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Natural radiation sources: a study on NORM in industrial sectors

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Abstract

In Italy some industrial processes involving Naturally Occurring Radioactive Materials (NORM in the following) are regulated by the Legislative Decree of 31 July 2020 n. 101 [1] which transposes the Council Directive 2013/59/Euratom[2]. For several sectors, the entry into radiation protection system is entirely new. The topic of NORM is quite recent in radiation protection system; in fact, it is only in the last few decades that more attention has been paid to this issue. Therefore, the information available is far less than for other topics in the radiation protection field and some aspects, such as sampling protocols, are still being defined.

For these reasons, this thesis aims to provide an overview of natural radioactivity content in some NORM-involving industries, selected from the Italian legislative decree 101/2020.

The study carried out in this research project can help to understand which kind of material is more critical from the radiation protection point of view or which radionuclides usually occur in it and can therefore be expected from the analysis of such a sample.

A great collection of data about the content of radioactivity in four categories of materials (raw materials, residues, products and effluents) from twelve NORM involving industrial sectors has been carried out. The collection considers radiological data (in terms of activity concentrations of ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra and ^{40}K) for more than 6200 samples, taken from international and national literature. Collected radiological data have been analyzed and the most significant results will be shown here. Complete data, instead, are reported in Appendix.

An inventory of the industries currently operating in Italy was updated in order to understand the impact of the Italian radiation protection legislation on NORM-related industrial activities and to identify the industrial sectors with an important radiological impact on population and workers.

Moreover, given the large number of industrial sectors, a general methodological approach was developed, which can be adapted and declined for the different NORM industry sectors indicated in the legislation. The methodology, elaborated taking into account a graded approach, consinsts of two phases and provides indications about the characterization of the most critical exposure scenarios and of the radiological content of NORMs involved in the different phases of the industrial processes.

Lastly, all data collected and analyzed in this study will be soon available online. In fact in the framework of the research project it is nearing completion a database on the "*Physical Agents Portal* (PAF)" website (https://www.portaleagentifisici.it/) that will allow not only data consultation, but also dose assessment for different scenarios.

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Chapter 1

Introduction

Contents

1.1 Motivation and objectives

This thesis stems from the need to fill a knowledge gap on natural radioactivity in industrial activities that are not part of the nuclear fuel cycle. The existence of natural radioactivity has long been known: the discovery of natural radioactivity is attributed to French physicist Henri Becquerel in 1896 [13]. Today, natural radioactivity is recognized as a common phenomenon that occurs in many materials, including rocks, soil, and even the human body. It is also known that it can have harmful effects, depending on the dose and type of radiation involved [14]. Consequently, the study of radioactivity and its effects on living organisms continues to be an important area of research in many scientific fields. Over the past few decades, many studies have demonstrated that elevated activity concentrations of radionuclides of natural origin can occur in materials (as products, by-products, residues and raw materials) deriving from a wide range of conventional industrial activities [15]–[17]. Consequently, starting with European Union Council Directive 96/29Euratom [18], the protection from natural sources of ionising radiation was regulated. In the European Commission Report "Radiation Protection 88 – Recommendations for the implementation of the Title VII of the European Basic Safety Standards (BSS) concerning significant increase in exposure due to natural radiation sources" there was an initial list of industries related with materials containing naturally occurring radionuclides (NORM) where "*enhanced exposure to natural sources of radiation might occur*" [19]. Clearly, the regulatory system was not as structured as in BSS 2013[2]. In fact, it was only in the latest directive 2013/59 EURATOM of 5 December 2013 that the European

Commission identified a list of non-nuclear industrial sectors as 'practices' and three articles regulate practices involving the use of materials containing naturally occurring radionuclides.
The Italian radiation protection legislation transposing the EU BSS [20] has dedicated the entire Title IV to natural sources of ionising radiation and, differently from the previous legislation, new industrial activities are now regulated (i.e., geothermal power plants, cement production, etc.): for them, the introduction in the radiation protection regulatory system is entirely new.
From here the necessity to better know this kind of industries from the radiological point of view. This thesis, therefore, aims to conduct a study on the type of materials and activity concentrations present in the various NORM involving industrial sectors, based on national and international bibliographic sources.
Activity concentration measurements of natural radionuclides from the U-238 and Th-232 series (mainly of ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra) and of K-40 were collected. With its 2290 records collected for a total of 6229 samples, the present thesis can be a tool to get a general overview of the activity concentration in NORM involving industries, in different countries of the world. In particular, this work will also provide an overview of the situation of NORM-involving industrial sectors in Italy: it may help to understand the impact that the recent Legislative Decree 101/2020 [20] and smi [21] transposing the EU BSS [22] has on the national territory.
Although there are few scientific studies on NORM compared to other topics, it has been possible to collect an important amount of data. This thesis can be regarded as a starting point: with the spotlight on the topic of NORMs, the number of scientific studies about it will undoubtedly increase from now on.
Data presented in this work are also used to create a database that will be available online and that will allow not only to visualize the data of interest collected, but also to estimate the dose. Since the NORM involving industrial sectors are very different from each other, it was not immediate to find a uniform way of collecting data; however, this work was necessary for the analysis and the realization of the database.

1.2 Thesis outline

The thesis is organized in four chapters.

Chapter 1 contains the background necessary to introduce research activities of the thesis and, consequently, the objectives of the work.

Chapter 2 introduces the Naturally Occurring Radioactive Materials and explain what is meant by industries involving NORM (par.2.2); an overview on the Regulation on radiation protection and on Clearance and Exemption of NOR materials is also presented (par.2.3). It concludes with the description of a (graded) methodological approach developed to characterize the exposure situations.

In Chapter 3 the collection of international and national data about the natural radioactivity content in NOR matrixes are presented; detailed data are discussed for twelve industrial sectors, for seven radionuclides (^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra and ^{40}K). Moreover, the paragraph 3.3 describes an open Italian database on NORM that brings together all the information collected in this work and that will be soon available online at the Physical Agents Portal (PAF) website (https://www.portaleagentifisici.it/)

Chapter 4 presents the update inventory about Italian NORM involving industrial activities and their distribution on national territory. It is a useful overview that helps to understand the impact of the radiation protection regulation about natural radioactivity in conventional industries in Italy.

Chapter 2

Main sources of natural radioactivity: the Naturally Occurring Radioactive Materials

Contents

2.1 Main sources of natural radioactivity

Most naturally occurring chemical elements are stable, but nuclei of some isotopes have an excess of energy that makes them unstable, so they tend to disintegrate to achieve a more stable state. This implies that they spontaneously transform into other elements, with particles and/or energy emission. These isotopes are called radionuclides, and the process of disintegration is called radioactive decay. Radiation produced by radioisotopes interacts with matter, transferring energy and ionizing matter with which they interact[23].

All living being are constantly exposed to ionizing radiation from natural sources: this is called "natural background". Ionizing radiation, in fact, has always existed naturally, and everything is continuously exposed to it [11]; but it was only just over a century ago that humans became aware of it. It was the French physicist Henri Becquerel to discover natural radioactivity, in 1896[24]; in fact, the name of the SI unit for measuring the amount of radioactivity is the "becquerel", in honor of him.

Natural radiation exposure is due to two contributors: cosmic rays reaching the Earth through the atmosphere and radioactive nuclides that originated in the earth's crust and are present everywhere, including the human body itself. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), each person is subjected to receiving an annual effective dose of 2.4 milliSievert (mSv), although the range is wider (from 1 to 13 mSv per year)[11], [25]. Natural sources of radiation are shown in table 2.1: from the point of view of health effects, some of them cause external exposure (i.e., cosmic rays and terrestrial radiations), others are responsible for internal exposure (through ingestion, mainly of radon, and inhalation)[11].

Table 2.1 Average radiation dose from natural sources [11]

Source		**Worldwide average annual effective dose (mSv)**
External exposure	Cosmic rays	0.4
	Terrestrial gamma rays	0.5
Internal exposure	Inhalation	1.2
	Ingestion	0.3
	TOTAL	2.4

In addition to exposure from natural sources, people are also exposed to ionizing radiation from human-made sources: the mankind has created artificial radionuclides and used them in various applications such as nuclear power plants, industrial activities involving radioactive materials and, above all, medical procedures for an average dose of 0.6 mSv per year (see figure 2.1) [25].

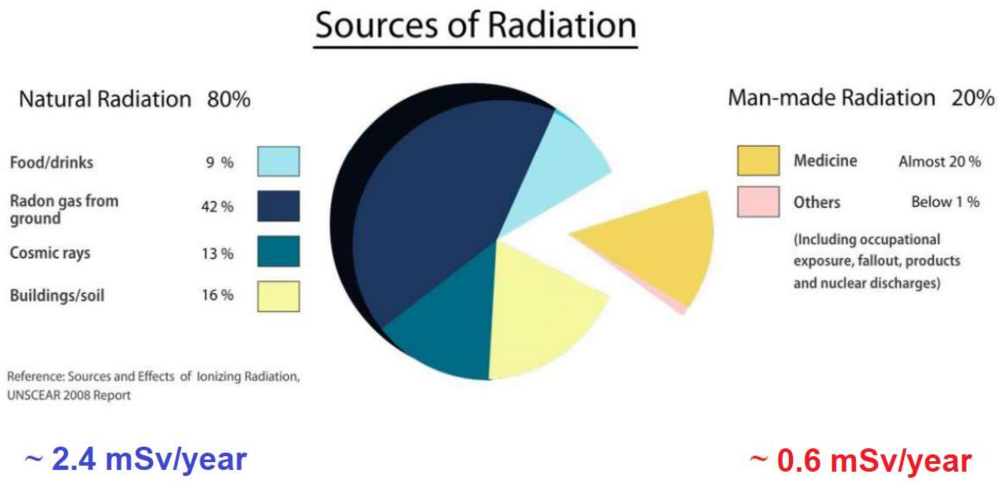


Figure 2.1 Average values of effective dose for natural and man-made radiation and percentage of relative contributes.

It is important to note that the risk associated with exposure to ionizing radiation is not zero, and that even small doses can increase the risk of cancer over time. This assumption underlies the "linear non-threshold (LNT)" model, that describes the relationship between risk of harmful effects and the amount of exposure to ionizing radiation[26].

So, it is important to minimize unnecessary exposures to ionizing radiation, to follow appropriate safety procedures when working with radioactive materials, and to follow medical recommendations for diagnostic tests and treatments that involve ionizing radiation.

The European Union sets regulatory limits on exposure to ionizing radiation to protect public health and the environment. The European Basic Safety Standards Directive (2013/59/Euratom) [2] establishes dose limits for occupational and public exposure. The directive recommends a limit of 1 milliSievert per year for members of the public and a limit of 20 milliSievert per year for workers.

From radiation protection point of view, some natural radionuclides are important to consider for the purposes: Uranium-238 and Thorium-232 decay series and Potassium-40. Usually, in human activities the levels of exposure to these radionuclides are not significantly greater than normal background levels and are not of concern for radiation protection. However, certain work activities can give rise to significantly enhanced exposures that it is necessary to regulate.

The activity concentration of natural radionuclides in materials can vary and it can increase due to natural and/or human-made processes. The most common natural processes that leads to accumulation of radionuclides in matter are geological processes, such as volcanic activity, weathering and erosion, that can transport radionuclides and concentrate them in specific areas. Another important accumulation may relate to radon gas, which is a decay product of uranium, and that can accumulate in buildings and other enclosed spaces, leading to increased levels of exposure to natural radiation.

Human-made processes can also lead to enhancement of natural radionuclides in materials. It can occur, in fact, that some industrial processes (such as the production of phosphate fertilizers or the extraction of oil and gas, etc.) may increase the concentrations of naturally occurring radionuclides in a type of material as residues or industrial products. Just to give an example, coal-fired power plants can release radionuclides in the environment through gaseous emission in atmosphere (volatile radionuclides such as ^{210}Pb and ^{210}Po are of interest) or through the combustion residues (i.e., ashes).

Therefore, the concentration of natural radionuclides in materials can vary widely depending on the geological, environmental, and industrial factors. It is important to monitor and manage naturally occurring radionuclides (NOR) materials to minimize health risks associated with exposure to ionizing radiation.

Following section will deal with a description of industrial processes with NORMs.

2.2 Naturally Occurring Radioactive Materials

Naturally Occurring Radioactive Materials (NORMs in the following) refers to those materials that are generally not considered radioactive, but containing naturally occurring radionuclides which may lead to not negligible levels of exposure for workers or members of the public.

NORMs also include materials in which the activity concentration of natural radionuclides could change by a process.

NORMs can be rich of following radionuclides: Uranium-238 and Thorium-232 and their progeny, and Potassium-40; many of them are characterised by long half-life[3].

The spectrum of Naturally Occurring Radioactive Materials is very wide. When dealing with NORMs we refer to raw materials (such as rocks, sand or minerals) but also industrial residues, products, by-products, semi-finished products and liquid or gaseous effluents.
To give some examples, typical NOR materials in numerous industrial sectors are scales and sludge (findable for instance in pipeline of the oil and gas production plant) or bottom and fly ashes in coal-fired power stations, or products like tiles or fertilizers.
How can activity concentration of radionuclides increase? The figure 2.2 from the Technical Reports Series No.419 of IAEA[3], shows that radioactivity content in a material can increase as a result of a technological process. The consequences from the point of view of radiological content are shown in the sequence below, in which each effect corresponds to the phase of the material respectively at the top: the initial enrichment of activity concentration occurs from the processing stage. These kinds of materials are sometimes referred to by the acronym *"TENORM" Technologically Enhanced Naturally Occurring Radioactive Material* indicating that the enrichment is due to non-natural reasons.

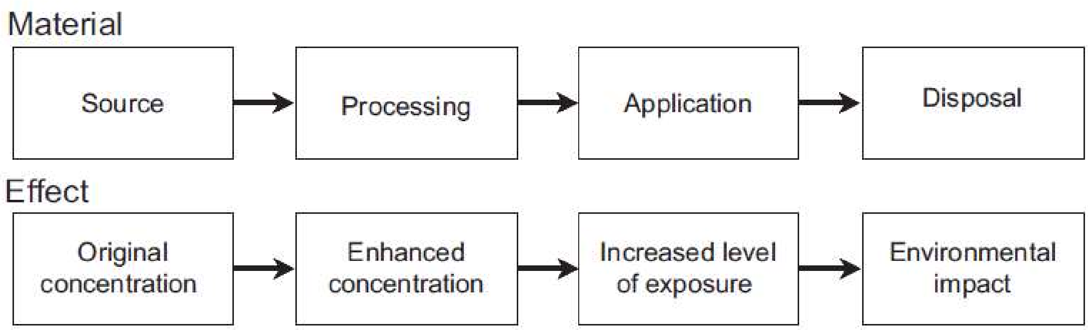


Figure 2.2 Processes leading to concentration enhancement and dispersal of NORM in the environment for NORM[3]

The presence of NORM might pose potential health risks for workers, members of the public and environment[3], [25]. Hence, it is important to develop an effective management system for materials with a high natural radioactivity content in order to protect the human health and the environment. To do this, the first step is to understand when and where NORM can occur within an industrial process. The 2013 European Union Council Directive (EU BSS)[2] identified the types of industrial activities that may determine NORM-related problems. The Italian legislation transposing the EU BSS[1] lists the industrial activities and the relative critical scenarios (see Table 2.2).

The above list highlights the large variety of typologies of industrial sectors related to NORMs. A brief description of these is given in the next paragraph. This is followed by an outline of Italian radiation-protection regulation.

Table 2.2 List of NORM involving industrial sectors and type/class of practices from Annex II of in Italian Legislative Decree 101/2020 smi [1]

Industrial Sector	**Classes or practices or critical exposure scenarios**
Coal-fired power plants	- Maintenance of boilers
Mining of ores other than uranium ore	- Extraction of granitoids, such as granites, orthogneiss, tuff, pozzolana, basalt, porphyry and lava
Zircon and zirconium industry	- Processing of zircon sands - Production of refractories, ceramics and tiles - Production of zirconium oxide and metallic zirconium
Mineral processing and primary iron production	- Extraction of rare earths from monazite - Extraction of tin, lead and copper - Processing of iron/niobium from pyrochlore ore - Extraction of aluminium from bauxite - Processing of iron/tantalum - Use of potassium chloride as additive in metals extraction by fusion
TiO_2 pigment production	- Management and maintenance of titanium dioxide production plants
Processing of phosphatic and potassium minerals	- Thermal phosphorus production - Phosphoric acid production - Production and wholesale of phosphate and potassium fertilisers - Production and wholesale of potassium chloride
Cement production	- Maintenance of clinker ovens
Production of thorium compounds and manufacture of thorium-containing products	- Production of thorium compounds and manufacture, management and conservation of thorium-containing products, in particular welding electrodes with thorium, optical components having thorium and nets for gas lamps
Geothermal energy production	- Maintenance of high or medium-enthalpy geothermal energy systems

Oil and gas production	- Oil extraction and refining, gas extraction, in particular to the presence of muds and scales in pipes and oil containers
Industries equipped with water filtration facilities	- Management and maintenance of facilities
Cutting and sandblasting processing	- Plants using abrasive sands or minerals

2.2.1 NORM in industry

- *Steel Production*

The production of steel is based on two processes: either steel is obtained directly from iron ore (iron oxides) or by smelting iron scrap. In the first case, steel is produced with a blast furnace, in the second with an electric furnace. The first one is the process of interest for this topic. In the integrated steel plant, the raw materials to be used are iron ore, coke and flux. The ore must be prepared and then processed by mixing it with hard coal (coke), limestone and other substances obtaining a compound that will be transformed into steel by means of a succession of processes: production of cast iron, production of steel and finally fabrication of products (see Fig. 2.3).

Raw materials from the mine are processed (pelletising, sintering, grinding, screening, etc.) in order to obtain an optimal size. Then the processed and agglomerated ore is sent to the blast furnace, where together with the coke and flux they form cast iron.

Cast iron is sent to oxygen converters where, through decarbonisation and oxidation of some of the impurities (silicon, sulphur, manganese and phosphorus), it is transformed into steel [4].

Iron ores have a low content of natural radionuclides. However, following high-temperature treatment, radionuclides volatilise and concentrate in emissions, particularly ^{210}Pb and ^{210}Po. For this kind of process (i.e. high temperature heat treatment), the critical processes are mineral agglomeration and blast furnace melting [27]. Most of the dust produced is retained by filters and then disposed of in landfills, the rest is released into the atmosphere. Similar problems can occur in coke production, where some ^{210}Pb and ^{210}Po contamination of the distillate condensate tar has been documented [4].

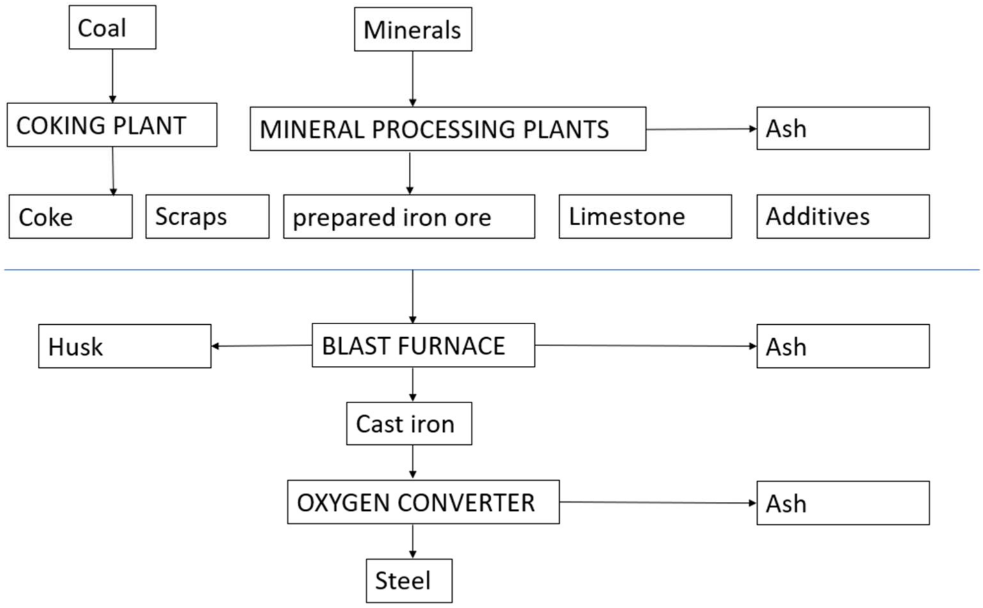


Figure 2.3 Diagram of the characteristic process of an integral cycle steel mill, taken from [4]

- *Extraction of aluminum from bauxite*

Aluminum is produced, besides scraps, from a rock containing aluminum oxide called "bauxite". It is a sedimentary rock dark red in colour that generally contains 30-54% alumina (Al2O3); the remaining part consists mainly of silicon dioxide, iron oxides and titanium dioxide [28]. Moderate concentration of natural radionuclides is contained in bauxite ores, but may become higher (mainly ^{210}Pb and ^{210}Po) in the emissions due to the high temperature treatment of the ore [29]. In fact, to separate the impurities and extract aluminum it is necessary to process it and the most commonly used method is the "Bayer process". The process is based on the digestion of bauxite with caustic soda at high temperature and pressure: it dissolves the alumina content of the bauxite separated. The alumina is then precipitated as a hydrate. The aluminum hdroxide is subjected to calcination, namely it is heated in a furnace at temperatures of about 1000°C to produce alumina: the water of crystallization is eliminated, trasforming the hydrate into aluminium oxide product (alumina)[4]. The processing of bauxite leaves a residue called "*red mud*": it is a highly alkaline, iron-rich and fine-grained material with a characteristic red color[5], [30].

The scheme of the Bayer process is shown in figure 2.4.

The inhalation of volatile dust of *red mud* may pose a risk for the population. For this reason heaps of *red mud* are usually wetted and, afterwords, covered.

In table 2.3 typical specific activity values associated with bauxite and redmud are given, taken from [12].

Raw materials and residues are of interest from the radiological point of view, because of their content of activity.

Table 2.3 Activity concentrations in bauxite and red mud [12]

Radionuclides	**Bauxite (Bq/kg)**	**Red Mud (Bq/kg)**
Uranium series	10-9000	100-3000
Thorium series	35-1400	100-3000
Potassium-40	10-600	10-100

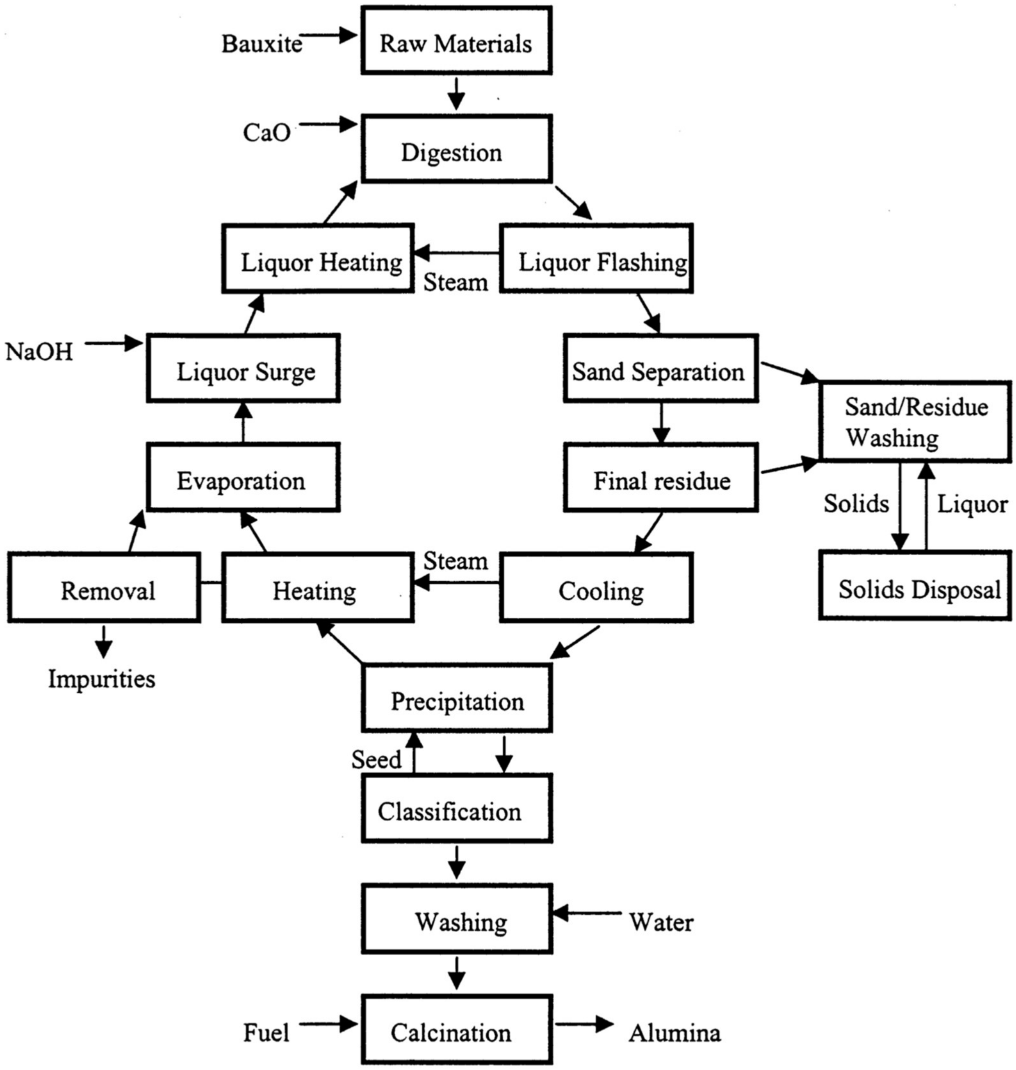


Figure 2.4 Schematic representation of the Bayer process [5].

- *Titanium dioxide pigment production*

Titanium dioxide is a white pigment widely used in various industries, including paint, cosmetic and medicines. Titanium is the ninth most abundant element in the Earth's crust and the fourth most abundant metal in terms of industrial importance after aluminum, iron and magnesium. To produce titanium dioxide pigment, the extraction of the titanium-containing minerals from the Earth is necessary. Its presence in nature is usually in chemical combination with oxygen and iron. Titanium-containing minerals are ilmenite, rutile and leucoxene. The mineral most used to produce titanium dioxide pigment is ilmenite [6], which is the poorest in the titanium content. This is why it is not common to use it directly but is first processed: a higher grade of ilmenite, in fact, contains a greater percentage of titanium dioxide and can be processed more efficiently to extract the titanium metal.

Not only ilmenite, but all three minerals contain many impurities, so they are often enriched in TiO_2: they are called higher-grade raw materials and for ilmenite and rutile they are called synthetic rutile, SREP (acronym for Synthetic Rutile Enhancement Process) and UGI (acronym for UpGraded Ilmenite [28].

Two are the methods to produce the titanium dioxide pigment and they are show in fig. 2.5. They are the "chloride process" and the "sulphate process". One can choose indiscriminately whether to use one or the other. Some factors that can affect the choice may be, for example, the availability of technology or the market conditions [6].

Titanium ores and the processed raw materials contain radionuclides of natural origin from the Th-232 and U-238 decay series in equilibrium[6]. Activity concentrations of the radionuclides are moderately high, however, above those normally found in rocks and soil. During treatment, radionuclides can be mobilised and migrate to dust, scales and other residues. This makes it possible to have higher concentrations of radionuclide activity than those present in the raw material. Radium isotopes, in particular, can concentrate in scales. By contrast, titanium dioxide and other titanium-containing products are essentially free of radioactivity. Literature [6] shows that thorium and uranium concentrations vary considerably among the minerals and that the thorium and uranium decay chains are in equilibrium. The following table (Table 2.4), taken from IAEA Safety Reports Series document no.76, shows the activity concentration levels of the Th-232 and U-238 radioactive series in titanium-containing ores. The concentrations of thorium and uranium vary from one ore to another; those in the table are ranges of activity concentrations taken from some literature data, but it is not excluded that values outside these ranges can be found.

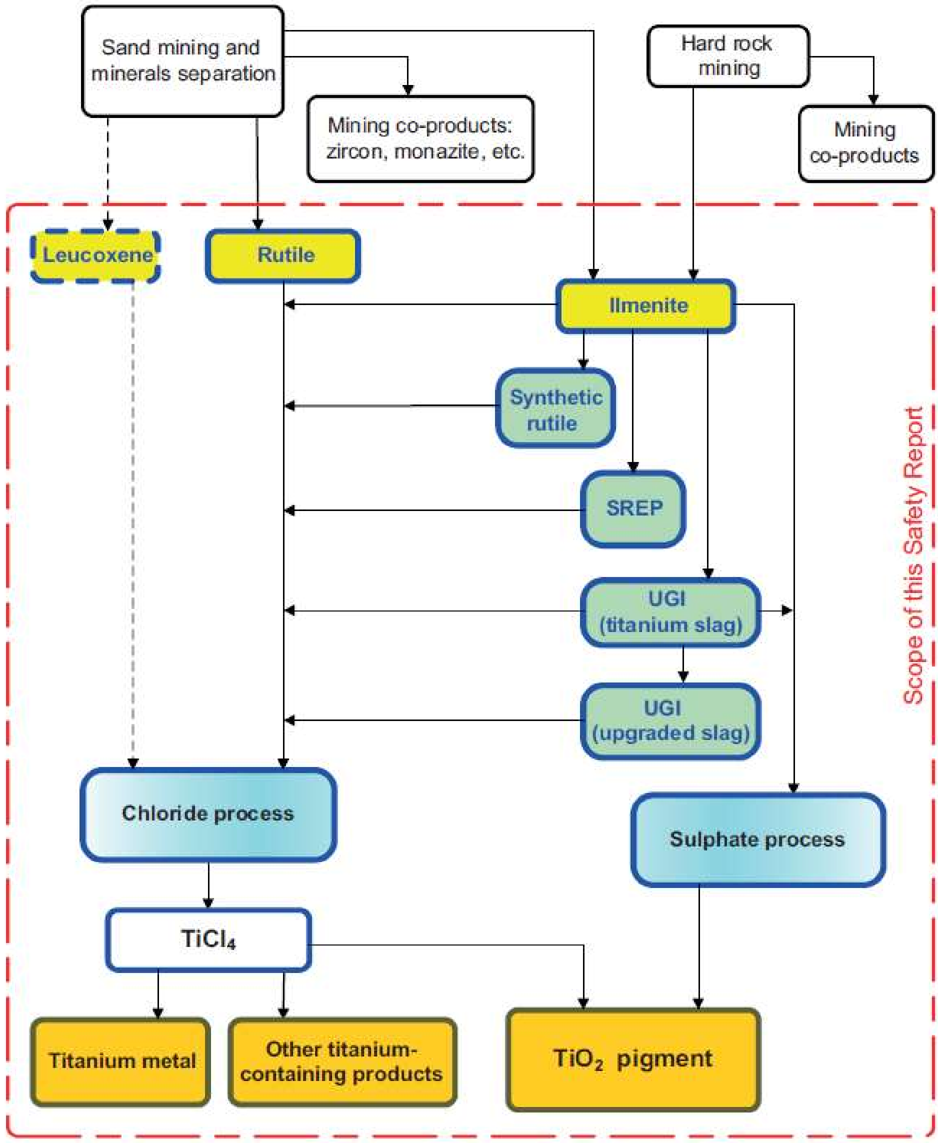


Figure 2.5 Diagram of the titanium dioxide pigment production. Total production is mainly due to the processing of rutile and ilmenite. Leucoxene makes a minimal contribution, which is why the lines associated with leucoxene are dashed [6]

Table 2.4 Typical range of radioactivity content in titanium minerals [6]

	TiO_2 content (%)	Th-232 decay series (Bq/g)	U-238 decay series (Bq/g)
Ilmenite sand	45-69	0.04-2	0.03-0.4
Ilmenite rock	34-45	0.001	0.001
Rutile	93-96.5	0.06-0.4	<0.1-0.7
Leucoxene	70-90	0.3-3	0.2-0.8

- *Cement production*

Cement is a hydraulic binder consisting of finely ground inorganic powder which, when mixed with water, forms a paste that hardens, developing mechanical strength. Raw materials are substances containing calcium carbonate (limestone or gypsum) and aluminum silicates (clay) mixed in appropriate ratios; after being pulverised, they are fired in a furnace at a high temperature (around 1500°C), thus forming the cement's main constituent: *clinker* (fig.2.6). This is then ground finely with the addition of gypsum. The addition of water to the resulting powder initiates a chemical reaction that leads to the formation of cement. Usually, in addition to water, inert material such as sand or gravel is also added, resulting in the formation of cement mortar or concrete[28], [31].

Figure2.6 A picture of the clinker, the cement's main constituent [7]

The different composition or proportion of the constituents of cement defines the cement "typology", characterising its mechanical properties and resistance to chemical or chemical-physical attack.
The Italian standard UNI EN/197-1 provides for five types of common cement, subdivided as follows in relation to the constituents used and the relative percentage of use[32]:

- (CEM I) Portland cement;
- (CEM II) Composite or blended Portland cement;
- (CEM III) Blast-furnace cement;
- (CEM IV) Pozzolanic cement;
- (CEM V) Composite cement.

Type I cements (CEM I) "*Portland cements*" consist of at least 95% clinker and 0 to 5% minor constituents such as filler, additive or sulphate (fig.2.7). They are generally used in the precasting of simple and prestressed reinforced concretes.

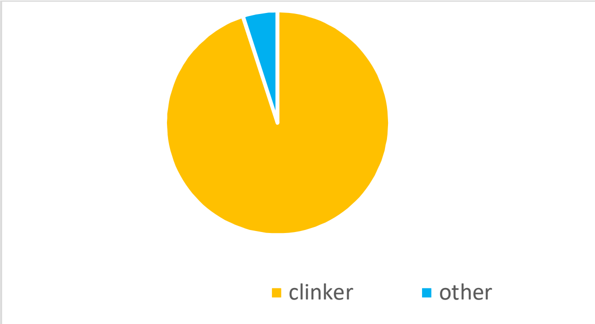


Figure 2.7 Constituents of Portland cement (CEM I)

Type II cements (CEM II) "Composite Portland Cement" have as their main constituents in addition to clinker, which is present in percentages varying from 65 to 94%, granulated blast furnace slag, microsilica, pozzolana, fly ash, calcined shale and limestone. They have properties very similar to those of CEM I, which make them suitable for the most common uses in normal and prestressed reinforced concrete and precast elements.

Type III (CEM III) "blast furnace cements" consist of clinker up to 64% and basic granulated blast furnace slag ranging from 36% to 95%. They are mainly suitable in situations where concrete is subject to chemically aggressive environments and for the construction of large-scale works.

Type IV cements (CEM IV) "pozzolanic cements" consist of clinker between 45 and 89%, and natural or artificial pozzolanic material in a proportion of between 11% and 55%. Type IV cement has the characteristic of having a high resistance to chemical attack. Cement Type V (CEM V) "Composite Cements" consist of a mixture of clinker (20-64%), blast furnace slag (18-50%) and pozzolana (18-50%) and are suitable for concretes exposed to moderately aggressive environments such as seawater, acidic waters, sulphate soils.

The cement production is characterized by six phases. The first one is the extraction of raw materials: calcium carbonate, clays and limestone. The raw materials are mixed to obtain a homogenous composition, then dried and ground. The 'raw flour' is deposited and homogenised in large-capacity silos and then fired in the furnace where reactions occur that transform the raw flour into clinker. This is the “core” of the cement production process. Inside the furnace, the flour undergoes progressive heating to a maximum temperature of around 1500°C. The rotary kiln consists of a tube several meters in diameter, slightly inclined on its axis, and lined inside with refractory material. During baking, the oven rotates on its axis and, thanks to its inclination, allows the material being baked to advance inside the oven, sliding along the walls. The flour agglomerates around 1300°C, taking the form of nodules [7], [28], [33]. The technological cycle of cement production ends with the grinding into a fine powder of the clinker mixed with gypsum (setting time regulator) and other components such as pozzolan, fly ash, limestone, etc. to obtain the various types of cement. Grinding takes place in cement factories or in special grinding centers. The cement thus obtained is stored and shipped loose or in bags.

There are two types of cement production plant: full-cycle (here abbreviated as CC) or grinding plants (abbreviated with “M”). Only full-cycle plants are characterised by the presence of the clinker oven. Oven maintenance is done periodically and involves a temporary shutdown of the plant; it is carried out to replace worn refractory bricks or to remove scales inside the oven. The Italian regulation identify only one scenario as practice: clinker kiln maintenance. However, additional scenarios for workers and the population have emerged from the literature and studies on Italian plants[11], [27], [28]. Furnace scaling management and raw material preparation are scenarios to be considered for workers in a cement production plant. Radiological criticalities are mainly due to an accumulation of ^{210}Pb and ^{210}Po in clinker oven and radiation from external exposure.
For the population, it is necessary to assess the emission of ^{210}Pb and ^{210}Po into the atmosphere.

- *Coal-fired power plants*

Coal (or hard coal) is one of the most complex, fossil-derived, carbon-rich natural substances. Formation is long and takes place through a geological process of fossilization and carbonization of forest organic matter: the carbon in them is gradually transformed into peat, lignite, lithanthracite and, as the last stage, anthracite. Each coal is unique, having been derived from different plant sources over geologic time [34]. The production of electricity from coal takes place via a thermodynamic cycle in which the heat produced by the fuel is converted first into mechanical energy and then into electrical energy (see Fig. 2.8). A thermal power plant consists of a boiler (or steam generator), that is the highest structure of the plant; next to it are the steam turbine, alternator and condenser. On the other side of the boiler there is a pathway, consisting of a series of filters, leading the flue gases from the boiler to the chimney. The boiler is fuelled by coal and is traversed by a coil in which water circulates. The water is heated by the heat produced by the combustion of the fossil and turns into steam. The steam goes into the turbine, where it expands and releases its kinetic energy. The steam is condensed and sent back to the boiler while the rotation of the turbine rotor is transmitted to the alternator via the drive shaft. Thanks to the phenomenon of electromagnetic induction on which the alternator is based, mechanical energy is converted into electrical energy.

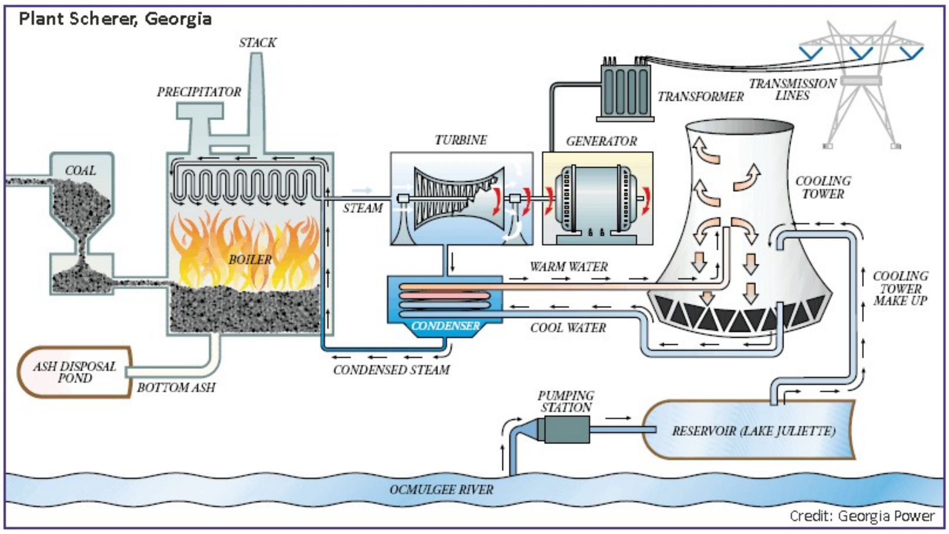


Figure 2.8Diagram of a coal-fired power plant. (In particular, the plant represented is the Scherer plant in Georgia, one of the largest in the USA)[8]

Most coal contains uranium, thorium, their decay products and potassium K-40[35]. In residues and gaseous emissions an enrichment of naturally occurring radionuclides can occur[4]. In particular, for this industrial sector, two phases are important from the radiological point of view: extraction and combustion. In Italy, the extraction process is absent; therefore, only combustion is of interest:the combustion process

at high temperatures, in fact, causes gaseous radionuclides such as Lead-210 and Polonium-210 volatilise and concentrate in ash.
The amount of coal ash burned depends on the type of coal and the type of boiler and, therefore, the concentration of radionuclides in coal ash can be up to 10 times higher than in coal[36]. Bottom ash is disposed of in landfills (where it can contaminate groundwater) after combustion. Fly ash is stored in landfills and surface impoundments as well as recycled as components of building materials (e.g. in the production of pozzolanic cement and of new building materials such as geopolymers). Volatile radionuclides (210Pb, 210Po) accumulate in the fly ash and smaller particles emitted during combustion, so they can escape the filters and be released down the chimney[12].

- *Zircon and zirconium industry*

Zirconium is an abundant metal in the earth's crust, but in nature it is not found in the elemental state but in the form of a mineral: it is mainly used as Zircon ($ZrSiO_4$) and baddeleyite (ZrO_2) for refractory materials, sands and ceramics. Sands with a high content of zirconium minerals (zirconiferous sands) are used in the production of ceramics and refractory materials as an opacifier and hardener. Due to their grain size of between 100 and 200 μm, imported sands are used directly in the production of refractory materials, while their use in the production of ceramics requires a grinding process, down to diameters in the order of even microns. The sands and powders of zirconium silicates produced by their grinding are then used not only in the ceramic industry, but also in colour and tile factories for the production of glazes, frits and porcelain stoneware [28].The natural radiological content in zirconiferous sands can vary, depending on the local origin, with values in the range of 0.4-40 Bq/g for Th-232 and 0.2-74 Bq/g for U-238 [11].
Generally in the ceramics industry, the raw materials used have rather low specific activities, with the exception of materials containing zirconium; therefore, the addition of zirconiferous material in the form of sand or flour to the mixtures in the preparation of porcelain stoneware and in glazes leads to the problem of radioactivity in the finished product [4].

- *Geothermal energy production*

Geothermal is the energy stored in the form of heat below the earth's surface. The heat still comes from the formation of the planet, but most of it is due to radioactive decay processes of certain elements (such as K, U and Th) contained in rocks. A geothermal system can be defined as a convective water system, which transports heat contained within the earth to the surface, where the heat is dispersed or utilised [28].
In geothermal plants, the radioisotopes mainly found are radon and radium, although the available data are still rather limited [28][27], [37].
The critical phases from the radiation protection point of view for potential NORM content are two:

- Excavation/drilling phase;
- Maintenance operations in which improper handling or treatment can cause radionuclides to be released into the environment.

An Italian study on high enthalpy geothermal plants found out that there are three different types of NORM residues: exhausted sand and dust from abatement filter of the ventilation system of the sandblasting cabin, exhausted adsorbent and filtering materials and tower sludge[38].
In many papers it is pointed out that, although uranium, thorium and their radioactive decay products occurr in the lithological formations from which geothermal fluids are extracted, geothermal fluids do not contain significant concentrations of them[3].

- *Extraction of Rare Earths from monazite*

Rare earths are a group of 15 chemical elements with an atomic number between 57 and 71 having almost the same chemical properties; since the first of these elements is lanthanum, the rare earth group is also called the lanthanide group or lanthanides (see fig.2.9). The elements belonging to the lanthanoid group have the same electronic configuration ($6s^2$) and this is the reason why these elements, despite having different atomic numbers, have similar chemical properties and ionization energies: the added electrons complete the inner layers, leaving the valence layer untouched. This is why they occupy only one place in the periodic table, in the 3rd group.

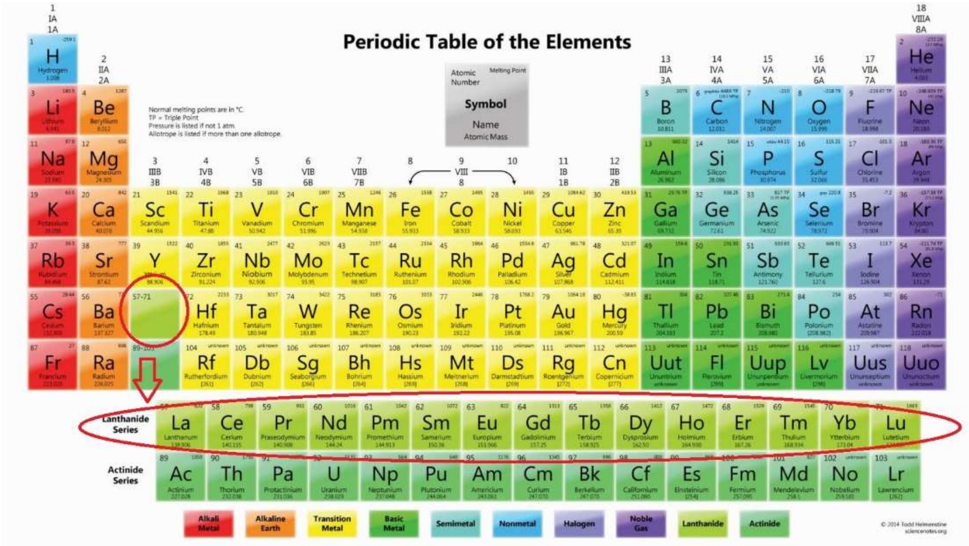


Figure 2.9 Periodic table of elements: the lanthanide group

They have been called "rare earths" because they were thought to be uncommon in nature. In reality, some of them, such as Cerium, are not rare at all, but they are not evenly distributed in the earth's crust and, moreover, are only found as compounds in particular minerals (in the form of oxides, carbonates, silicates, phosphates...). Moreover, as rare earths have similar chemical properties, they are difficult to separate. Rare earths are found in primary deposits associated with igneous intrusions, dikes and pegmatites and in secondary deposits of beach, dunes and alluvial plains [39]. They are contained in more than 200 minerals with concentrations above 0.01%, but those in which rare earths are present in such quantities that they can be mined are essentially Monazite, Bastnäsite, Xenotime, Loparite and Lateritic clay. More than 95% of these minerals are found in China (which alone has about 80%), the United States and India[39].

Raw materials of this industrial sectors are characterized by high concentrations of the natural series of Thorium and, to a lesser extent, Potassium and the decay series of Uranium. It should be borne in mind that radioactivity can migrate during ore processing: the processes could lead to an accumulation of radionuclides in various process residues such as dust and scales; in particular, isotopes of radium can concentrate in scales[39].

- *Processing of phosphatic and potassium minerals*

Phosphate ores are used in industry to produce phosphoric acid or elemental phosphorus, which are then processed into phosphate fertilisers, detergents, animal feed, food additives or pesticides[3].

Most phosphate rock is treated with acid to produce phosphoric acid and fertilisers[40]. This industrial process can lead to the formation of residues with high radiological content, mainly phosphogypsum[41]. The most critical processes are the production of phosphoric acid, the production of elemental phosphorus by thermal process and the production of fertilizers.

Generally, phosphoric acid (H_3PO_4) can be produced by wet or thermal process.

In the wet process the phosphorite, that is rich in uranium, is attacked with sulphuric acid to obtain phosphoric acid. This process produce a particular residue, called phosphogypsum. During the phosphoric acid production process, radium flows into the residue (with growth of lead and polonium), while the phosphoric acid enriches with Uranium-238 [27].

In the thermal process, phosphoric acid is produced from elemental phosphorus. The phosphoric acid produced by the thermal process is characterized by high level of purity, so it is used in the field of chemistry and food industry, instead the wet process phosphoric acid is used in fertilizer production[42].

The radiological content in fertilizers is variable and depends on the method of production and on the radiological content in raw materials [3].

- *Mining of ores other than uranium ore*

All rocks and soils contain radionuclides: because of their long live, Earth's crust contains still today the so-called primordial radionuclides (Uranium-238, Thorium-232, their decay products and Potassium-40); they are responsible for radioactivity in natural resources. Therefore, some minerals other than uranium ore can also have a high content of natural radioactivity, and human activities involving them, such as mining operations, can increase human exposure to ionizing radiation by bringing additional radioactivity[43].

- *Oil and gas*

Oil itself does not have significant concentrations of radionuclides, but already in the extraction process radionuclides come into play as they are transported by the water. Water leads to the formation of scales on the surfaces with which they are in direct contact, so that scales with a high content of radium and its decay products can be found in the extraction and treatment plants (particularly in well, phase separators, storage tanks, etc.). Radionuclides carried by the water can accumulate not only in scales but also in sludges at several points in the plant (separators, tanks) [27], [28]. These types of residues are mainly formed during the extraction and production processes, when the oil-gas-water mixture is brought to the surface, and also during the separation process. Potential radiological health risks could arise from the following activities[12]:

- Maintenance;
- Transport of waste and contaminated equipment;
- Storage of pipes and boreholes;
- Scaling treatment (scaling);
- Removal of scales from pipes;
- Pipe sectioning and cutting.

2.3 The Italian regulatory system on radiation protection for workers and members of the public in case of NORM involving industries

On December 5, 2013, the Council Directive 2013/59/Euratom has been published in Europe. It lays down basic safety standards for protection against the dangers arising from exposure to ionising radiation[2]. In the Section 2, Article 23 deals with the identification of practices involving the use of materials containing naturally occurring radionuclides. It lays down that "*Member States shall ensure the identification of classes or types of*

practice involving naturally occurring radioactive material and leading to exposure of workers or members of the public which cannot be disregarded from a radiation protection point of view. Such identification shall be carried out by appropriate means taking into account industrial sectors listed in Annex VI".
Annex VI contains the *"List of industrial sectors involving naturally occurring radioactive material as referred to in Article 23"*. They are:

- *Extraction of rare earths from monazite*
- *Production of thorium compounds and manufacture of thorium-containing products*
- *Processing of niobium/tantalum ore*
- *Oil and gas production*
- *Geothermal energy production*
- *TiO_2 pigment production*
- *Thermal phosphorus production*
- *Zircon and zirconium industry*
- *Production of phosphate fertilisers*
- *Cement production, maintenance of clinker ovens*
- *Coal-fired power plants, maintenance of boilers*
- *Phosphoric acid production,*
- *Primary iron production,*
- *Tin/lead/copper smelting,*
- *Ground water filtration facilities,*
- *Mining of ores other than uranium ore.*

In Italy, the Legislative Decree n. 101 of 2020, recently modified by the Legislative Decree 203/2022([1], [21]) transposes the Council Directive 59/2013/Euratom. The Legislative Decree 101/2020, currently in force, has introduced some novelties regarding the regulatory system on radiation protection in industries involving Naturally Occurring Radioactive Materials (NORM): the previous Italian legislation (Legislative Decree 230/95)[44], which transposed the Council Directive 96/29/Euratom Directive[45], provided already provisions on work activities with particular natural sources of radiation, but the current decree extends the field of application to industrial sectors never involved before. The Legislative Decree 101/2020 introduced another notable change: NORM industries are controlled as Planned Exposure

Situations (PES) and Exemption/Clearance Levels (EL/CL) as operational radioprotection tools were introduced.

"Exemption" means the *determination by a regulatory body that a source or practice need not be subject to some or all aspects of regulatory control on the basis that the exposure (including potential exposure) due to the source or practice is too small to warrant the application of those aspects*[46].

"Clearance" means *the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body. Removal from control in this context refers to control applied for radiation protection purposes*[46].

The exemption is the lowest level of the graded approach. A practice is exempt when the radiation risk is low enough to justify exemption from the notification and other obligations or when reasonable control measures would not significantly reduce the doses. Exemption levels allow to ensure this compliance.
According to the 2013 EUBSS, two types of ELs/CLs are introduced in the Italian regulation on NORM: ELs/CLs in terms of activity concentration and in terms of effective dose. The former applies only to solid matrices, such as raw materials and solid residues. Residues are defined in the Italian regulation as follows:

"Waste material, in solid or liquid form, from industrial production using materials containing radionuclides of natural origin, from which results in an exposure of workers or the public that is not negligible from a radiation protection point of view"[1].

In general, ELs and CLs have the values shown in Table 2.5; for some specific situations, however, values are different: this is the case for petroleum sludge, landfilling or reuse for road construction, and lastly, incineration. These values are summarized in Table 2.6 and consider those situations in which segments of the decay chains are not in equilibrium with the parent radionuclide, situation that occurs frequently for NOR materials used in industrial processes.
According to the graded approach, it is foreseen that if ELs and CLs are not met in terms of activity concentration, the effective dose for workers

and members of the public have to be assessed and compared with relevant ELs. The ELs and CLs is in terms of dose to workers and members of the public are shown in Table 2.7. In Italy, the dose criterion for workers is the same established in 2013 EUBSS, while for members of the public the Italian legislation confirms a more conservative dose criterion of 0.3 mSv/y established in previous legislation. The values of the Clearance Levels for residues disposed in conventional landfill or reused for road construction are, for all radionuclides, 50 percent of the Table 2.5's values (see Table 2.6). Where the residue is intended for incineration, the compliance with the effective dose for the individual representative of the population must always be demonstrated.
The figure 2.10 shows the diagram of the graded approach currently in force and just described for a NORM-involving industry in Italy.
In the following paragraph, a description of the development of protocols to implement the legislation is presented.

Table 2.5 General Exemption and Clearance Levels (ELs and CLs)

<table>
<tr><th colspan="2">Natural radionuclides</th><th>Exemption Levels (EL)</th></tr>
<tr><td>Radionuclides from U-238 and Th-232 series in secular equilibrium with their progeny</td><td>all radionuclides</td><td>1 kBq/kg</td></tr>
<tr><td rowspan="2">Radionuclides from U-238 and Th-232 series not in secular equilibrium</td><td>all radionuclides, with the exception of Pb-210 and Po-210</td><td>1 kBq/kg</td></tr>
<tr><td>Pb-210 and Po-210</td><td>5 kBq/kg</td></tr>
<tr><td colspan="2">K-40</td><td>10 kBq/kg</td></tr>
</table>

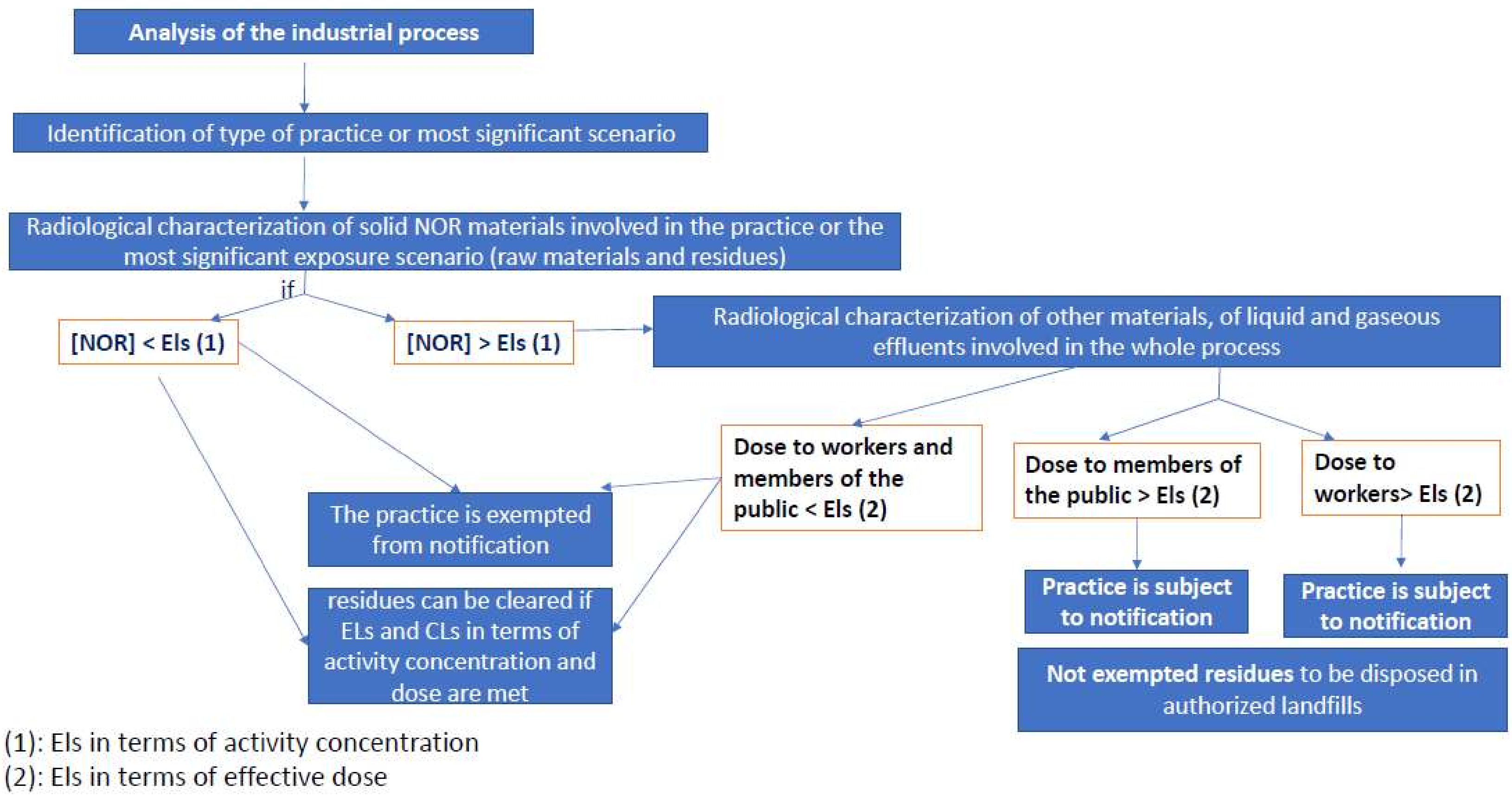
Table 2.6 Specific ELs and CLs for particular materials or residue destination.

Specific Situations	**Radionuclides**	**ELs**	**CLs**
Oil sludge	U-nat, Th-230, Th-232, Pb-210, Po-210	100 kBq/kg	100 kBq/kg
	Ra-228	10 kBq/kg	10 kBq/kg
	For all radionuclides of the U-238 and Th-232 series	5 kBq/kg	5 kBq/kg
	K-40	50 kBq/kg	50 kBq/kg
Disposal in landfill or reuse for road construction	U-238 and Th-232 series		0.5 kBq/kg
	Pb-210; Po-210		2.5 kBq/kg
	K-40		5 kBq/kg
Incineration			0.3 mSv/y

Table 2.7 ELs and CLs in terms of effective dose

For workers	1 mSv/y
For members of the public	0.3 mSv/y

Figure 2.10 Flow diagram of the graded approach to regulatory control management for NORM-related industries in the Italian Legislation currently in force



2.4 Development of a (graded) methodological approach to implement the legislation

With the recent Italian transposition of the European Council Directive 59/2013/Euratom (FONTE: 101/2020) NORM-involving industries must comply with new legal obligations. To support the fulfillment of these obligations that ensure the protection of workers and population, a methodological approach was developed, that integrates studies from the past with new research and analyses. It allows to identify the most critical exposure scenario and to verify the level of exposure of workers and member of the public.

The methodology addresses a number of radiation protection aspects, in particular:

- Identification of the matrices of interest and the radionuclides to be measured;
- Identification of the analysis methods to be used;
- Development of simplified methods for estimating the effective dose for workers and for the individual representative of the population.

It reflects the "*graded approach*" to which the EU-BSS 2013 [2] refers, and that origin from the ICRP Recommendations 103 of 2007 [26].

In fact, the proposed general methodology consists of two phases, both articulated in successive "'steps". The first one (Phase 1), shown in figure 2.11, begins with the identification of the practice and solid matrices and ends with the comparison of their activity concentrations values with ELs, in terms of kBq/kg as reported in tables 2.5 and 2.6.

Phase 2, instead, only begins if the activity concentration values of solid matrices sampled during the Phase 1 exceeds the ELs in terms of general and/or specific activity concentration. In this case, it is necessary to identify the most significant exposure scenarios for the public and workers (step 1), characterise any additional matrices of interest (step 2) and assess the dose to member of the public and workers (step 3). Phase 2, in fact, is finalized to verify the compliance with ELs in terms of effective dose (shown in table 2.7) (step 4) .

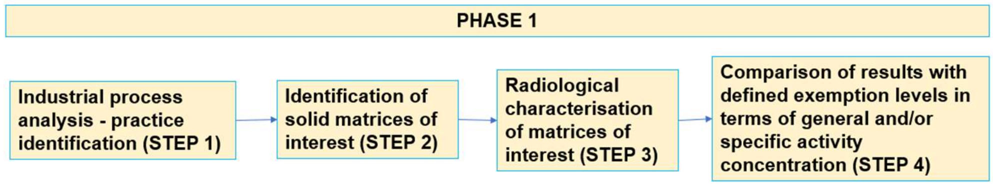


Figure 1.11 Scheme of the Phase 1 of the general methodology to characterize the most critical exposure scenarios in NORM involving industries

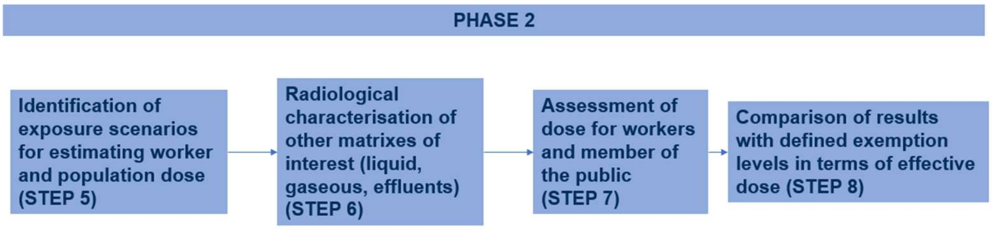


Figure 2.12 Scheme of the Phase 2 of the general methodology

What is briefly presented is a general method, which can be applied to different industries using appropriate adaptations. Some protocols have already been realised and will be soon published in dedicated papers. All of them are based on the general models given in Figures 2.14 for Phase 1 and in Figure 2.15 for Phase 2, so protocols will contain fields with the description of the matrices of interest (shown in figure 2.13), a list of the relevant radionuclides to be measured and the analytical method. More detailed information are given in this study [9].

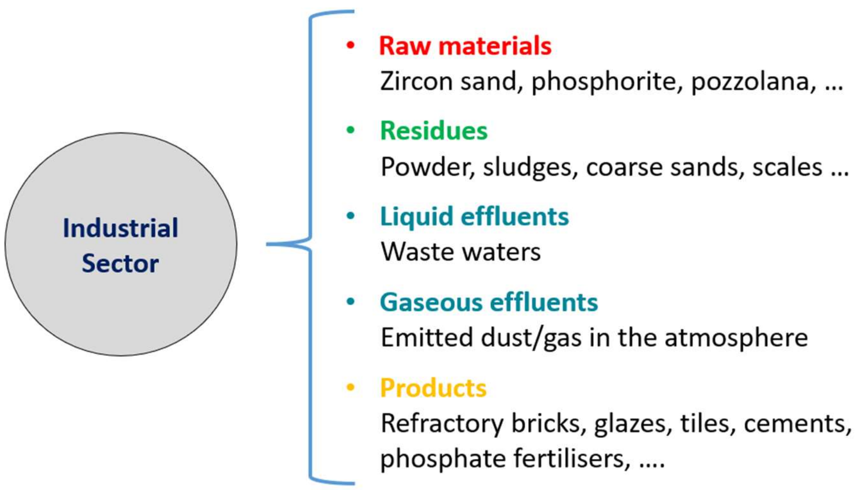


Figure 2.13 Matrices of interest in the production cycle of a NORM-involving industry

Solid Matrix		Analytical Method	Radionuclides
Raw material	Raw material of natural origin	Gamma spectrometry	^{40}K, series of ^{238}U and ^{232}Th
	Raw material from industrial process	Gamma spectrometry	^{40}K, chain segments of ^{238}U and ^{232}Th
Residue	Dried Residue 1 (e.g., from refractory industry)	Gamma spectrometry Alpha spectrometry	^{40}K, chain segments of ^{238}U, ^{232}Th and ^{210}Po
	Dried Residue 2 (e.g., from cement production)	Gamma spectrometry	^{40}K, chain segments of ^{238}U and ^{232}Th
	Wet residue (e.g., oil sludge)	Gamma spectrometry	^{40}K, chain segments of ^{238}U and ^{232}Th

Figure 2.14 General scheme of a protocol in support of the Phase 1 [9]

	Matrix	Exposure Scenarios Workers	Public
Industrial sector	Raw materials	Storage–Large quantity; transport; management	Transport
	Residues	Management (collection, loading, unloading, etc.)	Disposal (landfill, recycle, reuse, etc.); transport
	Final products	Finishing processes; packaging; transport	-
	Liquid effluents	-	Release of wastewater: exposure of members of the public to liquid effluents
	Gaseous effluents	-	Release of gaseous effluents from chimneys: exposure of members of the public living near the industrial plant

Figure 2.15 General scheme of a protocol in support of the Phase 2 [9]

Chapter 3

Collection of international/national data about the natural radioactivity content in NOR matrixes

Contents

The topic of NOR materials has been of interest to international Bodies and Institutions. The interaction between countries and organizations contributes to better exchange knowledge and experience. For this reason, to facilitate international collaboration, several projects started. International working groups were created: they provide an important opportunity to address radiation protection issues in NORM-involving industries, to deal with case study and discuss results of new research. In this way each member makes available the skills and can share own skills in the field of NOR materials.

As part of these projects, work has been done on the creation of a NORM inventory. The following paragraphs introduce the two projects: one international and one European.

3.1 IAEA

Under the IAEA framework, a network for environmental remediation and management of NORM was born in 2009: it is called "ENVIRONET", and it encourage the construction of national inventories of NORM involving industries. In fact, in 2017 under IAEA ENVIRONET Network, a project on NORM called "Promoting Good Practices and Providing Knowledge Transfer Applicable to the Management of NORM Residues and Wastes" started. With the aim of supporting IAEA member States to conduct an inventory, know how many NORM-involving industrial sectors are still active in own country and to gather information about the radiological impact on workers, members of the public and environment a task group has been set [47] [48] . The project can be a useful tool for obtaining an overview of existing NORM sites and their characteristics.

Also, at European level a project regarding NORM began three years ago. It is called RadoNORM. A summary of it is presented in the following paragraph.

3.2 RadoNORM

To support member States of the European Union in the implementation of the European Directive 59/2013/Euratom, on September 1, 2020, a project funded by the European Union began. The project falls under the EURATOM Horizon 2020 program, called "*RadoNorm- Towards effective radiation protection based on improved scientific evidence and social considerations – Focus on Radon and NORM*" (https://www.radonorm.eu/), with a duration of 5 years.

Fifty-five partners from 22 countries (18 EU countries, Switzerland, Norway, Ukraine, UK) take part in the project and it is coordinated by Germany. Most of the project is devoted to radon (about 70 percent), but several activities also deal with NORM-related issues.
The project *RadoNorm* is structured into 8 WorkPackages (WPs) lasting 60 months. The WP dedicated to NORM is the WP2.
Each WP is divided into Tasks. Specifically, WP2 is divided into 8 Tasks and the Italian group take part is engaged in 2 of them: Task 2.5(*Overview of NORM sites and exposure scenarios in Europe and their characteristics*) and Task 2.8 (*Updating approaches for modelling long-term prediction of NORM transfer in the environment*).
The Italian group contributing to NORM in the project consists by ISS, ARPA Veneto and INAIL – DIMEILA.

3.3 Database on radiological data about NORM involved in several industrial sectors

In this thesis, a data collection of information about activity concentrations of ^{238}U, ^{232}Th and ^{40}K in matrices from NORM-involving industries is set up. 6229 samples were collected of vary materials such as rocks, scales, sludges, and various type of products. The number of samples for each type of industrial activity is not divided equally: it was not possible to find a similar number of samples for each industrial activity because from the past to today NORM-involving industries have not been investigated in the same way: indeed, for some industries the available scientific studies are few. This gap will be surely filled in the next years as a result of the attention that NORM is beginning to enjoy.
The amount of collected samples is based on the bibliography available to date. It varies widely between sectors; in fact, they are:

- 1029 for Cement Production;
- 406 for Oil and Gas Production;
- 481 for Zircon and zirconium industry;
- 161 for TiO_2 pigment production;
- 70 for Geothermal energy production;
- 675 for Mining of ores other than uranium ore;
- 2199 for Coal-fired power plants;

- 101 for Extraction of rare earths from monazite;
- 66 for Primary iron production;
- 161 for Extraction of aluminum from bauxite;
- 403 for Production of phosphate and potassium fertilizers;
- 477 for Phosphoric acid production.

So, the industrial sector for whom it has been possible to collect most of the samples is that of the electricity production from coal; on the other hand, geothermal energy production and primary iron production are the activities with the least amount of data found in literature. A significant number of samples has been collected also for the cement production. A graph (fig. 3.1) shows the distribution of the samples gathered for this study.

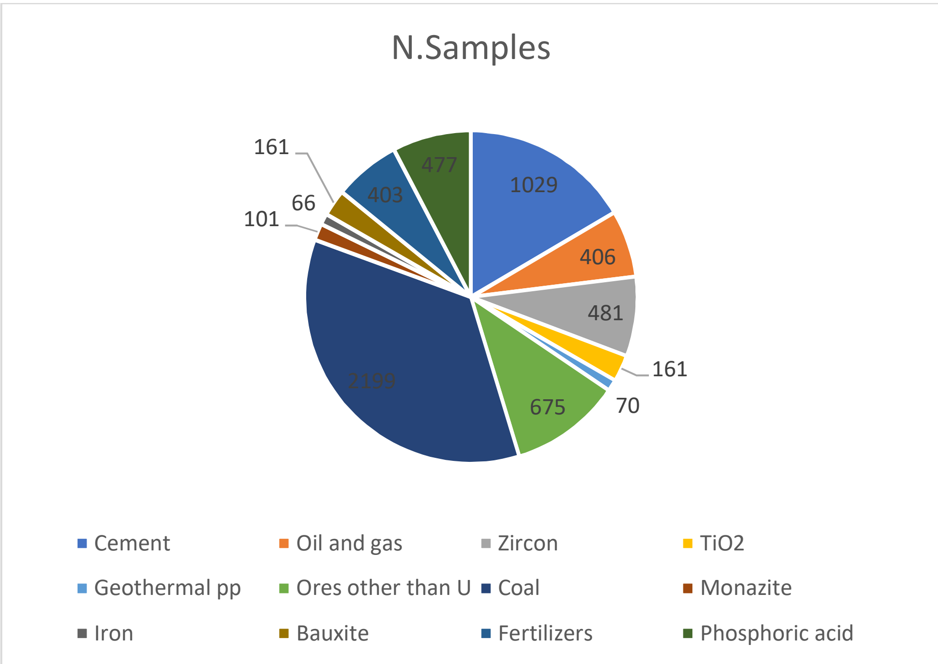


Figure 3.1 Distribution of samples collected for NORM-involving industrial sector analyzed in this work

These data come from an extensive collection of national and international literature. More than three hundred documents were consulted, and those that were deemed useful for the purposes of this research work number more than two hundred. For almost all the investigated sectors, the bibliographic literature has produced an important amount of data that yielded to significant results, allowing an overview of the radiological content for those NORM-related activities.

The number of references found for each sector is different from each other: more than 50 scientific articles were taken into account for the the most investigated sector (i.e., coal-fired power plants); for geothermal energy, on the other hand, more studies need to be carried out: the amount of information is scarce at the moment and only three references could be placed.
The total number of references used for each industrial activity is given in Table 3.1, where the amount of sample collected relating to each of the 4 types of materials is also given. In fact, even if each industrial sector has to deal with materials that can be totally different from one another, it was possible classified them into four broad categories: residues, products, raw materials and effluents.
It is important to note that the total number of samples involved could not be accurately assessed because some paper gives only average values, without specifying the number of samples measured. In these cases, this number was reported as 1. Therefore 6229, the total number of data collected, is certainly an underestimation.
Moreover, since in some publications only the range of activity concentrations values has been reported, in this case it has been assumed a number of samples equal to 2.
All data collected from literature are tabulated at the end of this thesis in the Appendix: values reported show the activity concentration for seven natural radionuclides (^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra and ^{40}K), listed for materials and industrial sector. The values calculated and not reported in the references are shown in the tables of the Appendix with the colour red.

A large number of NORM-related industrial sectors were analysed in this work. For each of the twelve industrial sectors NOR materials were divided into four categories:

- *Raw materials*
- *Residues*
- *Products*
- *Effluents*

It was not always possible to find data for each category. Here, therefore, there is an overview of what has been collected:

- Sector: Extraction of aluminium from bauxite
  - Raw materials (bauxite)
  - Residues (sludges, ashes, sand)
  - Product (aluminium)
  - Effluents (none)

- Sector: Coal-fired power plants
  - Raw materials (anthracite, coal, coke, lignite, inorganic materials, coal mix)
  - Residues (fly and bottom ash, coke, scales, coal slag)
  - Product and Effluents (none)

- Sector: Cement Production
  - Raw material (clay, ash, rock, clinker, phosphogypsum, metallurgical slag)
  - Residue (none)
  - Product (cement, portland cement, pozzolanic cement)
  - Effluent (none)

- Sector: Mining of ores other than uranium ore
  - Raw material (Rocks of various types: sillimanite, andesite, clay, basalt, kaolinite, kaolin, dacite, phonolite, gabbro, gravel, gneiss, migmatite gneiss, garnet, granite, migmatite, thorium ore, etc.)
  - Residue, product, effluent (none)

- Sector: Geothermal energy production
  - Raw material, product, effluent (none)
  - Residue (solid residues and dust)

- Sector: Primary iron production
  - Raw material (ore and rock)
  - Residue (blast furnace slag, dust, residues)
  - Product and effluent (none)

- Sector: Extraction of rare earths from monazite
  - Raw material (monazite)

- Residues
- Product and effluent (none)

- Sector: Oil and Gas Production
  - Raw material (crude shale oil, crude oil)
  - Residue (ash, sludge, scale, solid residue, spent shale)
  - Product (shale oil, petroleum products -naphtha, paraffin, gasoline, etc.-)
  - Effluent (liquid effluent: water)

- Sector: Phosphoric acid production
  - Raw material (phosphorite, phosphorous dioxide, rock)
  - Residue (lay, sludge, phosphogypsum, scaling, solid residues)
  - Product (phosphoric acid, calcium silicate)
  - Effluent (liquid effluent: water)

- Sector: Production of phosphate and potassium compounds
  - Raw material (phosphoric acid, phosphorite, limestone, dolomite)
  - Residue (iron phosphorus, solid residues, slag)
  - Product (various fertilizers -potassium chloride, potassium sulphate, etc.)
  - Effluent

- Sector: TiO_2 pigment production
  - Raw material (ilmenite, rutile, anastasium, leucoxene, synthetic rutile, titanium ore)
  - Residue (sludge, scale, sand, solid residue, sediment)
  - Product (titanium dioxide)
  - Effluent (various liquid effluents)

- Sector: Zircon and zirconium industry
  - Raw material (zircon sands, kaolin)
  - Residue, Product and Effluent (none)

Thus, a total of 2976 raw material, 2161 residues,1032 products and 60 effluents samples were collected. The smallest number of samples were collected for effluents (60 in total), the most for raw materials.

Table 3.1 Summary of number of samples and references used for industrial sectors and materials

Industrial sector	N. collected bibliographical references	Total number of samples analyzed	n. of samples - raw material	n. of samples - residue	n. of samples - product	n. of samples - liquids effluents
Cement production	38	1029	579	0	450	0
Oil and Gas Production	18	406	86	217	78	25
Zircon and zirconium industry	34	481	195	19	266	1
TiO_2 pigment production	13	161	98	36	6	21
Geothermal energy production	3	70	0	70	0	0
Mining of ores other than uranium ore	32	675	675	0	0	0
Coal-fired power plants	51	2199	778	1421	0	0
Extraction of rare earths from monazite	11	101	99	2	0	0
Primary iron production	8	66	12	54	0	0
Extraction of aluminium from bauxite	11	161	66	90	5	0

Production of phosphate and potassium fertilizers	23	403	190	13	194	6
Phosphoric acid production	24	477	198	239	33	7
Total	266	6229	2976	2161	1032	60

The first step in gathering radiological data in a database was to collect national and international bibliographic sources. The sources that have been collected refer to content published from the 1970s to today.

Activity concentrations values of the following radionuclides were selected from references: Uranium-238, Radium-226, Lead-210, Polonium-210, Thorium-232, Radium-228and Potassium-40. These data were collected and analysed by material type (raw material, residue, product, effluent) within each industrial sector.

Both arithmetic and weighted average were calculated; the latter was calculated to account for the numerosity of the data.

In addition to this, it should be considered that for each industrial sector, materials have been grouped into four categories (raw materials, residues, products and effluents); this means that within a category there are materials with different chemical, physical, and radiological characteristics (for example, the residues-category includes ashes, slags, scales and other general residues).

The analysis of the four categories of material is carried out for each sector using the following statistical indices: weighted mean, standard deviation, median, maximum and minimum values, and the quartiles.

It should also be noted that many of the scientific publications from which the activity concentration data were taken date back a few decades. Therefore, the measurements may be less accurate than they are today. The analysis performed for each NORM-involving industrial sector investigated is shown in the following sections.

3.3.1 Phosphoric acid production

A great amount of data was collected for the phosphoric acid production: the total number of samples, in fact, amounted to 482.
For this sector, it has been possible to collect samples for all four types of materials: data for 198 raw materials, 239 residues, 33 products and 7 effluents samples are available. A graphical representation of the data set distribution for the phosphoric acid production sector is shown in Figure 3.2. As reported, the major amount of material has been collected for raw materials and residues; even if in small quantities, it was possible find information for some product and effluent.

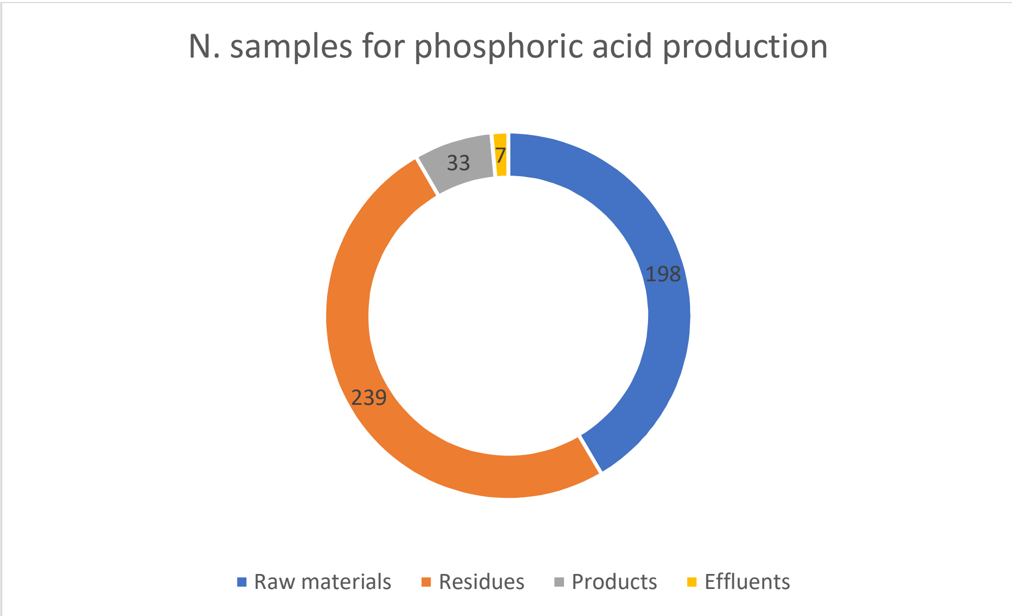


Figure 3.2 Distribution of samples for type of material for the sector of phosphoric acid production

- *Raw materials*

A great quantity of raw materials samples is collected. With information of activity concentrations of radionuclides, the weighted mean, standard deviation, median, minimum and maximum values are calculated. They are shown in Table 3.2.

Table 3.2 Analysis of activity concentration in phosphoric acid production – raw materials

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	171	1131	563	1180	10	4641	1186	650	1340
Ra226	193	979	663	799	2	5022	918	353	1373
Pb210	89	764	427	628	13	1660	771	590	1060
Po210	43	1185	434	1355	50	1868	976	965	1577
Th232	44	182	489	38	0.17	3344	295	10	202
Ra228	48	113	135	19	2	287	42	8	283
K40	54	161	235	86	10	1303	204	21	269

Most of these samples are phosphate rocks. Sedimentary phosphate rock may contain high concentrations of uranium, accumulated through the process of ionic substitution into the carbonate–fluorapatitic crystals or by adsorption [3]. In fact, the analysis carried out and summarized in table 3.2 shows that the uranium-238 series reports the highest values of activity concentration, with mean values exceeding the value of 1 Bq/g. Although 156 out of 198 samples are phosphatic rocks, the other samples refer to other raw materials. So, focusing on phosphatic rock samples and considering the singular scientific works, it allows another important characteristic to emerge. In fact, looking at data reported in [3], [49]–[57] it is possible to note that radionuclides of the same decay series have comparable values and this confirms that they are in secular equilibrium. Values of activity concentration for the two series are different: uranium-238 and its progeny are usually characterised by higher values (more than 1000 Bq/kg) than those for thorium-232 series (a few hundred at the most), with some exception as that one found in [58] where thorium-232 activity concentration value exceeds the value of uranium-238 due to local geological characteristics.

The figure 3.3 graphically shows the results just discussed.

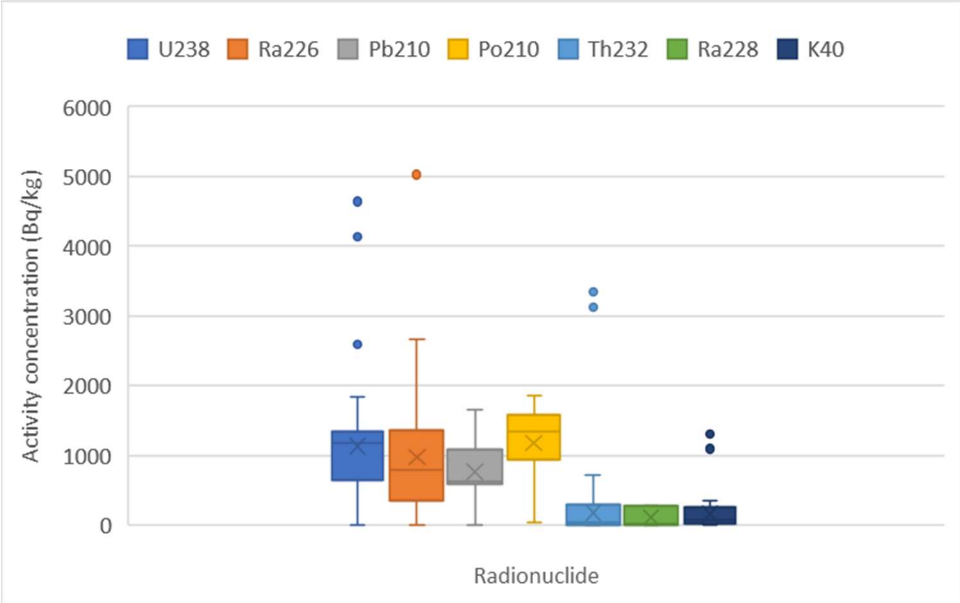


Figure 3.3 Box plot of activity concentration values in phosphoric acid production - raw materials

- *Residues*

As reported in literature [41], during the phosphoric acid production process the radioactive equilibrium present in raw materials is disrupted, and the radium precipitates with calcium in the chemical gypsum. This finds confirmation in the activity concentration values of radionuclides in phosphogypsum illustrated in Table 3.3, where the higher radiological content of Ra-226 and its descendants respect to other radionuclides results evident.

Although most of the residue samples were phosphogypsum, some scales and sludge measurements were also found in literature. Even if their number of samples is low, it is interesting to note the comparison of the two, that highlights their non-negligible radiological content of the uranium-series radionuclides, mainly for the scales; these can be an order of magnitude higher than those found in rock and phosphogypsum.

Regards to K-40 in phosphogypsum, instead, the activity concentration values are really low, as expected: the maximum value barely reaches 200 Bq/kg and the 75% of the residues have concentrations of no more than 40 Bq/kg.

*Table 3.3 Activity concentration values in phosphoric acid production residues (phosphogypsum, sludge and scales)**

	Phosphogypsum			Sludge			Scale		
	No. of samples	**Weighted Mean (Bq/kg)**	**Range (Bq/kg)**	**No. of samples**	**Weighted Mean (Bq/kg)**	**Range (Bq/kg)**	**No. of samples**	**Weighted Mean (Bq/kg)**	**Range (Bq/kg)**
U238	174	100	4-650	4	1373	910-2090	3	408	92-1040
Ra226	183	613	3-3219	4	1405	5-4300	5	3817	471-14238
Pb210	140	659	18-860	4	863	46-1900	4	391	116-665
Po210	97	777	41-1014	-	-	-	2	-	5-112
Th232	56	103	1-273	4	17	5-28	2	-	24-189
Ra228	43	131	4-247	4	22	2-65	-	-	-
K40	19	46	14-200	-	-	-	-	-	-

- *Products*

The type of sample analyzed for this sector is the product "*phosphoric acid*". The number of samples collected for this category is lower than for the other material types for the phosphoric acid production, and it is 33. For almost all samples, data were collected for uranium-238 and Radium-226; much less information is available for lead, polonium and the other radionuclides, as shown in Table 3.4. Data are in line with the results obtained above for raw materials and residues, confirming the presence of Uranium-238 in the phosphoric acid samples in elevated concentrations, with a mean value of 2039 Bq/kg, and the absence of Radium-226 because of the disruption of the secular equilibrium during the production process.

** Ranges are not reported in all cases in which only average values are available*

Table 3.4 Analysis of activity concentration in phosphoric acid production - products[*]

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	32	2039	685	2442	233	2888	1450	1675	2442
Ra226	32	8	8	6	2	52	10	-	-
Pb210	8	58	52	41	7	135	58	12	107
Po210	3	14	12	12	3	26	14	8	19
Th232	3	163	256	20	11	458	163	16	239
Ra228	3	6	1	6	5	7	6	6	7
K40	8	17	8	17	1	29	17	14	21

- *Effluents*

Only seven liquid effluent samples were collected. The analysis of these shows that the radiological content in these materials is, in general, low. Of all the radionuclides analysed, data on potassium and polonium are unfortunately absent. Among the nuclides available, however, it is uranium that is characterised by a higher activity content than the others, but however under the value of 1 Bq/g.

Table 3.5 Analysis of activity concentration in phosphoric acid production - effluents

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	7	96	105	56	0.1	230	96	0.4	192
Ra226	7	1	1	1	-	4	7	1	2
Pb210	6	25	32	13	8	89	25	10	16
Po210	-	-	-	-	-	-	-	-	-
Th232	5	3	5	0.1	0.01	12	3	0.03	1
Ra228	7	1	0.5	1	0.4	2	1	1	1
K40	-	-	-	-	-	-	-	-	-

[*] *Ranges are not reported in all cases in which only average values are available*

3.3.2 Extraction of aluminum from bauxite

For this industrial activity, data were not found for all four types of materials. In fact, samples were not collected for effluents and just 5 samples are relative to products. Instead, for the most important typologies of material for this activity, i.e., residues and raw materials, a total of 90 and 66 samples were collected, respectively.
A graphical representation of the distribution of the data collected for the extraction of aluminum from bauxite is shown in Figure 3.4.

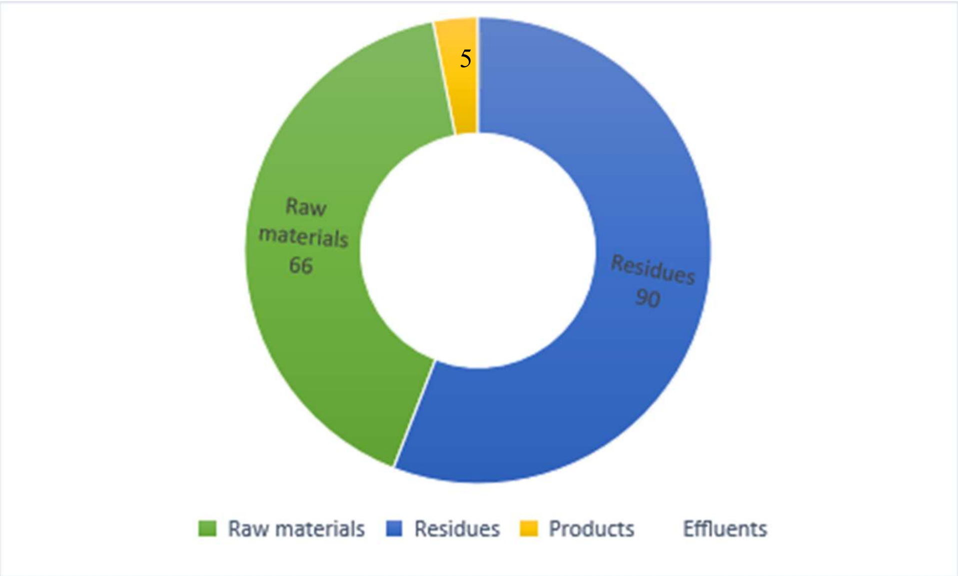


Figure 3.4 Distribution of samples for type of material for the extraction of aluminum from bauxite

- *Raw materials*

In general, it is well known that bauxite can be characterized by non-negligible content of uranium and thorium[59].
Sixty-six sample of bauxite are analyzed and shown in Table 3.6: this data set reports information on Radium-226, Thorium-232 and Potassium-40. Data of Lead-210 and Polonium-210 were not available. For Uranium-238 radiological data are few, but they show that uranium can reach high values. In fact, even if its minimum value is equal to 67 Bq/kg, the weighted mean is few less than 1000 Bq/kg, and the maximum values is 4505 Bq/kg. In terms of activity content, there are Radium-226 and Thorium-232 with average values around 300 Bq/kg.

As raw material, one expects to find radioactive secular equilibrium. Looking at the values, instead, this characteristic is not evident. This is because samples collected comes from different research and not all radionuclides are always measured. In fact, the samples of U-238 and Ra-226 collected (see Table 3.6) are numerically very different from each other, being 11 and 60 respectively, as well as for Th-232 and Ra-228, for whom the number of samples is 66 and 2. When information about both uranium and thorium series were available, the secular equilibrium emerges, as for instance in this work[4], where the activity concentration values for U-238 and Ra-226 are 97 Bq/kg and 91 Bq/kg repectively.
It can happen that the ore washing process before it reaches the industry disturbs the equilibrium[60], however generally in bauxite the secular equilibrium is expected.

*Table 3.6 Analysis of activity concentration in processing of bauxite– raw materials**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	11	963	1757	97	67	4505	609	75	435
Ra226	60	340	148	419	29	419	103	-	-
Pb210	-	-	-	-	-	-	-	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	66	294	125	256	85	760	358	-	-
Ra228	2	121	55	121	82	160	121	-	-
K40	51	55	51	47	2	305	82	-	-

- *Residues*

90 residues (red mud and generic residues) were analyzed. Table 3.7 shows the results of the residue analysis. No data were collected for Polonium-210; for Lead-210 and Radium-228 only a couple of data are available at most. Uranium data are also few in number, while for the remaining three radionuclides (^{226}Ra, ^{232}Th, ^{40}K) the number of samples is more significant. The highest mean value belongs to Ra-228, but the figure comes from only two samples.

* *Min, max and quartiles are not reported in all cases in which only average values are available*

With the exception of Pb-210 (for which, however, we have only one sample) and K-40, the other radionuclides can reach values exceeding 1000 Bq/kg.

*Table 3.7 Analysis of activity concentration in processing of bauxite– residues**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	17	370	476	200	9	1550	291	104	375
Ra226	78	302	152	347	0.1	1047	173	-	-
Pb210	1	310	310	-	310	310	310	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	89	374	364	283	1	1800	450	-	-
Ra228	2	785	517	785	419	1150	785	-	-
K40	71	61	59	48	1	350	119	-	-

- *Focus on "red mud"*

Out of 90 samples of residues, 75 are samples of red mud.

Unlike results of residues in Table 3.7, paying attention only to red mud (see Table 3.8) emerges that the minimum radiological content is surely higher. In fact, except for potassium, a content can be expected of at least one hundred Bq/kg for the other radionuclides.
Moreover, making a comparison with raw materials, where secular equilibrium is present, it is possible to note an increase in the radionuclide content from ore to red mud, depending on the bauxite ore grade [3]. In addition, literature data report that are the fine-grained red muds that have a higher radiological content[3], [61].

* *Min, max and quartiles are not reported in all cases in which only average values are available*

Table 3.8 Activity concentration in red mud samples

	Sample	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)
U238	12	326	104	1550	503
Ra226	66	347	90	1047	355
Pb210	1	310	310	310	310
Po210	-	-	-	-	-
Th232	74	283	118	1800	423
Ra228	2	785	419	1150	785
K40	68	48	15	350	63

- *Products*

Only five aluminum samples were collected: data are available for two radionuclides (^{226}Ra and ^{232}Th). For both, the values are very low, amounting to a few Bq/kg units.

- *Effluents*

No data for effluents are available.
However, the Technical Reports Series no.419 of IAEA[3] advises to pay attention to liquid effluents, due to the possible presence of uranium in alkaline leach solutions that can contaminate the environment.

3.3.3 Coal-fired power plants

Many studies have been carried out on coal-fired power plants from the point of view of radiological content. 51 publications were consulted, starting from 1978. Information gathered concerned raw materials and residues: in fact, in this work it was possible to collect 778 and 1421 samples of them respectively. With this number of data, the industrial sector of the coal-fired power plants has emerged as the most studied among the industrial sector related to NORM from the literature collection in this work.

- Raw materials

The number of samples of raw materials is high and equal to 778 (see Table 3.1). The coal samples analyzed are of various types and they are listed at the beginning of chapter three.
The radiological content of coal depends on geological characteristics of the coal mining area[3]. For radionuclides of the U-238 series and for K-40, although the values vary in a wide range whose maximum value can reach about 2000 Bq/kg; the 75% of samples (Q3) have a radiological content of U-238, Ra-226 and K-40 below 176, 314 e 143 Bq/kg respectively (see Table 3.9). Comparing the mean values of U-238 and Th-232 with those reported in UNSCEAR 2008[25], it is possible to note that they are in line for thorium, but not for uranium: the mean value of 98 Bq/kg exceeds that reported in UNSCEAR (20 Bq/kg), but some exception can occur. It is the case of a Greek lignite sample that has a content of U-238 of 1306 Bq/kg[62],and, as UNSCEAR reports [25], of some coal mines in Germany, where uranium concentrations of 15000 Bq/kg were found.

*Table 3.9 Analysis of activity concentration in coal-fired power plant– raw materials (coal)**

	Number of samples	**Weighted Mean (Bq/kg)**	**St.Dev. (Bq/kg)**	**Median (Bq/kg)**	**Min (Bq/kg)**	**Max (Bq/kg)**	**Arithmetic average (Bq/kg)**	**Q1 (Bq/kg)**	**Q3 (Bq/kg)**
U238	476	98	126	31	3	1306	84	16	176
Ra226	577	154	149	85	1	880	124	24	314
Pb210	136	195	153	134	10	808	165	-	-
Po210	33	42	28	36	5	118	44	27	61
Th232	522	22	20	18	0.4	280	27	11	26
Ra228	237	67	78	18	2	191	32	14	181
K40	736	120	104	100	6	1100	129	49	173

* *Min, max and quartiles are not reported in all cases in which only average values are available*

- Residues

In coal ashes it is possible to find radionuclides accumulated during the coal combustion process. The amount of the ash depends on type of coal and of boiler. Because of the thermal process, concentration of radionuclides in ash can be higher than that of coal, up to 10 times[8].

1421 samples of residues are analyzed. Not always data about all the radionuclides of interest were found in publications. In fact, for Polonium-210 just twelve samples were collected while, for the other radionuclides, more data are available.

With exception of two scales, all residues investigated are ashes (all data are reported in appendix). Part of the ashes (up to 50%, depending on the furnace) remains at the bottom, and for this reason they are called "bottom ash", while the remainder follows the gas flow in the outlet to the chimney, where it is preventively blocked by electrostatic filters or precipitators [4]. Looking at Table 3.10 it is evident that residues typically have a high activity concentration of natural radionuclides. In fact, the weighted mean values of activity concentration in residues are much higher than the respective radionuclides in coal, mostly for uranium series.

To study if there were differences between the two types of ashes, data about those residues that are reported in appendix as "fly ash" or "bottom ash" were analysed, separately. Samples whose type was not specified in the articles (i.e., whether they are fly or bottom) are those reported in the appendix with only the term "ash" and were excluded from this subdivision.

Table 3.10 Analysis of activity concentration in coal-fired power plant– residues[*]

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	841	654	400	934	30	2222	335	-	-
Ra226	1230	654	472	845	20	1990	335	140	904
Pb210	644	1031	561	1158	8	4504	675	1068	1158
Po210	12	287	475	72	9	1700	287	33	307
Th232	1010	75	40	54	1	356	102	52	89
Ra228	317	66	44	55	24	255	79	44	63
K40	1346	425	193	449	56	1668	390	315	454

- *Residues: Fly ash and Bottom ash*

Among the residues, 1042 are fly ash samples and 204 are bottom ash samples. Generally speaking, in coal ashes a high variability of specific concentrations of radionuclides can be observed, varying from a minimum of a few tens of Bq/kg to several hundreds or thousands of Bq/kg.

The analysis shows a different radiological characteristic for the two types of ashes: the natural radioactivity content is generally higher in fly ashes, particularly concerning elements of the Uranium-238 series (table 3.11). In fly ashes, the most critical radionuclide is Lead-210, whose activity concentration often exceeds 1000 Bq/kg, reaching values above 4000 Bq/kg.This is due to the fact that high-temperature processes cause the volatilisation of both 210Pb and 210Po. This may be one of the reasons why, when looking at both the first quartile and the weighted mean, there is much higher 210Pb than 226Ra or 238U. The same is not evident in 210Po data, probably due to the small amount of data.

For Th-232 series values are comparable for the two ash types (Tables 3.11-3.12); in particular results show that especially in fly ashes, values of Thorium series are far lower than for the Uranium series and they are at most around hundreds of Bq/kg.

The same emerges for Potassium-40, which values are comparable for the two types of residues, with 75% of the values within about 450 Bq/kg.

[*] *Min, max and quartiles are not reported in all cases in which only average values are available*

However, even in this case the values for fly ashes are higher than those in bottom ash, reaching a maximum value of 1668 Bq/kg.
Additionally, since fly ashes are widely used in building materials, it is worth considering that the elevated content of Radium-226 can lead to potential problem related to radon.

Table 3.11 Analysis of activity concentration in fly ashes of coal-fired power plant[*]

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	746	718	374	964	60	2222	-	-
Ra226	900	658	354	885	20	1990	195	904
Pb210	606	1091	522	1158	8	4504	-	-
Po210	8	416	546	264	33	1700	78	438
Th232	784	74	39	53	1	333	52	89
Ra228	199	76	51	56	30	255	51	67
K40	978	466	200	454	56	1668	387	463

Table 3.12 Analysis of activity concentration in bottom ashes of coal-fired power plant[*]

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	57	167	203	104	30	747	88	115
Ra226	175	349	242	546	23	799	100	587
Pb210	22	83	107	31	21	289	-	-
Po210	4	31	20	29	9	57	20	39
Th232	60	80	25	83	20	138	69	105
Ra228	111	47	12	44	24	78	-	-
K40	202	327	142	406	90	1077	225	423

[*] *Min, max and quartiles are not reported in all cases in which only average values are available*

- *Products and effluents*

In coal-fired power plants data about products and effluents are not expected.

3.3.4 Cement production

The NORM related industrial activity "cement production" is second in this work in terms of number of samples: more than one thousand samples were collected, divided into raw materials and products; no one for residues and effluents.

- *Raw materials*

Raw materials for cement production have different nature (clay, ash, …). For this study a total number of 579 raw material samples were collected and analyzed. Results of the analysis are shown in Table 3.13. These materials are mainly characterized by the presence of Potassium-40 and Radium-226: the highest activity concentration values recorded for these two radionuclides were 1660 and 1440 Bq/kg, respectively. For Uranium-238 only 4 samples were collected, but the radiological content of these showed low activity content. In fact, the maximum activity concentration value is 103 Bq/kg.
The opposite trend occurred for Potassium-40, where 420 out of 560 samples registered values of activity concentrations up to 470 Bq/kg.
Finally, standard deviation values show high variability in the collected samples: this is true in all radionuclides except in Radium-228: although the number of samples is high (i.e., 302), the standard deviation value and range are limited. This is because data for Ra-228 belong to samples of the same type, i.e., "ash."

Table 3.13 Analysis of activity concentration in cement production – raw materials[*]

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	4	43	42	33	4	103	43	22	54
Ra226	576	123	110	170	3	1440	85	-	-
Pb210	-	-	-	-	-	-	-	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	238	47	43	39	1	163	48	13	61
Ra228	302	139	10	140	100	150	130	-	-
K40	560	393	244	410	14	1660	396	311	470

- *Products*

450 samples of cement product have been collected (as given in Table 3.1). All samples are “cement” but, in particular: 140 are samples of "portland cement", 21 of "pozzolanic cement" and 289 are reported generically as "cement" and include samples that could not be included in the other two categories because either they were reported generically as "cements" in the publications, or because they refer to different products such as cement plasters or white or grey cements. The breakdown of these three kinds of product samples is shown in Figure 3.5.

As with the raw materials, data for lead and polonium are not available for the products of the cement production sector. The analysis results for the other nuclides show that Potassium-40 has the highest activity concentration (see table 3.14); instead, the other radionuclides have low radiological content, with average values of about few tens of Bq/kg.

Finally, 75% of activity concentration values are below 337 Bq/kg for K-40, with a maximum value of 2493 Bq/kg [63].

[*] *Min, max and quartiles are not reported in all cases in which only average values are available*

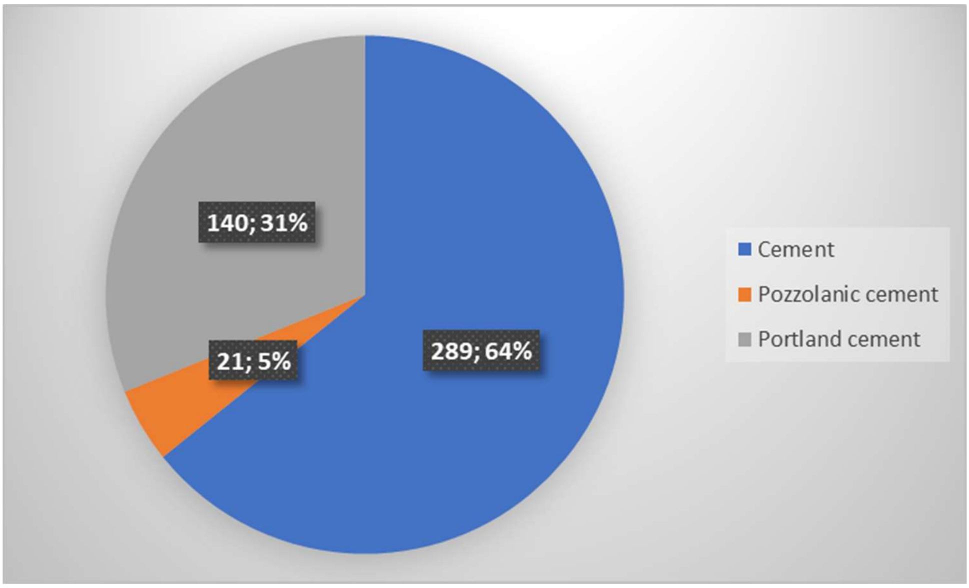


Figure 3.5 Breakdown of product samples from the cement production sector

*Table 3.14 Analysis of activity concentration in cement production- products**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	27	31	14	25	11	48	26	20	43
Ra226	426	55	27	49	7	160	44	35	78
Pb210	-	-	-	-	-	-	-	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	402	29	18	29	3	124	29	14	33
Ra228	23	43	8	45	18	45	32	-	-
K40	429	263	154	260	33	2493	243	180	337

- *Residues and effluents*

Data are not available.

It is worth noting the lack of radiological information for scales. This type of matrix was expected; in fact, the maintenance of clinker oven is regulated in EUBSS[2], having been identified as the most critical scenario for this industrial sector.

* *Min, max and quartiles are not reported in all cases in which only average values are available*

3.3.5 Mineral processing and primary iron production

Looking at the table II-1 of the annex II in the Italian Legislative Decree 101/2020[1], for this NORM-involving industrial sector there are several practices related to it. Not all of them are discussed in this section: monazite and bauxite are treated separately.
While a great deal of information could be found for bauxite and monazite, this has not been the case for the other minerals. In fact, information of just 66 samples for all the remaining practices were collected.
In addition, of the samples collected, most of the information was found for residues rather than for raw materials. In fact, only 12 samples of these were collected which, moreover, belong to different materials (e.g., copper oxides, zinc or iron). Because of the small number of raw material samples available, the analysis was carried out on the 12 samples as a whole which, although they are of different types, still all belong to the category "minerals".

- Raw materials

As already mentioned, the analysis for raw materials was carried out on just 12 samples of minerals of different nature. The wide range of the radiological content shows the variability of the natural radioactivity according to their mineral’s characteristics (see table 3.15). Moreover, results show that the radiological content of the matrices is low. The highest maximum value equal to 756 Bq/kg was found for K-40.

Table 3.15 Analysis of activity concentration for mineral processing and primary iron production - raw materials[*]

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	11	58	83	29	12	300	58	18	56
Ra226	4	61	79	28	11	178	61	13	76
Pb210	2	12	6	12	7	16	12	-	-
Po210	2	66	37	66	39	92	66	-	-
Th232	9	79	131	13	1	400	79	5	115
Ra228	1	5	-	-	-	-	-	-	-
K40	2	410	490	410	63	756	410	-	-

- *Residues*

The number of residue samples collected and analysed in this category is 54.

As for raw materials, it is possible to note the wideness of activity concentration range for each radionuclide, that confirms a great variability of the radiological content in these samples. In fact, differently from other NORM involving industrial sectors (for instance, the extraction of aluminum from bauxite), this one is characterized by a very large class of residues because the industrial processes from which they come can be very different from each other. In particular, it is interesting to note that the maximum activity concentration values in residues are much higher than those found in raw materials.

Except for ^{228}Ra, for which no data are available, for the other nuclides results of analyses are shown in Table 3.16. Even though only 12 samples for Lead-210 and Polonium-210 were analysed, it is evident that they are the radionuclides with the highest radioactivity content: the weighted mean values are in fact high, 7771 and 11404 Bq/kg respectively, but the maximum reach values of 47243 and 70000 Bq/g respectively. These elevated values were found in a particular type of residue: the blast furnace dust. In fact,

[*] *Min, max and quartiles are not reported in all cases in which only average values are available*

it is expected that this kind of residue is characterized by high content of Po-210 and Pb-210 because of their volatilization during the high temperature processes.
Moreover, from data emerged that just in full-cycle steel mills dust is characterized by a high natural radioactivity content: extremely lower values were found in dust produced in the thermal processes of an (Italian) non-integral-cycle electric steel mill[4].

Table 3.16Analysis of activity concentration for mineral processing and primary iron production - residues

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	10	630	1276	29	3	3050	361	19	50
Ra226	47	133	79	150	0.3	310	133	65	182
Pb210	12	7771	14006	916	5	47243	7771	161	9750
Po210	12	11404	22228	1301	19	70000	11404	361	6000
Th232	47	494	2134	11	1	10500	277	7	54
Ra228	-	-	-	-	-	-	-	-	-
K40	45	312	904	189	3	6219	312	139	242

- *Products and effluents*

No data available.

3.3.6 Production of phosphate and potassium fertilizers

Radiological information for 403 samples were collected. Data are not available for residues and effluents, so the analysis is made for the remaining two categories of materials, whose data are equally distributed.

- *Raw materials*

Rock and phosphoric acid are raw material samples collected in this sector.

The analysis of radiological content of the phosphoric acid have been already carried out in a previous section, with the difference in that process they were products, and here they are raw materials, but data set is the same. The analysis of them highlighted the rupture of secular equilibirum of the decay chains and the elevated activity concentration of Uranium-238 (see section 3.3.1).

With regard to the other type of raw material samples for the fertiliser industry, they were all phosphate rocks. Just two sample are dolostone and limestone. Since these last two type of rocks are radiologically not relevant, they were excluded from the analysis, which is thus only carried out for phosphorite; their values, however, are reported in Appendix.

As results show (see Table 3.17 and Appendix), phosphorite has high radiological content. The activity concentration values of radionuclide vary with local characteristics [28]. In fact, phosphorite from North Africa (Tunisia, Morocco, Egypt, Algeria) and Tanzania is rich in uranium (with values from around 500 Bq/kg to several thousands of Bq/kg)[3], [51], [54], [55], [64]. In other regions, as in Brasil, phosphorite is rich in Thorium-232 (more than 3000 Bq/kg) [58].

Table 3.17 Analysis of activity concentration for phosphorite in fertilizers production

	Weighted Average (Bq/kg)	**Min (Bq/kg)**	**Max (Bq/kg)**	**Median (Bq/kg)**
U238	1100	50	4641	1151
Ra226	863	44	5022	681
Pb210	822	20	1660	628
Po210	1185	50	1868	1355
Th232	193	1	3344	38
Ra228	132	8	287	21
K40	160	10	1303	52

- *Products*

Fertilizers are characterized by elevated concentrations of natural radioactivity content (see Table 3.18). In particular, in potassium fertilizer K-40 can be present at concentrations up to 15500 Bq/kg (see Table 3.18)[65].

For phosphate fertilizers (namely superphosphate (SSP) or triple superphosphate (TSP)), instead, the radionuclide most commonly contained is the Uranium-238. Its concentration can vary between some hundreds up to 7000 Bq/kg [64]. The radioactivity content of fertilisers is highly variable and depends on both the initial concentration of radionuclides in the raw materials and the method of production (for instance, the use of phosphoric acid in the fertilizers production process influences the concentration of uranium in the fertiliser).

Table 3.18 Analysis of activity concentration for of phosphate and potassium fertilizers production – products

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	121	1064	1279	785	2	7024	856	260	1200
Ra226	165	379	429	269	1	3394	269	53	677
Pb210	71	303	353	150	2	1037	237	105	300
Po210	31	850	1042	344	0.2	2410	308	2	2410
Th232	79	251	221	286	3	968	300	29	450
Ra228	45	5	2	6	1	9	4	3	8
K40	136	1843	3154	361	3	15500	3117	38	3700

- *Residues*

No data available.

- *Effluents*

Only 6 samples were collected for the effluent category of the fertiliser production, and they are shown in Appendix.

Looking at them, it appears clear that liquid effluents are not relevant from the radiological point of view. However, during the separation process of effluents by filtration, it is possible measure high levels of radionuclides (particularly of polonium) in the suspended material (i.e., phosphogypsum)[66].

3.3.7 Mining of ores other than uranium ore

- *Raw materials*

675 samples of minerals other than uranium are collected and analyzed. Figure 3.6 shows that the minerals collected are of various types (30 in total). The most numerous is granite: 375 of them were collected. For the other ones, the number goes up to a few dozen. For some of them, such as rhyolitic lava or basalt or schist, there are only one or two samples collected.

Collected materials were firstly considered together to obtain an overview of the radiological content in this group of ores (see Table 3.19). From this collection, just a sample of thorium ore was excluded (but it is present in Appendix) because it is characterized by too much higher radium levels respect to the rest of ores. In fact, unlike the other ores that have concentrations lower than about 600 Bq/kg of Ra-226 and 150 Bq/kg of Ra-228, its radiological content of Ra-226 and Ra-228 has values equal to 34000 and 338000 Bq/kg, respectively [67]. As the article itself reports, in fact, thorium, zirconium and titanium ores (the latter two are treated in this thesis in separate paragraphs) usually contain a high level of natural radiological content.

In this way (i.e., excluding the thorium sample), it is possible to better know how activity concentrations values are distributed between samples. The Figures 3.7-8 show it. The values of average, the median and the third quartile shown in Table 3.19 for the ore other than uranium ones reveal that these materials, in general, are no relevant from the radiological point of view. In particular, the most numerous collected (granite) is characterized by average values of activity concetration equal to about 50 Bq/kg for both uranium and thorium series, but higher content of K-40. Activity concentration values in excees of 1000 Bq/kg for U-238 were found just in rock samples from Cu deposits[68]. The minimum value of 0.05 for Th-232 is obtained using the Inductively Coupled Plasma Mass Spectrometry (ICP-MS) technique[69].

Table 3.19 Activity concentrations for ores other than uranium (without 1 samples of thorium ore)

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	191	111	442	20	0.3	4608	7	54
Ra226	602	57	58	36	1	434	17	69
Pb210	-	-	-	-	-	-	-	-
Po210	-	-	-	-	-	-	-	-
Th232	604	66	66	51	0.05	470	21	87
Ra228	155	107	88	64	1	370	32	200
K40	627	917	565	947	0.3	2920	385	1409

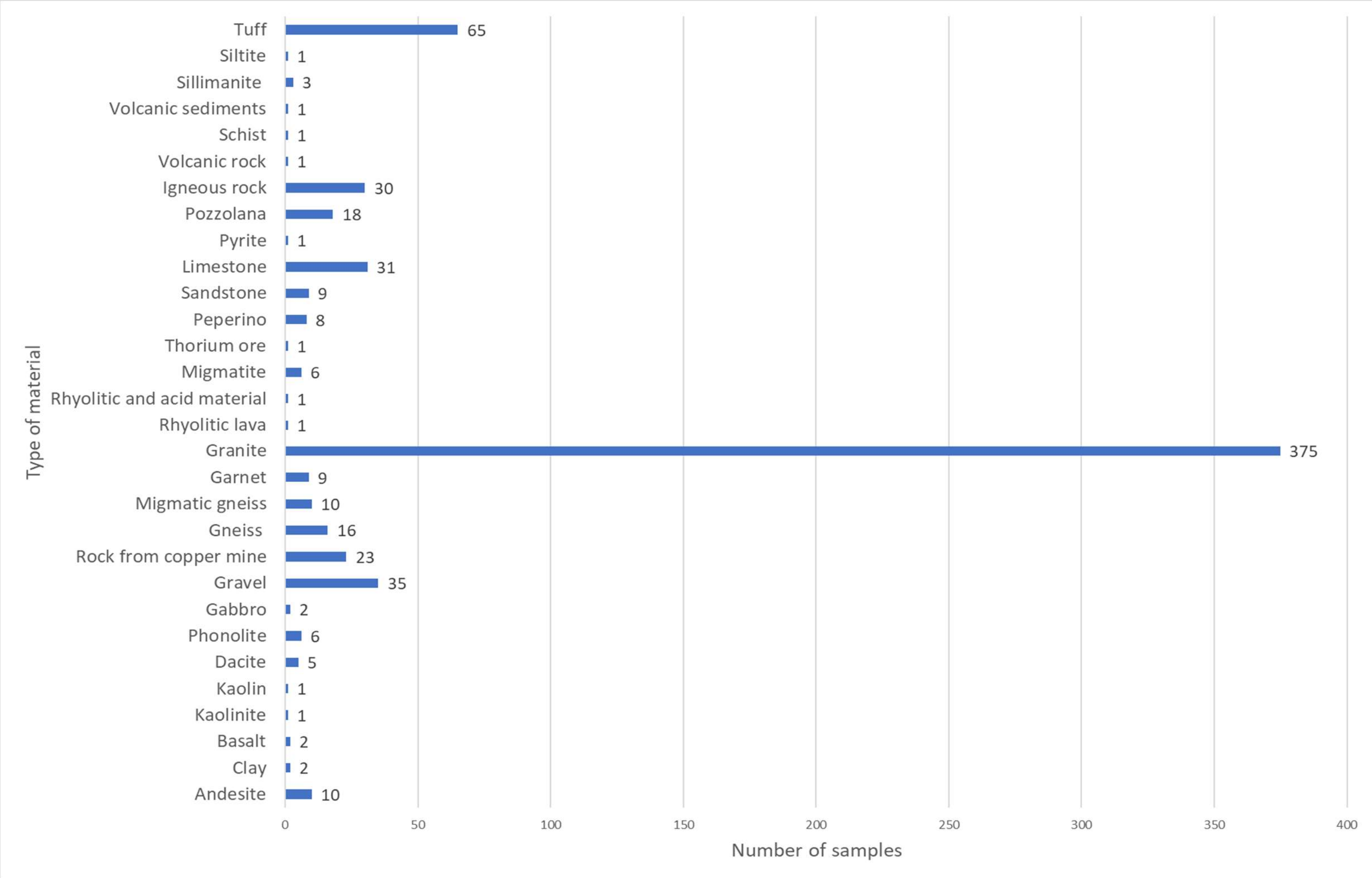


Figure 3.6 Number and type of analyzed mineral samples other than uranium

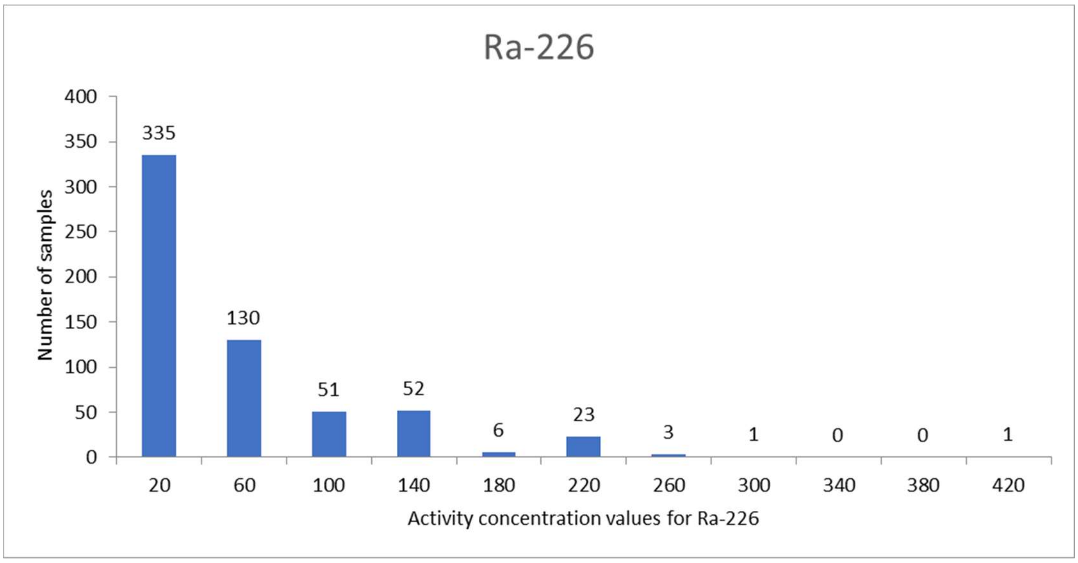


Figure 3.7 Frequency distribution of activity concentration per sample for Ra226 in ores other than uranium, without the thorium ore sample

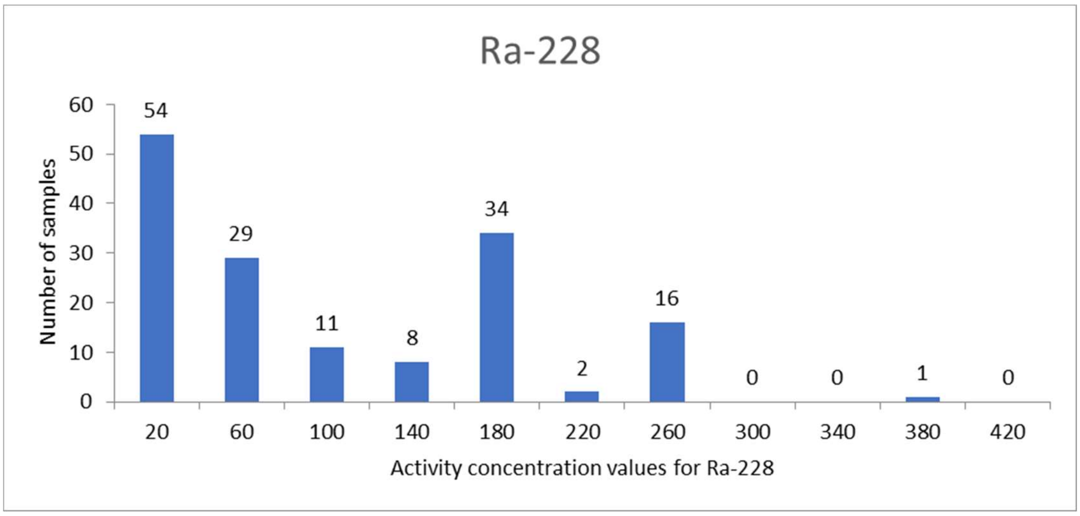


Figure 3.8 Frequency distribution of activity concentration per sample for Ra-228 in ores other than uranium, without the thorium ore sample

3.3.8 Extraction of rare earths from monazite

In this study, 101 samples for the extraction of rare earths from monazite were collected. Of these, only 2 samples are residues; the remaining 99 are of raw materials. Excluding the residues, for which no analysis is possible due to the small number of data, the following observations will only refer to the raw material 'monazite'. As can easily be seen from Table 3.20, the activity contained in this mineral is very high. The available data refer to U238, Th232 and K40 (for the others the data are either absent or present for only one sample). The activity concentration values of U238 fall in the range of 5-175 Bq/g, with the median in 35 Bq/g and the third quartile in 40 Bq/g; an order of magnitude lower are the activity concentration values for K-40, in the range of 11-19.6 Bq/g. It is the Th232 to have the highest radiological content and this is in line with what emerged also in [70], but the range of values of the activity concentrations that comes from the analysis (i.e., 5.4-175 Bq/g for U238 and11-610 Bq/g for Th232) is larger than those reported in the UNSCEAR 2000 (6-40 Bq/g for ^{238}U-series and 8-300 for ^{232}Th-series)[11].

*Table 3.20 Activity concentrations in minerals of monazite**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	75	37545	30097	35000	5455	175000	36968	21750	40580
Ra226	1	23000	-	23000	23000	23000	23000	-	-
Pb210	1	1900	-	1900	1900	1900	1900	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	96	247943	107456	233462	11000	610000	247850	182425	320000
Ra228	1	276000	-	276000	276000	276000	276000	-	-
K40	13	13709	3328	11300	11300	19570	16519	11300	16821

* *Min, max and quartiles are not reported in all cases in which only average values are available*

3.3.9 Oil and Gas Production

For the oil and gas sector, the literature search produced a large number of resulting data. For it, information was found for all four material types (raw material, residue, product and effluent). For each of them, 86, 217, 78 and 25 samples are here collected respectively, from national and international sources, for a total of 406 samples.

- *Raw materials*

The raw materials matrices considered are crude shale oil and crude oil. For these materials, almost all samples show data for Th232 and, in descending order, U238 and K40; data for Ra226 and Pb210 are few. Values of activity concentration for Po210 and Ra228, on the other hand, are completely absent (see Table 3.21).
From the analysis emerges that radionuclides with the highest radiological content are Ra226 and K40, whose values fall in the following ranges: 0.01-2669 Bq/kg and 0.06-969 Bq/kg, respectively; but 75% of the values (Q3) are lower than 57 Bq/kg for Ra226 and 429 Bq/kg for K40. This means that results indicate low radiological concentrations, with an exception for some crude oil sample for which the elevated radioactivity levels may be due to the presence of reservoir's sludge and water, which has not been decreased with a pre-treatment[71].

Table 3.21 Activity concentrations in oil and gas – raw materials

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	52	52	21	56	0.02	81	46	48	67
Ra226	28	299	670	27	0.01	2669	322	4	57
Pb210	2	50	29	50	30	70	50	40	60
Po210	-	-	-	-	-	-	-	-	-
Th232	82	51	146	23	0.03	913	77	13	24
Ra228	-	-	-	-	-	-	-	-	-
K40	65	262	227	429	0.03	969	168	16	429

- *Residues*

Oil and gas residues are the most interesting part from a radiological point of view. 217 samples were analyzed, and data are available for all seven radionuclides investigated, albeit in different quantities. It is important to point out that the residue samples are not of the same type: most are sludge and scales, but there are also other types of residues, as exhausted shale oil, according to the bibliographic sources consulted. The analysis is carried out considering different typologies of residues separately.

The analysis results on the natural radiological content in the exhausted shale oil (Table 3.22) show that the radioactivity level of this type of residue is low: radionuclides of the uranium series reach at most values close to about 100 Bq/kg, Th-232 even lower. The highest activity content is related to potassium, for which the weighted mean value is equal to 581 Bq/kg (instead for U-238 is 74 Bq/kg and for Th-232 is 26 Bq/kg).

Similar results were obtained for sludges and are shown in Table 3.23. In fact, also this kind of residue is characterized by a low radiological content: the highest wheighted mean value is equal to 333 Bq/kg (it belongs to K-40). Although the results show that Ra-226 activity concentration is generally low, it is possible to find a higher radiological content, as revealed by the maximum value (1786 Bq/kg).

Regarding scales, the analysis summarized in Table 3.24 highlighted that scales can contain even high activity concentration of Ra-226 and of the descendant Pb-210, with values that ranged from 1 to 3016000 Bq/kg for Ra-226 and from 35000 to 1590000 Bq/kg for Pb-210. The minimum value of activity concentration for Ra-226 comes from both a refinery scale and an old gasoline tank scale sample.

However, it is note from literature[4], [72] that high natural radiological content can be expected for both scales and sludges; in some cases, it can happen the sludge had higher activities than the scale samples, as reported in [73].

Table 3.22 Activity concentrations in oil and gas - exhausted shale oil

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	18	74	28	74	11	152	74	64	81
Ra226	4	85	24	74	69	121	85	71	87
Pb210	4	90	41	89	44	137	90	64	115
Po210	-	-	-	-	-	-	-	-	-
Th232	18	26	9	27	3	45	26	25	28
Ra228	-	-	-	-	-	-	-	-	-
K40	17	581	103	544	463	840	581	511	607

*Table 3.23 Activity concentration analysis in Oil&gas sector - sludges**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	47	26	15	29	0.02	53	13	38
Ra226	77	133	333	38	3	1786	19	52
Pb210	2	140	-	140	140	140	-	-
Po210	2	140	-	140	140	140	-	-
Th232	70	50	116	36	1	885	13	38
Ra228	6	22	1	22	21	22	21	22
K40	72	333	225	367	3	880	151	540

* *Min, max and quartiles are not reported in all cases in which only average values are available*

Table 3.24 Activity concentration analysis in Oil&gas sector - scales

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	23	5	12	0.02	0.02	54	0.02	1
Ra226	64	293029	662686	62	1	3016000	17	210328
Pb210	31	494143	438425	364000	35000	1590000	184250	707500
Po210	-	-	-	-	-	-	-	-
Th232	49	21	40	2	0.1	177	1	25
Ra228	-	-	-	-	-	-	-	-
K40	32	34	466	10	3	223	8	40

- *Products*

The analysis of data in table 3.25 shows that the problem of a potentially high concentration of radioactivity is absent for the products. In fact, the natural radiological content is not detectable or very low, of the order of few tens of Bq/kg at most.

Table 3.25 Analysis of activity concentrations in oil and gas - products

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	49	1	3	0.02	0.02	9	1	0.023	0.023
Ra226	74	1	3	0.05	0.01	18	2	0.014	0.65
Pb210	-	-	-	-	-	-	-	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	78	3	5	0.1	0.01	18	5	0.02	0.62
Ra228	-	-	-	-	-	-	-	-	-
K40	78	14	17	6	0.05	57	16	3	21

- *Effluents*

The samples collected refer to 25 water samples. As with the products, from the analysis it is evident the low radiological content for each nuclide; in particular U-238 and Th-232 concentrations are either not detectable or very low (see table 3.26).

Table 3.26 Analysis of activity concentrations i oil and gas - effluents

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	9	2	2	1	0.005	7	2	0.007	4
Ra226	20	73	157	3	0.04	510	73	0.3	27
Pb210	1	7	-	-	7	7	-	-	-
Po210	-	-	-	-	-	-	-	-	-
Th232	22	10	26	0.4	0.004	93	10	0.02	1
Ra228	-	-	-	-	-	-	-	-	-
K40	16	23	62	3	0.2	249	23	1	7

3.3.10 TiO2 pigment production

- *Raw materials*

98 samples of raw materials for the TiO_2 pigment production are analyzed. Several types of minerals were collected: predominant are ilmenite and rutile. Anatase and collected samples of titanium ores result no relevant from the radiological content. Leucoxene, on the other hand, can reach activity concentration values of up to 3000 Bq/kg in the ^{232}Th-series.
As shown in tables 3.27 and 3.28, ilmenite and rutile samples contain natural radioactive nuclides at various concentrations. The third quartile values reveal that 75% of the samples have activity concentration lower than about 340 Bq/kg for ^{232}Th-series in ilmenite samples. Both ilmenite and rutile can contain high radiological content, as show the maximum values: in ilmenite it is possible to find even 2300 Bq/kg of ^{226}Ra[74], for rutile the maximum value is about 1200 Bq/kg for the ^{238}U-series[75].
The typical concentration reported in the UNSCEAR 2000[11] for ilmenite and rutile is at most 1000 Bq/kg for both ^{232}Th and ^{238}U series; most of the activity concentration values of the samples

collected for these minerals are in line with them, but the data set show also that it is possible to exceed them.

*Table 3.27 Analysis of activity concentrations for titanium dioxide production raw materials - ilmenite**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)
U238	27	175	291	50	16	1500	172
Ra226	24	233	454	84	18	2300	233
Pb210	6	32	16	31	16	65	32
Po210	-	-	-	-	-	-	-
Th232	28	580	680	163	35	1971	563
Ra228	9	379	138	400	79	520	353
K40	16	9	5	7	4	25	9

*Table 3.28 Analysis of activity concentrations for titanium dioxide production raw materials - rutile**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)
U238	20	458	333	330	5	1211	485
Ra226	23	260	385	58	2	1235	309
Pb210	1	3	-	-	-	-	-
Po210	-	-	-	-	-	-	-
Th232	29	285	239	197	60	850	269
Ra228	13	56	41	71	2	100	51
K40	16	218	87	199	45	352	211

- *Residues*

Residues of this NORM involving industrial sector include sludges, scales, sand and other generic materials. The number of residues data set samples is 36 in total and the activity

* *Min, max are not reported in all cases in which only average values are available*

concentration values found in literature regard mainly ^{226}Ra and ^{228}Ra. So, Table 3.29 summarized the results of the analysis made for the four typologies of residues, and for the two isotopes of radium. From the analysis results evident that sludge and scales are the most important kind of residues because of their radiological content. In particular, the scale is the most critical type of residue. In fact, its radioactive content can reach values of about 65000 Bq/kg for ^{226}Ra and more than 1600000 Bq/kg for ^{228}Ra, respect to those of the sludges equal to of 1292 Bq/kg for ^{226}Ra and 1750 Bq/kg for ^{228}Ra.

Table 3.29 Analysis of activity concentrations for titanium dioxide production- residues

	Sludge		Scale		Sand		Other residues	
	Ra226	**Ra228**	**Ra226**	**Ra228**	**Ra226**	**Ra228**	**Ra226**	**Ra228**
No. of samples	8	8	8	8	9	9	10	10
Weighted Mean (Bq/kg)	302	576	64726	260686	11	32	110	143
Min (Bq/kg)	14	32	3	7	3	5	1	1
Max (Bq/kg)	1292	1750	419000	1644000	21	114	295	345
Median (Bq/kg)	83	465	76	265	9	21	110	143

- *Products and Effluents*

Few product samples were collected, and data are available only for the two isotopes of radium: they are characterized by activity concentration values of few tens of Bq/kg.

It was expected to find data about effluents; in fact, a collection of 21 samples was made. They are characterized by a very radiological content, at most 34 Bq/L for ^{228}Ra.

In conclusion, from the few information gathered for both products and effluents of TiO2 pigment production, no radiological criticality was found.

Complete data are available in Appendix.

3.3.11 Zircon and zirconium industry

- *Raw materials*

195 samples of raw materials were collected.
The type of materials analyzed in this work are zircon sands, rocks and minerals, and other raw materials. All samples are reported in Appendix. Apart from zircon sands, the other samples have a moderate radiological content that do not pose significant source of radiation hazard. So, the analysis is carried out focusing on the zircon sands. The analysis of the 113 zircon sands samples collected highlights the high level of natural radioactivity content in this kind of matrix. In fact, results given in table 3.30 show activity concetration of ^{238}U-series of about 600-13000 Bq/kg and activity concentrations of ^{232}Th of about 200-2600 Bq/kg. Values obtained for ^{238}U-series are in agreement with those reported by other authors in UNSCEAR 2000 [11], while the minimum value of ^{232}Th is even slightly lower.

*Table 3.30 Analysis of activity concentrations for zircon and zirconium – zircon sand**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	71	3667	2116	3300	672	13400	2684	3764
Ra226	75	3533	1496	3500	814	13400	2810	4000
Pb210	2	2804	136	2804	2707	2900	-	-
Po210	1	2748	-	2748	2748	2748	-	-
Th232	103	722	392	597	187	2650	510	757
Ra228	7	794	173	710	630	1100	695	865
K40	70	1742	3934	70	26	11300	33	325

* *Min, max and quartiles are not reported in all cases in which only average values are available*

- *Products*

Several products derive from the zircon and zirconium industry. 266 samples of them are collected in this work. They are of different types: ceramics, tiles, glaze and refractory materials. There are also 2 samples of products: one with mullite-zirconium and one without, but in both no radiological relevance results. Results for the 120 samples of ceramic indicate that it has low radiological content too; in fact, the mean values of activity concentration are 66Bq/kg for ^{226}Ra, 44,5 Bq/kg for ^{232}Th and 619 Bq/kg for ^{40}K; the only nuclide that can reach activity concentration values around 1000 Bq/kg is ^{40}K (see Table 3.31). Results obtained for glaze, give in Table 3.32, confirm that radionuclides tend to accumulate in in this product used on tiles[65]. Lastly, looking now at the Tables 3.33-3.34, instead, it is possible to note that they present the highest maximum values of activity concentration, especially for U-238. So, this have to be taken into account in the radiological risk assessment.

Table 3.31 Activity concentrations for zircon and zirconium – ceramic

	Weighted Mean (Bq/kg)	**Min (Bq/kg)**	**Max (Bq/kg)**
Ra226	66	27	174
Th232	45	29	75
K40	619	299	1049

Table 3.32 Activity concentrations for zircon and zirconium – glaze

	Weighted Mean (Bq/kg)	**Min (Bq/kg)**	**Max (Bq/kg)**
Ra226	805	51	1318
Th232	250	24	453
K40	691	520	1580

Table 3.33 Analysis of activity concentrations for zircon and zirconium – tiles

	Weighted Mean (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)
Ra226	259	7	3250
Th232	117	1	1050
K40	702	9	1580

Table 3.34 Analysis of activity concentrations for zircon and zirconium – refractory materials

	Weighted Mean (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)
Ra226	755	7	3250
Th232	345	1	1050
K40	104	9	788

- *Residues and Effluents*

Not so many data it was possible to collect for the residues of zircon and zirconium industry: 19 samples were analyzed in total. From the analysis results that radionuclides of the Uranium-238 series have the highest activity concentration values (see table 3.35). In particular, residues of this industrial sector are characterized by elevated content of Lead-210 and Polonium-210, that have 21050 and 46100 Bq/kg as maximum values respectively. Radium-228 has a quite high activity concentration value too, but it refers just to one sample.

For effluents, only one sample is collected, that has a very low radiological content. It is reported in appendix.

*Table 3.35 Analysis of activity concentrations for zircon and zirconium – residues**

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Median (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Arithmetic average (Bq/kg)	Q1 (Bq/kg)	Q3 (Bq/kg)
U238	15	542	1068	116	8	4000	566	13	285
Ra226	13	599	1058	114	10	3700	599	11	1000
Pb210	10	2425	6557	170	26	21050	2425	69	881
Po210	12	13490	15176	8850	91	46100	13490	1264	18250
Th232	17	140	332	38	1	1400	145	3	75
Ra228	1	840	-	-	840	840	840	-	-
K40	17	187	169	115	10	526	177	36	330

3.3.12 Geothermal energy production

70 residues samples from geothermal power plants in the USA and Italy were collected. No data were found on geothermal products and effluents, but they were not expected. In fact, the produced water is reinjected into the geothermal source formation, thanks to reinjection wells, or is used in the condenser to lower the temperature of the steam[3], [76].

In this section, the analysis of residues is carried out. They were studied separately, dividing filtering materials from other residues. Results of the analysis, given in tables 3.36 and 3.37, show that filtering materials are characterized by high radiological content. In fact, looking at the table 3.36, it can be seen that in filtering material it is predominant the presence of ^{226}Ra and its descendants, for which the mean values are higher than 5000 Bq/kg for ^{226}Ra and ^{210}Pb, and equal to 3563 Bq/kg for ^{210}Po; in particular, ^{226}Ra reaches very high values, over 18000 Bq/kg. ^{228}Ra has high activity concentration values too: the median is 2072 Bq/kg, and the maximum value is more than 6500 Bq/kg. The lowest

* *Min, max and quartiles are not reported in all cases in which only average values are available*

concentrations were observed in second clarifiers in an American study, that were sampled when there was more than one clarifier[77].

The results obtained in table 3.37, instead, show that other residues have low radiological content. Considering that this group of samples analyzed is composed of scales, tower sludges, and adsorbent and filtering materials [38] , and considering moreover the results obtained in the table above, it can be deduced that probably the highest values of activity concentration (as for example the value of 1040 Bq/kg for ^{210}Po) are relative to filtering materials. In fact, this table also contains values of some filter materials because in the bibliographic source [38] the data were reported all together (with a range) and could not be distinguished.

Table 3.36 Analysis of activity concentrations for residues of geothermal energy production sector– filter

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)	Median (Bq/kg)
U238	-	-	-	-	-	-
Ra226	8	5171	3548	370	9398	7050
Pb210	8	5483	6055	37	18924	5532
Po210	7	3563	2892	37	6401	5180
Th232	-	-	-	-	-	-
Ra228	8	2583	2692	37	6771	2072
K40	1	247	-	247	247	-

Table 3.37 Analysis of activity concentrations for of geothermal energy production sector– other residues

	Number of samples	Weighted Mean (Bq/kg)	St.Dev. (Bq/kg)	Min (Bq/kg)	Max (Bq/kg)
U238	62	32	25	13	164
Ra226	-	-	-	-	-
Pb210	62	274	103	51	327
Po210	62	881	311	125	1040
Th232	62	29	29	18	185
Ra228	-	-	-	-	-
K40	62	302	67	24	332

3.2 Results and discussion

A collection of radiological data on some nuclides of the Uranium-238 and Thorium-232 series (mainly ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra), as well as Potassium-40, have been collected for this work. Information gathered from collection and analysis gives an idea of the radiological content that can be expected for various types of industrial activities. Almost 200 bibliographic sources were used for data collection. References belong to national and international literature, starting from 70s. While for some sectors there has been interest already in past years, for others the amount of scientific information of interest to us is still scarce. This has meant that the amount of scientific information of interest to us for some sectors is more extensive (this is the case with power generation from coal-fired power plants or the oil and gas industry), while for others it is almost entirely absent (geothermal power generation) and there is a need for further investigation. In this regard, given the awareness in recent years regarding radiological hazards potentially arising from industrial sectors involving NORM, the interest of the international scientific community in these issues is growing, so more radiological data related to these types of industrial activities, i.e., NORM industries, will certainly be available in the future.

Furthermore, it should be noted that where more data are available, it is not necessarily for all radionuclides. In fact, the analysis shows that not all radionuclides of interest were always taken into account: in most works, measurements focused on gamma emitters, and alpha emitters (such as 210Po) were not measured. Typically, data is missing for two important nuclides from the radiological protection point of view: 210Pb and 210Po. In particular, Pb-210 is a gamma emitter with low energy emissions (lower than 50 keV) so it is difficult to measure. This is not a problem for the other categories, but for residues, where they usually accumulate, it is. For example, concerning the scales of the clinker ovens up to now the scientific literature does not provide data about 210Pb and 210Po, probably because the objectives of the publications found on this topic were not focused on the radiological protection of

workers. This highlights the need for a research effort to make further measurements of these nuclides.
As for materials in NORM-involving industries, the most sampled are, in order, raw materials and solid residues. Practically absent is information on effluents: in fact, out of over 6000 samples collected, only 60 belong to the effluent category (see table 3.1). But this is not always a lack, because there are situations for which they are not expected. This is, for instance, the case of geothermal power plants where the produced water is reinjected into the geothermal source formation so, no effluents are produced.
On the other hand, instead, for the TiO2 pigment production both liquid and gaseous effluents are intended.
As far as raw materials are concerned, they are not always of natural origin. it may happen that the raw material of an industrial sector is the product of another. This happens for fertilizers, for which one of the raw materials is phosphoric acid. The difference lies in the fact that raw materials of natural origin are usually characterised by the presence of secular equilibrium, while in the other categories of material the equilibrium could be rupted. The phosphoric acid, in fact, is rich in uranium, and the radium that was in the phosphatic rock during the production process precipitates in the gypsum.
With regard to residues, instead, they are materials that often need the most attention due to their radiological content. The "Red mud" coming from the extraction of aluminum from bauxite can be rich in uranium or in thorium.
Another important and well-known residue is the ash produced in the coal-fired power plant. Since thermal processes cause the volatilization of Pb-210 and Po-210, during the coal combustion process they tend to accumulate in the "fly ashes". In fact, the analysis carried out highlighted the differences in the radiological content between the coal, the "bottom ash" and the "fly ash". From the analysis it may conclude that the coal, as raw material, do not pose a radiological hazard because of its low radioactivity content, although sometimes in it the activity concentration of some radionuclides may exceed the value of 1 Bq/g; instead in ashes an elevated radiological content is expected.

For the same reason of the thermal process, scales in the cement production are important from the radiation protection point of view: radiological criticalities are mainly due to accumulation of ^{210}Pb and ^{210}Po in clinker oven.

Although iron ores have a low content of natural radionuclides, the high temperature heat treatment make radiologically critical the mineral agglomeration and blast furnace melting.

As in coal-fired power plants, also for the oil&gas the radiological content in raw materials is lower than in residues. The same happens in the titanium dioxide pigment production, where minerals contain already moderately high levels of activity concentrations of radionuclides, but during treatment they concentrate in scales. The production of TiO_2 pigment is possible starting from various ores; ilmenite and rutile are the main used and they can contain high radiological content, sometimes exceeding the typical activity concentration value reported by UNSCEAR 2000[11] (around 1000 Bq/kg for both ^{232}Th and ^{238}U series).

Among raw materials for a NORM-involving sector, there is the monazite, that is characterized by elevated values of radioactivity, especially of thorium.

Lastly, fertilizers are characterised by high content of natural radioactivity, with values often exceeding the exemption and clearance levels. When dealing with fertilisers, a significant presence of potassium-40 must be taken into account. In their raw materials it can expect activity concentrations values of radionuclides over than the exemption levels. In fact, main raw materials are phosphorite and phosphoric acid. The radioactivity content of fertilisers is highly variable and depends on both the initial concentration of radionuclides in the raw materials and the method of production.

3.2 Database PAF

The Physical Agents Portal (PAF) has been realized by the Public Health Laboratory of the Health Service of Tuscany, South-East Tuscany Health Unit (ex USL 7 Siena) in collaboration with the National Institute for Insurance against Accidents at Work (INAIL) under the INAIL Institutional Research Activities Plan. The portal is a useful tool to support risk assessment and prevention interventions in all working sectors. It can be use both by companies and by those called upon to carry out supervision and control. The website is constantly being updated and take into account the changes and additions to the regulations.

PAF website (https://www.portaleagentifisici.it/) already provides support for risk assessment and prevention occupational noise, vibrations, optical radiation (natural and artificial) and electromagnetic fields. There is also a section on ionizing radiation. At the beginning it only included artificial ionizing radiations. To support the adoption of radiation protection legislation (Legislative Decree 101/2020 [1] as modified with [21]), a section dedicated to "ionising radiation from natural sources" has been created within the PAF.

This section is composed by three sub-sections: one dedicated to radon on workplaces, one on natural radioactivity in building materials and another about radioactivity in NORM involving industrial sectors.

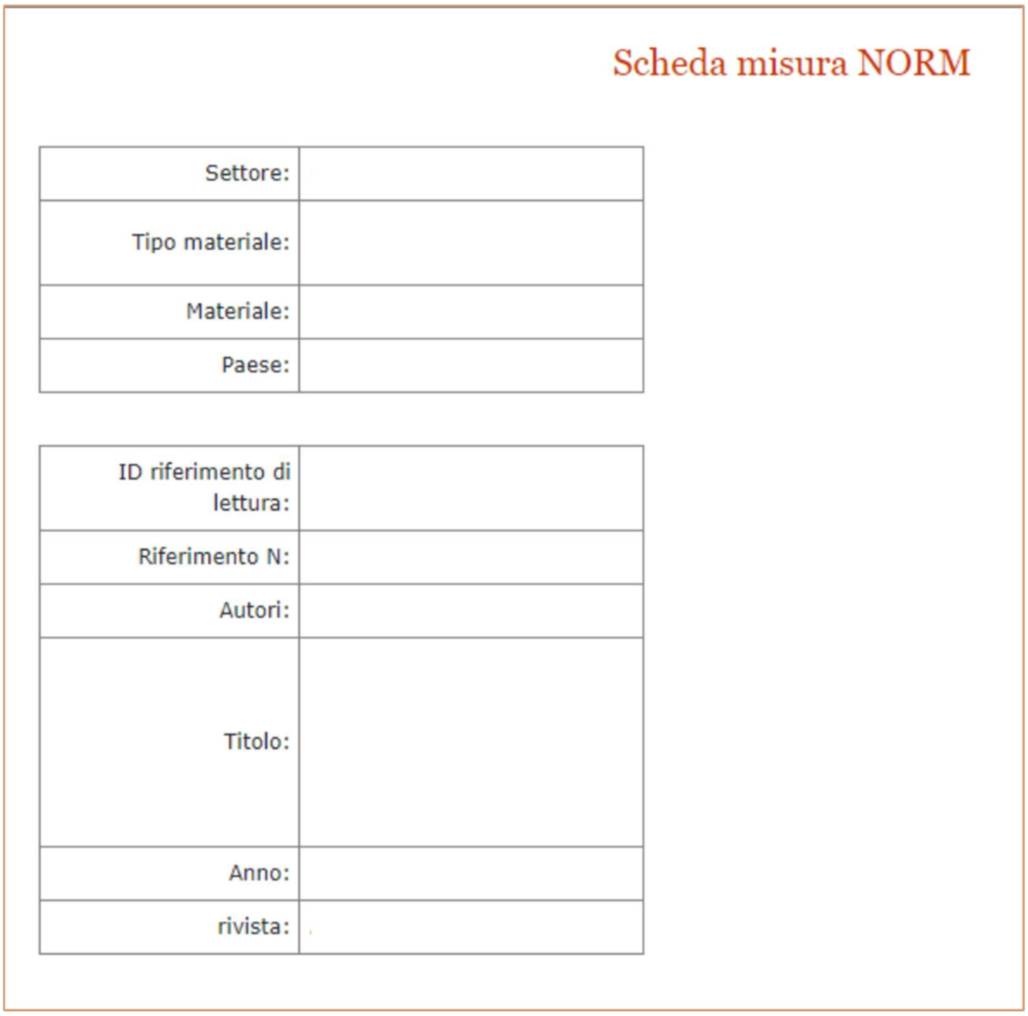
Within this last section, a database will be soon available. It is being set up to collect all radiological data (Uranium, Thorium, Potassium content) from Italian and international literature on NORM related industrial activities that are presented in this study. In the database it will be possible make a research filtering per industrial sectors, country, and type of materials (fig.3.9). In fact, it will be possible to choose some materials within the four macro-categories: raw materials, residues, products and effluents.

When options are selected, the database filters between the more than 6000 samples collected and gives a table with the activity concentrations per each material (fig.3.10). There are seven radionuclides interrogated and they are ^{238}U, ^{226}Ra, ^{210}Pb, ^{210}Po, ^{232}Th, ^{228}Ra and ^{40}K. For each data item there is a number corresponding to the bibliographic reference ("ref" in the figure 3.10); clicking on it will open a tab with all data of the bibliographic reference (fig.3.11).

Figure 3.9 Database on PAF website. Step one: the filter boxes for sector, type of material (raw material, residues, effluents, products)[10]

ref	U238	Ra226	Pb210	Po210	Th232	Th228	Ra228	K40	U.M.	Rn222 Bq/m3	Paese

Figure 3.10Database on PAF website. Step two: the table where filtered activity concentrations will appear [10]



Scheda misura NORM

Settore:	
Tipo materiale:	
Materiale:	
Paese:	

ID riferimento di lettura:	
Riferimento N:	
Autori:	
Titolo:	
Anno:	
rivista:	

Figure 3.11 Database on PAF website: the detailed bibliographic reference sheet [10]

Chapter 4

Census about Italian NORM involving industries

Contents

4.1 An overview on the NORM sites inventory

With the aim to understand the impact that the new Italian legislative decree on radiation protection[1] has in Italy, an inventory on the NORM-involving industrial sectors is carried out. The inventory updates a previous inventory made by the Italian Institute for Environmental Protection and Research (ISPRA) in 2014[28], taking into account the industrial sectors listed in Annex II of Legislative Decree 101/2020, here reported in Table 2.2.

It is worth to note that some International Bodies, like UNSCEAR[78], encourage the construction and the updating of national inventories of NORM involving industries. In the present inventory information has been selected taking into consideration a guidance drafted by the International Atomic Energy Agency (IAEA): the IAEA Environet NORM project [79], indeed, has developed a guidance document to support 176-Member States in the construction of a NORM inventory, taking into account the local situation.

Moreover, in order to provide support to the member states of the European Union in the implementation of Council Directive 59/2013/Euratom[2], on September 9th, 2020, a project called "*RadoNorm - Towards effective radiation protection based on improved scientific evidence and social considerations - focus on Radon and NORM*" was funded by the European Union under the EURATOM program Horizon 2020, with a

duration of five years and coordinated by BfS (Germany). Although much of this project is devoted to Radon (about 60-70%), several activities focused on NORM-related problems[80]. The European RadoNORM project includes activities and knowledge sharing that provide an overview of the characteristics of existing NORM sites in Europe, exposure scenarios and regulatory questions related to NORM.
The construction of a national inventory, therefore, is useful to provide support for assessments in the field of radiation protection by NORM.
Moreover, the national inventory allows to identify still active NORM-involving industrial sectors and relevant secondary processes. In the next section, a description of data collection about Italian NORM involving industrial sectors is given.

4.2 Data collection

Starting with a study conducted by ISPRA in 2014[28], a review and updating of national inventory of NORM-industrial sectors was carried out in 2022.
Data was collected through national and international bibliographic references, such as technical reports, conference proceedings, as well as by direct contact or through trade associations' websites.

The industrial sectors surveyed are:

- Cement production
- Geothermal energy production
- Zircon and zirconium industry (refractory materials, sanitary ceramics, manufacturers of ceramics)
- Extraction of aluminum from bauxite
- Coal-fired power plants
- Primary iron production
- Production of phosphate and potassium fertilizers
- Oil and Gas Production
- Titanium dioxide pigment production.
- Extraction of rare earths from monazite
- Tin, lead and copper extraction
- Extraction of iron-niobium from pyrochlore
- Processing of niobite-tantalite mixture

For each activity, information has been collected on the number of plants and their distribution throughout Italy.
It was not possible to find data on the number of workers; moreover, since just part of the total number of workers of an industrial sector are involved with NORMs, it is difficult to insert this information.
For the industrial activities considered, the number of NORM-related plants in Italy are reported in figure 4.1 and listed in table 4.1, where it is shown also a comparison between the previous inventory and his update in 2022.
Currently, industries involved in extraction of rare earths from monazite, extraction of tin, lead and copper, the iron-niobium extraction from pyrochlore, the production of thorium compounds and manufacture of thorium-containing products are not active in Italy.

Table 4.1 Inventory of the 2022 Italian NORM involving industrial sectors compared with the previous one of 2014.

Industrial Sector	**N. of Plants**	
	2014	**2022**
Cement production:	Total: 81	Total: 54
Integral cycle	57	32
Grinding	24	22
Geothermal energy production: high and medium enthalpy	34	34
Zircon sands industry:		
Tiles prod.	82	131
Refractories prod.	37	31
Sanitary ware prod.	-	30
Ceramic glazes and dyes prod.	-	15
Coal-fired power plants	13	6
Titanium dioxide production	1	1
Steel production:		
Integral cycle	2	1
Electric furnace	40	37
Oil & gas production:		
Oil production plants	1642 wells	1581 wells (25 plants)
Gas production plants		193
Refinery		10

Extraction of Aluminium from bauxite	1	1
Processing of phosphate and potassic ores Fertilizer production		22

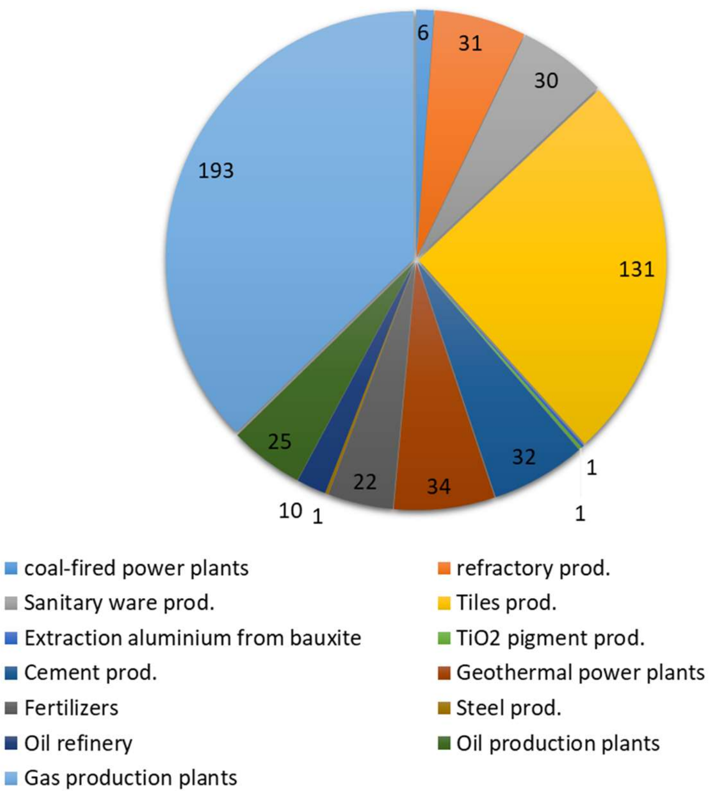
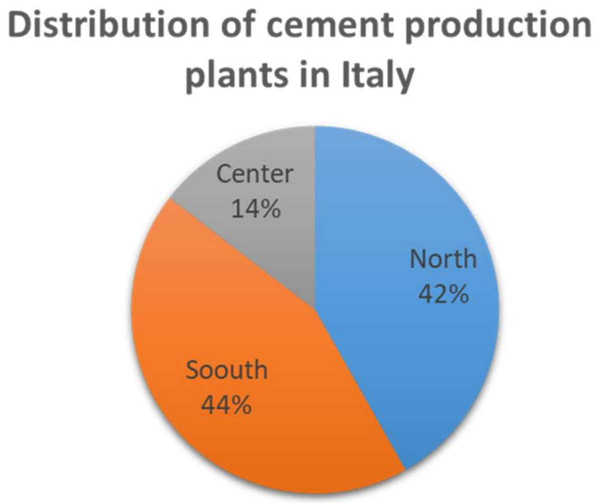


Figure 4.1 Number of plants for some NORM-involving industrial sectors in Italy in 2022

The Table 4.1 put in evidence that, from 2014 until 2022, a general decrease of plants of NORM-involving activities occurred. Moreover, some industrial sectors are surveyed for the first time.

As regards the cement industry, the number of facilities is much lower than 2014. This is due to the crisis of the construction industry, whereby the decreasing amount of new construction has led to the closure of many companies in the sector. Two types of cement production industries are present in Italy but, as already explained in Chapter 2, just those with an integral cycle are of interest for this study because of the presence of the clinker oven.

Cement plants are scattered all over the country; in particular, integral cycle cement plants are distributed rather evenly over the territory (fig. 4.2).



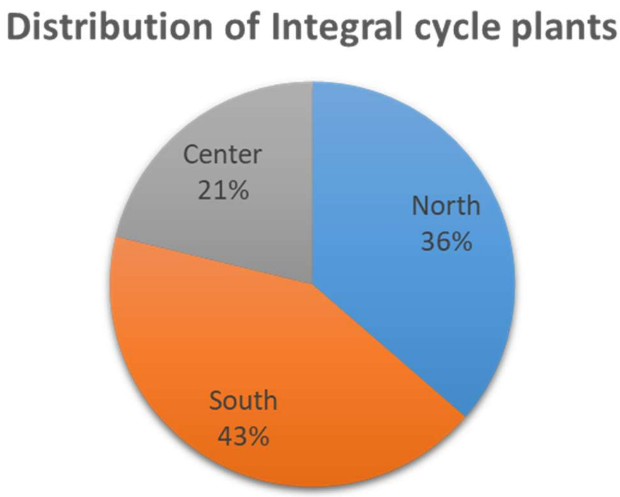


Figure 4.2 On the top, the distribution of all cement production facilities (integral cycle + grinding) in Italy in 2022; on the bottom the distribution only of cement production plants with integral cycle.

Although these types of installations are distributed throughout the country, there are regions where they are completely absent. This is the case of Liguria, Marche and Valle d'Aosta. In other regions, instead, only plants with integral cycle are present (as in Abruzzo, Basilicata or Lazio). The region with the largest number of integral cycle plants is Lombardia, which has five (fig. 4.3).

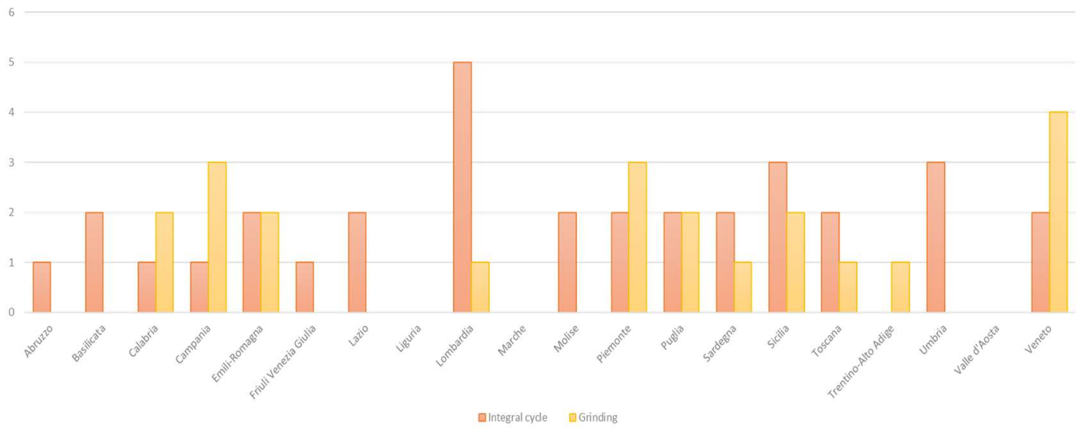


Figure 4.3 Regional distribution of the cement production plants (integral cycle in red and grinding in yellow) in Italy in 2022.

Referring to other sectors, from 2014 until now just one steel integrated plant has remained active, and it is in a region of southern Italy: Puglia.

There is also only one plant for the extraction of alumina from bauxite and the titanium dioxide production just one plant is present: that of the first sector is in Sardegna and the titanium dioxide production plant is in Toscana. Activities in the plant of extraction from bauxite are currently suspended but there is still a minimum number of personnel to maintain the plant.

The number of geothermal power plants remained the same. They are all located in the Tuscany region and are all managed by a single company. With its 34 plants, Italy is among the world's leading producers of geothermal energy and the plant located in Larderello is the first geothermal power plant built in the world (fig. 4.4)[81].

The only one that stands out from the general downward trend in the number of plants over the years is the tile manufacturing sector, which, on the contrary, experienced an increase in the number of plants from 82 to 131.

For the zirconiferous sands production, the updated inventory includes new types of plants such as manufacturers of glazes and dyes for ceramics and producers of sanitary ceramics. The latter are almost all located in the province of Viterbo (in the Lazio region).

The current survey showed that the oil and gas production sector currently has slightly fewer wells; more detailed information has been added for this sector compared to 2014.

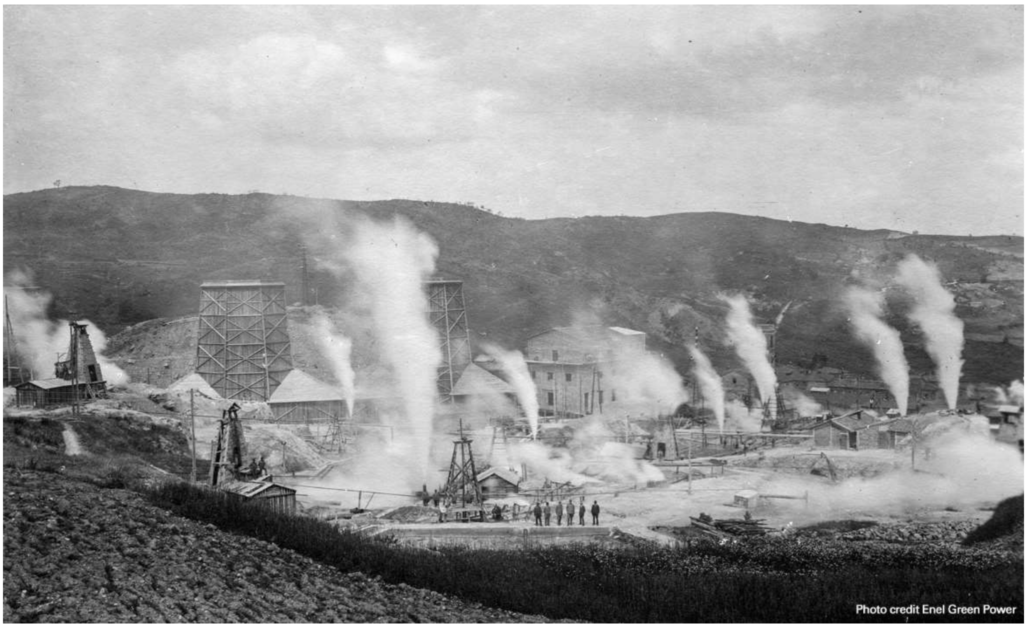


Figure 4.4 Picture of the first geothermal power plant in the world in Larderello (Italy) [81]

4.3 Results

Table 4.1 summarises the updated number of NORM-related industries in Italy in relation to some of the NORM-related industries listed in the European Directive 2013/59/Euratom[2] and in Decree No. 101 of July 2020[1] transposing it.

From this survey, which is useful to understand the impact of Italian radiological protection legislation on NORM industries, it appears that the vast majority, in terms of territorial presence, are gas production plants and those processing zirconiferous sands, particularly tile production. There are also numerous geothermal and cement production plants in the country.
From the inventory emerged that some sectors listed in Annex II of Legislative Decree 101/2020 (table 2.2) are currently not active in Italy. This is the case of:

- Extraction of rare earths from monazite;
- Extraction of tin, lead and copper;
- Extraction of iron-niobium from pyrochlore;
- Niobite/tantalite processing;
- Production of thorium compounds and manufacture of thorium-containing products.

The cement plants suffered a sharp drop compared to 2014. The number of geothermal plants, on the other hand, remained unchanged compared to 2014, as did that of titanium dioxide production. The sector of the cement production is not the only one to have suffered a decline in the number of plants, but also the coal-fired power plants: in fact, the 2014 ISPRA census referred to 13 active plants in Italy in 2010, but currently there are only 6 active plants.

On the other hand, the number of tiles production plants increased, passing from 82 to 131. Production of refractories, instead, declined slightly. Same was for the steel production through integral cycle which currently has only one plant in italy. For the zirconiferous sands production, the updated inventory includes new types of plants such as manufacturers of glazes and dyes for ceramics and producers of sanitary ceramics. The current survey showed that the oil and gas production sector currently has slightly fewer wells.

In conclusion, results show a very varied picture: for some sectors, few large plants are active (e.g., titanium dioxide industries or steel mills), for others, a large number of small/medium-sized plants can be observed (processing of zirconium sand, cement factories). The economic crisis and technological progress have led to significant changes compared to the number of establishments surveyed in 2014: some sectors, such as cement plants, have been strongly affected by this crisis and the data collected so far may be subject to further variations.

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*AP*PENDIX

In the following tables all data collected are provided. Values are rounded to the nearest whole number.

In the columns of radionuclides, in red are reported the arithmetic means computed by the author, considering the minimum and maximum values of the activity concentrations.

In some publications the range of activity concentrations values is reported without information about the number of samples. In this case it has been assumed a number of samples equal to 2: this is highlighted in red.

GEOTHERMAL ENERGY PRODUCTION

Activity concentrations in geothermal power plant-residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Residues	2		4884				6771		[3]
USA	Residues	1		7363	5883	5883	5883	5957		[77]
USA	Residues	1		9398	6401	6401	6401	6771		[77]
USA	Residues	1		814	296	296	296	333		[77]
USA	Residues	1		7474	5920	5920	5920	3293		[77]
USA	Residues	1		370	37	37	37	37		[77]
USA	Residues	1		6919	5180	5180	5180	3330		[77]

USA	Residues	1		1850	1221	1221	1221	851		[77]
ITALY	Residues	49	32		327	1040	1040		332	[38]

Activity concentrations in geothermal power plant-residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Residues	11	13		80	315	315		220	[38]
ITALY	Residues	2	164		51	125	125		24	[38]
ITALY	Residues	1		7180	18924			95	247	[27]

PHOSPHORIC ACID PRODUCTION

Activity concentrations in phosphoric acid production - raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Rock	1							31	[82]
AUSTRALIA	Rock	2	458	464			26			[3]
FLORIDA	Rock	2	1700	1800			38			[3]
MOROCCO	Rock	2	1600	1600			105			[3]
JORDAN	Rock	2	1575							[3]
TUNISIA	Rock	2	590	520			92			[3]
TOGO	Rock	2	1360	1200			110			[3]
USA	Rock	2	1850	300			10			[3]
IRAN	Rock	1		1674			61		354	[83]
USA	Rock	10	1263	1460	1441	1355				[84]
USA	Rock	4	692	642	690	648				[84]
ITALY	Rock	1	10	9	13			3	51	[85]
ITALY	Rock	1	19	20	20			5	120	[85]
ITALY	Rock	1	1150	1340	1230			21	32	[85]
ITALY	Rock	1	1400	1550	1060			25	34	[85]
ITALY	Rock	1	1000	1200	1160			19	33	[85]
USA	Rock	6	1425	1391						[86]
USA	Rock	13	1695	2124						[86]
USA	Rock	22	1180	1378						[86]
SPAIN	Rock	1	1650	1610	1660		25	22		[87]
SPAIN	Rock	1	1650	1630	1600		24	19		[87]
SPAIN	Rock	1	1630	1640	1610		22	21		[87]
SPAIN	Rock	1	1680	1380	1440		33	20		[87]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SPAIN	Phosphorous pentoxide	1	870	3	74		53	2		[87]
SPAIN	Phosphorous pentoxide	1	1070	6	78		10	2		[87]
SPAIN	Phosphorous pentoxide	1	870	3	74		53	2		[87]
SPAIN	Phosphorous pentoxide	1	470	6	225		6	2		[87]
SPAIN	Phosphorous pentoxide	1	290	2	135		0.17	2		[87]
NIGERIA	Rock	1		617					324	[51]
MOROCCO	Rock	1		1600			20		10	[51]
ALGERIA	Rock	1		619			64		22	[51]
INDIA	Rock	20	1340	1322						[88]
SPAIN	Rock	1	1530	1421	1530	1643	20	13	21	[52]
SPAIN	Rock	1	1665	1439	1603	1712				[52]
BRASILE	Rock	9	1151	328	843		294	283		[89]
BRASILE	Rock	9	650	348	495		390	287		[89]
PAKISTAN	Rock	10		428			49		269	[53]
JORDAN	Rock	10		799			20		148	[53]
EGYPT	Rock	1	523	514			37		19	[54]
EGYPT	Rock	1	408	287	224		24		21	[55]
SIRIA	Rock	9	517	353	590	1197	2,4			[56]
SIRIA	Rock	9	1039	308	610	1577	2,5			[56]

Activity concentrations in phosphoric acid production - raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
BRASILE	Rock	1	1270	295			3344		1303	[58]
BRASILE	Rock	1	1356	217			3131		1100	[58]
SUDAN	Rock	1	2598	2663		1868	3		52	[57]
SUDAN	Rock	1	684	555		577	0.83		23	[57]
TANZANIA	Rock	1		5022			717		286	[64]
TANZANIA	Rock	1	4140				628			[64]
TANZANIA	Rock	1	4641				616			[64]
JORDAN	Rock	15	586	681	628			8	21	[90]
CHINA	Rock	1	152	124	172	125				[91]
CHINA	Rock	1	90	102	70	140				[91]
CHINA	Rock	1	50	44	20	50				[91]
INDIA	Rock	1	1120	908	1130	900				[91]
INDIA	Rock	1	1150	900	1130	920				[91]
INDIA	Rock	1	1150	895	1170	940				[91]
INDIA	Rock	1	1180	940	1180	990				[91]
IRAN	Rock	1								[83]

Activity concentrations in phosphoric acid production - residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Phosphogypsum	9		451			11			[82
AUSTRALIA	Phosphogypsum	2	17	315	380	255	6			[3]
AUSTRALIA	Scale	2		1952	665	59				[3]
BRAZIL	Scale	2	92	471	116		107			[3]
USA	Phosphogypsum	65	132	907	860	860				[84]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Phosphogypsum	9	130	433	435	427				[84]
USA	Clay	10	1003	881						[86]
USA	Clay	1		1924						[86]
USA	Residue	24	174	192						[86]
USA	Phosphogypsum	10	19	958						[86]
USA	Scale	1	1040	14238						[86]
USA	Residue	2	26	2753						[86]
SPAIN	Residue	1	1000	6	76		3	2		[87]
SPAIN	Residue	1	1300	7	82		3	7		[87]
SPAIN	Residue	1	1340	4	60		7	1		[87]
SPAIN	Residue	1	460	470	520		14	14		[87]
SPAIN	Residue	1	560	760	870		14	14		[87]
SPAIN	Residue	1	450	590	590		16	9		[87]
SPAIN	Phosphogypsum	1	650	580	600		34	10		[87]
SPAIN	Phosphogypsum	1	370	640	640		19	10		[87]
SPAIN	Phosphogypsum	1	360	650	620		31	12		[87]
SPAIN	Phosphogypsum	1	318	670	620		18	11		[87]
SPAIN	Residue	1	280	9	6		0.05	2		[87]
SPAIN	Residue	1	250	525	610		22	9		[87]
SPAIN	Sludge	1	2090	7	46		22	2		[87]
SPAIN	Sludge	1	1260	5	84		5,2	2		[87]
SPAIN	Sludge	1	1230	4300	1900		28	65		[87]
SPAIN	Sludge	1	910	1310	1420		13	18		[87]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
NIGERIA	Phosphogypsum	1		3358			4		200	[51]
INDIA	Phosphogypsum	20	170	100						[88]
BRAZIL	Phosphogypsum	12	40	811	813		273	247		[89]
BRAZIL	Phosphogypsum	12	48	350	353		175	214		[89]
EGYPT	Phosphogypsum	1	134	411			19		16	[54]
SIRIA	Phosphogypsum	12	33	318	507	1014	2			[56]
TANZANIA	Phosphogypsum	1		3219					41	[64]
TANZANIA	Phosphogypsum	1	85				135			[64]
JORDAN	Phosphogypsum	15	22	376	391			4	40	[90]
CHINA	Phosphogypsum	1	15	85	82	82				[91]
CHINA	Phosphogypsum	1	20	83	78	82				[91]
CHINA	Phosphogypsum	1	25	42	18	41				[91]
INDONESIA	Phosphogypsum	1	43	473	480	450				[91]
INDONESIA	Phosphogypsum	1	40	459	470	475				[91]
INDIA	Phosphogypsum	1	60	510	490	420				[91]

Activity concentrations in phosphoric acid production – residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
INDIA	Phosphogy psum	1	30	510	483	418				[91]
INDIA	Phosphogy psum	1	10	505	500	450				[91]
INDIA	Phosphogy psum	1	54	539	594	560				[91]
KUWAIT	Phosphogy psum	1	4	3			0.55		14	[92]
EGYPT	Phosphogy psum	1	13				3			[63]

Activity concentrations in phosphoric acid production - products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Phosphoric acid	1							19	[82]
ITALY	Phosphoric acid	1	1700	6	10				15	[85]
ITALY	Phosphoric acid	1	1900	8	26				20	[85]
ITALY	Phosphoric acid	1	1600	2	7				29	[85]
USA	Phosphoric acid	1	233	4						[86]
USA	Phosphoric acid	1	633	7						[86]

Activity concentrations in phosphoric acid production – products (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Phosphoric acid	1	1110	15						[86]
SPAIN	Phosphoric acid	1	1300	4	135					[87]
SPAIN	Phosphoric acid	1	1830	8	109					[87]
INDIA	Phosphoric acid	20	2442	6						[88]
SPAIN	Phosphoric acid	1	1488	8	106	26	11	7	22	[52]
SPAIN	Phosphoric acid	1	1346	4	55	12		5	15	[52]
SPAIN	Phosphoric acid	1	2888	3	13	3	20	6	12	[52]
BRAZIL	Phosphoric acid	1	375	52			458		1	[58]

Activity concentrations in phosphoric acid production - effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SPAIN	Liquid effluent	1	202	4	89		0.55	2		[87]
SPAIN	Liquid effluent	1	182	1	8			1		[87]
SPAIN	Liquid effluent	1	0.054	1	11			1		[87]
SPAIN	Liquid effluent	1	0.44	0.4			0,007	0.4		[87]

Activity concentrations in phosphoric acid production – effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SPAIN	Liquid effluent	1	230	0.33	16		12	1		[87]
SPAIN	Liquid effluent	1	56	3	15		0.11	2		[87]
SPAIN	Liquid effluent	1	0.26	1	9		0.029	1		[87]

MINING OF ORES OTHER THAN URANIUM

Activity concentrations minerals other than uranium -raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
NIGERIA	Rock	10		85			87		1315	[93]
NIGERIA	Rock	10		23			62		1427	[93]
NIGERIA	Rock	10		52			66		1358	[93]
NIGERIA	Rock	10		59			87		1551	[93]
NIGERIA	Rock	10		17			114		1478	[93]
KUWAIT	Rock	1	19	13			28		326	[92]
KUWAIT	Rock	1	79	84			69		1315	[92]
INDIA	Rock	1	100				180			[94]
INDIA	Rock	1	90				160			[94]
INDIA	Rock	1	90				220			[94]
INDIA	Rock	1	250				140			[94]
INDIA	Rock	1	220				150			[94]
INDIA	Rock	1	200				140			[94]
INDIA	Rock	1	1796				28		486	[68]
INDIA	Rock	1	1045				45		257	[68]
INDIA	Rock	1	3130				24		62	[68]
INDIA	Rock	1	1495				19		231	[68]
INDIA	Rock	1	4608				37		434	[68]
INDIA	Rock	1	667				34		290	[68]
INDIA	Rock	1	136				48		54	[68]
INDIA	Rock	1	150				270			[94]
INDIA	Rock	1	150				250			[94]
INDIA	Rock	1	150				250			[94]

Activity concentrations minerals other than uranium -raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SERBIA	Rock	1		56			70		1302	[95]
SERBIA	Rock	1		46			40		405	[95]
SERBIA	Rock	1		49			50		408	[95]
SERBIA	Rock	1		44			41		419	[95]
SERBIA	Rock	1		58			50		908	[95]
SERBIA	Rock	1		54			55		1072	[95]
SERBIA	Rock	1		36			34		240	[95]
SERBIA	Rock	1		91			58		1245	[95]
SERBIA	Rock	1		54			52		951	[95]
SERBIA	Rock	1		36			42		775	[95]
SERBIA	Rock	1		8			20		85	[95]
SERBIA	Rock	1		4			21		24	[95]
SERBIA	Rock	1		14			15		358	[95]
ITALY	Rock	1		142			341		85	[96]
ITALY	Rock	1		158			398		187	[96]
ITALY	Rock	1		150			470		187	[96]
ITALY	Rock	1		97			195		128	[96]
ITALY	Rock	1		254			389		157	[96]
ITALY	Rock	1		124			183		149	[96]
ITALY	Rock	1		229			273		169	[96]
ITALY	Rock	1		294			380		161	[96]
AUSTRALIA	Rock	7		19			52		359	[97]
INDIA	Mineral	1		34000				338000		[67]
EGYPT	Rock	7		10			4		62	[98]

Activity concentrations minerals other than uranium -raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TAIWAN	Rock	5	53				68		1084	[99]
SAUDI ARABIA	Rock	1		21			18		523	[100]
SAUDI ARABIA	Rock	1		42			24		541	[100]
SAUDI ARABIA	Rock	1		37			26		897	[100]
SAUDI ARABIA	Rock	1		36			22		404	[100]
SAUDI ARABIA	Rock	1		54			38		829	[100]
SAUDI ARABIA	Rock	1		35			25		700	[100]
SAUDI ARABIA	Rock	1		77			83		1871	[100]
SAUDI ARABIA	Rock	1		10			9		378	[100]
SAUDI ARABIA	Rock	1		30			51		124	[100]
SAUDI ARABIA	Rock	1		9			13		350	[100]
SAUDI ARABIA	Rock	1		12			15		429	[100]
SAUDI ARABIA	Rock	1		81			64		1880	[100]
SAUDI ARABIA	Rock	1		18			13		488	[100]
SAUDI ARABIA	Rock	1		31			44		1182	[100]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SAUDI ARABIA	Rock	1		28			12		327	[100]
SAUDI ARABIA	Rock	1		47			37		924	[100]
SAUDI ARABIA	Rock	1		43			34		1321	[100]
SAUDI ARABIA	Rock	1		67			54		1480	[100]
SAUDI ARABIA	Rock	1		46			36		1127	[100]
SAUDI ARABIA	Rock	1		23			31		621	[100]
SAUDI ARABIA	Rock	1		6			24		472	[100]
SAUDI ARABIA	Rock	1		35			23		803	[100]
SAUDI ARABIA	Rock	1		7			15		453	[100]
SAUDI ARABIA	Rock	1		20			22		836	[100]
SAUDI ARABIA	Rock	1		43			23		505	[100]
SAUDI ARABIA	Rock	1		25			18		536	[100]
SAUDI ARABIA	Rock	1		83			69		2353	[100]
SAUDI ARABIA	Rock	1		37			45		1289	[100]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SAUDI ARABIA	Rock	1		23			43		1128	[100]
SAUDI ARABIA	Rock	1		25			15		540	[100]
YEMEN	Rock	1		36			71		2253	[101]
YEMEN	Rock	1		70			131		1682	[101]
YEMEN	Rock	1		56			179		1293	[101]
YEMEN	Rock	1		24			21		56	[101]
YEMEN	Rock	1		30			16		6	[101]
YEMEN	Rock	1		17			15		17	[101]
YEMEN	Rock	1		63			12		17	[101]
YEMEN	Rock	1		31			12		5	[101]
YEMEN	Rock	1		28			57		656	[101]
YEMEN	Rock	1		33			23		581	[101]
YEMEN	Rock	1		54			131		2677	[101]
YEMEN	Rock	1		63			122		2292	[101]
YEMEN	Rock	1		49			110		2054	[101]
YEMEN	Rock	1		213			109		32	[101]
HUNGARY	Rock	1	19	19			72		12	[75]
HUNGARY	Rock	1	17	18			68		6	[75]
HUNGARY	Rock	1	15	14			51		9	[75]
ITALY	Rock	1		27			74		1576	[102]
ITALY	Rock	1		18			44		785	[102]
ITALY	Rock	1		71			96		1369	[102]
ITALY	Rock	1		62			115		1409	[102]
SPAIN	Rock	1		94			80		1328	[102]
SPAIN	Rock	1		111			101		1252	[102]
NORWAY	Rock	1		65			71		1065	[102]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
BRAZIL	Rock	1		125			239		1154	[102]
BRAZIL	Rock	1		21			60		1106	[102]
BRAZIL	Rock	1		56			103		1323	[102]
BRAZIL	Rock	1		98			141		1542	[102]
INDIA	Rock	1		434			31		1002	[102]
INDIA	Rock	1		10			8		118	[102]
INDIA	Rock	1		38			19		1504	[102]
INDIA	Rock	1		3			31		410	[102]
SOUTH AFRICA	Rock	1		1			2		71	[102]
SOUTH AFRICA	Rock	1		21			34		357	[102]
KENYA	Rock	4		23			25		931	[103]
KENYA	Rock	11		57			95		916	[103]
KENYA	Rock	6		171			163		1048	[103]
KENYA	Rock	23		38			96		839	[103]
TURKEY	Rock	1	223				221		1618	[104]
TURKEY	Rock	1	202				188		1378	[104]
TURKEY	Rock	1	274				304		1409	[104]
TURKEY	Rock	1	172				187		1353	[104]
TURKEY	Rock	1	280				165		1275	[104]
TURKEY	Rock	1	343				319		1408	[104]
TURKEY	Rock	1	652				352		419	[104]
TURKEY	Rock	1	44				69		1034	[104]
TURKEY	Rock	1	44				51		864	[104]
TURKEY	Rock	1	53				54		915	[104]
TURKEY	Rock	1	46				51		857	[104]
TURKEY	Rock	1	135				276		1695	[104]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURKEY	Rock	1	83				293		928	[104]
TURKEY	Rock	1	64				276		1111	[104]
CHINA	Rock	1		14			30		1361	[105]
CHINA	Rock	1		17			30		1351	[105]
CHINA	Rock	1		17			25		1399	[105]
CHINA	Rock	1		18			24		1415	[105]
CHINA	Rock	1		12			25		1454	[105]
CHINA	Rock	1		17			31		1610	[105]
CHINA	Rock	1		19			24		643	[105]
CHINA	Rock	1		21			26		731	[105]
CHINA	Rock	1		21			20		700	[105]
CHINA	Rock	1		12			53		1097	[105]
CHINA	Rock	1		18			54		1040	[105]
CHINA	Rock	1		19			47		1018	[105]
CHINA	Rock	1		14			49		1090	[105]
CHINA	Rock	1		22			30		698	[105]
CHINA	Rock	1		14			29		718	[105]
CHINA	Rock	1		35			22		651	[105]
CHINA	Rock	1		29			24		698	[105]
CHINA	Rock	1		18			30		778	[105]
CHINA	Rock	1		11			30		960	[105]
CHINA	Rock	1		35			20		942	[105]
CHINA	Rock	1		30			27		961	[105]
CHINA	Rock	1		28			22		963	[105]
CHINA	Rock	1		20			28		1019	[105]
CHINA	Rock	1		21			28		964	[105]
CHINA	Rock	1		27			25		979	[105]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Rock	23		59			70		1560	[106]
TURKEY	Rock	1		33			35		613	[107]
TURKEY	Rock	1		41			10		264	[107]
TURKEY	Rock	1		11			43		721	[107]
TURKEY	Rock	1		13			45		723	[107]
TURKEY	Rock	1		48			41		801	[107]
TURKEY	Rock	1		29			38		573	[107]
TURKEY	Rock	1		39			49		720	[107]
TURKEY	Rock	1		35			39		699	[107]
TURKEY	Rock	1		34			71		898	[107]
TURKEY	Rock	1		76			71		1119	[107]
TURKEY	Rock	1		95			122		1470	[107]
TURKEY	Rock	1		41			50		708	[107]
TURKEY	Rock	1		66			75		903	[107]
TURKEY	Rock	1		46			56		697	[107]
TURKEY	Rock	1		73			99		1296	[107]
CAMEROON	Rock	2	24				139		1161	[108]
CAMEROON	Rock	2	19				26		304	[108]
CAMEROON	Rock	2	24				37		449	[108]
CAMEROON	Rock	2	16				14		460	[108]
EGYPT	Rock	1	25				18		1158	[63]
EGYPT	Rock	1	4				9		484	[109]
TURKEY	Rock	1		65			96		1033	[110]
TURKEY	Rock	1		42			39		747	[110]
TURKEY	Rock	1		50			62		813	[110]
TURKEY	Rock	1		97			96		1036	[110]
TURKEY	Rock	1		32			42		447	[110]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURKEY	Rock	1		18			17		229	[110]
PAKISTAN	Rock	1		11			1		3	[111]
PAKISTAN	Rock	1		10			1		3	[111]
PAKISTAN	Rock	1		14			1		0.25	[111]
PAKISTAN	Rock	1		15			1		7	[111]
PAKISTAN	Rock	1		12			2		4	[111]
PAKISTAN	Rock	1		11			2		19	[111]
PAKISTAN	Rock	1		7			0.49		1	[111]
PAKISTAN	Rock	1		8			2		5	[111]
PAKISTAN	Rock	1		14			1		2	[111]
PAKISTAN	Rock	1		14			2		21	[111]
PAKISTAN	Rock	1		13			2		6	[111]
PAKISTAN	Rock	1		13			2		9	[111]
PAKISTAN	Rock	1		16			3		14	[111]
PAKISTAN	Rock	1		15			1		3	[111]
PAKISTAN	Rock	1		16			1		9	[111]
PAKISTAN	Rock	1		16			4		8	[111]
PAKISTAN	Rock	1		8			1		3	[111]
PAKISTAN	Rock	1		14			1		5	[111]
PAKISTAN	Rock	1		13			4		33	[111]
PAKISTAN	Rock	1		13			1		1	[111]
PAKISTAN	Rock	1		19			4		47	[111]
PAKISTAN	Rock	1		26			6		54	[111]
PAKISTAN	Rock	1		14			2		13	[111]
PAKISTAN	Rock	1		18			2		20	[111]
PAKISTAN	Rock	1		14			2		19	[111]
PAKISTAN	Rock	1		17			5		60	[111]
PAKISTAN	Rock	1		15			1		3	[111]

Activity concentrations minerals other than uranium -raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CHINA	Rock	4		71			77		1426	[112]
CHINA	Rock	6		108			76		1445	[112]
CHINA	Rock	3		63			74		953	[112]
CHINA	Rock	5		48			76		932	[112]
CHINA	Rock	3		115			186		1415	[112]
CHINA	Rock	5		205			117		1016	[112]
CHINA	Rock	3		55			82		1176	[112]
CHINA	Rock	2		15			31		1435	[112]
CHINA	Rock	7		134			152		1415	[112]
CHINA	Rock	6		56			174		1121	[112]
CHINA	Rock	3		37			87		1352	[112]
CHINA	Rock	2		98			187		947	[112]
CHINA	Rock	4		125			169		1407	[112]
CHINA	Rock	8		109			167		1746	[112]
CHINA	Rock	4		32			17		757	[112]
CHINA	Rock	3		27			35		1355	[112]
CHINA	Rock	3		25			33		346	[112]
CHINA	Rock	2		26			37		564	[112]
CHINA	Rock	5		19			28		186	[112]
CHINA	Rock	3		17			243		2056	[112]
CHINA	Rock	2		10			14		353	[112]
CHINA	Rock	2		52			70		941	[112]
CHINA	Rock	2		80			100		1128	[112]
CHINA	Rock	2		127			159		2920	[112]
JAPAN	Rock	1	4	3			3	3	210	[69]
JAPAN	Rock	1	4	5			3	5	210	[69]
JAPAN	Rock	1	4	3			3	4	200	[69]
JAPAN	Rock	1	5	6			5		250	[69]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JAPAN	Rock	1	5	6			5	8	250	[69]
JAPAN	Rock	1	24	24			27	31	740	[69]
JAPAN	Rock	1	25	22			28	28	740	[69]
JAPAN	Rock	1	33	41			59	60	950	[69]
JAPAN	Rock	1	22	27			23	41	900	[69]
JAPAN	Rock	1	15	14			21	26	540	[69]
JAPAN	Rock	1	2	2			3		73	[69]
JAPAN	Rock	1	83	98			67	190	1300	[69]
JAPAN	Rock	1	10	12			10	17	1200	[69]
JAPAN	Rock	1	27	27			30	38	820	[69]
JAPAN	Rock	1	110	100			100	120	1300	[69]
JAPAN	Rock	1	86	110			89	110	1100	[69]
JAPAN	Rock	1	47	52			63	83	1100	[69]
JAPAN	Rock	1	99	90			140	160	1300	[69]
JAPAN	Rock	1	7	10			17	21	660	[69]
JAPAN	Rock	1	68	76			49	91	980	[69]
JAPAN	Rock	1	47	65			33	92	1200	[69]
JAPAN	Rock	1	56	99			27	94	1200	[69]
JAPAN	Rock	1	36	31			50	52	1100	[69]
JAPAN	Rock	1	97	110			75	150	1400	[69]
JAPAN	Rock	1	14	22			40	76	1000	[69]
JAPAN	Rock	1	21	29			29	52	1200	[69]
JAPAN	Rock	1	21	23			50	66	1300	[69]
JAPAN	Rock	1	41	44			42	55	1100	[69]
JAPAN	Rock	1	8	8			15	16	440	[69]
JAPAN	Rock	1	14	16			53	69	1300	[69]
JAPAN	Rock	1	78	99			51	140	1400	[69]
JAPAN	Rock	1	62	63			85	99	1300	[69]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JAPAN	Rock	1	100	120			130	140	790	[69]
JAPAN	Rock	1	35	40			8	61	1300	[69]
JAPAN	Rock	1	28	29			130	150	1500	[69]
JAPAN	Rock	1	19	20			56	64	1300	[69]
JAPAN	Rock	1	7	6			9	9	430	[69]
JAPAN	Rock	1	3	4			3	6	1100	[69]
JAPAN	Rock	1	16	15			26	28	510	[69]
JAPAN	Rock	1	120	150			120	230	1400	[69]
JAPAN	Rock	1	12	11			20	22	550	[69]
JAPAN	Rock	1	200	220			300	370	1600	[69]
JAPAN	Rock	1	91	110			98	170	1500	[69]
JAPAN	Rock	1	16	18			67	100	1500	[69]
JAPAN	Rock	1	250	250			230	230	1300	[69]
JAPAN	Rock	1	19	19			140	130	1200	[69]
JAPAN	Rock	1	25	38			35	59	1200	[69]
JAPAN	Rock	1	19	23			39	51	890	[69]
JAPAN	Rock	1	7	9			20	25	620	[69]
JAPAN	Rock	1	12	16			29	39	780	[69]
JAPAN	Rock	1	8	8			10	8,6	440	[69]
JAPAN	Rock	1	20	22			30	38	840	[69]
JAPAN	Rock	1	23	31			41	57	1000	[69]
JAPAN	Rock	1	39	50			28	50	1200	[69]
JAPAN	Rock	1	4	5			5	6	130	[69]
JAPAN	Rock	1	33	34			46	52	1100	[69]
JAPAN	Rock	1	31	30			57	53	1100	[69]
JAPAN	Rock	1	27	37			33	54	1100	[69]
JAPAN	Rock	1	40	50			47	59	1100	[69]
JAPAN	Rock	1	30	30			51	52	980	[69]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JAPAN	Rock	1	27	36			21	39	930	[69]
JAPAN	Rock	1	12	21			35	39	1000	[69]
JAPAN	Rock	1	7	10			22	26	630	[69]
JAPAN	Rock	1	10	14			26	31	720	[69]
JAPAN	Rock	1	17	20			29	30	1000	[69]
JAPAN	Rock	1	19	23			42	50	1200	[69]
JAPAN	Rock	1	14	16			22	23	850	[69]
JAPAN	Rock	1	20	26			32	33	1000	[69]
JAPAN	Rock	1	10	13			27	33	990	[69]
JAPAN	Rock	1	18	23			57	52	1300	[69]
JAPAN	Rock	1	7	11			33	36	530	[69]
JAPAN	Rock	1	12	15			47	48	630	[69]
JAPAN	Rock	1	11	14			73	67	670	[69]
JAPAN	Rock	1	7	9			34	39	820	[69]
JAPAN	Rock	1	12	12			42	51	850	[69]
JAPAN	Rock	1	8	10			23	29	760	[69]
JAPAN	Rock	1	8	12			38	36	630	[69]
JAPAN	Rock	1	25	24			27	54	1100	[69]
JAPAN	Rock	1	39	42			51	57	1000	[69]
JAPAN	Rock	1	79	73			86	96	1100	[69]
JAPAN	Rock	1	59	65			58	86	1100	[69]
JAPAN	Rock	1	54	62			63	71	1300	[69]
JAPAN	Rock	1	30	44			35	53	1000	[69]
JAPAN	Rock	1	7	7			20	21	710	[69]
JAPAN	Rock	1	6	8			18	21	800	[69]
JAPAN	Rock	1	6	8			17	17	710	[69]
JAPAN	Rock	1	6	10			21	24	890	[69]
JAPAN	Rock	1	23	26			34	38	910	[69]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JAPAN	Rock	1	93	120			160	250	1500	[69]
JAPAN	Rock	1	31	31			27	36	610	[69]
JAPAN	Rock	1	100	120			74	130	1800	[69]
JAPAN	Rock	1	2	2			2		70	[69]
JAPAN	Rock	1	10	10			13	16	230	[69]
JAPAN	Rock	1	62	7			7	10	1300	[69]
JAPAN	Rock	1	79	87			130	140	1400	[69]
JAPAN	Rock	1	55	66			35	61	1300	[69]
JAPAN	Rock	1	16	21			77	120	1200	[69]
JAPAN	Rock	1	18	18			28	33	330	[69]
JAPAN	Rock	1	2	2			0.09			[69]
JAPAN	Rock	1	14	13			1			[69]
JAPAN	Rock	1	1				0.25		8	[69]
JAPAN	Rock	1	11	10			0.53		25	[69]
JAPAN	Rock	1	5	4			0.22			[69]
JAPAN	Rock	1	2				0.18			[69]
JAPAN	Rock	1	8	6			0.05		10	[69]
JAPAN	Rock	1	2	1			0.05			[69]
JAPAN	Rock	1	2				0.32			[69]
JAPAN	Rock	1	1				0.19			[69]
JAPAN	Rock	1	5	5			0.065			[69]
JAPAN	Rock	1	2	1			0.23	1		[69]
JAPAN	Rock	1	1	1			0.17			[69]
JAPAN	Rock	1	14	14			0.075		23	[69]
JAPAN	Rock	1	0.48				0.087			[69]
JAPAN	Rock	1	0.25				0.08	3		[69]
JAPAN	Rock	1	2	4			0.17		13	[69]
JAPAN	Rock	1	2	3			0.18		15	[69]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JAPAN	Rock	1	3	3			0.1	2		[69]
JAPAN	Rock	1	1				0.049			[69]
JAPAN	Rock	1	36	34			0.12			[69]
JAPAN	Rock	1	4	4			0.048			[69]
JAPAN	Rock	1	1				1	2	23	[69]
JAPAN	Rock	1	2	1			1	2	33	[69]
JAPAN	Rock	1	54	49			0.35		10	[69]
JAPAN	Rock	1	1	1			3		49	[69]
JAPAN	Rock	1	4	3			0.34	1	10	[69]
JAPAN	Rock	1	6	5			0.14			[69]
JAPAN	Rock	1	8	6			2	1	10	[69]
JAPAN	Rock	1	1	1			1	2	18	[69]
JAPAN	Rock	1	15	14			0.46			[69]
JAPAN	Rock	1	13	12			0.29			[69]
JAPAN	Rock	1	20	20			0.2		9	[69]
JAPAN	Rock	1	2	2			2		42	[69]
JAPAN	Rock	1	1				1		9	[69]
JAPAN	Rock	1	23	20			1	3	16	[69]
JAPAN	Rock	1	0.39				0.18			[69]
JAPAN	Rock	1	29	26			0.36			[69]
JAPAN	Rock	1	1				0.17			[69]
JAPAN	Rock	1	19	20			19	28	670	[69]
JAPAN	Rock	1	6	7			7	12	260	[69]
JAPAN	Rock	1	22	20			28	32	680	[69]
JAPAN	Rock	1	20	20			31	39	920	[69]
BANGLADESH	Rock	11		25			55		228	[113]
PAKISTAN	Rock	1		13			23		169	[114]

Activity concentrations minerals other than uranium -raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
PAKISTAN	Rock	1		14			25		157	[114]
PAKISTAN	Rock	1		14			27		157	[114]
PAKISTAN	Rock	1		17			29		223	[114]
PAKISTAN	Rock	1		36			25		45	[114]
PAKISTAN	Rock	1		10			18		132	[114]
ITALY	Rock	6		160				190	1420	[115]
ITALY	Rock	15		210				250	1660	[115]
ITALY	Rock	26		160				200	1640	[115]
GREECE	Rock	1		39					310	[116]
GREECE	Rock	1		135					710	[116]
GREECE	Rock	1		15					20	[116]
GREECE	Rock	1		21					250	[116]
GREECE	Rock	1		6					20	[116]
GREECE	Rock	1		14					110	[116]
GREECE	Rock	1		36					490	[116]
IRAN	Rock	1		247			208		1220	[83]
EGYPT	Rock	1		7			10		590	[117]
EGYPT	Rock	1		7			12		472	[117]
EGYPT	Rock	1		5			9		374	[117]
EGYPT	Rock	1		6			8		307	[117]
EGYPT	Rock	1		5			8		347	[117]
EGYPT	Rock	1		5			7		281	[117]
EGYPT	Rock	1		24			31		388	[117]
EGYPT	Rock	1		16			21		309	[117]
EGYPT	Rock	1		15			22		353	[117]
EGYPT	Rock	1		19			25		365	[117]
EGYPT	Rock	1		17			21		340	[117]

Activity concentrations minerals other than uranium -raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Rock	1		12			17		271	[117]
EGYPT	Rock	1		21			26		383	[117]
EGYPT	Rock	1		4			5		358	[117]
EGYPT	Rock	1		5			9		375	[117]
EGYPT	Rock	1		5			8		418	[117]
EGYPT	Rock	1		23			20		375	[117]
EGYPT	Rock	1		16			12		408	[117]
EGYPT	Rock	1		16			16		351	[117]
EGYPT	Rock	1		71			22		340	[117]

EXTRACTION OF RARE EARTH FROM MONAZITE

Activity concentrations in mineral of monazite – raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Monazite	1	30340				251600			[39]
AUSTRALIA	Monazite	1	30000				240000			[39]
AUSTRALIA	Monazite	1	19000				230000			[39]
AUSTRALIA	Monazite	1					210000			[39]
AUSTRALIA	Monazite	2	36000				240000			[39]
AUSTRALIA	Monazite	2	26000				240000			[39]
AUSTRALIA	Monazite	2	45000				130000			[39]
AUSTRALIA	Monazite	1	40000				230000			[39]
AUSTRALIA	Monazite	2					225000			[39]
AUSTRALIA	Monazite	1					180000			[39]
AUSTRALIA	Monazite	2	18000				145000			[39]
BRAZIL	Monazite	1	22000							[39]
BRAZIL	Monazite	1	31000							[39]
CHINA	Monazite	2	55000				215000			[39]
CHINA	Monazite	1					140000			[39]
CHINA	Monazite	2					11000			[39]
CHINA	Monazite	2	5455				30000			[118]
CHINA	Residuo	2	4981				13980			[118]
NORTH KOREA	Monazite	1	19000				163000			[39]
INDIA	Monazite	2	37000				317000			[39]
INDIA	Monazite	2					340000			[39]
INDIA	Monazite	1					320000			[39]
INDIA	Monazite	1					340000			[39]
INDIA	Monazite	1	37000				290000			[39]
INDIA	Monazite	2					325000			[39]
INDIA	Monazite	1	28000				350000			[39]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
INDIA	Monazite	1	37000				320000			[39]
INDIA	Monazite	1	38000				370000			[39]
INDIA	Monazite	1	39000				340000			[39]
INDIA	Monazite	1	40000				230000			[39]
INDIA	Monazite	2					320000			[39]
INDIA	Monazite	2	37000				305000			[39]
INDIA	Monazite	2	35000				375000			[39]
SOUTH KOREA	Monazite	1	47000				205000			[39]
USA	Monazite	1					140000			[39]
USA	Monazite	1	160000				120000			[39]
IAEA	Monazite	2	35000				340000			[39]
IAEA	Monazite	2	21500				404000			[39]
IAEA	Monazite	2	21500				420000			[39]
IAEA	Monazite	1	26000				210000			[39]
IAEA	Monazite	2	175000				380000			[39]
IAEA	Monazite	1					295000			[39]
IAEA	Monazite	2	50000				235000			[39]
IAEA	Monazite	2	20000				215000			[39]
IAEA	Monazite	2					610000			[39]
IAEA	Monazite	2					270000			[39]
IAEA	Monazite	2	23000				154000			[39]
IAEA	Monazite	2	37000				325000			[39]
USA	Monazite	2	23000				195000			[6]
AUSTRALIA	Monazite	2	18000				145000			[119]
INDIA	Monazite	1	22000				295500			[94]
INDIA	Monazite	1	21500				312600			[94]
INDIA	Monazite	1	22400				292000			[94]
INDIA	Monazite	1	22000				325000			[94]
INDIA	Monazite	1	22500				312600			[94]

Activity concentrations in mineral of monazite – raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
INDIA	Monazite	1	21500				305000			[94]
EGYPT	Monazite	1	58312				228835		16821	[120]
EGYPT	Monazite	1	60956				212707		18988	[120]
EGYPT	Monazite	1	53296				204929		15227	[120]
EGYPT	Monazite	1	53871				231924		19570	[120]
EGYPT	Monazite	1	59273				208428		17205	[120]
AUSTRALIA	Monazite	1	20000				149000			[121]
AUSTRALIA	Monazite	1	17000				100000			[121]
AUSTRALIA	Monazite	1	22000				144000			[121]
AUSTRALIA	Monazite	1	6400				24000			[121]
AUSTRALIA	Monazite	1		23000	1900			276000		[122]
EGYPT	Monazite	8	40580				182425		11300	[106]

EXTRACTION OF ALUMINIUM FROM BAUXITE

Activity concentrations in mineral of bauxite – raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Bauxite	1	97	91			129		2	[4]
AUSTRALIA	Bauxite	2	4505				718		305	[3]
HUNGARY	Bauxite	46		419			256		47	[59]
USA	Bauxite	1	252				204			[123]
AUSTRALIA	Bauxite	1	70				400			[124]
AUSTRALIA	Bauxite	1	80				440			[124]
AUSTRALIA	Bauxite	1	410				760			[124]
EGYPT	Bauxite (Guinea)	1		46			151			[125]
EGYPT	Bauxite (Guinea)	1		44			245			[125]
EGYPT	Bauxite (Guinea)	1		49			272			[125]
EGYPT	Bauxite (Guinea)	1		66			239			[125]
EGYPT	Bauxite (India)	1		29			518			[125]
EGYPT	Bauxite (India)	1		67			508			[125]
EGYPT	Bauxite (India)	1		112			444			[125]
EGYPT	Bauxite (India)	1		75			525			[125]
EGYPT	Bauxite (India)	1		68			502			[125]
NETHERLANDS	Bauxite (Cina)	1	460	310			370			[74]

Activity concentrations in mineral of bauxite – raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
NETHERLANDS	Bauxite (Guyana)	1	80	50			230			[74]
INDONESIA	Bauxite	1	67	56			170	160	27	[67]
AUSTRALIA	Bauxite	1	69	57			85	82	28	[67]

Activity concentrations for extraction of aluminium from bauxite – products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Aluminum	1		4			11			[125]
EGYPT	Aluminum	1		9			10			[125]
EGYPT	Aluminum	1		5			3			[125]
EGYPT	Aluminum	1		3			5			[125]
EGYPT	Aluminum	1		7			7			[125]

Activity concentrations for extraction of aluminium from bauxite – residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Sludge	1	104	90			118		15	[4]
ITALY	Residue	1	9	0.1			0.5		3	[4]
ITALY	Residue	1	10	0.2			0.5		1	[4]
AUSTRALIA	Sludge	2		326			1129		30	[97]
AUSTRALIA	Residue	1		48			389		52	[97]
AUSTRALIA	Sludge	2	1550				1550			[3]
GREECE	Sludge	1	149	379			472	419	21	[126]
AUSTRALIA	Sludge	1	400	310	310			1150	350	[127]
AUSTRALIA	Sludge	2	375				1450		150	[126]
JAMAICA	Sludge	1		370			328		265	[126]
JAMAICA	Sludge	1		1047			350		335	[126]

Activity concentrations for extraction of aluminium from bauxite – residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CHINA	Sludge	1		477			705		153	[126]
HUNGARY	Sludge	58		347			283		48	[59]
USA	Sludge	1	278				185			[123]
USA	Sludge	1	204				463			[123]
AUSTRALIA	Sludge	1	200				1190			[124]
AUSTRALIA	Residue	1	20				390			[124]
AUSTRALIA	Sludge	1	190				1050			[124]
AUSTRALIA	Residue	1	40				380			[124]
AUSTRALIA	Sludge	1	660				1800			[124]
AUSTRALIA	Residue	1	170				710			[124]
EGYPT	Residue	1		9			13			[125]
EGYPT	Residue	1		6			10			[125]
EGYPT	Residue	1		11			12			[125]
EGYPT	Residue	1		11			5			[125]
EGYPT	Residue	1		8			15			[125]
EGYPT	Residue	1		4			7			[125]
EGYPT	Residue	1		11			9			[125]
EGYPT	Residue	1		8			15			[125]
EGYPT	Residue	1		10			12			[125]

COAL-FIRED POWER PLANTS

Activity concentrations for coal-fired power plants – raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALIA	Coal	16	16				11		70	[4]
ITALIA	Coal	34	6				4		39	[4]
ITALIA	Coal	25	30				26		28	[4]
ITALIA	Coal	16	6				7		49	[4]
ITALIA	Coal	14	23				14		737	[4]
ITALIA	Coal	8	5				4		45	[4]
ITALIA	Coal	2	31				37		275	[4]
ITALIA	Coal	6	10				9		62	[4]
ITALIA	Coal	1	23				18		218	[128]
ITALIA	Coal	2	22				19		100	[128]
ITALIA	Coal	2	32				35		31	[128]
ITALIA	Coal	1	25				14		65	[128]
ITALIA	Coal	1	9				10		47	[128]
AUSTRALIA	Coal	2	29				45		285	[119]
AUSTRALIA	Coal	2	13				10		55	[119]
AUSTRALIA	Coal	2	15				15		25	[119]
AUSTRALIA	Coal	1	5				10		10	[119]
AUSTRALIA	Coal	1	25				45		30	[119]
AUSTRALIA	Coal	1	26	26	26	61				[119]
GREECE	Coal	3		407			74		411	[129]
GREECE	Coal	5		33			15		96	[129]
GREECE	Coal	5		174			16		67	[129]
GREECE	Coal	5		85			15		78	[129]
GREECE	Coal	5		204			26		196	[129]
SPAGNA	Coal	2		63		67	19		113	[130]
SPAGNA	Coal	2		12		72	10		82	[130]
SPAGNA	Coal	9		23		36	23		59	[130]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SPAGNA	Coal	2		36		27	32		390	[130]
SPAGNA	Coal	4		4		5	6		22	[130]
SPAGNA	Coal	2		56		65	21		77	[130]
SPAGNA	Coal	4		18		47	20		62	[130]
SPAGNA	Coal	2		34		118	33		334	[130]
SPAGNA	Coal	2		5		14	5		28	[130]
GREECE	Coal	5		314				21	181	[131]
GREECE	Coal	5		321				21	191	[131]
GREECE	Coal	5		83				15	78	[131]
GREECE	Coal	5		175				16	68	[131]
USA	Coal	1		9				4		[131]
USA	Coal	1		16				7		[131]
FRANCIA	Coal	2		40			5		17	[131]
ITALIA	Coal	2		10			93			[131]
ITALIA	Coal	1	252							[131]
GREECE	Coal	2	281	175	162			13	79	[132]
GREECE	Coal	2	173	105	110			18	113	[132]
GREECE	Coal	2	345	160	160			13	71	[132]
GREECE	Coal	2	171	92	102			29	168	[132]
GREECE	Coal	26	106	89			13	13	68	[133]
GREECE	Other raw materials	29	58	47			14	14	103	[133]
INDIA	Coal	1	37				48		124	[134]
INDIA	Coal	1	38				53		155	[134]
INDIA	Coal	1	36				48		124	[134]
INDIA	Coal	1	25				39		124	[134]
INDIA	Coal	1	49				55		124	[134]
BRASILE	Coal	2	356	321	808			22	191	[135]
BRASILE	Coal	2	107	98	340			58	556	[135]
BRASILE	Coal	2	32	31	75			26	267	[135]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Coal	53	243	266	134			18	108	[136]
INDIA	Coal	1		81					200	[137]
INDIA	Coal	1		22					104	[137]
INDIA	Coal	1		15					70	[137]
INDIA	Coal	1		30					100	[137]
INDIA	Coal	1		44					115	[137]
INDIA	Coal	1		33					63	[137]
INDIA	Coal	1		19					123	[137]
INDIA	Coal	1		15					7	[137]
INDIA	Coal	1		19					15	[137]
INDIA	Coal	1		26					152	[137]
CINA	Coal	30		17					24	[138]
FILIPPINE	Coal	1	3	12			3	14	80	[139]
FILIPPINE	Coal	1	3	2			3	2	14	[139]
FILIPPINE	Coal	1	6	7			8	6	31	[139]
FILIPPINE	Coal	1	14	10			16	12	52	[139]
SPAGNA	Coal	1		304					106	[140]
ZAMBIA	Coal	1		45			54		168	[141]
ZAMBIA	Coal	1		45			58		186	[141]
ZAMBIA	Coal	1		45			44		186	[141]
ZAMBIA	Coal	1		34			43			[141]
ZAMBIA	Coal	1		34			39			[141]
ZAMBIA	Coal	1		39			52		53	[141]
ZAMBIA	Coal	1		51			64		61	[141]
ZAMBIA	Coal	1		88			120		104	[141]
ZAMBIA	Coal	1		51			56		65	[141]
ZAMBIA	Coal	1		40			52			[141]
ZAMBIA	Coal	1		49			62		382	[141]
ZAMBIA	Coal	1		45			50		170	[141]
ZAMBIA	Coal	1		37			44			[141]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ZAMBIA	Coal	1		40			52			[141]
ZAMBIA	Coal	1		40			50			[141]
ZAMBIA	Coal	1		63			79			[141]
SPAGNA	Coal	12	26				22		300	[142]
SPAGNA	Coal	20	31				23		295	[142]
SPAGNA	Coal	4	16				18		24	[142]
SPAGNA	Coal	1	86				16		249	[142]
TURKEY	Coal	1		156			19		344	[143]
TURKEY	Coal	1		13			16		395	[143]
TURKEY	Coal	1		20			25		400	[143]
TURKEY	Coal	1		34			43		431	[143]
TURKEY	Coal	1		21			29		372	[143]
TURKEY	Coal	1		49			61		665	[143]
TURKEY	Coal	1		46			52		466	[143]
TURKEY	Coal	1		15			20		365	[143]
TURKEY	Coal	1		19			23		390	[143]
TURKEY	Coal	1		17			17		396	[143]
TURKEY	Coal	1		16			19		400	[143]
TURKEY	Coal	1		22			20		389	[143]
TURKEY	Coal	1		37			54		584	[143]
TURKEY	Coal	1		164			280		484	[143]
TURKEY	Coal	1		105			119		1100	[143]
TURKEY	Coal	1		45			64		577	[143]
TURKEY	Coal	1		60			72		724	[143]
TURKEY	Coal	1		19			24		421	[143]
AUSTRALIA	Coal	1	28	24	30	28	27	64	72	[144]
AUSTRALIA	Coal	1	26	21	33	18	29	11	112	[144]
AUSTRALIA	Coal	1	22	19	20	16	17	48	81	[144]
AUSTRALIA	Coal	1	21					23	67	[144]
AUSTRALIA	Coal	1	25					27	140	[144]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Coal	1	21					20	63	[144]
AUSTRALIA	Coal	1	47					69	23	[144]
AUSTRALIA	Coal	1	9					11	43	[144]
TURKEY	Coal	1		15			11		123	[145]
GREECE	Coal	1	332	350	357		24		207	[146]
GREECE	Coal	1	248	331			23		198	[146]
GREECE	Coal	1	291	309	326		20		165	[146]
GREECE	Coal	1		346			19		152	[146]
GREECE	Coal	1	309	344	352		20		148	[146]
GREECE	Coal	1	352	395	409		21		169	[146]
POLAND	Coal	2	20	16	20		13		134	[147]
POLAND	Coal	3	21	15	21		12		106	[147]
POLAND	Coal	3	30	23	26		18		150	[147]
STATI UNITI	Coal	12	9	8	10			6	155	[148]
STATI UNITI	Coal	3	31	24	25			20	52	[148]
POLAND	Coal	2	38				30		294	[39]
GREECE	Coal	2	385	167						[39]
GREECE	Coal	2	323	144						[39]
UNITED KINGDOM	Coal	1	15	16			14		101	[149]
UNITED KINGDOM	Coal	1	13	11			7		90	[149]
UNITED KINGDOM	Coal	1	21	20			16		170	[149]
UNITED KINGDOM	Coal	1	19	17			11		115	[149]
UNITED KINGDOM	Coal	1	14	13			10		137	[149]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
UNITED KINGDOM	Coal	1	18	17			10		162	[149]
UNITED KINGDOM	Coal	1	136	18			13		202	[149]
UNITED KINGDOM	Coal	1	128	14			13		240	[149]
UNITED KINGDOM	Coal	1	30	26			17		182	[149]
UNITED KINGDOM	Coal	1	10	8			12		108	[149]
UNITED KINGDOM	Coal	1	17	18			9		176	[149]
UNITED KINGDOM	Coal	1	9	12			11		147	[149]
UNITED KINGDOM	Coal	1	12	11			8		138	[149]
UNITED KINGDOM	Coal	1	8	9			8		104	[149]
UNITED KINGDOM	Coal	1	10	10			10		104	[149]
UNITED KINGDOM	Coal	1	13	16			16		198	[149]
UNITED KINGDOM	Coal	1	14	16			12		119	[149]
UNITED KINGDOM	Coal	1	17	22			19		314	[149]
UNITED KINGDOM	Coal	1	10	9			7		55	[149]
UNITED KINGDOM	Coal	1	9	10			11		129	[149]
CANADA	Coal	1	12				13		72	[150]

Activity concentrations for coal-fired power plants – raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CANADA	Coal	1	12				8		26	[151]
NIGERIA	Coal	1	17				6		8	[6]
SERBIA	Coal	2	49				18			[152]
SERBIA	Coal	1	33				14			[152]
TURKEY	Coal	1	16	18			9			[153]
TURKEY	Coal	1	18	11			6		14	[153]
TURKEY	Coal	1	3	4			2		57	[153]
TURKEY	Coal	1	20	1			8		38	[153]
TURKEY	Coal	1	4	6			2		41	[153]
TURKEY	Coal	1	12	34			20		6	[153]
TURKEY	Coal	1	8	24			12			[153]
GREECE	Coal	2	510	530			20		170	[154]
INDIA	Coal	1	37				48		124	[155]
INDIA	Coal	1	38				53		155	[155]
INDIA	Coal	1	36				48		124	[155]
INDIA	Coal	1	25				39		124	[155]
INDIA	Coal	1	50				55		124	[155]
INDIA	Coal	30		24			395		83	[156]
CINA	Coal	12		26			37		100	[157]
GREECE	Coal	35		314				181	181	[131]
GREECE	Coal	35		321				191	191	[131]
TURKEY	Coal	1	236	82			49		97	[158]
TURKEY	Coal	1	37	12			3		26	[158]
TURKEY	Coal	1	56	14			5		19	[158]
TURKEY	Coal	1	11	11			4		58	[158]
TURKEY	Coal	1	52	20			45		34	[158]
TURKEY	Coal	1	57	19			48		42	[158]
TURKEY	Coal	1	12	9			13		36	[158]
TURKEY	Coal	1	74	54			30		78	[158]
TURKEY	Coal	1	42	11			40		360	[158]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURKEY	Coal	1	8	6			7		24	[158]
TURKEY	Coal	1	64	7			45		61	[158]
TURKEY	Coal	1	51	5			70		41	[158]
TURKEY	Coal	1	8	27			13		45	[158]
TURKEY	Coal	1	22	90			11		28	[158]
TURKEY	Coal	1	135	55			28		77	[158]
TURKEY	Coal	1	20	15			40		70	[158]
TURKEY	Coal	1	36	8			51		19	[158]
TURKEY	Coal	1	37	15			8		26	[158]
TURKEY	Coal	1	28	11			43		191	[158]
TURKEY	Coal	1	118	48			15		57	[158]
TURKEY	Coal	1	51	18			79		41	[158]
TURKEY	Coal	1	96	69			35		55	[158]
TURKEY	Coal	1	136	66			44		127	[158]
TURKEY	Coal	1	81	14			60		206	[158]
TURKEY	Coal	1	48	12			50		78	[158]
TURKEY	Coal	1	20	58			24		70	[158]
TURKEY	Coal	1	17	6			33		17	[158]
TURKEY	Coal	1	28	27			12		38	[158]
TURKEY	Coal	1	27	16			28		78	[158]
TURKEY	Coal	1	28	12			24		26	[158]
TURKEY	Coal	1	148	62			8		32	[158]
TURKEY	Coal	1	50	18			35		192	[158]
TURKEY	Coal	1	30	36			32		65	[158]
TURKEY	Coal	1	12	32			8		24	[158]
TURKEY	Coal	1	103	57			11		53	[158]
TURKEY	Coal	1	57	28			8		39	[158]
TURKEY	Coal	1	78	32			17		55	[158]
TURKEY	Coal	1	296	130			5		26	[158]
TURKEY	Coal	1	39	15			4		43	[158]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CANADA	Coal	1	27	30	20		20			[159]
CANADA	Coal	1	35	40	30		20			[159]
TURKEY	Coal	1	183	328			5		26	[160]
TURKEY	Coal	1	220	363			4		34	[160]
TURKEY	Coal	1	171	330			4		15	[160]
TURKEY	Coal	1	171	320			4		19	[160]
TURKEY	Coal	1	183	385			3		9	[160]
TURKEY	Coal	1	293	434			4		9	[160]
TURKEY	Coal	1	293	432			5		11	[160]
TURKEY	Coal	1		350					11	[161]
TURKEY	Coal	1		260					14	[161]
TURKEY	Coal	1		240					13	[161]
TURKEY	Coal	1		410					14	[161]
TURKEY	Coal	1		280					15	[161]
TURKEY	Coal	1		370					15	[161]
TURKEY	Coal	1		850					12	[161]
TURKEY	Coal	1		320					13	[161]
TURKEY	Coal	1		260					15	[161]
TURKEY	Coal	1		440					67	[161]
TURKEY	Coal	1		180					12	[161]
TURKEY	Coal	1		340					10	[161]
TURKEY	Coal	1		290					12	[161]
TURKEY	Coal	1		370					14	[161]
TURKEY	Coal	1		350					14	[161]
TURKEY	Coal	1		440					16	[161]
TURKEY	Coal	1		330					16	[161]
TURKEY	Coal	1		370					19	[161]
TURKEY	Coal	1		440					18	[161]
TURKEY	Coal	1		370					19	[161]
TURKEY	Coal	1		520					19	[161]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Coal	1	422	241			1			[62]
GREECE	Coal	1	296	130			0.44			[62]
GREECE	Coal	1		118			1			[62]
GREECE	Coal	1	1306	414			1			[62]
GREECE	Coal	1		200			1			[62]
GREECE	Coal	40	306	346	361		19		173	[162]
GREECE	Coal	1		880						[163]
GREECE	Coal	1		620						[163]
GREECE	Coal	1		480						[163]
GREECE	Coal	1		380						[163]
GREECE	Coal	1		510						[163]
GREECE	Coal	1		420						[163]
GREECE	Coal	1		270						[163]
GREECE	Coal	1		200						[163]
USA	Coal	1	63	37						[86]

Activity concentrations for coal-fired power plants – residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Bottom ash	13	88				70		352	[4]
ITALY	Fly ash	13	115				89		452	[4]
ITALY	Bottom ash	7	108				86		465	[4]
ITALY	Fly ash	12	135				93		489	[4]
ITALY	Bottom ash	7	119				106		489	[4]
ITALY	Fly ash	7	123				104		445	[4]
ITALY	Bottom ash	1	115				67		1046	[128]
ITALY	Fly ash	1	86				56		820	[128]
AUSTRALIA	Fly ash	15		96			170		204	[97]
AUSTRALIA	Fly ash	1		70			107		537	[97]
AUSTRALIA	Fly ash	1		81			133		540	[97]
AUSTRALIA	Fly ash	1		104			163		596	[97]
AUSTRALIA	Fly ash	1		122			167		581	[97]
AUSTRALIA	Fly ash	1		56			93		655	[97]
AUSTRALIA	Fly ash	1		93			130		699	[97]
AUSTRALIA	Fly ash	1		104			141		677	[97]
AUSTRALIA	Fly ash	1		107			148		677	[97]
AUSTRALIA	Fly ash	1		144			181		374	[97]
AUSTRALIA	Fly ash	1		159			196		307	[97]
AUSTRALIA	Fly ash	1		189			237		266	[97]
AUSTRALIA	Fly ash	1		196			244		266	[97]
AUSTRALIA	Fly ash	1		130			255		59	[97]
AUSTRALIA	Fly ash	1		178			315		89	[97]
AUSTRALIA	Fly ash	1		33			67		104	[97]
AUSTRALIA	Fly ash	1		33			63		100	[97]
AUSTRALIA	Fly ash	1		107			163		548	[97]
AUSTRALIA	Fly ash	1		118			170		555	[97]
AUSTRALIA	Fly ash	1		126			181		607	[97]
AUSTRALIA	Fly ash	2		115	165		150		650	[119]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Fly ash	2		20	15		15		110	[119]
AUSTRALIA	Fly ash	2		95	70		105		225	[119]
AUSTRALIA	Fly ash	2		165	168		190		115	[119]
AUSTRALIA	Fly ash	2		120	140		180		200	[119]
AUSTRALIA	Bottom ash	2		100	8		110		600	[119]
AUSTRALIA	Bottom ash	2		60	20		103		60	[119]
AUSTRALIA	Bottom ash	2		110	40		120		80	[119]
GREECE	Fly ash	1	640	500						[129]
GREECE	Fly ash	1		600			49		218	[129]
GREECE	Fly ash	1	340	192						[129]
GREECE	Fly ash	1	481	337						[129]
GREECE	Fly ash	1		385						**196**
GREECE	Fly ash	1		422						**196**
GREECE	Fly ash	1		307						**196**
GREECE	Fly ash	1		392						**196**
GREECE	Fly ash	1	60	747			67			**197**
CHINA	Fly ash	1	200	240	930	1700	70	130	265	**35**
SPAIN	Fly ash	1		190		257	74		310	[130]
SPAIN	Fly ash	1		158		505	154		250	[130]
SPAIN	Fly ash	1		94		416	93		1109	[130]
SPAIN	Fly ash	1		48		270	44		253	[130]
SPAIN	Bottom ash	1		149		57	66		238	[130]
SPAIN	Bottom ash	1		144		9	138		224	[130]
SPAIN	Bottom ash	1		86		24	89		1077	[130]
SPAIN	Bottom ash	1		23		33	20		135	[130]
GREECE	Fly ash	5		807				55	449	[131]
GREECE	Fly ash	5		845				56	502	[131]
GREECE	Bottom ash	5		546				44	406	[131]
GREECE	Bottom ash	5		587				44	423	[131]
GREECE	Fly ash	5		261				45	251	[131]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Fly ash	5		600				49	217	[131]
GREECE	Bottom ash	5		114				24	137	[131]
GREECE	Bottom ash	5		363				36	200	[131]
USA	Fly ash	1		161				84		[131]
USA	Fly ash	1		137				67		[131]
FRANCE	Fly ash	1		370			40		220	[131]
FRANCE	Fly ash	1		520						[131]
ITALY	Fly ash	2		56			333			[131]
ITALY	Fly ash	1	999							[131]
GREECE	Fly ash	2	642	463	352			40	237	[132]
GREECE	Fly ash	2	358	257	230			51	313	[132]
GREECE	Fly ash	2	793	592	379			50	270	[132]
GREECE	Fly ash	2	274	153	140			60	367	[132]
INDIA	Fly ash	1	117				146		334	[134]
INDIA	Fly ash	1	120				147		231	[134]
INDIA	Fly ash	1	115				144		234	[134]
INDIA	Fly ash	1	117				143		210	[134]
INDIA	Fly ash	1	99				142		308	[134]
INDIA	Fly ash	1	110				147		226	[134]
INDIA	Fly ash	1	118				136		308	[134]
INDIA	Fly ash	1	108				136		306	[134]
INDIA	Fly ash	1	114				126		298	[134]
INDIA	Fly ash	1	108				139		319	[134]
BRAZIL	Fly ash	1	64	62	150			52	534	[135]
BRAZIL	Fly ash	1	321	294	1020			174	1668	[135]
BRAZIL	Fly ash	1	1424	1284	3232			88	764	[135]
BRAZIL	Fly ash	1	2222	1990	4504			60	626	[135]
GREECE	Fly ash	1	340	192,4						[136]
GREECE	Fly ash	1	481	336,7						[136]
GREECE	Fly ash	1	640	500						[136]

Activity concentrations for coal-fired power plants – residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Scale	1	873	451						[136]
GREECE	Scale	1	599	355						[136]
GREECE	Fly ash	36	356	366	275			50	297	[136]
INDIA	Fly ash	1		159					340	[137]
INDIA	Fly ash	1		104					326	[137]
INDIA	Fly ash	1		70					348	[137]
INDIA	Fly ash	1		866						[137]
INDIA	Fly ash	1		759					56	[137]
INDIA	Fly ash	1		762						[137]
CHINA	Bottom ash	36		100					132	[138]
CHINA	Fly ash	38		140					178	[138]
PHILIPPINES	Bottom ash	1	30	29,9			42	37	260	[139]
PHILIPPINES	Bottom ash	1	58	52			73	56	204	[139]
PHILIPPINES	Fly ash	1	268	51			156	65	198	[139]
PHILIPPINES	Bottom ash	1	55	107			61	59	217	[139]
PHILIPPINES	Fly ash	1	83	110			63	67	230	[139]
PHILIPPINES	Bottom ash	1	100	83			81	67	401	[139]
PHILIPPINES	Fly ash	1	132	131			87	88	354	[139]
USA	Fly ash	1		185				70		[164]
USA	Fly ash	1		155				93		[164]
USA	Fly ash	1		141				96		[164]
USA	Fly ash	1		104				67		[164]
USA	Fly ash	1		178				100		[164]
USA	Fly ash	1		78				115		[164]
USA	Fly ash	1		48				30		[165]
USA	Fly ash	1						48		[165]
USA	Fly ash	1		85				81		[165]
USA	Fly ash	1		159				107		[165]
USA	Fly ash	5		85				115		[165]
USA	Fly ash	12		115				255		[165]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Fly ash	1		59				99,9		[165]
SPAIN	Fly ash	1		246					107	[140]
SPAIN	Bottom ash	1		168					90	[140]
ZAMBIA	Fly ash	1		99			133			[141]
ZAMBIA	Bottom ash	1		109			109			[141]
ZAMBIA	Fly ash	1		96			111			[141]
ZAMBIA	Bottom ash	1		97			99			[141]
ZAMBIA	Ash	1		262			356			[141]
SPAIN	Fly ash	68	91				89		1059	[142]
SPAIN	Fly ash	1	90				91		1039	[141]
AUSTRALIA	Fly ash	1	114	110	150	85	130	78	434	[144]
AUSTRALIA	Fly ash	1	78	68	85	58	85	67	170	[144]
AUSTRALIA	Fly ash	1	64	59	60	33	57	58	263	[144]
AUSTRALIA	Fly ash	1	107					126	430	[144]
AUSTRALIA	Fly ash	1	89					113	615	[144]
AUSTRALIA	Fly ash	1	81					77	220	[144]
AUSTRALIA	Fly ash	1	102					138	430	[144]
AUSTRALIA	Fly ash	1	76					57	350	[144]
INDIA	Fly ash	1	96				109		301	[166]
INDIA	Fly ash	1	92				105		280	[166]
INDIA	Fly ash	1	96				109		290	[166]
INDIA	Fly ash	1	93				101		267	[166]
INDIA	Fly ash	1	85				108		272	[166]
INDIA	Fly ash	1	96				98		355	[166]
INDIA	Fly ash	1	115				137		345	[166]
INDIA	Fly ash	1	95				104		288	[166]
INDIA	Fly ash	1	126				141		365	[166]
INDIA	Fly ash	1	99				118		326	[166]
TURKEY	Fly ash	1		149			58		94	[145]
TURKEY	Residue	1		50			25		376	[145]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Fly ash	1		873			57		489	[146]
GREECE	Fly ash	1	962	943	1192		52		425	[146]
GREECE	Fly ash	1	899	889	1028		50		405	[146]
GREECE	Fly ash	1	1051	1028	1322		52		403	[146]
GREECE	Fly ash	1	944	900	1120		55		485	[146]
GREECE	Fly ash	1		794			53		516	[146]
GREECE	Bottom ash	1		583			43		433	[146]
GREECE	Bottom ash	1	675	654	273		45		417	[146]
GREECE	Bottom ash	1	677	661	285		41		334	[146]
GREECE	Bottom ash	1		722			44		367	[146]
GREECE	Bottom ash	1	715	743	289		47		419	[146]
GREECE	Bottom ash	1	658	611	253		44		460	[146]
GREECE	Fly ash	12	771	863	538		56		508	[146]
GREECE	Fly ash	15	794	896	539		57		520	[146]
GREECE	Fly ash	27	859	876	1068		54		466	[146]
GREECE	Fly ash	16	934	893	1717		53		444	[146]
GREECE	Fly ash	13	1053	987	2119		53		387	[146]
GREECE	Fly ash	4	934	739	2404		49		487	[146]
GREECE	Fly ash	29	870	885	1167		54		463	[146]
GREECE	Fly ash	22	1001	963	1848		54		441	[146]
GREECE	Fly ash	15	1155	1067	2252		55		424	[146]
GREECE	Fly ash	3	906	654	2280		54		594	[146]
POLAND	Fly ash	3	116	86	112		66		608	[147]
POLAND	Residue	3	58	56	26		46		432	[147]
POLAND	Fly ash	3	131	93	148		74		611	[147]
POLAND	Residue	3	57	53	23		45		398	[147]
POLAND	Fly ash	3	156	104	183		84		721	[147]
POLAND	Residue	3	83	78	59		67		571	[147]
USA	Fly ash	9	70	85	52			63	300	[148]
USA	Bottom ash	7	56	70	21			56	252	[148]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Fly ash	6	130	107	81			89	233	[148]
USA	Bottom ash	10	104	93	31			78	229	[148]
USA	Ash	7	133	111	104			93	229	[148]
USA	Fly ash	2	200	122	159			100	259	[148]
USA	Fly ash	2	252	170	370			130	270	[148]
USA	Fly ash	2	370	196	518			148	278	[148]
USA	Fly ash	2	444	218	629			155	259	[148]
POLAND	Fly ash	2	97				74		728	[39]
GREECE	Fly ash	2	574	343						[39]
CANADA	Fly ash	1	106				114		618	[150]
CANADA	Fly ash	1	124				133		722	[150]
CANADA	Fly ash	1	124				133		722	[150]
CANADA	Fly ash	1	92				58		204	[151]
CANADA	Bottom ash	1	91				61		245	[151]
SERBIA	Ash	2	107				74			[152]
SERBIA	Ash	1	55				38			[152]
SERBIA	Fly ash	2	137				99			[152]
SERBIA	Fly ash	1	75				34			[152]
SERBIA	Residue	2	72				45			[152]
SERBIA	Residue	1	51				14			[152]
GREECE	Bottom ash	2	747	799			51		432	[154]
GREECE	Fly ash	2	992	1024			60		443	[154]
GREECE	Fly ash	2	1073	1060			58		449	[154]
INDIA	Ash	1	117				146		403	[155]
INDIA	Ash	1	1202				147		279	[155]
INDIA	Ash	1	115				144		282	[155]
INDIA	Ash	1	117				143		267	[155]
INDIA	Ash	1	99				142		372	[155]
INDIA	Ash	1	110				147		273	[155]
INDIA	Ash	1	118				136		372	[155]

Activity concentrations for coal-fired power plants – residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
INDIA	Ash	1	108				136		372	[155]
INDIA	Ash	1	114				126		360	[155]
INDIA	Ash	1	108				139		384	[155]
INDIA	Ash	1	107				140		369	[155]
INDIA	Ash	1	108				146		415	[155]
INDIA	Ash	1	114				141		403	[155]
INDIA	Ash	1	105				1302		360	[155]
INDIA	Fly ash	30		78			126		374	[156]
INDIA	Residue	30		89			137		378	[156]
CHINA	Fly ash	26		112			148		386	[157]
CHINA	Bottom ash	12		93			105		271	[157]
GREECE	Fly ash	35		807				55	449	[131]
GREECE	Fly ash	35		845				56	587	[131]
GREECE	Bottom ash	35		546				44	406	[131]
GREECE	Bottom ash	35		587				44	423	[131]
GREECE	Fly ash	1	858	385			7			[62]
GREECE	Fly ash	1	529	307			1			[62]
GREECE	Fly ash	1	492	392			7			[62]
EGYPT	Fly ash	3		102						[167]
GREECE	Fly ash	350	964	904	1158		52		454	[162]
GREECE	Bottom ash	1	681	662	275		41		405	[162]
HUNGARY	Residue	35		1962			42		198	[168]
HUNGARY	Residue	35		1912			83		352	[168]
HUNGARY	Residue	35		298			40		273	[168]

OIL & GAS PRODUCTION

Activity concentrations for oil & gas production– raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Crude shale oil	1	63	54	30		23		514	[169]
USA	Crude shale oil	1	63	46	70		23		522	[169]
USA	Crude shale oil	1	63	52			23		969	[169]
USA	Crude shale oil	10	67				18			[169]
USA	Crude shale oil	8	48				30			[169]
USA	Crude shale oil	2	72				32		261	[169]
USA	Crude shale oil	2	80				44		509	[169]
USA	Crude shale oil	1	57				26		496	[169]
USA	Crude shale oil	1	81				28		418	[169]
USA	Crude shale oil	1	52				20		437	[169]
USA	Crude shale oil	1	48				23		451	[169]
USA	Crude shale oil	1	59				23		455	[169]
USA	Crude shale oil	1	70				21		385	[169]
USA	Crude shale oil	21	56				24		429	[169]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Crude oil	1					1			[71]
EGYPT	Crude oil	1					1			[71]
EGYPT	Crude oil	1					1			[71]
EGYPT	Crude oil	1		31			14		46	[71]
EGYPT	Crude oil	1		52			19		3	[71]
EGYPT	Crude oil	1		719			181		3	[71]
EGYPT	Crude oil	1		913			288		16	[71]
EGYPT	Crude oil	1		2669			913		98	[71]
EGYPT	Crude oil	1		1803			812		3	[71]
EGYPT	Crude oil	1		73			22		3	[71]
EGYPT	Crude oil	1		49			1		3	[71]
EGYPT	Crude oil	1		1693			543		3	[71]
TUNISIA	Crude oil	1		0.31			0.1		1	[170]
TUNISIA	Crude oil	1		0.38			0.1		1	[170]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TUNISIA	Crude oil	1		0.106			0.12		0.057	[170]
SAUDI ARABIA	Crude oil	3	0.023	0.014			0.3		2	[73]
EGYPT	Crude oil	1		10			9		42	[171]
EGYPT	Crude oil	1		23			3		52	[171]
EGYPT	Crude oil	1		19			12		65	[171]
GHANA	Crude oil	1		10			12		34	[172]
GHANA	Crude oil	1		2			12		32	[172]
GHANA	Crude oil	1		9			13		21	[172]
GHANA	Crude oil	1		5			12		30	[172]
NIGERIA	Crude oil	1					0.17		6	[6]
NIGERIA	Crude oil	1					0.034		11	[6]
NIGERIA	Crude oil	1	0.39				0.09		2	[6]
NIGERIA	Crude oil	1	0.47				0.3		20	[6]
NIGERIA	Crude oil	1	1				0.25		14	[6]

Activity concentrations for oil & gas production– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
NIGERIA	Crude oil	1	1						20	[6]
ALGERIA	Crude oil	1		67						[173]
ALGERIA	Crude oil	1		20						[173]
ALGERIA	Crude oil	1		50						[173]

Activity concentrations for oil & gas production– residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Sludge	2		1300	140	140				[174]
EGYPT	Residue	1	7500	60400	4300				1900	[72]
EGYPT	Residue	1	4500	43000	4200				1100	[72]
EGYPT	Residue	1	6200	55400	4300				1300	[72]
EGYPT	Residue	1	9200	81100	5300				2500	[72]
EGYPT	Residue	1	11200	96500	4300				3400	[72]
EGYPT	Residue	1	9600	85400	4400				3600	[72]
EGYPT	Residue	1	7100	78300	4500				4300	[72]
EGYPT	Residue	1	11800	102000	6500				4800	[72]
EGYPT	Residue	1	7100	54500	2700				2500	[72]
ITALY	Scale	1	1	2890			1			[175]
ITALY	Scale	1	1	1126			1			[175]
ITALY	Scale	1	1	120			1			[175]
ITALY	Scale	1	24	30			19			[175]
ITALY	Scale	1	54	3			1			[175]
ITALY	Scale	1	11	110			1			[175]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TUNISIA	Scale	1	1	1189			1			[175]
TUNISIA	Scale	1	1	31			1			[175]
TUNISIA	Scale	1	8	64			5			[175]
CONGO	Scale	1	1	97			1			[175]
CONGO	Scale	1	3	151			2			[175]
TUNISIA	Sludge	1	5	66			6			[175]
TUNISIA	Sludge	1	5	169			10			[175]
TUNISIA	Sludge	1	7	453			3			[175]
USA	Residue	1	74	69	44		31		607	[169]
USA	Residue	1	74	76	70		27		540	[169]
USA	Residue	1	74	72	107		22		518	[169]
USA	Residue	1	152	121	137		45		703	[169]
ESTONIA	Residue	1	37				16		581	[169]
USA	Residue	1	67				31		574	[169]
USA	Residue	1	62.9				26		511	[169]
USA	Residue	1							736	[169]
USA	Residue	1	59				28		659	[169]
USA	Residue	1	67				28		607	[169]
USA	Residue	1	81				28		533	[169]
USA	Residue	1	74				25		544	[169]
USA	Residue	1	78				27		492	[169]
USA	Residue	1	107				36		503	[169]
USA	Residue	1	85				25		463	[169]
USA	Residue	1	81				25		466	[169]
USA	Residue	1	11				33		840	[169]
USA	Residue	1	63				28			[169]
USA	Residue	1	89				16			[169]
EGYPT	Sludge	1					1			[71]
EGYPT	Sludge	1		6			1		3	[71]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Sludge	1		55			17		3	[71]
EGYPT	Sludge	1		195			41		101	[71]
EGYPT	Sludge	1		403			59		3	[71]
EGYPT	Sludge	1		470			128		3	[71]
EGYPT	Sludge	1		520			163		880	[71]
EGYPT	Sludge	1		1482			455		119	[71]
EGYPT	Sludge	1		1786			885		126	[71]
EGYPT	Scale	1					1			[71]
EGYPT	Scale	1					1			[71]
EGYPT	Scale	1					1			[71]
EGYPT	Scale	1					1			[71]
EGYPT	Scale	1		7			1		3	[71]
EGYPT	Scale	1		17			1		3	[71]
EGYPT	Scale	1		16			1		223	[71]
EGYPT	Scale	1		15			17		120	[71]
EGYPT	Scale	1					1			[71]
EGYPT	Scale	1					1			[71]
EGYPT	Scale	1		23			38		3	[71]
EGYPT	Scale	1		59			20		91	[71]
EGYPT	Scale	1		83			98		26	[71]
EGYPT	Scale	1		315			177		3	[71]
TUNISIA	Scale	1		59			82		64	[170]
TUNISIA	Scale	1		51			74		34	[170]
TUNISIA	Scale	1		136			177		105	[170]
TUNISIA	Scale	1		60			59		5	[170]
SAUDI ARABIA	Sludge	5	16	13			11		156	[73]
SAUDI ARABIA	Scale	3	0.023	1			0.14		4	[73]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SAUDI ARABIA	Sludge	5	38	27			27		386	[73]
SAUDI ARABIA	Sludge	4	26	38			29		528	[73]
SAUDI ARABIA	Sludge	3	39	52			36		576	[73]
SAUDI ARABIA	Sludge	4	0.023	7			6		80	[73]
SAUDI ARABIA	Sludge	5	29	48			36		471	[73]
SAUDI ARABIA	Sludge	5	53	59			48		595	[73]
SAUDI ARABIA	Sludge	4	30	43			38		515	[73]
SAUDI ARABIA	Sludge	4	34	49			41		588	[73]
SAUDI ARABIA	Sludge	5	10	42			38		581	[73]
SAUDI ARABIA	Scale	4	0.023	1.5			3		9	[73]
SAUDI ARABIA	Scale	5	0.023	1			2		10	[73]
EGYPT	Ash	1		18983			9504		16378	[171]
EGYPT	Ash	1		18929			9551		17291	[171]
EGYPT	Ash	1		2382			1216		1300	[171]
EGYPT	Ash	1		18012			9456		15127	[171]
EGYPT	Ash	1		11505			6505		9595	[171]
EGYPT	Ash	1		10753			64660		9035	[171]
EGYPT	Ash	1		20411			10821		18002	[171]
EGYPT	Ash	1		2323			1346		1136	[171]
GHANA	Sludge	1		11			9		27	[172]
GHANA	Sludge	1		3			12		27	[172]
GHANA	Sludge	1		4			3		31	[172]
GHANA	Sludge	1		17			21		31	[172]
GHANA	Scale	1		29			17		43	[172]
GHANA	Scale	1		28			40		38	[172]
GHANA	Scale	1		36			18		32	[172]
GHANA	Scale	1		33			27		37	[172]
GHANA	Scale	1		39			28		39	[172]
GHANA	Scale	1		28			25		36	[172]

Activity concentrations for oil & gas production– residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GHANA	Sludge	1		16			222		39	[172]
GHANA	Sludge	1		3			4		30	[172]
GHANA	Scale	1		31			27		44	[172]
GHANA	Scale	1		48			29		44	[172]
GHANA	Sludge	1		19			32		190	[172]
GHANA	Sludge	1		26			41		153	[172]
GHANA	Sludge	1		36			56		169	[172]
GHANA	Sludge	1		26			34		165	[172]
GHANA	Sludge	1		20			33		167	[172]
GHANA	Sludge	1		19			33		165	[172]
GHANA	Sludge	1		26			37		144	[172]
GHANA	Sludge	1		24			37		166	[172]
ALBANIA	Sludge	3		19				22	348	[176]
ALBANIA	Sludge	1		18				22	314	[176]
ALBANIA	Sludge	2		20				21	175	[176]
ALBANIA	Bituminous sand	10		23				23	549	[176]
ALBANIA	Bituminous sand	2		12				14	366	[176]
NETHERLANDS	Scale	2		350000	125000					[177]
NETHERLANDS	Scale	2		325000	85000					[177]
NETHERLANDS	Scale	2		130000	35000					[177]
NETHERLANDS	Scale	2		1600000	450000					[177]
ALGERIA	Scale	1		289310						[173]
ALGERIA	Scale	1		18140						[173]
ALGERIA	Scale	1		645500						[173]
NETHERLANDS	Residue	1			29300					[178]
NETHERLANDS	Residue	1			8400					[178]
NETHERLANDS	Residue	1			20100					[178]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
NETHERLANDS	Residue	1			18300					[178]
NETHERLANDS	Residue	1			184700					[178]
NETHERLANDS	Residue	1			76400					[178]
NETHERLANDS	Residue	1			140000					[178]
NETHERLANDS	Residue	1			117150					[178]
NETHERLANDS	Residue	1			31300					[178]
NETHERLANDS	Residue	1			24600					[178]
NETHERLANDS	Residue	1			4800					[178]
NETHERLANDS	Scale	1		2840000	775000					[179]
NETHERLANDS	Scale	1		1516000	380000					[179]
NETHERLANDS	Scale	1		184000	57000					[179]
NETHERLANDS	Scale	1		2203000	1360000					[179]
NETHERLANDS	Scale	1		746000	605000					[179]
NETHERLANDS	Scale	1		3016000	1561000					[179]
NETHERLANDS	Scale	1		1087000	780000					[179]
NETHERLANDS	Scale	1			390000					[179]
NETHERLANDS	Scale	1			348000					[179]
NETHERLANDS	Scale	1			348000					[179]
NETHERLANDS	Scale	1			685000					[179]
NETHERLANDS	Scale	1			1590000					[179]
NETHERLANDS	Scale	1		695000	307000					[179]
NETHERLANDS	Scale	1		695000	307000					[179]
NETHERLANDS	Scale	1			380000					[179]
NETHERLANDS	Scale	1			271000					[179]
NETHERLANDS	Scale	1			288000					[179]
NETHERLANDS	Scale	1			950000					[179]
NETHERLANDS	Scale	1			860000					[179]
NETHERLANDS	Scale	1		2000	204000					[179]

Activity concentrations for oil & gas production– products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Crude shale oil	1		1			2		11	[169]
USA	Crude shale oil	1		1			2		15	[169]
ESTONIA	Crude shale oil	1		1			2		15	[169]
USA	Crude shale oil	1		1			1		7	[169]
USA	Crude shale oil	2	1				0.37		0.111	[169]
USA	Crude shale oil	1	1				0.37		0.074	[169]
USA	Crude shale oil	1	0.37				0.037		1	[169]
TUNISIA	Oil product	1		0.39			0.11		2	[170]
TUNISIA	Oil product	1		0.3			0.1		3	[170]
TUNISIA	Oil product	1		0.22			0.03		2	[170]
TUNISIA	Oil product	1		0.07			0.022		4	[170]
TUNISIA	Oil product	1		0.22			0.02		2	[170]
TUNISIA	Oil product	1		0.54			0.006		1	[170]
TUNISIA	Oil product	1		1			0.11		2	[170]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TUNISIA	Oil product	1		0.025			0.006		0.045	[170]
SAUDI ARABIA	Oil product	5	0.023	0.014			0.022		4	[73]
SAUDI ARABIA	Oil product	4	0.023	0.014			0.06		3	[73]
SAUDI ARABIA	Oil product	5	0.023	0.014			0.016		12	[73]
SAUDI ARABIA	Oil product	5	0.023	0.014			0.17		0.13	[73]
SAUDI ARABIA	Oil product	4	0.023	1			0.62		4	[73]
SAUDI ARABIA	Oil product	5	9	0.014			0.016		57	[73]
SAUDI ARABIA	Oil product	3	0.023	0.014			0.017		5	[73]
SAUDI ARABIA	Oil product	5	0.023	0.014			0.24		6	[73]
SAUDI ARABIA	Oil product	4	0.023	0.014			0.04		6	[73]
SAUDI ARABIA	Oil product	5	0.023	0.45			0.016		6	[73]
GHANA	Oil product	1		0.12			0.11		37	[172]
GHANA	Oil product	1		1.33			11		33	[172]
GHANA	Oil product	1		0.12			0.11		0.15	[172]

Activity concentrations for oil & gas production– products (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GHANA	Oil product	1		0.12			16		40	[172]
GHANA	Oil product	1		1			10		23	[172]
GHANA	Oil product	1		0.12			12		29	[172]
GHANA	Oil product	1		1			15		36	[172]
GHANA	Oil product	1		0.12			0.11		0.15	[172]
GHANA	Oil product	1		16			18		43.46	[172]
GHANA	Oil product	1		6			8		25.48	[172]
GHANA	Oil product	1		3			13		35	[172]
GHANA	Oil product	1		6			10		33	[172]
GHANA	Oil product	1		2			17		39	[172]
GHANA	Oil product	1		0.12			13		30	[172]
GHANA	Oil product	1		18			16		37.	[172]
GHANA	Oil product	1		4			12		33	[172]
GHANA	Oil product	1		3			14		36	[172]

Activity concentrations for oil & gas production– effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Liquid effluent	1	0.0045	20			0.004			[175]
ITALY	Liquid effluent	1	0.015	0.23			0.004			[175]
ITALY	Liquid effluent	1	0,0073	0.06			0.004			[175]
CONGO	Liquid effluent	1	0.0045	5			0.004			[175]
USA	Liquid effluent	1	4	0.259	7.4		0.592		7	[169]
USA	Liquid effluent	1	4	0.37			0.74		7	[169]
USA	Liquid effluent	1	1				0.037		1	[169]
USA	Liquid effluent	1	1				0.0111		1	[169]
USA	Liquid effluent	1	7				0.0155		1	[169]
EGYPT	Liquid effluent	1					1			[71]
EGYPT	Liquid effluent	1					1			[71]
EGYPT	Liquid effluent	1		27			1		3	[71]
EGYPT	Liquid effluent	1		27			1		3	[71]
EGYPT	Liquid effluent	1		218			77		3	[71]

Activity concentrations for oil & gas production– effluents (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Liquid effluent	1		114			93		249	[71]
TUNISIA	Liquid effluent	1		0.05			0.02		1	[170]
TUNISIA	Liquid effluent	1		0.26			0.11		1	[170]
TUNISIA	Liquid effluent	1		0.33			0.019		14	[170]
TUNISIA	Liquid effluent	1		19			40		66	[170]
TUNISIA	Liquid effluent	1		0.37			1		7	[170]
TUNISIA	Liquid effluent	1		1			1		7	[170]
TUNISIA	Liquid effluent	1		0.037			0.027		0.22	[170]
ALGERIA	Liquid effluent	1		510						[173]
ALGERIA	Liquid effluent	1		20						[173]
ALGERIA	Liquid effluent	1		500						[173]

CEMENT PRODUCTION

Activity concentrations for cement production– raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Clay	3		4			41		44	[97]
AUSTRALIA	Residue	3		181			100		141	[97]
AUSTRALIA	Rock	2		28			16		353	[127]
AUSTRALIA	Rock	2		35.5			51		144	[127]
AUSTRALIA	Residue	2		75			125			[127]
ITALY	Ash	151		170				140	410	[115]
USA	Fly ash	71		170				130	470	[115]
SUD AFRICA	Fly ash	70		170				150	330	[115]
ITALY	Bottom ash	10		130				100	470	[115]
GREECE	Rock	1		27					80	[116]
GREECE	Rock	1		11					60	[116]
GREECE	Clinker	1		32					210	[116]
GREECE	Clinker	1		87					150	[116]
GREECE	Rock	1		39					310	[116]
GREECE	Rock	1		135					710	[116]
GREECE	Rock	1		15					20	[116]
GREECE	Rock	1		21					250	[116]
GREECE	Rock	1		6					20	[116]
GREECE	Rock	1		14					110	[116]
GREECE	Rock	1		36					490	[116]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Phosphogy psum	1		524						[116]
GREECE	Phosphogy psum	1		570						[116]
GREECE	Fly ash	4		800					290	[116]
GREECE	Fly ash	4		330					190	[116]
EGYPT	Residue	5		323			40		158	[98]
EGYPT	Clay	4		26			25		312	[98]
EGYPT	Clay	5		26			24		282	[98]
EGYPT	Clay	4		24			23		301	[98]
INDIA	Rock	1		74					65	[180]
INDIA	Rock	1		8					27	[180]
KUWAIT	Rock	1	4	3			1		14	[92]
CHINA	Fly ash	3		102						[167]
ITALY	Rock	27		11			2		22	[181]
ITALY	Rock	5		6			2		32	[181]
ITALY	Rock	3		39			54		766	[181]
ITALY	Clay	7		34			38		513	[181]
PAKISTAN	Clinker	6		51			23		258	[182]
PAKISTAN	Rock	6		28			11		63	[182]
PAKISTAN	Rock	6		35			41		188	[182]
PAKISTAN	Rock	6		41			39		195	[182]
PAKISTAN	Rock	6		8			16		188	[182]
BRAZILE	Clay	1		15			33		84	[183]
BRAZILE	Rock	1		6					154	[183]
CHINA	Rock	1		17			15		136	[184]
CHINA	Rock	1		13			16		87	[184]
CHINA	Rock	1		21			18		129	[184]
CHINA	Rock	1		19			18		76	[184]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CHINA	Rock	1		28			24		143	[184]
CHINA	Rock	1		22			18		88	[184]
CHINA	Rock	1		26			20		120	[184]
CHINA	Rock	1		3			5		30	[185]
CHINA	Ash	1		164			96		220	[185]
CHINA	Ash	1		82			78		212	[185]
CHINA	Clay	1		41			86		763	[185]
BANGLAD ESH	Rock	6		68			107		1660	[186]
BANGLAD ESH	Rock	20		60			61		928	[186]
PAKISTAN	Rock	10		22			9		74	[187]
PAKISTAN	Rock	10		6			13		174	[187]
PAKISTAN	Rock	10		26			43		822	[187]
PAKISTAN	Rock	10		15			130		311	[187]
EGYPT	Rock	10		105						[188]
DANIMAR CA	Ash	1		150						[189]
DANIMAR CA	Rock	1		1440						[189]
AUSTRALI A	Clay	12		62.9			163		403	[97]
TAIWAN	Rock	1	37				59		790	[99]
TAIWAN	Rock	1	28				29		90	[99]
TAIWAN	Rock	1	103				84		605	[99]
TURCHIA	Clay	1		73			9		112	[190]
TURCHIA	Clay	1		50			63		692	[190]
TURCHIA	Clay	1		25			36		641	[190]
TURCHIA	Clay	1		17			23		535	[190]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURCHIA	Clay	1		12			16		366	[190]
TURCHIA	Clay	1		20			34		551	[190]
TURCHIA	Clay	1		9			24		317	[190]
TURCHIA	Clay	1		20			53		671	[190]
TURCHIA	Clay	1		14			18		382	[190]
TURCHIA	Clay	1		61			79		622	[190]
TURCHIA	Clay	1		37			56		1104	[190]
TURCHIA	Clay	1		22			36		663	[190]
TURCHIA	Clay	1		22			26		452	[190]
TURCHIA	Clay	1		22			27		462	[190]
TURCHIA	Clay	1		43			75		895	[190]
TURCHIA	Clay	1		15			19		476	[190]
TURCHIA	Clay	1		52			51		459	[190]
TURCHIA	Clay	1		74			96		578	[190]
TURCHIA	Clay	1		65			88		560	[190]
TURCHIA	Clay	1		55			51		601	[190]
TURCHIA	Clay	1		43			47		583	[190]
TURCHIA	Clay	1		51			41		499	[190]
TURCHIA	Clay	1		61			80		624	[190]
TURCHIA	Clay	1		48			50		573	[190]
TURCHIA	Clay	1		94			1197		798	[190]
TURCHIA	Clay	1		22			81		722	[190]
TURCHIA	Clay	1		11			18		514	[190]
TURCHIA	Clay	1		18			34		388	[190]
TURCHIA	Clay	1		14			6		352	[190]
TURCHIA	Clay	1		31			50		845	[190]
TURCHIA	Clay	1		58			67		640	[190]
TURCHIA	Clay	1		49			59		578	[190]
TURCHIA	Clay	1		70			93		531	[190]

Activity concentrations for cement production– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURCHIA	Clay	1		59			66		582	[190]
UNGHERIA	Clay	7		39			59		688	[59]
IRAN	Clay	1		145			120		1245	[123]

Activity concentrations for cement production– products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Cement	2		93.5			123.5		437	[127]
ITALY	Portland cement	2		26				18	210	[115]
ITALY	Pozzolanic cement	21		49				45	390	[115]
GREECE	Portland cement	1		32					210	[116]
GREECE	Portland cement	1		48					180	[116]
GREECE	Portland cement	2		71					240	[116]
GREECE	Portland cement	2		100					210	[116]
GREECE	Portland cement	2		78					180	[116]
GREECE	Portland cement	2		99					320	[116]
GREECE	Portland cement	2		160					230	[116]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
GREECE	Portland cement	2		118					260	[116]
GREECE	Cement	1		7						[116]
GREECE	Cement	1		11						[116]
GREECE	Cement	1		17						[116]
GREECE	Cement	1		8						[116]
GREECE	Cement	1		11						[116]
GREECE	Cement	1		11						[116]
EGYPT	Portland cement	3		31			11		49	[98]
EGYPT	Cement	3		108			19		49	[98]
EGYPT	Cement	6		10			3		61	[98]
GREECE	Portland cement	8		20			13		247	[191]
GREECE	Portland cement	22		92			31		310	[191]
INDIA	Cement	1		9			41		33	[180]
INDIA	Cement	1		16			37		36	[180]
INDIA	Cement	1		7			34		40	[180]
INDIA	Cement	1		152			58			[180]
INDIA	Cement	1					54		33	[180]
KUWAIT	Cement	1	13	13			9		240	[92]
KUWAIT	Cement	1	16	17			9		199	[92]
JORDAN	Cement	25		43			11		254	[192]
JORDAN	Cement	25		45			11		226	[192]
JORDAN	Cement	23		49			14		112	[192]
ZAMBIA	Portland cement	1	23				32		134	[193]
ZAMBIA	Cement	1	48				26			[193]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ZAMBIA	Cement	1	11				26			[193]
CHINA	Portland cement	3	43							[167]
ITALY	Portland cement	7		38			22		218	[181]
PAKISTAN	Portland cement	8		34			29		295	[182]
AUSTRIA	Portland cement	1		27			14		210	[194]
BELGIUM	Portland cement	1		62			76			[195]
BRAZILE	Cement	1		62			59		564	[183]
FINLAND	Portland cement	1		40			20		251	[112]
EGYPT	Portland cement	1		72			25		135	[196]
INDIA	Portland cement	1		37			24		432	[197]
MALAYSIA	Portland cement	1		81			59		203	[198]
NORWAY	Portland cement	1		30			19		259	[199]
CHINA	Cement	1		38			33		183	[184]
CHINA	Cement	1		32			28		125	[184]
CHINA	Cement	1		32			29		142	[184]
CHINA	Cement	1		32			33		149	[184]
CHINA	Cement	1		50			34		203	[184]
CHINA	Cement	1		55			31		228	[184]
CHINA	Cement	1		44			33		243	[184]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CHINA	Cement	1		51			32		202	[184]
CHINA	Cement	1		49			30		200	[184]
CHINA	Cement	1		32			56		277	[184]
CHINA	Cement	1		43			35		193	[184]
CHINA	Cement	1		42			36		196	[184]
CHINA	Cement	1		35			32.4		205	[184]
CHINA	Cement	1		45			33		190	[184]
CHINA	Cement	1		34			38		155	[184]
CHINA	Cement	1		29			40		170	[184]
CHINA	Cement	1		35			30		153	[184]
BANGLAD ESH	Cement	4		30			54.3		523	[186]
CHINA	Cement	3		36			20		205	[185]
PAKISTAN	Portland cement	25		26			29		273	[187]
MALAYSIA	Cement	1	19				26			[198]
MALAYSIA	Cement	5	48				26			[198]
AUSTRALIA	Cement	7		52			48		115	[110]
INDIA	Portland cement	1		37			24		432	[197]
EGYPT	Portland cement	10		120			88		416	[188]
EGYPT	Cement	10		72			46		250	[188]
MALAYSIA	Portland cement	3	20				20		269	[200]
MALAYSIA	Cement	3	25				23		362	[200]
MALAYSIA	Cement	3	42				29		614	[200]
KUWAIT	Cement	1	13	13			9		240	[92]
KUWAIT	Cement	1	16	17			9		199	[92]

Activity concentrations for cement production– products (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Portland cement	7		52			48		115	[97]
DANIMARCA	Cement	1		27						[189]
DANIMARCA	Cement	1		28						[189]
IRELAND	Cement	1		47			15		252	[201]
IRELAND	Cement	1		27			15		74	[201]
IRELAND	Cement	1		107			3		66	[201]
KENYA	Cement	1		11			66		891	[103]
EGYPT	Cement	85		78			33		337	[131]
CAMERUN	Portland cement	1	27				15		277	[108]
EGYPT	Cement	1	25				21		2493	[109]
BANGLADESH	Portland cement	18		62			59		329	[113]
IRAN	Cement	2		30			14		136	[202]
IRAN	Cement	3		38			8		117	[202]
IRAN	Cement	4		16			16		102	[202]
IRAN	Cement	2		27			16		109	[202]
IRAN	Cement	5		35			10		105	[202]
IRAN	Cement	3		42			11		114	[202]
IRAN	Cement	3		35			12		140	[202]
IRAN	Cement	4		23			10		127	[202]
IRAN	Cement	3		23			11		11	[202]
IRAN	Cement	3		31			14		111	[202]
IRAN	Cement	2		28			14		130	[202]
IRAN	Cement	3		38			17		142	[202]
IRAN	Cement	3		27			12		121	[202]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
IRAN	Cement	2		43			13		117	[202]

ZIRCON AND ZIRCONIUM INDUSTRY

Activity concentrations for zircon and zirconium industry– raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Other raw materials	2	42				56		854	[4]
ITALY	Zircon sand	1	2334				880			[4]
ITALY	Zircon sand	1	2084				858			[4]
ITALY	Zircon sand	1	3613	3219	2707	2748	517		0	[203]
ITALY	Other raw materials	1		1500			240		18	[204]
ITALY	Zircon sand	1	4080							[205]
ITALY	Zircon sand	1	3370							[205]
ITALY	Zircon sand	1	3720							[205]
ITALY	Zircon sand	1	3640							[205]
ITALY	Zircon sand	1	10300							[205]
ITALY	Zircon sand	1	11100							[205]
ITALY	Zircon sand	1	3900				680		46	[206]
ITALY	Zircon sand	1	3300				750		45	[206]
ITALY	Zircon sand	1	3400				680		56	[206]
ITALY	Zircon sand	1	3400				390		30	[206]
ITALY	Zircon sand	1	13400				2650		300	[206]
ITALY	Zircon sand	1	10800				1750		174	[206]
SERBIA	Zircon sand	1	2236	2312			367			[207]
SERBIA	Zircon sand	1	3540	2969			816			[207]
SERBIA	Zircon sand	1	4522	4147			665			[207]
SERBIA	Zircon sand	1	3855	3967			509			[207]
SERBIA	Zircon sand	1	3853	4350			885			[207]
SERBIA	Zircon sand	1	3948	3201			643			[207]
SERBIA	Zircon sand	1	2425	2732			526			[207]
SERBIA	Zircon sand	1	3055	3031			630			[207]

Activity concentrations for zircon and zirconium industry– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SERBIA	Zircon sand	1	3517	3993			555			[207]
SERBIA	Zircon sand	1	3410	3661			658			[207]
SERBIA	Zircon sand	1	2630	2961			570			[207]
SERBIA	Zircon sand	1	1867	2021			396			[207]
SERBIA	Zircon sand	1	2958	3511			454			[207]
SERBIA	Zircon sand	1	4037	3778			584			[207]
SERBIA	Zircon sand	1	2266	2603			460			[207]
SERBIA	Zircon sand	1	2687	2106			428			[207]
SERBIA	Zircon sand	1	672	814			187			[207]
SERBIA	Zircon sand	1	2859	2941			565			[207]
SERBIA	Zircon sand	1	3808	3008			596			[207]
SERBIA	Zircon sand	1	6524	4090			550			[207]
SERBIA	Zircon sand	1	3570	4092			624			[207]
IRAN	Zircon sand	2		3900			700			[208]
IRAN	Zircon sand	2		3800			670			[208]
IRAN	Zircon sand	2		4000			690			[208]
IRAN	Zircon sand	2		3500			550		55	[208]
IRAN	Zircon sand	2		3500			550		55	[208]
IRAN	Zircon sand	2		4100			600		260	[208]
IRAN	Zircon sand	2		3300			600		54	[208]
IRAN	Zircon sand	2		3511			550		296	[208]
IRAN	Zircon sand	2		2205			331		324	[208]
IRAN	Zircon sand	2		1715			378		442	[208]
IRAN	Zircon sand	2		2432			523		434	[208]
IRAN	Zircon sand	2		2820			607		334	[208]
IRAN	Zircon sand	2		1341			343		287	[208]
ITALY	Zircon sand	1	2400				520		34	[209]
ITALY	Zircon sand	1	2200				480		33	[209]
ITALY	Zircon sand	1	3200				520		32	[209]

Activity concentrations for zircon and zirconium industry– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Zircon sand	1	2900				450		32	[209]
ITALY	Zircon sand	1	1830				370		26	[209]
ITALY	Zircon sand	1	1860				380		32	[209]
ITALY	Zircon sand	1	2300				450		32	[209]
ITALY	Zircon sand	1	2300				470		32	[209]
ITALY	Zircon sand	1	2500				470		29	[209]
ITALY	Zircon sand	1	2600				490		29	[209]
ITALY	Zircon sand	1	2700				540		33	[209]
ITALY	Zircon sand	1	2800				540		32	[209]
ITALY	Zircon sand	1	2800				510		27	[209]
ITALY	Zircon sand	1	2700				520		26	[209]
ITALY	Zircon sand	1	2600				480		30	[209]
ITALY	Zircon sand	1	2800				500		31	[209]
AUSTRALIA	Zircon sand	3		2250			503		326	[97]
AUSTRALIA	Other raw materials	1		115			167		93	[97]
ITALY	Zircon sand	1	3445				763		68	[210]
IRAN	Zircon sand	1		13400			1260		1256	[83]
INDIA	Zircon sand	1	3450				2000			[94]
INDIA	Zircon sand	1	3500				1650			[94]
INDIA	Zircon sand	1	3400				1900			[94]
ITALY	Other raw materials	1	46	22	27		16		210	[211]
ITALY	Other raw materials	1	85	73	44		85		37	[211]
ITALY	Other raw materials	1	130	110	76		130		43	[211]
ITALY	Other raw materials	1		0.54	3.3		1		10	[211]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Other raw materials	1		1	3		1		10	[211]
ITALY	Other raw materials	1	81	55	22		250		27	[211]
ITALY	Other raw materials	1	130	96	42		230		30	[211]
ITALY	Other raw materials	1	81	54	25		210		14	[211]
ITALY	Other raw materials	1	66	38	15		110		13	[211]
ITALY	Other raw materials	1	490	380	150		410		49	[211]
ITALY	Other raw materials	1	500	380	160		410		59	[211]
ITALY	Other raw materials	1	580	410	220		440		72	[211]
ITALY	Other raw materials	1	450	310	200		450		210	[211]
ITALY	Other raw materials	1	480	370	200		400		63	[211]
ITALY	Other raw materials	1	230	180	5		240		54	[211]
ITALY	Other raw materials	1	210	170	4		230		22	[211]
ITALY	Other raw materials	1	190	140	8		220		17	[211]
ITALY	Other raw materials	1	450	320	6		420		47	[211]
ITALY	Zircon sand	1	2800	2400	2900		590		40	[211]
JAPAN	Zircon sand	1	3000	2800			690	690	39	[212]

Activity concentrations for zircon and zirconium industry– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JAPAN	Zircon sand	1	3200	2800			720	700	36	[212]
JAPAN	Zircon sand	1	3700	2900			890	760	29	[212]
JAPAN	Zircon sand	1	4800	3700			1100	970	58	[212]
JAPAN	Zircon sand	1	5000	3800			1400	1100	81	[212]
JAPAN	Zircon sand	1	4100	3400			830	710	43	[212]
JAPAN	Zircon sand	1	5600	2800			1200	630	30	[212]
AUSTRALIA	Zircon sand	1	4270				570			[121]
AUSTRALIA	Zircon sand	1	3700				630			[121]
AUSTRALIA	Zircon sand	1	3600				620			[121]
AUSTRALIA	Zircon sand	1	3800				660			[121]
IRAN	Zircon sand	1		13400						[83]
SPAIN	Zircon sand	1	3615				604		74	[213]
SPAIN	Zircon sand	1	2681				597		69	[213]
SPAIN	Zircon sand	1	3159				714		71	[213]
SPAIN	Zircon sand	1	3134				592		110	[213]
SPAIN	Zircon sand	1	2908				607		99	[213]
INDIA	Zircon sand	1	3500				1700			[94]
INDIA	Zircon sand	1	3500				1800			[94]
INDIA	Zircon sand	1	3450				1800			[94]
USA	Zircon sand	1		3330						[214]
CHINA	Zircon sand	2		15600			12800			[215]
CHINA	Zircon sand	6		13100			7900			[215]
CHINA	Zircon sand	6		5200			3000			[215]
AUSTRALIA	Zircon sand	3		5500			2100			[215]
AUSTRALIA	Zircon sand	4		4			25.9		1706	[97]
AUSTRALIA	Zircon sand	1		2700				590	51	[67]
AUSTRALIA	Zircon sand	1		2480				550		[67]
EGYPT	Rock	1	115				170		13	[216]
EGYPT	Rock	1	122				135		30	[216]

Activity concentrations for zircon and zirconium industry– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Rock	1	166				111		15	[216]
EGYPT	Rock	1	104				160		39	[216]
EGYPT	Rock	1	120				170		13	[216]
EGYPT	Rock	1	110				170		8	[216]
EGYPT	Rock	1	120				302		29	[216]
EGYPT	Rock	1	48				96		38	[216]
ASIA	Rock	1	8633				1079		134	[216]
TURCHIA	Rock	1	110				124		270	[216]
UNGHERIA	Zircon sand	1	3809	3970			660		156	[75]
UNGHERIA	Zircon sand	1	3546	3621			584		137	[75]
UNGHERIA	Zircon sand	1	3237	3148			456		129	[75]
EGYPT	Zircon sand	10		4910			1195		11300	[106]
TURKEY	Rock	1		106			62		688	[190]
TURKEY	Rock	1		73			78		174	[190]
TURKEY	Rock	1		126			90		135	[190]
TURKEY	Rock	1		20			56		28	[190]
TURKEY	Rock	1		107			65		976	[190]
TURKEY	Rock	1		80			24		15	[190]
TURKEY	Rock	1		29			61		107	[190]
TURKEY	Rock	1		120			184		663	[190]
TURKEY	Rock	1		124			161		1467	[190]
TURKEY	Rock	1		58			82		52	[190]
TURKEY	Rock	1		89			102		35	[190]
TURKEY	Rock	1		115			176		1026	[190]
TURKEY	Rock	1		59			64		38	[190]
TURKEY	Rock	1		17			57		263	[190]
TURKEY	Rock	1		116			164		1635	[190]
TURKEY	Rock	1		74			92		115	[190]
USA	Zircon sand	1		3900						[217]

Activity concentrations for zircon and zirconium industry– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Zircon sand	1		4000						[217]
USA	Zircon sand	1		3900						[217]

Activity concentrations for zircon and zirconium industry– residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Sludge	2	211				75		347	[4]
ITALY	Residue	1	359	147	21050	35000	27		10	[203]
ITALY	Residue	1				28000				[203]
ITALY	Residue	1	1191	1046	1033	1294	178		255	[203]
ITALY	Residue	1				6100				[203]
ITALY	Sludge	1	1635	1496	1167	1177	238		27	[203]
ITALY	Sludge	1		160			37		31	[204]
ITALY	Polveri	1		1000			170		36	[204]
ITALY	Sludge	1	116				45		320	[206]
ITALY	Sludge	1	193				62		330	[206]
JAPAN	Sludge	1	4000	3700			1400	840	45	[212]

Activity concentrations for zircon and zirconium industry– residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Residue	1	12	11	85	11600	1		115	[218]
ITALY	Residue	1	12	12	26	4660	1		16	[218]
ITALY	Residue	1	13	11	64	15000	3		39	[218]
ITALY	Residue	1	9	10	425	46100	3		369	[218]
ITALY	Residue	1	8	11	214	12700	1		53	[218]
ITALY	Residue	1	58	63	60	91	38		526	[218]
ITALY	Sludge	1	107	114	125	154	34		317	[218]

Activity concentrations for zircon and zirconium industry– products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Tile	2	182.5				65		764	[4]
ITALY	Tile	1	42				42		625	[4]
ITALY	Tile	1	39				41		768	[4]
ITALY	Tile	2	57.5				56		761	[4]
ITALY	Tile	1	1702	1400	952	1089	310		9	[203]
ITALY	Tile	1	1751	1638	753	685	262		0	[203]
ITALY	Tile	1	1715	1481	1344	1353	250		23	[203]
ITALY	Tile	1	20	8	31	46	2		81	[203]
ITALY	Product	1		300			70		40	[204]
ITALY	Product	1		25			21		130	[204]
ITALY	Tile	1	79				66		890	[206]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Tile	1	58				52		830	[206]
ITALY	Tile	1	50				59		520	[206]
IRAN	Glaze	2		880			190		1580	[208]
IRAN	Glaze	2		630			160		670	[208]
IRAN	Glaze	2		550			100		720	[208]
IRAN	Glaze	2		420			90		520	[208]
IRAN	Glaze	2		470			100		580	[208]
IRAN	Glaze	2		480			90		1190	[208]
IRAN	Glaze	2		370			80		620	[208]
ZAMBIA	Tile	1	52				96			[193]
MALAYSIA	Tile	2	28				25		382	[200]
MALAYSIA	Tile	2	25				22		400	[200]
ITALY	Refractory	1	310	240	95		290		51	[211]
ITALY	Refractory	1	370	280	51		300		44	[211]
ITALY	Refractory	1	60	35	14		110		21	[211]
ITALY	Refractory	1	490	380	230		420		57	[211]
ITALY	Refractory	1	240	190	110		220		49	[211]
ITALY	Refractory	1		13	4		8		9	[211]
ITALY	Refractory	1		7.3	8		1		9	[211]
ITALY	Refractory	1	350	310	81		370		63	[211]
ITALY	Refractory	1	100	100	35		100		160	[211]
JAPAN	Refractory	1	2400	2000			550	460	35	[212]
JAPAN	Refractory	2	4350	3250			1050	845	37	[212]
JAPAN	Refractory	2	3850	2250			985	520	28	[212]
ITALY	Refractory	1	72				77		788	[128]
CHINA	Glaze	6		51			24		760	[215]
CHINA	Glaze	16		1318			453		534	[215]
CHINA	Tile	17		29			57		619	[215]
CHINA	Tile	10		41			47		642	[215]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CHINA	Tile	36		109			102		599	[215]
SERBIA	Ceramic	1		36			29		786	[95]
SERBIA	Ceramic	1		174			42		684	[95]
SERBIA	Ceramic	1		46			30		504	[95]
SERBIA	Ceramic	1		25			33		440	[95]
SERBIA	Ceramic	1		27			33		299	[95]
SERBIA	Ceramic	1		50			47		365	[95]
SERBIA	Ceramic	1		45			46		411	[95]
SERBIA	Ceramic	1		103			34		559	[95]
SERBIA	Ceramic	1		50			51		726	[95]
SERBIA	Ceramic	1		79			71		1049	[95]
SERBIA	Ceramic	1		79			45		708	[95]
SERBIA	Ceramic	1		58			43		620	[95]
ITALY	Tile	1		66			61		949	[219]
IRELAND	Tile	1		74			32		785	[201]
IRELAND	Tile	1		124			26		222	[201]
IRELAND	Tile	1		60			36		859	[201]
IRELAND	Tile	1		68			27		785	[201]
IRELAND	Tile	1		66			25		376	[201]
IRELAND	Tile	1		92			25		704	[201]
IRELAND	Tile	1		68			28		498	[201]
IRELAND	Tile	1		88			26		1282	[201]
IRELAND	Tile	1		44			20		645	[201]
EGYPT	Ceramic	108		90			75		900	[106]
CAMERUN	Tile	2	16				20		319	[108]

Activity concentrations for zircon and zirconium industry– effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Liquid effluent	1		0.38		0.0044	0.15		2	[203]

TITANIUM DIOXIDE PIGMENT PRODUCTION

Activity concentrations for titanium dioxide pigment production– raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CZECH REPUBLIC	Mineral	1		165	65			79	6	[220]
CZECH REPUBLIC	Mineral	1	5	4	2.9			2	45	[220]
CZECH REPUBLIC	Mineral	1	4	5					64	[220]
NETHERLANDS	Mineral	1	1500	2300			1200			[74]
NETHERLANDS	Mineral	1	710	540			230			[74]
NETHERLANDS	Mineral	1	150	130			160			[74]
AUSTRALIA	Mineral	2	250				1100			[119]
AUSTRALIA	Mineral	2	400				1650			[119]
AUSTRALIA	Mineral	2	200				800			[119]
AUSTRALIA	Mineral	1	550				76			[119]
AUSTRALIA	Mineral	2	200				850			[119]
AUSTRALIA	Mineral	1	530				64			[121]
AUSTRALIA	Mineral	1	640				60			[121]
AUSTRALIA	Mineral	1	530				90			[121]
AUSTRALIA	Mineral	1	71				90			[121]
AUSTRALIA	Mineral	1	53				60			[121]
AUSTRALIA	Mineral	1	52				70			[121]
AUSTRALIA	Mineral	1	31				35			[121]
AUSTRALIA	Mineral	1		72	16			390		[122]
AUSTRALIA	Mineral	1		76	32			410		[122]
AUSTRALIA	Mineral	1		65				310		[122]
AUSTRALIA	Mineral	1		110	31			410		[122]
AUSTRALIA	Mineral	1		84	27			370		[122]
AUSTRALIA	Mineral	1		96	18			520		[122]

Activity concentrations for titanium dioxide pigment production– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Mineral	3		5				18		[122]
AUSTRALIA	Mineral	5		2				14		[122]
YUGOSLAVIA	Mineral	1		150				180		[221]
IRAN	Mineral	1		640			193		300	[83]
INDIA	Mineral	1	50				60			[94]
INDIA	Mineral	1	40				75			[94]
INDIA	Mineral	1	40				80			[94]
INDIA	Mineral	1	350				150			[94]
INDIA	Mineral	1	300				170			[94]
INDIA	Mineral	1	270				200			[94]
INDIA	Mineral	3					570	510		[222]
INDIA	Mineral	3					100	100		[222]
INDIA	Mineral	4					190	90		[222]
INDIA	Mineral	1	50				150			[94]
INDIA	Mineral	1	50				150			[94]
INDIA	Mineral	1	50				150			[94]
INDIA	Mineral	1	300				200			[94]
INDIA	Mineral	1	300				300			[94]
INDIA	Mineral	1	300				250			[94]
AUSTRALIA	Mineral	2		348			211		333	[97]
INDIA	Mineral	1	94	45			250	120	10	[67]
INDIA	Mineral	1	79	47			290	180	33	[67]
AUSTRALIA	Mineral	1	21	15			37	33	11	[67]
AUSTRALIA	Mineral	1	53	75			230	300	30	[67]
CANADA	Mineral	1	7	5			5	6	12	[67]
VIETNAM	Mineral	1	220	220			280	310	30	[67]
VIETNAM	Mineral	1	160	140			230	190	24	[67]
SUD AFRICA	Mineral	1	540	460			160	160	26	[67]
SUD AFRICA	Mineral	1	74	76			160	170	43	[67]

Activity concentrations for titanium dioxide pigment production– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
HUNGARY	Mineral	1	1148	1098			456		137	[75]
HUNGARY	Mineral	1	1211	1235			479		141	[75]
HUNGARY	Mineral	1	1042	1106			426		134	[75]
HUNGARY	Mineral	1	435	444			1971		10	[75]
HUNGARY	Mineral	1	402	408			1864		12	[75]
HUNGARY	Mineral	1	398	401			1897		16	[75]
HUNGARY	Mineral	1	347	353			1422		7	[75]
HUNGARY	Mineral	1	350	360			1938		25	[75]
HUNGARY	Mineral	1	273	286			1717		12	[75]
HUNGARY	Mineral	1	19	20			115		4	[75]
HUNGARY	Mineral	1	16	18			80		6	[75]
HUNGARY	Mineral	1	19	21			90		6	[75]
HUNGARY	Mineral	1	21	23			90		6	[75]
HUNGARY	Mineral	1	21	22			88		15	[75]
HUNGARY	Mineral	1	18	21			85		12	[75]
HUNGARY	Mineral	1	38	40			224		6	[75]
HUNGARY	Mineral	1	32	36			209		6	[75]
HUNGARY	Mineral	1	28	30			175		6	[75]
HUNGARY	Mineral	1		50					270	[75]
HUNGARY	Mineral	1		67					280	[75]
HUNGARY	Mineral	1		64					352	[75]
HUNGARY	Mineral	1		66					281	[75]
HUNGARY	Mineral	1		51					194	[75]
HUNGARY	Mineral	1		37					160	[75]
HUNGARY	Mineral	1		40					199	[75]
HUNGARY	Mineral	1		45					185	[75]
HUNGARY	Mineral	1		49					158	[75]

Activity concentrations for titanium dioxide pigment production– residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CZECH REPUBLIC	Sludge	1	200	1292	807			557	190	[220]
CZECH REPUBLIC	Residue	1	15	2	4			1	8	[220]
CZECH REPUBLIC	Residue	1	81	120	82			44	15	[220]
CZECH REPUBLIC	Residue	1	13	295	59			105	44	[220]
AUSTRALIA	Sludge	1	350				1200			[119]
AUSTRALIA	Residue	2	400				1100			[119]
AUSTRALIA	Residue	1		37				162		[122]
AUSTRALIA	Sludge	1		83				465		[122]
AUSTRALIA	Scale	1		419000				1644000		[122]
AUSTRALIA	Scale	1		77000				325000		[122]
AUSTRALIA	Residue	1		1				2		[122]
AUSTRALIA	Scale	1		13500				83200		[122]
AUSTRALIA	Scale	2		76				265		[122]
AUSTRALIA	Sludge	1		330				1750		[122]
AUSTRALIA	Sludge	1		81				190		[122]

Activity concentrations for titanium dioxide pigment production– residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Sludge	1		580				1530		[122]
AUSTRALIA	Sand	1		21				54		[122]
AUSTRALIA	Sand	1		8				13		[122]
AUSTRALIA	Sand	1		3				11		[122]
AUSTRALIA	Sand	1		3				5		[122]
AUSTRALIA	Sand	1		19				114		[122]
AUSTRALIA	Sludge	1		24				49		[122]
AUSTRALIA	Sand	1		15				45		[122]
AUSTRALIA	Sand	1		12				24		[122]
AUSTRALIA	Sand	1		8				17		[122]
AUSTRALIA	Sand	1		7				9		[122]
AUSTRALIA	Sludge	1		14				32		[122]
AUSTRALIA	Sludge	1		14				32		[122]
AUSTRALIA	Scale	1		3				7		[122]

Activity concentrations for titanium dioxide pigment production– residues (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Scale	1		15				42		[122]
AUSTRALIA	Scale	1		53				155		[122]
YUGOSLAVIA	Residue	1		94				180		[221]
YUGOSLAVIA	Residue	1		170				300		[221]
YUGOSLAVIA	Residue	1		160				345		[221]

Activity concentrations for titanium dioxide pigment production– products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Titanium dioxide	1		7				22		[122]
YUGOSLAVIA	Titanium dioxide	1		32				31		[221]
INDIA	Titanium dioxide	4					90	40		[222]

Activity concentrations for titanium dioxide pigment production– effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
CZECH REPUBLIC	Liquid effluent	1		5	3			1	5	[220]
CZECH REPUBLIC	Liquid effluent	1	0.15	0.1					1	[220]

Activity concentrations for titanium dioxide pigment production– effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
AUSTRALIA	Liquid effluent	1		11				32		[122]
AUSTRALIA	Liquid effluent	1		9				34		[122]
AUSTRALIA	Liquid effluent	1		2				2		[122]
AUSTRALIA	Liquid effluent	1						5		[122]
AUSTRALIA	Liquid effluent	2		2	1			7		[122]
AUSTRALIA	Liquid effluent	2		1	1			6		[122]
AUSTRALIA	Liquid effluent	2		1	1			5		[122]
AUSTRALIA	Liquid effluent	2		3	4			10		[122]
AUSTRALIA	Liquid effluent	2		3	3			11		[122]
AUSTRALIA	Liquid effluent	2						1		[122]

Activity concentrations for titanium dioxide pigment production– effluents

Country	Material	N. samples	U238 (Bq/L)	Ra226 (Bq/L)	Pb210 (Bq/L)	Po210 (Bq/L)	Th232 (Bq/L)	Ra228 (Bq/L)	K40 (Bq/L)	Ref.
AUSTRALIA	Liquid effluent	1		0.2				0.14		[122]
AUSTRALIA	Liquid effluent	1		0.01				0.1		[122]
AUSTRALIA	Liquid effluent	1						0.1		[122]

MINERAL PROCESSING AND PRIMARY IRON PRODUCTION

Activity concentrations for mineral processing and primary iron – raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
IRAN	Mineral	1		178			139		756	[83]
UNITED KINGDOM	Mineral	1	15							[223]
AUSTRALIA	Mineral	1	300				400			[119]
AUSTRALIA	Mineral	1	60				10			[119]
AUSTRALIA	Mineral	1	31	42	16	39				[119]
AUSTRALIA	Rock	1	20	14	7	92				[119]
USA	Mineral	1	16				13			[123]
USA	Mineral	1	29				23			[123]
USA	Mineral	1	24				3			[123]
USA	Mineral	1	81				115			[123]
USA	Mineral	1	52				1			[123]
AUSTRALIA	Mineral	1	12	11			5	5	63	[67]

Activity concentrations for mineral processing and primary iron – residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
HUNGARY	Residue	1			15000	70000				[223]
HUNGARY	Residue	1			8000	2800				[223]
ITALY	Residue	1			360	422				[4]
ITALY	Residue	1			50	59				[4]
ITALY	Residue	1	3	0.3	181	177	1		3	[218]
ITALY	Residue	1	18	26	665	632	11		83	[218]
ITALY	Residue	1	20	22	1583	1544	11		242	[218]
ITALY	Residue	1	27	32	1167	1058	5		180	[218]
ITALY	Residue	1	15	24	47243	42867	7		6219	[218]
AUSTRALIA	Residue	2	3050				10500			[119]
AUSTRALIA	Residue	1	57	6	5	19				[119]
AUSTRALIA	Residue	1	30		100	1670				[119]
AUSTRALIA	Residue	1	30	24	18900	15600				[119]
TURKEY	Residue	1		198			14		145	[224]
TURKEY	Residue	1		159			15		200	[224]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURKEY	Residue	1		143			12		171	[224]
TURKEY	Residue	1		124			10		143	[224]
TURKEY	Residue	1		108			4		109	[224]
TURKEY	Residue	1		139			3		102	[224]
TURKEY	Residue	1		151			7		206	[224]
TURKEY	Residue	1		158			10		186	[224]
TURKEY	Residue	1		174			9		189	[224]
TURKEY	Residue	1		136			5		105	[224]
TURKEY	Residue	1		81			5		44	[224]
TURKEY	Residue	1		150			8		149	[224]
TURKEY	Residue	1		172			9		173	[224]
TURKEY	Residue	1		200			16		276	[224]
TURKEY	Residue	1		221			8		202	[224]
TURKEY	Residue	1		185			7		216	[224]
TURKEY	Residue	1		98			6		82	[224]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURKEY	Residue	1		113			8		105	[224]
TURKEY	Residue	1		220			6		245	[224]
TURKEY	Residue	1		130			4		142	[224]
TURKEY	Residue	1		49			4		25	[224]
TURKEY	Residue	1		310			175		386	[224]
TURKEY	Residue	1		270			77		274	[224]
TURKEY	Residue	1		179			330		252	[224]
TURKEY	Residue	1		276			84		281	[224]
TURKEY	Residue	1		187			227		290	[224]
TURKEY	Residue	1		178			208		267	[224]
TURKEY	Residue	1		184			193		218	[224]
TURKEY	Residue	1		194			180		271	[224]
TURKEY	Residue	1		172			236		253	[224]
TURKEY	Residue	1		8			7		18	[224]
TURKEY	Residue	1		182			54		189	[224]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
TURKEY	Residue	1		181			51		216	[224]
TURKEY	Residue	1		180			53		208	[224]
TURKEY	Residue	1		116			30		139	[224]
TURKEY	Residue	1		16			12		153	[224]
TURKEY	Residue	1		182			55		204	[224]
TURKEY	Residue	1		135			36		200	[224]
TURKEY	Residue	1		20			11		155	[224]
TURKEY	Residue	1		14			10		137	[224]

PRODUCTION OF PHOSPHATE AND POTASSIUM FERTILIZERS

Activity concentrations for production of phosphate and potassium fertilizers– raw materials

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Rock	1							31	[82]
ITALY	Phosphoric acid	1							19	[82]
AUSTRALIA	Rock	2	458	464			26			[3]
FLORIDA	Rock	2	1700	1800			38			[3]
MOROCCO	Rock	2	1600	1600			105			[3]
JORDAN	Rock	2	1575							[3]
TUNISIA	Rock	2	590	520			92			[3]
TOGO	Rock	2	1360	1200			110			[3]
USA	Rock	2	1850	300			10			[3]
IRAN	Rock	1		1674			61		354	[83]
USA	Rock	10	1263	1460	1441	1355				[84]
USA	Rock	4	692	642	690	648				[84]
ITALY	Rock	1	10	9	13			3	51	[85]
ITALY	Rock	1	19	20	20			5	120	[85]
ITALY	Rock	1	1150	1340	1230			21	32	[85]
ITALY	Rock	1	1400	1550	1060			25	34	[85]
ITALY	Rock	1	1000	1200	1160			19	33	[85]
ITALY	Phosphoric acid	1	1700	6	10				15	[85]
ITALY	Phosphoric acid	1	1900	8	26				20	[85]
ITALY	Phosphoric acid	1	1600	2	7				29	[85]
USA	Rock	6	1425	1391						[86]
USA	Phosphoric acid	1	233	4						[86]

Activity concentrations for production of phosphate and potassium fertilizers– raw materials (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
USA	Phosphoric acid	1	633	7						[86]
USA	Phosphoric acid	1	1110	15						[86]
SPAIN	Rock	1	1650	1610	1660		25	22		[87]
SPAIN	Rock	1	1650	1630	1600		24	19		[87]
SPAIN	Rock	1	1630	1640	1610		22	21		[87]
SPAIN	Rock	1	1680	1380	1440		33	20		[87]
SPAIN	Phosphoric acid	1	1300	4	135					[87]
SPAIN	Phosphoric acid	1	1830	8	109					[87]
NIGERIA	Rock	1		617					324	[51]
MOROCCO	Rock	1		1600			20		10	[51]
ALGERIA	Rock	1		619			64		22	[51]
INDIA	Rock	20	1340	1322						[88]
INDIA	Phosphoric acid	20	2442	6						[88]
SPAIN	Rock	1	1530	1421	1530	1643	20	13	21	[52]
SPAIN	Rock	1	1665	1439	1603	1712				[52]
SPAIN	Phosphoric acid	1	1488	8	106	26	11	7	22	[52]
SPAIN	Phosphoric acid	1	1346	4	55	12		5	15	[52]
SPAIN	Phosphoric acid	1	2888	3	13	3	20	6	12	[52]
BRAZIL	Rock	9	1151	328	843		294	283		[89]
BRAZIL	Rock	9	650	348	495		390	287		[89]
PAKISTAN	Rock	10		428			49		269	[89]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
JORDAN	Rock	10		799			20		148	[89]
EGYPT	Rock	1	523	514			37		19	[54]
EGYPT	Rock	1	408	287	224		24		21	[55]
SYRIA	Rock	9	517	353	590	1197	2			[56]
SYRIA	Rock	9	1039	308	610	1577	3			[56]
BRAZIL	Rock	1	1270	295			3344		1303	[58]
BRAZIL	Rock	1	1356	217			3131		1100	[58]
BRAZIL	Phosphoric acid	1	375	52			458		1	[58]
SUDAN	Rock	1	2598	2663		1868	3		52	[57]
SUDAN	Rock	1	684	555		577	1		23	[57]
TANZANIA	Rock	1		5022			717		286	[64]
TANZANIA	Rock	1	4140				628			[64]
TANZANIA	Rock	1	4641				616			[64]
JORDAN	Rock	15	586	681	628			8	21	[90]
CHINA	Rock	1	152	124	172	125				[91]
CHINA	Rock	1	90	102	70	140				[91]
CHINA	Rock	1	50	44	20	50				[91]
INDIA	Rock	1	1120	908	1130	900				[91]
INDIA	Rock	1	1150	900	1130	920				[91]
INDIA	Rock	1	1150	895	1170	940				[91]
INDIA	Rock	1	1180	940	1180	990				[91]

Activity concentrations for production of phosphate and potassium fertilizers– residues

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Residue	1	720	370	570			7	550	[85]
ITALY	Residue	1	290	172	300			5	2100	[85]
ITALY	Residue	1	860	270	360			8	1040	[85]
ITALY	Residue	1	19	17	25			22	550	[85]
ITALY	Residue	1	22	21	28			27	660	[85]
ITALY	Residue	1	18	15	250			15	530	[85]
USA	Residue	4	2261	2261						[86]
USA	Residue	1	1513	70						[86]
BRAZIL	Residue	1	274	195			579		504	[58]
BRAZIL	Residue	1	353	214			631		532	[58]

Activity concentrations for production of phosphate and potassium fertilizers– products

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Fertilizer	1							13000	[82]
ITALY	Fertilizer	1							15000	[82]
ITALY	Fertilizer	1							26	[82]
ITALY	Fertilizer	1							2380	[82]
ITALY	Fertilizer	1							3920	[82]
ITALY	Fertilizer	1							2750	[82]
ITALY	Fertilizer	1							2790	[82]
ITALY	Fertilizer	1							2200	[82]
ITALY	Fertilizer	1							4810	[82]
ITALY	Fertilizer	1							3830	[82]
ITALY	Fertilizer	1							4400	[82]
ITALY	Fertilizer	1							4400	[82]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Fertilizer	1							4100	[82]
FINLAND	Fertilizer	1	110	43				6	3900	[225]
FINLAND	Fertilizer	1	390	53				6	3900	[225]
FINLAND	Fertilizer	1	140	53				6	3800	[225]
FINLAND	Fertilizer	1	55	2				2	4100	[225]
FINLAND	Fertilizer	1	120	32				6	3700	[225]
FINLAND	Fertilizer	1	240	90				9	3900	[225]
FINLAND	Fertilizer	1	400	44				5	3700	[225]
FINLAND	Fertilizer	1	610	110				2	4100	[225]
FINLAND	Fertilizer	1	600	110				3	4100	[225]
FINLAND	Fertilizer	1	370	96				3	3800	[225]
IRAN	Fertilizer	1		657			4		412	[83]
ITALY	Fertilizer	1							22	[85]
ITALY	Fertilizer	1		2					19	[85]
ITALY	Fertilizer	1							13000	[85]
ITALY	Fertilizer	1							12900	[85]
ITALY	Fertilizer	1							15300	[85]
ITALY	Fertilizer	1							15500	[85]
ITALY	Fertilizer	1	1400	6	36				34	[85]
ITALY	Fertilizer	1	1400	7	37			1	34	[85]
ITALY	Fertilizer	1	1500	7.8	30			2	37	[85]
ITALY	Fertilizer	1	1200	21	230			2	28	[85]
ITALY	Fertilizer	1	240	121	192			3	2200	[85]
ITALY	Fertilizer	1	310	60	78			2	4700	[85]
ITALY	Fertilizer	1	650	69	202			6	4200	[85]
ITALY	Fertilizer	1	330	109	181			3	3900	[85]
ITALY	Fertilizer	1	640	91	210				4300	[85]
ITALY	Fertilizer	1	420	167	250			5	4900	[85]
ITALY	Fertilizer	1	230	124	200			3	30	[85]

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
ITALY	Fertilizer	1	470	148	192			5	5200	[85]
ITALY	Fertilizer	1	340	131	181			4	4300	[85]
ITALY	Fertilizer	1	260	144	223			3	2900	[85]
ITALY	Fertilizer	1	350	230	350			8	2800	[85]
ITALY	Fertilizer	1	310	62	98			2	4500	[85]
ITALY	Fertilizer	1	200	126	156				4000	[85]
ITALY	Fertilizer	1	220	115	210			4	2400	[85]
ITALY	Fertilizer	1	190	131	250			4	25	[85]
ITALY	Fertilizer	1	430	174	280			5	4800	[85]
ITALY	Fertilizer	1	420	160	310			6	4700	[85]
ITALY	Fertilizer	1	600	74	250				4600	[85]
ITALY	Product	1	490	128	170				3400	[85]
ITALY	Product	1	290	151	290				2500	[85]
ITALY	Product	1	280	67	11				3800	[85]
ITALY	Fertilizer	1	960							[205]
ITALY	Fertilizer	1	750							[205]
TURCHIA	Fertilizer	1	1800							[205]
TURCHIA	Fertilizer	1	870							[205]
ITALY	Fertilizer	1	1670							[205]
ITALY	Fertilizer	1	960							[205]
USA	Fertilizer	8	2597	152						[86]
USA	Fertilizer	10	2091	729						[86]
SPAIN	Fertilizer	1	2957	25	150	89	26	5	48	[52]
SPAIN	Fertilizer	1	2488	96	438	344	6	4	44	[52]
PAKISTAN	Fertilizer	10		489			29		46	[53]
PAKISTAN	Fertilizer	10		593			40		361	[53]
PAKISTAN	Fertilizer	10		677			530		156	[53]
PAKISTAN	Fertilizer	10		701			450		24	[53]
PAKISTAN	Fertilizer	10		457			320		837	[53]

Activity concentrations for production of phosphate and potassium fertilizers– products (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
EGYPT	Fertilizer	1	473	301			24		3	[54]
SYRIA	Fertilizer	9	785	709	1037	2410	3			[56]
BRAZIL	Fertilizer	1	394	140			588		132	[58]
BRAZIL	Fertilizer	1	577	189			557		140	[58]
BRAZIL	Fertilizer	1	1007	304			286		5	[58]
BRAZIL	Fertilizer	1	690	262			272		5	[58]
BRAZIL	Fertilizer	1	857	7			408		5	[58]
BRAZIL	Fertilizer	1	538	9			311		5	[58]
BRAZIL	Fertilizer	1	613	5			200		5	[58]
BRAZIL	Fertilizer	1	1159	5			221		5	[58]
BRAZIL	Fertilizer	1	310	280			206		60	[58]
BRAZIL	Fertilizer	1	298	269			185		63	[58]
TANZANIA	Fertilizer	1		3116					362	[64]
TANZANIA	Fertilizer	1		3394					491	[64]
TANZANIA	Fertilizer	1	6819				698			[64]
TANZANIA	Fertilizer	1	6980				632			[64]
TANZANIA	Fertilizer	1	7024				650			[64]
TANZANIA	Fertilizer	1	3879				434			[64]
TANZANIA	Fertilizer	1	3596				408			[64]
JORDAN	Fertilizer	15	1033	37	111			8	38	[90]
CHINA	Fertilizer	1	2	1	2	0.3				[91]
CHINA	Fertilizer	1	3	1	3	0.3				[91]
CHINA	Fertilizer	1	30	7	22	0.18				[91]
CHINA	Fertilizer	1	20	139	132	120				[91]
CHINA	Fertilizer	1	10	137	134	120				[91]
CHINA	Fertilizer	1	45	90	30	89				[91]
INDONESIA	Fertilizer	1	15	9	4	2				[91]
INDONESIA	Fertilizer	1	19	9	5	2				[91]
INDONESIA	Fertilizer	1	98	730	800	603				[91]

Activity concentrations for production of phosphate and potassium fertilizers– products (cont.)

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
INDONESIA	Fertilizer	1	60	656	720	640				[91]
INDIA	Fertilizer	1	80	760	800	618				[91]
INDIA	Fertilizer	1	42	750	845	570				[91]
INDIA	Fertilizer	1	60	757	860	690				[91]
INDIA	Fertilizer	1	70	800	900	770				[91]
INDIA	Fertilizer	1	19	13	2	2				[91]
INDIA	Fertilizer	1	17	13	5	2				[91]
INDIA	Fertilizer	1	18	12	5	1				[91]
INDIA	Fertilizer	1	5	20	5	3.6				[91]
INDIA	Fertilizer	1	9	18	5	3				[91]
INDIA	Fertilizer	1	8	14	3	3				[91]
IRAN	Fertilizer	1								[83]

Activity concentrations for production of phosphate and potassium fertilizers– effluents

Country	Material	No. of samples	U238 (Bq/kg)	Ra226 (Bq/kg)	Pb210 (Bq/kg)	Po210 (Bq/kg)	Th232 (Bq/kg)	Ra228 (Bq/kg)	K40 (Bq/kg)	Ref.
SPAIN	Effluent	1	140			888				[66]
SPAIN	Effluent	1	115			1015				[66]
SPAIN	Effluent	1	129			540				[66]

Activity concentrations for production of phosphate and potassium fertilizers– effluents

Country	Material	N. samples	U238 (Bq/L)	Ra226 (Bq/L)	Pb210 (Bq/L)	Po210 (Bq/L)	Th232 (Bq/L)	Ra228 (Bq/L)	K40 (Bq/L)	Ref.
SPAIN	Effluent	1	1			1				[66]
SPAIN	Effluent	1	12			2				[66]
SPAIN	Effluent	1	4			1				[66]

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