

**JANUARY, 2014**

**M.Sc. THESIS IN ENGINEERING OF PHYSICS**

**SADIK ZUHUR**

**UNIVERSITY OF GAZIANTEP  
GRADUATE SCHOOL OF  
NATURAL & APPLIED SCIENCES**

**THE INVESTIGATION OF NATURAL RADIOACTIVITY LEVELS  
IN BUILDING MATERIALS  
USED IN GAZIANTEP REGION**

**M. Sc. THESIS  
IN  
ENGINEERING OF PHYSICS**

**BY  
SADIK ZUHUR  
JANUARY, 2014**

**The Investigation of Natural Radioactivity Levels  
in Building Materials  
Used in Gaziantep Region**

**M.Sc. Thesis  
in  
Engineering Physics  
University of Gaziantep**

**Supervisor  
Prof. Dr. A. Necmeddin YAZICI**

**by  
Sadık ZUHUR  
January, 2014**

© 2014 [Sadik ZUHUR]

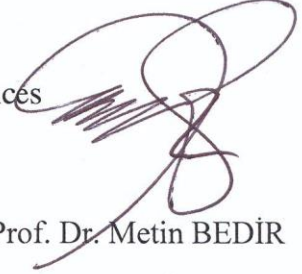
REPUBLIC OF TURKEY  
UNIVERSITY OF GAZİANTEP  
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES  
ENGINEERING PHYSICS

Name of the thesis: The Investigation of Natural Radioactivity Levels in Building Materials Used in Gaziantep Region

Name of the student: Sadık ZUHUR

Exam date: 06.01.2014

Approval of the Graduate School of Natural and Applied Sciences



Assoc. Prof. Dr. Metin BEDİR

Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science



Prof. Dr. A. Necmeddin YAZICI

Head of Department

This is to certify that we have read this thesis and that in our consensus/majority opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.



Prof. Dr. A. Necmeddin YAZICI

Supervisor

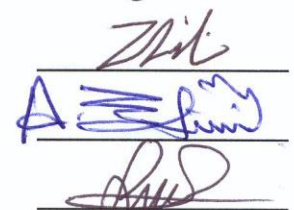
Examining Committee Members

Prof. Dr. Zihni ÖZTÜRK

Prof. Dr. A. Necmeddin YAZICI

Assist. Prof. Dr. Serap ÇELİK

Signature



*to Gaziantep...*

## **ABSTRACT**

### **THE INVESTIGATION OF NATURAL RADIOACTIVITY LEVELS IN BUILDING MATERIALS USED IN GAZİANTEP REGION**

**ZUHUR, Sadık**

**M.Sc. Thesis, Engineering Physics, University of Gaziantep**

**Supervisor: Prof. Dr. A. Necmeddin YAZICI**

**January 2014**

**65 pages**

In this study, the level of radioactivity in building materials used in Gaziantep was determined by using gamma spectrometry system. The gamma-ray spectras of the collected samples were measured by using NaI(Tl) detector and the specific activities of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  were identified from these spectras. It was found that the activity concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  were ranging from  $9,52\pm 3,65$  Bq/kg to  $123,89\pm 5,89$  Bq/kg,  $15,72\pm 11,50$  Bq/kg to  $50,88\pm 7,40$  Bq/kg and  $94,94\pm 47,20$  Bq/kg to  $871,29\pm 36,10$  Bq/kg, respectively. The absorbed dose rate indoor, the absorbed dose rate outdoor, the annual effective dose, the radium equivalent activity, the external hazard index, the internal hazard index and the gamma index were also found to be ranging from  $28,54$  nGy/h to  $200,86$  nGy/h,  $15,37$  nGy/h to  $104,03$  nGy/h,  $0,14$  mSv/y to  $0,99$  mSv/y,  $34,07$  Bq/kg to  $224,07$  Bq/kg,  $0,09$  to  $0,61$ ,  $0,12$  to  $0,94$ ,  $0,11$  to  $0,93$ , respectively. In conclusion, the results indicate that there is no radiological hazard in the region of Gaziantep.

**Key words:** Gamma Spectroscopy, NaI(Tl) detector, Building material, Natural radiation, Radioactivity.

## ÖZET

### GAZİANTEP İLİNDE KULLANILAN İNŞAAT MALZEMELERİNDE DOĞAL RADYOAKTİVİTE SEVİYESİNİN İNCELENMESİ

**ZUHUR, Sadık**

**Yüksek Lisans Tezi, Fizik Mühendisliği Bölümü,  
Gaziantep Üniversitesi**

**Tez Yöneticisi: Prof. Dr. A. Necmeddin YAZICI**

**Ocak 2014**

**65 sayfa**

Bu çalışmada, gama spektrometre sistemi kullanılarak Gaziantep ilinde kullanılan inşaat malzemelerindeki doğal radyoaktivite seviyesi belirlendi. Toplanan numunelerin gama spektrumları NaI(Tl) dedektörü kullanılarak ölçüldü ve  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ve  $^{40}\text{K}$  radyoaktif çekirdeklerinin spesifik aktiviteleri ölçülen gama ışını spektrumları kullanılarak bulundu.  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  ve  $^{40}\text{K}$  'ın aktivite konsantrasyonları sırasıyla;  $9,52\pm 3,65$  Bq/kg- $123,89\pm 5,89$  Bq/kg,  $15,72\pm 11,50$  Bq/kg- $50,88\pm 7,40$  Bq/kg ve  $94,94\pm 47,20$  Bq/kg- $871,29\pm 36,10$  Bq/kg değerleri arasında değiştiği bulundu. Ölçülen aktivite konsantrasyonlarından soğurulan gama doz hızları, yıllık etkin doz, radyum eşdeğer aktivite, radyasyon tehlike indeksleri, gama indeks değerleri belirlendi. Hesaplanan değerlerin, kapalı mekanda soğurulan gama doz hızı için  $28,54$  nGy/h -  $200,86$  nGy/h, açık havada soğurulan gama doz hızı için  $15,37$  nGy/h -  $104,03$  nGy/h, yıllık etkin doz için  $0,14$  mSv/y -  $0,99$  mSv/y, radyuma eşdeğer aktivite için  $34,07$  Bq/kg -  $224,07$  Bq/kg, harici radyasyon tehlike indeksi için  $0,09$  -  $0,61$ , dahili radyasyon tehlike indeksi için  $0,12$  -  $0,94$  son olarak da gama indeks için  $0,11$  -  $0,93$  aralığında değiştiği görüldü. Elde edilen sonuçlar Gaziantep yöresinde herhangi bir radyolojik tehlike olmadığını belirledi.

**Anahtar Kelimeler:** Gama Spektroskopisi, NaI(Tl) dedektör, İnşaat malzemesi, Doğal radyasyon, Radyoaktivite.

## ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to my valuable supervisor and head of Gaziantep University Engineering Physics Department, Prof. Dr. A. Necmeddin Yazıcı for his help and motivation.

Furthermore, I would like to thank to Dr. Gürsel Karahan and his colleagues at ÇNAEM and also Assoc. Prof. Dr. Nevzat Damla, Prof. Dr. Şeref Turhan and SANAEM employees Emin Yeltepe, Namık Kemal Şahin because of sharing their knowledge about gamma spectrometry.

I also thank to Examining Committee Members Prof. Dr. Zihni Öztürk and Assist. Prof. Dr. Serap ÇELİK, and thank to Assoc. Prof. Dr. Ahmet Bingül about uncertainty calculation and finally thank to Assist. Prof. Dr. Vural Emir Kafadar and Research Assistant Mustafa Kılın because of their assistance about collection of the samples.

Moreover, I heartily, thank to my colleagues that never leave me alone and precious staff of Engineering Physics Department for the unwavering moral, emotional and physical support.

Finally, I would like to deepest gratitude to my dear mother and father, my brother and his wife and the nephew, newest member of our family, Hüseyin Eren for moral support.



## TABLE OF CONTENTS

ABSTRACT.....	iii
ÖZET.....	iv
ACKNOWLEDGEMENTS .....	v
CONTENTS.....	vi
LIST OF TABLES .....	ix
LIST OF FIGURES .....	x
LIST OF SYMBOLS .....	xii
1.INTRODUCTION .....	1
2.THEORY .....	5
2.1.Radiation .....	5
2.2.Ionizing Radiation.....	5
2.2.1.Ionizing Electromagnetic Radiation.....	6
2.2.1.1.X-Rays .....	6
2.2.1.2.Gamma ( $\gamma$ ) Rays.....	8
2.2.2.Ionizing Particulate Radiation.....	9
2.3.Radioactivity .....	13
2.3.1.Radioactivity and Radioactive Decay Law .....	13
2.3.2.Sequential Decay Law.....	15
2.3.3.Radioactive Equilibrium .....	16
2.3.3.1.Transient Equilibrium .....	17
2.3.3.2.Secular Equilibrium .....	17
2.3.4.Natural Radioactive Series.....	18
2.3.4.1.Uranium Series.....	18
2.3.4.2.Thorium Series .....	20
2.3.4.3.Actinium Series.....	21
2.3.5.Potassium 40 .....	22
2.4.Ionizing Radiation Units .....	22
2.5.Radiation Sources.....	25
2.5.1.Natural Sources .....	25
2.5.1.1.Cosmic Radiation Sources .....	25
2.5.1.2.Terrestrial Radiation Sources.....	26
2.5.1.3.Internal Radiation Sources .....	27
2.5.2.Man-Made Sources .....	27

3.MATERIAL and METHOD .....	29
3.1.Gamma Spectrometry System.....	29
3.1.1.NaI(Tl) Detector.....	29
3.1.2.High Voltage Unit.....	31
3.1.3.Preamplifier.....	31
3.1.4.Amplifier.....	31
3.1.5.Analog to Digital Converter (ADC) .....	32
3.1.6.Multi-Channel Analyzer.....	32
3.2.Collection of Samples and Preparation to Counting .....	32
3.3.Energy Calibration .....	34
3.4.Calculation of Activity using Method of Comparison with the Standard.....	35
3.4.1.Peak Info Calculation .....	35
3.4.2.Efficiency .....	37
3.4.3.Activity.....	38
3.4.4.Uncertainty in Activity.....	39
3.4.5.MDA .....	39
3.5.Calculated Parameters on the basis of Activity.....	40
3.5.1.Absorbed Dose Rate.....	40
3.5.2.Annual Effective Dose .....	40
3.5.3.Radium Equivalent Activity.....	41
3.5.4.Hazard index .....	41
3.5.5.Gamma Index .....	42
4.RESULTS .....	43
4.1.Specific Activity.....	43
4.2.Calculated Parameters on the basis of Activity.....	46
4.2.1.Absorbed Dose Rate.....	46
4.2.2.Annual Effective Dose .....	48
4.2.3.Radium Equivalent Activity.....	49
4.2.4.Hazard index .....	50
4.2.5.Gamma Index .....	52
5.CONCLUSION .....	53
REFERENCES.....	55
APPENDIX 1 .....	60
APPENDIX 2.....	63

## LIST OF TABLES

<b>TABLES</b>	<b>Page</b>
<b>Table 2.1</b> Natural Radioactive Series .....	18
<b>Table 2.2</b> Isotopes of Natural Uranium .....	18
<b>Table 2.3</b> Radiation Quantities, Units and Conversion between old and SI units.....	25
<b>Table 3.1.</b> Information collected samples .....	33
<b>Table 3.2</b> Features of Calibration Sources .....	34
<b>Table 3.3</b> Gamma Index Limits.....	42
<b>Table 4.1</b> Specific Activities and Uncertainties of measured samples.....	44
<b>Table 4.2</b> Indoor Absorbed Doses in building materials in Gaziantep .....	46
<b>Table 4.3</b> Outdoor Absorbed Doses in building materials in Gaziantep.....	47
<b>Table 4.4</b> Annual Effective Doses in building materials in Gaziantep .....	48
<b>Table 4.5</b> Radium Equivalent Activities in building materials in Gaziantep .....	49
<b>Table 4.6.</b> External Hazard Indexes in building materials in Gaziantep .....	50
<b>Table 4.7</b> Internal Hazard Indexes in building materials in Gaziantep .....	51
<b>Table 4.8</b> Gamma Indexes in building materials in Gaziantep .....	52
<b>Table 5.1</b> In various studies $^{40}\text{K}$ , $^{232}\text{Th}$ , $^{226}\text{Ra}$ specific activities and radium equivalent activities .....	54

## LIST OF FIGURES

FIGURES	Page
Figure 2.1 Ionizing Radiations .....	6
Figure 2.2 Electromagnetic Spectrum .....	6
Figure 2.3 Schematic representation of an X-ray tube .....	7
Figure 2.4 Bremsstrahlung process .....	7
Figure 2.5 Characteristic X-ray generation .....	7
Figure 2.6 Alpha particle generation .....	8
Figure 2.7 Gamma emission .....	8
Figure 2.8 Penetration ranges of various ionizing radiations .....	10
Figure 2.9 Neutron .....	10
Figure 2.10 Proton .....	10
Figure 2.11 Alpha decay .....	11
Figure 2.12 $\beta^-$ decay .....	11
Figure 2.13 $\beta^+$ decay .....	12
Figure 2.14 Electron capture phenomenon .....	12
Figure 2.15 Graph of number of neutron versus to number of proton .....	13
Figure 2.16 Graph of Sequential Decay .....	16
Figure 2.17 $^{238}\text{U}$ Series Decay Chain .....	19
Figure 2.18 $^{232}\text{Th}$ Series Decay Chain .....	20
Figure 2.19 Actinium Series .....	21
Figure 2.20 Three points of associated with ionizing radiation measurement.....	22

<b>Figure 2.21</b> Exposure sources for collective effective dose of the Population of the United States, 2006 .....	28
<b>Figure 3.1.</b> NaI(Tl) Gama Spectroscopy System .....	29
<b>Figure 3.2</b> Schematic representation of the scintillation detector .....	30
<b>Figure 3.3.</b> Ortec digiBASE and 3''x3'' NaI(Tl) detector .....	31
<b>Figure 3.4.</b> Gama Spectrometer System.....	33
<b>Figure 3.5</b> <sup>137</sup> Cs and <sup>60</sup> Co decay scheme .....	34
<b>Figure 3.6</b> <sup>137</sup> Cs Spectrum and <sup>60</sup> Co Spectrum .....	35
<b>Figure 3.7</b> Energy Calibration Graph.....	35
<b>Figure 3.8</b> The deatail background calculation .....	36
<b>Figure 4.1.</b> A typical gamma spectrum from sample of Sand1 .....	43
<b>Figure 4.2</b> <sup>40</sup> K Activities (Bq/kg) in building materials used in Gaziantep .....	44
<b>Figure 4.3</b> <sup>226</sup> Ra Activities (Bq/kg) in building materials used in Gaziantep .....	45
<b>Figure 4.4</b> <sup>232</sup> Th Actvivities (Bq/kg) in building materials used in Gaziantep .....	45
<b>Figure 4.5</b> Indoor Abosorbed Doses (nGy/h) in building materials in Gaziantep ....	46
<b>Figure 4.6</b> Outdoor Absorbed Doses (nGy/h) in building materials in Gaziantep....	47
<b>Figure 4.7</b> Annual Effective Doses (mSv/y) in building materials in Gaziantep.....	48
<b>Figure 4.8</b> Radium Equivalent Activities in building materials in Gaziantep .....	49
<b>Figure 4.9</b> External Hazard Index in building materials in Gaziantep.....	50
<b>Figure 4.10</b> Internal Hazard Indexes in building materials in Gaziantep.....	51
<b>Figure 4.11</b> Gamma Indexes in building materials in Gaziantep.....	52

## LIST OF SYMBOLS

$\lambda$	Decay Constant
$t_{1/2}$	Half-life
$\tau$	Mean Life Time
Bq	Becquerel
Ci	Curie
EC	European Commission
Gy	Gray
HpGe	High Purity Germanium
ICRP	International Commission on Radiological Protection
MDA	Minimum Detectable Activity
NaI(Tl)	Thallium Activated Sodium Iodide
OECD	Organisation for Economic Co-operation and Development
R	Rontgen
Sv	Sievert
TAEK	Turkey Atomic Energy Agency
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

## 1. INTRODUCTION

Since the humanity's existence, they are accustomed to live with radiation. The natural long-lived (billions of years) radioactive elements have created a natural level of radiation which is accepted as normal and inevitable in our environment since the formation of the world. Over the past century, the natural level due to the nuclear bomb tests and the use of some technological products has increased with a great deal.

Natural radioactivity results especially due to the cosmic rays from outer space and the natural decay of radionuclides in rock, soil, water and air around us. The amount of cosmic radiation dose varies according to geomagnetic latitude circle and the elevation above sea level. The distribution of radioactive nuclei on earth depends on the geological structure, geographic location and radiochemical properties. The following factors such as rain, snow, low pressure, high pressure and wind direction also determine the magnitude of the natural radiation levels. People are always exposed to different types of radiations which have been released from these sources in their environment. The most common natural sources of radiation are isotopes of  $^{238}\text{U}$ ,  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  [1].

Natural sources are very important in the radiation dose assessments. Therefore, concentrations of natural radionuclides in environment are carried out to determine the level of natural radiation in order to ensure safety and assess the effect of radiation on biological systems.

The received radiation doses from the natural sources by the people and their biological effects on the human bodies were studied and examined by International Commission on Radiological Protection (ICRP), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), Turkey Atomic Energy Agency (TAEK), etc. other national and international organizations. Some of examples are given in below examples.

A study conducted by N. Ahmad and friends in Pakistan, natural radioactivity in soil and building materials were measured by HpGe dedector and  $^{40}\text{K}$ ,  $^{232}\text{Th}$  and  $^{226}\text{Ra}$  activity were found to be 52-1729 Bq/kg, 2,1-50,3 Bq/kg and 12,2-774 Bq/kg, respectively [2].

In India, the NaI(Tl) detector was used to measure the activity concentrations of  $^{40}\text{K}$ ,  $^{232}\text{Th}$  and  $^{226}\text{Ra}$  in the building materials (ceramics, sand, lime, cement, soil) and it was found that that their values vary from 24,3 to 121,5 Bq/kg, 14 to 67,3 Bq/kg and 3,1 to 151,7 Bq/kg, respectively [3].

$^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  activities were determined by using NaI(Tl) detector in the samples of sand, brick, and cement collected around the province of Manisa and their level were calculated to be 149,79-1556,10 Bq/kg, 20,68-142,10 Bq/kg and 68,52-1711,47, respectively [4].

Manys studies were carried out to determine the natural radiation field in the south-west coast of India (Radhakrishna et al., 1993). Due to the establishment of nuclear and thermal power stations in the south-west of the city of Karnataka in India, these studies were again carried out. The thermoluminescent dosimetric studies have shown that there are high gamma doses in the air around of these settlements. The measured gamma dose were measured in the range of 44 and 2102 nGyh<sup>-1</sup>. The gamma spectrometric analyses of the soil and sand samples of this high background area have been also carried out. The average activity of  $^{232}\text{Th}$ ,  $^{238}\text{U}$ , and  $^{40}\text{K}$  in soil samples were obtained as 2,971 Bq kg<sup>-1</sup>, 546 Bq kg<sup>-1</sup>, and 268 Bq kg<sup>-1</sup>, respectively. In sand samples, the respective activities are equal to 1,842 Bq kg<sup>-1</sup>, 374 Bq kg<sup>-1</sup>, and 158 Bq kg<sup>-1</sup> [5].

In 2003, the natural radioactivity of tar sand was measured using coaxial germanium detector by M.K. Fasasi et al. in Nigeria. The activity of  $^{214}\text{Bi}$  ( $^{238}\text{U}$ ) and  $^{208}\text{Tl}$  ( $^{232}\text{Th}$ ) were measured to be 165.64 Bq/kg and 150.25 Bq/kg [6].

In a study conducted in Mexico,  $^{40}\text{K}$ ,  $^{238}\text{U}$  and  $^{232}\text{Th}$  series concentrations were determined from the soil using high-resolution gamma spectrometry. Values for  $^{238}\text{U}$  and  $^{232}\text{Th}$  series are about 30 Bq/kg. Using liquid scintillation counter, the  $^{226}\text{Ra}$  concentration in drinking water was found as 4.3-42 kBq/m<sup>3</sup> [7].



R. Keser et al. (2004) measured the natural  $^{238}\text{U}$  and  $^{232}\text{Th}$  average activities in Rize Firtina Valley of soil samples as 65 Bq/kg and 64 Bq/kg, respectively. The average value of the activities of the  $^{238}\text{U}$  and  $^{232}\text{Th}$  in Firtina Valley sediment samples are approximately 50 Bq/kg and 53 Bq/kg [8].

The natural radioactivity in soil samples of Kocaeli was determined by Karakelle et al. using HPGe detector and they have found that the activities of  $^{238}\text{U}$ ,  $^{40}\text{K}$  and  $^{232}\text{Th}$  were 11-49 Bq/kg, 161-964 Bq/kg and 11-65 Bq/kg, respectively [9].

In Cyprus, a study was conducted by Michalis Tzortzis to measure the activity concentrations of  $^{232}\text{Th}$ ,  $^{238}\text{U}$  and  $^{40}\text{K}$  in characteristic geological rocks using gamma-ray spectroscopy and he measured their values as 1.3-52.8 Bq/kg, 0.9-90.3 Bq/kg and 13-894 Bq/kg, respectively [10].

In Libya, the levels of natural radioactivity in the soil were measured by M.A. Shenber using HPGe detector and he measured that the  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  activity concentrations were equal to 10.5, 9.5, and 270 Bq/kg, respectively [11].

20 pieces beach sand samples from the coast of the Black Sea region of Kocaeli Province were analyzed using HPGe detector by Z. Korkulu. It was found that the activity of  $^{238}\text{U}$ ,  $^{232}\text{Th}$ ,  $^{40}\text{K}$ ,  $^{137}\text{Cs}$  varies between the values 4.41 and 14.4 Bq/kg, 2.62 and 16.55 Bq/kg, 11.6 and 513.3 Bq/kg, and 0.56 and 5.43 Bq/kg, respectively.. According to the measured values, the gamma dose rates calculated for all the beaches range from 4.10 to 36.80 nGy/h and the average annual effective dose rates were found to be ranging from 5.05 to 45.25  $\mu\text{Sv/h}$  [12].

In 1999, the natural radionuclide activity concentrations of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in surface soils of Istanbul were measured as 21, 37 and 342 Bq / kg, respectively, by using the method of gamma spectroscopy [13].

In 2003, the natural radioactivity in soil in India was measured using NaI(Tl) dedector by S. Singh and et al. and the activity concentration of  $^{40}\text{K}$  ranges from 143.7 to 228.9 Bq/kg; activity concentration of  $^{232}\text{Th}$  ranges from 35.2 to 122.8 Bq/kg and the activity concentration of  $^{226}\text{Ra}$  ranges from 25.1 to 75.7 Bq/kg. These measurements were carried out by using samples weighing 250 g. In addition, the equivalent activity of  $^{226}\text{Rn}$  was calculated to be between 90.88- 275.33 Bq / kg in that study [14].

The natural radioactivity of soil samples was measured with NaI(Tl) detector in the west of Australia and the average activities of  $^{40}\text{K}$ ,  $^{232}\text{Th}$  and  $^{238}\text{U}$  were found as 160, 2.8 and 3.6 Bq/kg, respectively [15].

This study was conducted to determine the level of natural radioactivity in building materials used in Gaziantep region. For this purpose, 20 soil samples were collected from the region and the measurements were performed by using a gamma spectrometry system. Natural gamma radioactivity levels of samples were determined by using the obtained spectra and the absorbed dose rate, the effective dose rate, the external hazard index, the gamma index and the radium equivalent activity were calculated.

The radiation concept, types of ionizing radiation, radioactive decay law and units of ionizing radiation were described in Chapter 2. At the end of this chapter, the natural and artificial sources of radiation and their whereabouts were also discussed. The section of material and methods were given in the Chapter 3. In this chapter, the gamma spectrometry systems used in the determination of the gamma radiation; information about the features of the instruments used in the experiments were described. The obtained data and calculations were given in Chapter 4. Evaluation of the results was provided in Chapter 5.

## **2. THEORY**

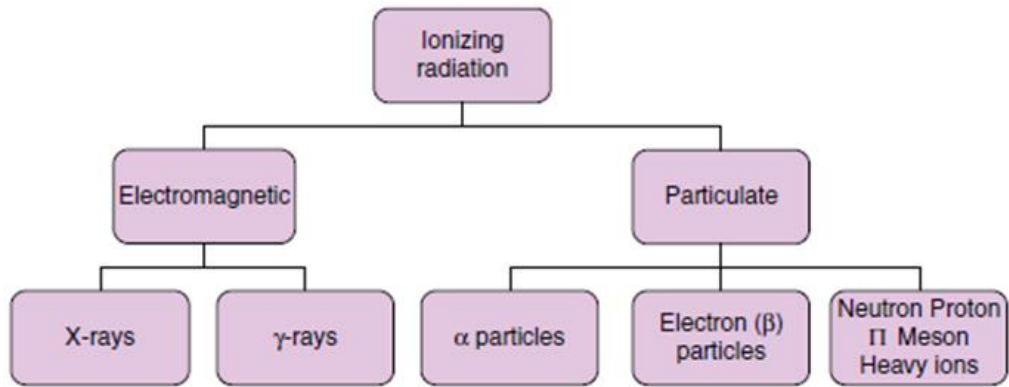
### **2.1. Radiation**

Radiation is called the spread of energy from a radioactive source to another medium [16]. This transfer of energy can take the form of electromagnetic radiation (i.e., electromagnetic waves) or particulate radiation. The different forms of radiation originating from atoms are classified together under the terms "the electromagnetic spectrum" or "electromagnetic radiation". Photon is the smallest unit of electromagnetic radiation and photons have no mass. Electromagnetic radiation spreads in a straight line and move at nearly 300.000 km/s speed of light. When electromagnetic radiation passes a medium, it transfers energy. This amount of energy transferred increases with increasing frequency, decreases with decreasing wavelength of radiation. The radiation energy is reduced passing through a material, due to scattering and absorption, this decrease in energy is negatively correlated with the square of the distance traveled through the material.

There are two types of electromagnetic radiation; nonionizing and ionizing radiations. Wavelengths of nonionizing radiations is  $\geq 10^{-7}$  m and energies of nonionizing radiations is  $< 12$  electron volts (eV). Nonionizing radiations have lowest energy in electromagnetic spectrum. Types of nonionizing electromagnetic radiation: Radio waves, Microwaves, Infrared light, Visible light and Ultraviolet light.

### **2.2. Ionizing Radiation**

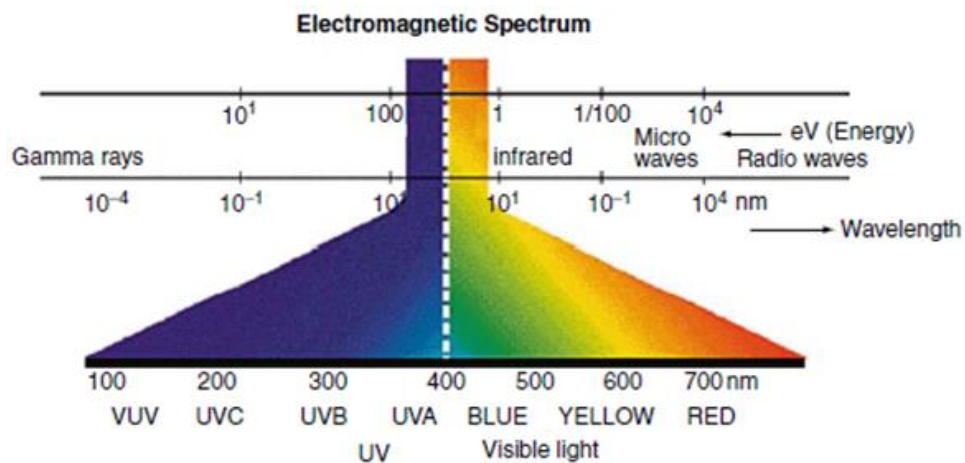
Ionizing radiations have highest energy in electromagnetic spectrum and they have ability to remove electrons from atoms; to ionize the atoms. Ionizing radiation can also be subdivided into electromagnetic and particulate radiations (Figure 2.1).



**Figure 2.1** Ionizing Radiations [16]

### 2.2.1. Ionizing Electromagnetic Radiation

The electromagnetic spectrum includes all types of electromagnetic radiation, ranging from ionizing radiations (high energy, short wavelength, high frequency) to radio waves (low energy, long wavelength, low frequency) (Figure 2.2).



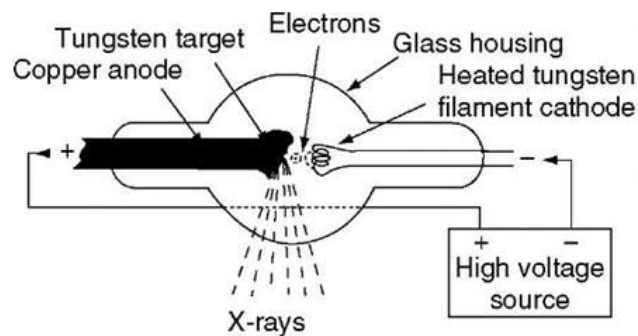
**Figure 2.2** Electromagnetic Spectrum [16]

When low-frequency radiation interacts with matter, electrons are separated from their atomic and molecular orbits. This process is called as ionization. Secondary electrons are produced by those electrons pending their passage through the material.

#### 2.2.1.1. X-Rays

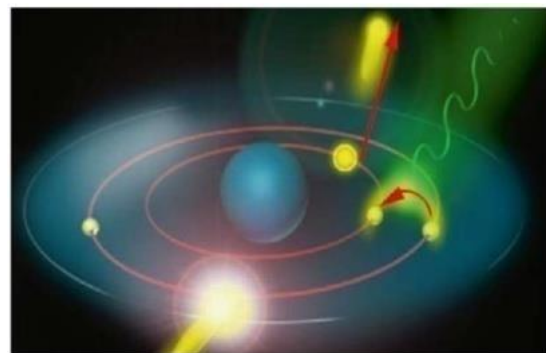
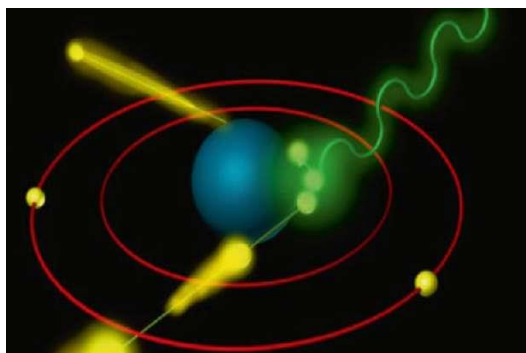
The German physicist Wilhelm Conrad Roentgen discovered X-rays in 1895. William David Coolidge developed the hot cathode Rontgen tube in 1913. The hot cathode Rontgen tube is a pressured (to  $10^{-3}$  mmHg) glass tube consisting of anode and cathode layers between which a high-energy ( $10^6$  - $10^8$  V) potential is applied

(Figure 2.3). The potential accelerate electrons produced by thermoionic emission in the cathode towards the anode. They thus hit the anode, which is a metal with high melting temperature. The sudden deceleration of these electrons produce X-ray due to Coulomb interactions with nuclei in the anode (this sudden deceleration of fast-moving electrons is known as bremsstrahlung; (Figure 2.4). The energy and the wavelength of the X-rays depend on the atomic number of the target (anode) metal, as well as the velocity and the kinetic energy of the electrons.



**Figure 2.3** Schematic representation of an X-ray tube [16]

X-rays are produced by extranuclear procedures. Two kinds of X-rays are created by X-ray tubes. The first type corresponds to the bremsstrahlung X-rays mentioned above. The second type occurs because an electron in an inner atomic orbital is knocked out by an incoming electron, and the resulting space in the orbital is filled by other electron that moves from an outer atomic orbital (Figure 2.5). This electron must shed energy to move in this manner, and the energy released is radiated as characteristic X-rays. They are characteristic due to the fact that their energy depends on the target metal onto which the electrons are accelerated.

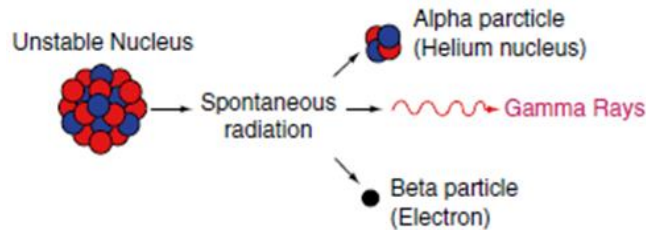


**Figure 2.4** Bremsstrahlung process [16] **Figure 2.5** Characteristic X-ray generation

X-rays produced by bremsstrahlung have a broad energy spectrum ( $\rightarrow$  heterogeneous), while characteristic X-rays are monoenergetic beams.

### 2.2.1.2. Gamma ( $\gamma$ ) Rays

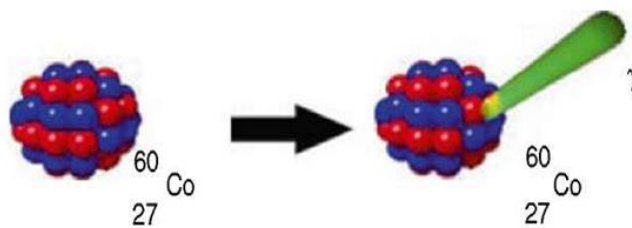
Gamma rays are physically identical to X-rays, but they are emitted from atomic nuclei (intranuclearly). An unstable atomic nucleus sheds its excess energy in the form of either an intranuclear electron ( $e^-$ ) (beta particle) or a helium nucleus (an "alpha particle") (Figure 2.6). If it still possesses excess energy after that, gamma rays are emitted in order to reach its steady state (Figure 1.7).



**Figure 2.6** Alpha particle generation [16]

The decay of a radioactive nucleus is a spontaneous process. There are three forms of radioactive decay. Alpha or beta particles are emitted during the alpha and beta decays of an unstable nucleus in order to reach a stable nucleus. A gamma decay occurs without any change in the form of the nucleus.

**Gamma Emission:** A nucleus is not always fully stable (i.e., at its basal energy level) just after it decays; sometimes, the nucleus will be in a semi-stable state instead (Figure 2.11). The excess energy carried by the nucleus is then emitted as gamma radiation. There is no change in the atomic or mass number of the nucleus after this decay, so it is termed an "isomeric" decay. The half-lives of gamma radiation sources are much shorter than sources of other types of decay, and are generally less than  $10^{-9}$  s. However, there are some gamma radiation sources with half-lives of hours or even years. Gamma energy spectra are not continuous.



**Figure 2.7** Gamma emission [16]

**Isotope:** Atoms with the same atomic number but different mass numbers are called isotopes (e.g.,  $^{11}_6\text{C}$ ,  $^{12}_6\text{C}$ ,  $^{13}_6\text{C}$ ).

**Isotone:** Atoms with the same number of neutrons, but different numbers of protons are called isotones (e.g.,  $^9_3\text{Li}$ ,  $^{10}_4\text{Be}$ ,  $^{10}_5\text{B}$ ,  $^{12}_6\text{C}$ ).

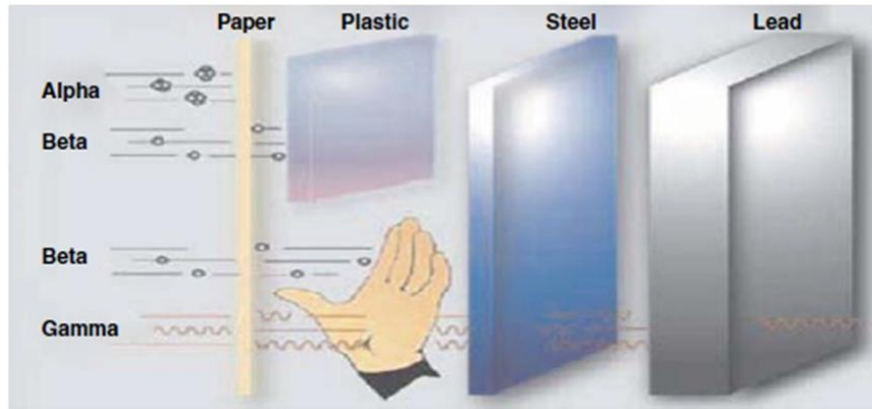
**Isobar:** Atoms with the same number of nucleons but different numbers of protons are called isobars (e.g.,  $^{12}_5\text{B}$ ,  $^{12}_6\text{C}$ ,  $^{12}_7\text{N}$ ).

**Isomer:** Atoms with the same atomic and mass numbers but which are in different energy states are called nuclear isomers ( $\text{Tc}^{99\text{m}}$ )

### 2.2.2. Ionizing Particulate Radiation

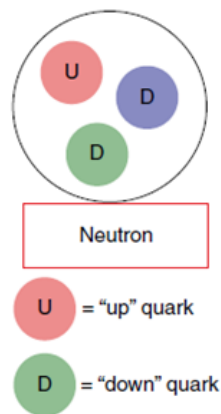
Electrons, protons, alpha particles, neutrons, pi mesons and heavy ions are all forms of ionizing particulate radiation.

Electrons, due to their negative charge and low mass, can be accelerated to high energies in linacs or betatrons. The mass of an electron is  $9.109\ 3826(16) \times 10^{-31}$  kg. The electrical charge of an electron is  $-1.6 \times 10^{-19}$  C. Electrons are normally bound to a (positively charged) nucleus. The number of electrons is equal to the number of protons in a neutral atom. However, an atom can contain more or less electrons than protons, in which case it is known as a negatively or positively charged ion, respectively. Electrons that are not bound to an atom are called free electrons; free electrons can be produced during nuclear decay processes, in which case they are called beta particles. Electrons have much smaller ranges (i.e., they travel smaller distances) in matter than gamma and X-rays, and can be absorbed by plastics, glass or metal layers (Figure 2.12).

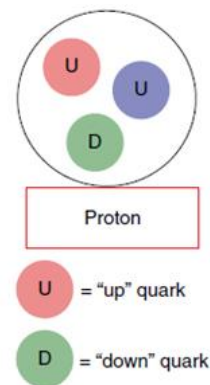


**Figure 2.8** Penetration ranges of various ionizing radiations [16]

Neutrons are the neutrally charged particles that enable the formation of stable large atomic nuclei (Figure 2.13) by decreasing the repulsion between the protons in the nucleus. However, neutrons, like protons, actually consist of particles called quarks; a neutron is one up quark and two down quarks, while a proton (Figure 2.14) is two up quarks and one down quark.



**Figure 2.9** Neutron [16]

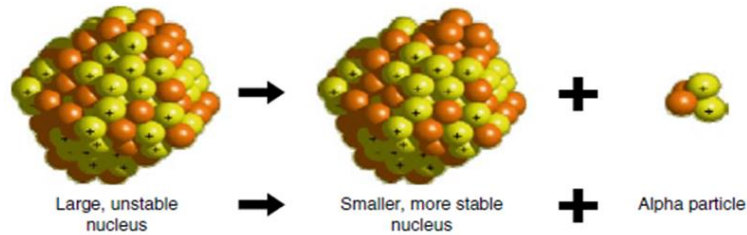


**Figure 2.10** Proton [16]

**Alpha Decay:** An alpha particle consisting of two protons and two neutrons is emitted if a nucleus is unstable because it has an excessive number of both protons and neutrons (Figure 2.7). After alpha decay, the alpha particle possesses most of the energy, due to the conservation of momentum and the fact that the alpha particle is much less massive than the residual nucleus. Although the  ${}^4_2\text{He}$  nucleus is very energetic, does not travel very far compared to most forms of radiation, due to its relatively heavy mass. Alpha decay is usually observed in nuclei with mass numbers of more than 190. The energy spectrum of alpha decay is not continuous, and varies

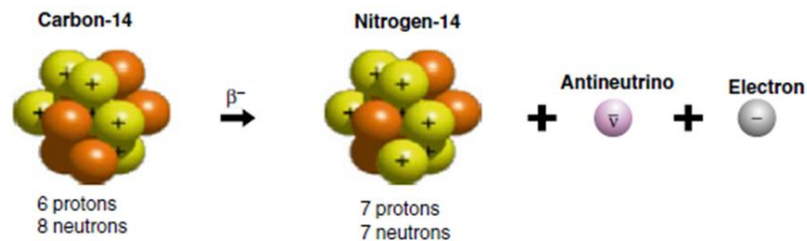


between 4 and 10 MeV. Alpha particles strongly interact with the electrons of the matter through which they pass, since they are charged particles.



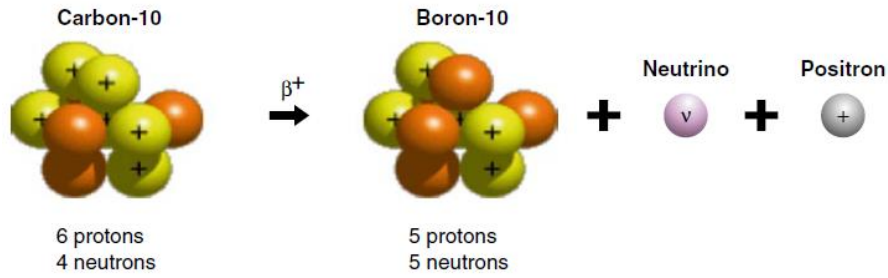
**Figure 2.11** Alpha decay [16]

**Beta Decay:** There are three types of beta decay. If a radionuclide is unstable because it has an excess number of neutrons in its nucleus, it transforms one of the neutrons into a proton and an electron in order to reduce the amount of energy in its nucleus (Figure 2.8). The electron is rapidly propelled out of the nucleus, while the proton remains. This high-speed electron called a  $\beta^-$  particle or negatron, and the process is termed  $\beta^-$  decay. The atomic number of the radionuclide increases by one, and thus it changes into the next element in the periodic table. Note that the mass number does not change (it is an "isobaric" decay).



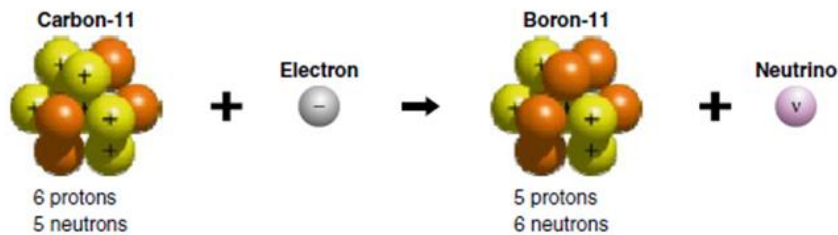
**Figure 2.12**  $\beta^-$  decay [16]

If a radionuclide is unstable due to an excess amount of protons or a lack of neutrons, one of the protons transforms into a neutron and a small positively charged particle called a positron in a process termed  $\beta^+$  decay. The neutron stays in the nucleus while the positron is propelled out of it (Figure 2.9). The atomic number of the radionuclide that emits the positron decreases by one, and thus it changes into the preceding element in the periodic table. Again, note that the mass number does not change.



**Figure 2.13**  $\beta^+$  decay [16]

If the nucleus is unstable due an excess amount of protons, one of the electrons close to the atomic nucleus, such as an electron in a K and L orbital, is captured by the nucleus (Figure 2.10). This electron then combines with a proton, yielding a neutron and a neutrino. This process is called *electron capture*. Note that no particle is emitted from the nucleus, but the atomic number decreases by one, as in positron decay. Yet again, the mass number does not change. The space in the inner orbital is filled by an electron from an outer orbital, resulting in the emission of characteristic X-rays.



**Figure 2.14** Electron capture phenomenon [16]

In all three types of beta decay, the mass number of the nucleus remains constant during the decay, while the numbers of protons and neutrons change by one unit. Furthermore, the emission of some massless, uncharged particles called neutrinos and antineutrinos is observed during each beta decay process. The existence of these particles was first suggested by Pauli in 1930, although it was Fermi that provided the name "neutrino".

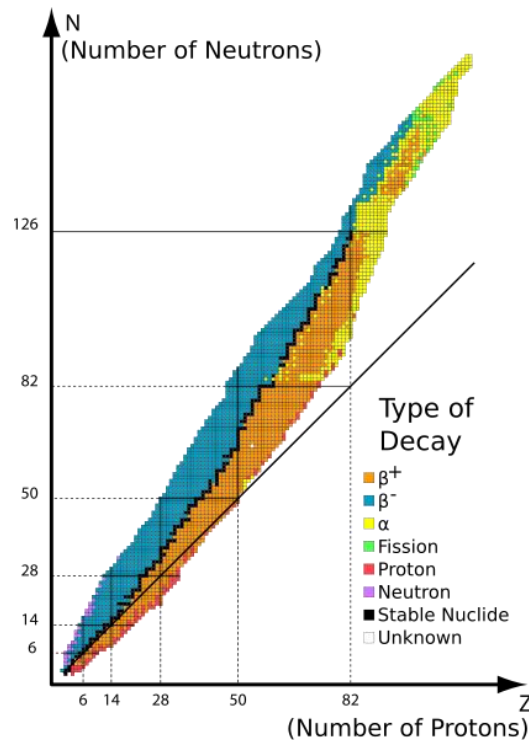
## 2.3. Radioactivity

### 2.3.1. Radioactivity and Radioactive Decay Law

Nuclei, with the same atomic number ( $Z$ ) and different mass number ( $A$ ) or neutron number ( $N$ ) are called isotope [1]. Stable isotopes are nuclei that do not change spontaneously over time. In contrast, the unstable radioactive nuclei are isotopes that change over time.

Nuclei with small atomic number tend to have equal number of neutrons and protons ( $N=Z$ ). If atomic number is increased, neutron number is increased faster than atomic number ( $N>Z$ ). Figure 2.15 shows neighboring nuclei to stability bar. According to the figure 2.15,  $N$  is approximately equal to  $Z$  ( $N \cong Z$ ) for small  $Z$  values and  $N \cong 1.6 \cdot Z$  for larger values.

There are approximately 250 stable isotopes. The numbers of stable isotopes vary with atomic number and neutron count is odd or even. In approximately 60% of stable isotopes, both atomic number and neutron count is even; in 20% of them, atomic number is even and neutron count is odd; in the other 20% of stable isotopes both atomic number and neutron count is odd. In only 5 stable isotopes, both atomic number and neutron count is odd.



**Figure 2.15** Graph of number of neutron versus to number of proton [17]

Unstable nuclei fling off excess energy carried by their by emitting particle or radiation. This event making conversion itself or emitting radiation is called radioactivity. Transformed into a nucleus to another isotope particle self-releasing or event the same isotope turned into another state is called radioactive decay.

Radioactive decay of radioactive atoms of a radioisotope is time-independent and represents completely a coincidental character. Number of fragments is proportional to only the current number of atoms and refers to number of decay per unit of time. Experimental results show that the properties of radioactive decays are exponential. In a radioactive disintegration, if decay constant  $\lambda$  indicates the decay probability per unit time, decay probability of any nucleus is  $\lambda dt$  for a  $dt$  time. If there are  $N$  radioactive nuclei at  $t$  moment, decayed number of nuclei in time  $t+dt$  is

$$dN = -\lambda N dt \quad (2.1)$$

The minus sign on the left side of the equation shows that the number of radioactive atoms decreases (inversely proportional) with increasing over time. Assuming that number of radioactive nuclei is  $N_0$  at  $t=0$  and if either side of Eq.(2.1) divided by  $N$ , then the equation is integrated with substituting boundary conditions;

$$N = N_0 e^{-\lambda t} \quad (2.2)$$

Eq.(2.2) is found. Where,  $N$  is the number of radioactive nuclei at any  $t$  time. This law, according to Eq.(2.2), the number of radioactive nuclei varies over time, is radioactive decay law. According to the time derivate of both side of Eq.(2.2);

$$\begin{aligned} A &= -\frac{dN}{dt} \\ A &= \lambda N \end{aligned} \quad (2.3)$$

where  $A$  is the activity. Another important characteristic value of radioactive substances is the half-life. Half-life, abbreviated  $t_{1/2}$ , is the period of time it takes for the amount of a substance undergoing decay to decrease by half. To determinate half-life, in Eq.(2.2) if  $t$  equal to  $t_{1/2}$  and  $N$  equal to  $N_0/2$ , correlation between half-life and decay constant is

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \quad (2.4)$$

The average time that has undergone until decaying of a nucleus is called mean lifetime ( $\tau$ ).  $N$  is the number of nuclei remaining intact in time  $t$  and  $t + dt$  ranges the number of decay nuclei is  $|dN / dt| dt$ . In this case, the mean lifetime,

$$\tau = \frac{\int_0^{\infty} t |dN / dt| dt}{\int_0^{\infty} |dN / dt| dt} \quad (2.5)$$

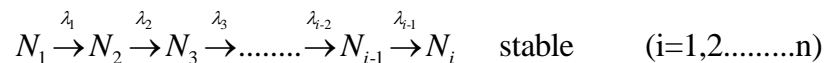
equation is written. Term at denominator is the total number of nuclear decays. The integral is taken,

$$\tau = \frac{1}{\lambda} \quad (2.6)$$

is found. Mean lifetime, simply, is the opposite of decay constant.

### 2.3.2. Sequential Decay Law

Radioactive isotopes decay may occur in case of successive ruptures[18]. The main radioactive element to another product, the product of radioactive decay is another element. This decay ends up the product being a decisive element. A radioactive decay, such as  $N_1, N_2, N_3, \dots, N_{i-1}, N_i$  the actual process resulted in the radioactive product. This process is continued until the latest stable isotope.



Here,  $N_1, N_2, N_3, \dots, N_{i-1}, N_i$  ( $N_i$  stable nucleus) members of any series of degradation at time  $t$  and  $\lambda_1, \dots, \lambda_i$ , indicate decay constants of these radioactive nuclei. At any  $t$  time the number of nuclei, description of the activity, the number of decay per unit of time, given to the following differential equations :

$$\begin{aligned} \frac{dN_1}{dt} &= -\lambda_1 N_1 \\ \frac{dN_2}{dt} &= \lambda_1 N_1 - \lambda_2 N_2 \\ \frac{dN_i}{dt} &= \lambda_{i-1} N_{i-1} - \lambda_i N_i \end{aligned} \quad (2.7)$$

Solutions of these equations depend on the initial conditions. For the initial time  $t = 0$  there is only the main nucleus, if we accept that daughter and grandchildren are not available nuclei :  $N_1=N_{10}$  and  $N_2=N_3=N_4=.....=N_i=0$ . Thus,

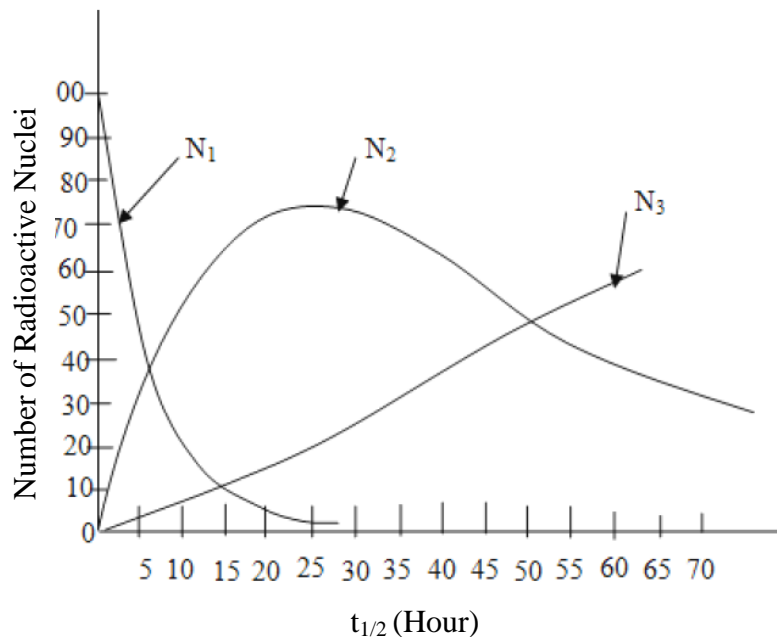
$$N_1 = N_{10}e^{-\lambda_1 t}$$

$$N_2 = N_{10}\lambda_1 \left[ \frac{e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_2 - \lambda_1)} \right] \quad (2.8)$$

the complete solution:

$$N_i = N_{10} \prod_{j=1}^{i-1} \lambda_j \sum_{j=1}^{j=i} \frac{e^{-\lambda_j t}}{\prod_{\substack{k=1 \\ k \neq j}}^{k=i} (\lambda_i - \lambda_k)} \quad (2.9)$$

are obtained in the form. In sequential decay change over time the number of nuclei Fig.2.16 is also shown.



**Figure 2.16** Graph of Sequential Decay [1]

### 2.3.3. Radioactive Equilibrium

When we apply some special cases to the decay chain equations, the two equilibrium occur. First of these special cases occurs when  $\lambda_1 \cong \lambda_2$ , this case is temporary equilibrium. Second case occurs when  $\lambda_1 < \lambda_2$ , this case is stable equilibrium.

### 2.3.3.1. Transient Equilibrium

Consider that  $\lambda_1$  is the decay constant of one main nucleus and  $\lambda_2$  is decay constant of its product. Suppose that the same extent to the average life of these two types nucleus and thus  $\lambda_1 \cong \lambda_2$ . In this case,

$$N_2 = \frac{\lambda_1}{(\lambda_2 - \lambda_1)} N_{10} (e^{-\lambda_1 t} - e^{-\lambda_2 t}) \quad (2.10)$$

at this equation if take derivative according to t and and set equal to zero, find  $t_m$  which  $N_2$  reaches maximum value. After  $t_m$  time,  $\lambda_1$  and  $\lambda_2$  whichever is smaller will be effective on decay rate. Here it is;

- i) if  $\lambda_1 < \lambda_2$ , at Eq.(2.10)  $e^{-\lambda_2 t}$  term quickly reach zero, and therefore the term can be omitted. So,

$$N_2 = \frac{\lambda_1}{(\lambda_2 - \lambda_1)} (N_{10} e^{-\lambda_1 t}) \quad (2.11)$$

$$N_2 = \frac{\lambda_1}{(\lambda_2 - \lambda_1)} N_1 \quad (2.12)$$

Eq.(2.12) shows that first product decay with decay constant of main nucleus.

- ii) if  $\lambda_2 < \lambda_1$ ,

$$N_2 = \frac{\lambda_1}{(\lambda_2 - \lambda_1)} (-N_{10} e^{-\lambda_2 t}) \quad (2.13)$$

This equation shows that after a certain time first product decay with itself decay constant  $\lambda_2$ .

### 2.3.3.2. Secular Equilibrium

Let us consider the status of the  $\lambda_2 \ll \lambda_1$  at Eq.,(2.10). In this instance, it will be  $\lambda_2 - \lambda_1 \cong \lambda_2$  and  $e^{-\lambda_1 t} \cong 1$

$$N_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_{10} (1 - e^{-\lambda_2 t}) \quad (2.14)$$

Moreover, if t is greater than the mean lifetime of the product element ( $t \gg 1/\lambda_2$ ),  $e^{-\lambda_2 t}$  term goes to zero.

$$N_2 = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_{10} \quad (2.15)$$

This expression shows that  $N_2$  is fixed. In this expression, activity has stopped and there is a continuous equilibrium between the main element and first product element. The main element is a huge amount of half-life is almost constant ( $N_{10}=N_1$ ). Because of

$$\lambda_1 N_1 = \lambda_2 N_2 \quad (2.16)$$

continuous equilibrium condition is obtained.

### 2.3.4. Natural Radioactive Series

Natural radioactive series consisted of three groups as Thorium, Uranium and Actinium. Natural radioactive series and features are given Table 2.1.

**Table 2.1** Natural Radioactive Series

Name of Serie	The longest life member		
	Nucleus	Half-life (year)	Last Product (Stable)
Uranium	$^{238}\text{U}$	$4,47 \times 10^9$	$^{206}\text{Pb}$
Thorium	$^{232}\text{Th}$	$1,41 \times 10^{10}$	$^{208}\text{Pb}$
Actinium	$^{235}\text{U}$	$7,04 \times 10^8$	$^{207}\text{Pb}$

#### 2.3.4.1. Uranium Series

Features given in the table 2.2 with three isotopes of uranium is a naturally occurring element in nature. There are lower amounts of uranium in layers of rock and soil that produce building materials. Uranium decay chain is seen Figure 2.17.

**Table 2.2** Isotopes of Natural Uranium

Isotope	Half-life (year)	Natural Abundance
$^{238}\text{U}$	$4,47 \times 10^9$	% 99,29
$^{235}\text{U}$	$7,04 \times 10^8$	% 0,71
$^{234}\text{U}$	$2,45 \times 10^5$	% 0,006



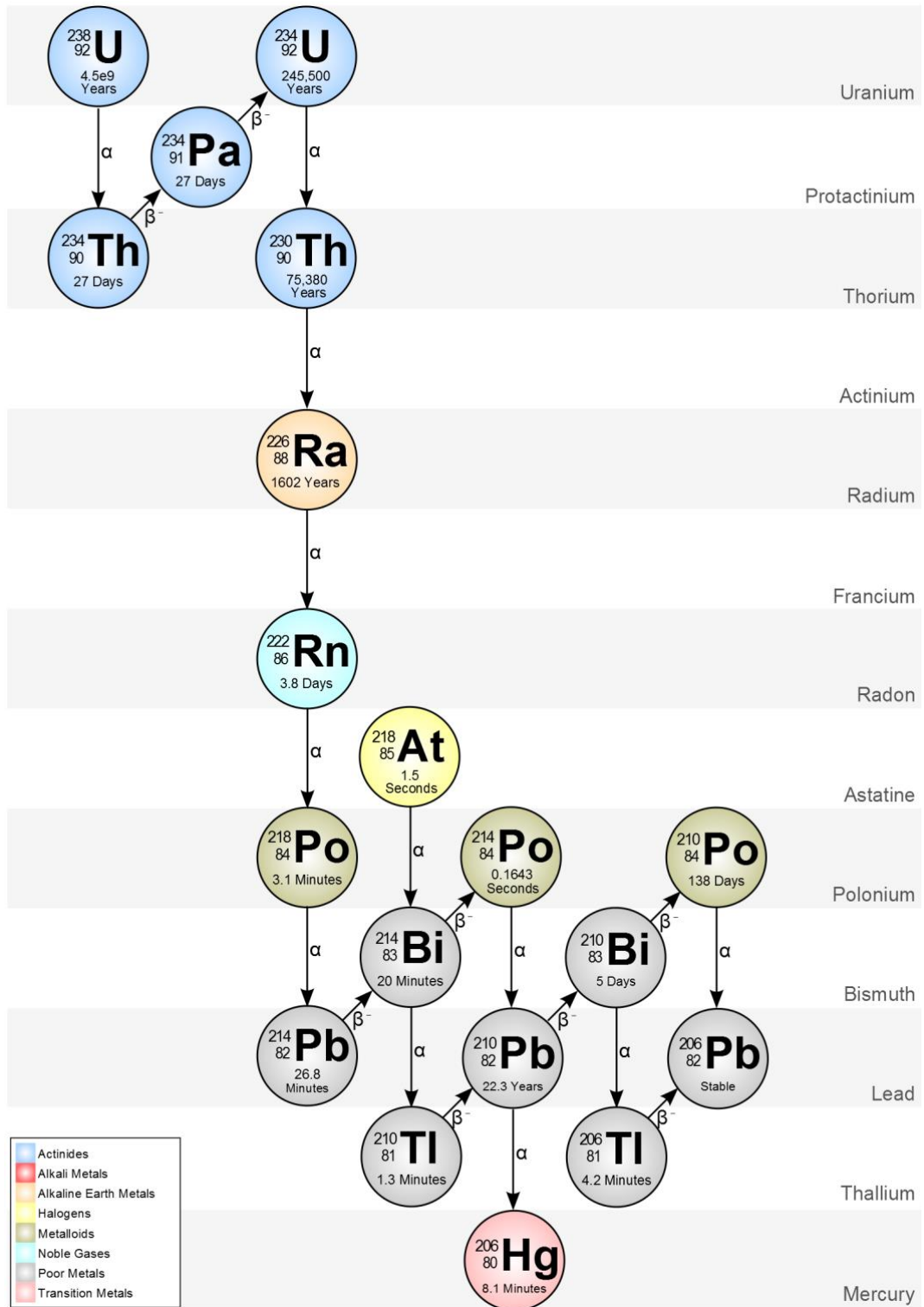


Figure 2.17  $^{238}\text{U}$  Series Decay Chain [19]

$^{238}\text{U}$  emits 8  $\alpha$  and 6 $\beta$  and decays until it turns to last non-radioactive daughter  $^{206}\text{Pb}$ . Situated among the first products consisting and especially in indoor environments  $^{222}\text{Rn}$  gas is very important for human health.

Uranium series gamma spectrum is very complex, so there is no peak characteristic to make quantitative measurements. Uranium spectrum has many gamma peaks and 1760 keV peak of  $^{214}\text{Bi}$  is used to make quantitative analysis.

### 2.3.4.2. Thorium Series

Nuclides of thorium series contain 11 products. There is a complex spectrum of thorium series and almost all of them are always unstable. Thorium decay chain is given in Figure 2.18. The appropriate gamma peak of thorium series used in analysis is 2615 keV energy peak of  $^{208}\text{Tl}$ .

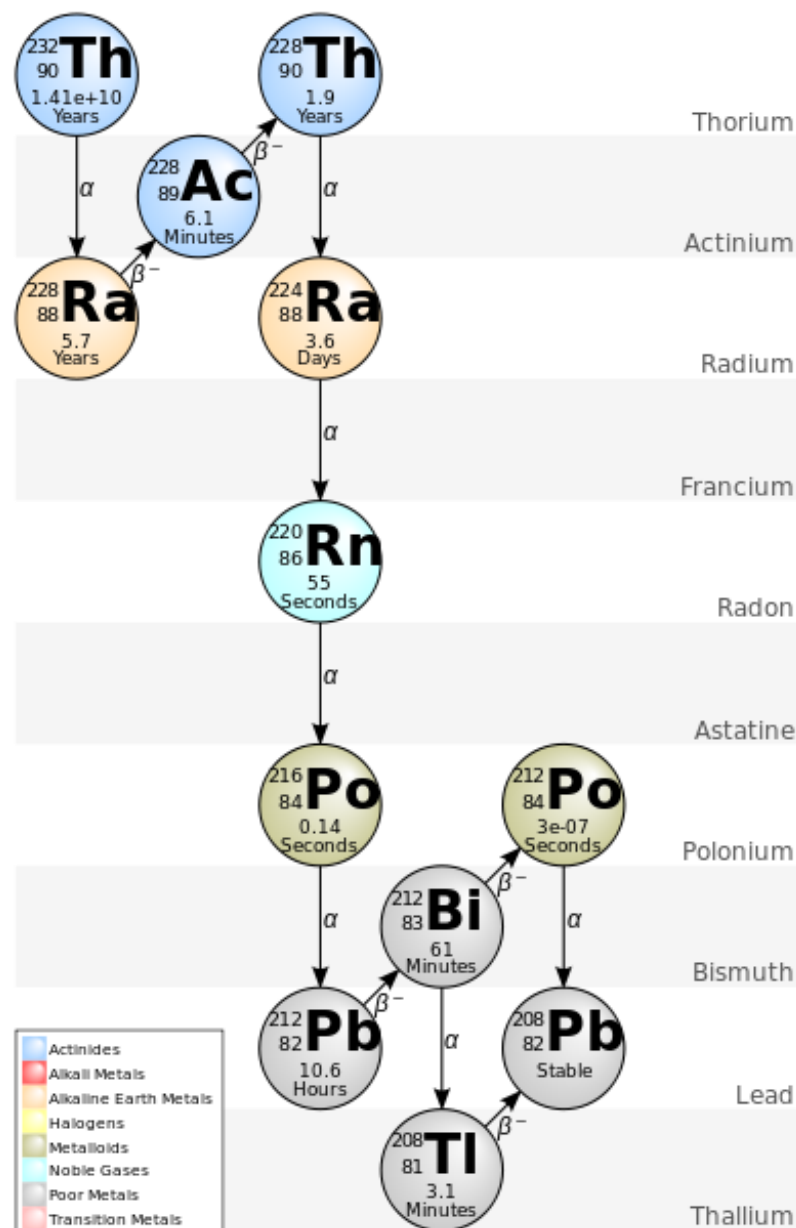
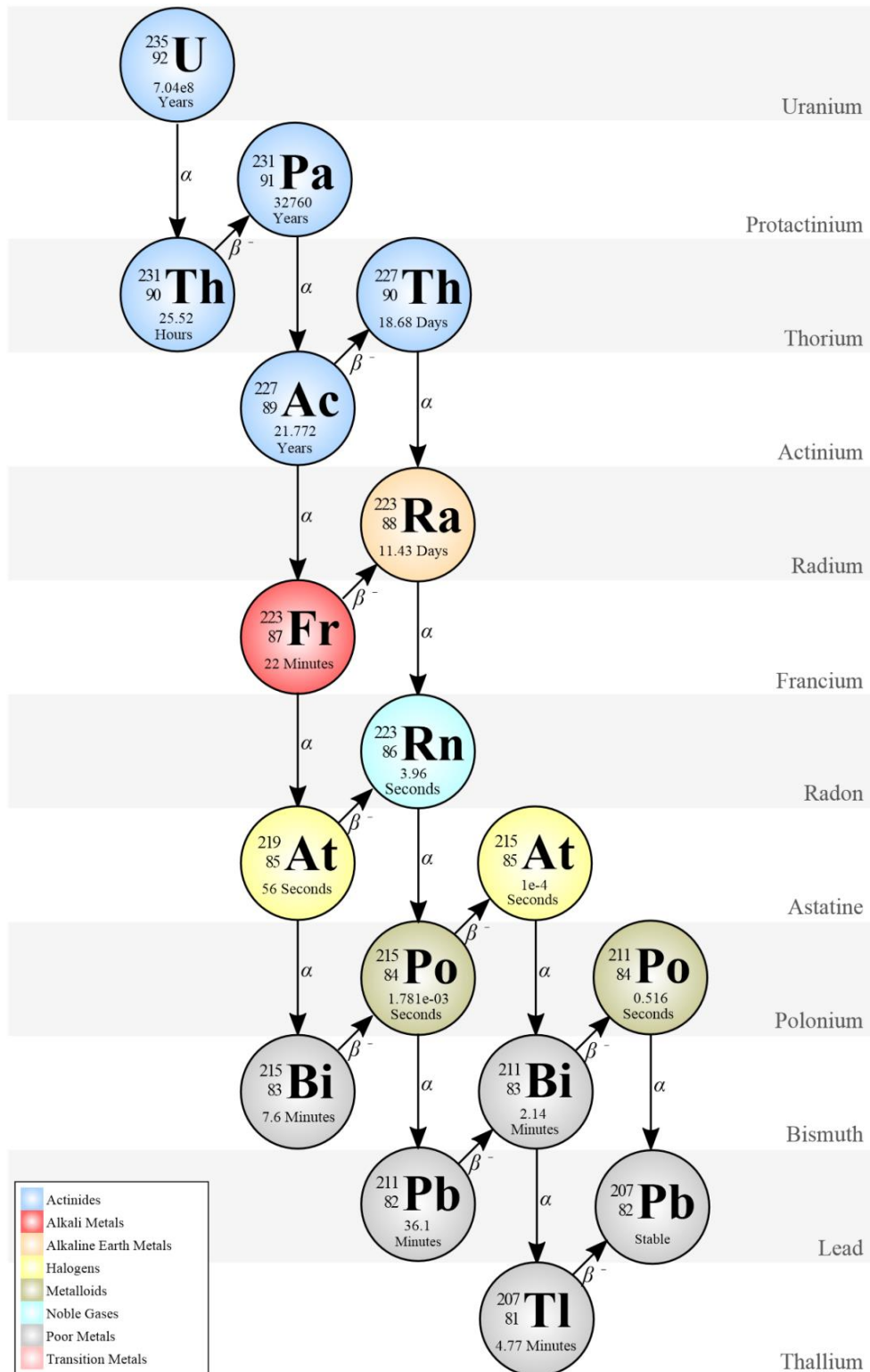


Figure 2.18  $^{232}\text{Th}$  Series Decay Chain [19]

### 2.3.4.3. Actinium Series

$^{235}\text{U}$  is the main element of the series and natural abundance of  $^{235}\text{U}$  is %0.72.

Ending with  $^{207}\text{Pb}$  isotope. Actinium series decay chain is given in Figure 2.19.



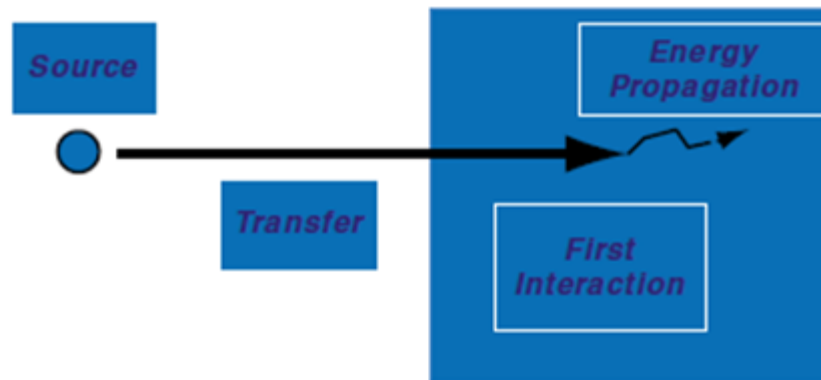
### 2.3.5. Potassium 40

Potassium in the crust which is equal to 2.6% is an important element. Small amount of natural potassium (0.12%) is radioactive  $^{40}\text{K}$ . Gamma ray energy of 1.461 MeV is released as a result of decay of  $^{40}\text{K}$ . After the decay, nucleus produced is stable. Abundance of radioactive potassium is approximate 0.012 and half-life is  $1.26 \times 10^9$  year and specific activity is 3.3 Bq/g.

### 2.4. Ionizing Radiation Units

The amount of radiation delivered needs to be known in order to determine possible harmful biological effects and to reach definite conclusions in studies that use ionizing radiation. Specific units are required for radiation measurement. The measured quantities associated with ionizing radiation can be briefly summarized as follows (Figure 2.17):

Source → activity units  
The first interaction point → kinetic energy released in matter (kerma)  
Matter → absorbed dose



**Figure 2.20** Three points of associated with ionizing radiation measurement

**Activity unit.** This is the number of spontaneous nuclear disintegrations ( $N$ ) per unit time ( $t$ ) ( $A = N/t$ ), as measured in becquerels (Bq). Note that an older system of units, the curie (Ci), is also often encountered.

**Radioactivity:** This is the transition of an unstable nucleus to a steady state through the emission of particulate or electromagnetic radiation from the nucleus.

**Curie (Ci):** This is an activity of  $3.7 \times 10^{10}$  disintegrations per second.

**Becquerel (Bq):** This is an activity of one disintegration per second and  $1 \text{ Bq} = 2.7 \times 10^{-11} \text{ Ci}$  or  $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$ .

*Kerma (kinetic energy released in the medium):* This is the sum of the initial kinetic energies of all of the charged particles liberated by uncharged ionizing radiation (neutrons, protons) in a sample of matter divided by the mass of the sample. The kerma is measured in the same units as absorbed dose (Gy).

The *reference air kerma* is used to define the visible activity. It is the dose delivered in one hour to air one meter away from a source with an activity of 1 MBq. Its units are  $1 \mu\text{Gy}^{-1} \cdot \text{m}^2 = 1 \text{ cGy} \cdot \text{h}^{-1} \cdot \text{cm}^2$ .

*Absorbed dose:* The basic quantity associated with radiation measurement in radiotherapy is the absorbed dose. This defines the amount of energy absorbed from a radiation beam per unit mass of absorbent material. It is measured in grays (Gy), although an older unit, the rad, is also still used.

**Rad.** This is the amount of radiation that causes one erg (of energy) to be absorbed per gram of irradiated material (rad=radiation absorbed dose).

$$1 \text{ rad} = 100 \text{ erg/g.}$$

**Gray (Gy).** This is the amount of radiation that causes one joule to be absorbed per kilogram of irradiated material.

$$1 \text{ Gy} = 1 \text{ J/kg.}$$

$$1 \text{ Gy} = 100 \text{ cGy} = 100 \text{ Rad.}$$

**Exposure:** This is the amount of ionization produced by photons in air. Since it is impossible to directly measure the absorbed dose in tissue, the measurement of radiation is performed in air. The exposure is the amount of radiation required to liberate a positive or negative charge of one electrostatic unit of charge (esu) in  $1 \text{ cm}^3$  of dry air at standard temperature and pressure (this corresponds to the generation of approximately  $2.08 \times 10^9$  ion pairs). It is measured in coulombs per kilogram (C/kg), although the old unit of the roentgen (R) is also commonly encountered.

**Roentgen (R):** In normal air conditions ( $0^\circ\text{C}$  and 760 mmHg pressure), this is the amount of X-radiation or gamma radiation that produces  $2.58 \times 10^{-4}$  coulombs of electrical charge (in the form of ions) in one kilogram of air.

**C/kg:** In normal air conditions, this is the amount of radiation that produces one coulomb of electrical charge (in the form of ions) in one kilogram of air.

**Integral dose:** This is the total energy absorbed in the treated volume (in  $\text{J}=\text{kg} \times \text{Gy}$ ).

**Equivalent dose:** Since different radiations have different harmful effects on human tissues, the basic dosimetric unit of absorbed dose (Gy) is not sufficient for studies of radiation protection. Thus, the absorbed dose in tissue must be multiplied by a radiation-weighting factor that depends on the type of radiation employed. The resulting dose is called the equivalent dose, and it is measured in sieverts (Sv), although an older unit, the rem (roentgen equivalent man), is often used too.

$$H = D \times W_R \quad (2.17)$$

$H$  = equivalent dose (Sv)

$W_R$  = radiation-weighting factor (no unit)

$D$  = dose (Gy)

1 Sv = 1 J/kg = 100 rem

The roentgen and C/kg are only used for photonic radiation (X-rays and gamma rays), not for particulate radiation. The energies of therapeutic or diagnostic gamma rays and X-rays are in the kilovolt (kV) or megavolt (MV) range, while the energies of therapeutic electrons are in the megaelectronvolt (MeV) range. The most important radiation quantities and their units are listed in Table 1.1. Also listed are the definitions of the various quantities and the relationships between the old and the SI units for these quantities [20].

**Table 2.3** Radiation Quantities, Units and Conversion between old and SI units

Quantity	Definition	SI unit	Old unit	Conversion
<b>Exposure (X)</b>	$X = \frac{\Delta Q}{\Delta m_{air}}$	$2.58 \times \frac{10^{-4} C}{kg \text{ air}}$	$R = \frac{1 \text{esu}}{cm^3 \text{air}_{STP}}$	$1R = 2.58 \times \frac{10^{-4} C}{kg \text{ air}}$
<b>Dose (D)</b>	$D = \frac{\Delta E_{ab}}{\Delta m}$	$1Gy = 1 \frac{J}{kg}$	$1 \text{ rad} = 100 \frac{\text{erg}}{g}$	$1Gy = 100\text{rad}$
<b>Equivalent dose (H)</b>	$H = D w_R$	1 Sv	1 Rem	1 Sv=100 rem
<b>Activity (A)</b>	$A = \lambda N$	1 Bq=1 s <sup>-1</sup>	1 Ci=3.7×10 <sup>10</sup> s <sup>-1</sup>	1 Bq= $\frac{1 \text{ Ci}}{3.7 \times 10^{10}}$
<b>ΔQ</b>	<b>is the charge of either sign collected;</b>			
<b>Δm<sub>air</sub></b>	<b>is the mass of air;</b>			
<b>ΔE<sub>ab</sub></b>	<b>is the absorbed energy;</b>			
<b>Δm</b>	<b>is the mass of medium;</b>			
<b>w<sub>R</sub></b>	<b>is the radiation weighing factor;</b>			
<b>λ</b>	<b>is the decay constant;</b>			
<b>N</b>	<b>is the number of radioactive atoms;</b>			
<b>R</b>	<b>stands for roentgen;</b>			
<b>Gy</b>	<b>stands for gray</b>			
<b>Sv</b>	<b>stands for sievert</b>			
<b>Bq</b>	<b>stands for becquerel</b>			
<b>Ci</b>	<b>stands for curie;</b>			
<b>STP</b>	<b>stands for standart temperature (273.2 K) and standart pressure (101.3 kPa).</b>			

## 2.5. Radiation Sources

### 2.5.1. Natural Sources

There are three types of natural sources of radiation: cosmic, terrestrial, and internal [21]. Exposure from most of these sources is very minimal and therefore does not cause any measurable damage to our bodies. However, as it will be seen later in this section, there are some potentially hazardous materials, such as radon in our surroundings, which indeed are a cause of concern since they are capable to delivering high integrated doses.

#### 2.5.1.1. Cosmic Radiation Sources

The outer space is filled with radiation that comes from a variety of sources such as burning (for example, our Sun) and exploding (for example, Supernovae) stars. These bodies produce immense amounts of radiation, some of which reach earth. Fortunately the earth's atmosphere acts as a shield to the worst of these radiations, such as ultraviolet rays from the Sun are blocked by the ozone layer. However not all of the harmful radiation is blocked and some reach the surface of earth causing skin

burns and cancer in people who remain exposed to sun light for extended periods of time. The situation is even worse in places where the ozone layer has depleted due to some reasons.

On top of these localized sources of radiation there is also a background radiation of low energy photons. It is known as cosmic microwave background radiation since the photon spectrum peaks in the microwave region of the electromagnetic spectrum. Although these photons reach the earth's surface but due to their low energies, they are not deemed harmful.

Apart from photons, there are other particles as well that are constantly being produced in the outer space. Most of them, however, never reach the earth either due to magnetic deflection or the earth's upper protective atmosphere. Some of the particles, like muons, electrons, and neutrinos, are produced when other cosmic particles interact with atoms in the upper atmosphere. Shower of these particles reach earth's surface time but due to their low energies and low interaction probabilities, they do not pose any significant health hazard.

Muons and neutrinos directly produced by luminous objects in space also manage to reach earth due to their low interaction capabilities but are not considered hazardous to health due to their extremely low interaction cross sections.

#### **2.5.1.2. Terrestrial Radiation Sources**

This type of radiation is present in small quantities all around us and is more or less inescapable. Our surroundings, the water we drink, the air we breathe in, and the food we consume, all are contaminated with minute quantities of radiation emitting isotopes. Although these isotopes, in general, are extremely hazardous, they are not supposed to cause any appreciable harm to our bodies except when they are present in higher than normal concentrations.

The main source of terrestrial radiation is the element uranium and its decay products such as thorium, radium, and radon. Although the overall natural concentration of these radioactive materials is within the tolerable range of humans, some parts of the world have been identified where higher levels of uranium and thorium in surface soil have increased the radiation to dangerous levels. Unfortunately man has also



contributed to this dilemma by carrying out nuclear explosions and by dumping nuclear waste.

The two isotopes of radon,  $^{222}\text{Rn}$  and  $^{220}\text{Rn}$ , and their daughter products are the most commonly found hazardous radioactive elements in our surroundings. The main cause of concern with respect to these  $\alpha$ -emitting isotopes is their inhalation or digestion, in which case the short range  $\alpha$ -particles continue to cause damage to internal organs that can lead to cancer.

### **2.5.1.3. Internal Radiation Sources**

Human bodies contain some traces of radioactive elements that expose our tissues to continuous low level radiation. This internal radiation primarily comes from Potassium-40 and Carbon-40 isotopes. However the absorbed dose and the damage to tissues due to this radiation is minimal.

### **2.5.2. Man-Made Sources**

Right after the discovery of radiation and realization of its potentials, scientists started working on developing sources that can be used to produce radiation in controlled laboratory environments. These sources are made for specific purposes and generally give off one type of radiation. Common examples of such sources are

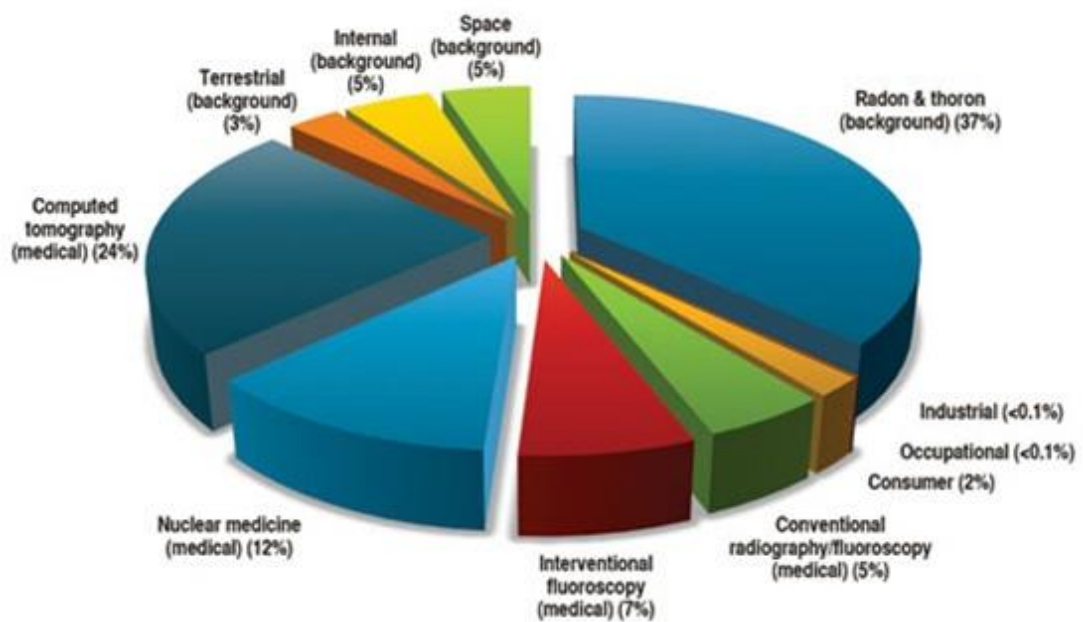
- ▶ medical x-ray machines,
- ▶ airport x-ray scanners,
- ▶ nuclear medicines,
- ▶ particle accelerators, and
- ▶ lasers.

Out of all these sources, the ones used in medical diagnostics and therapy expose the public to the most significant amounts of radiation. For example a single chest x-ray exposes the patient to about 20 mrem of radiation, which is a significant fraction of about 360 mrem of total radiation exposure to general public due to all types of radiation. Repeated x-rays of patients are therefore discouraged unless there is absolute medical necessity.

There are also some consumer products that give off radiation although they have been made for some other purpose. Examples of such sources are

- ▶ television,
- ▶ smoke detectors, and
- ▶ building materials.

The down chart is taken from the National Council on Radiation Protection and Measurements (NCRP) Report No. 160.



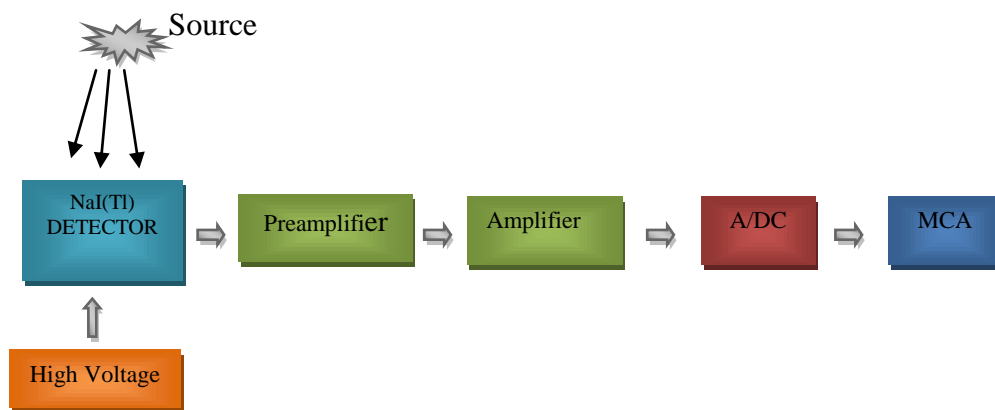
**Figure 2.21** Exposure sources for collective effective dose of the Population of the United States, 2006 [22].

### 3. MATERIAL and METHOD

#### 3.1. Gamma Spectrometry System

Gamma spectrometry is a system that detects whether a material is radioactive or not and if it is radioactive it enables us to discover this radioactivity stems from which radioisotope and separate gamma rays released by these radioactive elements according to their energies [23].

The radiation emitted from a particular source generates a current pulse is proportional to the absorbed energy interacting with detector. This pulse is translated to voltage pulse with the help of amplifiers, amplified, shaped and come in multi-channel analyzer (MCA). Information translated and digitized in analyzer is observed on the spectrum. Information on this spectrum is taken out for consideration by an appropriate input/output (I/O) connected to MCA. A gamma spectrometer is made up of NaI(Tl) detector, high voltage unit (HV), preamplifier, amplifier, multi-channel analyzer (MCA) and computer (PC).

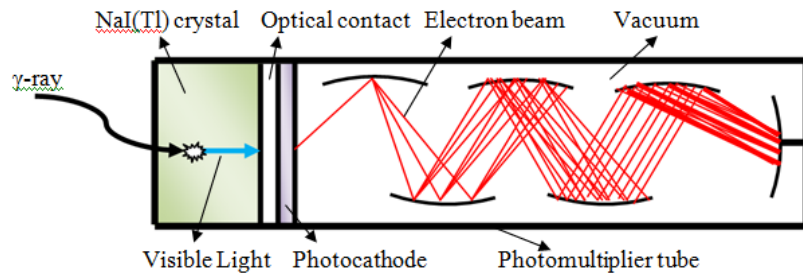


**Figure 3.1.** NaI(Tl) Gamma Spectroscopy System

##### 3.1.1. NaI(Tl) Detector

Scintillation detectors consists a substance used as a scintillator and a photomultiplier tube connected directly behind it. Ionization and excitation occurs as a result of ionizing radiation interacting with solid, liquid or gaseous of certain substances called scintillator. When supplied energy to the electron is not enough to break the

electron orbit, visible light (about wavelength between  $3300 \text{ \AA}$  and  $5000 \text{ \AA}$ ) is emitted with the induced electron returning to its previous state (Figure 3.2). Light emitted by the scintillator is converted into voltage pulse collected by photomultiplier tubes. Occurring pulse amplitude is proportional to the radiation energy. These detectors are used for counts, as well as energy separation.



**Figure 3.2** Schematic representation of the scintillation detector

A result of the absorption of  $\gamma$ -rays falling on the crystal consists of crystal light gleams. Passing through photomultiplier tube glitters cause removing electrons from the surface of the photocathode. These removed electrons drifting towards enhancements voltage will be placed one after the other way 800 to 1500 volts applied potential of many metals replicator. Each of these electrons drifting electron multiplier replicator transformed into more electrons allows the formation of large quantities of electrons at the replicator end of the tube. All of these events are speeded up less than a microsecond. Here, these electrons are converted to a load pulses. Height of this pulse is proportional to the energy of the photons. These pulses are amplified and counted with a counter.

Iodine's atomic number in NaI scintillator is higher which makes it possible to obtain high yields of gamma rays detection. Generally the crystal is activated by adding a small amount of Thallium. Composed of this structure is called as NaI(Tl).



**Figure 3.3.** Ortec digiBASE and 3''x3'' NaI(Tl) detector [24]

The above figure shows the used detector (Ortec 3"x3" NaI(Tl)) and digiBASE tube base in this study for the measurements. The digiBASE is a 14-pin photomultiplier tube base for gamma-ray spectroscopy applications with NaI(Tl) scintillation detectors. The digiBASE combines a miniaturized preamplifier and detector high voltage (0 to +1200 V bias) with digital signal processing, multichannel analyzer, tube base with a USB connection.

### **3.1.2. High Voltage Unit**

High voltage unit provides supply voltage (800V-1200V for NaI(Tl) detector) to detector. There are voltage units to create the electric field necessary for charge buildup [25].

### **3.1.3. Preamplifier**

Preamplifier is used to enlarge the small signal coming from the detector, to adjust the level of resistance detector and subsequent components, to adjust the signal shape and to format.

### **3.1.4. Amplifier**

Amplifier amplifies signals coming from preamplifier to able to analyze the signals and makes forming allowing the separation of energy.

### **3.1.5. Analog to Digital Converter (ADC)**

Amplified and adjusted analog signal coming to analog to digital converter is converted to digital signal proportional to its amplitude.

### **3.1.6. Multi-Channel Analyzer**

Multi-channel analyzer (MCA) places each digital signal coming to MCA to a memory channel proportional to its amplitude. Each channel corresponds to a specific energy in MCA and peak occurs by accumulation of the signals during the counting. The resulting peaks' spectrum is monitored on the computer screen.

## **3.2. Collection of Samples and Preparation to Counting**

The purpose of this study is to determine the level of radioactivity in building materials which are produced in Gaziantep and how much dose received by the people from these materials. 20 unit construction materials (plaster, cement, joint filler, faience, tile adhesive, granite, limestone, sand, marble, ceramic and brick from construction and dealers) have been collected. The samples were brought to the laboratory in plastic bags. Marble, granite, brick, ceramic samples were pulverized by grinder. All these powdered examples were dried at 105 °C for 24 hours. After drying, each sample was placed into plastic containers of 100ml sieving by sieve of 0.1mm thick. Cover is closed and edges of cover are wrapped up with parafilm to prevent gas output. The prepared samples were stored to equilibrate radionuclides with their decay products for 40 days.

The measurements were taken 55000 seconds by the NaI(Tl) gamma spectrometer for each sample. Detector shielded with 3 cm thick layer of lead in order to prevent external background radiation from the environment is shown in figure 3.4.  $^{40}\text{K}$  activity from its gamma peak,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  activities from daughter radionuclides' peaks in constantly equilibrium with themselves is determined by spectrums taken from NaI(Tl) detector gamma spectrometry system.

**Table 3.1.** Information collected samples

No	Sample	Product Description
1	Sand1	Black Sand Gaziantep
2	Sand2	Black Sand Gaziantep
3	Sand3	White Sand Gaziantep
4	Sand4	White Sand Gaziantep
5	Cement1	Kahramanmaraş Cement
6	Cement2	Sanko Barbeti
7	Cement3	Unknown
8	Lime	Nuhoğlu
9	Gypsum	Decowav
10	Gypsum Plasterboard	ABS
11	Joint Sealant Mortar	Weber Derzçim
12	Ytong	Ytong Gaziantep
13	Ytong Adhesive	Ytong Gaziantep
14	Faience	Unknown
15	Bricks	Gaziantep
16	Marble1	Antique Pink
17	Marble2	Emperdor
18	Marble3	Muğla White
19	Granite1	Nero
20	Granite2	Beta



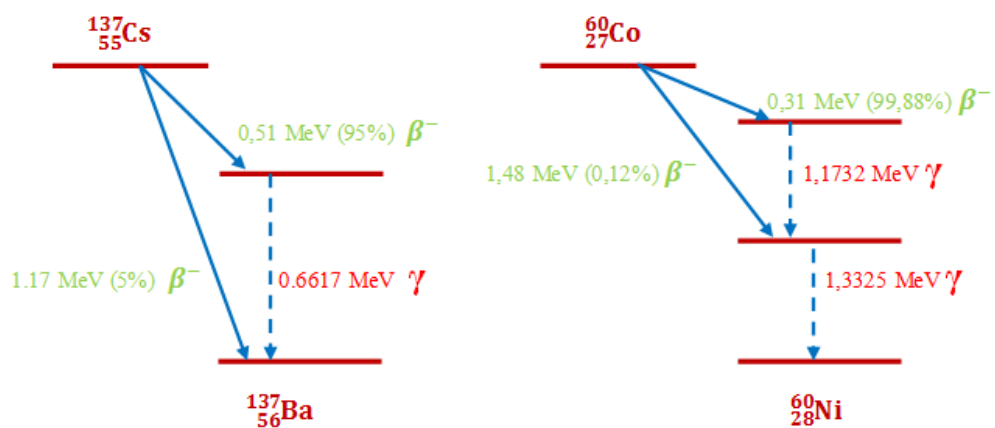
**Figure 3.4.** Gama Spectrometer System

### 3.3. Energy Calibration

For the correct radioactivity analysis of the collected samples, the energy calibration should be performed before experimental measurements with known radioisotopes [26]. Then the spectra in the computer memory will be compared with the measured spectras of collected samples. In order to energy calibration, the energy of the gamma rays emitted by the radioactive sources must be known and therefore the standard radioactive sources whose energies are known were first used in this study. Table 3.2 provides information on standard radioactive sources ( $^{137}\text{Cs}$  (661,6 keV) and  $^{60}\text{Co}$  (1173 keV-1332,5 keV)) used for calibration of NaI(Tl) detector systems in this study and the decay scheme of these sources is shown in figure 3.5. The standard source first was placed in front of the detector and then its spectrum was recorded by the computer. The recorded spectrums of  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  are shown in figures 3.7 and the energy according to the channel is shown in the figure 3.8.

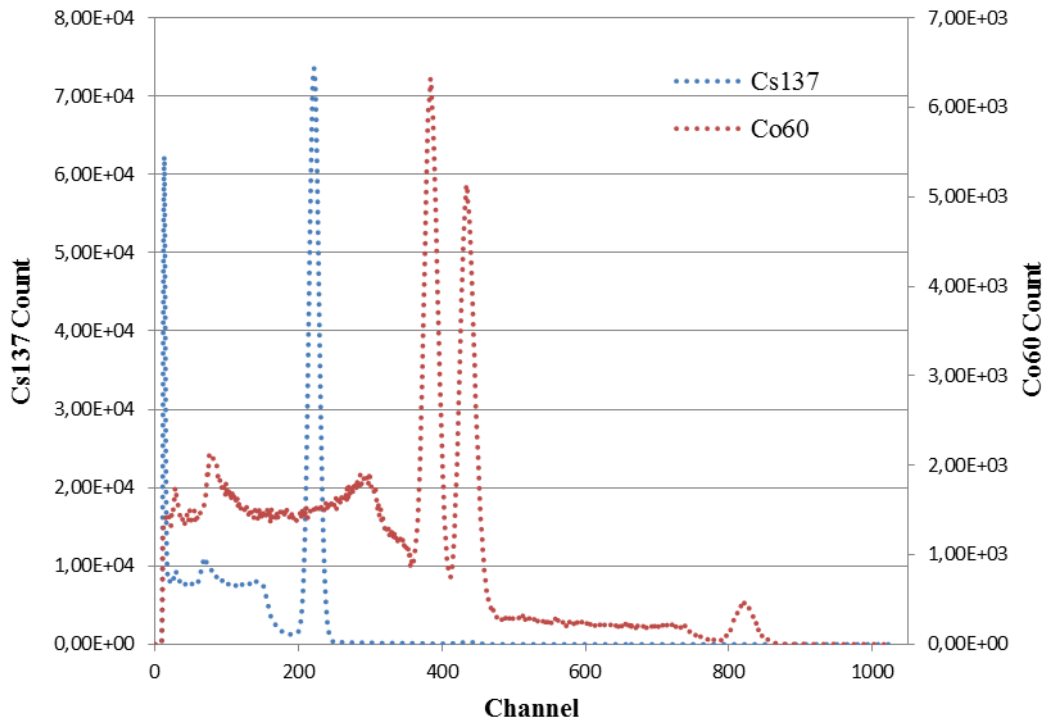
**Table 3.2** Features of Calibration Sources

Radionuclide	Energy (keV)	Ratio of $\gamma$ -rays to disintegrations
$^{137}\text{Cs}$	661,6	85,2%
$^{60}\text{Co}$	1173	99,9%
$^{60}\text{Co}$	1332,5	100%

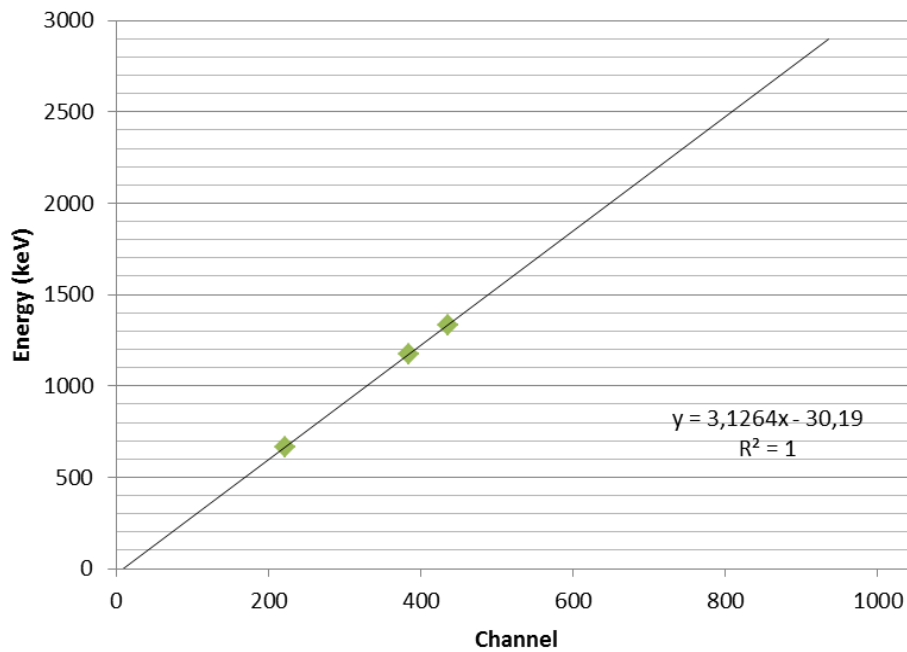


**Figure 3.5**  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  decay scheme





**Figure 3.6** The gamma spectrum of  $^{137}\text{Cs}$  and  $^{60}\text{Co}$ .



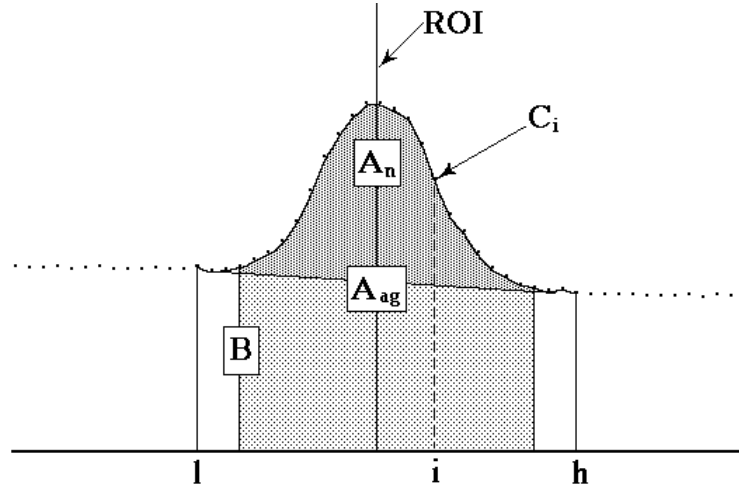
**Figure 3.7** Energy Calibration Graph

### 3.4. Calculation of Activity using Method of Comparison with the Standard

#### 3.4.1. Peak Info Calculation

After the samples were counted with detector, the net area under interested peak in the measured spectrum should be calculated to obtain the activity of the samples [27]. In this study; a commercial Ortec ScintiVision software program was used for

calculation of peak area. This program is commonly used to calculate the area of a single peak. ScintiVision peak area calculation is based on Coval Method. The method is explained in below and another peak does not contribute to interested peak as shown in figure.



**Figure 3.8** The detail background calculation.

The background is given by:

$$B = \left( \sum_{i=l}^{l+2} C_i + \sum_{i=h-2}^h C_i \right) \frac{h-l+1}{6} \quad (3.1)$$

where:

$B$  = the background area

$l$  = the region of interest (ROI) low limit

$h$  = the ROI high limit

$C_i$  = the contents of channel  $i$

$6$  = the number of data channels used (three on each end)

The gross area is the sum of all the channels marked by the ROI according to following:

$$A_g = \sum_{i=l}^h C_i \quad (3.2)$$

where:

$A_g$  = the gross count

$l$  = the ROI low limit

$h$  = the ROI high limit

$C_i$  = the contents of channel  $i$

The adjusted gross area is the sum of all the channels marked by the ROI but not used in the background, calculated as follows:

$$A_{ag} = \sum_{i=l+3}^{h-3} C_i \quad (3.3)$$

where:

$A_{ag}$  = the adjusted gross counts in the ROI

$l$  = the ROI low limit

$h$  = the ROI high limit

$C_i$  = the contents of channel  $i$

The net area is the adjusted gross area minus the adjusted calculated background, as follows:

$$A_n = A_{ag} - \frac{B(h-l-5)}{(h-l+1)} \quad (3.4)$$

The uncertainty in the net area is the square root of the sum of the squares of the uncertainty in the adjusted gross area and the weighted error of the adjusted background. The background uncertainty is weighted by the ratio of the adjusted peak width to the number of channels used to calculate the adjusted background. Therefore, the net peak-area uncertainty is given by:

$$\sigma_{A_n} = \sqrt{A_{ag} + B \left( \frac{h-l-5}{6} \right) \left( \frac{h-l-5}{h-l+1} \right)} \quad (3.5)$$

where:

$A_{ag}$  = the adjusted gross area

$A_n$  = the net area

$B$  = the background area

$l$  = the ROI low limit

$h$  = the ROI high limit

### 3.4.2. Efficiency

In gamma spectroscopy, the area under the interested peak represents the amount of radioactivity. Therefore, peak area and efficiency are needed to determine the radioactivity. Efficiency establishes a relationship between number of gamma rays

emitted from sources and the number of counts counted in spectrum. Efficiency of the detector system depends on the effects of arising from the detector itself, the effects of the source-detector geometry, the impact of substances, the materials around the detector and the effect of self-absorption in source material. Peak efficiency is determined using activity of certainly known standard sources. Standard sources and samples must have the same geometry and density to obtain correct results. Peak efficiency is determined by the equation for required gamma energies.

$$\varepsilon_{\gamma} = \frac{N_{net}}{AI_{\gamma}t} \quad (3.6)$$

wherein  $\varepsilon_{\gamma}$  counting efficiency for energy  $E_{\gamma}$ ,  $N_{net}$  peak area formed by the photon energy  $E_{\gamma}$ ,  $t$  counting time of standard source in detector,  $A$  radionuclides known activity in the gamma standard source,  $I_{\gamma}$  ratio of  $\gamma$ -rays emission by radionuclide to disintegrations.

### 3.4.3. Activity

Activity is defined as number of decayed nuclei per unit of time, can be determined by Eq.(3.7).

$$A = \frac{N_{net}}{\varepsilon t I_{\gamma}} \quad (3.7)$$

where, calculated activity  $A$ ,  $\varepsilon$  detector photo peak efficiency,  $t$  counting time,  $I_{\gamma}$  gamma emission probability per decay. The specific activity of samples  $SA$  (Bq/kg) can be calculated as follows.

$$SA = \frac{A}{m} \quad (3.8)$$

where,  $m$  is the mass of sample. Net peak area of interest in spectrum obtained after counting is calculated by background radiation correction.

$$SA_{sample} = \frac{CPS_{sample} - CPS_{background}}{\varepsilon I_{\gamma} m_{sample}} \quad (3.9)$$

where;  $CPS$  is count rate proportion of  $N_{net}/t$ . Activity of the sample, were to compare the activity of the reference material;

$$SA_{sample} = \frac{SA_{reference} (CPS_{sample} - CPS_{background}) m_{reference}}{(CPS_{reference} - CPS_{background}) m_{sample}} \quad (3.10)$$

#### 3.4.4. Uncertainty in Activity

Magnitudes in experimental measurements always contain a specific error (uncertainty) [12]. Many times a magnitude is function of several other magnitude and statistical error can be calculated by measured values and their errors. If variables of  $f$  function  $f=(x_1, x_2, \dots, x_n)$  is  $x_i$  and their errors is  $\Delta x_i$ , error of measurement of  $f$  function  $\Delta f$ :

$$\Delta f = \sqrt{\sum_{i=1}^n \left( \frac{\partial f}{\partial x_i} \Delta x_i \right)^2} \quad (3.11)$$

According to Eq.(3.11), uncertainty in specific activity  $\Delta SA_{sample}$  is equal to Eq.(3.11).

$$\Delta SA_{sample} = \sqrt{\left( \frac{\partial SA_{sample}}{\partial SA_{reference}} \Delta SA_{reference} \right)^2 + \left( \frac{\partial SA_{sample}}{\partial CPS_{sample}} \Delta CPS_{sample} \right)^2 + \left( \frac{\partial SA_{sample}}{\partial CPS_{background}} \Delta CPS_{background} \right)^2 + \left( \frac{\partial SA_{sample}}{\partial m_{reference}} \Delta m_{reference} \right)^2 + \left( \frac{\partial SA_{sample}}{\partial CPS_{reference}} \Delta CPS_{reference} \right)^2 + \left( \frac{\partial SA_{sample}}{\partial m_{sample}} \Delta m_{sample} \right)^2} \quad (3.12)$$

#### 3.4.5. MDA (Minimum Detectable Activity)

The MDA is then given as the following formula:

$$MDA = \frac{2.71 + 3.29 \sqrt{2 \times \sum_{i=l}^h C_i}}{\varepsilon \times T \times \gamma_d} \quad (3.13)$$

where

- $C_i$  = the channel contents of background channel I
- $l$  = the peak lower limit
- $h$  = the peak higher limit

- $\varepsilon$  = the efficiency at the peak energy  
 $T$  = the live time of the acquisition  
 $\gamma_d$  = the branching ratio

It should be noted that the MDA value will not always represent the maximum activity of a particular nuclide that might be present in a sample. Rather, it measures the limit of detection for that particular nuclide. Theoretically, if a nuclide activity exceeds the detection limit, the peak will be calculated.

For peaks of  $^{214}\text{Bi}$  (609keV),  $^{40}\text{K}$  (1460keV) and  $^{218}\text{Tl}$  (2614keV), MDA values in used detector are 9 Bq/kg, 47 Bq/kg and 15 Bq/kg, respectively.

### 3.5. Calculated Parameters on the basis of Activity

#### 3.5.1. Absorbed Dose Rate

Absorbed dose in indoor air and appropriate annual effective dose due to gamma ray emission from radioactive nuclei ( $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ ) in construction material are calculated by formula and information provided by UNSCEAR (2000) and EC (1999) [28-29]. Dose conversion coefficients have been calculated for a standard room in reports of EC and UNSCEAR. The room size is 4m x 5m x 2,8m. Thickness of the walls is 20 cm and wall, floor and ceiling density is 2350 kg/m<sup>3</sup> for concrete. These conversion coefficients are 0.08 nGy/h per Bq/kg for  $^{40}\text{K}$ , 1.1nGy/h per Bq/kg for  $^{232}\text{Th}$  and 0.92nGy/h per Bq/kg for  $^{226}\text{Ra}$ .

$$D_{\text{indoor}} (\text{nGy} / \text{h}) = 0,92 \times A_{\text{Ra}} + 1,1 \times A_{\text{Th}} + 0,08 \times A_{\text{K}} \quad (3.14)$$

where,  $A_{\text{Ra}}$ ,  $A_{\text{Th}}$  and  $A_{\text{K}}$  are specific activity of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ , respectively. Dose conversion coefficients for outdoors are 0.46 nGy/h per Bq/kg for  $^{226}\text{Ra}$ , 0.62 nGy/h for  $^{232}\text{Th}$  and 0.041 nGy/h per Bq/kg for  $^{40}\text{K}$ .

$$D_{\text{outdoors}} (\text{nGy} / \text{h}) = 0,46 \times A_{\text{Ra}} + 0,62 \times A_{\text{Th}} + 0,041 \times A_{\text{K}} \quad (3.15)$$

#### 3.5.2. Annual Effective Dose

The indoor occupancy factor and conversion coefficient are taken into account to calculate annual effective dose. According to UNSCEAR (2000) reports, in recent times worldwide the average time spent indoors was determined to be 80% so indoor

occupancy factor determined as 0.8 and exposure by adults absorbed dose in air to effective dose conservation factor of 0.7 Sv/Gy value was used.

$$AED(mSv/y) = D(nGy/h) \times 8760(h/y) \times 0,8 \times 0,7(Sv/Gy) \times 10^{-6} \quad (3.16)$$

where,  $D$  is the value of the absorbed gamma dose rate.

### 3.5.3. Radium Equivalent Activity

The distributions of natural radionuclides are not homogeneous in the samples under analysis. So it is a common radiological index is introduced to assess radiation damages on radioactive nuclei and actual level of  $^{40}\text{K}$ ,  $^{232}\text{Th}$  and  $^{226}\text{Ra}$  activity in samples. This index is generally known as radium equivalent activity and Beretka and Mathew (1985) determined by the expression,

$$Ra_{eq} = A_{Ra} + 1.43A_{Th} + 0.077A_K \quad (3.17)$$

where,  $A_{Ra}$ ,  $A_{Th}$  and  $A_K$  are specific activity of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ , respectively [30]. In the definition of  $Ra_{eq}$  is assumed that 10 Bq/kg of  $^{226}\text{Ra}$ , 130 Bq/kg of  $^{40}\text{K}$  and 7 Bq/kg of  $^{232}\text{Th}$  have the same gamma dose.

### 3.5.4. Hazard index

Krieger (1981) and Amrani and Tahtat (2001), in their studies, made a modeling of the risk of radiation exposure from building materials in areas that come into contact with the open air without doors and windows with thick walls [31-33]. This modeling is called as external hazard index ( $H_{ex}$ ) and is calculated using the following formula.

$$H_{ex} = A_{Ra} / 370 + A_{Th} / 259 + A_K / 4810 \leq 1 \quad (3.18)$$

$H_{ex}$  value recognized in the world, in materials made of building blocks containing natural radionuclides  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  should be less than 1. One of the most dangerous gases that can damage the internal organs is  $^{222}\text{Rn}$  product of  $^{226}\text{Ra}$  with very short half life. Krieger (1981) and Beretka and Matthew estimated acceptable concentration limits of  $^{226}\text{Ra}$  for indoor environments. This criterion is called as the internal hazard index ( $H_{in}$ ).

$$H_{in} = A_{Ra} / 185 + A_{Th} / 259 + A_K / 4810 \leq 1 \quad (3.19)$$

For living beings,  $H_{in}$  value universally accepted should be less than 1 for residences made of building blocks that contain  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ .

### 3.5.5. Gamma Index

EU countries do not allow construction materials can cause containing amounts of radioactivity over annual effective dose of 1 mSv. Gamma index corresponds to the dose;  $A_{Ra}$ ,  $A_{Th}$  and  $A_K$  are specific activity of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ , respectively, to be calculated by the formula (EUROPEAN COMMISSION REPORT, 1999):

$$I_\gamma = \frac{A_{Ra}}{200} + \frac{A_{Th}}{300} + \frac{A_K}{3000} \quad (3.20)$$

According to the materials used, gamma index ( $I_\gamma$ ) should not exceed the following values.

**Table 3.3** Gamma Index Limits

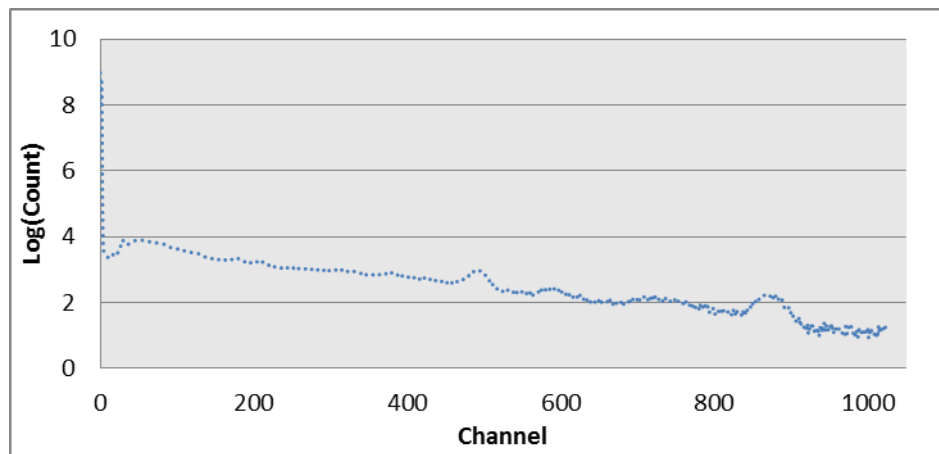
Material	$I_\gamma$
Materials used for construction of building (concrete, etc.)	1
Surface materials (tile, ceramic, etc.)	6

The value of  $I_\gamma \leq 0,5$  is equal or less than annual effective dose of 0.3 mSv and value of  $I_\gamma \leq 1$  is equal or less than annual effective dose of 1 mSv [34].



## 4. RESULTS

Gamma spectra of all samples studied in this thesis was obtained after energy and efficiency calibration of the dedector using standard calibration sources. The specific activities of all samples were calculated on the basis of gamma spectra of calibration samples. All radiation parameters were calculated on the basis of the specific activities obtained from the samples. Figure 4.1 shows a typical gamma spectrum obtained from sample of Sand1.



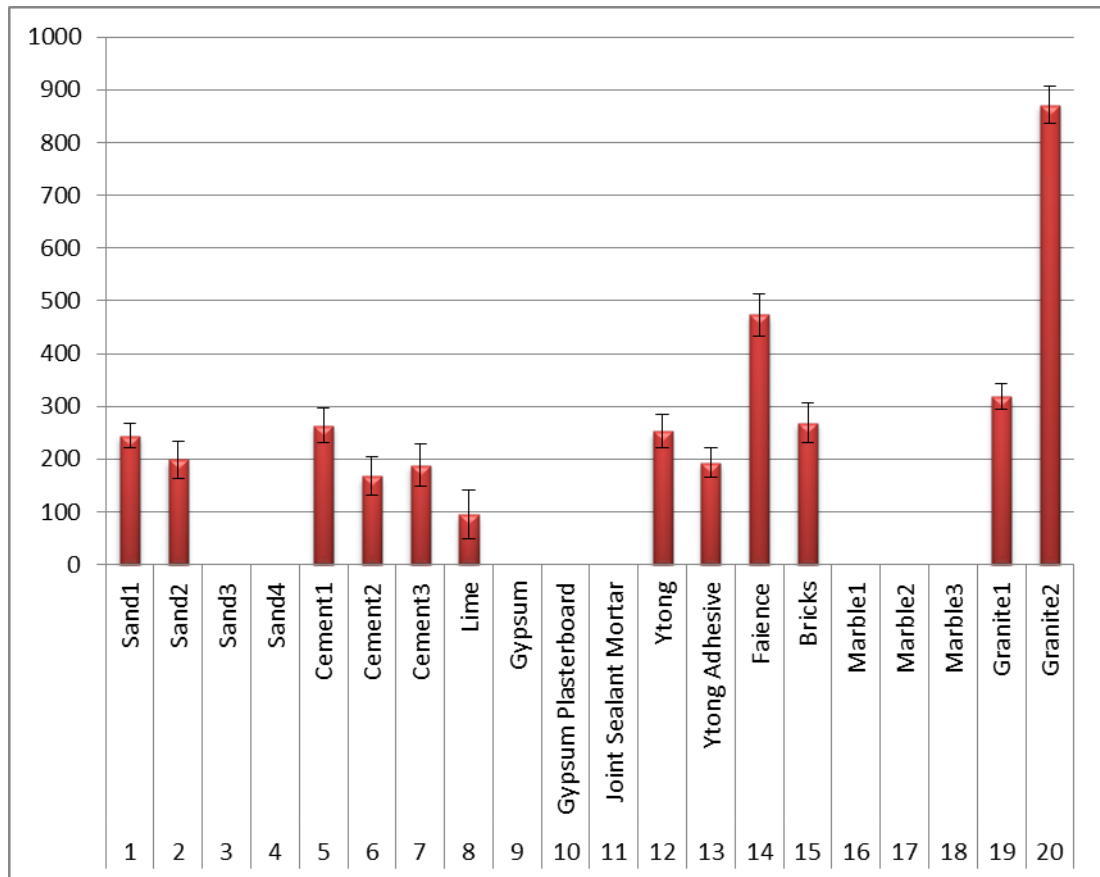
**Figure 4.1.** A typical gamma spectrum from sample of Sand1

### 4.1. Specific Activity

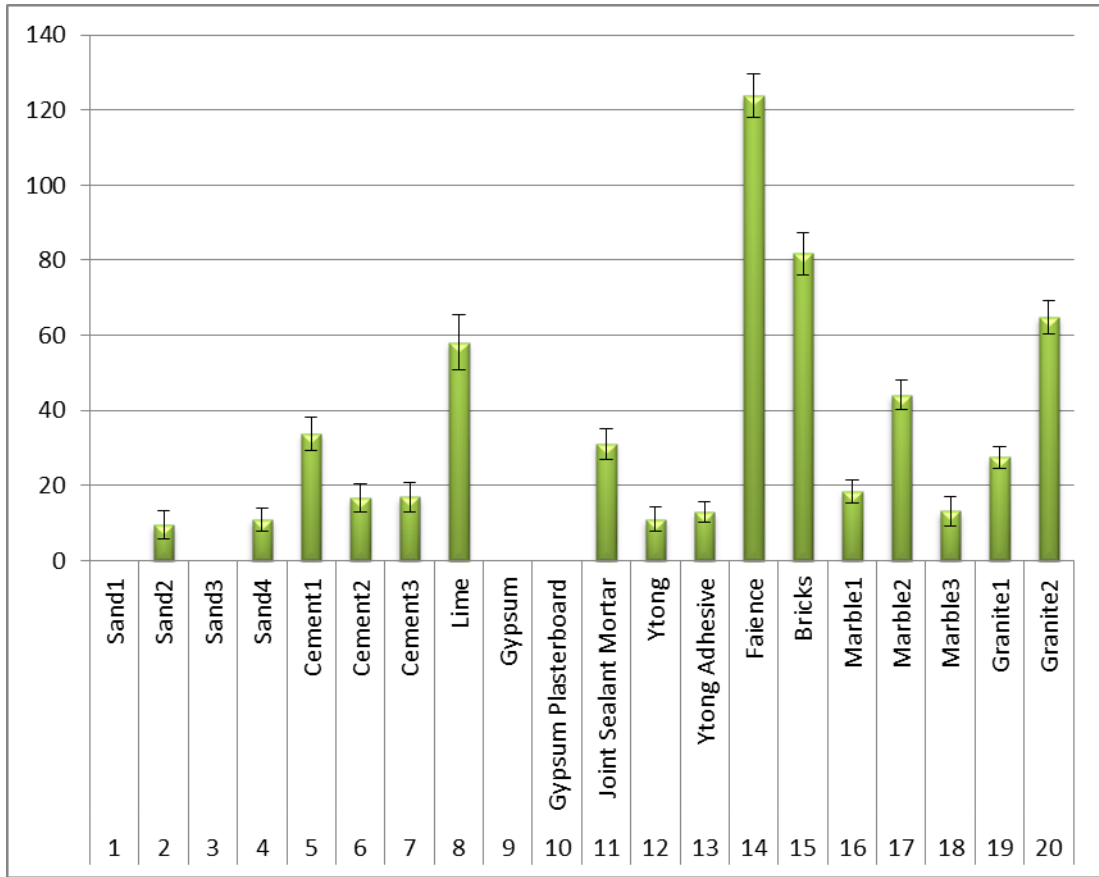
According to the analysed results obtained from the counted gamma spectra, the activity concentration of  $^{40}\text{K}$  is ranged from  $94,94 \pm 47,20$  Bq/kg (Lime) to  $871,29 \pm 36,10$  Bq/kg (Granite2) and its average is  $294,44 \pm 34,83$  Bq/kg. The activity concentration of  $^{226}\text{Ra}$  is ranged from  $9,52 \pm 3,65$  Bq/kg (Sand2) to  $123,89 \pm 5,89$  Bq/kg (Faience) and its average is  $35,93 \pm 4,31$  Bq/kg. The activity concentration of  $^{232}\text{Th}$  is ranged from  $15,72 \pm 11,50$  Bq/kg (Cement3) to  $50,88 \pm 7,40$  Bq/kg (Granite2) and its average is  $29,19 \pm 9,93$  Bq/kg. The activity graphics of  $^{40}\text{K}$ ,  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  are shown in figures 4.1-4.3. The calculated specific activities and uncertainties of measured samples are given in table 4.1.

**Table 4.1** Specific activities and uncertainties of measured samples

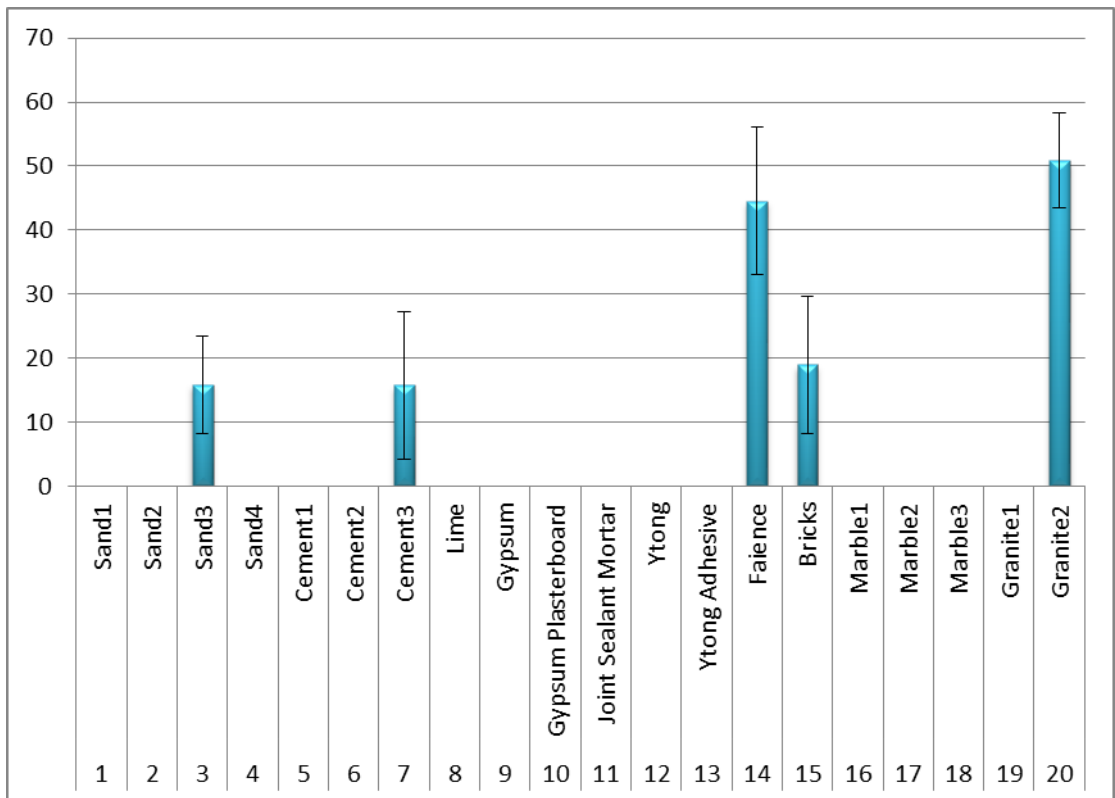
No	Sample	Activity <sup>40</sup> K (Bq/kg)	Error	Activity <sup>226</sup> Ra (Bq/kg)	Error	Activity <sup>232</sup> Th (Bq/kg)	Error
1	Sand1	244,16	22,82	MDA		MDA	
2	Sand2	198,85	34,71	9,52	3,65	MDA	
3	Sand3	MDA		MDA		15,82	7,62
4	Sand4	MDA		10,94	3,12	MDA	
5	Cement1	262,82	32,75	33,79	4,46	MDA	
6	Cement2	167,40	36,00	16,64	3,67	MDA	
7	Cement3	188,29	39,34	17,01	3,96	15,72	11,50
8	Lime	94,94	47,20	58,16	7,48	MDA	
9	Gypsum	MDA		MDA		MDA	
10	Gypsum Plasterboard	MDA		MDA		MDA	
11	Joint Sealant Mortar	MDA		31,08	4,09	MDA	
12	Ytong	252,35	31,06	11,00	3,19	MDA	
13	Ytong Adhesive	193,30	27,89	12,87	2,71	MDA	
14	Faience	473,18	40,46	123,89	5,89	44,57	11,56
15	Bricks	268,11	38,15	81,84	5,60	18,96	10,69
16	Marble1	MDA		18,44	3,20	MDA	
17	Marble2	MDA		44,09	3,88	MDA	
18	Marble3	MDA		13,25	3,93	MDA	
19	Granite1	318,57	23,48	27,46	2,97	MDA	
20	Granite2	871,29	36,10	64,83	4,44	50,88	7,40



**Figure 4.2** <sup>40</sup>K Specific Activities (Bq/kg) in building materials used in Gaziantep



**Figure 4.3**  $^{226}\text{Ra}$  Specific Activities (Bq/kg) in building materials used in Gaziantep



**Figure 4.4**  $^{232}\text{Th}$  Specific Activities (Bq/kg) in building materials used in Gaziantep

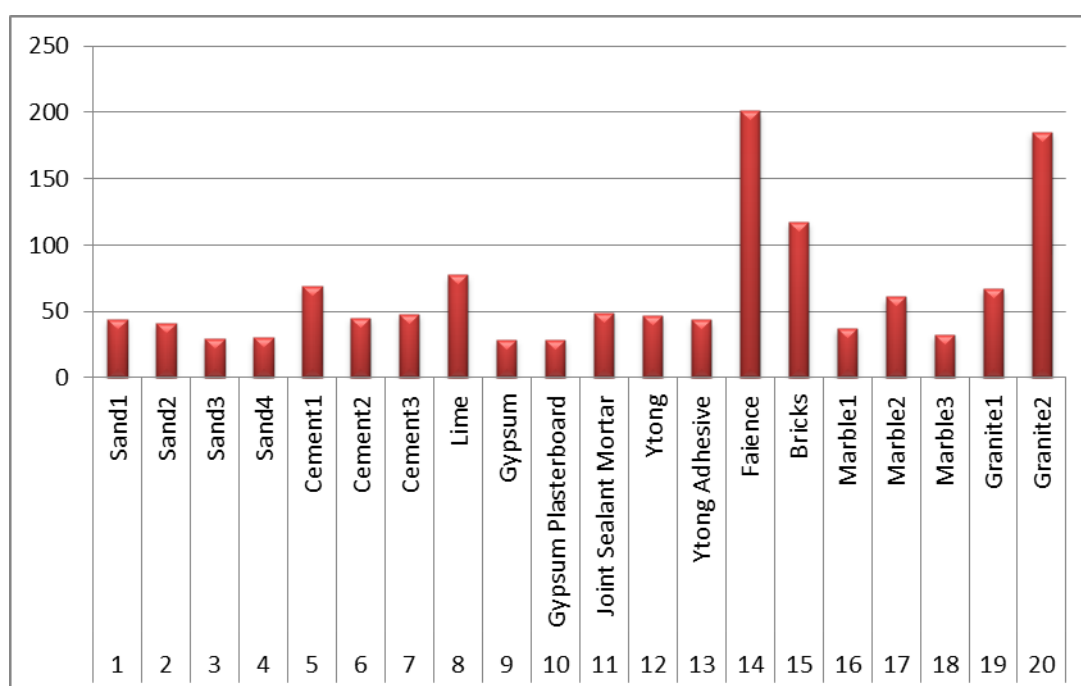
## 4.2. Calculated radiation parameters on the basis of specific activities

### 4.2.1. Absorbed Dose Rate

The calculated indoor absorbed dose rates indicate that they are ranged from 28,54 nGy/h (Gypsum) to 200,86 nGy/h (Faience). The average absorbed dose rate outdoor is 64,14 nGy/h. Indoor absorbed dose rates of building materials are given in table 4.2 and their graphics are shown in figure 4.4.

**Table 4.2** Indoor Absorbed Doses in building materials in Gaziantep

No	Sample	Indoor Absorbed Dose(nGy/h)	No	Sample	Indoor Absorbed Dose(nGy/h)
1	Sand1	44,31	11	Joint Sealant Mortar	48,85
2	Sand2	41,16	12	Ytong	46,81
3	Sand3	29,44	13	Ytong Adhesive	43,81
4	Sand4	30,33	14	Faience	200,86
5	Cement1	68,61	15	Bricks	117,59
6	Cement2	45,20	16	Marble1	37,22
7	Cement3	48,00	17	Marble2	60,82
8	Lime	77,60	18	Marble3	32,45
9	Gypsum	28,54	19	Granite1	67,25
10	Gypsum Plasterboard	28,54	20	Granite2	185,32

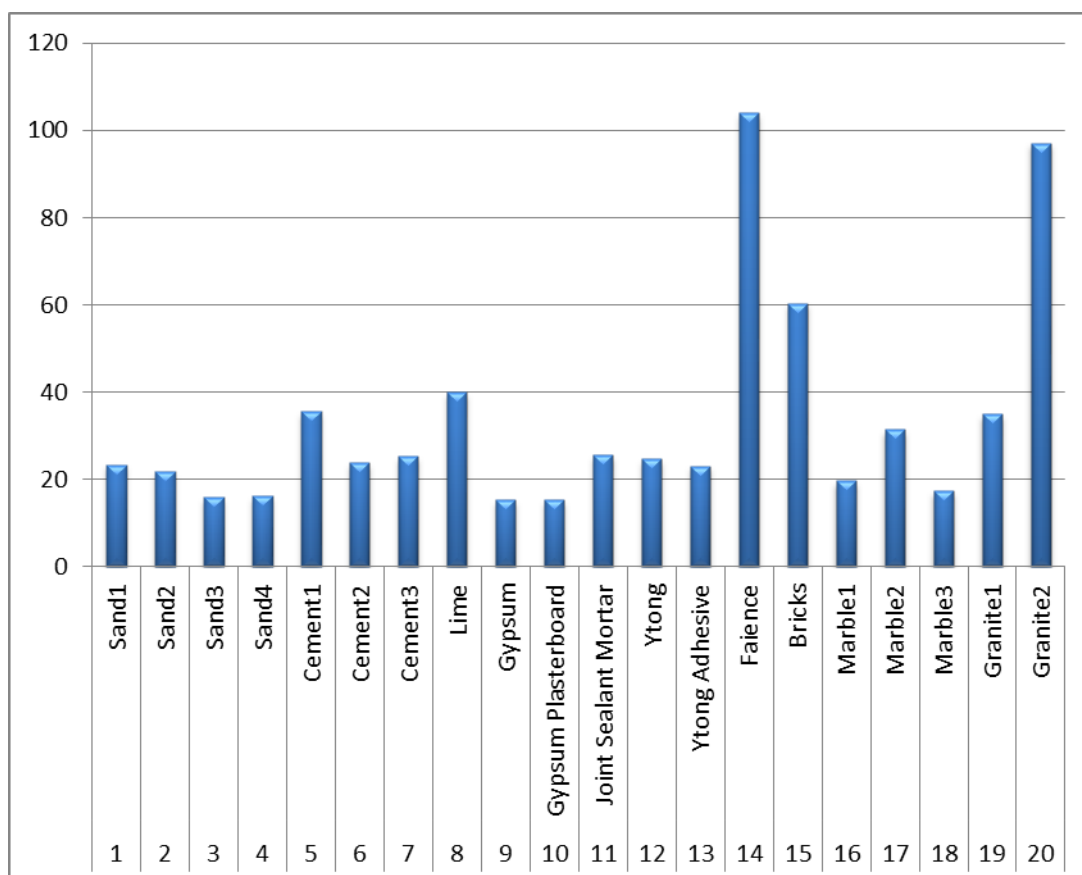


**Figure 4.5** Indoor Absorbed Doses (nGy/h) in building materials in Gaziantep

Outdoor absorbed dose rate is ranged from 15,37 nGy/h (Gypsum) to 104,03 nGy/h (Faience) and average outdoor absorbed dose rate is 33,56 nGy/h. Absorbed dose rates outdoor of samples are given in Table 4.3 and their graphics are shown in Figure 4.5.

**Table 4.3** Outdoor Absorbed Doses in building materials in Gaziantep

No	Sample	Outdoor Absorbed Dose(nGy/h)	No	Sample	Outdoor Absorbed Dose(nGy/h)
1	Sand1	23,45	11	Joint Sealant Mortar	25,52
2	Sand2	21,83	12	Ytong	24,71
3	Sand3	15,87	13	Ytong Adhesive	23,15
4	Sand4	16,26	14	Faience	104,03
5	Cement1	35,62	15	Bricks	60,39
6	Cement2	23,82	16	Marble1	19,71
7	Cement3	25,29	17	Marble2	31,51
8	Lime	39,95	18	Marble3	17,32
9	Gypsum	15,37	19	Granite1	34,99
10	Gypsum Plasterboard	15,37	20	Granite2	97,09



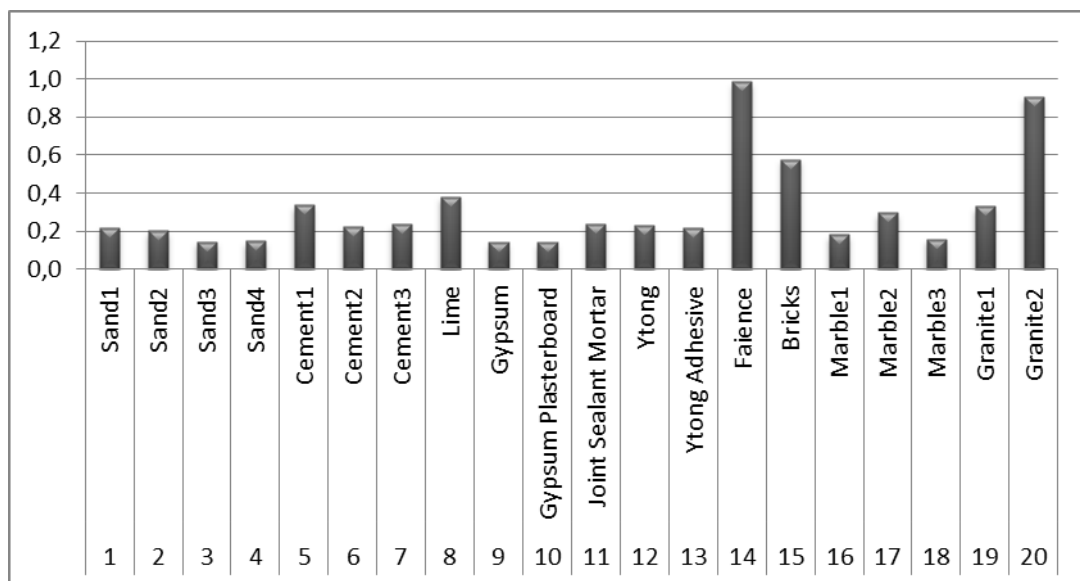
**Figure 4.6** Absorbed Doses Outdoor (nGy/h) in building materials in Gaziantep

#### 4.2.2. Annual Effective Dose

Annual effective dose was calculated using absorbed dose indoor and annual effective dose values which are shown in table 4.4 and figure 4.6. As shown the annual effective dose range varies from 0,14 mSv/y (Gypsum) to 0,99 mSv/y (Faience) and according to these results the average annual effective dose is 0,31 mSv/y. The average annual effective dose value on world-wide exposure in the building was calculated as 0,41 [35]. As seen from table 4.4, the annual effective dose values of widely used materials in building in Gaziantep province are quite close to the average value of world.

**Table 4.4** Annual Effective Doses in building materials in Gaziantep

No	Sample	Annual Effective Dose (mSv/y)	No	Sample	Annual Effective Dose (mSv/y)
1	Sand1	0,22	11	Joint Sealant Mortar	0,24
2	Sand2	0,20	12	Ytong	0,23
3	Sand3	0,14	13	Ytong Adhesive	0,21
4	Sand4	0,15	14	Faience	0,99
5	Cement1	0,34	15	Bricks	0,58
6	Cement2	0,22	16	Marble1	0,18
7	Cement3	0,24	17	Marble2	0,30
8	Lime	0,38	18	Marble3	0,16
9	Gypsum	0,14	19	Granite1	0,33
10	Gypsum Plasterboard	0,14	20	Granite2	0,91



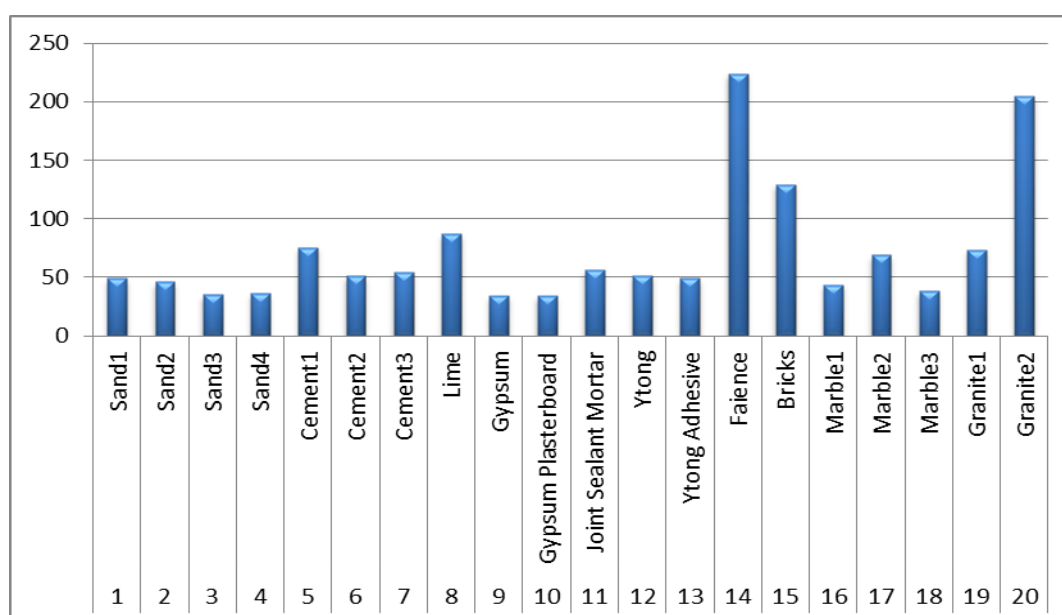
**Figure 4.7** Annual Effective Doses (mSv/y) in building materials in Gaziantep

### 4.2.3. Radium Equivalent Activity

In this study, the radium equivalent activity was calculated to be ranging from 34,07 Bq/kg (Gypsum Plasterboard) to 224,07 Bq/kg (Faience) and average radium equivalent activity is calculated on the order of 72,11 Bq/kg. In 1979, the OECD has set the limit value of radium equivalent activity as 370 Bq/kg [36]. The radium equivalent activity in building materials used in Gaziantep was well below 370 Bq/kg. The calculated radium equivalent activities of samples studied in this thesis and their graphics are given in table 4.5 and figure 4.7.

**Table 4.5** Radium Equivalent Activities in building materials in Gaziantep

No	Sample	Radium Equivalent Activity (Bq/kg)	No	Sample	Radium Equivalent Activity (Bq/kg)
1	Sand1	49,25	11	Joint Sealant Mortar	56,15
2	Sand2	46,28	12	Ytong	51,88
3	Sand3	35,24	13	Ytong Adhesive	49,21
4	Sand4	36,01	14	Faience	224,07
5	Cement1	75,48	15	Bricks	129,59
6	Cement2	50,98	16	Marble1	43,51
7	Cement3	53,98	17	Marble2	69,16
8	Lime	86,92	18	Marble3	38,32
9	Gypsum	34,07	19	Granite1	73,44
10	Gypsum Plasterboard	34,07	20	Granite2	204,68



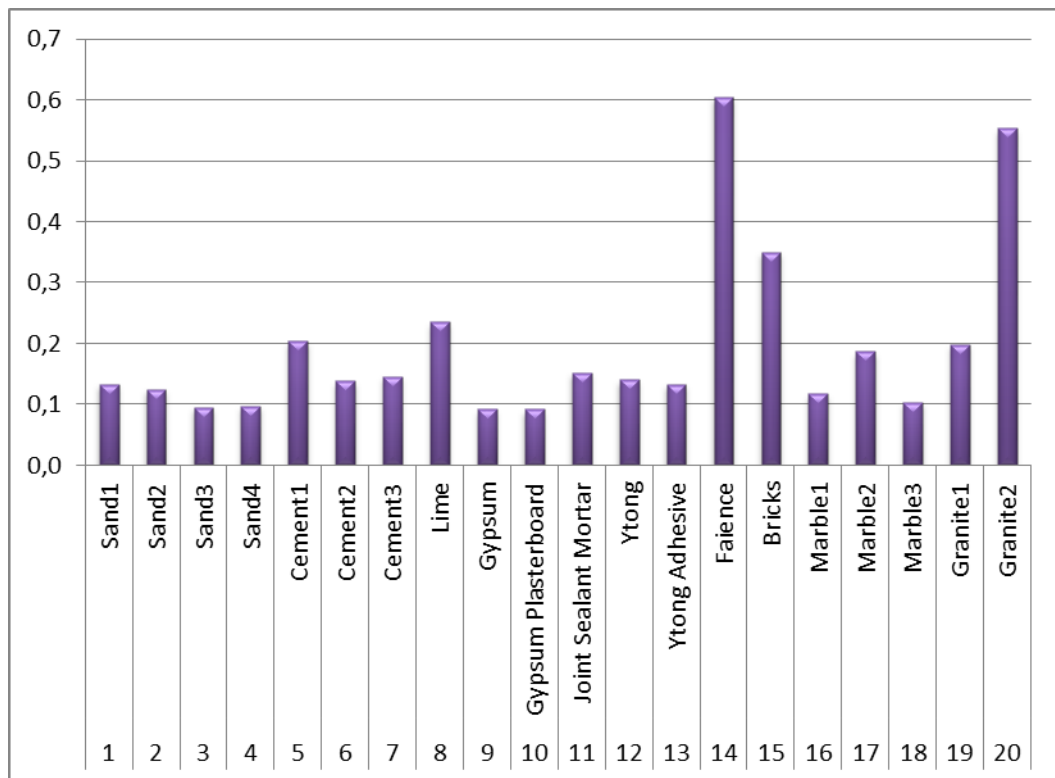
**Figure 4.8** Radium Equivalent Activities (Bq/kg) in building materials in Gaziantep

#### 4.2.4. Hazard Index

The external hazard index is ranged from 0,09 (Gypsum) to 0,61 (Faience) and average external hazard index is 0,19. The external hazard index should be less than 1 [31-33]. All calculated external hazard index values in the given study are less than 1 and their values and graphs are given in table 4.6. and figure 4.8.

**Table 4.6.** External Hazard Indexes in building materials in Gaziantep

No	Sample	External Hazard Index	No	Sample	External Hazard Index
1	Sand1	0,13	11	Joint Sealant Mortar	0,15
2	Sand2	0,12	12	Ytong	0,14
3	Sand3	0,10	13	Ytong Adhesive	0,13
4	Sand4	0,10	14	Faience	0,61
5	Cement1	0,20	15	Bricks	0,35
6	Cement2	0,14	16	Marble1	0,12
7	Cement3	0,15	17	Marble2	0,19
8	Lime	0,23	18	Marble3	0,10
9	Gypsum	0,09	19	Granite1	0,20
10	Gypsum Plasterboard	0,09	20	Granite2	0,55



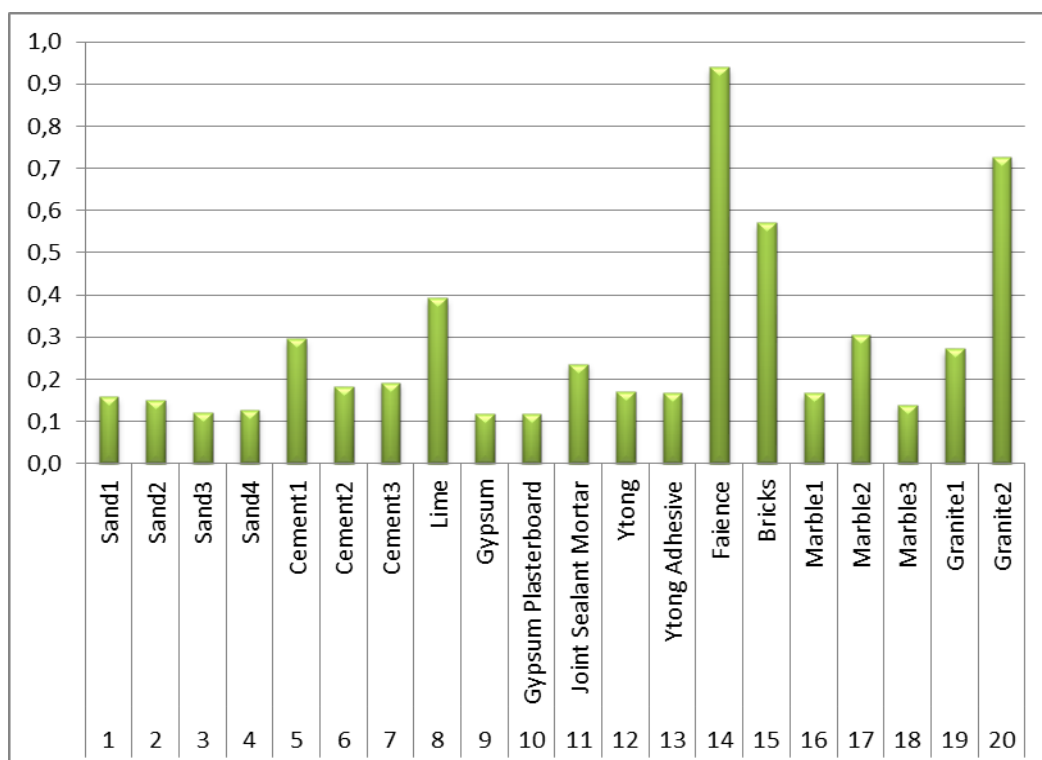
**Figure 4.9** External Hazard Index in building materials in Gaziantep



Similarly, in this study, the internal hazard index of all samples was also obtained and it was found to be ranging from 0,12 (Gypsum) to 0,94 (Faience) and according to these results the average internal hazard index is found as 0,28. Their values and figures are given in table 4.7 and figure 4.9.

**Table 4.7** Internal Hazard Indexes in building materials in Gaziantep

No	Sample	Internal Hazard Index	No	Sample	Internal Hazard Index
1	Sand1	0,16	11	Joint Sealant Mortar	0,24
2	Sand2	0,15	12	Ytong	0,17
3	Sand3	0,12	13	Ytong Adhesive	0,17
4	Sand4	0,13	14	Faience	0,94
5	Cement1	0,30	15	Bricks	0,57
6	Cement2	0,18	16	Marble1	0,17
7	Cement3	0,19	17	Marble2	0,31
8	Lime	0,39	18	Marble3	0,14
9	Gypsum	0,12	19	Granite1	0,27
10	Gypsum Plasterboard	0,12	20	Granite2	0,73



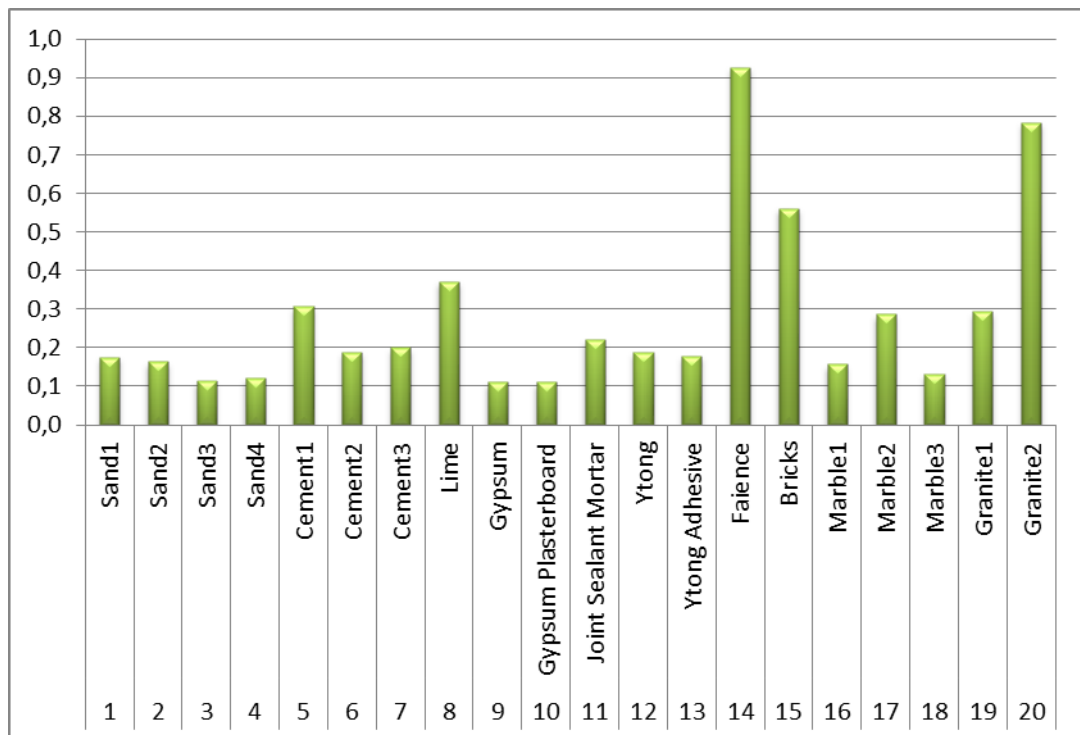
**Figure 4.10** Internal Hazard Indexes in building materials in Gaziantep

#### 4.2.5. Gamma Index

In the given study, the gamma index values of samples used in the building in Gaziantep are ranged from 0,11 (Gypsum) to 0,93 (Faience) and its average is 0,28. The calculated values of gamma indexes of samples are given in table 4.8 and their graphics are shown in figure 4.10.

**Table 4.8** Gamma Indexes in building materials in Gaziantep

No	Sample	Gamma Index	No	Sample	Gamma Index
1	Sand1	0,18	11	Joint Sealant Mortar	0,22
2	Sand2	0,16	12	Ytong	0,19
3	Sand3	0,11	13	Ytong Adhesive	0,18
4	Sand4	0,12	14	Faience	0,93
5	Cement1	0,31	15	Bricks	0,56
6	Cement2	0,19	16	Marble1	0,16
7	Cement3	0,20	17	Marble2	0,29
8	Lime	0,37	18	Marble3	0,13
9	Gypsum	0,11	19	Granite1	0,29
10	Gypsum Plasterboard	0,11	20	Granite2	0,78



**Figure 4.11** Gamma Indexes in building materials in Gaziantep

## 5. CONCLUSION

In this study, the gamma spectrometric analysis method was used to determine the levels of natural radioactivity in construction materials used and produced in Gaziantep province. To do this, in total, 20 samples were supplied from sand, cement, lime, gypsum, gypsum plasterboard, joint sealant mortar, ytong, ytong adhesive, faience, brick, marble and granite. The gamma spectrometric analyses of these samples were studied in detail and the obtained results were given in the tables in the previous chapter.

All studied building materials contain various amounts of natural radionuclides. Samples obtained from rocks and soils contain natural radioactive nuclei of  $^{226}\text{Ra}$  and  $^{232}\text{Th}$  series and radioactive isotope of  $^{40}\text{K}$ . The average concentrations of  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  in earth crust throughout the world are about 40 Bq/kg, 40 Bq/kg and 400 Bq/kg. The obtained values in this study were generally below the world average values. However, it is found that the activity concentration of  $^{232}\text{Th}$  in Granite2, the activity concentrations of  $^{226}\text{Ra}$  and  $^{40}\text{K}$  in faience and granite-2 are above the world average.

To determine how safe is the people in the building, the radium equivalent activity, radiation hazard and gamma indexes limit values were also calculated by using calculated activity concentrations of building material in the present study. It was seen that the calculated values of them (except granite's and faience's values) are always under the specified limits supposed by the ICRP and therefore these materials could be used safely.

The obtained results in this study were finally compared with the obtained values in previous studies in the world and Turkey [3,30,32,37-39] and the results are shown in table 5.1. As seen from this table, the obtained amounts of radioactivity in the building materials used and produced in Gaziantep are not much different from other previously published studies.

**Table 5.1:** The specific and radium equivalent activities of  $^{40}\text{K}$ ,  $^{232}\text{Th}$ ,  $^{226}\text{Ra}$  published in previous studies [24].

Sample	Country	$^{40}\text{K}$	$^{232}\text{Th}$	$^{226}\text{Ra}$	Raeq	Reference
Cement	Gaziantep	188,29	15,72	17,01	53,98	This study
	Ankara	316,5	26,4	39,9	101,9	Turhan et al. [37]
	Australia	115	48,1	51,8	129	Beretka and Mathew [30]
	Brazil	564	58,5	61,7	189	Malanca at al. [38]
	China	173,8	51,7	68,3	162,8	Xinwei [39]
	India	39,6	34,1	7,1	58,91	Kumar at al.[3]
	Algeria	422	27	41	112	Amrani at al. [32]
Brick	Gaziantep	268,11	18,96	81,84	129,59	This study
	Ankara	775,8	37,2	31,2	144,0	Turhan et al.
	Australia	681	88,8	40,7	220	Beretka and Mathew
	Brazil	747	65,3	51,7	203	Malanca at al.
	China	713,9	50,4	58,6	178,3	Xinwei
	India	47,2	53,9	12,6	93,31	Kumar at al.
	Algeria	675	51	65	190	Amrani at al.
Sand	Gaziantep	198,85	MDA	9,52	46,28	This study
	Ankara	527,2	26,4	22,9	101,2	Turhan et al.
	Australia	44,4	40	3,7	65,3	Beretka and Mathew
	Brazil	807	18	14,3	102	Malanca at al.
	China	302,6	21,5	40,7	96,4	Xinwei
	India	60,5	51,5	MDA	78,3	Kumar at al.
	Algeria	74	7	12	28	Amrani at al.
Gypsum	Gaziantep	MDA	MDA	MDA	34,07	This study
	Ankara	59	5,2	5,2	16,4	Turhan et al.
	Brazil	96	14,2	10,3	38	Malanca at al.
	India	26,7	MDA	8,3	10,36	Kumar at al.
Faianca	Gaziantep	473,18	44,57	123,89	224,07	Bu çalışma
	Ankara	476,9	62,1	70,3	195,8	Turhan et al.
	Brazil	991	77,8	70,2	257,8	Malanca at al.
	India	24,3	63,7	28,2	121,16	Kumar at al.
	Algeria	410	41	55	145	Amrani at al.
Lime	Gaziantep	94,94	MDA	58,16	86,92	This study
	Ankara	52,7	5,4	11,9	20,8	Turhan et al.
	Australia	MDA	11,1	MDA	15,9	Beretka and Mathew
	Brazil	205	7	24,3	50,1	Malanca at al.
	China	63,2	13,4	19,5	46,6	Xinwei
	India	64,6	MDA	73,9	78,87	Kumar at al.
	Algeria	36	13	16	37	Amrani at al.
Marble	Gaziantep	MDA	MDA	18,44	43,51	This study
	Ankara	49,7	4,9	5,4	9,8	Turhan et al.
	Brazil	52	MDA	7,7	11,7	Malanca at al.
	Algeria	310	18	23	73	Amrani at al.
Granite	Gaziantep	871,29	50,88	64,83	204,68	This study
	Ankara	915,3	77,4	67,5	244,3	Turhan et al.
	Brazil	1436	451,4	50,6	806,7	Malanca at al.

## REFERENCES

- [1] Dizman S. (2006). Rize İli ve İlçelerindeki Doğal Gama Radyoaktivite Düzeyinin Belirlenmesi. M. Sc. Thesis. Trabzon: Karadeniz Technical University Institute of Natural Sciences.
- [2] Ahmad, N., Hussein, Aslam, A.J.A. (1998). Natural radioactivity in Jordian soil and building materials and the associated radiation hazard. *Journal of Environmental Radioactivity*. **39**, 9-22.
- [3] Kumar, A., Kumar, M., Singh, B., Singh, S. (2003). Natural activities of U-238, Th-232 and K-40 in some Indian building materials. *Radiation Measurements*. **36**, 465-469.
- [4] Dayanıklı, Ş.A. (2004). Manisa ilinde Kullanılan Bina Materyallerinde Radyoaktivite Tayini. M. Sc. Thesis. Manisa: Celal Bayar University, Institute of Natural Sciences.
- [5] Radhakrishna, A. P., Somashekarappa, H. M., Narayana, Y., Siddappa, K. (1993). A new natural background radiation area on the southwest coast of India. *Health Physics*. **65(4)**, 390-395.
- [6] Fasasi, M. K. (2003). Natural radioactivity of the tar-sand deposits of Ondo State, Southwestern Nigeria. *Nuclear instruments & Methods in Physics Research*. **505**, 449-453.
- [7] Sujo, L. C., Cabrera, M. E. M., Villalba, L., Villalobos, M. R., Moye, E. T., León, M. G., García-Tenorio, R., García, F. M., Peraza, E. F. H., Aroche, D. S. (2004). Uranium-238 and thorium-232 series concentrations in soil, radon-222

indoor and drinking water concentrations and dose assessment in the city of Aldama, Chihuahua, Mexico. *Journal of Environmental Radioactivity*. **77**, 205-219.

[8] Keser R. (2004). Fırtına Vadisi'nin Çamlıhemsin'den Yukarı Kısımının Doğal Radyoaktivite Seviyesinin Belirlenmesi. M. Sc. Thesis. Trabzon: Karadeniz Technical University, Institute of Natural Sciences.

[9] Karakelle, B., Öztürk, N., Köse, A., Varinlioglu, A., Erkol, A. Y., Yılmaz, F. (2002). Natural radioactivity in soil samples of Kocaeli basin, Turkey. *Journal Of Radioanalytical and Nuclear Chemistry*. **254**, 649-651.

[10] Tzortzis, M., Tsertos, H., Christofides, S., Christodoulides, G. (2003). Gamma-ray measurements of naturally occurring radioactive samples from Cyprus characteristic geological rocks. *Radiation Measurements*. **37**, 221-229.

[11] Shenber, M. A. (1997). Measurement of natural radioactivity levels in soil in Tropolı. *Applied Radiation and Isotopes*. **48**, 147-148.

[12] Korkulu, Z. (2010). Kocaeli İli Karadeniz Sahil Kumlarını Doğal Radyoaktivite Seviyelerinin Belirlenmesi. M. Sc. Thesis. Kocaeli: Kocaeli University Institute of Natural Sciences.

[13] Karahan, G., Bayulken, A. (2000). Assessment of Gamma Dose Rates Around Istanbul. *Journal of Environmental Radioactivity*. **47**, 213-221

[14] Singh S., Singh B., Kumar A. (2003). Natural radioactivity measurements in soil samples from Hamirpur district, Himachal Pradesh, India. *Radiation Measurements*. **36**, 547-549.

[15] Garimella, S., Prasad, U. (2002). Distribution of  $^{40}\text{K}$ ,  $^{232}\text{Th}$  and  $^{238}\text{U}$  in Soils of Southern and Western Coasts of Viti Levu, Fiji. *S. Pac. J. Nat. Sci.* **20**, 9-14.

[16] Beyzadeoglu M, Ozyigit G, Ebruli C. (2010). Basic Radiation Oncology. Springer Heidelberg Dordrecht London New York: Springer-Verlag Berlin Heidelberg.

- [17] Wikipedia. Table of Isotopes. [http://en.wikipedia.org/wiki/File:Table\\_isotopes\\_en.svg](http://en.wikipedia.org/wiki/File:Table_isotopes_en.svg), 15.11.2013
- [18] Bostancı S. (2011). Ondokuz Mayıs Üniversitesi Kurupelit Kampüsü ve Samsun İl Merkezinin Doğal Radyoaktivite Seviyesinin Belirlenmesi. M. Sc. Thesis. Samsun: Ondokuz Mayıs University Institute of Natural Sciences.
- [19] Nuclear Forensic Search Project. Decay Chains. <http://metadata.berkeley.edu/nuclear-forensics/Decay%20Chains.html>, 31.10.2013.
- [20] Podgorsak E. (2005). Radiation Oncology Physics. Vienna: IAEA
- [21] Ahmed S. N. 2007. Physics&Engineering of Radiation Detection. Amsterdam: Elsevier
- [22] Diagnostic Imaging. Ionizing radiation exposure skyrockets since 1980`s. <http://www.diagnosticimaging.com/articles/ionizing-radiation-exposure-skyrockets-1980s-0>, 01.11.2013.
- [23] Mavi B. (2010). Isparta'daki bazı yapı malzemelerinde doğal radyoaktivite tayini. Ph. D. Thesis. Isparta: Süleyman Demirel University Institute of Natural Sciences.
- [24] ORTEC. Multi Channel Analysers. <http://www.ortec-online.com/Solutions/multichannel-analyzers.aspx>, 31.10.2013.
- [25] Dişçi T. (2012). Samsun ilinde üretilen ve kullanılan inşaat malzemelerinde doğal radyoaktivite ölçümleri. M. Sc. Thesis. Samsun: Ondokuz Mayıs University Institute of Natural Sciences.
- [26] Aras İ. (2009). Kars ilindeki bazı yapı malzemelerinde radyoaktivitenin incelenmesi. M. Sc. Thesis. Kars: Kafkas University Institute of Natural Sciences.
- [27] ORTEC. (2003). ScintiVision-32 for Microsoft Windows 95, 98, NT, 2000, and XP MCA Emulation and Analysis Software for Scintillation Detector Spectra A35-B32 Software User's Manual. USA: Advanced Measurement Technology.

- [28] UNSCEAR, (2000). Sources and effects of ionizing radiation. New York: United Nations Publication.
- [29] EUROPEAN COMMISSION REPORT, (1999). Radiation Protection 112 (Radiological Protection Principles Concerning the Natural Radioactivity of Building Materials).
- [30] Beretka, J. ve Mathew, P.J. (1985). Natural radioactivity of Australian building materials, industrial wastes and by-products. *Health Physics*. **48**, 87-95.
- [31] Krieger, R. (1981). Radioactivity of construction materials. *Betonwerk Fertigteil Technol.* **47**, 468.
- [32] Amrani, D. and Tahtat, M. (2001). Natural radioactivity in Algerian building materials. *Appl. Radiat. Isot.* **54**, 687-689.
- [33] Aykamış A. (2008). Türkiye’de yapı malzemesi olarak kullanılan bazı doğal taşlardaki radyoaktivite seviyelerinin belirlenerek, kimyasal ve mineralojik bileşim ilişkilerinin araştırılması. Ph. D. Thesis. Adana: Çukurova University Institute of Natural and Applied Sciences.
- [34] Turhan, Ş. (2008). Assessment of the natural radioactivity and radiological hazards in Turkish cement and its raw materials. *Journal of Environmental Radioactivity*. **99(2)**, 404-414.
- [35] TAEK. Doğal Radyasyon Kaynakları. <http://taek.gov.tr/bilgi-kosesi/184-radyasyon-insan-ve-cevre/radyasyonla-birlikte-yasiyoruz/501-dogal-radyasyon-kaynaklari.html>, 31.10.2013.
- [36] OECD. (1979). Organization for Economic Cooperation and Development, Exposure to radiation from the natural radioactivity in building materials. Paris: OECD.
- [37] Turhan, Ş., Baykan, U.,N , Şen, K. (2008). Measurement of the natural radioactivity in building materials used in Ankara and assessment of external doses. *Journal of Radiological Protection*. **28**, 83-91.



[38] Malanca, A., Pessina, V., Dallara, G. (1993). Radionuclide Content of Building Materials and gama ray dose rates in Dwellings of Rio Grande Do Norte, Brazil. *Radiation Protection Dosimetry*. **48(2)**, 199-203.

[39] Xinwei, L. (2005). Natural radioactivity in some building materials of Xi'an China. *Radiation Measurements*. **40**, 94-97.

[40] ICRP. (1987). Lung Cancer Risk from Indoor Exposures to radon Daughters. International Commission on Radiological Protection, ICRP Publication 50, Oxford: Pergamon Press.

[41] ICRP. (1993). Protection Against Radon at Home and at Work. International Commission on Radiological Protection, ICRP Publication 65, Oxford: Pergamon Press.

## APPENDIX 1

### IAEA-RGU-1 , Uranium Ore

#### Inorganic , Ores

- Unit Size: 500g
- Price per Unit: 50 EUR
- Report: [IAEA/RL/148](#)
- Date of Release: 1987-01-01
- Producing Laboratory: [email](#)

Both, IAEA-RGU-1 and IAEA-RGTh-1 reference materials were prepared on behalf of the International Atomic Energy Agency by the Canada Centre for Mineral and Energy Technology by dilution of a uranium ore BL-5 (7.09% U) and a thorium ore OKA-2 (2.89% Th, 219 µg U/g) with floated silica powder of similar grain size distribution, respectively. No evidence for between-bottles inhomogeneity was detected after mixing and bottling. BL-5 has been certified for uranium, <sup>226</sup>Ra and <sup>210</sup>Pb confirming that it is in radioactive equilibrium. The agreement between radiometric and chemical measurements of thorium and uranium in OKA-2 shows both series to be in radioactive equilibrium.

Analyte	Value	Unit	95% C.I.	N	R/I/C
<sup>232</sup> Th	< 4 <sup>?</sup>	Bq/kg	-	None	I
<sup>235</sup> U	228 <sup>?</sup>	Bq/kg	226 - 230	None	R
<sup>238</sup> U	4940 <sup>?</sup>	Bq/kg	4910 - 4970	None	R
<sup>40</sup> K	< 0.63 <sup>?</sup>	Bq/kg	-	None	I
K	< 20	mg/kg	-	None	I
Th	< 1	mg/kg	-	None	I
U	400	mg/kg	398 - 402	None	R

(Value) Concentration calculated as a mean of the accepted laboratory means

(N) Number of accepted laboratory means which are used to calculate the recommended or information values and their respective confidence intervals

(R/I/C) Classification assigned to the property value for analyte (Recommended/Information/Certified)

(?) Natural radionuclide activity concentrations derived from the elemental concentrations on basis of isotopic abundance and half-life data

The values listed above were established on the basis of a gravimetric dilution of materials with known uranium, thorium and potassium composition. The details concerning the criteria for qualification as a recommended or information value can be found in the respective report (attached).

## IAEA-RGTh-1 , Thorium Ore

### Inorganic , Ores

- Unit Size: 500g
- Price per Unit: 50 EUR
- Report: [IAEA/RL/148](#)
- Date of Release: 1987-01-01
- Producing Laboratory: [email](#)

Both, IAEA-RGU-1 and IAEA-RGTh-1 reference materials were prepared on behalf of the International Atomic Energy Agency by the Canada Centre for Mineral and Energy Technology by dilution of a uranium ore BL-5 (7.09% U) and a thorium ore OKA-2 (2.89% Th, 219 µg U/g) with floated silica powder of similar grain size distribution, respectively. No evidence for between-bottles inhomogeneity was detected after mixing and bottling. BL-5 has been certified for uranium, <sup>226</sup>Ra and <sup>210</sup>Pb confirming that it is in radioactive equilibrium. The agreement between radiometric and chemical measurements of thorium and uranium in OKA-2 shows both series to be in radioactive equilibrium.

Analyte	Value	Unit	95% C.I.	N	R/I/C
<sup>232</sup> Th	3250 <sup>?</sup>	Bq/kg	3160 - 3340	155	R
<sup>235</sup> U	3.6 <sup>?</sup>	Bq/kg	3.3 - 3.9	145	R
<sup>238</sup> U	78 <sup>?</sup>	Bq/kg	72 - 84	145	R
<sup>40</sup> K	6.3 <sup>?</sup>	Bq/kg	3.1 - 9.5	45	I
K	200	mg/kg	100 - 300	45	I
Th	800	mg/kg	784 - 816	155	R
U	6.3	mg/kg	5.9 - 6.7	145	R

(Value) Concentration calculated as a mean of the accepted laboratory means

(N) Number of accepted laboratory means which are used to calculate the recommended or information values and their respective confidence intervals

(R/I/C) Classification assigned to the property value for analyte  
(Recommended/Information/Certified)

(?) Natural radionuclide activity concentrations derived from the elemental concentrations on basis of isotopic abundance and half-life data

The values listed above were established on the basis of a gravimetric dilution of materials with known uranium, thorium and potassium composition. The details concerning the criteria for qualification as a recommended or information value can be found in the respective report (attached).

## IAEA-RGK-1 , Potassium Sulfate

### Inorganic , Ores

- Unit Size: 500g
- Price per Unit: 50 EUR
- Report: [IAEA/AL/148](#)
- Date of Release: 1987-01-01
- Producing Laboratory: [email](#)

The IAEA-RGK-1 material is produced from high purity (99.8%) potassium sulphate supplied by the Merck Company. The potassium property value and its uncertainty were obtained from repeated measurements performed at the IAEA Laboratories Seibersdorf and the results confirmed the value certified by Merck. The upper limits for the uranium and thorium property values were estimated by the IAEA Laboratories Seibersdorf using fluorimetry and activation analysis, respectively.

Analyte	Value	Unit	95% C.I.	N	R/I/C
<sup>40</sup> K	14000 <sup>?</sup>	Bq/kg	13600 - 14400	20	R
K	448000	mg/kg	445000 - 451000	20	R
Th	< 0.01	mg/kg	-	20	I
U	< 0.001	mg/kg	-	20	I

(Value) Concentration calculated as a mean of the accepted laboratory means

(N) Number of accepted laboratory means which are used to calculate the recommended or information values and their respective confidence intervals

(R/I/C) Classification assigned to the property value for analyte  
(Recommended/Information/Certified)

(?) Natural radionuclide activity concentrations derived from the elemental concentrations on basis of isotopic abundance and half-life data

The values listed above were established on the basis of a gravimetric dilution of materials with known uranium, thorium and potassium composition. The details concerning the criteria for qualification as a recommended or information value can be found in the respective report (attached).

## APPENDIX 2

```
// Program of Radioactivity Analyses
#include <iostream>
#include <cmath>
#include <iomanip>

using namespace std;

double Ak, mk, SHn, SHb, SHk, mn;

enum { TAK=1, TMK, TSHN, TSHB, TSHK, TMN};

double An(){
    return Ak*mk*(SHn-SHb)/((SHk-SHb)*mn);
}

//~~~~~
double Turev(int k){
    double h = 0.001, f1=0, f2=0;
    if(k==1){
        double oAk = Ak;
        Ak = oAk + h; f1 = An();
        Ak = oAk - h; f2 = An();
        Ak = oAk;
        return (f1-f2)/(2*h);
    }
    else if(k==2){
        double omk = mk;
        mk = omk + h; f1 = An();
        mk = omk - h; f2 = An();
        mk = omk;
        return (f1-f2)/(2*h);
    }
    else if(k==3){
        double oSHn = SHn;
        SHn = oSHn + h; f1 = An();
        SHn = oSHn - h; f2 = An();
        SHn = oSHn;
        return (f1-f2)/(2*h);
    }
    else if(k==4){
        double oSHb = SHb;
        Ak = oSHb + h; f1 = An();
        Ak = oSHb - h; f2 = An();
        Ak = oSHb;
        return (f1-f2)/(2*h);
    }
    else if(k==5){
        double oSHk = SHk;
        SHk = oSHk + h; f1 = An();
        SHk = oSHk - h; f2 = An();
    }
}
```

```

        SHk = oSHk;
        return (f1-f2)/(2*h);
    }
    else if(k==6){
        double omn = mn;
        mn = omn + h; f1 = An();
        mn = omn - h; f2 = An();
        mn = omn;
        return (f1-f2)/(2*h);
    }
}
//~~~~~

//-----
int main(){

cout<<"*****" <<endl;
cout<<"PROGRAM of RADIOACTIVITY ANALYSES" <<endl;
cout<<"*****" <<endl;
cout<<endl;

double x, t, NPAn, dNPAn, NPAb, dNPAb, NPAk, dNPAk, dAn;

cout<<"Press for 40K Analyses 1, for 226Ra Analyses 2, for 232Th Analyses 3" <<endl;
cin>>x;

if(x<=1){ cout<<"*Potassium Analyses" <<endl;}

if(x==2){ cout<<"**Uranium Analyses" <<endl;}

if(x>=3){ cout<<"***Thorium Analyses" <<endl;}
cout<<endl;

cout<< "Counting Time = ";
cin>> t;

cout<< "Mass of Sample (Enter two digit after , )= ";
cin>> mn;

cout<< "Net Peak Area of Sample = ";
cin>> NPAn;

SHn=NPAn/t;
cout<< "Error of Net Peak Area of Sample = ";
cin>> dNPAn;

cout<< "Net Peak Area of Background = ";
cin>> NPAb;
SHb=NPAb/t;

cout<< "Error of Net Peak Area of Background = ";
cin>> dNPAb;

cout<< "Net Peak Area of Reference = ";
cin>> NPAk;
SHk=NPAk/t;

```

```

cout<< "Error Net Peak Area of Reference = ";
cin>> dNPAk;

double dAk, dmK;
if(x<=1){ Ak=14000; dAk=400;
          mk=149; dmK=0.005;}

if(x==2){ Ak=4940; dAk=30;
          mk=140; dmK=0.005;}

if(x>=3){ Ak=3250; dAk=10;
          mk=140.93; dmK=0.005;}

double dSHn=dNPAh/t;
double dSHb=dNPAb/t;
double dSHk=dNPAk/t;
double dmn=0.005;

cout<<"-----" <<endl;
cout<< "AKTIVITY = " <<An() <<endl;

dAn = sqrt( Turev(TAK)*Turev(TAK)*dAk*dAk +
            Turev(TMK)*Turev(TMK)*dmK*dmK +
            Turev(TSHN)*Turev(TSHN)*dSHn*dSHn +
            Turev(TSHB)*Turev(TSHB)*dSHb*dSHb +
            Turev(TSHK)*Turev(TSHK)*dSHk*dSHk +
            Turev(TMN)*Turev(TMN)*dmn*dmn );

cout<<"Error of Statistical = +- " <<setprecision(9) <<dAn <<endl;
cout<<endl;
cout<<endl;
cout<<endl;
cout<<endl;
cout<<endl;
cout<<endl;
cout<<"The program is working for reference material 149g RGK-1, 140g RGU-1 ve 140.93g RGTh-1" <<endl;
cout<<endl;
cout<<endl;
double g;
cin>>g;
} /* main */

```