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SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

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ANNEX B

Exposures from natural radiation sources

CONTENTS

thoron decay products similar to that for radon decay products. The value of 40 nSv (Bq h m^{-3})$^{-1}$ for equilibrium equivalent concentrations of thoron, derived in Annex A, "*Dose assessment methodologies*", seems appropriate for evaluating exposures both indoors and outdoors.

155. The concentration of ^{220}Rn is about 10 Bq m^{-3} outdoors and approximately the same indoors. However, it is not possible to use the concentration of the gas in dose evalua-tion, since the concentration is strongly dependent on the distance from the source. Starting with the assumed represen-tative equilibrium equivalent concentrations, as discussed above, the annual effective dose may be derived as follows:

Indoors: 0.3 Bq m^{-3} (EEC) × 7,000 h × 40 nSv (Bq h m^{-3})$^{-1}$ = 0.084 mSv

Outdoors: 0.1 Bq m^{-3} (EEC) × 1,760 h × 40 nSv (Bq h m^{-3})$^{-1}$ = 0.007 mSv

The average annual effective dose from thoron decay products is thus estimated to be 0.09 mSv.

156. For completeness, the contributions to effective dose from two relatively minor pathways of exposure to radon and thoron can be added, namely dissolution of the gases in blood with distribution throughout the body and the presence of radon in tap water. The dose coefficients for radon and thoron dissolved in blood following inhalation intake are those used in the UNSCEAR 1993 Report [U3]. The dose estimate for radon is

Indoors: 40 Bq m^{-3} × 7,000 h × 0.17 nSv (Bq h m^{-3})$^{-1}$ = 0.048 mSv

Outdoors: 10 Bq m^{-3} × 1,760 h × 0.17 nSv (Bq h m^{-3})$^{-1}$ = 0.003 mSv

For thoron, it is

Indoors: 10 Bq m^{-3} × 7,000 h × 0.11 nSv (Bq h m^{-3})$^{-1}$ = 0.008 mSv

Outdoors: 10 Bq m^{-3} × 1,760 h × 0.11 nSv (Bq h m^{-3})$^{-1}$ = 0.002 mSv.

157. Radon in tap water may lead to exposures from the ingestion of drinking water and from the inhalation of radon released to air when water is used. The concentration of radon in water and the release to air were discussed earlier. Although the calculated result is shown below, this is not a separate contribution to the effective dose, since the radon source from water usage would have been included in the measured indoor radon concentrations. The parameters for the inhalation pathway were presented in paragraph 114: concentration in water of 10 kBq m^{-3}, air-water concentration ratio of 10^{-4}, indoor occupancy of 7,000 hours per year. The inhalation dose coefficient applied is that for the gas. The ingestion of tap water was estimated in the UNSCEAR 1993 Report [U3] to be 100, 75, and 50 l a^{-1} by infants, children, and adults. Assuming the proportion of these groups in the population to be 0.05, 0.3, and 0.65, the weighted estimate of consumption is 60 l a^{-1}. A conservative estimate of the ingestion dose coefficient has recently been evaluated [N10]. The estimated exposures from radon in water are therefore

Inhalation: 10 kBq m^{-3} × 10^{-4} × 7,000 h × 0.4 × × 9 nSv (Bq h m^{-3})$^{-1}$ = 0.025 mSv

Ingestion: 10 kBq m^{-3} × 60 l a^{-1} × 10^{-3} m^3 l^{-1} × × 3.5 nSv Bq^{-1} = 0.002 mSv.

158. The total annual effective dose from radon is thus 1.1 mSv from inhalation of ^{222}Rn and its decay products present in air from all sources, 0.05 from radon gas dissolved in blood, and 0.002 from radon gas in ingested tap water (total = 1.15 mSv). The estimates for thoron are 0.09 from inhalation of ^{220}Rn and its decay products and 0.01 from thoron gas dissolved in blood (total = 0.10 mSv).

159. Considering the range of radon exposures determined from survey data and the generally log-normal distribution of such exposures in particular areas, one would expect to find many large populations around the world (~10^6 individuals) whose average exposures differ from the above-estimated global averages by a factor of more than 2, and many smaller populations (~10^4 individuals) whose average exposures differ by a factor of more than 10. Thus the estimates of the global averages are significant primarily because they define the normal radon and thoron exposures and typical effective doses.

III. ENHANCED EXPOSURES FROM INDUSTRIAL ACTIVITIES

160. There are a number of circumstances in which materials containing natural radionuclides are recovered, processed, used, or brought into position such that radiation exposures result. This human intervention causes extra or enhanced exposures. Although any indoor exposure from building materials surrounding the body would fall in this category, such an exposure is considered a normal component of the natural radiation background. The exposures generally included in the category of enhanced exposures are those arising from the mineral processing industries and from fossil fuel combustion.

161. The Committee generally reviews enhanced exposures in its evaluations of natural radiation sources, as in the latest assessment in the UNSCEAR 1993 Report [U3]. The contribution to the total exposure is usually rather minimal. The UNSCEAR 1982 Report [U6] provided more detailed review of enhanced exposures from natural sources, referring to them at that time as technologically modified exposures. There are also some practices that lead to diminished exposures such as paving roads and using building materials of low radioactive content. These alterations in exposures are usually of less significance than those that cause enhanced exposures.

162. In general, the topic of enhanced exposures is receiving greater attention with several meetings devoted to this subject having recently taken place and several publications issued, e.g. [B26, E6, E7, K20, K21, M34]. Since the Committee has not yet undertaken a wider review of this subject, the reader is referred to the topical publications and proceedings for updated information.

163. In this Chapter, exposures of the general public arising from emissions of naturally occurring radionuclides to the environment from industrial activities are reviewed. Industry uses many different raw materials that contain naturally occurring radioactive materials, sometime abbreviated NORM. These raw materials are mined, transported, and processed for further use. The consequent emissions of radionuclides to air and water lead to the eventual exposure of humans. The main industries are identified below, along with the raw materials and by-products or wastes they generate. The radionuclide content of these raw materials and wastes is summarized in Table 27.

164. ***Phosphate processing***. This industry may be subdivided into (a) wet processing, (b) thermal processing, and (c) fertilizer production. The primary product is phosphoric acid. In the thermal process, the product may be phosphorus or, using nitric acid, phosphoric acid. Phosphoric acid is used in the manufacture of fertilizers. In the wet phosphate processing industry, phosphogypsum is produced as a by-product. The thermal process (using cokes and silica) produces a slag ($CaSiO_3$) as a waste product.

165. ***Metal ore processing***. Important metal ores are cassiterite or tinstone (tin), tantalite, columbite, fergusonite, koppite, samarskite, and pyrochlore (niobium, iron, manganese, and others). Most of the metals are separated using charcoal or coke. Furnace slag from the processing is often used in cement production. Another by-product, tar coal, is used to produce electrode pitch, creosote oil, carbolineum, soot oil, and road tar mix.

166. ***Uranium mining***. There are several locations that contain the residues of former uranium mining operations, for example, in eastern Germany [B29, E9, R23]. The procedures to deal with the landfills, waste rock and slag piles and the radiological consequences are being evaluated.

167. ***Zircon sands***. Important zirconium minerals are zircon ($ZrSiO_4$) and baddeleyite (ZrO_2). Sorting discriminates these minerals from other heavy minerals or simple silica. The processing involves procedures such as sieving, washing, drying, and grinding. These processes do not produce any specific waste products.

168. ***Titanium pigment production***. Titanium pigments include titanium dioxide (TiO_2) and synthetic rutile. Processing waste products include large quantities of cokes, ore and SiO_2 particles, and filter cake (classified as chemical waste).

169. ***Fossil fuels***. For electric power production the most important fossil fuels are coal, natural gas, and oil. Large amounts of fly ash and bottom ash result from coal combustion. Gypsum is recovered if a desulphurization installation is present.

170. ***Oil and gas extraction***. The large volumes of production water needed for the extraction of oil and gas may contain natural radionuclides, mainly ^{226}Ra and its decay products. Scalings may form as a result of precipitation at the oil/water interface, or radon decay products (especially ^{210}Pb and ^{210}Po) may be deposited in the installations.

171. ***Building materials***. Materials used by the building industry that may be of radiological significance include marl, blast furnace slag, fly ash, Portland clinker, and anhydrate (in the cement industry) and clay (in the ceramics industry). In the cement industry, some silex is produced as a waste product.

172. ***Thorium compounds***. Thorium is used mainly as an additive in other products, such as welding electrodes, gas mantles, and special alloys and is retrieved from monazite, thorite, or thorianite. The activity content of the compounds is present mainly in the primary product, metallic thorium.

173. ***Scrap metal industry***. Scrap metal such as tubing, valves, and heat exchangers from various process industries may contain scales with enhanced levels of natural radionuclides. The particular radionuclides and their concentrations would depend on the origin of the scrap. Since objects from nuclear industries and the uncontrolled releases of radioactive sources may add to this material, which may be recycled, the scrap-metal industry is a source of variable and heterogenous releases of radionuclides into the environment.

174. ***Emissions***. The natural radionuclides present in the raw materials or wastes of these industries are those of the ^{238}U and ^{232}Th series. Releases are mainly to air or water, although landfills after dredging or wastes disposed on land may also provide pathways of exposure.

175. Emissions of radionuclides to air and water from these industries are listed in Table 28. The throughput of ore or raw material is for a typical installation. One of the main radionuclides released to air is ^{222}Rn. It is released by the phosphate and cement industries, gas and oil extraction, gas-fired power production, and, generally, industries that burn natural gas. For example, in the phosphate industry, enhanced radon concentrations between 35 and 780 Bq m^{-3} have been observed, depending on the working area and season [V6]. Important sources of ^{210}Pb to air are the elementary phosphorus and iron and steel production industries. Cement production gives rise to much of the ^{210}Po released. Brick and tile installations may also be of importance because they are so numerous.

176. A special problem is imposed by the storage of uranium-containing minerals in museums [V6]. In a museum in Brussels, where radium- and uranium-containing minerals

from Katanga were stored, concentrations of radon of about 10-15 kBq m^{-3} were found in spite of enhanced ventilation. Besides radon emissions, high levels of gamma radiation were also observed in the vicinity of the storage rooms. In the house of the museum caretaker who lived nearby, gamma levels of 5-6 μSv h^{-1} were found. After shielding of the minerals, the radiation level was reduced to 1-2 μSv h^{-1}.

177. The radionuclides released to the atmosphere by large thermal processes such as those used by elementary phosphorus production, iron and steel production, and the cement industry, are dispersed over great distances. Smaller thermal processes, such as the brick and tile industry, are also sources of airborne releases. For other mineral processing industries, dusty conditions during handling and shipment of ores are the main reason for the releases of radionuclides to air. In those circumstances, the rather coarse particles are generally released mainly to the immediate surroundings of the plant.

178. The largest releases of radionuclides to water are from the phosphate processing, followed by oil and gas production and primary iron and steel production. As an example, two phosphoric acid plants in the Netherlands are responsible for some 90% of all discharges of ^{210}Pb and ^{210}Po to water [L18]. These two plants release about 0.6-0.8 TBq of ^{226}Ra per year [L24], which is comparable to the estimated annual release of ^{226}Ra with process water into the North Sea by the offshore oil production industry in the United Kingdom, Norway, the Netherlands, and Denmark [L25]. Annual releases into rivers of ^{226}Ra and of ^{226}Ra present in diluted brines from single Upper Silesian coal mines may be as high as 20 and 30 GBq, respectively, resulting in locally enhanced concentrations in bottom sediments [L26, S63].

179. The large amounts of gypsum slurry discharged in phosphoric acid production may be released into the sea as is the case in the Netherlands, but industrial wastes are sometimes also stored on land or in large landfills. Radionuclides released to water in, for example, discharges from oil and gas extraction offshore are generally diluted by the large volumes of water involved. Onshore process water is often pumped back into the oilfield. The treatment of production waters before they are released may significantly reduce the radionuclide concentration [L26].

180. Enhanced levels of radionuclides in the environment can come from the processing and use of scrap and recycled metals [B28, L22]. Although in general extensive measures are taken to ensure the continuous quality of the scrap and the new metal that is manufactured from it, enhanced radiation levels are sometimes found. The number of reports on such incidents is growing, partly because of increased awareness of the problem and partly because more measurements are being made. The enhanced exposures may arise from lost radium radiation sources or from naturally occurring radionuclides in pipes with scale containing enhanced concentrations [T15]. Similar problems arise from man-made sources, for example, ^{22}Na, ^{54}Mn [W15], ^{60}Co [C31], ^{137}Cs [B27, J12] or ^{192}Ir, leading to contaminated scrap and recycled metals. The levels vary greatly, and the consequences depend on specific local circumstances.

181. ***Exposures.*** Both external and internal exposures may result from naturally occurring radionuclides released by industrial activities. In general, installations are located away from residential areas, and because external radiation levels decrease with distance from the plant, local residents are not significantly exposed. The workers, however, may receive low doses in connection with ore stock piles or waste deposits. Estimated and measured doses are in the range 0.1-300 μSv a^{-1} from direct exposures, with the higher values for locations near mineral-sands-handling industries. The maximum effective doses are summarized in Table 29.

182. Radionuclides dispersed in air may contribute to external irradiation while airborne and after deposition. The contributions to total dose appear to be negligible. Inhalation and ingestion are the pathways that contribute to internal exposure. Inhalation contributes to exposure only in the vicinity of the plant, particularly with mineral-sands-processing plants. Doses depend on distance and could be up to 50 μSv a^{-1} for office workers in a building just outside the plant site [L18].

183. Because most food products consumed by individuals are produced in large agricultural regions, possible dose from ingestion of radionuclides are small. For a typical situation, a small population in the vicinity of an elementary phosphorus plant, the calculated dose would be of the order 100 μSv a^{-1} [L18]. More generally, the estimated doses would be 1-10 μSv a^{-1}. Ingestion doses that could result from discharges of wastes to water are negligible compared to those by the other pathways.

184. In the United Kingdom, the doses from sintering plants of the steel industry to critical groups of the population were calculated to be between about 1.5 and 18 μSv a^{-1}. The highest dose was attributed to a sinter site with relatively low stacks. Inhalation contributed less than 22%, with the main exposure route being the ingestion of food. The annual collective dose calculated for the population (to a distance of 3,000 km) was estimated to be between about 2.9 and 5.5 man Sv [H33].

185. Penfold et al. [P10] made a pilot study of the radiological impact of coal-fired stations in the United Kingdom. Various pathways of exposure were considered. The highest dose rate for a critical group (about 250 μSv a^{-1}) came from the use of fly ash in building materials. Other pathways caused dose rates for critical groups between 0.07 and 55 μSv a^{-1}.

186. The radiation exposure of critical groups of the population surrounding a site with a wood-chip-burning oven was determined in a Swedish study [H34]. The maximum individual dose rate was found to be 2.4 nSv a^{-1}.

187. Annual per caput effective doses from process industries documented in the UNSCEAR 1993 Report ranged from 1 nSv to 20 μSv and for critical groups up to about 1 mSv. Those mentioned above and other more recent data are for very specific situations or critical groups. On the whole, however, they are in agreement with the earlier estimates, and they support the conclusions of the UNSCEAR 1993 Report [U3].

188. ***Summary.*** The industrial activities enhancing exposure from natural sources involve large volumes of raw materials containing natural radionuclides. Discharges from industrial plants to air and water and the use of by-products and waste materials may be the main contributors to enhanced exposure of the general public. For typical industries and releases, exposures occur primarily in close proximity to the plants. A complete review is made difficult by the diversity of industries involved and the local circumstances associated with the exposures. Estimated maximum exposures are greatest for phosphoric acid production and the mineral-sands-processing industries. Although exposure rates of the order of 100 μSv a^{-1} could be received by a few local residents, levels of 1-10 μSv a^{-1} would be more common. These exposure rates constitute a negligible component of the total annual effective dose from all natural sources of radiation.

IV. WORLDWIDE AVERAGE EXPOSURE FROM NATURAL SOURCES

189. The components of exposure caused by natural radiation sources have been reassessed in this Annex based on new information and data from measurements and on further analysis of the processes involved. These exposure components can now be added to provide an estimate of the total average exposure. It must first be stated that the average exposure probably does not pertain to any one individual, since there are wide distributions of exposures from each source and the exposures combine in various ways at each location, depending on the specific concentrations of radionuclides in the environment and in the body, the latitude and altitude of the location, and many other factors.

190. In a few countries the proportion of the population at various levels of total exposures has been assessed. These data are included in Table 30, and the combined distribution is shown in Figure XV. The average annual exposure for this distribution is 2.0 mSv. The distribution rises in a few dose intervals to the peak exposure and then tails off to decreasing population at doses 2 to 3 times the average. To smooth the distribution somewhat, most exposure intervals have been subdivided. The general shape of the distribution is probably fairly relevant. Although populations living in areas of high background exposures are not well represented in this particular distribution, they would not be expected to be a prominent feature, in part because not all components of their exposure are enhanced at the same time and because there is a relatively small proportion of the population of most countries with significantly elevated exposures.

191. Average worldwide exposure determined by adding the various components is summarized in Table 31. The changes from the earlier assessment of the Committee [U3] are also indicated. There are only rather minor changes for the exposure components. The worldwide average annual exposure to natural radiation sources remains 2.4 mSv. Neither the magnitude nor the precision of this estimate should be overemphasized. As indicated in Figure XV, based on the sample population of Table 30, a broad distribution of exposures would be expected in any large population.

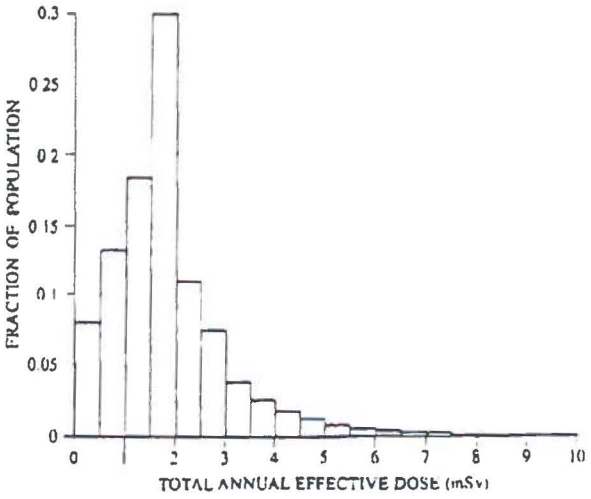

Figure XV. Distribution of population of fifteen countries with respect to total annual effective dose.

192. The normal ranges of exposures to the various components of natural radiation are indicated in Table 31. This accounts for common variations in exposures but excludes those individuals at the extreme ends of the distributions. On this basis, worldwide annual exposures to natural radiation sources would generally be expected to be in the range 1 10 mSv, with 2.4 mSv being the present estimate of the central value.

CONCLUSIONS

193. Since exposures to natural radiation sources are more significant for the world's population than most exposures to man-made sources, the natural background baseline warrants evaluation in some detail. Efforts should continue to broaden the database used for determining both representative values and extremes in exposures and to improve dosimetric procedures.

194. Because of the wide variations in natural background exposures even within relatively small regions, more efforts will be required to determine the detailed distributions of populations within dose intervals for the various components of exposure. Initial, still limited evaluations of distributions of external exposures outdoors and indoors and of the total exposure have been presented in this Annex. These evaluations seem to reveal patterns that would be expected to be generally valid for other countries and for the world population as a whole. The analysis of distributions will provide an improved basis for deriving worldwide average exposures and their normal and extreme variations.

195. The main uncertainties in the assessment of dose from natural radiation sources arise less from the limited number of measurements than from the complications of the dosimetric considerations. The situation with respect to radon decay products is well known, but similar problems exist for cosmic radiation and ingested radionuclides. For cosmic radiation, more information is needed on exposures to neutrons at all altitudes and latitudes, especially high-energy neutrons and high-Z nuclei at aircraft altitudes, along with critical data or improved models to allow a reasonable estimation of effective doses from these components of the radiation field. For ingested radionuclides, good dosimetric models are available, but the problem is to estimate representative intake amounts of the radionuclides and associate them with relatively fewer determinations of concentrations in tissues of the body.

196. There are many circumstances in which individuals receive enhanced exposures to natural radiation. Living inside buildings is considered normal in this regard, and flying in airplanes usually involves an insignificant proportion of most people's time. In the past, the Committee has reviewed the exposures caused from the release of natural radionuclides in mineral processing industries, the use of phosphate fertilizers, and the combustion of fossil fuels. These enhanced exposures are usually quite insignificant compared with the normal background exposure from natural sources. This conclusion is still valid, based on a brief review of new information in this Annex.

197. The evaluations in this Annex of exposures from natural radiation sources indicate that the average annual effective dose to the world population is approximately 2.4 mSv, which is the same as the previous estimate of the Committee [U3]. The value of the estimated average exposure should not be taken to be too precise, since broad averaging is involved. For individuals, annual exposures ranging from 1 mSv to two or three times the world average are frequently encountered. It is estimated that about 65% of individuals have exposures between 1 and 3 mSv, about 25% of the population have exposures less than 1 mSv, and 10% have exposures greater than 3 mSv. Although the database continues to expand and characterization of the distributions of populations with respect to the various components of natural background radiation is being improved, the generally assessed exposure levels to which the broad spectrum of the world population is exposed seem reasonably well substantiated.

Table 11
Areas of high natural radiation background

Country	*Area*	*Characteristics of area*	*Approximate population*	*Absorbed dose rate in air [a] (nGy h^{-1})*	*Ref*
Brazil	Guarapari	Monazite sands; coastal areas	73 000	90-170 (streets) 90-90 000 (beaches)	[P4, V5]
	Minas Gerais and Goias			110-1 300	[A17, P4]
	Pocos de Caldas Araxá	Volcanic intrusives	350	340 average 2 800 average	[V5]
China	Yangjiang Quangdong	Monazite particles	80 000	370 average	[W14]
Egypt	Nile delta	Monazite sands		20-400	[E3]
France	Central region	Granitic, schistous, sandstone area	7 000 000	20-400	[J3]
	Southwest	Uranium minerals		10-10 000	[D10]
India	Kerala and Madras	Monazite sands, coastal areas 200 km long, 0.5 km wide	100 000	200-4 000 1 800 average	[S19, S20]
	Ganges delta			260-440	[M13]
Iran (Islamic Rep. of)	Ramsar	Spring waters	2 000	70-17 000	[S21]
	Mahallat			800-4 000	[S58]
Italy	Lazio	Volcanic soil	5 100 000	180 average	[C12]
	Campania		5 600 000	200 average	[C12]
	Orvieto town		21 000	560 average	[C20]
	South Toscana		~100 000	150-200	[B21]
Niue Island	Pacific	Volcanic soil	4 500	1 100 maximum	[M14]
Switzerland	Tessin, Alps, Jura	Gneiss, vercano, ^{226}Ra in karst soils	300 000	100-200	[S51]

[a] Includes cosmic and terrestrial radiation.

Table 12
Distribution of population with respect to the indoor absorbed dose rate in air from terrestrial gamma radiation

Region / country	*Population (10^3) residing in areas with various levels of indoor absorbed dose rate in air*											
	< 20 nGy h^{-1}	*20-29 nGy h^{-1}*	*30-39 nGy h^{-1}*	*40-49 nGy h^{-1}*	*50-59 nGy h^{-1}*	*60-69 nGy h^{-1}*	*70-79 nGy h^{-1}*	*80-89 nGy h^{-1}*	*90-99 nGy h^{-1}*	*100-199 nGy h^{-1}*	*200-299 nGy h^{-1}*	*>300 nGy h^{-1}*
North Europe												
Denmark		80	300	600	1 100	1 300	1 000	600	200	50	10	
Finland		144	633	779	636	398	474	491	470	1 122		
Lithuania			23	145	239	633	746	798	338	807		
West Europe												
Belgium			600	2 000	2 500	2 500	2 000	620				
East Europe												
Bulgaria					270	3 362	2 370	2 572	201	102		
Hungary	245	581	306	245	357	696	696	903	1 150	4 988	17	16
Romania			23	272	1 498	2 293	5 538	7 038	5 176	794	68	
Russian Federation		460	7 670	20 970	21 020	24 660	12 810	4 860	38 670	16 980		
South Europe												
Greece			329	900	5 536	1 043	1 135	417	293	603		
Italy	800	2 175	4 225	5 400	4 400	3 975	4 850	8 500	6 800	8 875	4 025	3 250
Spain					1 115	5 490	1 285	8 908	4 015	15 584	906	
Total	1 045	3 440	14 109	31 311	38 671	46 350	32 904	35 707	57 313	49 905	5 026	3 266
Fraction of total	0.003	0 011	0.044	0.10	0 12	0.15	0.10	0.11	0.18	0.16	0 016	0.010
Cumulative total	1 045	4 485	18 594	49 905	88 576	134 927	167 831	203 537	260 851	310 755	315 781	319 047
Cumulative fraction	0.003	0.014	0 058	0.16	0.28	0.42	0.53	0 64	0 82	0.97	0.99	1.000

Table 13
Reference annual intake of air, food, and water
[I7, W1]

Intake	*Breathing rate ($m^3 a^{-1}$)*		
	Infants (1 year)	*Children (10 years)*	*Adults*
Air	1 900	5 600	7 300

Intake	*Food consumption rate ($kg a^{-1}$)*		
	Infants	*Children*	*Adults*
Milk products	120	110	105
Meat products	15	35	50
Grain products	45	90	140
Leafy vegetables	20	40	60
Roots and fruits	60	110	170
Fish products	5	10	15
Water and beverages	150	350	500

Table 14
Concentrations of uranium and thorium series radionuclides in air

Region / country	*Concentration ($\mu Bq\ m^{-3}$)*									*Ref.*
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
North America										
United States	0.9 - 5	0.6	0 6	100-1 000	10-40	0.4		1 0	0.04	[F3, L8, M15, P5, W6]
Europe										
Germany	0.3 - 1 7	0.3 - 1.7	1 2 3 3	28 - 2 250	12-80	0.2 - 0.9	<0.3-1.5			[H31, K4, K10]
Netherlands				410						[N21]
Norway	0.02 - 0.06	0.02 0.07				0.01 - 0.07				[K4]
Poland	1 - 18		0 8 - 32	<40 - 710						[K5]
Switzerland				200-2 000						[S51]
Reference value	1	0.5	1 (0 5) [a]	500	50	0.5 (1) [a]	1	1	0.05	[U3]

a Revised value; previous value [U3] in parentheses.

Table 15
Concentrations of uranium and thorium series radionuclides in foods and drinking water

Region / country	Concentration (mBq kg^{-1})									Ref.
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
Milk products										
North America United States	0.7	0.4	5.7	11		0.27			0.05	[F3, M16]
Asia China India Japan	13 17 0.55		6 12	16	13 15	1.2 0.29	21		0.6	[Z1] [D6, K6] [S22]
Europe Italy Germany Poland Romania U.K	 2.6 0.1-4.9	 1.2 	 3-19 2-130 10 0.9-44 <0.4-200	 5-280 18 11-15 35-88	 2-80 16 13-140 20-220	 1.2 	 	 56	 	[M17] [B3, J4, M18] [P3, P7] [B20,R20] [B2]
Reference value	1	0.5	5	15 (40) [a]	15 (60)	0.3	5	0.3	0.05	
Meat products										
North America United States	0.8-2.3	0.5-3	20	18		0.3-2			0.02	[F3,M16]
Asia China India Japan	10 13		41 36	140	120 440	4.3 2.3	120		0.5	[Z1] [K6] [S22]
Europe Germany Poland Romania U.K.	1-20 1.6-5.6 4.9	 0.7-3.0 	30-220 11-19 2-30 2.6-74	100-1 000 98-105 15-19 40-3 700	37-4 000 99-102 38-110 62-67 000	 0.5-3.6 	 	 22-93	 	[B3, G5,M18] [P3, P7] [B20,R20] [B2]
Reference value	2	2	15	80	60	1	10	1	0.05	
Grain products										
North America United States	3-23	0.9-10	7-100	33-81		0.1-2.8			0.1-1.3	[F3,M16]
Asia China India Japan	9.8 7.4-67 1.2		17 14	34	42 15-120	13 1.2	38		0.5	[Z1] [D6, K6] [S22]
Europe Germany Poland Romania U.K	20-400 4.7-11 6.1-85 6.2-35	 1.4-17 	20-2 900 80-110 30-90 0.7-5 200	40-4 000 110-160 49-59 56-120	37-1 900 90-140 20-360 27-260	 2.0-21 1.6-33 12	 	 180-2300	 	[B3, G5] [P3, P7] [B20,R20] [B2]
Reference value	20	10	80	50 (100)	60 (100)	3	60	3	1	
Leafy vegetables										
North America United States	24	20	56	41		18			1.2	[F3,M16]
Asia China India	16 61-72		75	360	430 320	23	220		0.7	[Z1] [D6, K6]

Table 15 (continued)

Region / country	Concentration ($mBq\ kg^{-1}$)									Ref.
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{234}U	
Europe										[B3,
Germany	6-2 200		6-1 150	4-4 100	4-7 400					G5,M18]
Italy			27-44							[D9]
Poland	14-15	6-9	37-43	43-51	40-67	4-7				[P3, P7]
U.K.	9.8-400	80-380	2.2-170	16-3 300	37-3 300					[B2]
Reference value	20	20	50	80 (30)	100 (30)	15	40	15	1	
Root vegetables and fruits										
North America										
United States	0.9-7.7	0.2-1.1	7-47	8-150		0.08-1.4			0.1	[F3,M16]
Asia										
China	13		63	27	29	4.7	110		0.6	[Z1]
India	0.4 77				16-140					[D6, K6]
Japan	26		11			2.3				[S22]
Europe										[B3,
Germany	10-2 900		5-9 400	20-4 900	22-5 200					G5,M18]
Italy			14-25							[D9]
Poland	0.9-10	0.7 7.5	11-215	24-93	28-210	0.7 7.1				[P3, P7]
Romania	6 120		9-190	19 44	12-140	0.4-2.1		22		[B20,R20]
U.K.	6		9.0-41	18-76						[B2]
Reference value	3	0.5	30	30 (25)	40 (30)	0.5	20	0.5	0.1	
Fish products										
North America										
United States	13-1 900	1.2-29	30 59	14-1 800	150-55 000	1.2-30			0.4-90	[F3, M16, S23]
Asia										
China	12		39	3 500	4 900	1.3	320		0.5	[Z1]
Europe										
France			37							[P6]
Germany			100-7 400	20-4 400	50-5 200					[G5,M18]
Poland			28-43	81 93	3 100-3 800					[P7]
Portugal					80-120 000					[C14]
U.K.	2.5		8 5-2 100	180-4 800	60-53 000			56-700		[B2]
Reference value	30	10	100	200	2 000	10		100		
Drinking water										
North America										
United States	0 3-77	0 1	0.4-1.8	0.1 1.5		0.05	0-0.5		0.04	[C15, F3, H11, M20]
Asia										
China	0.1 700		0.2 120			0 04-12				[N3]
India	0.09-1.5									[D6]
Europe										
Finland	0.5-150 000		10-49 000	0.2-21 000	0.2-7 600		18-570			[A16,S11]
France	4.4-930		7-700			0-4.2				[D8, P6]
Germany	0.4-600		1 1 800	0.2-200	0.1-200					[B3, G5, G6]
Italy	0.5-130		0.2 1200							[S55]
Poland	7.3	1.4	1 7 4.5	1.6	0.5	0.06				[P3, P7]
Romania	0.4-37		0.7-21	7-44	7-44	0.04-9.3				[B20,R20]
Switzerland	0-1 000		0-1500				0-200		0-50	[S51]
Spain	3.7-4.4		<20-4 000							[S24]
U.K.			0-180	40-200						[B2]
Reference value	1	0.1	0.5	10	5	0.05	0.5	0.05	0.04	

[a] Revised value with previous value [U3] (if different) in parentheses.

Table 16
Annual intake of uranium and thorium series radionuclides in diet

Region / country	Annual intake (Bq)									Ref.
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
North America										
Puerto Rico			9.1							[H13]
United States	5.5-6.2	2.2-3.7	10-24	16-23	22	1.1-2.2	13-16	7.3-8.0		[B8, F3, F5, H12, L9, M23, M24, P8, S31, S33, W6]
South America										
Argentina			9.5		18					[B7, U8]
Brazil			40				40			[L10, P9]
Asia										
China	57		12-32	75-110	68-130	9.3	66		2.6	[L16, Y5, Y6, Z1]
India	2.9		8.8	46	20	3.3	47			[C16, D5, L11, S41]
Japan	3.2-6.6	0.6	9-15	73-80	220	0.6-0.8				[K7, N13, S22, S27, S42, S45]
Europe										
Belgium			16							[S28]
Bulgaria				22-28						[K8]
Czech Rep.			40							[T6]
France	4.4		14-19	18						[G7, S32, U8]
Germany	11	3.4	40	62		2.2	17	17		[F4, G8, M22]
Italy			11-19	40	40					[C17, D9, M21]
Netherlands			27							[S28]
Poland	6.4	2.1	19-20	45	44	1.2				[P3, P7]
Romania	5.8		19	57	51	2.2		2.2		[I12]
Russian Fed.	16			55-84	40-55					[D7, L12]
U.K.	4.4		11-16	16-30	28-44					[C18, H14, H15, S29, S30]
Reference value [a]	5.7	3.0	22	30	58	1.7	15	3.0	0.2	

a Intake by adults; consumption rates from Table 13 and reference concentrations in foods and water from Table 15.

Table 17
Annual effective dose from inhalation of uranium and thorium series radionuclides

Radionuclide	Concentration in air ($\mu Bq\ m^{-3}$)	Effective dose coefficient [19] ($\mu Sv\ Bq^{-1}$)			Committed effective dose [a, b] (μSv)			
		Infants	Children	Adults	Infants	Children	Adults	Age-weighted
^{238}U	1	9.4	4	2.9	0.018	0.022	0.021	0.021
^{234}U	1	11	4.8	3.5	0.021	0.027	0.026	0.026
^{230}Th	0.5	35	16	14	0.033	0.045	0.051	0.048
^{226}Ra	1	11	4.9	3.5	0.021	0.027	0.026	0.026
^{210}Pb	500	3.7	1.5	1.1	3.5	4.2	4.0	4.0
^{210}Po	50	11	4.6	3.3	1.0	1.3	1.2	1.2
^{232}Th	0.5	50	26	25	0.048	0.073	0.091	0.084
^{228}Ra	1	10	4.6	2.6	0.019	0.026	0.019	0.021
^{228}Th	1	130	55	40	0.25	0.31	0.29	0.29
^{235}U	0.05	10	4.3	3.1	0.001	0.001	0.001	0.001
Total					5.0	6.0	5.8	5.8

a Assumed breathing rates: infants 1,900 $m^3\ a^{-1}$, children 5,600 $m^3\ a^{-1}$, adults 7,300 $m^3\ a^{-1}$.
b Committed effective dose from the annual intake. Age distribution for weighted values: infants 0.05, children 0.3, adults 0.65.

Table 18
Annual intake and effective dose from ingestion of uranium and thorium series radionuclides

Radionuclide	Activity intake [a] (Bq)			Effective dose coefficient [12, 121] ($\mu Sv\ Bq^{-1}$)			Committed effective dose [b] (μSv)			
	Infants	Children	Adults	Infants	Children	Adults	Infants	Children	Adults	Age-weighted
^{238}U	1.9	3.8	5.7	0.12	0.068	0.045	0.23	0.26	0.25	0.25
^{234}U	1.9	3.8	5.7	0.13	0.074	0.049	0.25	0.28	0.28	0.28
^{230}Th	1.0	2.0	3.0	0.41	0.24	0.21	0.42	0.48	0.64	0.58
^{226}Ra	7.8	15	22	0.96	0.80	0.28	7.5	12	6.3	8.0
^{210}Pb	11	21	30	3.6	1.9	0.69	40	40	21	28
^{210}Po	21	39	58	8.8	2.6	1.2	180	100	70	85
^{232}Th	0.6	1.1	1.7	0.45	0.29	0.23	0.26	0.32	0.38	0.36
^{228}Ra	5.5	10	15	5.7	3.9	0.69	31	40	11	21
^{228}Th	1.0	2.0	3.0	0.37	0.15	0.072	0.38	0.30	0.22	0.25
^{235}U	0.1	0.2	0.2	0.13	0.071	0.047	0.011	0.012	0.012	0.011
Total							260	200	110	140

a Consumption rates from Table 13 and concentrations in foods and water (reference values) from Table 15.
b Committed effective dose from the annual intake. Age distribution for weighted values: infants 0.05, children 0.3, adults 0.65.

Table 27
Typical concentrations of radionuclides in raw and produced materials and in wastes of the mineral processing industry

Material	*Typical concentration in ore / raw material (kBq kg^{-1})*		*Typical concentration in product or tailings / wastes (kBq kg^{-1})*	
	^{238}U-series	*^{232}Th-series*	*^{238}U-series*	*^{232}Th-series*
Phosphate industry				
Phosphate	0.2 - 1.5 1.5 (Florida ore) 0.03 (Kovdor ore) 0.11 (Palfos ore)	0.02 (Florida ore)	0.9 - 1.3 [a] 100 (^{210}Po) 600 (^{210}Pb) in calcinate 1 (Phosphorus slag)	0.02 (Phosphorus slag)
Artificial fertilizer	0.3 - 3 0.2 - 1 (^{226}Ra and ^{210}Pb) 2.2 (TSP)	0 008 - 0.04 0.005 (TSP)		
Rare earths, thorium compounds				
Monazite	6 - 40	4% (by weight) 8 - 300	450 [b]	3000 [b]
Oil and gas extraction				
Natural gas Oil	0.34 kBq m^{-3} (^{222}Rn)		(Scale) 1 - 1 000 (scale) 8 - 42 kBq m^{-3} (production water)	
Metal ores				
Iron ore			0.1 - 0.3 (coal tar) 0.15 (blast furnace slag) / zinc-rich filtercake	0.15 (blast furnace slag)
Cassiterite Pyrochlore	1 6 - 10	0.3 7 - 80	1 (slag)	4 (slag)
Coal tar treatment				
Coal tar	0.1 - 0.3 (^{210}Po and ^{210}Pb)		0.2 - 0 6 (electrode pitch)	
Cokes and electric power production				
Coal	0.01 - 0 025	0.01 - 0.025	0.02 - 0.04 (cokes) 0.1 - 0.3 (coal tar) 0.2 (fly and bottom ash) 0.4 (fly dust)	0 2 (fly dust)
Cement industry				
Marl	0.022	0.003	0 05 - 0.11 (cement) 0 02 (silex)	0.03 - 0.1 (cement) 0.003 (silex)
Schist Portland clinker	0.04 0 08	0.056 0.05		
Mineral sands handling				
Zirconium sand Bauxite Ilmenite Rutile	0.2 - 74 0.4 - 0.6 2.3 (1.5 : ^{238}U) 3.8	0.4 - 40 0.3 - 0.4 1.2 0.56	Rutile	
Titanium pigment production				
Ilmenite Titanium ore	2.3 (1.5 : ^{238}U) 0.07 - 9	1.2 0.07 - 9	400 [c] 0.15 (VBM) 2.3 (filtercake) 0.03 (water)	up to 1 500 (scale) 0.13 (VBM) 2.6 (filtercake) 0.01 (water)

a Phosphogypsum, Central Florida ore.
b ^{226}Ra in sulphate precipitate.
c ^{226}Ra precipitate.

Table 28
Release of radionuclides from typical installations of mineral processing industries
[L18]

Industry	*Ore throughput (kt a^{-1})*	*Releases to atmosphere (GBq a^{-1})*							*Releases to water (GBq a^{-1})*						
		^{238}U	^{232}Th	^{226}Ra	^{222}Rn	^{210}Pb	^{210}Po	^{40}K	^{238}U	^{232}Th	^{226}Ra	^{222}Rn	^{210}Pb	^{210}Po	^{40}K
Elementary phosphorus	570				563	66	490		-	-	-	-	24	166	-
– Transport		0.06	0.001	0.06	0.03	0.06	0 06	0 004	0.18	0 002	0.18	0.18	0.18	0.18	0.013
Phosphoric acid	700	0 07	0.002	0.09	820	0.08	0 14	0.008	336	8	737	-	654	997	79
Fertilizer plant	375				221	0.044	0.034		-	-	-	-	0.054	0.057	-
– Transport		0.02	0.0001	0 02	0.02	0 02	0.02	0.001	0.07	0.0004	0 07	0.07	0.07	0.06	0.002
Iron and steel production	7 500				180	55	90		-	-	-	-	0 51	8	-
– Transport		0 01	0.01	0.01	0.01	0.01	0 01	0.01	0 03	0.03	0.03	0.03	0 04	0.04	0.04
Coal tar treatment	120					-0	-0		-	-	-	-	-	-	-
Coal-fired power plant (600 MW e)	1 350	0.16	0 08	0.11	34	0.4	0.8	0.27	-	-	-	-	-	-	-
– Transport		0.004	0 004	0 004	0.004	0.004	0.004	0 012	0.011	0.011	0.011	0.011	0.011	0.011	0.036
Coke production	885	0.013	0.009	0 013	13	0 012	0.07	0.032	-	-	-	-	0.024	0.032	-
– Transport		0.001	0.001	0.001	0.001	0.002	0.001	0 004	0.004	0.003	0.004	0.004	0 005	0.004	0.011
Cement industry	2 000	0.2	0.05	0.2	157	0.2	78	0.4	-	-	-	-	-	-	-
Ceramics	3 200	0.03		0 03	0.03	0.09	0.3	0.14	-	-	-	-	-	-	-
Mineral sands handling	183 [a]	0.97	0.12	0 73	0.73	0.73	0.73		0.088	0.011	0 066	0.066	0.066	0.066	-
Titanium pigment	50	0 001	0 001	0.001	6 2	0.001	0 001		0 002	0.003	0.002	0.002	0.003	0.002	-
Gas-fired power plant (400 MW e)	600 [b]				230				-	-	-	-	-	-	-
Oil extraction	3 500				540					217	174	174	174	174	
Gas extraction	72 000 [b]				500					2.7	32	32	32	32	

a Zirconium.
b 10^6 m^3 a^{-1}.

Table 29
Maximum effective doses from natural radionuclides released from typical installations or operations of the mineral processing industry
[L18]

Industry	*Maximum effective dose rate (μSv a⁻¹)*		
	External irradiation	*Air dispersion pathways*	*Water dispersion pathways*
Elementary phosphorus production	130	2	<0.4
Phosphoric acid production	8	~2 000 [b]	2
Fertilizer production	20	<0.4	15
Primary iron and steel production	8	<0.4	3
Coal tar processing	4	<0.4	
Cokes production	4	<0.4	
Coal-fired power plant	12	<0.4	4
Gas-fired power plant	<0.4	<0.4	-
Oil and gas extraction	2 [a]	<0.4 [b]	
Cement production	5	<0.4	
Ceramic industry plant	<0.4	<0.4	
Mineral sands handling	60	<0.4	320
Titanium pigment production	<0.4	<0.4	1

a Inhalation dose (radon) due to land fill with harbour sludge below a residential area.
b Rather uncertain value.