, recycling and building industry include; i) coal-fired power plant coal fly- (ash, slag and bottom ash), ii) primary and secondary tin slags - steel or stainless steel, lead slags, copper slags from iii) primary iron production - unprocessed slag iv) thermal phosphorus production -phosphorus slag v) pyro-metallurgies producing platinum group metals or rare earth elements red-mud - alumina production and specific residues originating (www.norm4building.org).

Man-made activities also contribute significant quantities of NORM. For example, during combustion, higher concentration levels of radionuclides are retained in fly ash, which is used for concrete making in the building industry. Also, underground coal mining has elevated radium and K-40 radionuclides levels, which contributes significantly to increasing radon levels (IAEA, TRS 413, 2003).

Other gamma radiation emitters include; building materials or additives of natural igneous origin such as granites, volcanic tuff, pozzolana (pozzolanic ash), and lava and from industrial processing residues (Euratom, 2014; Mjones, Falk, & Nyblom, 1996). The specific levels of gamma and radon exposure depend upon the content of ^{238}U and ^{232}Th in the building materials, the geological composition of the soil and rocks ((European Commission [EC 112], 1999; Sciocchetti, Clemente, Ingrao, & Scacco, 1983). The initial production of radon is determined by the distribution of radium content in the earth`s upper crust and building materials (UNSCEAR, 2009).

Indoor exposures pathways are influenced by various human activities and practices (WHO, 2009); in Nairobi for example, these include large-scale landscape modifications; housing project constructions, soil erosion and construction-related vibration causing disturbance in some structures (Onyancha, Mathu, Mwea, & Ngecu, 2011) and indoor exposure challenges.

1.2.3 Ionizing radiation and Human Cell Effects

The primary target of ionizing radiation to the human cell is; damaging the Deoxyribonucleic Acid (DNA), which controls the cell`s function and ability to reproduce. Mutation and chromosomal changes in cells and organisms occur either through deposition of ionizing radiation energy directly in DNA (direct effect) forming ion radicals or by indirect effect of ionizing molecules associated with DNA to form free radicals ((Ward, 1975; UNSCEAR, 2009). These ionizing radiations are absorbed following interaction with water forming ions, free radicals and molecules, to cause damage or alter the DNA (Lieser, 2001; James Martin, 2006 ; WHO, 2009).

In practice, following radiation exposure, the first possible outcome is cell damage is repaired, secondly; cell is totally damaged (death) and thirdly; the cell either survives but mutated causing stochastic health effects such as radiation induced cancerous or hereditary effects. Undoubtedly, lung cancer is a result of stochastic health effects due to exposure to radon gas (UNSCEAR, 2000; Darby, et al., 2005; ICRP, 2010).

In UK homes for example, about 1100 deaths are due to lung cancer is caused by exposure to radon each year (WHO, 2009). A typical USA resident receives an annual dose equivalent of 2.0 mSv from radon and its decay products (William & Russell, 2002). Other studies in Europe, North America, and China have collaborated on the evidence of the risks of lung cancer from residential exposure to radon (Lubin, et al., 1998; Krewski, et al., 2005; Krewski., et al., 2006; Darby, et al., 2005); Darby, et al., 2006; WHO, 2009). High NORM levels also lead to excess lifetime cancer risks.

1.3 Problem Statement

Natural radionuclides in building materials result in internal and external exposure, with NORM being a major contributor to the total effective dose received (UNSCEAR, 2000; IAEA, TRS 413, 2003).

Radiation doses exposure presents hazardous health effects e.g lung cancer from prolonged exposure to radon, and its progeny decay products (polonium -218 and polonium 214) (International Agency for Research on Cancer [IARC], 1988; National Research Council [NRC], BEIR VI, 1999; WHO, 2009). Studies of exposed miners have consistently found associations between radon and lung cancer (IARC, 2001; Darby, et al., 2005; WHO, 2009; UNSCEAR, 2009; ICRP, 2010).

Radon is emitted in varying quantities from rocks, soils, underground water sources and building materials (UNSCEAR, 2009). In ground water, and it can be transported over large distances from the point of production to the point of release (UNSCEAR, 2000). Radon is the second leading cause of lung cancer after tobacco smoking (WHO, 2009).

Nairobi city has the largest share of the total urban population accounting for 34% (KNBS, 2009a). Urban development housing infrastructure has been identified as a major challenge, with the medium term goal of annual production of housing units from 35,000 to over 200,000. Since housing is recognized as a basic human right (Constitution of Kenya, 2010), the degradation of catchment areas, deforestation with endless human activities such as landscape modifications and developments, has resulted to residential houses being built on areas with poor subsoil characteristics such as river valleys, swamps, former springs and dumpsites.

Various studies show that higher ventilation rates reduce indoor health effects (Bornehag, Sundell, Hagerhed-Engman, & Sigsgaard, 2005; Carrer, et al., 2015; Engvall, Wickman, & Norbäck, 2005; Seppänen, Fisk, & Mendell, 1999; J.Sundell, 1994; Sundell, et al., 2011; Wargocki, et al., 2002). These studies shows significant association between lower ventilation rate and increased Sick Building Symptom prevalence. Therefore reduction of indoor air contamination and control of source emission levels alone, is not sufficient in reducing indoor contaminants. Other measures that are needed to control indoor air quality for example include the ventilation of indoor spaces.

In Kenya, building materials are mostly derived from rocks and soil; cement baked bricks, blocks, concrete, marble, clay and sand (Kenya National Planning and Building Authority [KNP&BA], 2009; Ministry of Land, Housing and Urban Development [MOLHUD], 2012/13; The Kenya Government Printer [TKGP], 1997). Their radioactivity levels are usually not considered. Various authorities worldwide have examined the issue of regulatory control of building materials with regards to content of naturally occurring radionuclides. In Kenya, there are no standards or guidelines for the construction industry in relation to radiation protection and indoor air quality.

According to radiological studies by (Mustapha, Patel, & Rathore, 2002), results indicate the existence of radon problem in some sources of drinking water, homes, workplaces and classrooms. The present study seeks to investigate further the contributions of radioactivity from NORM in Nairobi residential houses due to type of building materials used and assess the indoor radiological hazards.

1.4 Main Objective

The overall objective of this study was to assess the associated radiological hazards from NORM indoor dose exposure in selected residential houses of different types of building materials for walls, floors and ceiling within Nairobi city.

1.4.1 Specific objectives

a) To determine the indoor activity and dose rate of natural radionuclide content (^{238}U, ^{232}Th, ^{226}Ra+daughthers and ^{40}K) and ambient gamma equivalent dose in selected residential houses (floor, walls and ceiling) in Nairobi;

b) To assess the indoor absorbed dose, annual effective dose and excess lifetime cancer risk in Nairobi residential houses;

c) To establish the correlation between dose rate and type of building material, also with topography (geology) of the study area;

d) To determine residential ventilation rate and its contribution to indoor air quality.

1.5 Justification and Significance of the Study

Overall, most people spend 80-90% time indoors daily; homes, offices, schools, health care centers and private or public buildings, and as such, air quality is a determinant health outcomes of these occupants ((WHO, 2010, 2009a). Although various indoor air pollutants have been classified as carcinogenic, few studies have investigated the role of residential ventilation in reducing the impact of these indoor pollutants on health.

Studies show that in many developing countries, there is rapid increase in cancer and other non-communicable diseases resulting from exposure to risk factors such as tobacco use, use of alcohol and exposure to environmental carcinogens ((WHO, 2009, 2018).

Approximately, 85% of the radiation dose public exposure is due to natural radiation sources from members of the radioactive series; uranium (^{238}U), actinium (^{235}U), thorium (^{232}Th). The major source and contributor of indoor natural background radiation is dependent on type of house and building materials used. Primordial radionuclides within these building materials pose radiological hazards either externally due to gamma ray emissions exposure or internally through inhalation and ingestion (UNSCEAR , 2008, 2000, 1993)

Furthermore, in Kenya, building materials are mostly derived from rocks and soil; cement baked bricks, blocks, concrete, marble, clay and sand (KNP&BA, 2009; TKGP, 1997; MOLHUD, 2012/13). There are no standards or guidelines for the construction industry in relation to radiation protection and indoor air quality. This study's findings provides a baseline to practice for formulation of radiation protection and safety standards in the building and construction industry of residential houses.

1.6 Scope and Limitations of the study

This study was limited to indoor *in situ* measurements of NORMs and ambient gamma equivalent dose rate, and the ventilation rate of the main living rooms in Nairobi County, there were no preferences of selection of residential houses and the type of building material used.

The main living room was selected at the lowest level only according to the (The American Association of Radon Scientists and Technologists [AARST] & The National Radon Proficiency Program [NRPP], 2012) protocols for conducting radon and radon decay product measurements in multifamily buildings.

Radioactivity and dose rate measurements were conducted at each site based on the EPA 2014 closed building protocol and (UNSCEAR, 2000) direct measurements and (UNSCEAR , 2008) cosmic correction coefficients.

The European Commission Directive 93/67EEC indoor risk assessment model was utilized in this study.

CHAPTER 2:

LITERATURE REVIEW

2.1 Introduction

This chapter describes the basis of this study, namely; Section 2.2 reviews the studies on natural radionuclides in buildings and building materials activity, exposures and radiological hazards. The situation analysis of NORM and radon exposure in Kenya is discussed in section 2.3. Section 2.4 explains the cancer risk associated with NORM exposure while Section 2.5 explores the existing geology and indoor exposure correlation.

Further, Section 2.6 describes the indoor NORM exposure variation with building materials and ventilation rate. The indoor air quality and health effects resulting from indoor exposures in relation to ventilation rate, ventilation openable areas and air exchange per hour (ACH) are discussed. Section 2.7 reviews the existing national and international regulations and standards on acceptable NORM in building materials and residential houses. Lastly, section 2.7 is a summary of the literature review.

2.2 Natural Occurring Radioactive Materials Exposures: Global View

Exposure to background radiation is a continuous process either due to natural occurring radiations comprising of cosmic rays, terrestrial or to man-made radiations sources that include medical diagnosis, consumer products, industrial by products and waste, occupational, nuclear etc (UNSCEAR, 2009; WHO, 2009; ICRP, 2007; Euratom, 2011, 2014) .

The main sources of radiation exposure are the three natural decay series namely; uranium, actinium and thorium series. Each series generates several radionuclides following radioactivity decay. The distribution of these radionuclides and their decay products cause significant radiological hazards to both the environment and the public (Harb, El-Kamel, Abd El-Mageed, Abbady, & Wafaa, 2014; Euratom, 2014; IAEA, GSR Part 3, 2014; UNSCEAR, 2000).

Whereas most sources of radioactivity in building materials are from natural origin rocks, soils and the earth`s crust, with an average activity concentration of ^{232}Th, ^{226}Ra and ^{40}K as 30, 35 and 400Bq/kg respectively (UNSCEAR, 2000); industrial products, by-products, residues and wastes with high levels of NORM are also extensively used in the construction industry. These include fly ash, coal slag and phosphogypsum there by posing health and environmental hazards.

In 2005 for instance, Northern America produced 71.1 million tons of fly ash of which 29.1 million was recycled. In addition, since 2008, China has produced 50% of global annual fly ash of which

91% is utilized in building and construction for cement, concrete, bricks making etc, and by 2013 it was estimated to be 520 tons (Jinder, et al., 2015). Furthermore, coal ash a waste product in combustion of coal, is used as an additive to cement and in concrete while coal slag is used as an insulating fill material in floor structures and phoshogypsum is used in plasterboard (E.Stranden, 1983; Somlai, Jobbágya, Kovácsb, Tarjánc, & Tibor, 2008). These naturally occurring radioactive materials (NORM) are also widespread in sands, soils rocks, and many minerals, commercial products, and recycled residues.

Radionuclides in building materials are the major sources of external prolonged exposures of 0.41 mSv/year; from walls, floor and ceiling, and radon and its progeny alpha particles 1.15 mSv/y cause internal exposure of radiological significance, (UNSCEAR, 2000, 2008; WHO, 2009; WHO, 2014).

In Australia, seminal studies by (Beretka & Mathwew, 1985) investigated the presence of NORM in conventional raw materials, industrial wastes and by-products using gamma-ray spectrometry. Samples from red mud, phosphogypsum, zircon products and fly ash had higher levels of radioactivity than the OECD countries acceptable limits of 1490-2390 Bq/kg, 120-1100 Bq/kg, 1730-3700 Bq/kg and 140-630 Bq/Kg respectively. The study also indicated solutions of reducing this higher radioactivity levels in building materials by sieving.

Xinwei (2005) study in China, investigated the ^{226}Ra, ^{232}Th, and ^{40}K levels in cement and its products manufactured in Shaanxi area. The concentrations for cement brick were 46.2, 28.4, and 137.4 Bq/kg of ^{226}Ra, ^{232}Th, and ^{40}K respectively and 64.7, 48.7, and 161.3 Bq/kg respectively for plaster cement. The radiological hazards assessed were radium equivalent activities (Ra_{eq}), external hazard index (Hex) and internal hazard index (Hin). The findings showed Ra_{eq} values for cement and its products were lower than the acceptable limit of 370 Bq/kg.

Activity concentrations of ^{226}Ra, ^{228}Ra and ^{40}K in heavy sand minerals and building materials were evaluated in Cairo, Egypt (El Afifi, Hilal, Khalifa, & Aly, 2006). The measurements were investigated using γ-ray spectrometry. The resultant activity concentrations varied depending on sample origin. High activity levels, radium equivalent activity, absorbed-gamma dose rate and effective annual dose rate were found in monazite, zircon and phosphogypsum wastes with mean concentrations of ^{238}U 40580 ± 1370 Bq/kg, ^{232}Th 182425 ± 9870 Bq/kg and ^{40}K 11300 ± 9570 Bq/kg, respectively.

Somlai et al., (2008) study carried out in Hungary, the use of red mud, bauxite, and clay additives used in production of special cements were examined. ^{226}Ra and ^{232}Th activity concentrations in

Hungarian bauxite, red mud and clay additive levels were found to be similar with other countries restricted building materials limits. Somlai et al., therefore recommended prohibition of direct usage of Hungarian bauxite, red mud and clay additives in the building industry.

Koblinger, (1978) semantic study verified that gamma ray exposure in a room is emitted from NORM and its decay products. Koblinger developed a Monte Carlo code, based on basic photon transport models for calculation of exposure rate in a standard room (4m x 5m x 2.8 m) from radionuclides in the walls. His findings indicated high variability of gamma dose rate with wall thickness and density and low variability of specific dose rate with changing position in and dimensions of the room.

Furthermore, Maduar & Hiromoto, (2004) study in Brazil supported the correlation of density and thickness of the construction material to indoor gamma exposure rate. The study used a numerical method for the calculation of the gamma dose rate in dwellings based upon the definition of volumetric radiation sources, dose factors, attenuation coefficients and build-up factors. The external gamma doses due to volumetric sources code was used in evaluation of dose conversion factors for different geometries of a single rectangular compartment, by varying the thickness and density of the building material, the compartment dimension and the coordinates of the calculation point.

However, another approach developed by (De Jong & Van Dijk, 2008) in the Netherlands, takes into account the characteristics of every specific house such as the construction parts, the building materials used, the internal partitioning, doors and windows, etc as independent factors affecting the dose rate in a dwelling. In 2009, De Jong and van Dijk in the Netherlands conducted indoor measurements of ambient dose equivalent rate for 300 dwellings living room and obtained a mean of 0.89 mSv/a and indoor external effective dose contribution of 0.35 mSv/a from building materials (De Jong & Van Dijk, 2009) .

Natural and fabricated building materials used in Egypt were measured for both natural radionuclides content and radon exhalation rate (Sharaf, Mansy, El Sayed, & Abbas, 1999). Concentration of natural radionuclides were determined using γ-ray spectroscopy with HPGe detector and radon exhalation rate measurements of fabricated samples by the CR-39 plastic track detectors. The radiation hazard indices were estimated. The results of radon exhalation rate varied between 197 mBq $m^{-2} h^{-1}$ (cement brick) and 907 mBq $m^{-2} h^{-1}$ (blast furnace slag cement). Therefore, the study discouraged the use of blast furnace slag cement for coating the internal walls of urban buildings in Egypt and recommended the replacement of clay brick.

In India, a systematic study of gamma radiation levels (indoor and outdoor) in the villages surrounding the uranium-enriched regions in Jaduguda, was undertaken by monitoring selected dwellings in six villages for a year using card-based CaSO4:Dy- thermoluminescent Dosimeters with two study variables; seasonal variations (spring, summer, monsoon and winter) and the type of building materials. Marginal variation of the indoor gamma was observed with the type of building materials used and none with seasonal weather. The annual effective doses was 0.6 and 0.1 (mSv/year) for indoor and outdoor respectively (Mandakini, Swarnkar, Chougaonkar, Mayya, & Sengupta, 2010).

Babai, Punniyakotti, Poongothai, Lakshmi, & Meenakshisundaram, (2012) study, estimated indoor radon levels and absorbed dose rates in different types of dwellings in Chennai city, Tamilnadu, India. The method involved use of a solid state nuclear track detector (LR-115, Type II). The radon concentrations varied with different types of floor- materials and weather seasons. For a given season, the average maximum radon concentration observed from cement floor was (118.96 Bq m^{-3}) followed by tiled floor (75.25 Bq m^{-3}) and marble floors (74.04 Bq m^{-3}). The average highest indoor radon concentration was observed during winter (86.08 Bq m^{-3}) and the lowest in summer (42.50 Bq m^{-3}). The absorbed dose rate for radioactivity content of NORM around the dwellings was 62.11 ±10.05 nGy/ h, using the NaI (Tl) scintillation detector-based gamma-ray spectrometer.

In Nigeria, NORM studies of soil samples from different tin mine dumpsites in Jos Plateau, Rayfield area were examined using gamma-ray spectrometry, 7.62 cm by 7.62 cm NaI(Tl) detector Masok, Masiteng, & Jwanbot, (2015). The radiological hazards (absorbed dose rate, radium equivalent dose, indoor annual effective dose rate and outdoor annual effective dose) were calculated from the average activity concentration of ^{226}Ra, ^{232}Th and ^{40}K using existing models (UNSCEAR, 1982, 1993), 2000).

The absorbed dose rate ranged between 114.29 nGy/h to 751.86 nGy/h with an average of 293.27 nGyh/1. The indoor annual effective doses range of 0.56 mSv/y to 3.69 mSv/y with an average of 1.44 mSv/y were obtained. The absorbed mean dose and indoor effective dose were higher than the world average value of 59 nGyh-1 and 0.48mSv respectively (UNSCEAR, 2000, 2008).

In another study, six different types of residential houses: mud house, burnt mud house, dirty block house, unplastered concrete, plastered concrete but not painted and concrete plastered were sampled (Ononugbo, Avwiri, & Tutumeni, 2015). Alert-100 detector with Geiger- Muller tube measured indoor and outdoor *insitu* gamma exposure rates at 1.0 m height above the floor levels and ground. The highest indoor and outdoor exposure dose rate of 0.0237±0.140 mR/h and 0.0181±0.002mR/h respectively were obtained in mud houses while the least indoor exposure rate of 0.0134±0.001 mR/h in concrete but not plastered houses. The indoor and outdoor exposure dose rates of all the sampled residential houses exceeded the (ICRP, 1993) Standard value of 0.013 mR/h.

Ononugbo et al., 2015, evaluated the annual effective dose equivalent from absorbed gamma dose rates using UNSCEAR 1993 model while the excess lifetime cancer risk, (ICRP, 1991) model was used. The lifetime cancer risk calculated from indoor effective doses in all the residential houses ranged from 1.90×10^{-3} to 3.32×10^{-3} while that from outdoor effective dose ranged from 0.75×10^{-3} to 0.887×10^{-3}.

Mud and burnt mud houses recorded the highest dose rates, effective doses and lifetime cancer risk than other types of residential houses.

2.3 Review of NORM and Radon Case Studies in Kenya

In 1999, exposures to various category of natural background radiation; terrestrial gamma radiation, cosmic radiation, inhalation of ^{222}Rn and radon concentration in air and drinking water, were estimated using measured activity concentrations of natural radionuclides (^{40}K, ^{226}Ra and ^{232}Th) and UNSCEAR 1993 conversion factors (Mustapha, Patel, & Rathore, 1999). The gamma ray spectrometer 76 mm by 76 mm NaI(Ti) detector and EG&G ORTEC Multichannel Analyzer were used to measure this activity concentrations from samples of rock, soil and building materials assembled from different parts of the country. The average annual effective dose (3.79 mSv/y**)** was higher than the global average of 2.4 mSv/y (UNSCEAR 1993) with the major contributor being terrestrial gamma radiation 0.1 to 2.0 mSv/year, radon (^{222}Rn) 0. 4 to 6.0 mSv/year and indoor effective dose range of 0.1 - 1.6 mSv/y.

Mustapha, Narayana, Patel, & Otwoma in their studies in 1997 investigated natural radioactivity in building materials in Kenya and their contribution to indoor external exposure doses. Different types of rock and soil samples were analyzed with gamma ray spectrometer and the following activity concentrations determined: 50 to 1500 Bq/kg for ^{40}K; 5 to 200 Bq/kg for ^{226}Ra; and 5 to 300 Bq/kg for ^{232}Th. A mean indoor absorbed dose rate of 128 nGy/h and indoor effective dose of 0.47 mSv/yr were assessed from radionuclide concentrations, dimensions of typical dwellings using indoor occupancy factor of 0.6%.

Another radiological study was carried out Kinyua, Atambo, & Ongeri, (2011) in which the activity concentrations of NORM ranged from 38.6 to 271.7 Bq/kg for ^{232}Th, 43.1 to 360 Bq/kg for ^{226}Ra, and 245 to 1780 Bq/kg for ^{40}K using high-resolution gamma-ray spectroscopy while the absorbed dose rate was measured using a Canberra Radiagem 2000 model. The average absorbed dose rate was 541.4 nGy/h for an occupancy factor of 0.4, the corresponding annual effective dose rate due to the radionuclides ranged from 0.22 to 0.88 mSv/y with a mean of 0.44 mSv/y.

Mustapha et al (2002) determined typical concentrations of ^{222}Rn in dwellings. Three different passive integrating devices were used in the measurements of ^{222}Rn in air. The concentration of ^{222}Rn in air was estimated from the activities measurement of gamma rays emitted by ^{214}Pb and ^{214} Bi with NaI (Ti) detector. This survey indicated the existence of radon problems in some water sources and dwellings with the highest values recorded in ground water sources and from basement of buildings.

An average indoor radon concentration of 148.3 ± 61 Bq m^{-3} was obtained from typical indoor living environments, resulting to un-weighted indoor effective dose of 3.2 mSv/y, which is twice the world average value. Thus indoor radon measurements preliminary reports in Kenya, show wide variability; 5 – 1200 Bq m^{-3} according to (Mustapha et al, 2002), 5 – 704 Bq m^{-3} according to (Maina, Kinyua, Nderitu, Agola, & Mangala, 2004) and 30.2 – 315.4 Bq m^{-3} by (Chege, Rathore, Chhabra, & Mustapha, 2009).

The radiological hazard of NORM in Homa Mountain, Kenya was investigated by Otwoma, Patel, Bartilol, & Mustapha, (2013). All calculated radiological indices were higher than the recommended limits with the mean absorbed dose rate of 383.36 nGy/h and annual effective dose ranging from 28.6 to 1681.2 mSv with mean of 470.4 mSv. Even though several studies have been conducted in Kenya, not much has been done regarding radiations in buildings such as dependence of radiation on; the type of building materials, residential ventilation type and dwellings local geology. There is no Kenyan standard prescribing acceptable levels of radioactivity content of building materials in the building industry.

2.4 Cancer Risk due to NORM and Radon Exposure

Gamma rays are capable of inducing cancer in almost all tissues of the human body, however the risk of cancer in a particular tissue depends upon the radiation dose response. The (UNSCEAR, 2013) shows age-related factors that contribute to differences in radiation effects and risks from childhood exposure to size of the individual and organs, and rate of development at different ages including physical activity.

Yamaguchi, (1994) findings from the calculated dose rate coefficients for six age groups (newborn, 1-, 5-, 10-, 15-year-old and adult), the isotropic radiation fields, showed that the effective dose coefficients for infants were about 20–30% higher than those for adults. Also, UNSCEAR and ICRP effective dose coefficients are age dependent (ICRP, 1991, 1995), Pub 69, 1995, 1996; UNSCEAR, 1988, 1993, 2000, 2008).

Kendall, et al., (2013) study in the United Kingdom analyzed childhood leukemia risk in relation to natural residential background external radiation levels and radon levels. Radiation doses were based on estimated mean exposure levels for the county district in which the mother resided at the child's birth. The measure of radiation cumulative exposure to the red bone marrow (RBM), the imputed external exposure rate plus radon dose rate, based on the geographic location of the mother's domicile and age at diagnosis were computed. The mean RBM cumulative dose at diagnosis was 4.0 mSv, of which 10% was contributed by radon on average. The analysis produced a highly significant trend, with an estimated risk of ERR mSv^{-1} of 12% (i.e. ERR of 120 Sv-1).

Many studies have found no association between indoor residential radon exposure and incidence of childhood leukemia (Kaletsch, et al., 1999; Kendall, et al., 2013; Lubin, et al., 1998; Steinbuch, Weinberg, Buckley, Robison, & Sandler, 1999). However, (Raaschou-Nielsen, et al., 2008), examined domestic radon levels and childhood leukemia incidence in Denmark and found statistically significant dose response with a 56% increase in the rate of ALL per 103 Bq/m^3-years. Furthermore, the study by (Law, 2000) on adult acute leukaemia found no association with indoor residential radon exposure.

The (ICRP 74, 1996) estimates the lifetime fatal probability coefficient to be 0.05 Sv^{-1} among a population of all ages from non-CLL after exposure to low doses. Currently, there is enough scientific consensus that radiation-related DNA damage plays a fundamental role in the induction of carcinogenesis, even at low doses as those from exposure to normal natural background radiation (ICRP, 2005; NRC, BEIR VII, 2006). Even so, the UNSCEAR 2012 Annex A, concluded that, repair mechanisms need a certain amount of DNA damage in order to be activated for example, after very low doses, the amount of damage might be too low to trigger repair. However, those unrepaired lesions might cause problems later in life.

Subsequently, the decay products of radon are electrically charged, they deposit in the lung delivering energy to the cellular structure of the surface of the bronchi and the lung, which strike individual lung cells causing physical and/or chemical damage to DNA damages and killing cells. Whereas the body can tolerate and replace the dead cells, the damaged lung tissue cells can replicate and eventually lead to lung cancer (James, 2006; ICRP, 2010; WHO, 2009).

Some studies, however, indicate health benefits of exposure to low radiation levels; by acting as stimulant to accelerate DNA damage repair, reduction of genetic instability and enhance immune responses leading to cyto protection from low radiation (L. Feinendegen, 2003; Feinendegen, Pollycove, & Neumann, 2012; Pandey, Sarma, Shukla, & Mishra, 2006; Cuttler, 2013).

2.5 Indoor Exposure and Geology

The magnitude of natural radiation exposures depends on geographical location and human activities. For example, the height above sea level and altitude affects the dose rate from cosmic radiation; the terrestrial gamma-ray dose radiation depends on the local geology while dose rate from indoor radon depends on local geology, the type of construction and ventilation of houses (UNSCEAR, 1993). Furthermore, geologic and topographic characteristics have been correlated with unusual or sizable variations in indoor radon concentrations (Florou & Kritidis, 1992). Indoor radon levels has been correlated to geology types (Miles & Appleton, 2000; Miles & Appleton, 2005). If the buildings foundation is connected to a sub-surface cavity system, large variations occur. For example, buildings in limestone-rich areas or areas with fault, radon transport occurs in an unusual manner. Furthermore, natural building materials reflect their geologic formation and origin Lust & Realo, (2012).

Indirect indicators of indoor radon are used to derive maps of radon prone areas (in Germany (Kemski, Siehl, Stegemann, & Valdivia-Manchego, 2001; Czech Republic (Mikšová & Barnet, 2002) and England (Appleton & Ball, 2002). These indicators include concentration of radium or radon in the ground, soil gas radon, and soil permeability.

2.6 Indoor NORM Exposure due to Building Materials and Ventilation

Ventilation in buildings is essential to sustain quality life (Etheridge & Sandberg, 1996; Awbi, 2003). Ventilation is pivotal in indoor air quality, comfort, and productivity of occupants (Wyon, 2004). It regulates the indoor air quality, failure to which condensation occur on ceilings, walls, floors etc. that result to growth of molds and other related health hazard like; acute health effects such as eye irritation, transmission of airborne diseases, chest symptoms etc (Awbi, 2003).

The floor area per person is an indicator of housing conditions, ventilation and comfort (United Nations Centre for Human Settlements [UN HABITAT], 1996) and varies among countries, with a global range between 2 to 69m^2 and median of 14,4 m^2 (UN, 1993). It is the result of the size of dwelling (m^2 floor area) and the number of persons living in the dwelling. In Sub-Saharan Africa and South Asia the floor area per person is the smallest (McGee & Ira, 1995) For example, the average floor area per person in Europe is 42,56 m^2 per person while in Africa it ranges from

5 - 9 m^2 per person depending on the type of building. In Kenya, the floor area per person is 3.5 m^2 (KNPBA, 2009).

Furthermore, according to ASHRAE, 62.1/2016 and EN 15251:2007 standards, ventilation rate due to dilute occupant emissions, it ranges from 9.0 to 36 m^3 h^{-1} per person and 14.4 to 36 m^3 h^{-1} per person respectively. While from building emissions, the ventilation rate ranges from 1.1 to 4.5 m^3 $h^{-1}m^{-2}$ in ASHRAE 62.1-2016 and 1.1 to 7.2 m^3 $h^{-1}m^{-2}$ in EN 15251:2007.

According to Carrer, et al., 2015 minimum ventilation rates are defined on the basis of health effect such as; i) respiratory symptoms, asthma and allergy; 2) airborne infectious diseases and sick leave; iii) acute health symptoms and iv) performance and learning in indoor environments.

Indoor concentrations of ^{222}Rn and its progeny are higher than outdoor except for well ventilated dwellings in high altitudes (UNSCEAR, 1993). The internal radiation exposure from building materials is dependent on ventilation rate (Cozmuta, Van der Graaf, & De Meijer, 2003).

Krisiuk, (1980) study found the dependence of indoor radon concentration on exhalation rate from building material, dimensions of the house (surface to volume ratio) and the ventilation rate. He utilized the indoor concentration of radon and thoron daughters in air, taking into account the exhalation rate and diffusion processes of building materials, room dimensions, and ventilations rates. The mean findings for radon and thoron daughter concentrations were 0.10 pCi/*l.* and 0.0064 pCi/*l*, respectively, which correspond to a lung dose equal to 126 mSv/yr.

Furthermore, in Hong Kong, Leung, Tso, & Ho, (1998) findings indicated that occupancy behavior influenced the radon concentration. Leung et al conducted surveys in buildings by assessing the seasonal variation of indoor ^{222}Rn levels, the dependence of indoor ^{222}Rn concentration on the living environment, the indoor gamma dose rate and its relation to indoor ^{222}Rn concentration, and the dependence of ^{222}Rn progeny concentration and equilibrium factor on the environment in high-rise buildings. He also found that the main source of indoor radon in high-rise buildings to be the building material.

In addition, there is an inverse relationship between air-change rates and airborne radon levels (UNSCEAR, 2009). The time dependency of the gas concentration *Ci(t)* inside a single room is dependent on radon exhalation rate of concrete (Bq/m^2/s), exhalation surface area (m^2), volume of room (m^3), radon level (Bq/m^3) of outside air, ventilation rate(s^{-1}), and decay constant of radon ($2.1x10^{-6}$ s^{-1}).

The pulmonary air uptake in human beings is proportional to ventilation rate, duration of exposure at lower atmospheric concentrations, and the concentration of inspired air (Agency for Toxic

Substances and Disease Registry [ATSDR], 1997). Thus, sufficient ventilation can reduce indoor exposure, humidity levels, volatile organic substances, dust and other toxic substances in the indoor air.

In a study on residence ventilation rates in European countries (Asikainen, et al., 2013), over 126 million of people were found to live in residences with low ventilation rates. The study evaluated the ventilation rate in 26 European countries using a model that utilized measured existing air exchange rates and regulations including ventilation limit values based on: i) the European standard CEN15251, 2007 that defines the limit to be 0.35 *l*/s per m^2 floor space (corresponds to 0.5 ACH with standard room height of 2.5 m, ii) based on USA standard - (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE] 62.1, 2004), which defines the limit to be 2.5 *l*/s per person plus 0.3 *l*/s per m^2 floor space (applicable for dwelling in high-rise buildings), and iii) fixed limit value of 8 *l*/s per person, based on association between ventilation rates and asthma and sick building syndrome (Bornehag, Sundell, Hagerhed-Engman, & Sigsgaard, 2005; Engvall, Wickman, & Norbäck, 2005).

The findings indicated that the mean ventilation rate in 36% of the residences in European countries is below the limit value of 0.5 AC/H, it varied from 0.6 ± 0.4 h^{-1} in northern Europe to 1.1 ± 0.8 h^{-1} in Southern Europe. These studies are similar to (Brelih & Seppänen, 2011; Dimitroulopoulou, 2012) findings that ventilation requirements receive major attention in building regulations across Europe, but in practice the ventilation rates are lower.

Other studies show that higher ventilation rates results in reduction in indoor related health effects (J.Sundell, 1994; Seppänen et al., 1999; Wargocki, et al., 2002; Bornehag et al., 2005; Engvall, et al., 2005; Sundell, et al., 2011). There is significant association between lower ventilation rate and increased Sick Building Symptom prevalence. Other measures that improve indoor air quality include increasing indoor spaces.

For instance, in Italy, the requirements of indoor air quality, the ventilation requirements for residential buildings and airflow rates as stipulated in the Italian Ministerial Decree 05.07.75 where the naturally ventilated dwellings ventilation requirement is 0.35 to 0.5 ACH for normal living space of 15 m^3/h per person. While in England, the British Building Regulations prescribe rapid ventilation of 1/20th of floor area (England and Wales, 2010).

In Kenya, the minimum recommended ventilation rate is 8 litres/sec per person, supply of fresh air recommended and ventilation-opening controlled, and the floor area per person is 3.5 m^2 and the total area of any openable areas like windows, doors not less than 5% of the floor area of the room. For communal residential buildings and dwellings (including high-rise dwellings) recommended ventilation rates in terms of Air Changes per Hour (ACH) is 0.5 to 1.0 h^{-1} (KNP&BA, 2009).

However, the Ministry of Health is responsible for controlling the building materials (Public Heath Act Cap 242- Revised 2012 Section 126A) and to make by laws on matters regarding buildings; i) the construction of buildings, and the materials types to be used; and control of space buildings, the lighting and ventilation etc. (MOH, Public Health Act Cap- 242, 2012).

2.7 Regulation of NORM in the Construction and Building Industry

International organizations such as the International Commission on Radiological Protection (ICRP, 2007; the World Health Organization WHO, (2009); International Atomic Energy Agency (IAEA-TRS 474, 2013); Euratom, 2014) have adopted and developed measures to mitigate radiation exposures through formulation of standards, guidelines and legislation, for reference levels, action levels, building codes, radiological protection principles, measurement protocols of dose rates, dose criteria and limits are among actions for member states to implement.

In Poland for example, there are two categories of NORM regulation in building namely, A and B; where category A, covers building designated for living, occupation by patients in health care buildings, occupation of children in educational buildings, and for food products storage, while category B is designated for occupation in public utility buildings except those listed under category A and auxiliary spaces. While in Japan, the Gypsum Board Industry has adapted use of low radium phosphate gypsum for built industry.

The (IAEA GRS Part 1, 2016) “International Basic Safety Standards” sets out requirements for governments to control public exposure to radon; that includes collection of data on the activity concentrations of radon in dwellings and other buildings; provision of information due to radon exposure and the associated health risks; and development of an action plan for controlling public exposure to radon.

Regulatory controls on radioactivity levels in building materials are based on dose criteria and exemption limits. In principle, the purpose of setting such controls is to provide guidance on the levels of radioactivity in building materials, to limit radiation exposure and to ensure that the public exposure is kept as low as reasonably achievable. For example, (Euratom, 2011) stipulates all the essential requirements for construction works; buildings be designed and built in a way that exposure to radiation does not become a health hazard to the occupants and the public.

In 2013, the European Council have adopted a directive for basic safety standards for protection against the dangers arising from exposure of ionizing radiation. It contains provisions for protection from radon in buildings; workplaces (article 54) and in dwellings (article 74). In accordance to article 103 "*EU Member States shall establish a national action plan addressing long term risks from radon exposures in dwellings, buildings with public access and workplaces for any source of radon ingress, whether from soil, building materials or water*".

Further, these EC directives 2013/59 *'Basic Safety Standards'* requires Member States to establish a national radon action plan that addresses long-term risks to radon exposure. The directive stipulates that radon risk occurs mainly, due to air-tightness of the house envelope, ventilation rate and radon potential which combines radon soil gas concentration and gas permeability of the soil, where by the radon soil gas concentration, is determined by geology and the radon permeability.

2.8 Summary of Literature Review

Several studies have established significant NORM levels in industrial products, by products, building materials and minerals (Koblinger, 1978; Stranden, 1983; Somlai, 2008; Beretka & Mathwew, 1985; Xinwei, 2005; El Afifi, 2006; Mandakini M., 2010; Babai. K. S, 2012; Masok , 2015; Ononugbo, 2015; Mustapha et al, 1997;1999; Chege et al, 2009; Otwoma et al, 2013). In addition, various studies have established the existence of indoor absorbed dose in air and the corresponding annual effective dose due to gamma ray emission from NORM in the building.

External and internal exposures in dwellings are estimated from radionuclide concentrations in the building materials and their radon exhalation rate (L. Koblinger, 1984; (Markkanen, 1995; Koblinger, 1978; CEN, 2017; UNSCEAR 1993, 2000, 2008).

Long-term exposures gamma rays are capable of inducing cancer in almost all tissues of the human body. Exposure to radiation, damages the human tissue by changing cell structure and the DNA, which cause various health problems including cancer. These damage due to exposure to radiation depends on several factors such as the type of radiation, amount of radiation dose, duration of exposure etc. (UNSCEAR, 2009; James Martin, 2006; Darby, et al., 2005; (ICRP, 2010).

International organizations ICRP, WHO, IAEA, European Council (Euratom, 2014) have adopted and developed measures to mitigate these radiation exposures through formulation of standards, guidelines and legislation, for reference levels, action levels, building codes, radiological protection principles and measurement protocols of dose rates, dose criteria and limits. However in Kenya, there are no standards or guidelines for the construction industry in relation to radiation.

CHAPTER 3:

THEORETICAL FRAMEWORK

3.1 Introduction

In this chapter, the theoretical framework of the study is discussed beginning in Section 3.2 that decribes the radioactivity decay, ingrowth and radioactive equilibrium theory. Section 3.3 describes the principles of gamma spectroscopy, detection and measurements respectively. Section 3.4 describes the various models used for estimation of indoor NORM activity concentration.

Section 3.5 describes the indoor gamma dose assessment models including direct gamma measurements, radiological hazard estimations of absorbed dose and effective dose. Section 3.6 explains the indoor air quality based on ventilation opening area, air exchange rate and ventilation rate. Lastly, Section 3.7 describes the estimation of radiological excess lifetime cancer risk models.

3.2 Radioactivity Decay, Ingrowth and Secular Equilibrium Theory

A radionuclide is identified by the characteristics of the radiation it emits; the decay rate, or half-life of the radionuclide, and the type and energy of radiation emitted. As a radionuclide decays, it becomes an isotope of another element hence resulting into a decay series (L'Annunziata, 2012). ^{238}U, ^{235}U, and ^{332Th} are the decay parents of three natural decay series namely uranium (U) series, the actinium series and the thorium (Th) series.

Each of these series consists of many daughter products generated through successive decay of parent radionuclides. The distribution and behavior of these decay series in the environment are based on their radionuclides biogeochemistry and half-life ($t_{1/2}$). During this process, energetic particles or γ ray photons or both are emitted. Radioactive decay is statistical in nature, which introduces the decay law concept,

$$\boldsymbol{N_A = N_{Ao}e^{-\lambda_A t}} \qquad (3.1)$$

Where, N_A is the radioactive nuclei present at time t, λ is the decay constant and N_{Ao} is the original number of nuclei present at time t=0 (L'Annunziata, 2012).

The decay of the daughter nuclide is dependent on its own decay rate and that of the parent. The ingrowth of the daughter radionuclide is expressed in equation 3.2 as

$$\boldsymbol{N_B = \frac{\lambda_A}{\lambda_B - \lambda_A} N_{A0}\left(e^{-\lambda_A t} - e^{-\lambda_B t}\right) + N_{B0}e^{-\lambda_B t}} \qquad (3.2)$$

The amount of activity at various stages between parent and daughter decay and formation is achieved through radioactive equilibrium conditions (L'Annunziata, 2012). For secular radioactive equilibrium, where the parent is long-lived and the decay rate is constant during many subsequent half-lives of its short-lived daughter nucleus such that for

$$\boldsymbol{\lambda_A \ll \lambda_B}, \text{ and } \boldsymbol{-\lambda_A t = 1}$$

$$\boldsymbol{\frac{\lambda_A}{\lambda_B} \leq 10^{-4}} \tag{3.3}$$

For example, the ^{238}U decay series, ^{226}Ra whose half-life is 1600 years decays to ^{222}Rn with half-life of 3.82 days. Here, the daughter nuclide decays more rapidly than the parent nuclide and reaches secular equilibrium after approximately 7 half-lives, where the ^{226}Ra radionuclide and ^{222}Rn have the same activity.

In general, assuming equilibrium, the activity of the nth nuclide in the decay chain is calculated in terms of the decay constants of all preceding members' equation 3.4.

$$\boldsymbol{\lambda_1 N_1 = \lambda_2 N_2 = \lambda_3 N_3 \ldots. = \lambda_n N_n} \tag{3.4}$$

3.3 Basic Principles of Gamma Ray Spectroscopy

Gamma-ray photons detection depends on their interaction with the orbital electrons of the absorber material whose atomic number either by transferring all or part of their energies while creating fast photoelectrons. These photoelectrons moreover loss their energies through ionization, excitation and bremsstrahlung emissions.

For a typical gamma ray spectroscopy, its assumed that complete electron absorption occurs so that the escape of secondary electrons and bremsstrahlung emissions remain insignificant. Therefore, with these assumption that no secondary photons or electrons escape after multiple interactions, the photons are absorbed by the detector crystal. It is these full energy absorption events which form the basis of gamma-ray spectroscopy, because it gives the information needed to identify the radionuclide. The photon interaction processes may result in pair production, where positrons are slowed down on their path through matter creating electron ion or electron hole pairs. In semiconductor detectors, this electrons and holes are collected on the detectors' electrode directly.

Gamma rays interactions with matter through the following processes; photoelectric absorption, Compton scattering, and pair production change their probability of interaction depending on the energy of the incident gamma ray and the atomic number of the medium of interaction. In practice, a typical gamma ray spectrometer consists of a detector, preamplifier, an amplifier and multichannel analyzer. Fig (3.1) represents the schematic diagram of a typical gamma ray spectrometer.

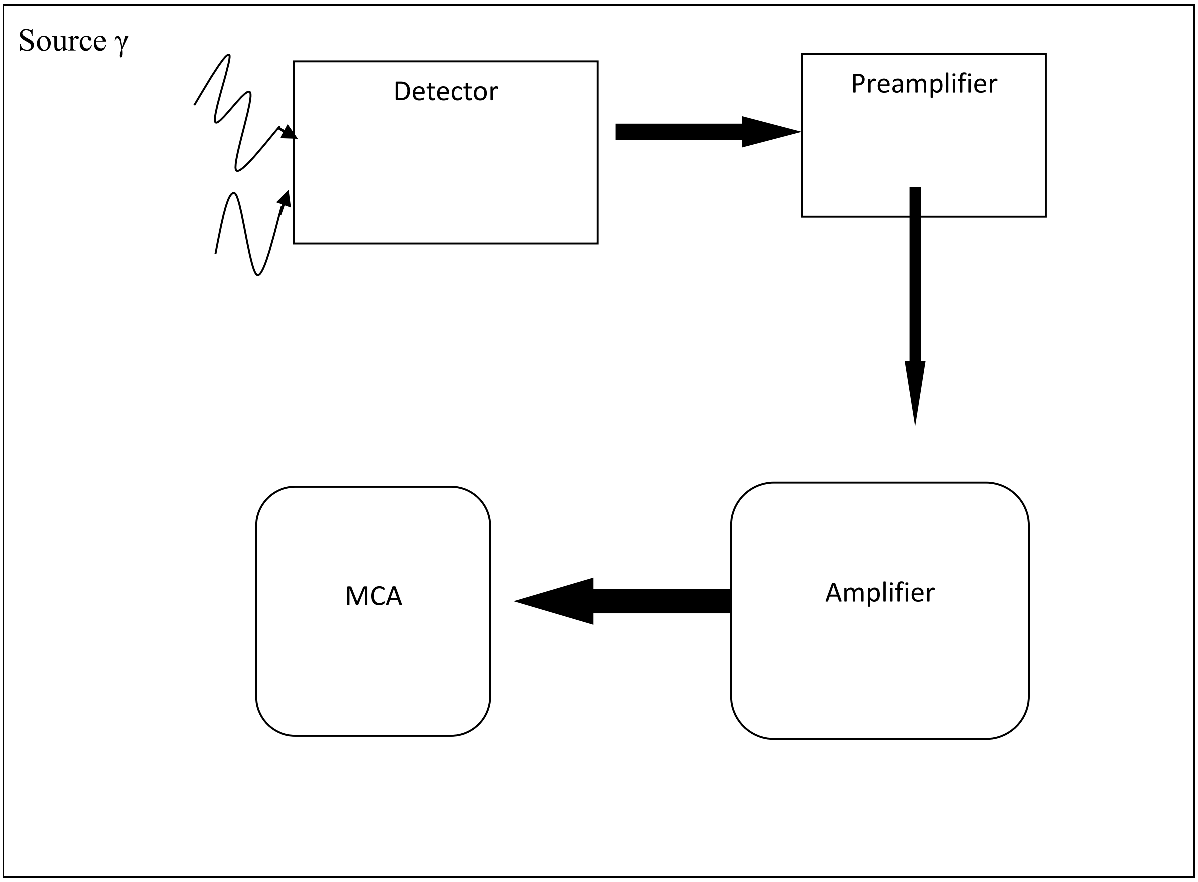


Figure 3. 1 : Schematic Typical Gamma Ray Spectrometer

The multichannel analyzer records and stores pulses according to their height and shape, each storage unit called a channel. The height of the pulse has known proportional relationship to the energy of the particle entering into the detector (Knoll, 2010). Each pulse stored in a particular channel corresponding to certain energy and the distribution of pulses in the channels is an image of the distribution of the energies of particles (Knoll, 2010). At the end of each counting period, the recorded spectrum is displayed on the screen of the MCA. Where the horizontal axis is the channel number or particle energy and the vertical axis is the number of particles recorded per channel. The MCA consists the Analog Digital Converter (ADC) and the memory. The ADC converts the analog signal into a digital number that is proportional to the amplitude of the pulses present at the input. The memory provides one addressable location for every channel number (Knoll, 2010).

The NaI (TI) detector measures and identifies radionuclides by pulse height, spectrum shape and energy with photoelectric absorption as its basis of measurement. The incident photons deposits energy to the detector crystal by interacting with the detection material and transferring their energies to electrons or positrons. These particles then loss their energy within the detector crystal, creating ionized atoms and ion pairs that forms the basis of the signal detection by the photomultiplier tube, which is converted to voltage pulse through the pre-amplifier.

The amplifier shapes the pulse and provides voltage gain for pulse height to volts from the pre-amplifier pulses in millivolts. These resulting pulse height spectrums determine the energies of the incident photons. The MCA digitalizes the pulses, sorting them by height or energy and storing them in channel numbers based on the principle of converting analog signal (the pulse amplitude) to an equivalent digital number. This process is achieved using the NaI (TI) crystal consists of two bands namely valence and conduction.

The conduction band states are usually empty while the valence band states are full. The incoming radiation excites the electrons across the forbidden energy gap into the conduction band creating a hole in the valence band. On de-excitation through the (TI) activator (which increases photon emission and reduces self-light absorption as it provides activator states in the energy gap), light photon is emitted and the electron returns to the valence band. The light photon emitted is proportional to the energy deposited by the incident photon (Knoll, 2010).

3.4 Indoor NORM Activity Concentration Assessment Models

In order to determine the radiological hazards associated to natural radioactivity in building materials, several models for both indoor and outdoor gamma dose have been developed. The radiological parameters and indices of interest include; radium equivalent activity, representative level, gamma activity, external and internal hazard, indoor absorbed gamma dose, annual effective dose and excess lifetime cancer risks.

Estimation of indoor external and internal exposures utilizes radionuclide concentrations in building materials. Various mathematical models with defined conversion factors are used to calculate the indoor external gamma dose from NORM, with specific exposure geometries and natural radionuclide distribution (UNSCEAR, 1988, 1993, 2000; ICRP, 1991, 2007)

Examples of radiation exposure estimation of building materials due to natural radioactivity models assessment (Stranden, 1979; L. Koblinger, 1984; R. Mustonen, 1984); Markkanen, 1995), assume radioactive equilibrium in the ^{238}U and ^{232}Th chains and also depend on the building`s geometry variation of the, building design and type of building materials, density and wall thickness (Table 3.1).

Table 3.1 : Indoor NORM Activity Concentration Assessment Models

References	**Specific dose rate (nGy/h per Bq/kg)**			**Room Dimensions (m)**	**Density (Kg/m^3)**	**Wall Thickness (m)**
	^{238}U	**^{232}Th**	**^{40}K**			
Markkanen, 1995	0.908	1.06	0.0767	4 x 5 x 2.8	2320	0.20
Mirza et al., 1991	1.21	1.29	0.10	4 x 5 x 2.8	2320	0.20
Mustonen, 1984	0.922	1.10	0.0806	4 x 5 x 2.8	2320	0.20
Toth, 1983 in Mustonen, 1992	0.954	1.13	0.030	Spherical shell		
Stranden, 1979	0.918	1.10	0.0775	4 x 5 x 2.8		0.20
Koblinger, 1978	0.918	1.02	0.0777	4 x 5 x 2.8	2500	0.20
Krisiuk, 1971 in Mustonen, 1992	1.26	1.79	0.0958	Hole in an infinite medium		

Source: (Risica, Bolzan, & Nuccetelli, 1999)

Mustonen (1984) utilized the method of calculating gamma dose in building materials using activity index of the construction materials and investigation levels in dwellings. The activity index assessed the maximum annual dose limit while omitting the extreme release of radon.

$$\textbf{Building material } \boldsymbol{Index}\ (\boldsymbol{I}) = \frac{\boldsymbol{C_{Ra}}}{\mathbf{300}\ \boldsymbol{Bq/kg}} + \frac{\boldsymbol{C_{Th}}}{\mathbf{200}\ \boldsymbol{Bq/kg}} + \frac{\boldsymbol{C_{K}}}{\mathbf{3000}\ \boldsymbol{Bq/kg}} \qquad (3.5)$$

Where C_{Ra}, C_{Th} and C_K are the activity concentrations (Bq/kg) of the ^{226}Ra,^{232}Th and ^{40}K in the building material.

Moreover, Mustonen theoretical estimation of gamma dose rate in the middle of the room, the dose rate in the middle of the room approximates the average dose rate in the room, by summing the separate calculated dose rates caused by walls, floor and ceiling.

Koblinger (1978) described a Monte Carlo code, based on basic photon transport models, for the calculation of the exposure rate in a standard room of (4m by 5m by 2.8m) from radionuclides in the wall. The method calculates the uncollided part of the dose, while the collided part is treated by different approaches: using modified attenuation coefficients during the evaluation of the "optical distance" between the source and the detection point, by build-up factors or by Monte Carlo simulations.

This theory found low variability of specific dose rate with changing position in and dimensions of the room and, high variability with wall thickness and density. Similar studies by Stranden (1979) proposed high dose variability with wall thickness and density. For Markkanen, (1995), the absorbed dose rate in air varies with the position in and dimensions of the room, the thickness and density of the walls, floor and ceiling, and presence of windows and doors.

Scattered radiation accounted for the average gamma energies of radionuclides of ^{226}Ra and ^{232}Th chains and of build-up factors. Besides, several studies (Mustonen, 1985; Jong & Dijk, 2008; Al-Jundi, Ulanovsky, & Prohl, 2009) have proved that the variation in dose rate with positions in rooms, is small (10–15%) and therefore the dose rate in the middle of the room is sufficient for estimation of average dose rate in the room.

The European Union dose limits of building materials range between 0.3 to 1mSv/year (Euratom, 2014) based on dose criterion and activity concentration index (ACI). The calculation of this dose also considers the density, thickness of the material, type of building and the intended use of the material (bulk or superficial). Thus specific coefficients derived from model room (similar to a bunker of 4 m x 5 m x 2.8 m) with walls, ceiling and floor of 20 cm thick and with a density similar to concrete's (2350 kgm-^{3}) are computed and Index derived as

$$\boldsymbol{Index\ (I)} = \frac{C_{Ra226}}{300\frac{Bq}{kg}} + \frac{C_{Th232}}{200\frac{Bq}{kg}} + \frac{C_{\ K40}}{3000\frac{Bq}{kg}} \qquad (3.6)$$

Where C is the activity concentrations (Bq/kg) of radionuclides in the building material (EC 112, 1999); Euratom, 2014).

In practice, indoor dose exposures for building materials can also be assessed using the activity index *I* (Organization for Economic Co-operation and Development–Nuclear Energy Agency [ECD-NEA], 1979; EC 112, 1999). For example, a building material with an index, *I*, equal to 1 or less, corresponds to building material radioactivity being safe for use. According to the recommendations by the European Commission (EC 112, 1999) for materials used in bulk amounts, the activity index is less than 0.5 while for superficial and other materials with restricted use the corresponding activity index is between 2 and 6. A conversion factor of 0.7 Sv/Gy is used to convert the absorbed dose in air to the effective dose with an average indoor occupancy of 7,000 hours per year (CEN, 2017).

Nonetheless, assessment of NORM can also be based on direct measurement of radionuclides concentrations in building materials or indoors dose rate measurement (UNSCEAR, 2000) model.

3.5 Assessment of Radiation Exposure

Exposures from natural radionuclides in the environment are estimated primarily from cosmic radiation and naturally occurring radionuclides. Since indoor exposures are dependent on type of house and building material, direct measurements of gamma dose rate of radionuclides are assessed based on the soil, shielding factor and type of building material. Mathematical conversion coefficient are used to convert the dose measured as function of time and age dependency. The following subsections describes these indoor gamma dose assessment models utilized in this study.

3.5.1 Cosmic Background Radiation Correction

Cosmic radiation interact with the atmospheric nuclides resulting into secondary particles and electromagnetic radiation. The cosmic dose rate at the ground level is dependent on altitude, altitude and shielding effects. The cosmic radiation constitutes the directly ionizing and neutron components. Several studies indicate population exposure to cosmic radiation and cosmic dependence on latitude, altitude and buildings shielding effect (Tollefsen, Cinelli, Bossew, Gruber, & De Cort, 2014; UNSCEAR 1988, 2000, 2008; Mustapha et al., 1999).

(Bouville & Lowder, 1988) stipulated the distribution of cosmic radiation. The variation from both the ionizing and neutron component as a function of altitude as expressed in equations (3.7 and 3.8).

$$\boldsymbol{H_1(z) = H_1(0)[0.21e^{-1.649Z} + 0.79e^{-0.4528Z}} \tag{3.7}$$

For ionizing component and the neutron component for z < 2 km as

$$\boldsymbol{H_N(z) = H_N(0)e^{1.04Z}} \tag{3.8}$$

here z is altitude in km, $H_1(0) = 240\mu Sv/a$; the annual effective dose of the directly ionizing component at sea level and $H_N(0) = 30\mu Sv/a$

The cosmic photon and ionizing component (UNSCEAR, 2000, 2008) reported an annual effective dose of 0.28 mSv at sea level and (Wissmann, Dangendorf, & Schrewe, 2005) Wissmann at latitude of 52º 17'N and longitude 10º 28' reported 0.29 mSv while considering a mean shielding factor of 0.8 and occupancy factor of 0.8 for adults.

In Kenya, (Mustapha et al., 1999) annual effective dose for cosmic radiation at sea level for the directly ionizing component at 0.19 mSv and the neutron component at 0.022 mSv, with an indoor occupancy of 0.6 and shielding factor of 0.8. The direct indoor dose rate measurements were estimated by correcting for the cosmic radiation (UNSCEAR, 2000, 2008) and the increasing effect of neutrons evident at high altitudes.

3.5.2 Direct Gamma Dose Rate Measurement

According to (UNSCEAR, 2000) model, external exposure from natural occurring radionuclides is assessed through direct measurement of gamma dose rate in air indoor and outdoors, and by correcting for the cosmic radiation. This model assumes that gamma emitted is dependent on the type of building material, activity concentration of building materials distribution in the building, geometrical conditions of irradiation and building dimensions.

The dose conversion factors account for the building materials both as a source of radiation and attenuator of outdoor radiation. In addition, other correction coefficient account for doors and windows. The indoor to outdoor ratio of absorbed dose in air is computed on the assumption that radioactive concentration in the building material is equal to that of the soil in the outdoor environment (UNSCEAR 1982, 2000, 2008).

Further, the ratio also describes the relationship between the indoor and the outdoor absorbed dose rate which depends on the type of building material and its origin, If the material is of local origin, the ratio lies between 1 and 2 due to change in geometry and presence of windows and doors (UNSCEAR, 1982). The wall thickness and dimension when taken into account, ratio yields 1.35 for brick dwellings and 1.48 for concrete (UNSCEAR , 1988).

3.5.3 Ambient Equivalent Dose and Effective Equivalent Dose Models

For all types of radiation, the operational quantities for area monitoring are defined based on a phantom, ICRU tissue sphere. It is a sphere of tissue-equivalent material (diameter: 30 cm) that effectively approximates the human body regarding to scattering and attenuation of the radiation fields under consideration. The ambient dose equivalent is determined at the depth of interest (10 mm for effective dose approximation) measured along the radius that directly opposes the direction of the incident field.

When determining the gross and net contribution of building materials to the gamma dose rate indoors, it is important to measure (i) the gamma dose rate indoors, (ii) the gamma dose rate outdoors due to terrestrial and secondary cosmic radiation, and (iii) the shielding factors for terrestrial and secondary cosmic radiation (UNSCEAR , 1993, 2000, 2008). Whereas (ICRP, 1991) model, assumes ambient dose equivalent as a surrogate for effective dose.

This study estimated effective dose equivalent to absorbed dose in air by using the quotient conversion coefficient of 0.7 Sv/Gy (UNSCEAR 2000; ICRP, 1991; ICRU 47, 1992).

$$\boldsymbol{Effective\ Dose\ \ Equivalent}\left(\frac{\boldsymbol{mSv}}{\boldsymbol{y}}\right) = \left[\boldsymbol{D}\left(\mu\frac{\boldsymbol{Gy}}{\boldsymbol{h}}\right) \times \boldsymbol{T}(\mathbf{0.8}\boldsymbol{x}\mathbf{24}\boldsymbol{x}\mathbf{365}\boldsymbol{x})\boldsymbol{hx}\frac{\mathbf{0.7}\boldsymbol{Sv}}{\boldsymbol{Gy}}\right] \qquad (3.9)$$

3.5.4 Absorbed Dose, Effective Dose and Age Based Dose Assessment

Absorbed dose is a good basis for radiological risk assessment. It is equivalent to air kerma on the assumption that secondary charged particle equilibrium exists in air. Since the absorbed dose at the point includes contributions from both primary photons and scattered photons of the ICRU tissue sphere with Monte Carlo simulations.

This photon doses now published as conversion factors or conversion coefficients (ICRU 47, 1992, 39, 1985, 43, 1988) are used in computation of absorbed dose. For example, an isotropic geometry the conversion factor of 0.7 Sv/Gy is used to convert gamma dose (Gray) in air to biological exposure (Sieverts).

Effective dose is used as a risk-related quantity for the optimization of protection below constraints and reference levels as the central quantity in the control of radiation exposure. According to ICRP Pub 103, (2007), the radiation exposure assessment is obtained by measuring or estimating the (H*10) and applying conversion coefficients.

Whereas ICRP Pub 60, 1991 effective dose relates the risk of a radiation-induced cancer or a severe hereditary effect and it estimates; the absorbed doses due to irradiation by external sources, absorbed dose due to intakes of radioactive materials delivered to the separate organs or tissues of the body, the relative effectiveness of different radiation types in inducing cancers or severe hereditary effects.

The UNSCEAR 2008, utilizes the effective dose quantity for exposure assessment. The annual effective dose computed from the shielding factor and occupancy fraction of absorbed dose indoors and outdoors as.

$$\boldsymbol{E_{ext}} = \mathbf{0.7}\boldsymbol{D}[(\mathbf{1} - \boldsymbol{I_{in}}) + (\boldsymbol{SF} * \boldsymbol{I_{in}})] \qquad \textbf{(}3.10)$$

Where D is mean absorbed dose , SF - shielding factor , I_{in} - occupancy fraction and ($1-I_{in}$) outdoor occupancy factor.

The worldwide average indoor effective dose due to gamma rays from building materials is estimated to be about 0.4 mSv per year (Jwanbot, 2014; UNSCEAR 2000).

Age based dose Assessment: Assessment of population exposures to natural radiation confirms that, the assessment for both for external and internal exposure must be age based (ICRP, BEIR VII, 2006 and UNSCEAR models). The ICRP considers age-related factors in developing models for dosimetry purposes. For example (ICRP, 1994) for the respiratory tract and (ICRP, 1995) for the skeleton etc. Furthermore, ICRP has derived age-dependent dose coefficients based of various radionuclides (ICRP, 1995) and against external radiation (ICRP, 1996).

The (UNSCEAR, 2000) adopted an annual effective dose estimate for infants, children and adult dose conversion coefficient factors of 0.7, 0.8 and 0.9, respectful. Futhermore (Kendall, Hughes, Oatway, & Jones, 2006) study in the United Kingdom found terrestrial gamma annual effective doses for infants and children to be greater than those for adults by 30% and 15% respectively.

3.5.5 Reduction Coefficient Residential Exposure Assessment

Residence exposure dose rate is assessed using the reduction coefficient for radiation levels in houses and buildings. The reduction coefficient is the ratio of indoor and outdoor ambient dose equivalent rates for evaluating indoor exposure doses (IAEA TECDOC-1162, 2000). This resident's exposure dose rate is evaluated using the outdoor and indoor dose rates and the number of hours for outdoor activity.

The provided reduction coefficient is 0.4 with a range of 0.2 - 0.5 for wooden houses; for concrete and brick houses, the coefficient is 0.2 with a range of 0.04 - 0.4. Conversely, these values are evaluated based on European house style and radioactive contamination (IAEA TECDOC-1162, 2000) where only the average reduction coefficient at the centers of the houses of 0.04 to 0.4 is provided.

3.6 Indoor Air Quality

3.6.1 Ventilation Opening Area, Air exchange Rate and Ventilation Rate Assessment

The high exposure conservative scenario was used to estimate the radon exposure. This uses realistic estimates of the parameters like living space area, occupancy factor and ventilation rate. This model assumes complex mixing of indoor radon in the living room. Ventilation rate for residential houses is based on either volume of the house, the conditioned space, the floor area, number of occupants, ventilation systems etc.

The ventilation openable area depends on the type of window (Single or double hinged) and external doors. For i) hinged or pivoted windows that opens 30 degrees or more or for a sliding sash window, the height and width of the opening part should be at least 5% of the floor area of the room. ii) a window that opens less than 30 degrees, the height and the width opening should be at least 10% of the floor room area and iii) a room that contains more than one openable window, the areas of all the opening parts may be added to achieve the right proportion of the floor area. The required proportion is determined by the opening angle of the largest window in the room (ASHRAE, 62.1/2007; England and Wales, 2010) building regulations.

While for the external doors, the height and width of the opening part should be at least 5% of the floor area of the room. If the room contains more than one external door, the areas of all the opening parts may be achieved at least 5% of floor room area. If the room contains a combination of at least one external door and at least one openable window, the areas of all the opening parts may be added to achieve at least 5% of the floor area (ASHRAE, 62.1/2007) standard; (England and Wales, 2010) regulations). The World Health Organization (WHO) accepted standards for floor space per person is shown in Table 3.2.

Table 3.2: WHO Standards for Floor Space Per Person per Dwelling

Area in square Metre	**No of persons**
11 or more	2 persons
9 to 10	1.5 persons
7 to 9	1 person
5 to 7	0.5 person
Under 5	Nil

The ventilation rate criteria are expressed as flow rate per number of persons, flow rate per floor area, flow rate per number of rooms, fixed flow rate per room type, number of air changes per hour, using various units or combination of different units.

According to (CEN 15251, 2007) Europe standard for the indoor air quality, it explains the required level of ventilation and the recommended design ventilation rates for residential buildings.

This study examined the ventilation rate in residential housing based on ventilation rate per person and per square meter floor area method, for indoor air quality and ventilation rates of residential buildings using the (CEN 15251, 2007) European standard. The limit value of 0.35 *l*/s per m^2 floor space that corresponds to 0.5 ACH with standard room height of 2.5m was utilized. The study assumed complete mixing of indoor pollutants concentrations in the living room. The relationship between ventilation rate in *l*/s and air-change rate as

$$\text{Ventilation rate } \left(\frac{\text{l}}{\text{s}}\right) = \frac{\text{Air Change per Hour } (\text{h}^{-1}) \times 1000 \ \left(\frac{\text{l}}{\text{m3}}\right) \times \text{ room volume } (\text{m}^3)}{3600 \ \left(\frac{\text{s}}{\text{hr}}\right)} \tag{3.11}$$

and the

$$\text{Occupancy Rate } = \frac{(\text{Floor area})\text{m}^2}{\text{Floor area per person } (\text{m}^2)} \tag{3.12}$$

Where,

The air exchanges per hour (ACH) - is the volume fraction of ventilated air per hour that estimates infiltration of outdoor air pollution indoors and diluting indoor space emissions.

The ventilation rate - is the volume of fresh air introduced into the space per hour that accounts for the bioefluents emitted by occupants and the ventilation rate per surface area - estimate the dilution need of emissions from surfaces.

The study also utilized the USA standard ASHRAE 62.1, 2004 which defines the limit to 0.35 air changes per hour but not less than 15 cfm (7.5 *l*/s) per person for residential living areas of private dwellings, single and multiple dwellings.

3.7 Excess Lifetime Cancer Risk Assessment Model

Various cancer risk theoretical principles due to radiation exposure exist. For example, ICRP consideration, the risk incurred by a population is estimated by assuming a linear dose-effect relationship with no threshold. For whole body exposure to low dose and low dose rate radiation, the fatal cancer risk factor is 0.05 Sv^{-1} (ICRP, 2007; UNSCEAR, 2009; National Research Council [NRC], BEIR VII, 2006). The risk factor states the probability of a person dying of cancer increases by 5% for a total dose of 1Sv received during his lifetime.

However, ICRP Pub 103, 2007 further incorporates the risk of fatal cancer and latency periods for weighted non-fatal cancers and hereditary effects. The estimated lifetime probability for all fatal and weighted non-fatal cancers and hereditary disorders is 7.3% per 1 Sv. For members of the public, The ICRP dose limits are based on risk of fatal and weighted non-fatal cancer and hereditary conditions with levels of risk between 10^{-5} and 10^{-4} per year at a rate of exposure of 1 mSv/year over a lifetime of 70 years, the ICRP total lifetime risk for all fatal and weighted non-fatal cancers and hereditary defects is 6×10^{-3}.

Therefore, the probability of death from cancer due to 'natural incidence' increases from about 25% to 30% following a total lifetime exposure of 1 Sievert. The estimation of cancer risk for an adult person is with the relationship:

$$\mathbf{Risk} \ = \mathbf{Dose}\ (\mathbf{Sv}) \times \mathbf{risk\ factor}\ (\boldsymbol{Sv^{-1}}) \qquad (3.13)$$

Where Dose implies Dose (mSv)x lifespan (years).ose mSvx lifespan years.

The excess lifetime cancer risk for Nairobi residents was calculated using equation 3.13 with lifetime of 70 years and 7.3% per 1Sv. Kenya`s average life expectancy according to WHO country Life expectancy profile was 67 years in 2016 (https://www.who.int/countries/ken/en/).

CHAPTER 4:

METHODOLOGY

4.1 Introduction

Section 4.2 describes the study area and different types of building materials used for building residential houses, while Section 4.3 expounds on the sampling methodology utilized in the study for data collection and analysis while section 4.4 describes sampling procedure. Section 4.5 explains the presampling conditions and procedure**.** Section 4.6 describes the sampling instrument used, its calibration validity, and lastly, Section 4.7 outlines the data analysis approach used in the study.

4.2 Description of the study area

4.2.1 Geographical Location, Population and Climate

Nairobi is located in south-central Kenya, 140 kilometers south of the equator at 1, 680m above sea level at latitude and longitude**:** 1 ° 16'S, 36 ° 48'E. The City is an economic hub for Kenya, East and Central Africa regions. Nairobi is sub-divided into four zones, south, west, north and eastern regions (Fig 4.1) and is the most densely populated county in Kenya with more than a total population of 3,138,369. Nairobi East District and Nairobi North District has a population of 1,144,416(36.47%) and 1,062,086 (33.84%) representing about 70% of the total population in Nairobi. The age brackets distribution being 20-30 years (46.4%), 30-40 years (25.2%), below 20 years (4.6%) and above 60 years (2.3%) (KNBS, 2009a).

The study area covered residential households in sub-locations of Nairobi city for sampling in;, Kasarani, Garden Thome, Githurai 45 and Mathare North, and in Nairobi East District; Komarock, Imara Diama, Salka, Kayole and Nairobi South sublocations were sampled (KNBS, 2009a)

Nairobi has a subtropical highland climate, in which the temperature ranges from 18-25ºC. The mean annual rainfall ranges between 800 mm to 1,300 mm. The relative humidity varies in the morning to between 75-85% and evening to between 45-60% with an average precipitation of 925 mm. The strongest winds occur during the dry season before the long March rains with speed of 20 to 25 m.p.h winds episodes of short -lived wind speed of 70 m.p.h also occur.

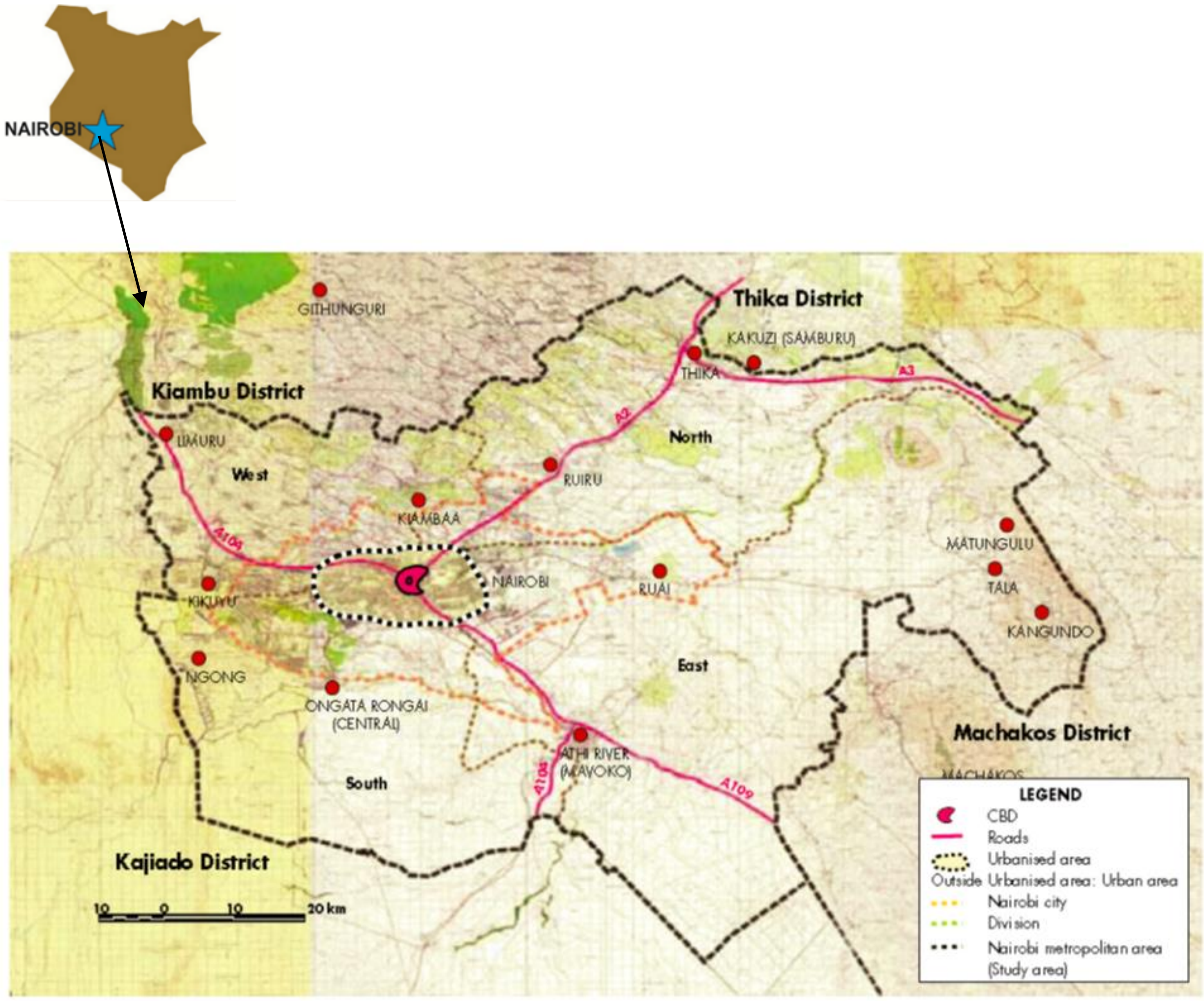


Figure 4. 1 : Nairobi City four zones; North, East, South and West
Source: JICA 2004

4.2.2 The Geology and Topography

The topography and surface geology of the Nairobi city are the result of the Cenozoic volcanic processes (Saggerson, 1964). The eruptive products of the volcanoes provide the most topographic expression of Nairobi (including the present study area) with the extrusion of Nairobi phonolites dated at 10 Ma (Pliocene) dominating Eastern Parts of Nairobi City, while Nairobi Trachyte dated 4 Ma (Pliocene) and Kapiti phonolite dated 13 Ma (Mid Miocene) dominate the Central Business District and Northern parts of Nairobi (Figure 4.2).

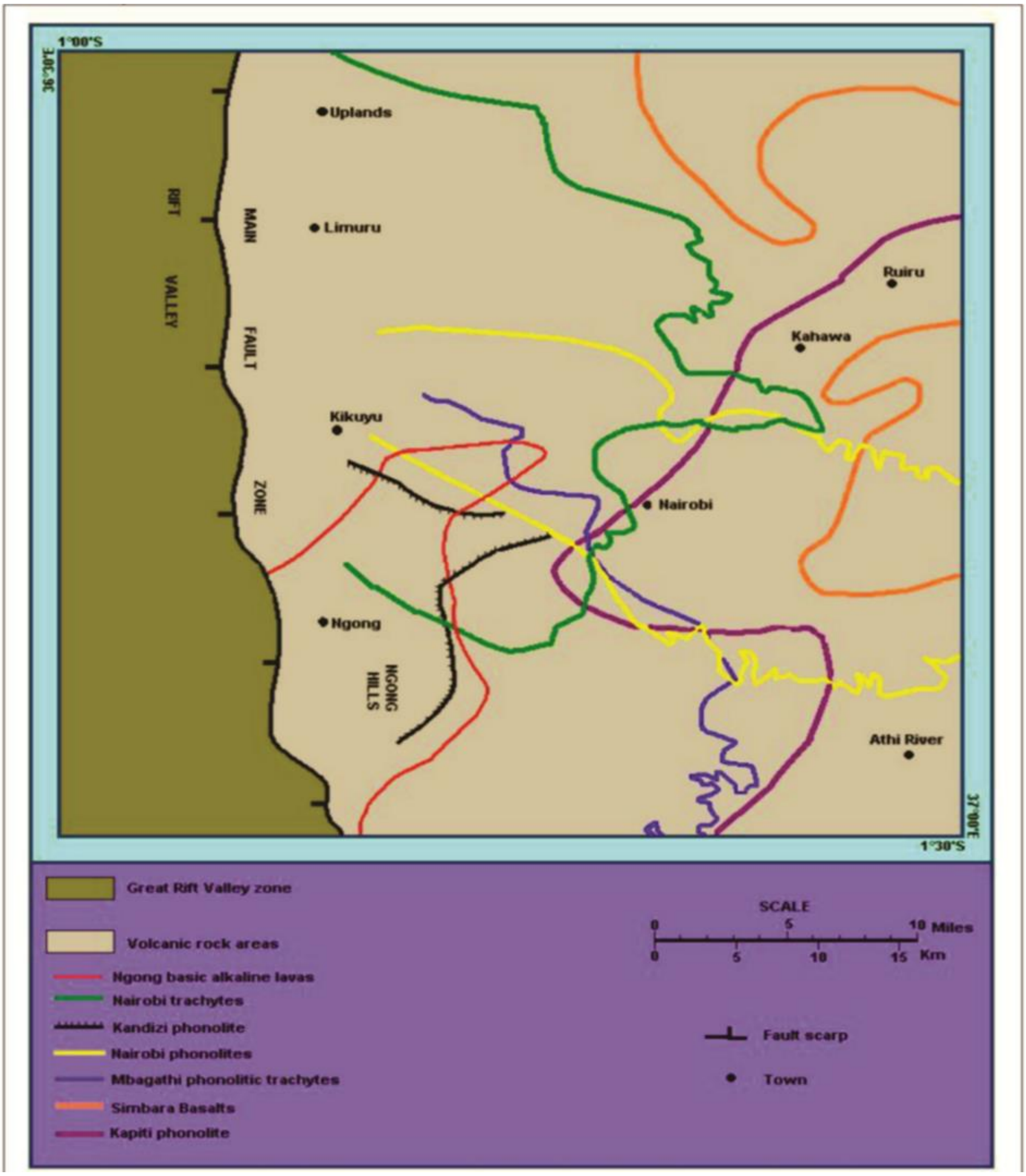


Figure 4. 2 : Geology of Nairobi
Source : Modified from Saggeron 1991

In general, the geology of Nairobi is, characterized by a succession of pyroclastic volcanic rocks of Cenozoic age (E. Saggerson, 1991). Underlying the volcanic rocks is a foundation of folded crystalline metamorphic rocks (Gneisses and schists) of Precambrian age, which belongs to the Mozambique Belt. The geological history of Nairobi is dominated by volcanic activity where a thick succession of alkaline lavas and associated tuffs began accumulating in mid-Miocene time and continued into the upper Pleistocene (E. Saggerson, 1991).

4.2.3 Type of Building Materials: Nairobi Residential Houses

In general, most residential buildings in Kenya are categorized as; high, middle and low income depending on the residential location, design and cost of building materials used for constructions (Fig 4.3, 4.4, 4.5). The main roofing materials used; include iron sheets, tiles and concrete. Tiles, cement and earth are used as flooring materials and stones, bricks and blocks are used for walls. In Nairobi, 77.2 % of the floor, is concrete, 41% of walls are made of stones, 19.84%, iron sheets and 14.34% bricks or blocks (KNP&BA, 2009; MOLHUD, 2012/13; TKGP, 1997)

Figure 4. 3 : High Income Residential House at Thome Estate, Nairobi North.

Figure 4. 4 : Middle Income Residential buildings; Imara Diama and Pipeline Estate, N. East.

Figure 4. 5 : Low Income residential buildings Kayole (N.East) and Mathare, N. North

4.3 Research Design

This study used quantitative research design (Rudestam & Rae, 2015), which attempted to identify the indoor radiological risks and their associations with other factors of residential houses in relation to indoor air quality. The current National Sample Survey and Evaluation Program V (NASSEP V) frame which is a household-based sampling frame developed and maintained by Kenya National Bureau of Statistics was used.

This sampling NASSEP V framework has been utilized in various household studies in Kenya, namely: the 2014 Kenya National Demographic and Health Survey, the 2012/2013 Kenya National housing survey and also during the 2009 population and housing census, where each sub-location was subdivided into 96,000 census Enumeration Areas (KNBS, 2009a). These current NASSEP V is the recommended frame for household surveys and utilizes the county boundaries using a two-stage stratified cluster sampling format with the first stage involving selection of Primary Sampling Units (PSUs) i.e EAs using Probability Proportional to Size (PPS) method and the second stage the selection of households.

The household distribution in Nairobi is 53% and 47% in North and East district respectively. In this study, the distribution by type of building materials for floor, walls and ceiling in the sample was then exactly to this proportion (KNBS, 2009). The two stage multistage cluster methodology was considered because of the availability of data for type of residential house and type of building materials used for (floor, ceiling and walls) within administrative levels of districts namely: Northern, Eastern, West-lands and Nairobi (KNBS, 2009). The natural clusters of the population of residential houses were confined within sub locations of the districts under study.

4.4 Sampling

Ten sublocations primary units were selected by probability proportional to size (PPS) and secondary units' residential households selected by probability proportional to size (PPS) of the type of building material of floor, roof and walls within each selected primary unit. Proportional allocation method was used to determine the sample size of each cluster, where the sizes of the samples from the different clusters were allocated randomly but kept proportional to the types of building material of North and East district (KNBS, 2009). Three hundred and thirty (300) residential houses were sampled in this study using these two-stage multistage sampling method.

For each house sampled, direct measurements of ambient gamma dose rate, NORM activity and dose rate were measured in the main living room. At each sample site in the sampled house, NORM identification and analysis were conducted with respect to the floor, wall and ceiling.

Direct ambient gamma dose rate were measured at a distance of I meter from the floor, ceiling and at least two side walls in the living room. At each site, three measurements spanning for over 2 minutes were counted and averaged to a single value for the floor, walls and ceiling. In total 3960 sites (Table 4.1) were sampled in ten clusters sampling locations.

Table 4.1: Sampling Location and Sample Codes

No	**Sampling Cluster**	**No. of household per cluster - cluster size**	**Sample Code**
1	Kayole	35	H1- H35
2	Komarock	35	H36 – H70
3	Imara Daima	35	H71 – H105
4	Salka	35	H106 – H140
5	Nairobi South	35	H141 – H175
6	Githurai	31	H176 – H206
7	Kasarani	31	H207– H237
8	Gardern Thome	31	H238 – H268
9	Ruaraka	31	H269 – H299
10	Mathare North	31	H300 – H330
		330	

The ten sampled clusters in Nairobi City included; Kayole, Komarock, Imara Daima, Salka, Nairobi South, Githurai 145, Kasarani, Gardern Thome, Ruaraka and Mathare North sub locations. A portable global positioning coordination system Garmin GPS+G10 NASS etrex 10 was used for sampled location sites Figure (4.6)

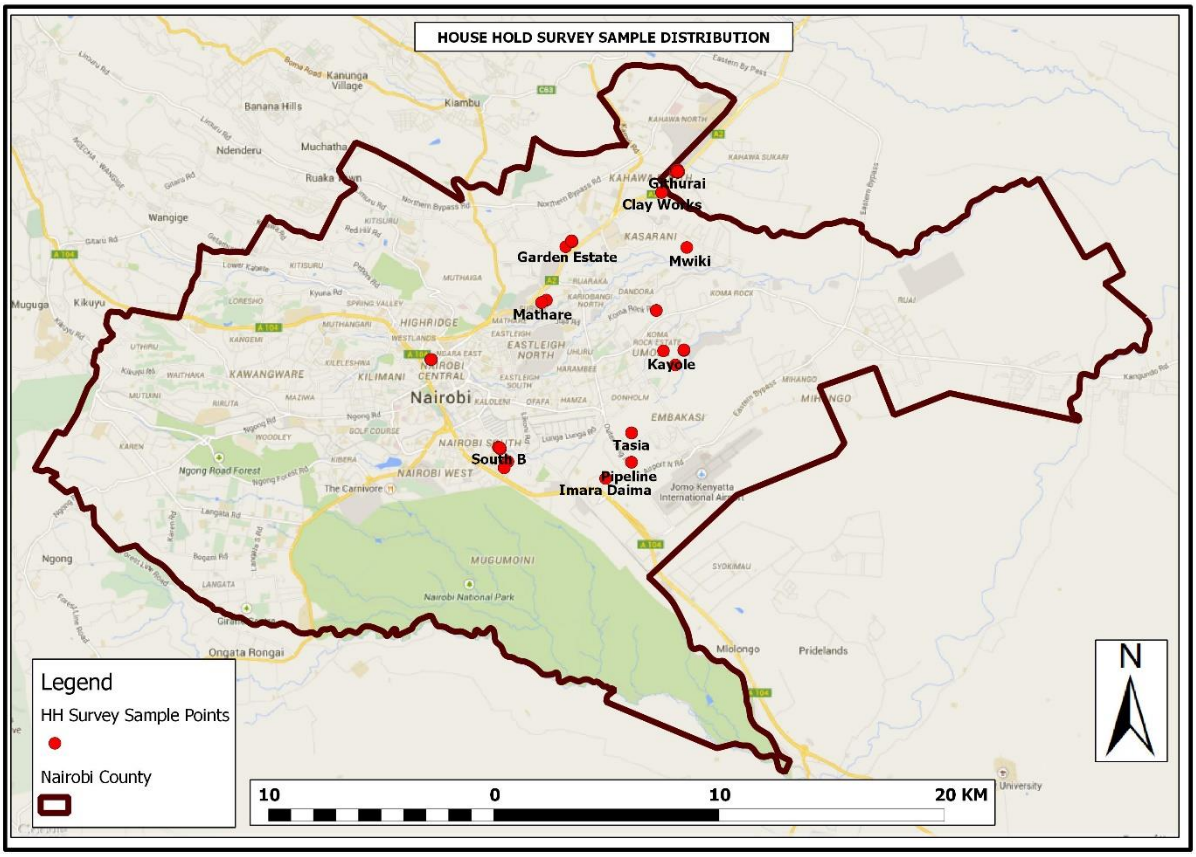


Figure 4. 6 : Main Map of Sampled Residential Estates in Nairobi City

Source: Sampled using the portable global positioning system Garmin GPS+G10 NASS etrex 10 Model between March and April 2014.

In this study, 330 residential houses were sampled, that belong to members of Life Reformation Centre Church. Table 4.1 shows the sampled clusters, where each cluster constituted a targeted population ranging from 31-35 households (Figure 4.7) made of different types of building materials.

The choice of houses selected in this study (Cox, Mage, & Immerman, 1988), depended on the availability of the completed lists of consent for participation by members from Life Reformation Centre Church, who reside in different parts of estates within Nairobi City. The selected house occupants were then contacted for pre-sampling and sampling schedule preparations per estate (Appendix I).

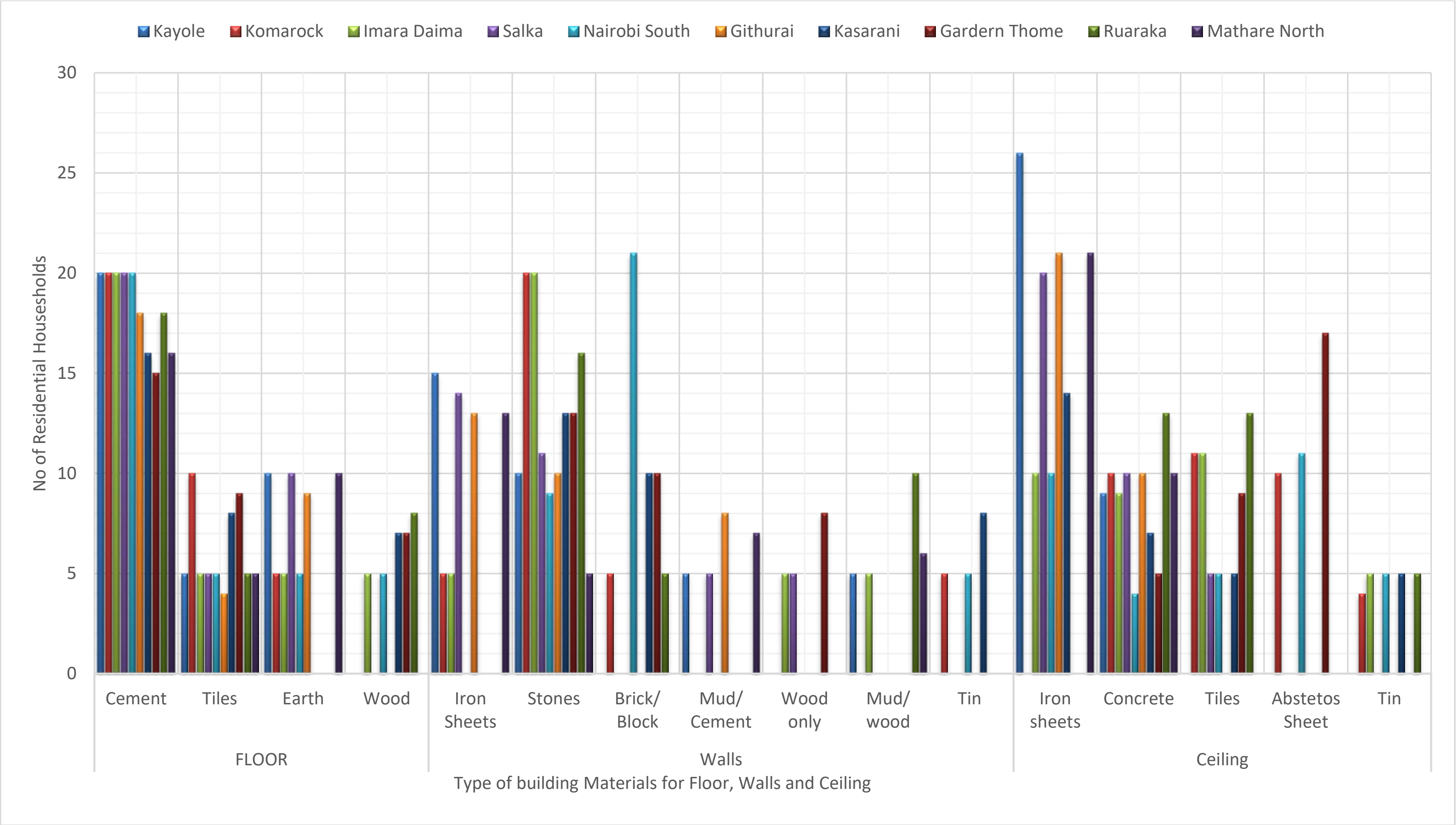


Figure 4. 7 : Sampled Residential Houses within Clusters per Type of Building Material

4.5 Presampling Conditions and Procedure

i. Closed-building conditions were exercised through prior notification as per Closed-building protocol (Environmental Protection Agency [EPA], 1993). That is, i) closed-building conditions for 12 hours prior to the measurements were maintained throughout the test period. ii) all windows remained closed and all external doors except for momentary entry and exit and iii) heating and cooling systems were set to normal occupant operating temperatures; No fan or blower were used.

ii. Tests were conducted in accordance to the AARST&NRPP (2012) protocol for each living room level that is in contact with the ground or above a crawl space, utility tunnel or garage (Fig. 4.8a) and b) and higher floors. The upper floor test locations were selected so that units on one floor were not directly above or below units on other floors (Fig. 4.8c).

iii. Geologic considerations were considered for selection of residential ; areas with faulting.

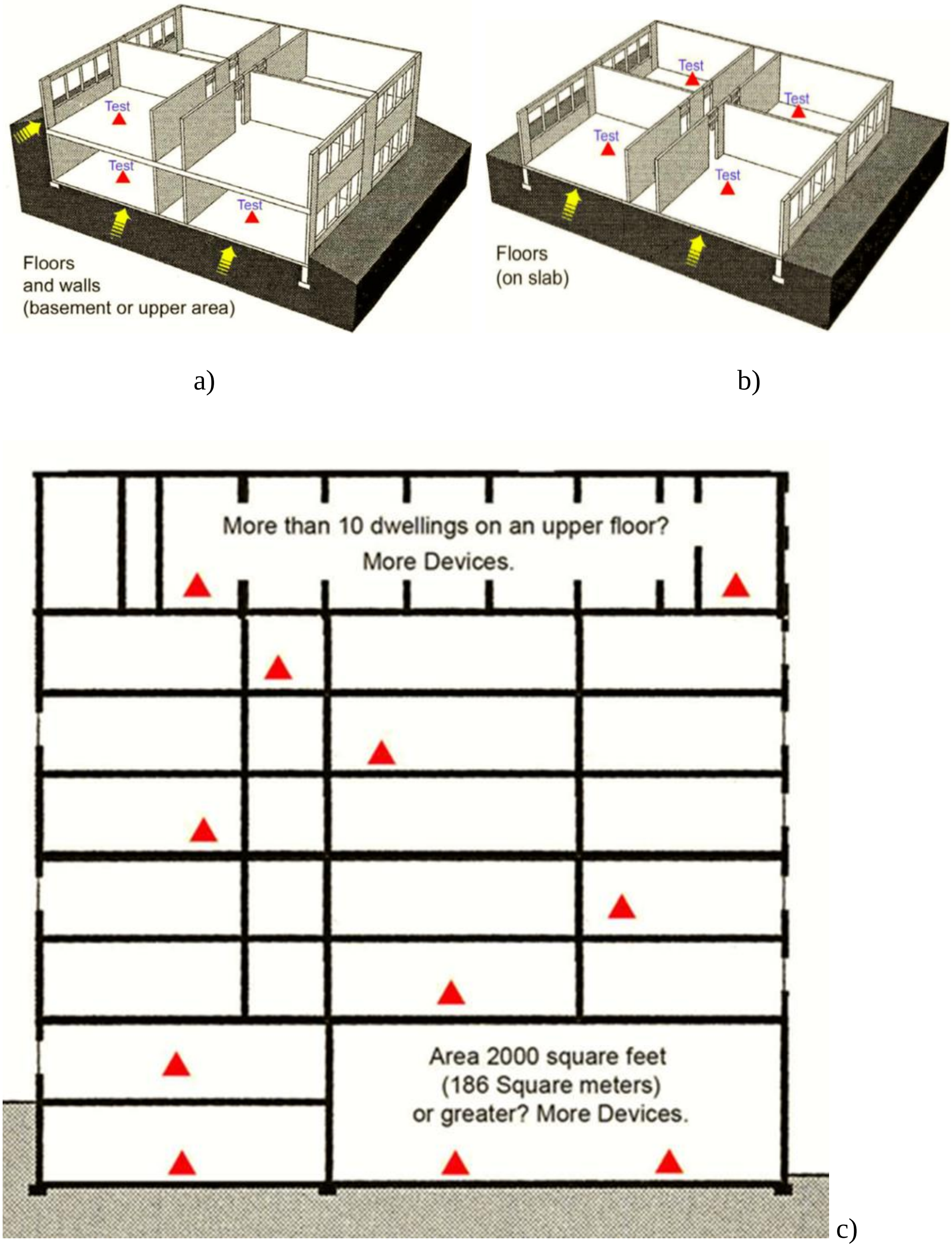
iv. In each residential house, measurements of the living room space volume, window and door size and the opening angle of the window, and door in respective living rooms were using the tape measure and the protractor and number of occupants per houses.

v. Gamma dose rates were measured at 1 meter distance from the floor, walls and ceiling. At each location, three measurements for over 2 minutes were conducted and averaged to a single value.

vi. For measuring gamma emitted from ^{226}Ra in a room, the location of measurements were as follows: i) 1 meter above the floor, from 0.5 m to 1m from the ceiling and 0.4 – 0.5m from the wall ii) 1cm above the surface/floor for gamma ray and less than 1m away from the walls for ^{232}Th measurements since thoron concentration strongly decreases with the distance from the wall.

vii. The UNSCEAR 2000 and 2008 dose assessment models were used to measure direct measurements i.e

   a) Identification of NORM 1 meter from the ceiling, floor and walls,
   b) Determining pertinent gamma activity concentrations of NORMS,
   c) Measuring the dose rate of these NORMS, gamma emissions and background,
   d) Measuring ambient gamma dose from the floor, ceiling and walls, and
   e) Measuring the ourdoor dose rate around residential houses without pavements



a) b) c)

Figure 4. 8 : Location of Dose Rate Measurements in the Main Living Room

viii. The net indoor absorbed dose in air was computed using the UNSCEAR model from direct dose measurements by subtracting the background radiation, computed at a latitude of 1670m above sea level;

ix. The available geological data of Nairobi City districts and the statistical analysis approach (Martin & Harbinson, 1972) followed geogenic with comparison of the absorbed dose rate.

x. The annual effective dose was computed from the absorbed dose using the UNSCEAR 2008 model.

xi. The excess lifetime cancer risks were computed using the ICRP, 2007 excess lifetime cancer risk model at life expectancy of 70years.

xii. The ventilation of openable areas were computed using the (ASHRAE, 62.1/2007) standard and the (England and Wales, 2010) ventilation building regulations.

xiii. The ventilation rates were computed using the ventilation rate per person and per m^2 floor area method (CEN 15251, 2007) standard.

xiv. The air exchange rate per hour for Nairobi residential houses was calculated using ASHRAE 62.1, 2004) model.

4.6 Sampling Instrument: Inspector 1000 Survey meter

4.6.1 Instrument Description

The following a brief summary of Inspector 100 0 INIK specifications;

- The dose rate equivalent on 10mm of human tissue [H*(10)]
- Dose rate range: 0.01µsv/h to 100mSv/h
- Real time isotope identification with activity and dose by isotope calculation
- High-performance spectroscopy useful for monitoring exposure hazards because of its high efficiency and good resolution (Canberra, 2007).
- NaI (Tl) crystal has good light yield, excellent linearity and the high atomic number of its Iodine constituent. The high Z of iodine in NaI gives **good efficiency** for gamma ray detection and **resolution** achievable ranges from 7.5%-8.5% for the 662 keV gamma ray from 137Cs (Knoll, 2010).
- The digital stabilizer senses the position of the peak in the measured spectrum during the course of measurement and compares its position with the known reference. In case of an

error signal, the stabilizer communicates with MCA and adjusts the gain of a preceding amplifier according to the errors signal sensed by the stabilizer (Knoll, 2010; Canberra, 2007).

- Background subtraction- a background spectrum file was used to subtract the environment background's radiation from each new current spectrum. This ensured that the spectrum represented only radiation emitted by the suspect gamma source within each location (Canberra, 2007).

The Inspector 1000 INIK Serial No. 06064893 used was calibrated with Cs-137 at Tanzania Atomic Commission Secondary Standards Dosimetry Laboratory. The 3.49 mGy/h value of the physical quantity air kerma at source detector distance of 300cm and instrument linearity response of 85% were determined (Appendix II - Inspection 1000 Survey Meter Calibration Certificate).

Inspector 1000 Survey meter ambient dose equivalent detector, with energy ranging from 50 kev to 3 Mev was used for ***in situ*** measurements. Inspector 1000 detector is used for any field measurements applications requiring dose and count rate measurements, nuclide identification with activity and dose, radiation source location and for spectrum acquisition and analysis (Canberra, 2007).

Its mode of data acquisition has the following; i) **Locator Mode**-to locate the source of radioactivity and display real-time radiation histogram showing the amount of radiation being detected ii) **Nuclide Identification (NID) Mode**- which provides real-time identification of individual isotopes and their calculated activity, with the results displayed on the screen iii) **Dose Mode -** is always running in the background, it measures and displays both the instantaneous dose rate and the cumulative dose in several different display modes and units as specified by the user e.g a choice from Sievert, roentgen or rem. and iv) **Spectroscopy Mode -** collects and analyse radionuclide spectra (Fig. 4.9). (Canberra, 2007).

Figure 4. 9 : Inspection 1000 Survey Meter : **Source: (Canberra, 2007)**

4.7 Data Analysis

Statistical analysis was used to determine the average indoor gamma dose rate per cluster using Microsoft Excel software. The two-stage multistage cluster sampling was conducted, including the statistical tests of dispersion, variation, design effect, mean population proportions, mean population totals, confidence interval and finite population correction factor (Lohr, 1999)

The t -test distribution was used to test the variation of the indoor dose rate in µSv/h for the type of building materials of the floor, ceiling and walls at the 95% confidence.

To evaluate the indoor radiological hazard of natural radioactivity due to type of building materials; the the gamma-absorbed dose rate, effective dose and excess lifetime cancer risk were computed using UNSCEAR 2000, 2008 and ICRP 2007 models.

Furthermore, residential ventilation parameters were assessed in accordance with CEN 15251, 2007 standard and WHO, 2009 model.

CHAPTER 5:

RESULTS AND DISCUSSION

5.1 Introduction

The results of measurements of natural radionuclides content, ambient gamma equivalent dose rate, mean absorbed dose, effective dose, excess lifetime cancer risk and the ventilation of the main living room in Nairobi residential houses are reported using Tables, Figures and Bar Charts.

Section 5.2 describes the validation of measurements; ambient gamma equivalent dose rate and radioactivity and calibration of Inspection 1000 Survey Meter for energy response. Section 5.3 - 8 presents' main findings of the study namely; Subsection 5.3 Indoor NORM dose rate and radioactivity measurements, 5.4 indoor ambient gamma dose rate, subsection 5.5 showing calculated absorbed dose rate. Subsection 5.6 describes the relation of study area geology and absorbed dose rate, subsections 5.7 describes the age based annual effective dose and excess lifetime cancer risk of Nairobi residences. Lastly subsection 5.8 presents the potential radon exposure due to insufficient ventilation rate in Nairobi residential houses.

5.2 Validation of Measurements

5.2.1 Dose Rate Measurements: Calibration

The Inspector 1000 INIK detector was calibrated at the Tanzania Atomic Energy Commission (TAEC) in November 2013 with Reference Instruments Secondary Standard, PTW 32002 Serial Number 070 and Ionization Chamber with Electrometer PTW UNIDOS Serial Number 20229 This dosimetry standard, was previously calibrated by the IAEA in September 2010 is traceable to International Bureau of Weights and Measures. The non-linearity of response was within ±15% while the mean calibration factor was 1.10±0.05. This corresponds with the manufacturer accuracy estimation of stabilized IPRON 2" x 2" NaI probe detectors at 15 to 25%, with 1 standard deviation using substitution calibration method (Appendix II: Inspection 1000 Survey Meter Calibration Certificate).

5.2.2 Calibration of Inspection 1000 Survey Meter for Energy Response

Energy calibration establishes a relationship between the spectral energy and channel number. Energy calibration was done with known γ energies of standard calibration sources, ^{137}Cs-137 reference source with primary rays 661.66 keV and Co-60 of γ energies 1173.2 kev and 1332.5 kev. Figure (5.1)

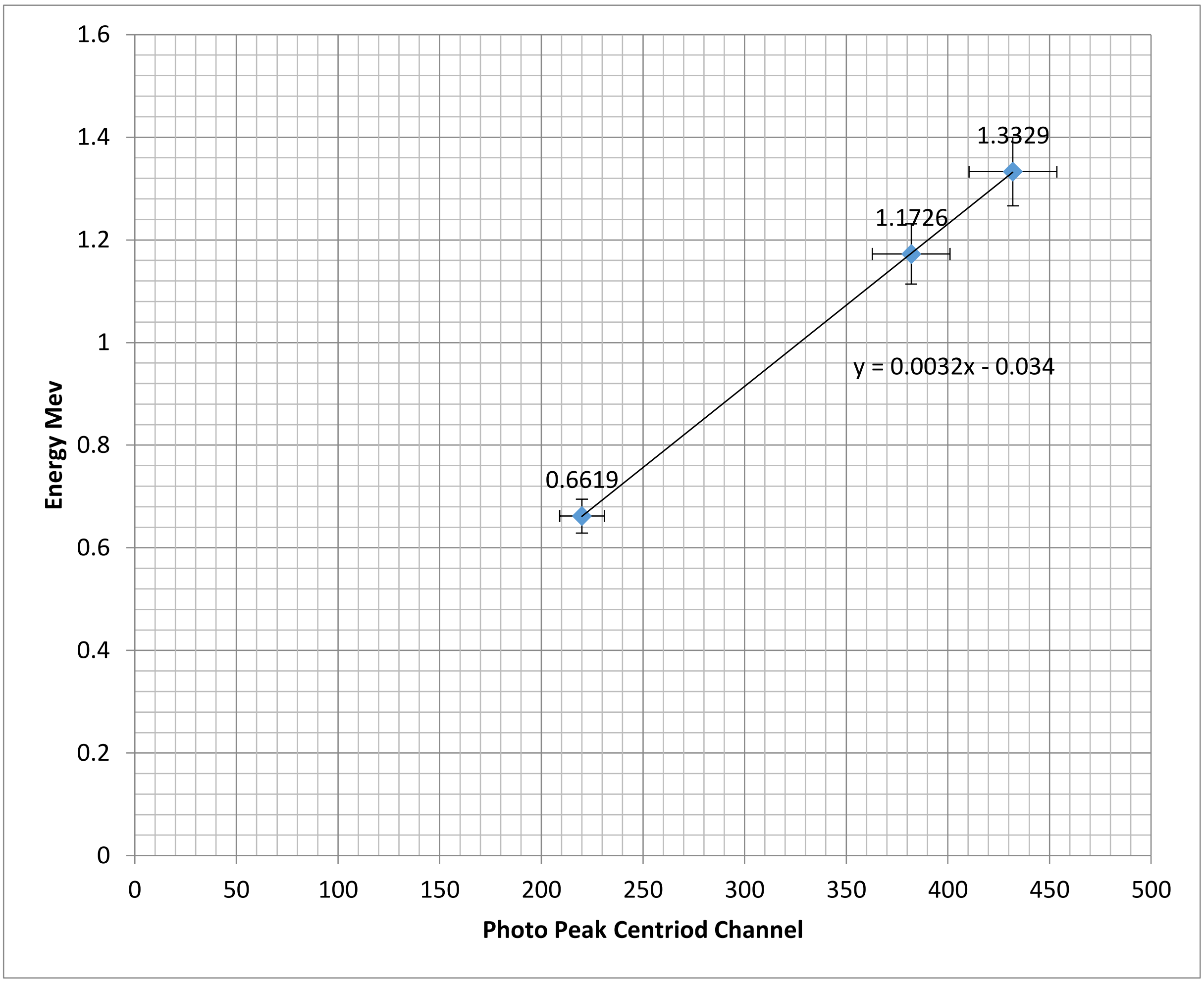


Figure 5.1 : Inspection 1000 Survey Meter Energy Calibration Response

5.2.3 Accuracy of Radioactivity Measurements

For purposes of determining γ-ray activities in the residential houses, the accuracy of activity measurements was performed with standard reference Cs-137 No. NV 808, Cs-137 No. NV 809, Co-60 Disk Check Source from Canberra Industries The results show that both the measured and computed activity is within ± 5% error (Table 5.1)

Table 5.1 : Activity Measurements of Standard Calibration Sources

Reference source	γ Energy keV	Date & Activity Ao (kBq)	Half-life (yrs)	Time t (yrs)	Measured activity (kBq) 25/02/2014	Calculated Activity (kBq) 25/02/2014
Cs-137 No. NV 808	661.66	1/1/ 2006 36.9kBq	30.14	8.15	29.5kBq	30.59
Cs-137 No. NV 809	661.66	1/1/2006 37.4kBq	30.14	8.15	29.9kBq	31.1
Co-60 Disk Check Source	1172.2 1332.5	7/03/2007 37kBq	5.27	7.04	14.6kBq	14.66

5.3 Indoor NORM Dose Rate and Radioactivity Measurements

Appendix III and IV show the results of measurements for dose rate and radioactivity of NORM for the floor, ceiling and walls including the type of building material used. The NORM dose rate mean 0.037 µSv/hr (0.02 -0.10) µSv/hr (floor), mean 0.039µSv/hr (0.017 – 0.042) µSv/hr (walls) and mean 0.039 µSv/hr (0.02 – 0.045) µSv/hr (ceiling). The ^{238}U, ^{232}Th, ^{226}Ra+daughters radionuclides were below their detection limit. The dominant radionuclide identified was ^{40}K; mean 107 kBq (103 -163) kBq (floor), mean 140 kBq (97 -344) kBq (walls) and mean 120 kBq (84 -167) kBq (ceiling).

The results suggest marginal potential exposure associated with natural radionuclides content from the type of building materials used on the floor, ceiling and walls. These NORM dose rate results correspond to annual dose rate; 0.32 mSv/y from the floor, and 0.34 mSv/y from both walls and ceiling compare well with related studies on the indoor dose rate of both bulk and superficial building materials for regulation by European Commission of 0.3 mSv/y to 1 mSv/year (EC 112, 1999).

5.4 Indoor Ambient Gamma Dose Rate Measurements

The results of ambient gamma dose rate measurements assumes the following: i) Radioactive equilibrium in the ^{238}U and ^{232}Th chains, *and ii)* ambient gamma dose rates were calculated taking into account the ambient gamma dose equivalent (H*10) in accordance with (ICRP, 1991, 2007) publications and iii) the paint on the walls did not attenuate the gamma rays. A detection limit of

0.02 µSv/h was assumed based on the background count above which the measured count was considered statistically significant for detection. The critical level of 0.05 µSv/h as the decision level of measurable activity was calculated using the (Currie, 1968) equation of

$$L_C = 2.326\sigma NB \ldots\ldots\ldots\ldots\ldots.. (5.1)$$

Where σNB is the standard deviation of counts, on the assumption that significant fluctuations of measurement occur due to counting statistics and Lc is the critical level with 95% certainty of confidence. Figures 5.2, 5.3 and 5.4 show the summary of indoor ambient gamma dose rate per type of building material for the ceiling, floor and walls in Nairobi city.

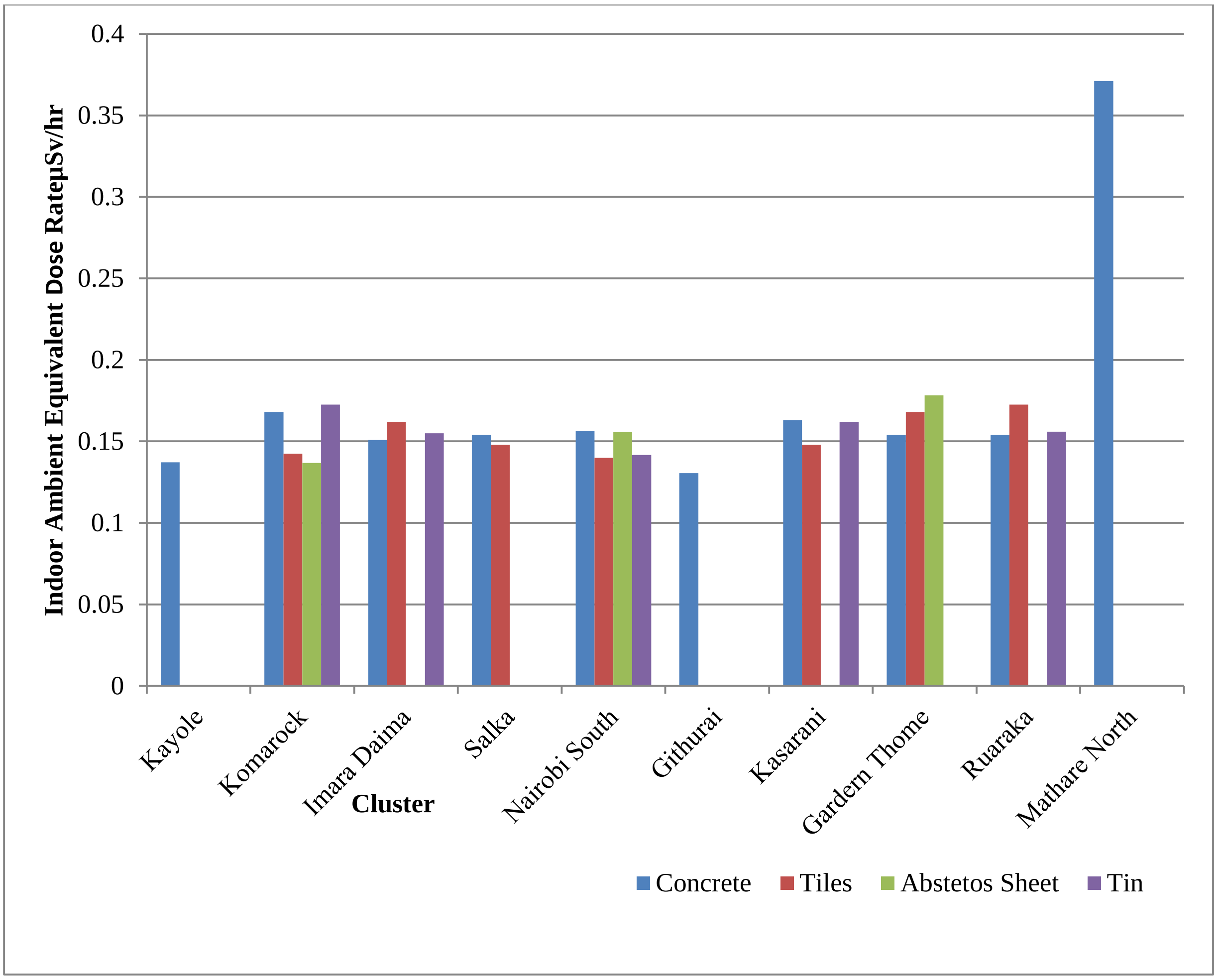


Figure 5.2 : Indoor Mean Ambient Gamma Equivalent Dose (µSv/h) per Cluster - Ceiling

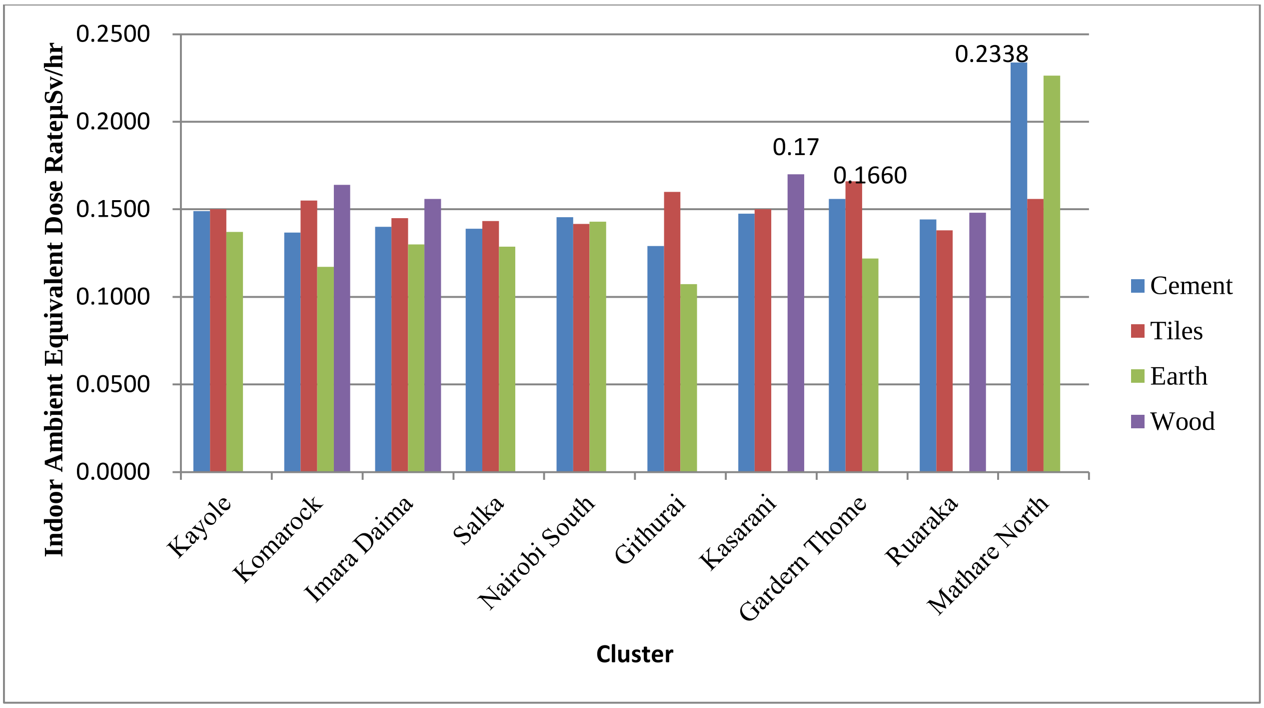


Figure 5.3 : Indoor Mean Ambient Gamma Equivalent Dose (µSv/h) per cluster - Floor

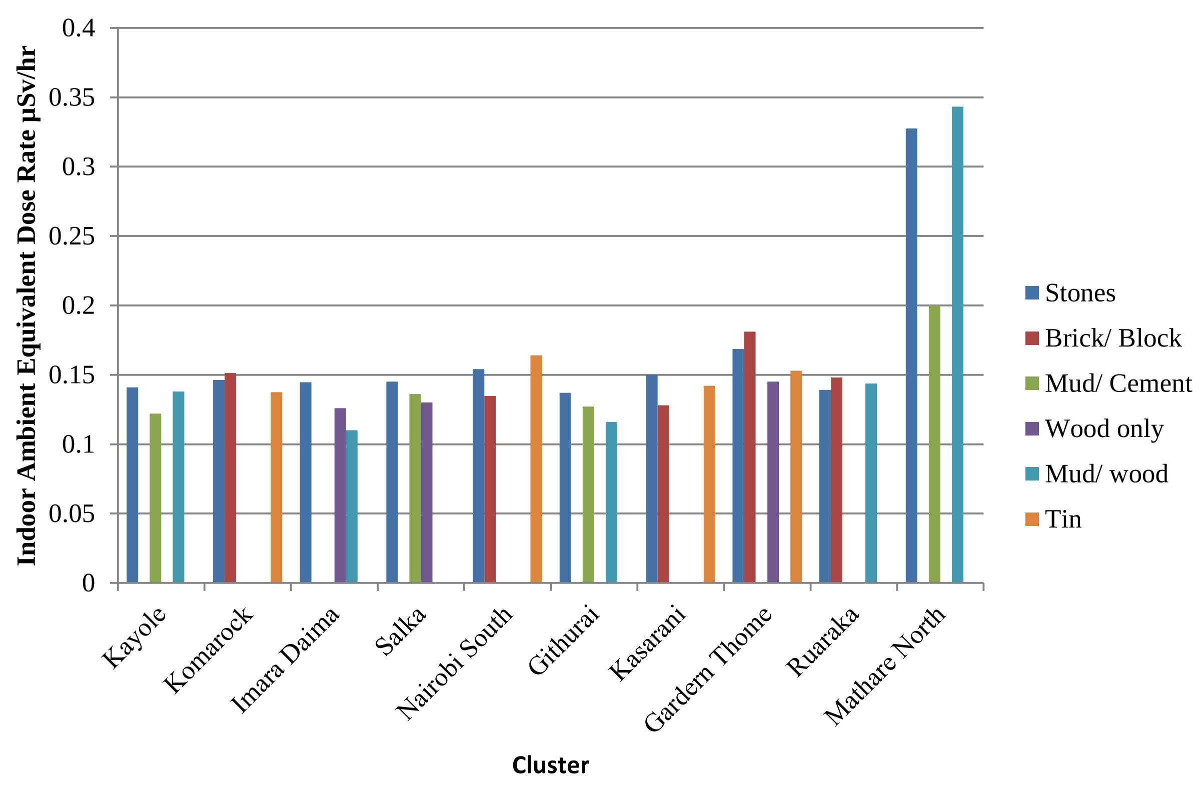


Figure 5.4 : Indoor Mean Ambient Gamma Equivalent Dose (µSv/h) per cluster - Walls

Mathare North cluster had the highest dose rate at 0.37 µSv/hr from the concrete ceiling, 0.34 µSv/hr from the walls and floor 0.23 µSv/hr. Garden Thome cluster followed with a dose between 0.15 to 0.18 µSv/hr from the ceiling, 0.17 to 0.18 µSv/hr from walls and 0.12 to 0.17 µSv/hr from the floors. The least dose rate was recorded in roofed iron sheet houses for floor and walls, below the detection limit of 0.02 µSv/hr. The maximum indoor dose rate was found in concrete ceiling and stone walls (0.37 µSv/hr and 0.34 µSv/hr). These findings, imply that the mean gamma dose rate varies with type of building materials used in the residential houses for the ceiling, floor and walls and compares with similar studies (Mandakini, 2010; UNSCEAR, 2008; CEN, 2017; Smetsers & Tomas, 2019).

The results of variation in dose rate due to dimensions of houses; most ceiling thickness varied from 26-30cm and wall thickness of 25 cm. The dimensions of most houses varied between 2.4m to 7.0m for length and between 2.6m to 4.4m, for width and between 2.4 to 2.8m for height (Appendix V). This is in agreement with (UNSCEAR, 2000 and Markkanen, 1995) findings that high variability of gamma dose rate depends on the building`s dimension and Koblinger (1978) and Stranden (1979) wall thickness and density findings.

There was significant gamma dose rate deviation for both type of building and type of building materials for floor, ceiling and walls thus suggesting that level of NORM in building material forms the major basis of external indoor exposure (concrete ceiling, stoned walls, tiled floor). Since natural radiation background for decades has provided significant baseline of radiation exposure, the findings give a fundamental benchmark for consideration of radiation protection reference levels and limits.

5.5 Indoor Absorbed Dose

Figure 5.5 shows the indoor absorbed dose variation for different type of building materials used for the floor, walls and ceiling, prior to cosmic background radiation correction.

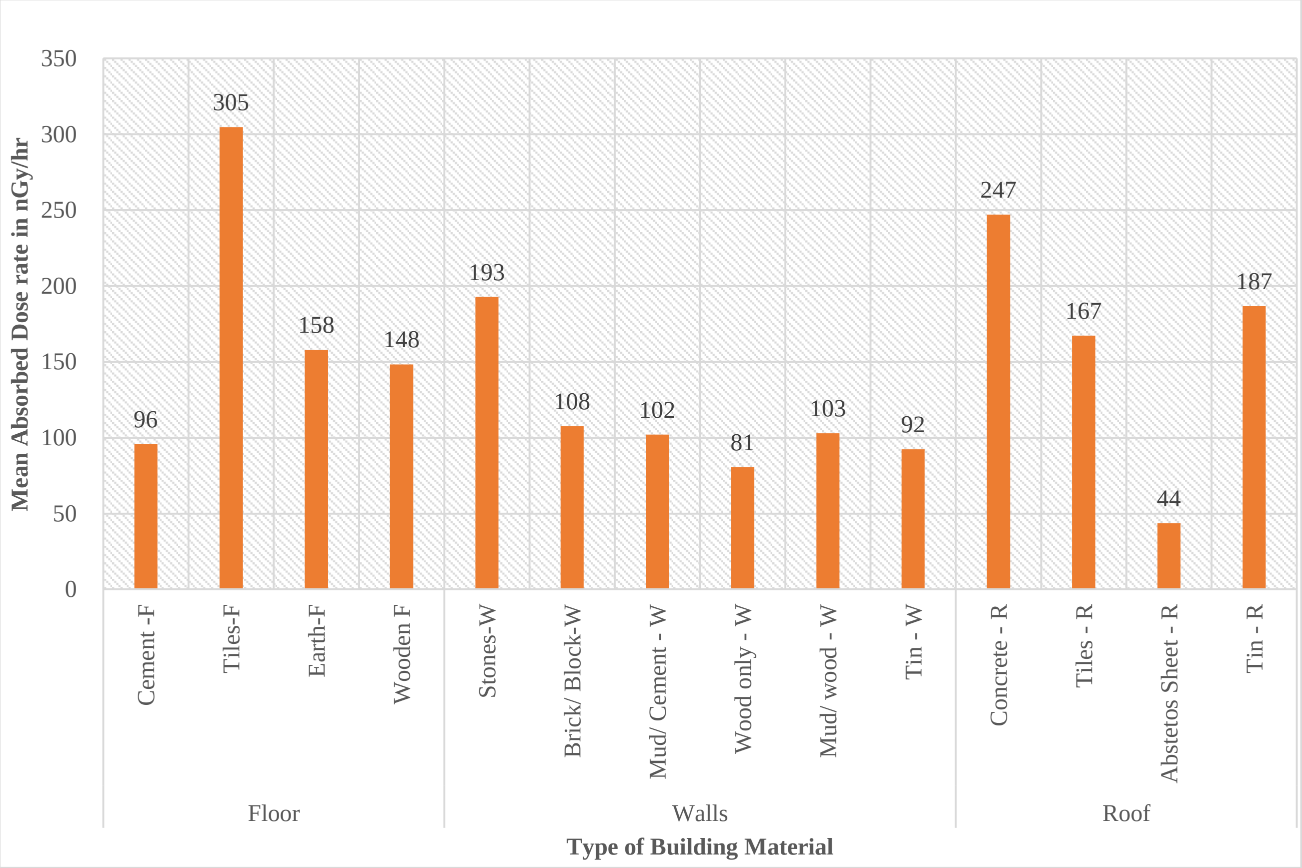


Figure 5.5: Indoor mean absorbed dose variation with type of building materials

The indoor absorbed dose for different types of residential building materials for floor, walls and ceiling ranged from 81 nGy/h to 305 nGy/h except for abstetoes sheet roofed house, with the average value of 145 nGy. From the mean absorbed dose rate findings, stone walls, tiled floor and concrete ceiling are the dominant source of exposure.

Table 5.2 summaries the results of indoor and outdoor absorbed dose measurement (corrected for cosmic background radiation).

Table 5.2 : Indoor and Outdoor Mean Absorbed Dose

Site Location	Type of building Material	Indoor Mean Absorbed Dose rate in nGy/hr	Outdoor Mean Absorbed Doserate nGy/hr	Reduction Coefficient
Floor	Cement	63.74 ± 5.43	87 ± 11	0.73
	Tiles	272.73 ± 71.47	98 ± 20	2.78
	Earth	125.93 ± 40.67	79 ± 11	1.59
	Wooden	116.44 ± 40.67	98 ± 10	1.19
Walls	Stones	160.82 ± 51.57	100 ± 10	1.61
	Brick/ Block	75.65 ± 29.67	120 ± 20	0.63
	Mud/ Cement	70.1 ± 30.57	115 ± 23	0.61
	Wood only	48.69 ± 26.07	113 ± 21	0.43
	Mud/ wood	71 ± 31.47	120 ± 10	0.59
	Tin	60.34 ± 33.97	95 ± 20	0.64
Ceiling	Concrete	215.09 ± 53.37	107 ± 20	2.01
	Tiles	135.4 ± 41.87	101 ± 30	1.34
	Asbestos Sheet	11.77 ± 3.33	97 ± 22	0.12
	Tin	154.77 ± 64.67	87 ± 11	1.78
		113 ± **37.49**	98 ± 11	
			85 ± 10	
			89 ± 20	
			99.35 ± **16.47**	

Dose corrected for cosmic radiation, altitude and latitude factor

The indoor absorbed dose rate ranged from 60.34 - 272.73 nGy/h with a mean value of 113 nGy/h. There is significant level of increase in residential exposure due to the type of building materials with Mustapha at el., 1999 results for indoor mean absorbed dose findings. For instance, concrete (77.5nGy/hr to 215.09nGy/hr), Bricks (55.5 to 75.65 nGy/hr), stones (138.5 to 160.83 nGy/hr) and soil/earth (69.5 to 125.93 nGy/hr).

For purposes of establishing the indoor-outdoor dose ratio, measurement of outdoor absorbed dose rate in air were obtained by taking seventeen measurements randomly outdoor in the sampled clusters outside sampled houses without pavements around them and with an outdoor occupancy factor of 20%. In this study, the Nairobi measured outdoor dose rate ranged between 79 -120 nGy/h with average mean of 99.35 nGy/h (Table 5.2).

After correction for cosmic radiation background (9.97 nGy/h) and assuming 20% outdoor occupancy, the outdoor absorbed dose rate in air due to terrestrial gamma radiation was (89.38 nGy/h), approximately 26% lower than the indoor absorbed dose rate in air. The indoor to outdoor ratio in Nairobi is 1.26 commensurate with the acceptable worldwide indoor-outdoor absorbed dose rate ratio range between 1 and 2, with a mean terrestrial gamma dose rate indoor of 1.4 times higher than outdoors (UNSCEAR, 1993, 2000, 2008, 2012). This ratio correlates to structural properties of buildings (materials, thicknesses and dispositions).

This study indicates a significance correlation between the type of building material and indoor absorbed dose rate of 26%, with potential of external exposure from the walls, the ceilings and the floor. The contribution of building materials to the gamma absorbed dose rate indoors is 29 nGy/h .These study`s findings are within the world absorbed dose rate estimations of 24 – 160 nGy/h indoors and 20 to 190 nGy/ outdoors but higher than the worldwide average indoor absorbed dose rate in air of 84 nGy/h due to indoor natural radionuclides contained in building materials (UNSCEAR, 2000, 2008).

The household residence exposure for Nairobi residents is higher in tiled, earthen and wooden floor, and tiled, concrete and tin roofed houses (Table 5.2). Therefore, indoor exposure based on the type of building materials for the floor, ceiling and walls results in to differences of NORM levels and exposure. The computed mean population weighted dose rate, D_w for Nairobi residence is 0.28 nGy/h (1.72mSv/y).

The indoor absorbed dose in Nairobi is relatively lower than in Nigeria which ranges from 114.29 nGy/h to 751.86 nGy/h and average of 293.27 nGy/h but higher than that in India dwellings (Masok et al., 2015 ; Babai et al, 2012).

Table 5.3, is a summary of the statistics of indoor mean absorbed dose in this study.

Table 5.3 : **Summary of Statistics of Indoor Mean Absorbed Dose rates**

House Location	Type of building material	Dose Rate in μGy/hr at 95% CI	Mean population (μ) Dose rate in μGy/hr CI at 95%	Design Effect factor-(Deff)	Intracluster Correlation (ICC)
Floor	cement	31.56 ± 18.97	0.10 ± 0.06	0.69	0.64
	Tiles	100.53 ± 74.02	0.30 ± 0.22	5.99	0.44
	Earth	52.09 ± 51.97	0.16 ± 0.16	1.21	0.50
	Wood	48.96 ± 51.97	0.15 ± 0.16	3.57	0.58
Walls	Iron sheets	<0.02	<0.02		
	Stones	63.60 ± 59.77	0.19 ± 0.18	1.94	0.70
	B/Blocks	35.50 ± 44.10	0.11 ± 0.13	2.51	0.57
	Mud/Cement	33.66 ± 44.74	0.10 ± 0.14	1.54	0.54
	Wood only	26.60 ± 41.52	0.08 ± 0.13	3.14	0.55
	Mud/Wood	33.96 ± 45.39	0.10 ± 0.14	1.67	0.54
	Tin	30.44 ± 47.17	0.09 ± 0.14	3.77	0.59
Ceiling	Iron sheets	<0.02	<0.02		
	Concrete	81.62 ± 61.06	0.25 ± 0.19	1.76	0.53
	Tiles	55.44 ± 52.83	0.17 ± 0.16	3.36	0.53
	Abstetos Sheet	14.41 ± 20.47	0.03 ± 0.06	0.93	0.66
	Tin	61.60 ± 69.15	0.15 ± 0.21	6.18	0.54

The results of the statistics of absorbed dose rate in Table 5.3 shows the variations of design effect factors for the floors, walls and ceiling for different types of building materials used between 0.69 – 2.51. In principle, the term design effect is used to explain the homogeneity of sample.

Therefore , the mean absorbed dose rate range between 100 to 300 nGy/hr for the floor, 100 to 370 nGy/hr from the walls and 90 to 440 nGy/h for the ceiling for different type of building materials used in residential houses in Nairobi, except for the tin, tiles and wooden materials.

5.6 Indoor Exposure and Geology

The statistical analysis examined the relationship between the dose rate and the existing geology of Nairobi has the basis for the foundation of most residential buildings and source of construction materials as shown in Figure 5.6.

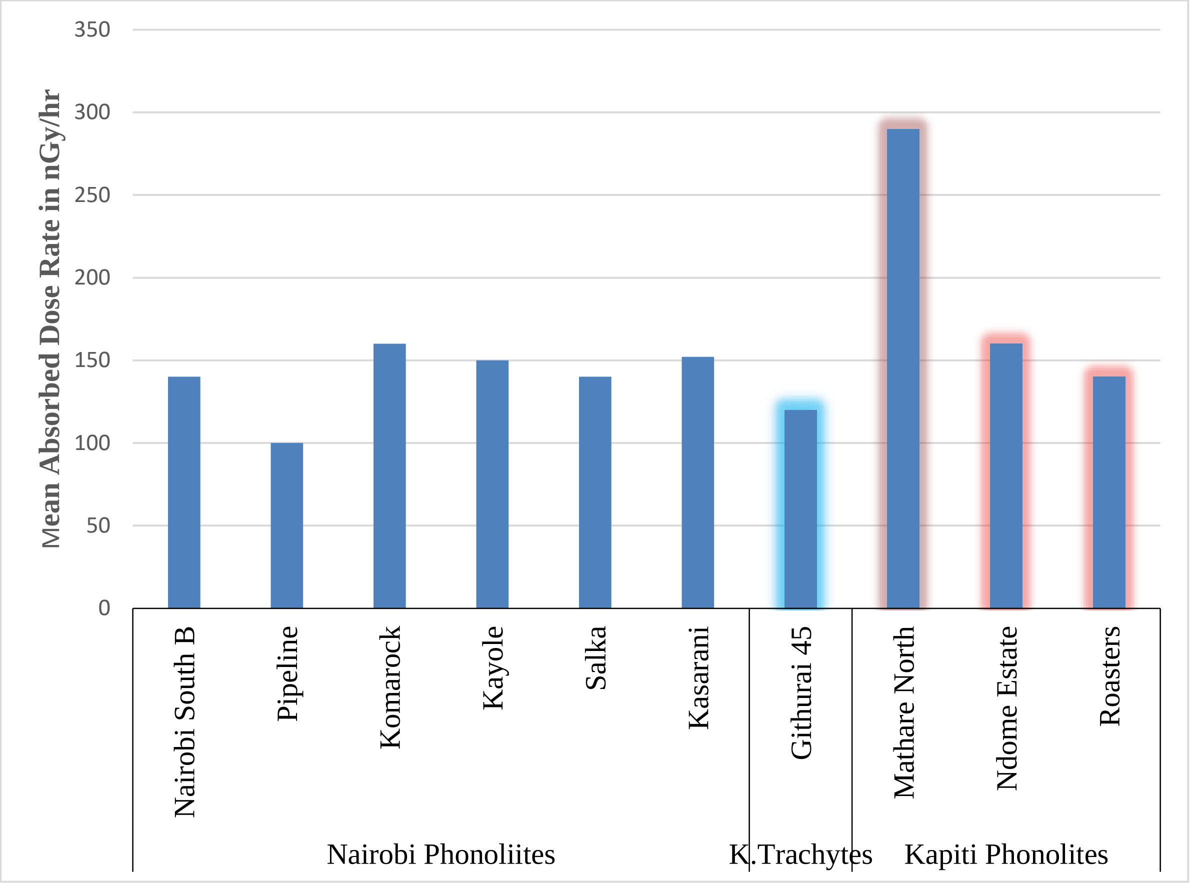


Figure 5.6: The Indoor mean dose rate variation with Nairobi geology

In summary, figure 5.6 shows that Kapiti Phonolites has a relatively higher absorbed dose rate exposure than Nairobi Phonolites. The later constitutes the Northern part of Nairobi; Kasarani, Garden Thome, Githurai 45 and Mathare North. These findings are in agreement with the existing studies that specific levels of gamma exposure depend upon; the geological composition of the soil, rocks and the type of building materials used for residential houses (EC 112, 1999; Sulaiti, 2008; UNSCEAR, 1993, 2000, 2008; Lust & Realo, 2012).

5.7 Indoor Annual Effective Dose and Excess Lifetime Cancer Risk

Table 5.4 shows the results of indoor annual effective dose (mSv/y) and excess lifetime cancer risk for adults, children and infants per type of building material for the floor, walls and ceiling.

Table 5.4 : Indoor Annual Effective Dose (mSv/y) and Excess Lifetime Cancer Risk for adults, children and infants per type of building material for the floor, walls and Ceiling

Site	Type of building Material	Effective Dose Adult	Effective Dose Children	Effective Dose Infants	Excess Lifetime Cancer Risk for Adult	Excess Lifetime Cancer Risk for Children	Excess Lifetime Cancer Risk for Infants
Floor	Cement	0.31 ± 0.03	0.36 ± 0.00	0.4 ± 0.03	1.60E-03 ± 0.001	1.60E-03 ± 0.000	2.05E-03 ± 0.000
	Tiles	1.34 ± 0.35	1.53 ± 0.40	1.72 ± 0.45	6.84E-03 ± 0.003	6.84E-03 ± 0.002	8.79E-03 ± 0.002
	Earth	0.62 ± 0.20	0.71 ± 0.20	0.79 ± 0.26	3.16E-03 ± 0.002	3.16E-03 ± 0.001	4.06E-03 ± 0.001
	Wooden	0.57 ± 0.20	0.65 ± 0.20	0.73 ± 0.26	2.92E-03 ± 0.002	2.92E-03 ± 0.001	3.75E-03 ± 0.001
Walls	Stones	0.79 ± 0.25	0.9 ± 0.30	1.01 ± 0.33	4.03E-03 ± 0.002	4.03E-03 ± 0.001	5.18E-03 ± 0.002
	Brick/ Block	0.37 ± 0.15	0.42 ± 0.20	0.48 ± 0.19	1.90E-03 ± 0.002	1.90E-03 ± 0.001	2.44E-03 ± 0.001
	Mud/ Cement	0.34 ± 0.15	0.39 ± 0.20	0.44 ± 0.19	1.76E-03 ± 0.002	1.76E-03 ± 0.001	2.26E-03 ± 0.001
	Wood only	0.24 ± 0.13	0.27 ± 0.20	0.31 ± 0.16	1.22E-03 ± 0.001	1.22E-03 ± 0.001	1.57E-03 ± 0.001
	Mud/ wood	0.35 ± 0.15	0.4 ± 0.20	0.45 ± 0.20	1.78E-03 ± 0.002	1.78E-03 ± 0.001	2.29E-03 ± 0.001
	Tin	0.3 ± 0.17	0.34 ± 0.20	0.38 ± 0.21	1.51E-03 ± 0.002	1.51E-03 ± 0.001	1.94E-03 ± 0.001
Ceiling	Concrete	1.06 ± 0.26	1.21 ± 0.30	1.36 ± 0.34	5.39E-03 ± 0.002	5.39E-03 ± 0.002	6.93E-03 ± 0.002
	Tiles	0.66 ± 0.21	0.76 ± 0.20	0.85 ± 0.26	3.39E-03 ± 0.002	3.39E-03 ± 0.001	4.36E-03 ± 0.001
	Abstetos Sheet	0.06 ± 0.02	0.07 ± 0.00	0.07 ± 0.02	2.95E-04 ± 0.001	2.95E-04 ± 0	3.79E-04 ± 0
	Tin	0.76 ± 0.32	0.87 ± 0.4	0.98 ± 0.41	3.88E-03 ± 0.002	3.88E-03 ± 0.002	4.99E-03 ± 0.002
Total		**0.55 ± 0.18**	**0.63 ± 0.2**	**0.71 ± 0.24**	**2.83E-03 ± 0.002**	**3.24E-03 ± 0.001**	**3.64E-03 ± 0.001**

(<0.01) - Below detectable limit of instrument 0.01µSv/h, F-floor, W-walls and R-roof, n= Total number of samples per estate (in all house-site) and σ= Standard deviation

From the results in Table 5.4, the mean annual effective dose ranged between 0.31 ± 0.03 mSv to 1.340 ± 0.35 mSv from the floor, 0.66±0.21 mSv to 1.06 ±0.26 mSv from the ceiling and 0.24±0.13 mSv to 0.79±0.25 mSv walls. The highest effective dose was observed from tiled floor, stone walled and concrete roofed residential houses 1.34±0.35, 0.79±0.25 and 1.06±0.26 mSv/a respectively. This results indicate that building materials are a major source of indoor exposure (Mustapha at el., 1999, UNSCEAR, 2000, 2006, 2008, 2012; IAEA, GSR Part 3, 2014; ASHRAE, 62.1/2016).

The overall annual effective dose due to indoor exposure for adults, children and infants was estimated to be 0.55 ±0.18 mSv, 0.63±0.21 mSv and 0.71±0.24 mSv respectively.

This study`s indoor annual effective dose (0.55 ±0.18 mSv) is higher than UNSCEAR, 2008 indoor effective dose for adults of 0.41 mSv. In addition, estimated outdoor effective dose was 0.11 mSv and is comparable to the UNSCEAR, 2008 recommended value of 0.07 mSv.

Therefore, the annual effective exposure rate for adult residence in Nairobi is 0.66 mSv/a (both indoor and outdoor) and for children and infants at 0.73±0.21 mSv and 0.81±0.24 mSv respectively which reflect the 10% and 30% exposure rate of adults' annual effective dose of 0.66 mSv.

The resultant annual exposure due to terrestrial external effective dose (0.66mSv/a) for Nairobi residence is within the acceptable dose limits for the general public of 1mSv/year (ICRP, 2007; UNSCEAR, 2008) external indoor and outdoor terrestrial range of 0.3mSv to 1mSv.

This study indicate potential exposure from tiled floors and concrete roof whose effective dose of 1.34 mSv/year and 1.06 mSv/year, respectively. Furthermore, type of building material used for residential houses within Nairobi city is predisposition to indoor exposure.

In addition, Table 5.4 further shows computed excess lifetime cancer risk from annual effective doses. From this study, the dominant excess lifetime cancer risk is 6.84×10^{-3} ±0.003 from the tiled floor, $5.39\text{x}10^{-3}$ ±0.002 from the concrete roof and $4.03\text{x}10^{-3}$ ±0.002 from stone wall residential houses. However, overall indoor excess lifetime cancer risk from residential houses in Nairobi is $2.83\text{x}10^{-3}$±0.002.

The excess lifetime cancer risk investigated in residential houses in Nairobi City is within the ICRP 2007 cancer risk of $6\text{x}10^{-3}$ except for residential houses with tiled floor, stoned walls and concrete ceiling. However, caution is needed to ensure indoor exposure do not pose radiation hazards and that the recommended safety limit of 7.3% per Sv cancer risk factor is not exceeded.

These findings are higher than those from indoor effective doses in all the residential houses (1.90 $\times 10^{-3}$ to 3.32 $\times 10^{-3}$) in Nigeria but differs with Mud and burnt mud houses which recorded the highest dose rates, effective doses and lifetime cancer risk than other types of residential houses (Ononugbo et al, 2015).

The findings are further in agreement with the associated cancer risks from low-dose radiation assessed based on the linear no-threshold theory (a 5% excess risk of death from cancer with a 1 Sv (1000 mSv) dose), which holds that excess cancer risks related to low-dose radiation are directly proportional to the dose (ICRP, 2007).

5.8 Indoor Air quality

Appendix VI summaries the findings of Air Change per Hour (ACH) and ventilation rate in residential houses in this study.

5.8.1 Ventilation Opening Area

The window opening area, with an opening angle of 30º to 60º was observed for most sampled houses except in Mathare North cluster which had an opening angle less than 30. Overall, these affects ventilation rates in most houses.

In high-income residential houses, the living room had ventilation openings, with an area greater than 5% of the floor area except for Garden Thome cluster where some houses do not meet the 5% criterion of the floor area.

For middle income houses; Nairobi South (Akiba and Balozi), Ruaraka, Kasarani (Sunton and Clayworks) openable area is greater than 5% of the floor area except for Roasters cluster.

For low income houses, only Salka cluster meets the 5% criteria, but Pipeline in Imara Diama Cluster, Kayole, Githurai 45 and Mathare North have openable area less than 5% of the floor area.

These results indicate noncompliance of the Kenya building code regulations (KNP&BA, 2009).

5.8.2 Air Changes per Hour

The residential houses in Nairobi city air change rate per hour ranges between 0.48 to 0.61 h^{-1}. In high-income residential houses, it ranged from 0.50 – 0.51 h^{-1} with a mean of 0.51 h^{-1}. For middle income houses; it ranges from 0.48 to 0.53 h^{-1}. For the low income residential houses air change rate ranged from 0.45 to 0.61 h^{-1}. Therefore, these findings indicate a mean Air Changes per Hour of 0.51 h^{-1} for most residential houses in Nairobi, which imply that most residential houses do not comply the minimal requirement of Air Changes per Hour within the Kenyan building code standard, that ranges between 0.5 to 1 h^{-1} (KNP&BA, 2009). Evidence exists to the effect that ACH of 0.5 reduces the frequency of respiratory symptoms (Bornehag et al., 2005; Engvall, et al., 2005).

Therefore, increase of ventilation openable areas are recommended for preventative indoor exposures related diseases.

5.8.3 Ventilation Flow Rate

The majority of the high income residential houses have ventilation flow rate ranging between 2.9 *l*/s to 8.3 *l*/s with a mean of 4.6 *l*/s. For middle income residential houses, the ventilation rate range between 2.31*l*/s to 7.5 *l*/s with a mean of 3.98 *l*/s and lower income residential houses having a mean ventilation rate of 3.39 l/s and range between 2.09 - 4.27 *l*/s. The results indicate poor residential ventilation flow rate for most residential classes, below the recommended ventilation rate of 7.5 *l*/s - 8 *l*/s per person for Kenya, Europe and USA (KNP&BA, 2009;CEN 15251, 2007; ASHRAE 62.1, 2004) respectively. Only a few residential houses in Ndome, Roasters and Komarock comply with the 8 litres/sec per person ventilation flow rate.

Low ventilation rates is a possibility of indoor radon accumulation. Other studies Suggests the possibility of a direct relationship between ventilation rate and incidences of respiratory health effects (Bornehag et al., 2005; Carrer, et al., 2015; Engvall et al, 2005; Seppänen et al., 1999; Sundell, et al., 2011 ; Sundell, J., 1994; Wargocki, et al., 2002). The study recommends regulatory controls for building materials in the construction and building industry and for the design of residential houses that compliant to air quality regulations.

CHAPTER 6:

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Building materials are a major part of indoor exposure. This study indicated a significance correlation between the type of building material and indoor dose rate of 26%, and potential radiation exposure from the walls, the ceilings and the floor. Stone walls, tiled floor and concrete ceiling are the dominant source of indoor exposure. The gamma dose rate variation with geometrical dimensions and type of building materials was also and is similar to (UNSCEAR, 2000; Markkaneen, 1995; UNSCEAR, 2012; IAEA, 2014; Koblinger,1978; Stranden 1979).

The indoor absorbed dose ranged from 60.34 - 272.73 nGy/h with a mean value of 113 nGy/h, that is within the world absorbed dose rate estimations of 24 - 160nGy/h indoors (UNSCEAR, 2000, 2008) .The highest effective dose was observed from tiled floor, stone walled and concrete roofed residential houses. The annual effective exposure rate for adults, children and infants' residence in Nairobi as 0.66 mSv, 0.73±0.21 mSv and 0.81±0.24 mSv respectively. From the study, the building materials of radiological significance are concrete ceiling, tiled floor and stoned walls.

Furthermore, the results indicate poor residential ventilation flow rate across all residential classes, and is below the recommended ventilation rate of 7.5 *l*/s - 8 *l*/s. In practice, residential ventilation remains a significant problem worldwide and continues to receive the attention by relevant regulatory authorities.

6.2 Recommendations

i. Radiation Protection Regulatory Authority to spearhead the regulation of NORMs in different types of building materials used in the building industry of residential houses.
ii. Public awareness compaigns about NORM indoor exposure and associated radiological hazards, exposure pathways and indoor air quality.
iii. Compliance with building regulations and codes for indoor air quality at the level of professionals (builders, architects, radiation protection professionals, engineers, land owners, health, real estate etc.).
iv. The study recommends further research on assessment of indoor radon exposure given the relatively poor ventilation rate, minimal ACH and living space of Nairobi residences.

v. Further investigations of the associations between indoor air quality and respiratory diseases and the air change rate in homes could be considered, since previous studies show that higher ventilation rates reduces indoor health effects (Bornehag et al., 2005; Carrer, et al., 2015; Engvall et al., 2005; Seppänen et al., 1999; Sundell, et al., 2011; Sundell, J 1994; Wargocki, et al., 2002).

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APPENDICES

Appendix I: Residential House Dose Rate Measuements Surveys: Participation Consent Form

Introduction

This survey is being undertaken in fulfillment of The Master's Degree Research requirement in Nuclear Science at the University of Nairobi. The research study seeks to assess radiological hazards associated with indoor NORM dose exposure in selected residential houses in Nairobi city. The information you provide will be treated with utmost confidentiality and only for the purpose of this study.

About the Survey

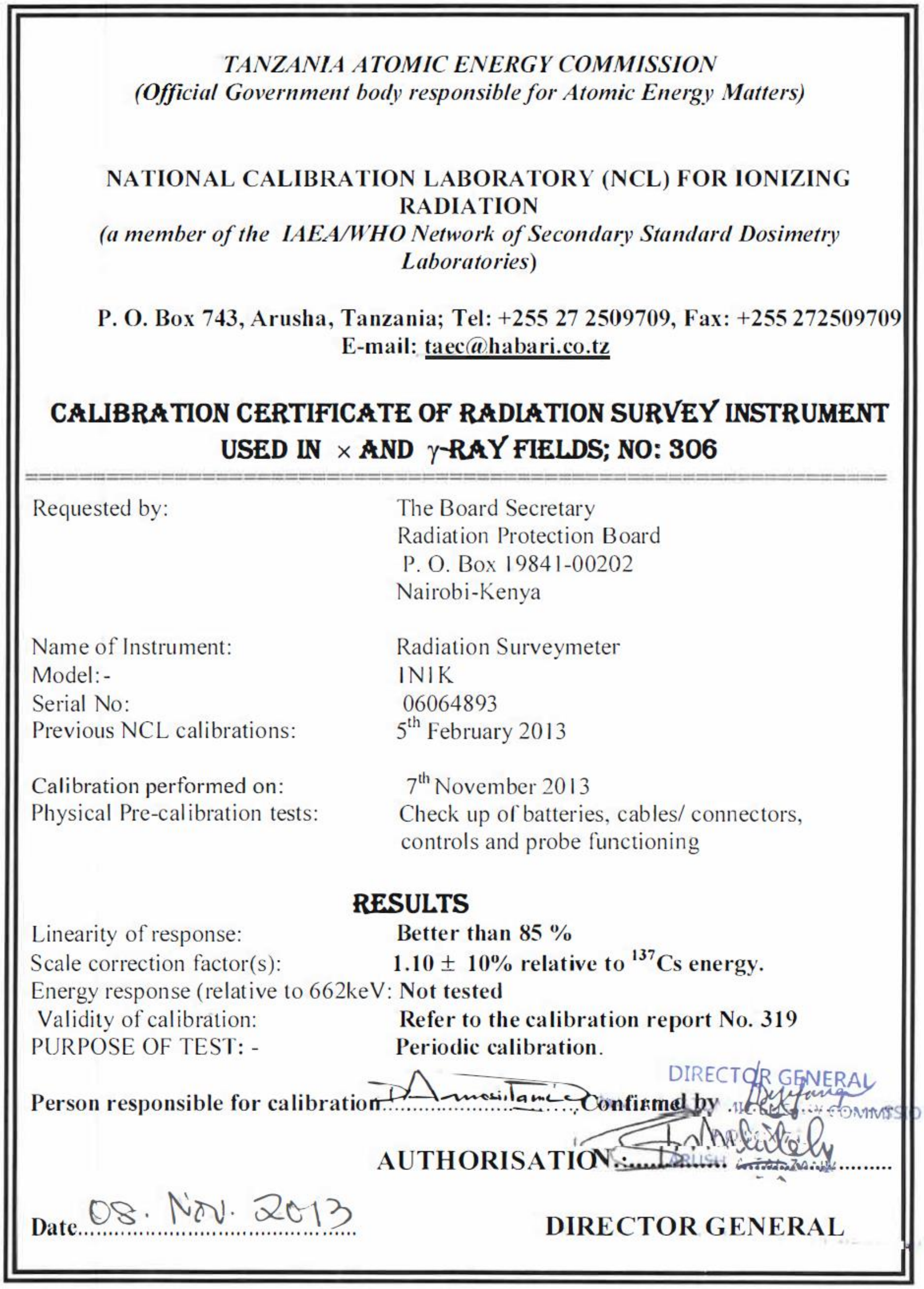
The nature of my research is to carry out indoor measurement of background gamma radiation within Nairobi County households. The reference literature indicates that levels levels vary depending on the type of material used in building the house, the type of floor material and the floor number. Radiation has biological effects on human tissues and cells e.g DNA and is the second leading cause of lung cancer after tobacco smoking worldwide according to World Health Organization. The results obtained from this study will provide baseline information to formulation of radiation protection and safety standards in the building and construction industry. Approximately 5-10 houses per Estate will be sampled for a duration of between half an hours to 1 hour. This sampling exercise is scheduled for the period between 1st March, 2014 to 30th April, 2014.

Role of Participants

The exercise is equipment centred which only samples the air within the house and the **sampling area** is restricted to the **main living room.** Attached is the registration form for consent of participation and the **deadline** for participate in the survey is **17th February 2014**.

REGISTRATION FORM NAME OF ESTATE-------------------------- Sub Location Name---------------						
	Participant Name	Physical Location e.g flat name, street, Hse No etc	Sampling period (March –April 2014) Indicate the date of your choice	Day e.g Tuesday ,Monday	Time e.g Between 10am-11am:	Contacts (Phone/ Email)

Appendix II : Inspection 1000 Survey Meter Calibration Certificate



TANZANIA ATOMIC ENERGY COMMISSION
(Official Government body responsible for Atomic Energy Matters)

NATIONAL CALIBRATION LABORATORY (NCL) FOR IONIZING RADIATION
(a member of the IAEA/WHO Network of Secondary Standard Dosimetry Laboratories)

P. O. Box 743, Arusha, Tanzania; Tel: +255 27 2509709, Fax: +255 272509709
E-mail: taec@habari.co.tz

CALIBRATION CERTIFICATE OF RADIATION SURVEY INSTRUMENT USED IN × AND γ-RAY FIELDS; NO: 306

Requested by: The Board Secretary
Radiation Protection Board
P. O. Box 19841-00202
Nairobi-Kenya

Name of Instrument: Radiation Surveymeter
Model:- INIK
Serial No: 06064893
Previous NCL calibrations: 5th February 2013

Calibration performed on: 7th November 2013
Physical Pre-calibration tests: Check up of batteries, cables/ connectors, controls and probe functioning

RESULTS

Linearity of response: **Better than 85 %**
Scale correction factor(s): **1.10 ± 10% relative to ^{137}Cs energy.**
Energy response (relative to 662keV: **Not tested**
Validity of calibration: **Refer to the calibration report No. 319**
PURPOSE OF TEST: - **Periodic calibration.**

Person responsible for calibration.............................**Confirmed by** ....

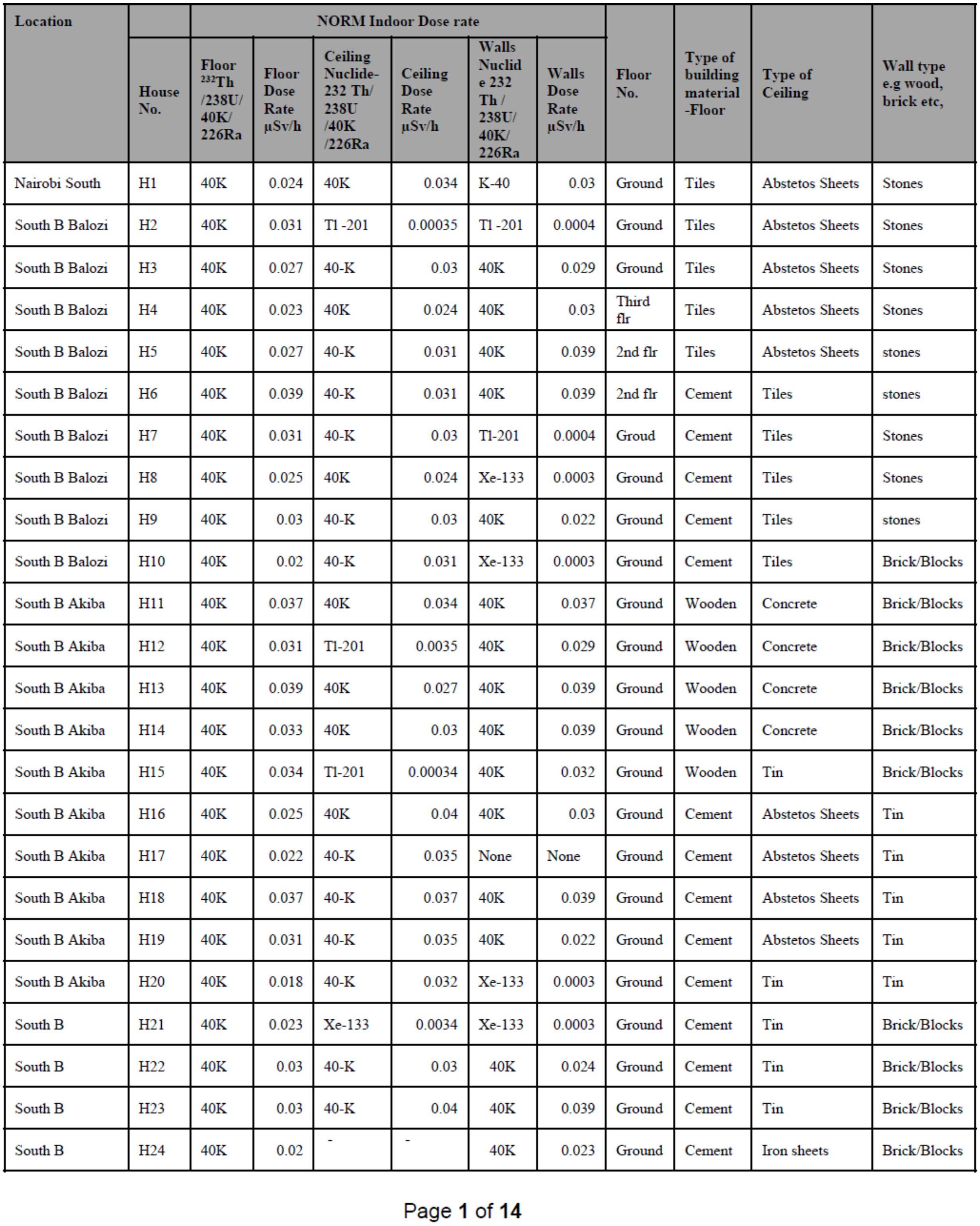
DIRECTOR GENERAL

AUTHORISATION:.......................................

Date. 08. Nov. 2013 ....

DIRECTOR GENERAL

Appendix III : Distribution of Indoor NORM dose rate in Nairobi Residentail Houses



Location		NORM Indoor Dose rate									
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h	Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
Nairobi South	H1	40K	0.024	40K	0.034	K-40	0.03	Ground	Tiles	Abstetos Sheets	Stones
South B Balozi	H2	40K	0.031	Tl -201	0.00035	Tl -201	0.0004	Ground	Tiles	Abstetos Sheets	Stones
South B Balozi	H3	40K	0.027	40-K	0.03	40K	0.029	Ground	Tiles	Abstetos Sheets	Stones
South B Balozi	H4	40K	0.023	40K	0.024	40K	0.03	Third flr	Tiles	Abstetos Sheets	Stones
South B Balozi	H5	40K	0.027	40-K	0.031	40K	0.039	2nd flr	Tiles	Abstetos Sheets	stones
South B Balozi	H6	40K	0.039	40-K	0.031	40K	0.039	2nd flr	Cement	Tiles	stones
South B Balozi	H7	40K	0.031	40-K	0.03	Tl-201	0.0004	Groud	Cement	Tiles	Stones
South B Balozi	H8	40K	0.025	40K	0.024	Xe-133	0.0003	Ground	Cement	Tiles	Stones
South B Balozi	H9	40K	0.03	40-K	0.03	40K	0.022	Ground	Cement	Tiles	stones
South B Balozi	H10	40K	0.02	40-K	0.031	Xe-133	0.0003	Ground	Cement	Tiles	Brick/Blocks
South B Akiba	H11	40K	0.037	40K	0.034	40K	0.037	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H12	40K	0.031	Tl-201	0.0035	40K	0.029	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H13	40K	0.039	40K	0.027	40K	0.039	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H14	40K	0.033	40K	0.03	40K	0.039	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H15	40K	0.034	Tl-201	0.00034	40K	0.032	Ground	Wooden	Tin	Brick/Blocks
South B Akiba	H16	40K	0.025	40K	0.04	40K	0.03	Ground	Cement	Abstetos Sheets	Tin
South B Akiba	H17	40K	0.022	40-K	0.035	None	None	Ground	Cement	Abstetos Sheets	Tin
South B Akiba	H18	40K	0.037	40-K	0.037	40K	0.039	Ground	Cement	Abstetos Sheets	Tin
South B Akiba	H19	40K	0.031	40-K	0.035	40K	0.022	Ground	Cement	Abstetos Sheets	Tin
South B Akiba	H20	40K	0.018	40-K	0.032	Xe-133	0.0003	Ground	Cement	Tin	Tin
South B	H21	40K	0.023	Xe-133	0.0034	Xe-133	0.0003	Ground	Cement	Tin	Brick/Blocks
South B	H22	40K	0.03	40-K	0.03	40K	0.024	Ground	Cement	Tin	Brick/Blocks
South B	H23	40K	0.03	40-K	0.04	40K	0.039	Ground	Cement	Tin	Brick/Blocks
South B	H24	40K	0.02	-	-	40K	0.023	Ground	Cement	Iron sheets	Brick/Blocks

Page **1** of **14**

Location		NORM Indoor Dose rate									
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h	Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
South B	H25	40K	0.02	-	-	40K	0.024	Ground	Cement	Iron sheets	Brick/Blocks
South B	H26	40K	0.027	-	-	40K	0.039	Ground	Cement	Iron sheets	Brick/Blocks
South B	H27	40K	0.02	-	-	40K	0.033	Ground	Earth	Iron sheets	Brick/Blocks
South B	H28	40K	0.025	-	-	40K	0.034	Ground	Earth	Iron sheets	Brick/Blocks
South B	H29	40K	0.03	-	-	40K	0.039	Ground	Earth	Iron sheets	Brick/Blocks
South B	H30	40K	0.03	-	-	40K	0.023	Ground	Earth	Iron sheets	Brick/Blocks
South B	H31	4K	0.021	-	-	40K	0.024	Ground	Earth	Iron sheets	Brick/Blocks
South B	H32	40K	0.02	-	-	40K	0.035	Ground	Cement	Iron sheets	Brick/Blocks
South B	H33	40k	0.02	-	-	40K	0.023	Ground	Cement	Iron sheets	Brick/Blocks
South B Akiba	H34	4K	0.027	40-K	0.039			Ground	Cement	Abstetos Sheets	Brick/Blocks
South B Akiba	H35	40K	0.025	40K	0.024	Xe-133	0.0005	Ground	Cement	Abstetos Sheets	Brick/Blocks
Imara Diama	H36	40k	0.025	40-K	0.039			Groud	Cement	Tiles	Stones
Imara Diama	H37	40K	0.03	40-K	0.023	Xe-133	0.0003	Ground	Cement	Tiles	Stones
Imara Diama	H38	40K	0.029	40-K	0.023	Xe-133	0.0004	Ground	Cement	Tiles	Stones
Imara Diama	H39	40K	0.037	40K	0.034	40K	0.037	Ground	Wooden	Tiles	Stones
Imara Diama	H40	40K	0.031	Tl-201	0.0035	40K	0.029	Ground	Wooden	Tiles	Stones
Imara Diama	H41	40K	0.039	40K	0.027	40K	0.039	Ground	Wooden	Concrete	Stones
Imara Diama	H42	40K	0.033	40K	0.03	40K	0.039	Ground	Wooden	Concrete	Stones
Imara Diama	H43	40K	0.034	Tl-201	0.00034	40K	0.032	Ground	Wooden	Concrete	Stones
Pipeline	H44	40K	0.017	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H45	40K	0.022	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H46	40K	0.02	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H47	40K	0.019	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H48	40K	0.021	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H49	40K	0.027	40K	0.03	40K	0.033	2nd flr	Cement	Concrete	stones
Pipeline	H50	40K	0.027	40K	0.037	40K	0.03 3	2nd flr	Cement	Concrete	stones

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Pipeline	H51	40K	0.039	40K	0.027	40K	0.031	2nd flr	Cement	Concrete	stones
Pipeline	H52	40K	0.027	40K	0.032	40K	0.033	Ground	Cement	Concrete	stones
Pipeline	H53	40K	0.031	40K	0.033	40K	0.034	Ground	Cement	Concrete	stones
Imara Diama	H54	40K	0.027	40K	0.039	40K	0.027	2nd flr	Cement	Tiles	stones
Imara Diama	H55	40K	0.039	40K	0.031	40K	0.027	3rd	Tiles	Tiles	stones
Imara Diama	H56	40K	0.037	40K	0.029	TI-201	0.0005	3rd	Tiles	Tiles	Stones
Imara Diama	H57	40K	0.037	40K	0.029	40K	0.031	2nd	Tiles	Tin	Stones
Imara Diama	H58	40k	0.03	40k	0.031	40K	0.034	Ground	Tiles	Tin	Stones
Imara Diama	H59	40K	0.039	40K	0.031	40K	0.027	3rd	Tiles	Tin	stones
Imara Diama	H60	40K	0.027	40K	0.023	40K	0.031	Ground	Cement	Tiles	Stones
Imara Diama	H61	40K	0.038	40K	0.021	40K	0.0271	Ground	Cement	Tiles	Wood Only
Imara Diama	H62	40K	0.027	40K	0.029	40K	0.039	Ground	Cement	Tin	Wood Only
Imara Diama	H63	40K	0.031	40K	0.031	40K	0.036	Ground	Cement	Tin	Wood Only
Imara Diama	H64	40K	0.037	40K	0.02	40K	0.034	Ground	Cement	Tiles	Wood Only
Imara Diama	H65	40K	0.039	40K	0.03	40K	0.017	Ground	Cement	Tiles	Wood Only
Pipeline	H66	40K	0.037	-	-	40K	0.022	Ground	Earth	Iron sheets	Mud/Wood
Pipeline	H67	40K	0.036	-	-	40K	0.02	Ground	Earth	Iron sheets	Mud/Wood
Pipeline	H68	40k	0.03	-	-	40K	0.025	Ground	Earth	Iron sheets	Mud/Wood
Pipeline	H69	40K	0.048	-	-	40K	0.018	Ground	Earth	Iron sheets	Mud/Wood
Pipeline	H70	40K	0.041	-	-	40K	0.019	Ground	Earth	Iron sheets	Mud/Wood
Kayole	H71	40k	0.025	40k	0.037	40K	0.027	Ground	Cement	Concrete	Stones
Kayole	H72	40K	0.024	40K	0.025	TI-201	0.313	2nd	Cement	Concrete	Stones
Kayole	H73	40K	0.037	40K	0.03	TI-201	0.348	Ground	Cement	Concrete	Stones
Kayole	H74	40K	0.023	40K	0.027	TI-201	0.249	Ground	Cement	Concrete	Stones
Kayole	H75	40K	0.022	40K	0.039	40K	0.027	2nd	Cement	Iron sheets	Stones
Kayole	H76	40k	0.02	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Kayole	H77	40K	0.025	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets

Location		NORM Indoor Dose rate									
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h	Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
Kayole	H78	40K	0.02	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Kayole	H79	40K	0.023	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Kayole	H80	40K	0.022	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Kayole	H81	40k	0.025	40k	0.031	40K	0.027	Ground	Tiles	Concrete	Stones
Kayole	H82	40K	0.039	40K	0.025	TI-201	0.313	2nd	Tiles	Concrete	Stones
Kayole	H83	40K	0.036	40K	0.03	TI-201	0.348	1st	Tiles	Concrete	Stones
Kayole	H84	40K	0.027	40K	0.027	TI-201	0.249	1st	Tiles	Concrete	Stones
Kayole	H85	40K	0.032	40K	0.038	40K	0.027	2nd	Tiles	Concrete	Stones
Kayole	H86	40K	0.027	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Kayole	H87	40K	0.039	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Kayole	H88	40K	0.027	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Kayole	H89	40K	0.031	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Kayole	H90	40K	0.022	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Kayole	H91	40K	0.02	-	-	-	-	Groud	Cement	Iron sheets	Mud/Cement
Kayole	H92	40K	0.019	-	-	-	-	Groud	Cement	Iron sheets	Mud/Cement
Kayole	H93	40K	0.021	-	-	-	-	Groud	Cement	Iron sheets	Mud/Cement
Kayole	H94	40K	0.027	-	-	-	-	Groud	Cement	Iron sheets	Mud/Cement
Kayole	H95	40K	0.027	-	-	-	-	Groud	Cement	Iron sheets	Mud/Cement
Kayole	H96	40K	0.025	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Kayole	H97	40K	0.018	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Kayole	H98	40K	0.019	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Kayole	H99	40K	0.017	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Kayole	H100	40K	0.02	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Kayole	H101	40K	0.06	-	-	-	-	Groud	Earth	Iron sheets	Mud/Wood
Kayole	H102	40K	0.05	-	-	-	-	Groud	Earth	Iron sheets	Mud/Wood
Kayole	H103	40K	0.034	-	-	-	-	Groud	Earth	Iron sheets	Mud/Wood

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Kayole	H104	40K	0.04	-	-	-	-	Groud	Earth	Iron sheets	Mud/Wood
Kayole	H105	40K	0.031	-	-	-	-	Groud	Earth	Iron sheets	Mud/Wood
Komarock	H106	40K	0.037	40k	0.037	40K	0.027	2nd flr	Tiles	Concrete	Stones
Komarock	H107	40K	0.031	40K	0.029	40K	0.039	Ground	Tiles	Concrete	Stones
Komarock	H108	40K	0.033	40K	0.037	40K	0.027	Ground	Tiles	Concrete	Stones
Komarock	H109	40K	0.027	40K	0.03	40K	0.03	Ground	Tiles	Concrete	Stones
Komarock	H110	40K	0.03	40K	0.027	40K	0.029	Ground	Tiles	Concrete	Stones
Komarock	H111	40K	0.025	40k	0.037	40K	0.027	Ground	Cement	Tiles	Stones
Komarock	H112	40K	0.024	40K	0.025	TI-201	0.313	2nd	Cement	Tiles	Stones
Komarock	H113	40K	0.037	40K	0.03	TI-201	0.348	Ground	Cement	Tiles	Stones
Komarock	H114	40K	0.023	40K	0.027	TI-201	0.249	Ground	Cement	Tiles	Stones
Komarock	H115	40K	0.022	40K	0.039	40K	0.027	2nd	Cement	Tiles	Stones
Komarock	H116	40K	0.03	40K	0.039	40K	0.037	1st Floor	Tiles	Abstetos Sheets	Stones
Komarock	H117	40K	0.029	40K	0.031	40K	0.025	2nd flr	Tiles	Abstetos Sheets	Stones
Komarock	H118	40K	0.039	40K	0.037	40K	0.027	Ground	Tiles	Abstetos Sheets	Stones
Komarock	H119	40K	0.027	40K	0.039	40K	0.039	Ground	Tiles	Abstetos Sheets	Stones
Komarock	H120	TI-201	0.024	40K	0.039	40K	0.024	Ground	Tiles	Abstetos Sheets	Stones
Komarock	H121	TI-201	0.037	40K	0.039	40K	0.037	2nd	Cement	Abstetos Sheets	Brick/Blocks
Komarock	H122	40K	0.023	40K	0.031	TI-201	0.023	Ground	Cement	Abstetos Sheets	Brick/Blocks
Komarock	H123	40K	0.022	40K	0.037	TI-201	0.022	Ground	Cement	Abstetos Sheets	Brick/Blocks
Komarock	H124	40K	0.02	40K	0.03	40K	0.02	2nd	Cement	Abstetos Sheets	Brick/Blocks
Komarock	H125	40K	0.024	40K	0.037	40K	0.024	Ground	Cement	Abstetos Sheets	Brick/Blocks
Komarock	H126	40K	0.037	40K	0.025	40K	0.037	Ground	Cement	Concrete	Tin
Komarock	H127	40K	0.023	TI-201	0.027	40K	0.023	Ground	Cement	Concrete	Tin
Komarock	H128	40K	0.022	TI-201	0.039	40K	0.022	1st Floor	Cement	Concrete	Tin

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Komarock	H129	40K	0.02	40K	0.03	40K	0.02	Ground	Cement	Concrete	Tin
Komarock	H130	40K	0.024	40K	0.025	40K	0.024	Ground	Cement	Tin	Tin
Komarock	H131	40K	0.037	40K	0.027	40K	0.037	Ground	Cement	Tiles	Stones
Komarock	H132	40K	0.023	40K	0.039	40K	0.023	Ground	Cement	Tiles	Stones
Komarock	H133	40K	0.022	40K	0.025	40K	0.022	Ground	Cement	Tiles	Stones
Komarock	H134	40K	0.02	40K	0.027	40K	0.02	Ground	Cement	Tiles	Stones
Komarock	H135	40K	0.016	40K	0.039	40K	-	Ground	Cement	Tiles	Stones
Komarock	H136	40K	0.017	40K	-	40K	-	Ground	Earth	Iron sheets	Iron sheets
Komarock	H137	40K	0.02	40K	-	40K	-	Ground	Earth	Iron sheets	Iron sheets
Komarock	H138	40K	0.06	40K	-	40K	-	Ground	Earth	Iron sheets	Iron sheets
Komarock	H139	40K	0.05	40K	-	40K	-	Ground	Earth	Iron sheets	Iron sheets
Komarock	H140	40K	0.1	40K	-	40K	-	Ground	Earth	Iron sheets	Iron sheets
Salka	H141	40K	0.027	40K	0.037	TI-201	0.0003	Ground	Tiles	Concrete	Stones
Salka	H142	40K	0.03	40K	0.039	40K	0.037	Ground	Tilles	Concrete	Stones
Salka	H143	40K	0.029	40K	0.031	40K	0.025	Ground	Tiles	Concrete	Stones
Salka	H144	40K	0.039	40K	0.037	40K	0.027	Ground	Tiles	Concrete	Stones
Salka	H145	40K	0.027	40K	0.039	40K	0.039	Ground	Tiles	Concrete	Stones
Salka	H146	40K	0.027	40K	0.037	TI-201	0.0003	Ground	Cement	Concrete	Stones
Salka	H147	40K	0.03	40K	0.039	40K	0.037	Ground	Cement	Concrete	Stones
Salka	H148	40K	0.029	40K	0.031	40K	0.025	Ground	Cement	Concrete	Stones
Salka	H149	40K	0.039	40K	0.037	40K	0.027	Ground	Cement	Concrete	Stones
Salka	H150	40K	0.029	40K	0.031	40K	0.025	Ground	Cement	Concrete	Stones
Salka	H151	40K	0.039	40K	0.037	40K	0.027	Ground	Cement	Tiles	Stones
Salka	H152	40K	0.03	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H153	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H154	40K	0.039	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H155	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H156	40K	0.03	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Salka	H157	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H158	40K	0.039	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H159	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H160	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H161	40K	0.039	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H162	40K	0.03	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H163	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H164	40K	0.039	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H165	40K	0.029	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Salka	H166	40K	0.03	40K	0.03	40K	0.039	Ground	Earth	Tiles	Mud/Cement
Salka	H167	40K	0.029	40K	0.029	40K	0.025	Ground	Earth	Tiles	Mud/Cement
Salka	H168	40K	0.039	40K	0.039	40K	0.022	Ground	Earth	Tiles	Mud/Cement
Salka	H169	40K	0.03	40K	0.039	40K	0.022	Ground	Earth	Tiles	Mud/Cement
Salka	H170	40K	0.029	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Cement
Salka	H171	40K	0.039	-	-	40K	0.039	Ground	Earth	Iron sheets	Wood Only
Salka	H172	40K	0.029	-	-	40K	0.025	Ground	Earth	Iron sheets	Wood Only
Salka	H173	40K	0.03	-	-	40K	0.022	Ground	Earth	Iron sheets	Wood Only
Salka	H174	40K	0.03	-	-	40K	0.039	Ground	Earth	Iron sheets	Wood Only
Salka	H175	40K	0.029	-	-	40K	0.025	Ground	Earth	Iron sheets	Wood Only
Githurai 45	H176	40K	0.025	-	-	Tl-201	0.0004	Groud	Cement	Iron sheets	Mud/Cement
Githurai	H177	40K	0.022	-	-	Xe-133	0.0003	Ground	Cement	Iron sheets	Mud/Cement
Githurai 145	H178	40K	0.037	-	-	40K	0.022	Ground	Cement	Iron sheets	Mud/Cement
Githurai 45	H179	40K	0.031	-	-	Xe-133	0.0003	Ground	Cement	Iron sheets	Mud/Cement
Githurai 45	H180	4K	0.018	-	-	-	-	Ground	Cement	Iron sheets	Mud/Cement
Githurai 45	H181	40K	0.023	-	-	Xe-133	0.0005	Ground	Cement	Iron sheets	Mud/Cement

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Githurai 45	H182	40k	0.025	-	-	None	-	-	Cement	Iron sheets	Mud/Cement
Githurai 45	H183	40K	0.03	-	-	Xe-133	0.0003	Ground	Cement	Iron sheets	Mud/Cement
Githurai 45	H184	40K	0.039	-	-	Xe-133	0.0004	Ground	Cement	Iron sheets	Mud/Cement
Githuai 45	H185	40K	0.031	-	-	40K	0.03	Ground	Cement	Iron sheets	Iron sheets
Githurai 45	H186	40K	0.025	-	-			Ground	Cement	Concrete	Stones
Githurai 45	H187	40K	0.03	-	-	40K	0.039	Ground	Cement	Concrete	Stones
Githurai	H188	40K	0.02	-	-	40K	0.022	Ground	Cement	Concrete	Stones
Githurai 45	H189	40K	0.027	-	-	Xe-133	0.0003	Ground	Cement	Concrete	Stones
Githurai 45	H190	40K	0.025	Xe-133	0.00037	Xe-133	0.0003	Ground	Cement	Concrete	Stones
Githurai 45	H191	40K	0.027	40K	0.037	Xe-133	0.0002	Ground	Cement	Concrete	Stones
Githurai 45	H192	40K	0.029	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Githurai 45	H193	40K	0.039	-	-	-	-	Groud	Cement	Iron sheets	Iron sheets
Githurai 45	H194	40K	0.027	40K	0.031	40K	0.031	1st Floor	Tiles	Concrete	Stones
Githurai 45	H195	40K	0.037	40K	0.025	40K	0.025	1st Floor	Tiles	Concrete	Stones
Githurai 45	H196	40K	0.025	40K	0.03	40K	0.03	Groud	Tiles	Concrete	Stones
Githurai 45	H197	40K	0.024	40K	0.02	40K	0.02	Groud	Tiles	Concrete	Stones
Githurai 45	H198	40K	0.023	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H199	40K	0.022	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H200	40K	0.021	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H201	40K	0.02	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H202	40K	0.019	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H203	40K	0.018	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H204	40K	0.017	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H205	40K	0.016	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets
Githurai 45	H206	40K	0.015	-	-	-	-	Groud	Earth	Iron sheets	Iron sheets

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Mathare North	H207	40K	0.031	40K	0.033	TI-201	0.0004	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H208	40K	0.033	40K	0.031	40K	0.035	Ground	Cement	Iron sheets	Iron sheets
Mathere North	H209	40K	0.035	40K	0.03	40K	0.035	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H210	40K	0.032	40K	0.034	40K	0.033	Ground	Cement	Iron sheets	Iron sheets
Mathere North	H211	40K	0.037	40K	0.033	40K	0.029	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H212	40K	0.03	40K	0.029	Xe-133	0.039	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H213	40K	0.039	40K	0.043	40K	0.042	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H214	40K	0.04	40K	0.045	40K	0.039	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H215	40K	0.041	40K	0.039	40K	0.035	Ground	Cement	Iron sheets	Iron sheets
Mathare North	H216	40K	0.037	40K	0.041	40K	0.04	Ground	Cement	Iron sheets	Mud/Cement
Mathare North	H217	40K						ground	Cement	Iron sheets	Mud/Cement
Mathare North	H218	40K	0.035	40K	0.043	40K	0.042	2nd flr	Cement	Concrete	Stones
Mathare North	H219	40K	0.032	40K	0.045	40K	0.039	3rd	Cement	Concrete	Stones
Mathare North	H220	40K	0.037	40K	0.039	40K	0.035	5th	Cement	Concrete	Stones
Mathare North	H221	40K	0.03	40K	0.041	40K	0.04	5th	Cement	Concrete	Stones
Mathare North	H222	40K	0.039	40K	0.039	40K	0.035	3rd	Cement	Concrete	Stones
Mathare North	H223	40K	0.04	40K	0.041	40K	0.04	4th flr	Tiles	Concrete	Stones
Mathare North	H224	40K	0.041	40K	0.043	40K	0.042	4th flr	Tiles	Concrete	Stones
Mathare North	H225	40K	0.032	40K	0.045	40K	0.039	4th	Tiles	Concrete	Stones
Mathare North	H226	40K	0.037	40K	0.039	40K	0.035	3rd	Tiles	Concrete	Stones
Mathare North	H227	40K	0.03	40K	0.041	40K	0.04	3rd	Tiles	Concrete	Stones
Mathare North	H228	40K	0.032	-	-	-	-	Ground	Earth	Iron sheets	Iron sheets
Mathare North	H229	40K	0.037	-	-	-	-	Ground	Earth	Iron sheets	Iron sheets
Mathare North	H230	40K	0.03	-	-	-	-	Ground	Earth	Iron sheets	Iron sheets
Mathare North	H231	40K	0.032	-	-	-	-	Ground	Earth	Iron sheets	Iron sheets

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Mathare North	H232	40K	0.037	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Wood
Mathare North	H233	40K	0.03	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Wood
Mathare North	H234	40K	0.032	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Wood
Mathare North	H235	40K	0.037	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Wood
Mathare North	H236	40K	0.03	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Wood
Mathare North	H237	40K	0.035	-	-	40K	0.039	Ground	Earth	Iron sheets	Mud/Wood
Thome Estate	H238	40K	0.024	40k	0.024	40k	0.029	Ground	Tiles	Concrete	stones
Thome Estate	H239	40k	0.025	TI-201	0.0004	40k	0.037	Ground	Tiles	Concrete	Stones
Thome Estate	H240	40K	0.037	40K	0.039	TI-201	0.0209	Ground	Tiles	Concrete	Stones
Thome Estate	H241	40k	0.027	40K	0.033	TI-201	0.411	Ground	Tiles	Concrete	Stones
Thome Estate	H242	40K	0.037	40k	0.024	40K	0.019	Ground	Tiles	Concrete	stones
Thome Estate	H243	40k	0.029	40k	0.024	40K	0.024	Ground	Tiles	Abstetos Sheets	stones
Thome Estate	H244	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Tiles	Abstetos Sheets	stones
Thome Estate	H245	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Tiles	Abstetos Sheets	stones
Thome Estate	H246	TI-201	0.411	40K	0.033	40k	0.027	Ground	Tiles	Abstetos Sheets	stones
Thome Estate	H247	40K	0.019	40k	0.024	40K	0.037	Ground	Wooden	Abstetos Sheets	stones
Thome Estate	H248	40k	0.024	40k	0.024	40k	0.029	Ground	Wooden	Abstetos Sheets	stones
Thome Estate	H249	TI-201	0.0004	TI-201	0.0004	40k	0.037	Ground	Wooden	Abstetos Sheets	stones
Thome Estate	H250	40K	0.039	40K	0.039	TI-201	0.0209	Ground	Wooden	Abstetos Sheets	stones
Thome Estate	H251	40K	0.033	40K	0.033	TI-201	0.411	Ground	Wooden	Abstetos Sheets	Brick/Blocks
Thome Estate	H252	40k	0.024	40k	0.024	40K	0.019	Ground	Wooden	Abstetos Sheets	Brick/Blocks
Thome Estate	H253	40k	0.029	40k	0.024	40K	0.024	Ground	Wooden	Abstetos Sheets	Brick/Blocks
Thome Estate	H254	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Cement	Abstetos Sheets	Brick/Blocks
Thome Estate	H255	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Cement	Abstetos Sheets	Brick/Blocks
Thome Estate	H256	TI-201	0.411	40K	0.033	40k	0.027	Ground	Cement	Abstetos Sheets	Brick/Blocks

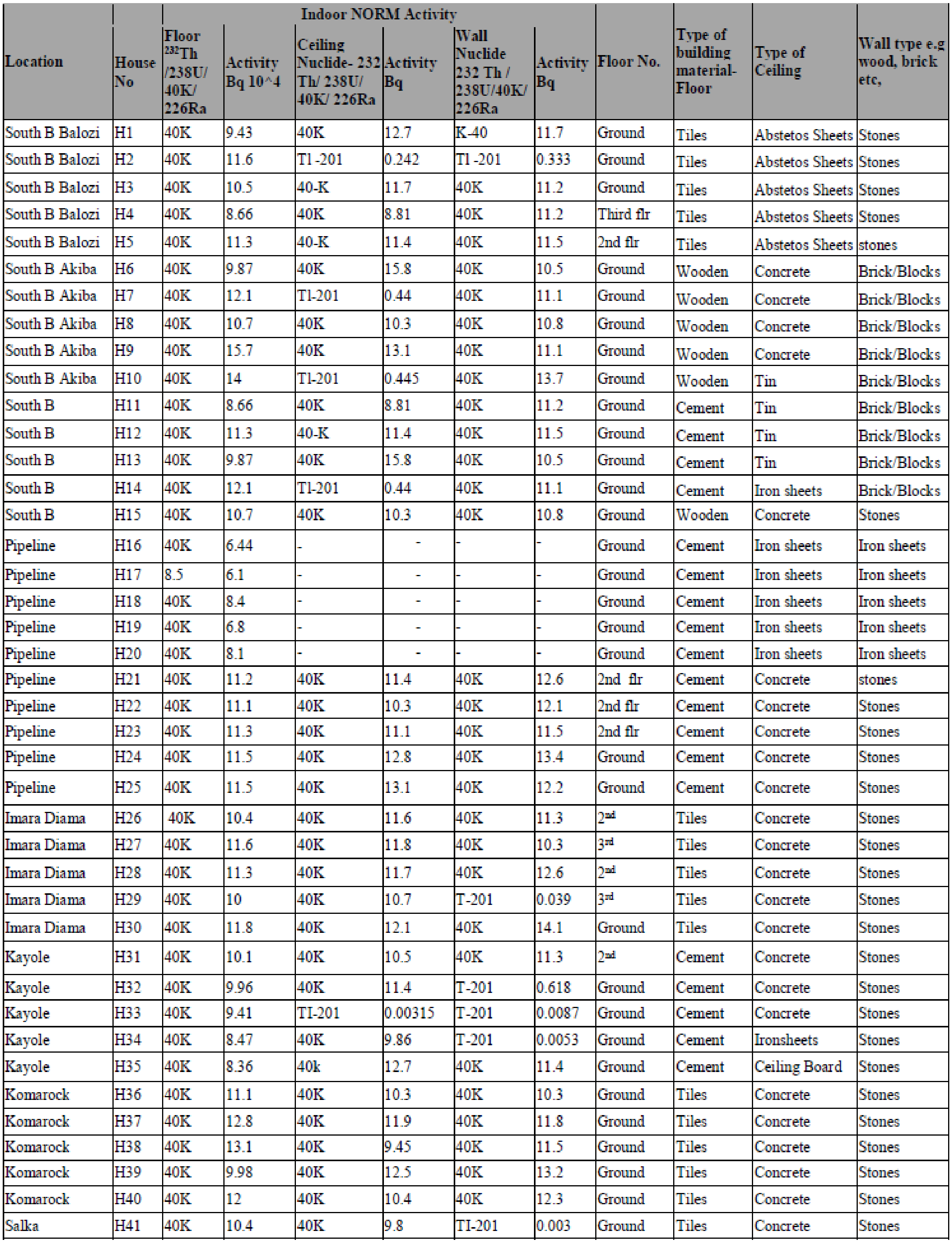
Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Thome Estate	H257	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Abstetos Sheets	Brick/Blocks
Thome Estate	H258	40k	0.029	40k	0.024	40K	0.024	Ground	Cement	Abstetos Sheets	Brick/Blocks
Thome Estate	H259	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Cement	Abstetos Sheets	Brick/Blocks
Thome Estate	H260	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Cement	Abstetos Sheets	Brick/Blocks
Thome Estate	H261	TI-201	0.411	40K	0.033	40k	0.027	Ground	Cement	Tiles	Wood Only
Thome Estate	H262	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Wood Only
Thome Estate	H263	40k	0.029	40k	0.024	40K	0.024	Ground	Cement	Tiles	Wood Only
Thome Estate	H264	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Cement	Tiles	Wood Only
Thome Estate	H265	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Cement	Tiles	Wood Only
Thome Estate	H266	TI-201	0.411	40K	0.033	40k	0.027	Ground	Cement	Tiles	Wood Only
Thome Estate	H267	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Wood Only
Thome Estate	H268	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Wood Only
Roasters	H269	40k	0.024	40K	0.023	40K	0.023	Ground	Tiles	Concrete	Stones
Roasters	H270	40K	0.023	40K	0.023	40K	0.022	3rd	Tiles	Concrete	Stones
Roasters	H271	40k	0.022	40K	0.023	40K	0.023	3rd	Tiles	Concrete	Stones
Roasters	H272	40k	0.021	40K	0.023	40K	0.023	Ground	Tiles	Concrete	Stones
Roasters	H273	40K	0.023	40K	0.02	40K	0.019	Ground	Tiles	Concrete	Stones
Roasters	H274	40k	0.029	40k	0.024	40K	0.024	Ground	Wooden	Concrete	Stones
Roasters	H275	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Wooden	Concrete	Stones
Roasters	H276	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Wooden	Concrete	Stones
Roasters	H277	TI-201	0.411	40K	0.033	40k	0.027	Ground	Wooden	Concrete	Stones
Roasters	H278	40K	0.019	40k	0.024	40K	0.037	Ground	Wooden	Concrete	Stones
Roas1st ters	H279	40K	0.019	40k	0.024	40K	0.037	Ground	Wooden	Concrete	Stones
Rauraka	H280	40k	0.029	40k	0.024	40K	0.024	Ground	Wooden	Concrete	Stones
Rauraka	H281	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Wooden	Concrete	Stones
Rauraka	H282	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Cement	Tiles	Stones
Rauraka	H283	TI-201	0.411	40K	0.033	40k	0.027	Ground	Cement	Tiles	Stones
Rauraka	H284	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Stones

Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Rauraka	H285	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Brick/Blocks
Rauraka	H286	40k	0.029	40k	0.024	40K	0.024	1st flr	Cement	Tiles	Brick/Blocks
Rauraka	H287	40k	0.037	TI-201	0.0004	40k	0.025	1st flr	Cement	Tiles	Brick/Blocks
Rauraka	H288	TI-201	0.0209	40K	0.039	40K	0.037	1st fl	Cement	Tiles	Brick/Blocks
Rauraka	H289	TI-201	0.411	40K	0.033	40k	0.027	Ground	Cement	Tiles	Brick/Blocks
Rauraka	H290	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Mud/Cement
Rauraka	H291	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tiles	Mud/Cement
Rauraka	H292	40k	0.029	40k	0.024	40K	0.024	Ground	Cement	Tiles	Mud/Cement
Rauraka	H293	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Cement	Tiles	Mud/Cement
Rauraka	H294	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Cement	Tiles	Mud/Cement
Rauraka	H295	TI-201	0.411	40K	0.033	40k	0.027	Ground	Cement	Tin	Mud/Cement
Rauraka	H296	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tin	Mud/Cement
Rauraka	H297	40K	0.019	40k	0.024	40K	0.037	Ground	Cement	Tin	Mud/Cement
Rauraka	H298	40k	0.037	TI-201	0.0004	40k	0.025	Ground	Cement	Tin	Mud/Cement
Rauraka	H299	TI-201	0.0209	40K	0.039	40K	0.037	Ground	Cement	Tin	Mud/Cement
Sunton-Kasarani	H300	40K	0.027	40K	0.031	40K	0.033	Ground	Cement	Iron sheets	Stones
Sunton-Kasarani	H301	40K	0.039	None	None	40K	0.031	Ground	Cement	Iron sheets	Stones
Sunton-Kasarani	H302	40K	0.031	None	None	40K	0.033	Ground	Cement	Iron sheets	Stones
Sunton-Kasarani	H303	40K	0.031	None	None	40K	0.034	Ground	Cement	Iron sheets	Stones
Sunton-Kasarani	H304	40K	0.027	None	None	40K	0.027	1st	Cement	Iron sheets	stones
Clayworkasarani	H305	40K	0.029	40K	0.031	40K	0.032	Ground	Tiles	Concrete	stones
Clayworks-Kasarani	H306	40K	0.037	40K	0.029	40k	0.037	1st	Tiles	Concrete	Stones
Clayworks-Kasarani	H307	40K	0.039	40K	0.029	40K	0.031	1st	Tiles	Concrete	Stones
Clayworks-Kasarani	H308	40k	0.03	40k	0.031	40K	0.034	Ground	Tiles	Concrete	Stones

Location		NORM Indoor Dose rate									
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h	Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
Clayworks-Kazarani	H309	40K	0.037	40K	0.031	40K	0.029	1st	Tiles	Concrete	Stones
Clayworks-Kazarani	H310	40K	0.029	40K	0.034	40K	0.029	1st	Tiles	Concrete	Stones
Clayworks-Kazarani	H311	40K	0.037	40K	0.032	40K	0.037	Ground	Tiles	Tiles	Stones
Clayworks-Kazarani	H312	40K	0.039	40K	0.033	40K	0.039	1st Floor	Tiles	Tiles	Stones
Clayworks-Kazarani	H313	40k	0.03	40K	0.039	40k	0.03	2nd flr	Cement	Tiles	Brick/Blocks
Clayworks-Kazarani	H314	40K	0.037	40K	0.039	40K	0.037	2nd flr	Cement	Tiles	Brick/Blocks
Clayworks-Kazarani	H315	40K	0.037	40K	0.029	40k	0.037	2nd flr	Cement	Tiles	Brick/Blocks
Clayworks-Kazarani	H316	40K	0.039	40K	0.029	40K	0.031	Ground	Cement	Iron sheets	Brick/Blocks
Clayworks-Kazarani	H317	40k	0.03	40k	0.031	40K	0.034	Ground	Cement	Iron sheets	Brick/Blocks
Clayworks-Kazarani	H318	40K	0.037	40K	0.031	40K	0.029	Ground	Cement	Iron sheets	Brick/Blocks
Clayworks-Kazarani	H319	40K	0.029	40K	0.034	40K	0.029	Ground	Cement	Iron sheets	Brick/Blocks
Clayworks-Kazarani	H320	40K	0.037	40K	0.032	40K	0.037	Ground	Cement	Iron sheets	Brick/Blocks
Clayworks-Kazarani	H321	40K	0.039	40K	0.033	40K	0.039	Ground	Cement	Iron sheets	Brick/Blocks
Sunton-Kasarani	H322	40K	0.037	40K	0.029	40k	0.037	Ground	Cement	Iron sheets	Brick/Blocks
Sunton-Kasarani	H323	40K	0.039	40K	0.029	40K	0.031	Ground	Cement	Iron sheets	Tin
Sunton-Kasarani	H324	40k	0.03	40k	0.031	40K	0.034	Ground	wooden	Tin	Tin
Sunton-Kasarani	H325	40K	0.037	40K	0.031	40K	0.029	Ground	wooden	Tin	Tin
Sunton-Kasarani	H326	40K	0.029	40K	0.034	40K	0.029	Ground	wooden	Tin	Tin
Sunton-Kasarani	H327	40K	0.037	40K	0.032	40K	0.037	Ground	wooden	Tin	Tin

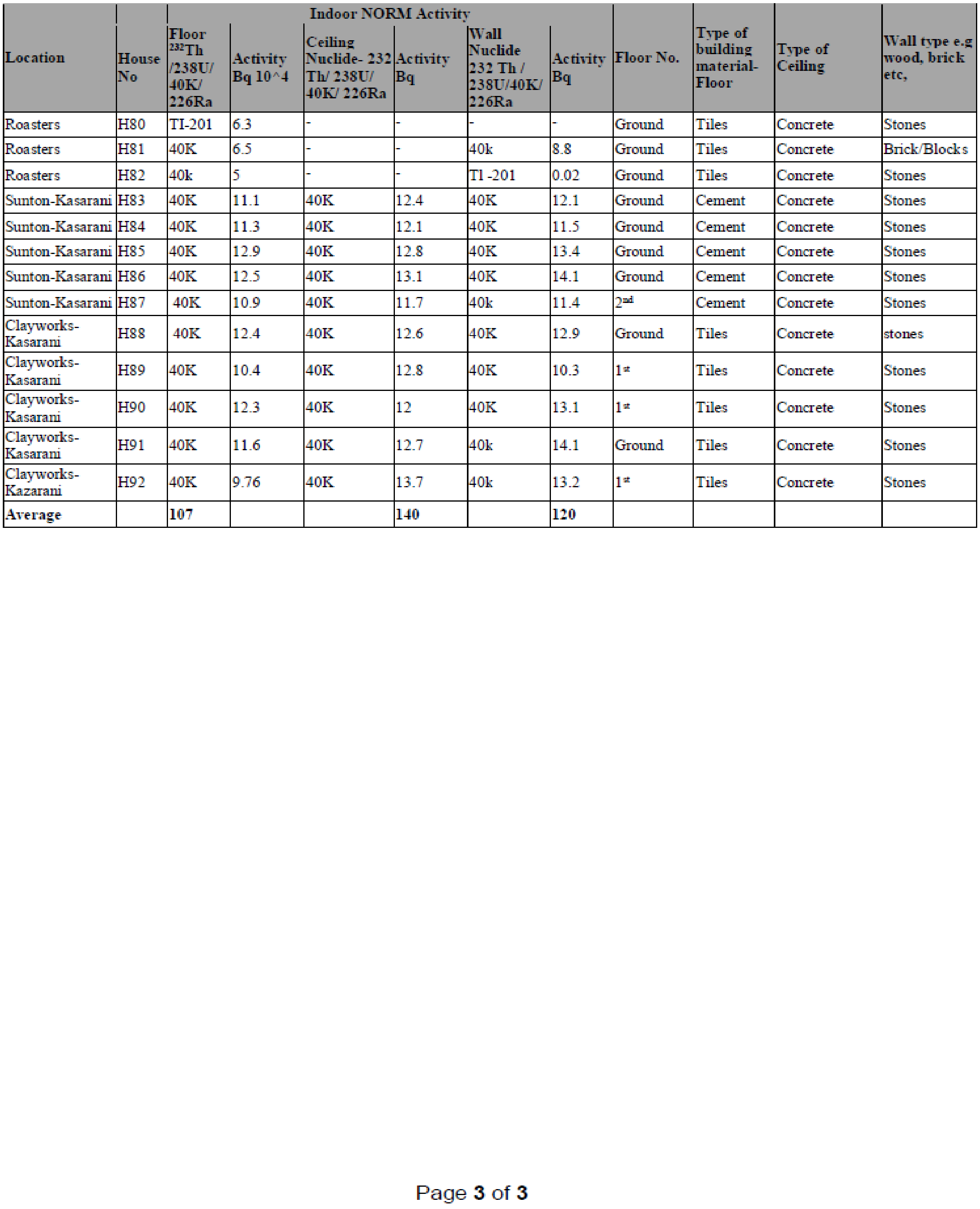
Location		NORM Indoor Dose rate						Floor No.	Type of building material -Floor	Type of Ceiling	Wall type e.g wood, brick etc,
	House No.	Floor ^{232}Th /238U/ 40K/ 226Ra	Floor Dose Rate µSv/h	Ceiling Nuclide-232 Th/ 238U /40K /226Ra	Ceiling Dose Rate µSv/h	Walls Nuclide 232 Th / 238U/ 40K/ 226Ra	Walls Dose Rate µSv/h				
Sunton-Kasarani	H328	40K	0.039	40K	0.033	40K	0.039	Ground	wooden	Tin	Tin
Sunton-Kasarani	H329	40K	0.037	40K	0.032	40K	0.037	Ground	wooden	Iron sheets	Tin
Sunton-Kasarani	H330	40K	0.039	40K	0.033	40K	0.039	Ground	wooden	Iron sheets	Tin
AVERAGE			**0.037**		**0.039**		**0.039**				

Appendix IV : Indoor NORM activity in Nairobi Residential Houses



Location	House No	Indoor NORM Activity						Floor No.	Type of building material-Floor	Type of Ceiling	Wall type e.g wood, brick etc,
		Floor ^{232}Th /238U/ 40K/ 226Ra	Activity Bq 10^4	Ceiling Nuclide- 232 Th/ 238U/ 40K/ 226Ra	Activity Bq	Wall Nuclide 232 Th / 238U/40K/ 226Ra	Activity Bq				
South B Balozi	H1	40K	9.43	40K	12.7	K-40	11.7	Ground	Tiles	Abstetos Sheets	Stones
South B Balozi	H2	40K	11.6	Tl -201	0.242	Tl -201	0.333	Ground	Tiles	Abstetos Sheets	Stones
South B Balozi	H3	40K	10.5	40-K	11.7	40K	11.2	Ground	Tiles	Abstetos Sheets	Stones
South B Balozi	H4	40K	8.66	40K	8.81	40K	11.2	Third flr	Tiles	Abstetos Sheets	Stones
South B Balozi	H5	40K	11.3	40-K	11.4	40K	11.5	2nd flr	Tiles	Abstetos Sheets	stones
South B Akiba	H6	40K	9.87	40K	15.8	40K	10.5	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H7	40K	12.1	Tl-201	0.44	40K	11.1	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H8	40K	10.7	40K	10.3	40K	10.8	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H9	40K	15.7	40K	13.1	40K	11.1	Ground	Wooden	Concrete	Brick/Blocks
South B Akiba	H10	40K	14	Tl-201	0.445	40K	13.7	Ground	Wooden	Tin	Brick/Blocks
South B	H11	40K	8.66	40K	8.81	40K	11.2	Ground	Cement	Tin	Brick/Blocks
South B	H12	40K	11.3	40-K	11.4	40K	11.5	Ground	Cement	Tin	Brick/Blocks
South B	H13	40K	9.87	40K	15.8	40K	10.5	Ground	Cement	Tin	Brick/Blocks
South B	H14	40K	12.1	Tl-201	0.44	40K	11.1	Ground	Cement	Iron sheets	Brick/Blocks
South B	H15	40K	10.7	40K	10.3	40K	10.8	Ground	Wooden	Concrete	Stones
Pipeline	H16	40K	6.44	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H17	8.5	6.1	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H18	40K	8.4	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H19	40K	6.8	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H20	40K	8.1	-	-	-	-	Ground	Cement	Iron sheets	Iron sheets
Pipeline	H21	40K	11.2	40K	11.4	40K	12.6	2nd flr	Cement	Concrete	stones
Pipeline	H22	40K	11.1	40K	10.3	40K	12.1	2nd flr	Cement	Concrete	Stones
Pipeline	H23	40K	11.3	40K	11.1	40K	11.5	2nd flr	Cement	Concrete	Stones
Pipeline	H24	40K	11.5	40K	12.8	40K	13.4	Ground	Cement	Concrete	Stones
Pipeline	H25	40K	11.5	40K	13.1	40K	12.2	Ground	Cement	Concrete	Stones
Imara Diama	H26	40K	10.4	40K	11.6	40K	11.3	2nd	Tiles	Concrete	Stones
Imara Diama	H27	40K	11.6	40K	11.8	40K	10.3	3rd	Tiles	Concrete	Stones
Imara Diama	H28	40K	11.3	40K	11.7	40K	12.6	2nd	Tiles	Concrete	Stones
Imara Diama	H29	40K	10	40K	10.7	T-201	0.039	3rd	Tiles	Concrete	Stones
Imara Diama	H30	40K	11.8	40K	12.1	40K	14.1	Ground	Tiles	Concrete	Stones
Kayole	H31	40K	10.1	40K	10.5	40K	11.3	2nd	Cement	Concrete	Stones
Kayole	H32	40K	9.96	40K	11.4	T-201	0.618	Ground	Cement	Concrete	Stones
Kayole	H33	40K	9.41	TI-201	0.00315	T-201	0.0087	Ground	Cement	Concrete	Stones
Kayole	H34	40K	8.47	40K	9.86	T-201	0.0053	Ground	Cement	Ironsheets	Stones
Kayole	H35	40K	8.36	40k	12.7	40K	11.4	Ground	Cement	Ceiling Board	Stones
Komarock	H36	40K	11.1	40K	10.3	40K	10.3	Ground	Tiles	Concrete	Stones
Komarock	H37	40K	12.8	40K	11.9	40K	11.8	Ground	Tiles	Concrete	Stones
Komarock	H38	40K	13.1	40K	9.45	40K	11.5	Ground	Tiles	Concrete	Stones
Komarock	H39	40K	9.98	40K	12.5	40K	13.2	Ground	Tiles	Concrete	Stones
Komarock	H40	40K	12	40K	10.4	40K	12.3	Ground	Tiles	Concrete	Stones
Salka	H41	40K	10.4	40K	9.8	TI-201	0.003	Ground	Tiles	Concrete	Stones

		Indoor NORM Activity									
Location	House No	Floor ^{232}Th /238U/ 40K/ 226Ra	Activity Bq 10^4	Ceiling Nuclide- 232 Th/ 238U/ 40K/ 226Ra	Activity Bq	Wall Nuclide 232 Th / 238U/40K/ 226Ra	Activity Bq	Floor No.	Type of building material- Floor	Type of Ceiling	Wall type e.g wood, brick etc,
Salka	H42	40K	11.8	40K	11.8	40K	9.98	Ground	Tiles	Concrete	Stones
Salka	H43	40K	12.2	40k	13.1	40K	9.94	Ground	Tiles	Concrete	Stones
Salka	H44	40K	11.6	40K	10.5	40K	10.2	Ground	Tiles	Concrete	Stones
Salka	H45	40K	10.5	40K	11.7	40K	11.3	Ground	Tiles	Concrete	Stones
Githurai 45	H46	40K	9.52	-	-	TI-201	0.298	Groud	Cement	Ironsheets	Stones
Githurai 45	H47	40K	8.47	-	-	Xe-133	3.92	Ground	Cement	Ironsheets	Stones
Githurai 145	H48	40K	9.83	-	-	40K	8.54	Ground	Cement	Ironsheets	stones
Githurai 45	H49	40K	11.8	-	-	Xe-133	0.464	Ground	Cement	Ironsheets	Stones
Githurai 45	H50	4K	6.74	-	-	-	None	Ground	Cement	Ironsheets	Wood
Githurai 45	H51	40K	8.8	-	-	Xe-133	0.592	Ground	Cement	Ironsheets	Stones
Githurai 45	H52	40k	9.37	-	-	-	None	Ground	Cement	Ironsheets	Stones
Githurai 45	H53	40K	11.4	-	-	Xe-133	0.716	Ground	Cement	Iron sheets	stones
Githurai 45	H54	40K	11.1	-	-	Xe-133	0.725	Ground	Cement	Iron Sheets	stones
Githuai 45	H55	40K	12.1	-	-	40K	11.4	Ground	Cement	Iron sheets	Stones
Githurai 45	H56	40K	9.8	-	-	-	-	Ground	Cement	Iron sheet	Stones
Githurai 45	H57	40K	11.2	-	-	40K	10.6	Ground	Cement	Iron sheets	Stones
Githurai	H58	40K	7.6	-	-	40K	8.14	Ground	Cement	Iron Sheet	Stones
Githurai 45	H59	40K	1.03	-	-	Xe-133	34.4	Ground	Cement	Concrete	stones
Githurai 45	H60	40K	9.59	Xe-133	0.785	Xe-133	5.52	Ground	Cement	Conrete	Stones
Githurai 45	H61	40K	10.5	40K	9.94	Xe-133	0.21	Ground	Cement	Concrete	stones
Mathare North	H62	40K	11.9	40K	13.1	TI-201	0.264	4th flr	Cement	Concrete	stones
Mathare North	H63	40K	12.5	40K	12.9	40K	13.5	4th flr	Cement	Concrete	stones
Mathere North	H64	40K	13.2	40K	12.1	40K	13.1	4th	Cement	Concrete	Stones
Mathare North	H65	40K	12	40K	13.1	TI -201	0.256	th flr	Cement	Concrete	Stones
Mathere North	H66	40K	14.3	40K	13.5	40K	12.2	3rd	Cement	Concrete	Stones
Mathare North	H67	40K	11.3	40K	13.3	40K	11.7	3rd	Cement	Concrete	Stones
Mathare North	H68	40K	15.7	40K	12.3	40K	16.8	Ground	Cement	Concrete	Stones
Mathare North	H69	40K	16.3	40K	16.7	40K	15.9	Ground	Cement	Concrete	Stones
Mathare North	H70	40K	16.1	40K	16.1	40K	13.5	Ground	Cement	Concrete	Stones
Mathare North	H71	40K	14.5	40K	16.3	40K	16.7	Ground	Cement	Concrete	Stones
Ndome Estate	H72	40K	9.33	40k	9.13	40k	12.5	Ground	Tiles	Concrete	stones
Ndome Estate	H73	40k	9.65	TI-201	0.363	40k	10.6	Ground	Tiles	Concrete	Stones
Ndome Estate	H74	40K	9.87	40K	11.3	TI-201	0.269	Ground	Tiles	Concrete	Stones
Ndome Estate	H75	40k	10.3	40K	12.3	TI-201	0.984	Ground	Tiles	Concrete	Stones
Ndome Estate	H76	40k	10.5	40K	8.4	40k	9.8	Ground	Tiles	Concrete	stones
Roasters	H77	40k	9.4	-	-	-	-	Ground	Tiles	Concrete	Brick/Blocks
Roasters	H78	40K	8.59	-	-	40k	8.8	3rd	Tiles	Concrete	Brick/Blocks
Roasters	H79	40k	9	-	-	-	-	3rd	Tiles	Concrete	Blocks/Stones



		Indoor NORM Activity									
Location	**House No**	**Floor ^{232}Th /238U/ 40K/ 226Ra**	**Activity Bq 10^4**	**Ceiling Nuclide- 232 Th/ 238U/ 40K/ 226Ra**	**Activity Bq**	**Wall Nuclide 232 Th / 238U/40K/ 226Ra**	**Activity Bq**	**Floor No.**	**Type of building material- Floor**	**Type of Ceiling**	**Wall type e.g wood, brick etc,**
Roasters	H80	TI-201	6.3	-	-	-	-	Ground	Tiles	Concrete	Stones
Roasters	H81	40K	6.5	-	-	40k	8.8	Ground	Tiles	Concrete	Brick/Blocks
Roasters	H82	40k	5	-	-	Tl -201	0.02	Ground	Tiles	Concrete	Stones
Sunton-Kasarani	H83	40K	11.1	40K	12.4	40K	12.1	Ground	Cement	Concrete	Stones
Sunton-Kasarani	H84	40K	11.3	40K	12.1	40K	11.5	Ground	Cement	Concrete	Stones
Sunton-Kasarani	H85	40K	12.9	40K	12.8	40K	13.4	Ground	Cement	Concrete	Stones
Sunton-Kasarani	H86	40K	12.5	40K	13.1	40K	14.1	Ground	Cement	Concrete	Stones
Sunton-Kasarani	H87	40K	10.9	40K	11.7	40k	11.4	2nd	Cement	Concrete	Stones
Clayworks-Kasarani	H88	40K	12.4	40K	12.6	40K	12.9	Ground	Tiles	Concrete	stones
Clayworks-Kasarani	H89	40K	10.4	40K	12.8	40K	10.3	1st	Tiles	Concrete	Stones
Clayworks-Kasarani	H90	40K	12.3	40K	12	40K	13.1	1st	Tiles	Concrete	Stones
Clayworks-Kasarani	H91	40K	11.6	40K	12.7	40k	14.1	Ground	Tiles	Concrete	Stones
Clayworks-Kazarani	H92	40K	9.76	40K	13.7	40k	13.2	1st	Tiles	Concrete	Stones
Average		**107**			**140**		**120**				

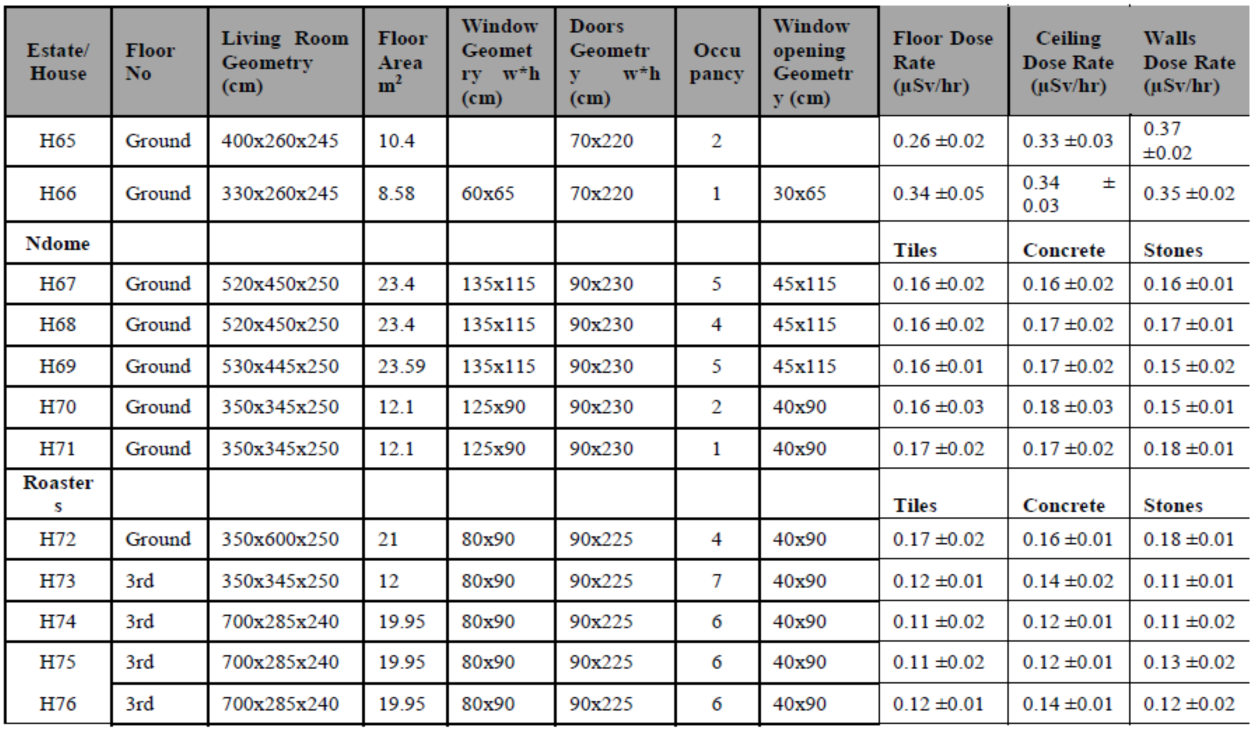
Page **3** of **3**

- ^{238}U*, ^{232}Th*, ^{226}Ra* radionuclide identified recurring activities at 2.84kBq, 7.13kBq and 3.15kBq respectively.
- The aveage is for ^{40}K radionuclide

Appendix V : Dimensions of Nairobi Residential House and Dose Rate Variations

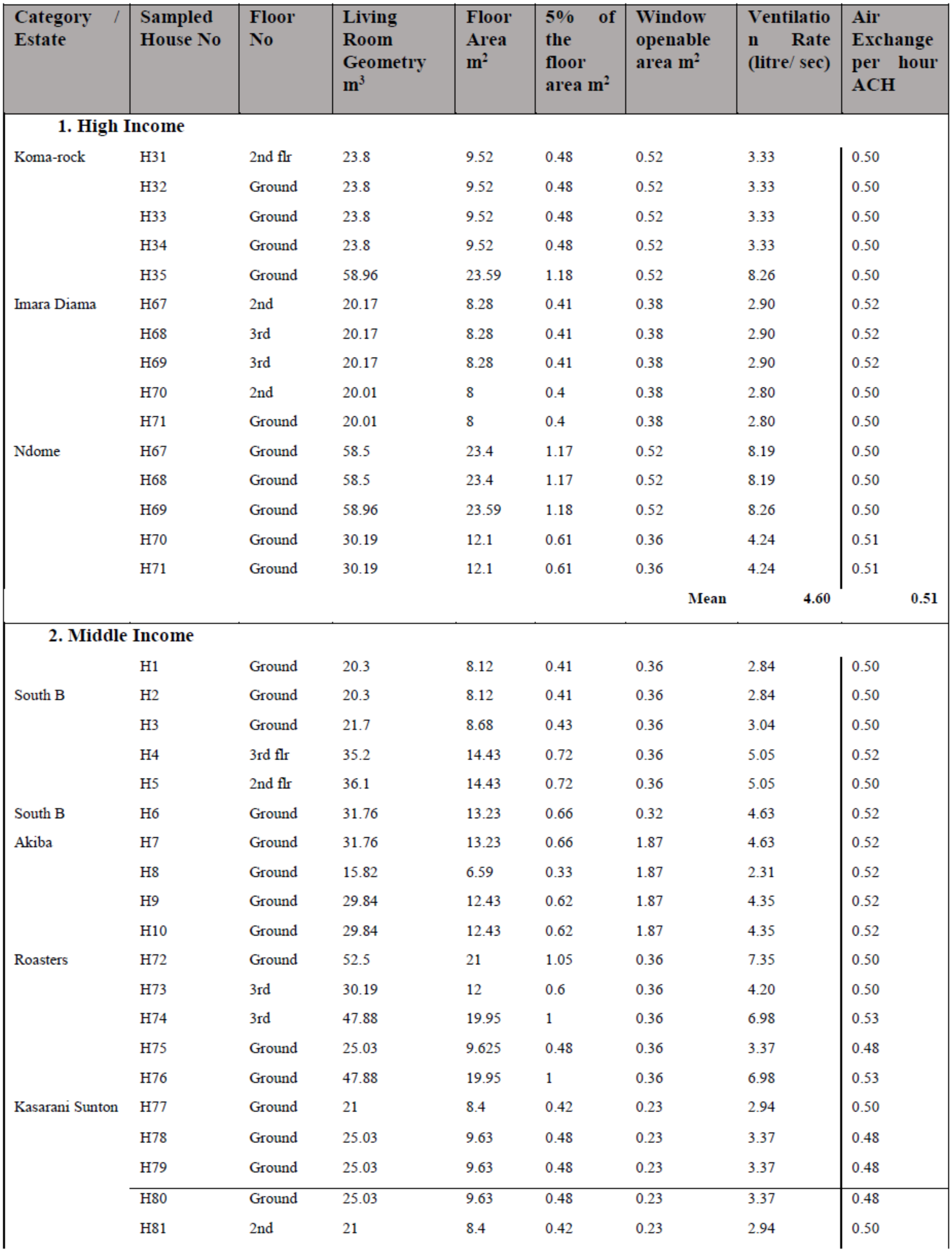
Estate/ House	Floor No	Living Room Geometry (cm)	Floor Area m^2	Window Geometry w*h (cm)	Doors Geometry w*h (cm)	Occupancy	Window opening Geometry (cm)	Floor Dose Rate (µSv/hr)	Ceiling Dose Rate (µSv/hr)	Walls Dose Rate (µSv/hr)
South B								**Wooden**	**Concrete**	**Stones**
H1	Ground	290x280x250	8.12	125x90	90x230	1	40x90	0.14 ±0.01	0.17 ±0.02	0.15 ±0.01
H2	Ground	290x280x250	8.12	125x90	90x230	3	40x90	0.13 ±0.02	0.16 ±0.02	0.13 ±0.02
H3	Ground	310x280x250	8.68	125x90	90x230	5	40x90	0.16 ±0.03	0.16 ±0.02	0.16 ±0.01
H4	3rd flr	325x444x244	14.43	125x80	85x230	5	40x90	0.15 ±0.02	0.19 ±0.01	0.16 ±0.01
H5	2nd flr	325x444x250	14.43	125x90	90x230	4	40x90	0.15 ±0.01	0.19 ±0.02	0.16 ±0.01
South B Akiba								**Tiles**	**Concrete**	**Stones**
H6	Ground	556x238x240	13.23	125x80	85x220	5	40x80	0.14 ±0.01	0.14 ±0.01	0.13 ±0.01
H7	Ground	556x238x240	13.23	125x80	85x220	5	85x220	0.13 ±0.01	0.14 ±0.01	0.13 ±0.01
H8	Ground	277x238x240	6.59	125x80	85x220	5	85x220	0.14 ±0.01	0.15 ±0.01	0.14 ±0.01
H8	Ground	280x444x240	12.43	125x80	85x220	5	85x220	0.15 ±0.01	0.13 ±0.01	0.15 ±0.01
H10	Ground	280x444x240	12.43	125x80	85x220	5	85x220	0.14 ±0.01	0.14 ±0.01	0.15 ±0.01
Pipeline								**Cement**	**Ironsheets**	**Ironsheets**
H11	Ground	340x278x250	9.45	105x90	90x225	2	35x90	0.04 ±0.04	<0.02)	<0.02)
H12	Ground	340x279x250	9.49	105x90	90x225	3	35x90	0.09 ±0.01	<0.02)	<0.02)
H13	Ground	340x278x250	9.45	105x90	90x225	3	35x90	0.07 ±0.05	<0.02)	<0.02)
H14	Ground	280x436x240	12.21	105x80	85x220	4	35x85	0.06 ±0.05	<0.02)	<0.02)
H15	2nd flr	280x436x240	12.21	105x80	85x220	4	35x85	**Cement**	**concrete**	**Stones**
H16	2nd flr	280x436x240	12.21	105x80	85x220	2	35x85	0.14 ±0.01	0.13 ±0.01	0.14 ±0.01
H17	2nd flr	280x436x240	12.21	105x80	85x220	1	35x85	0.12 ±0.02	0.13 ±0.01	0.14 ±0.02
H18	2nd flr	280x436x240	12.21	105x80	85x220	2	35x85	0.13 ±0.01	0.13 ±0.01	0.14 ±0.01
H19	Ground	280x436x240	12.21	105x80	85x220	5	35x85	0.15 ±0.01	0.15 ±0.01	0.13 ±0.02
H20	Ground	280x436x240	12.21	105x80	85x220	3	35x85	0.16 ±0.01	0.15 ±0.01	0.15 ±0.02
Imara Diama								Tiles	Concrete	Stones
H21	2nd	300x276x250	8.28	125x95	90x230	5	40x95	0.14 ±0.01	0.15 ±0.01	0.13 ±0.01
H22	3rd	300x276x250	8.28	125x95	90x230	5	40x95	0.13 ±0.02	0.15 ±0.01	0.13 ±0.01
H23	3rd	300x276x250	8.28	125x95	90x230	4	40x95	0.13 ±0.01	0.14 ±0.01	0.13 ±0.01
H24	2nd	290x276x250	8	125x95	90x230	3	40x95	0.11 ±0.01	0.13 ±0.01	0.11 ±0.01
H25	Ground	290x276x250	8	125x95	90x230	2	40x95	0.15 ±0.01	0.16 ±0.02	0.14 ±0.01
Kayole										
H26	Ground	326x392x240	12.78	100x80	85x220	4	33x85	0.19 ±0.01	0.18 ±0.015	0.16 ±0.01
H27	2nd	326x392x240	12.78	100x80	85x220	5	33x85	0.14 ±0.02	0.17 ±0.015	0.14 ±0.01
H28	Ground	370x260x230	9.62	60x70	70x220	2	30x70	0.13 ±0.01	0.14 ±0.01	0.12 ±0.02
H29	Ground	270x340x270	9.18	105x90	95x225	1	35x90	0.12 ±0.01	0.10 ±0.01	0.11 ±0.01
H30	2nd	270x340x270	9.18	105x90	95x225	3	35x90	0.16 ±0.01	0.17 ±0.02	0.15 ±0.02
Koma-rock								**Tiles**	**Concrete**	**Stones**

Estate/ House	Floor No	Living Room Geometry (cm)	Floor Area m^2	Window Geometry w*h (cm)	Doors Geometry w*h (cm)	Occupancy	Window opening Geometry (cm)	Floor Dose Rate (μSv/hr)	Ceiling Dose Rate (μSv/hr)	Walls Dose Rate (μSv/hr)
H31	2nd flr	340x280x250	9.52	135x115	95x230	4	45x115	0.11 ±0.01	0.102 ±0.01	0.10 ±0.01
H32	Ground	340x280x250	9.52	135x115	95x230	5	45x115	0.15 ±0.01	0.16 ±0.02	0.15 ±0.02
H33	Ground	340x280x250	9.52	135x115	95x230	6	45x115	0.16 ±0.02	0.15 ±0.01	0.14 ±0.01
H34	Ground	340x280x250	9.52	135x115	95x230	5	45x115	0.18 ±0.01	0.1833 ±0.02	0.18 ±0.01
H35	Ground	530x445x250	23.59	135x115	95x230	5	45x115	0.14 ±0.01	0.1567 ±0.02	0.15 ±0.02
Salka								**Tiles**	**Concrete**	**Stones**
H36	Ground	230x260x250	5.98	90x95	75x225	3	30x95	0.1233 ±0.02	0.11 ±0.01	0.11 ±0.01
H37	Ground	350x300x250	10.5	90x95	75x225	1	30x95	0.13 ±0.01	0.14 ±0.01	0.13 ±0.01
H38	Ground	230x260x250	5.98	90x95	75x225	2	30x95	0.12 ±0.01	<0.02)	0.12 ±0.01
H39	Ground	230x260x250	5.98	90x95	75x225	2	30x95	0.12 ±0.01	<0.02)	0.12 ±0.01
H40	Ground	350x300x250	10.5	90x95	75x225	4	30x95	0.14 ±0.02	<0.02)	0.13 ±0.01
Githurai 45								**Cement**	**Ceiling Board**	**Stones**
H41	Ground	350x300x250	10.5	60x65	70x220	2	30x65	0.14 ±0.01	<0.02)	0.13 ±0.01
H42	Ground	350x300x250	10.5	60x65	70x220	3	30x65	0.11 ±0.02	<0.02)	0.4 ±0.05
H33	Ground	350x300x250	10.5	60x65	70x220	1	30x65	0.12 ±0.01	<0.02)	0.11 ±0.01
H44	Ground	350x300x250	10.5	60x65	70x220	1	30x65	0.11 ±0.02	<0.02)	0.13 ±0.01
H45	Ground	345x300x250	10.35	60x65	70x220	3	30x65	0.17 ±0.01	<0.02)	0.15 ±0.02
H66	Ground	300x280x250	8.4	60x65	70x220	3	30x65	0.17 ±0.01	0.2 ±0.01	0.17 ±0.01
H47	Ground	280x290x250	8.12	60x65	70x220	5	30x65	0.18 ±0.03	0.20 ±0.02	0.20 ±0.02
H48	Ground	237x320x280	7.58	60x65	70x220	4	30x65	0.17 ±0.02	0.19 ±0.02	0.18 ±0.01
H49	Ground	290x280x250	8.12	60x65	70x220	2	30x65	0.17 ±0.02	0.18 ±0.01	0.17 ±0.01
H50	Ground	300x270x250	8.1	60x65	70x220	1	30x65	0.12 ±0.01	0.15 ±0.01	0.14 ±0.01
H51	Ground	345x300x250	10.35	60x65	70x220	3	30x65	0.13 ±0.01	0.14 ±0.02	0.14 ±0.01
H52	Ground	280x290x250	8.12	60x65	70x220	4	30x65	0.25 ±0.02	0.32 ±0.02	0.32 ±0.05
H53	Ground	280x290x250	8.12	60x65	70x220	3	30x65	0.3 ±0.04	0.30 ±0.02	0.32 ±0.03
H54	Ground	237x320x280	7.58	60x65	70x220	4	30x65	0.26 ±0.02	0.33 ±0.03	0.37 ±0.02
Mathare North								**Cement**	**Concrete**	**Stones**
H57	4th flr	320x260x245	8.32	60x65	70x220	2	30x65	0.17 ±0.01	0.2 ±0.01	0.17 ±0.01
H58	4th flr	405x260x245	10.53		70x220	2		0.18 ±0.03	0.20 ±0.02	0.20 ±0.02
H59	4th	400x260x245	10.4		70x220	4		0.17 ±0.02	0.19 ±0.02	0.18 ±0.01
H60	4th flr	330x260x245	8.58		70x220	2		0.17 ±0.02	0.18 ±0.01	0.17 ±0.01
H61	3rd	310x290x40	8.99	60x65	70x220	3	30x65	0.12 ±0.01	0.15 ±0.01	0.14 ±0.01
H62	3rd	310x290x240	8.99		70x220	2		0.13 ±0.01	0.14 ±0.02	0.14 ±0.01
H63	Ground	300x280x250	8.4		70x220	3		0.25 ±0.02	0.32 ±0.02	0.32 ±0.05
H64	Ground	320x260x245	8.32		70x220	2		0.3 ±0.04	0.30 ±0.02	0.32 ±0.03



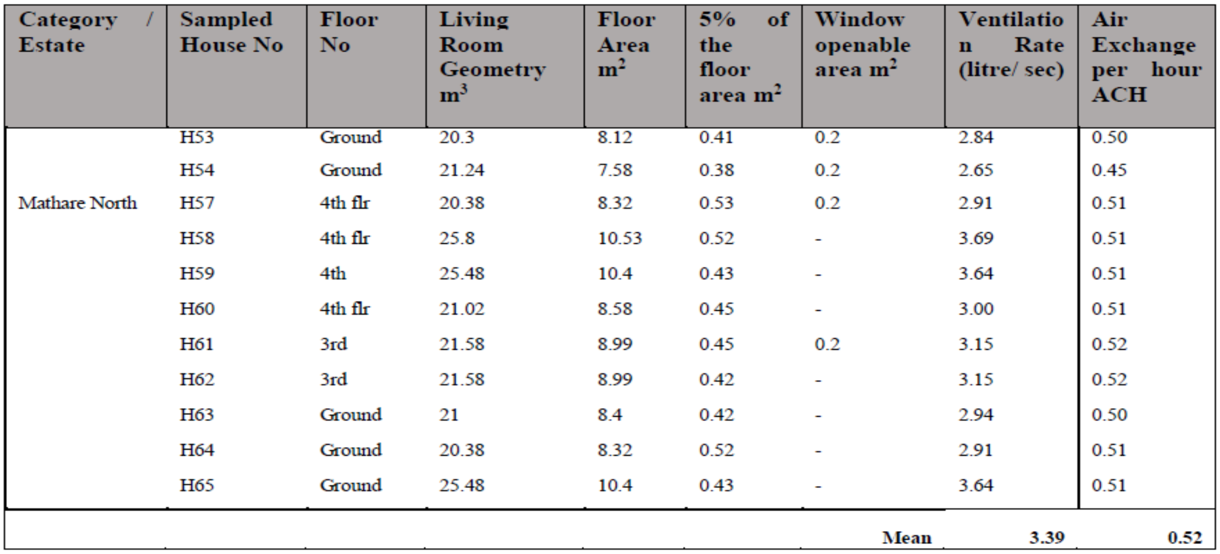
Estate/ House	Floor No	Living Room Geometry (cm)	Floor Area m^2	Window Geometry w*h (cm)	Doors Geometry w*h (cm)	Occupancy	Window opening Geometry (cm)	Floor Dose Rate (μSv/hr)	Ceiling Dose Rate (μSv/hr)	Walls Dose Rate (μSv/hr)
H65	Ground	400x260x245	10.4		70x220	2		0.26 ±0.02	0.33 ±0.03	0.37 ±0.02
H66	Ground	330x260x245	8.58	60x65	70x220	1	30x65	0.34 ±0.05	0.34 ± 0.03	0.35 ±0.02
Ndome								**Tiles**	**Concrete**	**Stones**
H67	Ground	520x450x250	23.4	135x115	90x230	5	45x115	0.16 ±0.02	0.16 ±0.02	0.16 ±0.01
H68	Ground	520x450x250	23.4	135x115	90x230	4	45x115	0.16 ±0.02	0.17 ±0.02	0.17 ±0.01
H69	Ground	530x445x250	23.59	135x115	90x230	5	45x115	0.16 ±0.01	0.17 ±0.02	0.15 ±0.02
H70	Ground	350x345x250	12.1	125x90	90x230	2	40x90	0.16 ±0.03	0.18 ±0.03	0.15 ±0.01
H71	Ground	350x345x250	12.1	125x90	90x230	1	40x90	0.17 ±0.02	0.17 ±0.02	0.18 ±0.01
Roasters								**Tiles**	**Concrete**	**Stones**
H72	Ground	350x600x250	21	80x90	90x225	4	40x90	0.17 ±0.02	0.16 ±0.01	0.18 ±0.01
H73	3rd	350x345x250	12	80x90	90x225	7	40x90	0.12 ±0.01	0.14 ±0.02	0.11 ±0.01
H74	3rd	700x285x240	19.95	80x90	90x225	6	40x90	0.11 ±0.02	0.12 ±0.01	0.11 ±0.02
H75	3rd	700x285x240	19.95	80x90	90x225	6	40x90	0.11 ±0.02	0.12 ±0.01	0.13 ±0.02
H76	3rd	700x285x240	19.95	80x90	90x225	6	40x90	0.12 ±0.01	0.14 ±0.01	0.12 ±0.02

Appendix VI: Air Change per Hour and Ventilation Rate in Residential Houses



Category / Estate	Sampled House No	Floor No	Living Room Geometry m^3	Floor Area m^2	5% of the floor area m^2	Window openable area m^2	Ventilation Rate (litre/ sec)	Air Exchange per hour ACH
1. High Income								
Koma-rock	H31	2nd flr	23.8	9.52	0.48	0.52	3.33	0.50
	H32	Ground	23.8	9.52	0.48	0.52	3.33	0.50
	H33	Ground	23.8	9.52	0.48	0.52	3.33	0.50
	H34	Ground	23.8	9.52	0.48	0.52	3.33	0.50
	H35	Ground	58.96	23.59	1.18	0.52	8.26	0.50
Imara Diama	H67	2nd	20.17	8.28	0.41	0.38	2.90	0.52
	H68	3rd	20.17	8.28	0.41	0.38	2.90	0.52
	H69	3rd	20.17	8.28	0.41	0.38	2.90	0.52
	H70	2nd	20.01	8	0.4	0.38	2.80	0.50
	H71	Ground	20.01	8	0.4	0.38	2.80	0.50
Ndome	H67	Ground	58.5	23.4	1.17	0.52	8.19	0.50
	H68	Ground	58.5	23.4	1.17	0.52	8.19	0.50
	H69	Ground	58.96	23.59	1.18	0.52	8.26	0.50
	H70	Ground	30.19	12.1	0.61	0.36	4.24	0.51
	H71	Ground	30.19	12.1	0.61	0.36	4.24	0.51
						Mean	**4.60**	**0.51**
2. Middle Income								
	H1	Ground	20.3	8.12	0.41	0.36	2.84	0.50
South B	H2	Ground	20.3	8.12	0.41	0.36	2.84	0.50
	H3	Ground	21.7	8.68	0.43	0.36	3.04	0.50
	H4	3rd flr	35.2	14.43	0.72	0.36	5.05	0.52
	H5	2nd flr	36.1	14.43	0.72	0.36	5.05	0.50
South B	H6	Ground	31.76	13.23	0.66	0.32	4.63	0.52
Akiba	H7	Ground	31.76	13.23	0.66	1.87	4.63	0.52
	H8	Ground	15.82	6.59	0.33	1.87	2.31	0.52
	H9	Ground	29.84	12.43	0.62	1.87	4.35	0.52
	H10	Ground	29.84	12.43	0.62	1.87	4.35	0.52
Roasters	H72	Ground	52.5	21	1.05	0.36	7.35	0.50
	H73	3rd	30.19	12	0.6	0.36	4.20	0.50
	H74	3rd	47.88	19.95	1	0.36	6.98	0.53
	H75	Ground	25.03	9.625	0.48	0.36	3.37	0.48
	H76	Ground	47.88	19.95	1	0.36	6.98	0.53
Kasarani Sunton	H77	Ground	21	8.4	0.42	0.23	2.94	0.50
	H78	Ground	25.03	9.63	0.48	0.23	3.37	0.48
	H79	Ground	25.03	9.63	0.48	0.23	3.37	0.48
	H80	Ground	25.03	9.63	0.48	0.23	3.37	0.48
	H81	2nd	21	8.4	0.42	0.23	2.94	0.50

Category / Estate	Sampled House No	Floor No	Living Room Geometry m^3	Floor Area m^2	5% of the floor area m^2	Window openable area m^2	Ventilation Rate (litre/ sec)	Air Exchange per hour ACH
Kasarani Clay works	H82	Ground	25.03	9.63	0.48	0.34	3.37	0.48
	H83	1st	25.03	9.63	0.48	0.34	3.37	0.48
	H84	1st	21	8.4	0.42	0.34	2.94	0.50
	H85	Ground	21	8.4	0.42	0.34	2.94	0.50
	H86	1st	21	8.4	0.42	0.34	2.94	0.50
						Mean	**3.98**	**0.51**
3. Low Income								
Pipeline	H11	Ground	23.63	9.45	0.47	0.32	3.31	0.50
	H12	Ground	23.72	9.49	0.47	0.32	3.32	0.50
	H13	Ground	23.63	9.45	0.47	0.32	3.31	0.50
	H14	Ground	25.11	12.21	0.61	0.3	4.27	0.61
	H15	2nd flr	25.11	12.21	0.61	0.3	4.27	0.61
	H16	2nd flr	25.11	12.21	0.61	0.3	4.27	0.61
	H17	2nd flr	25.11	12.21	0.61	0.3	4.27	0.61
	H18	2nd flr	25.11	12.21	0.61	0.3	4.27	0.61
	H19	Ground	25.11	12.21	0.61	0.3	4.27	0.61
	H20	Ground	25.11	12.21	0.61	0.3	4.27	0.61
Kayole	H26	Ground	30.67	12.78	0.64	0.28	4.47	0.53
	H27	2nd	30.67	12.78	0.64	0.28	4.47	0.53
	H28	Ground	22.13	9.62	0.48	0.21	3.37	0.55
	H29	Ground	24.79	9.18	0.46	0.32	3.21	0.47
	H30	2nd	24.79	9.18	0.46	0.32	3.21	0.47
Salka	H36	Ground	14.95	5.98	0.3	0.29	2.09	0.50
	H37	Ground	26.25	10.5	0.53	0.29	3.68	0.50
	H38	Ground	14.95	5.98	0.3	0.29	2.09	0.50
	H39	Ground	14.95	5.98	0.3	0.29	2.09	0.50
	H40	Ground	26.25	10.5	0.53	0.29	3.68	0.50
Githurai 45	H41	Ground	26.25	10.5	0.53	0.2	3.68	0.50
	H42	Ground	26.25	10.5	0.53	0.2	3.68	0.50
	H43	Ground	26.25	10.5	0.53	0.2	3.68	0.50
	H44	Ground	26.25	10.5	0.53	0.2	3.68	0.50
	H45	Ground	25.88	10.35	0.52	0.2	3.62	0.50
	H46	Ground	21	8.4	0.42	0.2	2.94	0.50
	H47	Ground	20.3	8.12	0.41	0.2	2.84	0.50
	H48	Ground	21.24	7.58	0.38	0.2	2.65	0.45
	H49	Ground	20.3	8.12	0.41	0.2	2.84	0.50
	H50	Ground	20.25	8.1	0.41	0.2	2.84	0.50
	H51	Ground	25.88	10.35	0.52	0.2	3.62	0.50
	H52	Ground	20.3	8.12	0.41	0.2	2.84	0.50



Category / Estate	Sampled House No	Floor No	Living Room Geometry m^3	Floor Area m^2	5% of the floor area m^2	Window openable area m^2	Ventilation Rate (litre/ sec)	Air Exchange per hour ACH
	H53	Ground	20.3	8.12	0.41	0.2	2.84	0.50
	H54	Ground	21.24	7.58	0.38	0.2	2.65	0.45
Mathare North	H57	4th flr	20.38	8.32	0.53	0.2	2.91	0.51
	H58	4th flr	25.8	10.53	0.52	-	3.69	0.51
	H59	4th	25.48	10.4	0.43	-	3.64	0.51
	H60	4th flr	21.02	8.58	0.45	-	3.00	0.51
	H61	3rd	21.58	8.99	0.45	0.2	3.15	0.52
	H62	3rd	21.58	8.99	0.42	-	3.15	0.52
	H63	Ground	21	8.4	0.42	-	2.94	0.50
	H64	Ground	20.38	8.32	0.52	-	2.91	0.51
	H65	Ground	25.48	10.4	0.43	-	3.64	0.51
						Mean	**3.39**	**0.52**