SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

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Report to the General Assembly, with Scientific Annexes

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Sources, Effects and Risks of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2016 Report to the General Assembly, with Scientific Annexes — Scientific Annexes A, B, C and D

Corrigendum

1. Annex B (Radiation exposures from electricity generation), page 142, table 1, footnote a

The footnote *should read*

The value for the nuclear fuel cycle was 5.7 man Sv/(GW a); for globally-circulating radionuclides after 100 years the value was 12 man Sv/(GW a); for uranium mine and mill tailings after 100 years of radon releases, the value was 0.25 man Sv/(GW a).

2. Annex B (Radiation exposures from electricity generation), page 142, table 1, footnote e

The footnote *should read*

The value for the nuclear fuel cycle was 3.0 man Sv/(GW a); for globally-circulating radionuclides after 10,000 years the value was 50 man Sv/(GW a); for uranium mine and mill tailings after 10,000 years of radon releases, the value was 150 man Sv/(GW a).

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ANNEX B

RADIATION EXPOSURES FROM ELECTRICITY GENERATION

CONTENTS

I. INTRODUCTION

1. A reliable and affordable supply of electricity is important to improve human health and welfare worldwide, an objective recognized by both the United Nations Millennium Development Goals [U2, U3] and Sustainable Development Goals.[1] However, policy makers and the general public also have interest in the impacts of electricity generation on humankind and the environment.

2. Interest in exposure of the public and workers to radiation due to nuclear power dates back to the earliest use of the technology. The first UNSCEAR Report to the General Assembly in 1958 included data on exposures of contract employees of the United States Atomic Energy Commission and a recognition of the need to keep track of the exposure of workers in view of the anticipated growth in the use of nuclear technology and the associated worker population [U4]. Since then, the Committee has periodically reviewed exposures of both the public and of workers, related to nuclear power [U5, U6, U7, U8, U9, U11]. As a result, the Committee's records of exposures of workers and the public from nuclear power provide one of the most complete and accurate global pictures of radiation exposures from any source of ionizing radiation.

3. The Committee has conducted evaluations of radiation exposures of the public arising from forms of electricity generation other than nuclear power to a much more limited extent. Radiation exposures from industrial activities outside of the nuclear sector are generally not monitored or reported in a systematic manner; consequently, the assessment of these exposures has often relied on incomplete data from isolated surveys or ad hoc collection of data from various reports and publications.

4. The Committee's thematic priorities identified in its strategic plan[2] for 2009–2013 included radiation levels of energy production and in its plan[3] for 2014–2019 the global impact of energy production. The Committee decided to update its assessments of the exposures from electricity generation, considering the principal relevant commercial technologies, both nuclear and non-nuclear.

5. The world's mix of electricity-generating technologies changes over time in response to the landscape of climatic, environmental, resource, political and economic challenges. Governments and researchers may conduct various comparative studies that among other things take into account the various implications for the public and the environment of the different technologies. Exposure to ionizing radiation is only one of the many factors that such assessments may take into account. However, the Committee considers that an update and extension of its past assessments of radiation exposures of the public and workers from electricity generation could be a useful source of information for such studies.

6. This scientific annex thus presents an analysis of the total population exposure, public and occupational, to ionizing radiation from the different life cycle stages of electricity-generating technologies, normalized to the electricity generated during one year for that technology. The annex is also an update and extension of the Committee's earlier evaluations of radiation exposures resulting from discharges associated with different electricity-generating technologies. The Committee

[1] *Transforming our world: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015. General Assembly, Seventieth session, Agenda items 15 and 116 (A/RES/70/1).*
[2] *Official Records of the General Assembly, Sixty-third session, Supplement No. 46 (A/63/46).*
[3] *Official Records of the General Assembly, Sixty-eighth session, Supplement No. 46 (A/68/46).*

emphasizes that the objective of this study was comparative in nature. Common approaches, available data and balanced assumptions for assessing the main exposures and identifying the dominant components of those exposures for different electricity-generating technologies have been used to the extent possible.

7. Specifically, the following core questions have been addressed:

- How do the individual and population exposures of humans to ionizing radiation that result from different phases of the life cycle of each electricity-generating technology compare with each other across the world and by region?
- What are the main factors, in terms of principal sources, radionuclides, time periods and exposed populations, contributing to the exposure for each technology?
- What would be needed to improve such assessments in the future in terms of data and research?

8. To conduct the assessment, the Committee has in parallel reviewed and revised its methodology for estimating exposures of the public due to radioactive discharges (annex A). Other exposures, such as occupational exposures, are assessed using other methods described here.

A. Scope

9. This annex describes an assessment of the exposures to ionizing radiation in the life cycle of electricity-generating technologies that are currently deployed commercially, and fuelled by nuclear energy, combustion of coal, oil or gas, geothermal energy, solar energy, wind or biomass. The assessment includes exposures from activities in the life cycle of each technology that are relevant to the radiological impact, from construction to decommissioning. For electricity-generating technologies using solar energy, wind and biomass, the only activity that has been assessed in this context is the mining of metals needed for construction. Exposures from electrical energy storage, transmission and distribution are not considered. Moreover, the evaluation does not address energy generation other than electricity generation, such as process heat generation or other means of distributing energy, such as district heating.

10. The assessment considers normal operations only. Exposures from incidents and accidents are not considered in detail here; the Committee has earlier reviewed radiation exposures in accidents (annex C [U12]), and considered in detail the radiation exposures from the 1986 accident at the Chernobyl nuclear power plant (annex D [U12]) and the 2011 accident at the Fukushima-Daiichi nuclear power station (annex A [U13]) and continues to monitor developments after these accidents. The annex discusses their significance only in drawing conclusions from this assessment for the General Assembly.

11. The assessment is limited to considering individual and population exposure of humans. Exposures of non-human biota in the environment are not considered. Assessing impacts other than radiation exposure from electricity generation, such as social benefits, economic issues, or non-proliferation or security matters, is outside of the Committee's remit and competence.

12. This work aims to compare exposures to ionizing radiation for different electricity-generating technologies where individual and collective doses may be used for performing a comparative exposure assessment. However, calculated doses are recommended only for comparative purposes and not for

estimations related to health effects. It is important to state that collective doses, as used here, are solely an instrument to compare radiation exposures for different technologies used for electricity generation. Collective dose is not intended as a tool for epidemiological risk assessment. Moreover, the aggregation of very low individual doses over extended time periods is inappropriate for use in risk projections and, in particular, the calculation of numbers of cancer deaths from collective doses based on individual doses that are well within the variation in background exposure should be avoided. Collective doses estimated in this annex only provide information for decision makers and researchers on radiation exposures from different electricity generation technologies. Dose estimations for the evaluation of implications for health should be more specific to each exposure situation.

13. The annex begins with a chapter providing background information to support the study, followed by a chapter discussing the assessment approach and the end points for the study. That chapter also includes a description of terminology relevant to applying the methodology for estimating public exposures due to radioactive discharges (see annex A). The following chapters cover the radiation exposures arising from electricity generation from each of the electricity-generating technologies: nuclear fuel cycle, fossil fuel energy (coal, oil and gas) and geothermal energy. Next comes a chapter on assessing occupational doses from the mining of metals for the construction phase of the electricity-generating technologies: nuclear, coal, natural gas and the renewable technologies (biomass, solar and wind). Finally, there are chapters that include comparisons of exposures from the principal electricity-generating technologies, discussions of uncertainties, suggestions for future work that could improve understanding, and concluding remarks. Note that all supporting values and calculations were manipulated with full precision and any discrepancies in the numbers presented in tables and figures are due to rounding.

II. BACKGROUND

14. The Committee's past assessments in this field have covered each stage of the nuclear fuel cycle: resource extraction (uranium mining and milling); fuel manufacture (uranium enrichment and fuel fabrication); power generation (nuclear power reactors); reprocessing of spent nuclear fuel to recover uranium and plutonium for subsequent use in nuclear fuels; and the management of solid wastes generated at the various stages. They have also included exposures from transportation activities within and between the fuel-cycle stages [U5, U6, U7, U8, U9, U11].

15. The Committee's most recent and comprehensive review of public exposures due to non-nuclear electricity generation (coal, oil, natural gas, peat and geothermal technologies) was published in 1993 [U8], based principally on the parameters and assessments presented in the UNSCEAR 1988 Report [U7] and the assessment methodology adopted in the UNSCEAR 1982 Report [U6]. Public exposures were expressed in terms of the collective effective dose normalized to electricity generated, in units of man–sieverts per gigawatt–year. The results from those earlier UNSCEAR assessments of normalized collective effective doses to the public from discharges for various electricity-generating technologies are summarized in table 1.

16. According to the UNSCEAR 1993 Report, public exposures in terms of collective effective dose per year of practice and per unit of electricity generated due to the burning of coal and peat, and due to geothermal sources exceeded that due to operational discharges from nuclear power generation. However, with continued improvements in efficiency of electricity generation from fossil-fuel plants and in emission control technology, those earlier estimates of the Committee were deemed very likely to be outdated and potentially misleading. Reductions in exposures were expected from newer and retrofitted power plants.

Since its 1993 evaluation, the Committee had only updated its estimates of exposures from the generation of nuclear power, where the most recent estimates showed a decrease for the normalized collective effective dose to the public from power plant operation from 0.45 man Sv/(GW a) for the period 1990–1994 to 0.27 man Sv/(GW a) for the period 1998–2002 [U11].

Table 1. Collective effective dose to the public normalized to electricity generated due to discharges from different electricity-generating technologies from previous UNSCEAR assessments

UNSCEAR Report	*Normalized collective effective dose to public (man Sv/(GW a))*					
	Nuclear power plant operation	*Coal*	*Peat*	*Gas*	*Oil*	*Geothermal*
1982 [U6]	4.2[a]	2	—	—	—	6
1988 [U7]	2.5[b]	4[c]	2	0.03	0.5	2
1993 [U8][d]	1.34[e]	20[f]	—	(0.03)	(0.5)	(2)
2000 (for 1990-1994) [U9]	0.45[g]	—	—	—	—	—
2008 (for 1998-2002) [U11]	0.27[h]	—	—	—	—	—

[a] The value for the nuclear fuel cycle was 5.7 man Sv/(GW a); for globally-circulating radionuclides after 100 years the value was 12 man Sv/(GW a); for uranium mine and mill tailings after 100 years of radon releases, the value was 0.25 man Sv/(GW a).

[b] The value for the nuclear fuel cycle was 4.0 man Sv/(GW a); for mine and mill tailings and globally-circulating radionuclides the total was 200 man Sv/(GW a).

[c] The value was 6 man Sv/(GW a) for older coal-fired power plants, which were considered to constitute two thirds of the world total and 0.3 man Sv/(GW a) for modern coal-fired power plants, which were considered to constitute one third of the world total.

[d] The values reported in the UNSCEAR 1993 Report [U8] for gas, oil and geothermal technologies were not from new assessments but taken from the UNSCEAR 1988 Report [U7].

[e] The value for the nuclear fuel cycle was 3.0 man Sv/(GW a); for globally-circulating radionuclides after 10,000 years the value was 50 man Sv/(GW a); for uranium mine and mill tailings after 10,000 years of radon releases, the value was 150 man Sv/(GW a).

[f] From coal-fired power plants (assumed one third modern-style, one third old-style and one third Chinese-style [U8]).

[g] The reported dose value is for power plant operation only.

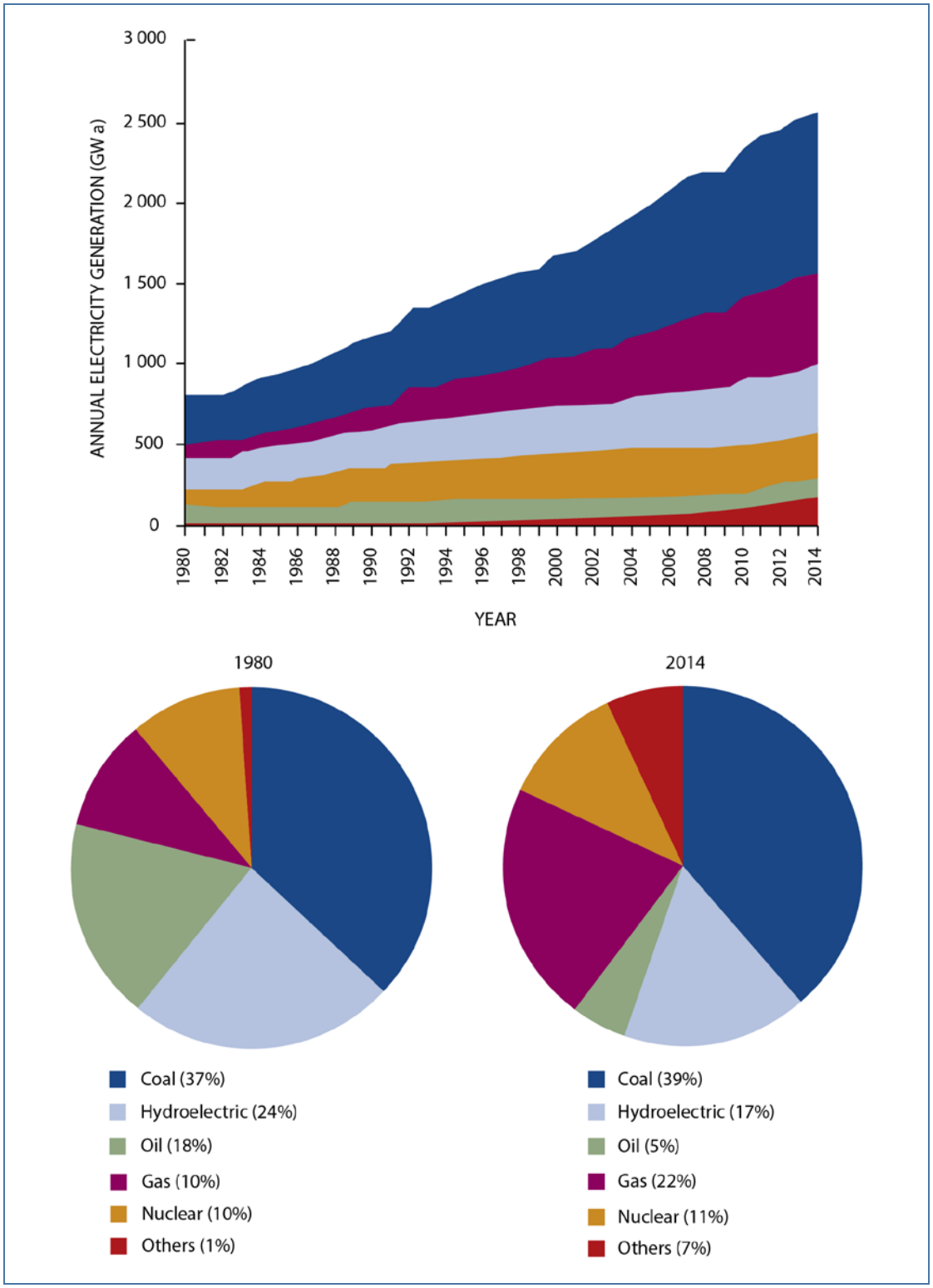
[h] The value for the nuclear fuel cycle was 0.72 man Sv/(GW a).

A. Global trends in electricity generation technology

17. Figure I shows the global trends in electricity generation and contributions made by the various electricity-generating technologies between 1980 and 2014. Combustion of coal for electricity generation has dominated during this period with nearly 40% of total electricity generated; at the same time, total global electricity generation has grown by about a factor of three. The use of both natural gas and nuclear fuels to generate electricity has grown as a percentage of the total and also in total amount of electricity generated over the same period. The use of oil has fallen as a percentage of the total, but only slightly in total electricity generated. The use of hydropower has increased in the total amount of electricity generation, although it has fallen as a percentage of the total. The contribution of the "others" category, which includes renewable energies (geothermal, wind, solar and biomass), has increased from 1% to 7% during the 34 years, with a faster increase in their use since about 2008.

Figure I. Trends in worldwide electricity generation (GW a) from 1980 to 2014

The "others" category comprises geothermal, solar, wind, biomass and waste [W13]. Supporting values were expressed as full precision and any discrepancies in the numbers presented are due to rounding



B. Electricity generation worldwide in 2010

18. The reference year for assessments presented in this annex is 2010. Table 2 and figure II summarize worldwide electricity generation in 2010 [I15]. Total electricity generation worldwide in 2010 is reported as 2,452 GW a (table 2), which also shows the contribution by type for the six geographical regions of the world as adopted by the United Nations Environment Programme (UNEP). These regions are the same as those used in annex A. Marginally different values for electricity generated by nuclear power in 2010 were obtained from IAEA [I6] and used in the application of the revised methodology for estimating public exposures due to radioactive discharges (annex A). The IAEA database [I6] provided detailed data on electricity generated in 2010 both by region and as a function of reactor type; these data were not used to generate table 2, but were used in the more detailed assessments discussed in chapter IV.B.2.

19. Total annual average worldwide electricity generated from nuclear power plants 1998–2002 was reported as 278 GW a in table 16 and table A-5 from [U11], which can be compared to 314 GW a for 2010.

Table 2. Summary of worldwide electricity generated in 2010

Supporting values were manipulated with full precision and any discrepancies in the numbers presented are due to rounding

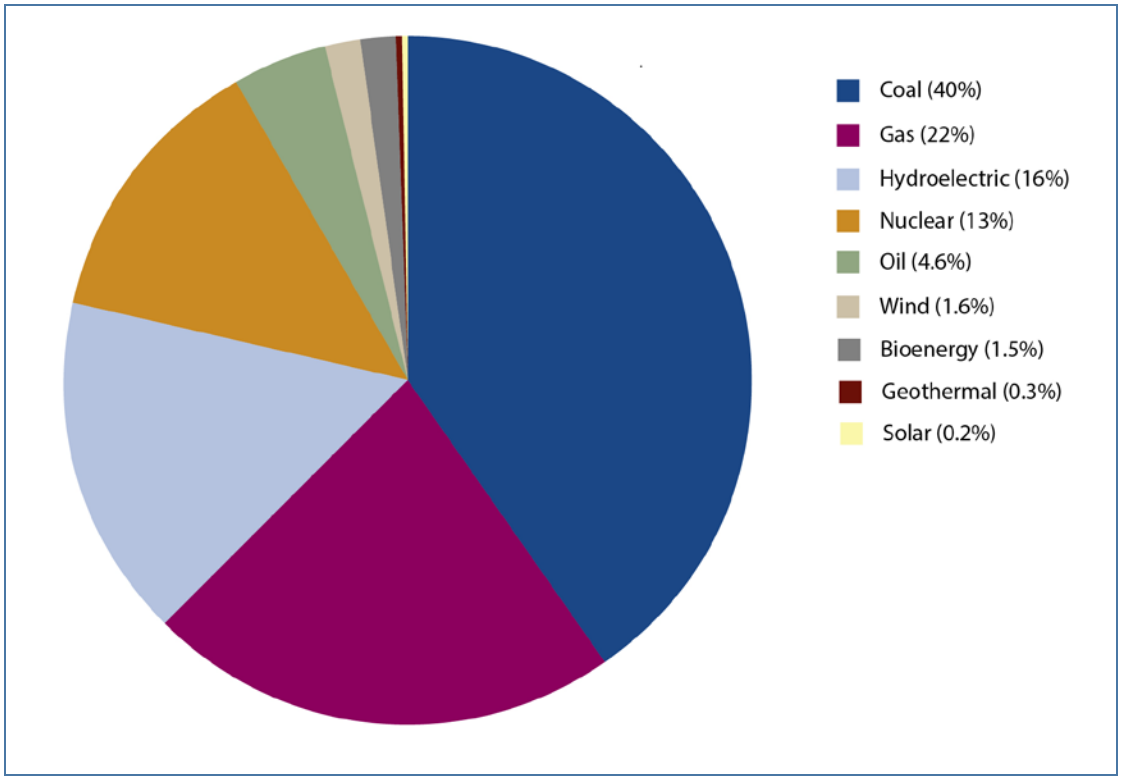
Type	*Electricity generated in 2010 (GW a)* [I15, I16]						
	Africa	*Asia and Pacific*	*Europe*	*Latin America and Caribbean*	*North America*	*West Asia*[a]	*Total*
Nuclear[b]	1.38	66.4	137.4	3.14	106.0	—	314.3
Coal	29.6	567.7	150.6	6.26	237.4	0.00	991.6
Gas	22.7	146.9	177.0	35.8	122.0	39.4	543.8
Oil	9.26	36.9	12.8	20.2	6.33	27.1	112.6
Geothermal	0.17	3.19	1.28	1.13	2.00	—	7.77
Solar	0.06	0.68	2.62	0.03	0.47	0.00	3.86
Wind	0.23	8.80	17.4	0.14	11.9	0.00	38.5
Biomass	0.09	5.95	17.3	4.85	9.59	0.00	37.8
Hydro	12.4	128.6	105.3	80.9	72.7	0.94	400.8
Tide	—	—	0.11	0.02	0.00	—	0.13
Other	—	0.00	0.55	—	0.10	—	0.65
Total	76	965	622	153	569	67	2 452

[a] The numerical entry 0.00 corresponds to no electricity generated and the entry — corresponds to no data available. West Asia is omitted in all tables generated from the assessments reported in this annex, except for the assessments on gas and oil.

[b] Marginally different values, obtained from IAEA [I6], were used in the application of the revised methodology for estimating public exposures due to radioactive discharges (annex A) for the electricity generated by nuclear power in 2010.

Figure II. Breakdown of the electricity generated worldwide in 2010 by generation technology

Derived from data in table 2 (excluding contributions from "Tide" and "Other". Supporting calculations were made to full precision and any discrepancies in the final numbers are due to rounding



III. ASSESSMENT APPROACH AND END POINTS

20. The main end point in this annex is an assessment and comparison of collective doses, and collective doses normalized to the electricity produced, for one year of different electricity-generating technologies, using consistent assessment approaches. To this end, the dominant exposure pathways for each of the electricity-generating technologies considered in this study have been assessed.

21. The Committee conducted this study by investigating sources of exposure from electricity-generating technologies based on *(a)* nuclear power, *(b)* the combustion of coal, natural gas, oil and biofuels, and *(c)* geothermal, wind and solar power. Two electricity-generating technologies (nuclear power and combustion of coal) were investigated in detail, because a more robust database existed for these technologies. The Committee evaluated the main sources of radioactive discharges from the life cycle of these electricity-generating technologies. For nuclear power, these sources included uranium mining and milling, mill tailings, power plant operation and reprocessing activities. For combustion of coal, they were the mining for coal, power plant operation for a prototype of both a modern coal plant and an older-style coal plant, and deposits of coal ash. These sets of sources will hereafter be called the "nuclear fuel cycle" and "coal cycle", respectively, for simplicity.

22. The Committee pursued two paths for the assessments presented in this annex. First, UNSCEAR's revised methodology for estimating public exposures due to radioactive discharges (annex A) was used to assess components of exposure due to electricity generation from the nuclear fuel cycle and from the coal cycle in a consistent manner. These two technologies were chosen for substantive treatment, because reasonably reliable input data existed and, from previous assessments, they were known to be important. The use of a common methodology for these assessments allowed consistent comparison of estimated exposures from the two technologies. A significant end point to these assessments was to identify and discuss dominant sources of exposure from these two electricity-generating technologies, and the dominant radionuclides contributing to those exposures.

23. The second path was to derive reasonable estimates of public exposures arising from the other electricity-generating technologies, and occupational exposures from all the electricity-generating technologies considered. This permits a rough comparison of the total human exposure from each of the electricity-generating technologies normalized to the energy generated by each technology.

24. For those electricity-generating technologies relying on power plants that burn natural gas or oil as fuel, and power plants driven by geothermal energy, an important exposure pathway is radon gas discharged to atmosphere. The Committee's revised methodology for estimating public exposures due to radioactive discharges (annex A) has been used for assessing atmospheric discharges from these technologies.

25. The revised methodology (annex A) was designed for assessing public exposures from routine releases of radionuclides to the environment during normal operations, and not for assessing occupational exposures. Thus, occupational exposures due to electricity generation from the nuclear fuel cycle and from the coal cycle have been assessed here primarily from data on occupational exposure from the UNSCEAR 2008 Report [U11], adjusted for electricity generated in 2010. In some cases, particularly occupational exposures from mining for coal and uranium and other metals, relevant new data have been obtained and estimates of dose commitments have been updated for 2010. Occupational exposures from the mining of metal ores needed for the construction of power plants or power-generating equipment have been assessed and compared for the various electricity-generating technologies.

26. Assessments have also been made of collective effective doses for the entire decommissioning phase of nuclear power plants based on available data on occupational exposures from existing decommissioned plants.

27. Exposures of the public and workers due to radioactive materials from conventional hydroelectricity generation were not included in this annex. This is because no radioactive materials are discharged during normal operations, and the magnitude of discharges of radioactive materials and resulting exposures when constructing dams were deemed negligible when compared to other exposures (for example, the mining of metals or mining for other fuels, such as coal or uranium). The main exposure situation associated with hydroelectricity generation was considered to be occupational exposure during the mining of metals needed for construction of the power plants. However, this exposure was not evaluated because hydroelectric plants have considerable variation in their size, leading to large uncertainties when adopting a standard plant design for assessment.

28. Finally, the total exposures during one year, including both public and occupational, for each electricity-generating technology (nuclear fuel cycle, coal cycle, oil, natural gas, geothermal, solar and wind), have been compared. Three main phases that contribute to the total exposure of the public and workers for each technology have been considered: preparation, operation and decommissioning. For all discharges, the same methodology has been used to estimate public exposures—a significant improvement over the Committee's earlier assessments.

A. Recapitulation of key features of the methodology for estimating public exposures due to radioactive discharges

29. The following paragraphs recapitulate some of the key features of the methodology described in annex A that are relevant for the assessment here.

30. *World-average*. This term is used to qualify data that are intended to represent a value averaged across the whole world. For example, for the default population distributions (shown in table 3 of annex A), the world-average population for a distance band is derived from the average of the values for the distance band within each UNEP region, weighted by the population in each region. Similarly, world-average consumption rates for terrestrial and aquatic foods are derived from the values for each UNEP region weighted by the populations in each region.

31. *Dose*. In all cases and unless otherwise stated, dose refers to the protection quantity, effective dose. The annual effective dose is the sum of the dose from external exposure in that year plus the committed dose from intakes by inhalation and ingestion in that year. For doses integrated over a period, it is the sum of integrated doses from external exposure over the period and committed doses from the integrated intakes by inhalation and ingestion over the period. Doses to the public are only estimated for adults and the period considered for the committed dose is 50 years, i.e. adult ages from 20 to 70 years.

32. *Characteristic individual dose*. The individuals considered are those living in the area local to the point of discharge with behaviour indicative of the majority of people living in that area. The dose to these characteristic individuals is referred to here as the "characteristic individual dose".

33. For discharges to atmosphere, the characteristic individuals were assumed to live 5 km from the discharge point and to obtain 25% of their food from this distance. For discharges to rivers, the characteristic individual was assumed to be exposed to riverbank sediment 5 km downstream from the discharge point, to drink all of their water from the river, and to eat 25% of the freshwater fish in their diet from the river plus 25% of their dietary grain and leafy vegetables irrigated with water from the river. For discharges to marine environments, the characteristic individual was assumed to be exposed to external irradiation from radionuclides in sediments from the local marine compartment using a factor to represent average occupancy of beaches. The characteristic individual is also assumed to consume marine foods with 25% of their dietary fish from the local marine compartment and 75% from the regional compartment, while 100% of the dietary consumption of crustacea and molluscs were assumed to be from the local compartment. In all cases the consumption rates used were the average for a population. These assumptions are discussed in detail in annex A.

34. *Collective doses*. The standard collective dose calculated here is the integrated dose to 100 years from one year's discharge. (For the modelling of the globally-circulating radionuclides, collective doses integrated to 500 and 10,000 years are also calculated, see paragraph 39.) The end point for all radionuclides calculated in annex A was the collective dose per unit discharge integrated to 100 years. For releases to atmosphere, the local and regional components of the collective doses derive from doses to populations within a distance of 1,500 km from the discharge point and are based on four different types of population distributions:

(a) A default population distribution based on population densities for 2010. Values of population density are given for six different regions (as adopted by UNEP) and also a world-average value (a population-weighted average of the population density for the UNEP regions). These are used to assess collective doses due to discharges from the coal cycle, combustion of gas and oil, and geothermal energy.

(b) The population distribution around nuclear power stations situated on the coast. Values of the average population within distance bands around coastal nuclear power stations are given for five regions as adopted by UNEP (but not West Asia because there was no operating nuclear power station in this region at the time of the assessment) and also an average value for the world. The population densities were based on data for coastal sites of actual nuclear power stations throughout the world and the distributions are arithmetic means of the data for distance bands around each coastal site located in the region of interest.

(c) The population distribution around nuclear power stations situated inland. Values of the average population within distance bands around inland nuclear power stations are given for four regions as adopted by UNEP (but not Africa or West Asia because there were no operating nuclear power stations located inland in these regions at the time of the assessment) and also an average value for the world. The population densities were based on data for inland sites of actual nuclear power stations throughout the world and the distributions are arithmetic means of the data for distance bands around each inland site located in the region of interest.

(d) A single value of population density for remote sites of 5 km^{-2}. This is used to assess collective doses due to discharges from uranium mines and mill tailings, which are located in areas of very low population density. This value is also used in an alternate calculation to assess collective doses due to discharges from geothermal sites. Values for regions of the world are not provided for these cases.

35. For releases to atmosphere, a distinction could be made between the local component of collective dose (to populations within a distance of 100 km) and a regional component of the collective doses (to populations between 100 and 1,500 km). For aquatic releases to rivers and lakes, it was not possible to distinguish between local and regional components of the collective dose because of the method used to calculate collective dose. However, for discharges to marine environments, local and regional compartments were used to model the dispersion of the released radionuclide, and therefore local and regional components of the collective doses could be provided. Note that the use of the word "regional" here is distinct from its potential use as a qualifier meaning "related to the geographical regions adopted by UNEP".

36. *Globally-circulating radionuclides*. Four radionuclides (^{3}H, ^{14}C, ^{85}Kr and ^{129}I) were assumed to become globally circulated and to continue to expose the world population for decades and, with regards to ^{14}C, centuries, and ^{129}I, millions of years. These radionuclides contribute to the local and regional component of collective dose when they are initially discharged (due to the so-called "first pass") and this component was modelled as for all other radionuclides. However, a global component needs to be added separately for these radionuclides. Thus, an additional collective dose due to global circulation was also modelled and results calculated. Results of the global model are provided for discharges to atmosphere and to marine environments; for aquatic discharges to freshwater systems, the results were assumed identical to those for a marine environment for the purposes of calculating the global component of collective dose.

37. *Integration times*. The methodology applies to discharges that can be assumed to be continuous. Account is taken of the build-up of long-lived radionuclides in the environment and the associated continued exposure after the discharges have stopped. This is done by considering a year's discharge of a radionuclide, its dispersion in the environment and the subsequent exposure of people over many years; the resulting dose rates are then integrated. A value of 100 years is used for the integration period for the standard case (see further details in annex A).

38. Using the integrals it is also possible to consider that the discharges continue for many years from the same site. This is because the integrated dose to 100 years from one year's discharge is numerically

equal to the dose in the 100th year from a continuous discharge at a constant rate over a 100-year period. The characteristic individual doses are calculated by integrating dose rates to 100 years, which also represent the annual dose that would be received in the 100th year of discharge.

39. Collective doses can be integrated to various times, but for most radionuclides it was sufficient to integrate to 100 years because most of the collective dose commitment (i.e. the collective dose theoretically integrated to infinity) is delivered during this period. However, for globally-circulating radionuclides (i.e. ^{3}H, ^{14}C, ^{85}Kr and ^{129}I), the integrated collective dose continues to increase for many years beyond 100 years (see annex A, paragraph 14). Therefore, for globally-circulating radionuclides, collective doses integrated to 500 and 10,000 years were also calculated.

40. The main results of the revised methodology (annex A) are for a unit discharge for one year integrated to 100 years and can be used to estimate the impact of one-year's practice by, for example, scaling the results by the discharge of radionuclides per unit of electricity generated, or the total discharges from a particular type of electricity generation.

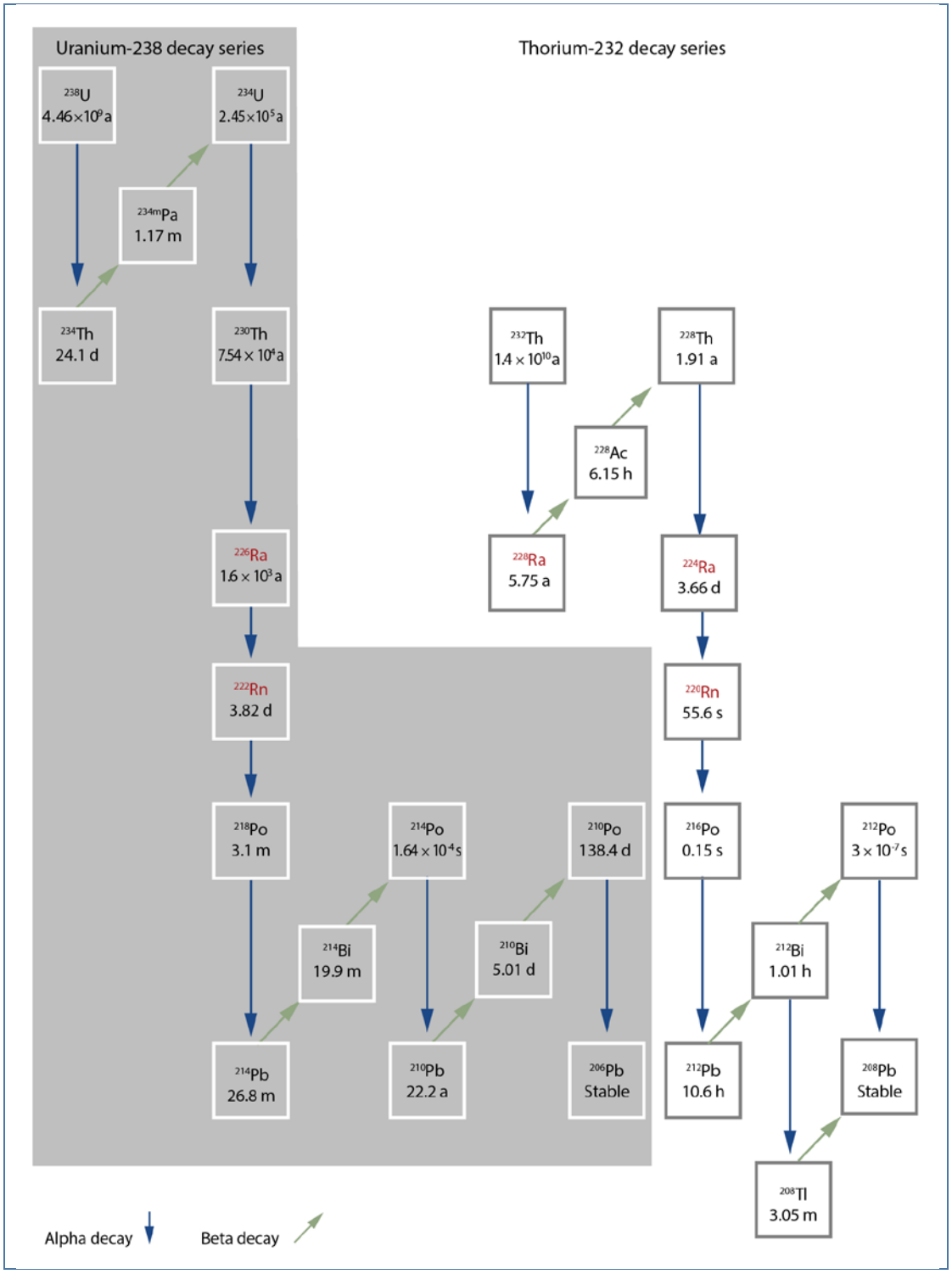
41. *Waste residues from uranium mining and from coal-fired power stations*. These wastes, uranium mill tailings and coal ash, are often disposed of on the surface of the ground and they contain enhanced levels of naturally occurring radionuclides, notably ^{226}Ra which decays into the gas ^{222}Rn, which can be emitted into the air for many years after the disposal occurs. The radon and its decay products give rise to human exposure (see figure III).

42. In this case one-year's practice gives rise to a continuing discharge to atmosphere for many years. Current best practice would rehabilitate mill tailings such that emissions were reduced to background levels (i.e. the levels that would occur from that area if the mine had not been present). Information from Australia and elsewhere indicates that this process might take some 50 years and that monitoring is expected to continue for some 20 to 30 years to ensure that the rehabilitation has been successful and to monitor for any deterioration [S2, W1]. The question remains whether the site could deteriorate once institutional control has finished, and radon emissions increase again. A base case integration time of 100 years seems reasonable with 10,000 years a cautious upper estimate.

43. Therefore, for radon discharges from land disposal of mill tailings or coal ash, allowance has to be made for this continued discharge and this was done by multiplying the results for one year's discharge by 100 to allow for the discharge continuing for 100 years (see annex A, paragraph 17). This 100-year multiplication is chosen for both individual and collective doses because 100 years is not much different from a human lifetime. The Committee has also considered the effect on the integrated collective dose of a continuing discharge for 500 and 10,000 years.

Figure III. The ^{238}U and ^{232}Th decay series

Half-life is expressed in a = year; d = day; h = hours; m = minutes; s = seconds



44. *Representative radionuclides for nuclear power plants*. Discharges of radionuclides from nuclear power plants are commonly reported by operators and regulatory bodies aggregated in groups. For example in UNSCEAR 2008 discharges were reported as "noble gases" and "particulates" for atmospheric discharges, or "other nuclides" for liquid discharges. Accurate assessments of doses can only be carried out on a radionuclide-specific basis and so where groups of radionuclides had been reported, it was necessary either to apportion the discharge for the groups of nuclides among the radionuclides, or to use a "representative" radionuclide. The European Commission [E1] gives the percentage of radionuclides discharged for different reactor types sited in Europe for different groupings. For AGRs, FBRs and GCRs,[4] the discharges were split between the radionuclides considered in the workbooks for the appropriate groupings (atmospheric noble gases, atmospheric particulates and other liquids). The breakdown for GCRs was based on United Kingdom sites because these were the only ones operational in 2010. For atmospheric particulate discharges from BWRs and PWRs, ^{54}Mn was selected as the representative radionuclide for any radionuclides not considered explicitly in the workbooks. The grouping of "other liquids" did not previously include ^{14}C and, for many countries and most reactor types, liquid discharges of ^{14}C are not reported. However, examination of EC RADD [E2] shows that for European PWRs liquid discharges of ^{14}C are significant and therefore 30% of discharges from "other liquids" were assumed to be ^{14}C for PWRs. For BWRs and PWRs any liquid discharges for radionuclides not included in the workbooks were allocated equally between ^{54}Mn and ^{58}Co. For HWRs, ^{41}Ar, ^{60}Co and ^{137}Cs were assumed to represent discharges for noble gases, atmospheric particulates and other liquids respectively, based on information in [B3, B5, C2]. For LWGRs information was taken from the EC RADD database [E2].

IV. RADIATION EXPOSURES ARISING FROM ELECTRICITY GENERATION BY NUCLEAR POWER

A. Introduction

45. The Committee has studied radiation exposures arising from electricity generation by nuclear power repeatedly over the years since its first publication on this subject in 1958 (see especially [U6, U7, U8, U9, U11]). These studies have consistently shown that the major contribution to public exposures has been through the discharges of natural radionuclides, primarily from: radon and its progeny released during uranium mining and milling, and from mill tailings, associated with the nuclear fuel cycle; and from carbon-14, primarily associated with reactor operation and fuel reprocessing.

46. The revised methodology for estimating public exposures due to radioactive discharges (annex A) has been used here to assess public exposures from the following processes: uranium mining and milling; electricity generation from nuclear power reactors; and fuel reprocessing. The assessments and results for these processes are presented in the following section. The processes—uranium enrichment, fuel fabrication and solid waste disposal—and their exposure characteristics are discussed in sections

[4] The following abbreviations are used for the different nuclear power reactor types, categorized according to their coolant systems and moderators: light-water-moderated and cooled pressurized or boiling-water reactors (PWRs and BWRs); heavy-water-cooled and moderated reactors (HWRs); gas-cooled, graphite-moderated reactors (GCRs and AGRs); light-water cooled, graphite-moderated reactors (LWGRs); and the liquid metal cooled fast-breeder reactors (FBRs).

IV.B.4 and IV.B.5, and dose estimates for these processes that were published in the UNSCEAR 2008 Report [U11] have been used here. This chapter begins with the assessment of public exposures, followed by that of occupational exposures, and ends with considering the occupational exposures associated specifically with the decommissioning process.

B. Public exposure

1. Mining and milling

47. Uranium ore can be extracted from the earth by physically removing it through conventional surface or underground mining methods or by chemically dissolving the uranium out of the rock ore through either heap leaching or in-situ leaching (ISL) (sometimes referred to as in situ recovery or ISR) [U18]. Surface mining (also referred to as opencast, open pit or strip mining) techniques are applied to ore bodies that are close to the surface, and are also a generally cost-effective method for extracting large volumes of lower-grade ore, that may then be combined with other bulk extraction techniques (such as conventional milling, leaching and extraction, or alternative techniques such as heap leaching) which would be uneconomical for underground operations. Underground mining involves extracting rock through a tunnel or opening in the side of a hill or mountain and is generally applied for the extraction of higher-grade ores. In-situ leaching is generally applied to shallow deposits that exist in non-porous shale or mudstone, or in situations where uranium can be recovered from otherwise inaccessible or uneconomical formations [U18].

48. Uranium ores typically contain from about 0.05 to 0.3% uranium oxide (U_3O_8) [U18]. After extraction from the ground, the mined uranium ore is sent to a mill, which is usually located close to the mine. This next step in the nuclear fuel cycle, called “milling”, involves the extraction and purification of uranium from the uranium ore. After a first purification process, the uranium is precipitated in a partially refined form, known as “yellowcake”. The uranium concentrate, typically containing 75 to 95% uranium, is shipped to a chemical plant for further purification and chemical conversion [B4].

49. In-situ leaching is an alternative method for extracting uranium from low-grade ores or shallow deposits that exist in non-porous shale or mudstone. An ISL plant chemically alters the uranium ore underground before it is pumped out for processing. In the ISL process, wells are drilled into rock containing uranium ore. An alkaline or acidic solution (known as lixiviant) is injected down the wells to dissolve the uranium in the rock. In the case of alkaline solutions, the lixiviant is usually *(a)* water mixed with oxygen and/or *(b)* hydrogen peroxide mixed with sodium carbonate or carbon dioxide. In the acid leach processes (used in Kazakhstan and Australia), sulphuric acid usage can result in lixiviant solutions with pH as low as 1 being circulated into the ore body (the process in Kazakhstan is typically strongly acidic, while in Australia only mildly acidic). In some cases, an oxidant is added to increase the efficiency of leaching. The lixiviant is then collected in a series of recovery wells, through which it is pumped to a processing plant. At the processing plant, the uranium is extracted from the solution through an ion-exchange process, and the uranium oxide concentrate (yellowcake) is then precipitated, dried and packed.

50. After recovery of the uranium, the barren solution is re-fortified with oxidant (if required) before being returned to the well field via the injection wells. However, a small flow (about 0.5%) is bled off to maintain a pressure gradient in the well field and this, with some solutions from surface processing, is treated as waste. This waste water contains various dissolved ions such as chloride, sulphate, sodium, radium, arsenic and iron from the ore body and is re-injected into approved disposal wells in a depleted

portion of the ore body. Wells must be monitored to ensure that extraction fluids do not leave the facility or contaminate groundwater. Waste from this process, usually filters and piping, can be disposed in a tailings pile at a mill site or a licensed disposal facility. In-situ leaching facilities have no radon discharge during the "mining" phase, and no surface tailings and little radon emission after closure [U11]. There can however be discharge of radon during the "leaching" phase of the ISL mining process, which here has been assumed to be the same as the radon discharge occurring during the milling phase [B6, B7]. Chapter IX discusses the need for further study regarding the ISL mining process.

51. In 2014, 51% of the world's uranium was mined using ISL operations, a share that has risen steadily mainly because of mining operations in Kazakhstan [W8]. Table 3 shows the percentage contribution from ISL-mining to total uranium production during the period from 2008 to 2012 in each of the UNEP regions. For the reference year of 2010 used in this annex, the total uranium production for 15 countries is given in table 4.

Table 3. Contribution of ISL-mining to total uranium production between 2008 and 2012

Information on percentage ISL compared with other types of mining is taken from [W10]

Region	*Contribution to world production (%)*		
	Total	*ISL*	*Others*
Asia and Pacific	51.6%	38%	13.6%
North America	21.1%	2%	19.1%
Africa	18.4%	0%	18.4%
Europe	8.6%	1%	7.6%
Latin America	0.3%	0%	0.3%
World	100%	41%	59%

Table 4. Uranium production in 2010 [O8]

The production numbers come from OECD/NEA (table 1.21, page 60, Historical uranium production [O8]). Countries that had a label "Secretariat estimate" are not included here (Pakistan, Romania and India). Also excluded are a few countries that had very small production which came from mine rehabilitation efforts only

Country (UNEP region)	*Uranium production (t U)*
Kazakhstan (Asia and Pacific)	17 803
Canada (North America)	9 775
Australia (Asia and Pacific)	5 900
Namibia (Africa)	4 503
Niger (Africa)	4 197
Russian Federation (Europe)	3 563
Uzbekistan (Asia and Pacific)	2 874
United States (North America)	1 630
China (Asia and Pacific)	1 350

Country (UNEP region)	*Uranium production (t U)*
Ukraine (Europe)	837
Malawi (Africa)	681
South Africa (Africa)	582
Czech Republic (Europe)	254
Brazil (Latin America)	148
Iran, Islamic Rep. of (Asia and Pacific)	7
Total	54 104

(a) *Input to assessments for mining and milling*

52. The Committee's revised methodology for estimating public exposures due to radioactive discharges (annex A) has been used to assess the collective doses and characteristic individual doses from four categories of sources for radon discharges:

(a) Mining (underground uranium mining)

(b) Milling (natural radionuclides other than radon are also discharged)

(c) Operational mill tailings

(d) Mill tailings

53. The third category, operational mill tailings, refers to the mill tailings produced during the milling process, and the fourth category, mill tailings, represents the tailings that are positioned in some other place for more permanent holding. They can be eventually treated or mitigated to reduce the discharge of radionuclides. Assessments were conducted using the methodology described in annex A for the four categories of sources above. They were performed using the discharges normalized to energy generated shown in table 5 and table 6, and the values for electricity generation for each region given in table 7 to estimate characteristic individual doses to the public. As noted in the tables, many of the values for the normalized discharges were taken from previous UNSCEAR reports. However, the estimate for the discharge of radon from mill tailings has been updated. A value for the discharge of radon per energy produced of 0.3 TBq/(GW a), based on a tailings area of 1 hectare and a radon emanation rate of 1 Bq s^{-1} m^{-2}, was used in [U9]. This was lower than the previous value of 1 TBq/(GW a). Information on emissions from Australian mine tailings [L2] is that the value of 1 Bq s^{-1} m^{-2} is high compared to the range of levels that are measured. Measurements taken over a number of years at the El Sharena mines were in the range 9–36 mBq s^{-1} m^{-2} with an average baseline value of 17 mBq which is equivalent to 0.005 TBq/(GW a) based on a tailings area per electricity generated of 1 ha/(GW a). In other cases where the tailings have been rehabilitated, the emissions rates are at background levels. A study at the Ranger uranium mine found that the emission rates ranged from 0.2 to about 0.9 Bq s^{-1} m^{-2}. The studies related to trial landforms intended to develop their rehabilitation strategies with the aim of reducing the long-term radon emission rates. For Olympic Dam, an emission rate of 0.5 Bq s^{-1} m^{-2} was published, a value equivalent to 0.15 TBq/(GW a) while other information gives emission rates of 0.3, 0.14 and 0.04 Bq s^{-1} m^{-2} for the inner mine, outer mine and region. These are equivalent to 0.1, 0.04 and 0.01 TBq/(GW a) based on 1 ha/(GW a). These Australian values indicate that the UNSCEAR 2000 value (0.3 TBq/(GW a)) may be too high based on mines operating with best practice for which a value of 0.1 or lower may be more appropriate. In the light of this, the Committee agreed that a rounded emission rate of 0.1 TBq/(GW a) should be used in this study.

Table 5. Discharges of radon from the uranium mining and milling process normalized to electricity generated

Source	*Normalized* discharges *(TBq/(GW a))*
Mining (world average, all mines except ISL, only radon discharges)	66[a]
Mining (world average, all ISL mines, only radon discharges from leaching phase of ISL mining process)	3
Milling (world average, all mines, radon discharges plus nuclides in table 6)	3[b]
Operational mill tailings (world average, all mines except ISL, only radon discharges)	3[c]
Mill tailings (world average, all mines except ISL, only radon discharges)	0.1[d]

[a] A value of 75 TBq/(GW a) was used in earlier UNSCEAR assessments [U8], and was based on the assumption that there were on average 300 GBq of radon released per tonne of uranium oxide [U8].

[b] From UNSCEAR 1993 Report [U8].

[c] From UNSCEAR 2000 Report [U9].

[d] From annex A.

Table 6. Airborne discharges during the milling process (all mines including ISL) ([U8] tables 19 and 22)

Radionuclide	*Activity discharged per unit of electricity generated (TBq/(GW a))*
^{210}Po	2×10^{-5}
^{210}Pb	2×10^{-5}
^{226}Ra	2×10^{-5}
^{234}U	4×10^{-4}
^{238}U	4×10^{-4}
^{230}Th	2×10^{-5}

54. The estimate for the discharge of radon from uranium mining (non-ISL mines) has also been updated. Total uranium production in 2010, shown in table 4 [O8], was assumed to be the amount that was mined in that year. Values were summed for all countries to give a rounded total of 54,100 tonnes of uranium. Similarly, total uranium production in 2010 from table 4 is assumed to equal the total amount of uranium milled. The value for the mass of uranium required per unit of electricity generated given in the UNSCEAR 2008 Report was 220 t/(GW a) ([U11] table 18A), which is lower than the value of 250 t/(GW a) used earlier by the Committee [U7, U8, U9]. The trend in uranium required per unit of electricity generated (the uranium requirement) is generally downwards, because of increasing efficiencies in power plant operation and lower enrichment tails assays. For example, the 2014 Red Book [O8] reported that the generic reactor uranium consumption had reduced from 175 t/GW(e) per year at 0.30% tails assay [O6] to 163 t/GW(e) per year at 0.25% tails assay. The corresponding figures for U_3O_8 are 206 and 192 tonnes, respectively.

55. The value of 220 t/(GW a) used in the UNSCEAR 2008 Report is the value used in this assessment. Given the information in the previous paragraph, this is possibly a slight overestimate; however, it was retained for continuity with the previous UNSCEAR assessments. This gives a value for the discharge of radon from the mining process normalized to electricity generated of 66 TBq/(GW a), which is lower than the value of 75 TBq/(GW a) used in earlier UNSCEAR studies [U7, U8, U9].

56. In modern ISL facilities, the circulating lixiviant goes directly from the well field to the header houses and the dissolved uranium is extracted from the lixiviant through the ion exchange process. The lixiviant is then reconstituted and returned directly to the well field in an essentially closed (pressurized) system. In older non-pressurized systems (such as at Crow Butte, United States), the resin column is not pressurized, so the lixiviant is exposed to normal atmospheric conditions, which results in super-saturated radon being discharged. The discharged radon gas is vented through an exhaust stack to the atmosphere. This discharge is most similar to that from the milling phase, not from the mining phase. The assessments in this annex have assumed radon discharges during ISL uranium mining are the same as those from the milling phase.

57. In order to perform assessments of the characteristic individual doses to the public for each region, electricity generation in 2010—broken down into ISL and non-ISL mining sources—was needed for the different regions. Total uranium production for 15 countries in 2010 is given in table 4. Table 3 shows the contribution from ISL-mining to the total uranium production in each UNEP region between 2008 and 2012. Using the value for uranium requirement of 220 t/(GW a), the electricity generated from the total uranium production for each region could be estimated as shown in table 7. Assessments for mining and milling using the revised methodology for estimating public exposures due to radioactive discharges (annex A) used the values for total electricity generated with the normalized discharges for milling, the total electricity generation from ISL mining with the normalized discharges for ISL mining processes, and the total electricity generation excluding ISL mining sources with the normalized discharges for the processes mining (non-ISL), operational mill tailings and mill tailings, to calculate characteristic individual doses. Collective doses resulting from mining and milling were assessed assuming a low population density (defined in annex A), and no aquatic discharges were included in the assessment.

Table 7. Inferred electricity generation from the uranium production in each region and from ISL and non-ISL contributions

The assessment assumes 220 tonnes of uranium per gigawatt-year. Note that the total inferred electricity generation is 246 GW a, which is somewhat less than the world total nuclear electricity generation in 2010 at 314 GW a (table 2). However, this difference is not unreasonable because current reactor fuel requirements were met from primary supply (direct mine output: 78% in 2009) and secondary sources: commercial stockpiles, nuclear weapons stockpiles, recycled plutonium and uranium from reprocessing used fuel, and some from re-enrichment of depleted uranium tailings (left over from original enrichment) [O6, W11]

Region	*% of world production*	*% from ISL*	*% from other production methods*	*Mass of uranium from ISL (tonnes)*	*Mass of uranium from other production methods (tonnes)*	*Inferred electricity generated from ISL (GW a)*	*Inferred electricity generated from other production methods (GW a)*	*Total inferred electricity generated (GW a)*
Africa	18.4	0	18.4	0	9 954	0	45	45
Asia and Pacific	51.6	38	13.6	20 558	7 358	93	33	126
Europe	8.6	1	7.6	541	4 112	3	19	22
Latin America	0.3	0	0.3	0	162	0	1	1
North America	21.1	2	19.1	1 082	10 333	5	47	52
Total	100	41	59.0	22 181	31 919	101	145	246

2. Electricity generation from nuclear power reactors

58. The nuclear power reactors used for electricity generation that are treated here can be categorized according to their coolant systems and moderators: light-water-moderated and cooled pressurized or boiling-water reactors (PWRs and BWRs); heavy-water-cooled and moderated reactors (HWRs); gas-cooled, graphite-moderated reactors (GCRs and AGRs); and light-water cooled, graphite-moderated reactors (LWGRs). These reactor types are all thermal reactors that use the moderator material to slow down the fast fission neutrons to thermal energies. In fast-breeder reactors (FBRs), the coolant is a liquid metal, there is no moderator and fast neutrons induce fission.

(a) *Assessments for nuclear reactor operation*

59. The distribution of electricity generated by geographic region and type of location of the nuclear power plants in the world are presented in table 8. The electricity generated in 2010 by nuclear power was about 300 GW a according to the IAEA PRIS database [I6] (table 9). PWRs contributed most to the total electricity generated worldwide from nuclear reactors (about 68%), followed by BWRs (about 21%) [I6]. The distribution of electricity generated by geographic region from nuclear power plants in 2010 by reactor type is shown in table 9. (The ordering of the individual reactor types in all relevant tables and figures in this annex is according to their world share of electricity generated in 2010, as shown in table 9.)

60. Radionuclide discharges and electricity generation data used with the revised methodology for estimating public exposures due to radioactive discharges (annex A), for assessing discharges from nuclear power plants in 2010 normalized to the electricity generated, are described in table 10. The main basis for deriving the normalized discharge values was the IAEA PRIS database [I6], the EC RADD database [E2] and the discharge data for the year 2002 in the UNSCEAR 2008 Report [U11]. Using these data the normalized discharges for 2002 were recalculated and adjusted to electricity generation in 2010, for use with the revised methodology for estimating public exposures due to radioactive discharges (annex A) to assess the exposures for the reference year 2010.

61. A summary of the activities of radionuclides, or radionuclide groups, discharged in airborne and liquid effluents from nuclear reactors during routine operation in 2010, normalized to the electricity generated in 2010, are reported in table 11. The method for determining how the aggregated nuclides were characterized, i.e. the noble gases and particulates in the atmospheric discharges, and the “other liquids” listed in the liquid discharges, has been addressed in earlier studies by UNSCEAR (e.g. [U7, U8, U9]). The aggregated nuclides were called “representative radionuclides for nuclear power plant discharges” in those studies, and the term “representative radionuclides” is used in this annex also. Chapter III.A, paragraph 44 in this annex explains how the representative radionuclides, were chosen for use in the current study with the revised methodology for estimating public exposures due to radioactive discharges (annex A) applied to nuclear power plants.

62. The revised methodology for estimating public exposures due to radioactive discharges (annex A) was used to assess doses due to discharges from nuclear power plants. The assessments considered atmospheric and aquatic discharges. Collective dose estimates for discharges to atmosphere were based on the population distributions around coastal or inland nuclear power plants, using the population distributions generated for the different regions adopted by UNEP (see annex A). Where appropriate, contributions from globally-circulating radionuclides were included in the assessment of collective

doses. The characteristic individual doses and collective doses were calculated separately for each of the reactor types (PWR, BWR, HWR, LWGR, AGR, GCR and FBR).

Table 8. Number of reactors by type, location and UNEP region (2010 data)

Data from the IAEA PRIS database [I6]

Reactor type	*Africa*	*Asia and Pacific*	*Europe*	*Latin America and Caribbean*	*North America*	*Grand total*
PWR total	2	55	141	2	69	269
Coastal	2	54	34	2	16	108
Inland	0	1	107	0	53	161
BWR total	0	36	19	2	35	92
Coastal	0	36	9	2	2	49
Inland	0	0	10	0	33	43
HWR total	0	24	2	2	18	46
Coastal	0	11	0	0	1	12
Inland	0	13	2	2	17	34
LWGR total	0	0	15	0	0	15
Coastal	0	0	4	0	0	4
Inland	0	0	11	0	0	11
AGR (all coastal)	0	0	14	0	0	14
GCR total	0	0	4	0	0	4
Coastal	0	0	2	0	0	2
Inland	0	0	2	0	0	2
FBR (all inland)	0	0	2	0	0	2
Grand total	2	115	197	6	122	442

Table 9. Electricity generation from nuclear power plants in 2010 by reactor type and UNEP region (from [I6])

The values for the total electricity generation from nuclear power plants for each UNEP region [I9] are marginally different from those shown in table 2 [I15]. The IAEA database [I6] provided detailed data on electricity generation in 2010 both by region and as a function of reactor type, which was not available from the database used to generate table 2, and the more detailed data were therefore chosen for use in the assessments discussed in this chapter

Reactor type	*Electricity generation (GW a)*							*% total per reactor type*
	Africa	*Asia and Pacific*	*Europe*	*Latin America and Caribbean*	*North America*	*West Asia*	*Total*	
PWR	1.47	38.47	102.47	1.57	60.89	0.00	204.88	68
BWR	0.00	19.66	12.18	0.64	31.25	0.00	63.72	21
HWR	0.00	5.34	1.22	0.76	9.76	0.00	17.09	6
LWGR	0.00	0.00	8.15	0.00	0.00	0.00	8.15	3
AGR	0.00	0.00	5.01	0.00	0.00	0.00	5.01	2
GCR	0.00	0.00	0.93	0.00	0.00	0.00	0.93	0
FBR	0.00	0.00	0.42	0.00	0.00	0.00	0.42	0
Total	1.47	63.47	130.39	2.97	101.89	0.00	300.21	100

Table 10. Key data sources and assumptions used to assess public exposures due to radioactive discharges from nuclear power plants

Data sources	*Commentary*
Discharges, 2002	Taken from tables A6-A12 in UNSCEAR 2008 Report [U11]. Note that WWER was regrouped under PWR. Data for discharges from FBR are from 2001. Discharges of particulates to air and other liquids for United Kingdom AGRs/GCRs were taken from the EC RADD database [E2]
Electricity generation, 2002	Taken from [I6]. Note that HWLWR was regrouped under HWR and PHWR under HWR. Generation data for FBR are from 2001
Electricity generation, 2010	Taken from [I6]. Note that HWLWR was regrouped under HWR and PHWR under HWR. Includes a calculation of generation from reprocessing countries as a fraction of all generation
Countries	Countries and regions as adopted by UNEP (see annex A)
Location data	Inland/coastal location of reactors, taken from [I6]
Normalized discharge data	For each reactor type:[a,b] the normalized discharges were scaled to the electricity generation ratio using the 2002 to 2010 electricity generation data; information summarized in paragraph 44 was used to apportion discharge between specific radionuclides; and location data were used to apportion between inland/coastal locations

[a] For FBRs, values of normalized discharges of ^{3}H, ^{131}I, ^{14}C, liquid tritium and other liquids were taken from table 17, annex B, UNSCEAR 2008 Report [U11] because no discharge data were available. Data for the radionuclide mix were taken from [E1].

[b] For LWGRs, normalized discharge data were taken from table 17, annex B, UNSCEAR 2008 Report [U11]. EC RADD [E2] data for European LWGR reactors were used to infer mix of noble gases, particulates and other liquids.

Table 11. Estimated normalized discharges from nuclear power plants 2010

Reactor type	*Estimated normalized discharges per unit of electricity generated (TBq per GW a)*							
	Discharges to atmosphere						*Aquatic discharges*	
	Noble gases	*Tritium*	*^{131}I*	*^{14}C*	*Partic-ulates*	*^{35}S*	*Liquid tritium*	*Other liquid*
PWR	5.8×10^{0}	1.5×10^{0}	8.0×10^{-5}	8.3×10^{-2}	3.6×10^{-5}	0	1.8×10^{1}	3.8×10^{-3}
BWR	1.8×10^{1}	1.3×10^{0}	4.2×10^{-4}	1.3×10^{-1}	1.8×10^{-3}	0	8.2×10^{-1}	2.1×10^{-3}
HWR	3.5×10^{1}	2.0×10^{2}	2.3×10^{-5}	6.0×10^{-1}	1.7×10^{-5}	0	1.7×10^{2}	3.1×10^{-2}
LWGR	4.6×10^{2}	2.6×10^{1}	9.9×10^{-3}	1.3×10^{0}	2.7×10^{-3}	0	7.8×10^{-1}	2.0×10^{-3}
AGR	1.9×10^{1}	4.0×10^{0}	3.2×10^{-5}	1.4×10^{0}	2.2×10^{-5}	6.6×10^{-2}	4.1×10^{2}	8.1×10^{-1}
GCR	1.7×10^{3}	5.0×10^{0}	0	5.5×10^{0}	3.0×10^{-4}	3.7×10^{-1}	4.7×10^{0}	1.2×10^{0}
FBR	4.4×10^{1}	4.9×10^{1}	2.0×10^{-4}	1.2×10^{-1}	1.4×10^{-4}	0	1.7×10^{0}	2.3×10^{-2}

3. Fuel reprocessing

63. Reprocessing of used nuclear fuel has been practised for several decades in a number of countries, mainly for extracting and recycling fissile materials. Current recycling practices are primarily focused on the conversion of fertile[5] ^{238}U to fissile plutonium, for which a significant amount of the plutonium recovered from used fuel has been recycled into mixed oxide (MOX) fuel. Table 12 shows the current location of reprocessing facilities in the world, with operations in France, the Russian Federation and the United Kingdom dominating. Not shown in the table is the Rokkasho facility in Japan, which is expected to start operations in 2018 and to have a commercial reprocessing capacity of 800 tonnes per year. As of 2015, about 31% (90,000 tonnes of 290,000 tonnes) of used fuel from commercial power reactors has been reprocessed [W12].

64. Characteristic individual doses and collective doses were calculated for Sellafield in the United Kingdom, La Hague in France and Ozersk (Mayak) in the Russian Federation, which are also the three main reprocessing facilities (table 12), using available data on discharges. The doses due to discharges from fuel reprocessing facilities were assessed using the revised methodology for estimating public exposures due to radioactive discharges (annex A).

65. Data for both atmospheric and aquatic discharges were obtained for the reprocessing facilities at Sellafield, United Kingdom and La Hague in France for the year 2010 [E2] and for atmospheric discharges only at Ozersk (Mayak), Russian Federation [F2]. These data include discharges from other activities on site but it could be assumed that most discharges are related to reprocessing activities. Discharges normalized to electricity generation were calculated for La Hague based on the assumption that discharges from the reprocessing facility were related to the reprocessing of fuel equivalent to that required to power French PWRs in 2010, 47 GW a [I6, W9]. However, for Sellafield and Mayak it was not possible to relate the discharges to electricity generated.

[5] Fertile material is a material that is not fissionable by thermal neutrons, but can be converted into a fissile material by neutron absorption and subsequent nuclei conversions.

66. The discharges for reprocessing facilities are shown in table 13. Consequently, characteristic individual doses and collective doses (as defined in section III) could be assessed for all three of these facilities, all located in the region named Europe (as adopted by UNEP). However, because discharges normalized to electricity generation were only available for La Hague in France, the characteristic dose normalized to electricity generated could be assessed only for this facility. Collective doses normalized to electricity generation for Europe and the whole world were also based on La Hague, but took into account the fraction of electricity generated by all French PWRs in 2010 compared to Europe and the whole world, 0.55 and 0.24 respectively, for the calculation of the doses due to the first pass.

Table 12. World commercial reprocessing capacity [N1, O2, W12]

Fuel type	*Facility*	*Commercial reprocessing capacity (tonnes per year)*
LWR fuel	France, La Hague	1 700
	United Kingdom, Sellafield (THORP)	600
	Russian Federation, Ozersk (Mayak)	400
	Total LWR	approximately 2 700
Other nuclear fuels	United Kingdom, Sellafield (Magnox)	1 500
	India (PHWR, 4 plants)	330
	Japan, Tokai (MOX)	40
	Total other	approximately 1 870
Total civil capacity		approximately 4 570

Table 13. Discharges from reprocessing facilities [E2]

Discharged radionuclide	*Discharges to atmosphere*			*Aquatic discharges*		
	Sellafield	*La Hague*	*Mayak*	*Sellafield*	*La Hague*	*Mayak*
DISCHARGES PER UNIT OF ELECTRICITY GENERATED (TBq/(GW a))						
^{3}H	—	3.8×10^{4}	—	—	6.7×10^{6}	—
^{14}C	—	1.1×10^{4}	—	—	5.0×10^{3}	—
^{41}Ar	—	—	—	—	—	—
^{54}Mn	—	—	—	—	1.4×10^{0}	—
^{58}Co	—	—	—	—	7.0×10^{-2}	—
^{60}Co	—	4.9×10^{-3}	—	—	4.4×10^{1}	—
^{85}Kr	—	1.5×10^{8}	—	—	—	—
^{90}Sr	—	—	—	—	9.1×10^{1}	—
^{106}Ru	—	4.8×10^{-2}	—	—	1.4×10^{3}	—
^{129}I	—	3.1×10^{0}	—	—	9.3×10^{2}	—
^{131}I	—	1.6×10^{-1}	—	—	7.9×10^{0}	—
^{135}Xe	—	—	—	—	—	—

Discharged radionuclide	*Discharges to atmosphere*			*Aquatic discharges*		
	Sellafield	*La Hague*	*Mayak*	*Sellafield*	*La Hague*	*Mayak*
^{134}Cs	—	3.6×10^{-3}	—	—	5.1×10^{1}	—
^{137}Cs	—	3.0×10^{-3}	—	—	7.3×10^{2}	—
^{239}Pu	—	1.3×10^{-3}	—	—	6.3×10^{0}	—
^{241}Am	—	—	—	—	1.3×10^{1}	—
AVERAGE DISCHARGE RATE OVER A YEAR (Bq/s)						
^{3}H	3.1×10^{6}	1.8×10^{6}	—	4.4×10^{7}	3.2×10^{8}	—
^{14}C	8.7×10^{3}	5.1×10^{5}	—	1.4×10^{5}	2.3×10^{5}	—
^{41}Ar	—	—	1.2×10^{6}	—	—	—
^{54}Mn	—	—	—	—	6.4×10^{1}	—
^{58}Co	—	—	—	—	3.3×10^{0}	—
^{60}Co	—	2.3×10^{-1}	3.4×10^{-1}	3.1×10^{3}	2.0×10^{3}	—
^{85}Kr	1.4×10^{9}	7.1×10^{9}	—	—	—	—
^{90}Sr	1.3×10^{0}	—	4.2×10^{1}	3.2×10^{4}	4.2×10^{3}	—
^{106}Ru	2.4×10^{1}	2.2×10^{0}	5.7×10^{0}	3.7×10^{4}	6.5×10^{4}	—
^{129}I	3.1×10^{2}	1.4×10^{2}	—	8.7×10^{3}	4.3×10^{4}	—
^{131}I	1.2×10^{1}	7.7×10^{0}	2.5×10^{1}	—	3.7×10^{2}	—
^{135}Xe	—	—	1.8×10^{5}	—	—	—
^{134}Cs	—	1.7×10^{-1}	—	3.5×10^{3}	2.4×10^{3}	—
^{137}Cs	3.0×10^{0}	1.4×10^{-1}	2.1×10^{1}	1.5×10^{5}	3.4×10^{4}	—
^{239}Pu	6.2×10^{-1}	5.9×10^{-2}	1.3×10^{1}	4.2×10^{3}	2.9×10^{2}	—
^{241}Am	1.2×10^{0}	—	—	1.1×10^{4}	6.2×10^{2}	—

(a) *Results—public exposures from mining and milling, electricity generation from nuclear power reactors and fuel reprocessing*

67. Characteristic individual doses to the public—for the nuclear fuel cycle processes: mining and milling; electricity generation from nuclear power reactors; and fuel reprocessing—normalized to the electricity each process generated in 2010 are summarized in table 14. Doses for the characteristic individual from mining and milling are shown for both non-ISL and ISL mines. The characteristic individual was assumed to be located 5 km from the source. The doses represent the radiation exposure from all discharges in a year and, in the case of mill tailings, the doses are associated with those emissions for a period of 100 years (see chapter III).

68. The largest estimated characteristic individual doses normalized to electricity generation in 2010 for all discharges come from mining and milling activities in non-ISL mines in all regions, followed by operational discharges from nuclear power plants. Estimated characteristic individual doses from ISL mines are about an order of magnitude smaller than those from non-ISL mines, owing to the differences in radon discharges from the two processes. Estimated characteristic individual doses from mining and milling are primarily associated with radon exposures, while those from nuclear power plant operations reflect differences in the type and relative proportion of the different reactor types and thus different

radionuclide discharge mixes within a region, and to a lesser extent, variations in food consumption patterns across regions. Estimated characteristic individual doses for a region normalized to electricity generated that are associated with reprocessing are only reported for the region Europe, where the French, British and Russian reprocessing facilities are located. All of the estimated characteristic individual doses are very low.

Table 14. Summary of characteristic individual doses to the public normalized to electricity generated in 2010 for mining and milling, electricity generation from nuclear power reactors, and fuel reprocessing (mSv/(GW a))

Discharge type and source	*Characteristic individual doses [a,b] to the public (mSv/(GW a))*				
	Africa	*Asia and Pacific*	*Europe*	*Latin America*	*North America*
ATMOSPHERIC DISCHARGES					
Mining and milling[c] - non-ISL mines	6.9×10^{-3}	6.9×10^{-3}	6.9×10^{-3}	6.9×10^{-3}	6.9×10^{-3}
Mining and milling - ISL mines	—	5.5×10^{-4}	5.5×10^{-4}	—	5.5×10^{-4}
Power plants	1.3×10^{-5}	5.1×10^{-5}	7.2×10^{-5}	1.1×10^{-4}	5.8×10^{-5}
Reprocessing	—	—	5.7×10^{-5}	—	—
AQUATIC DISCHARGES					
Mining and milling - non-ISL mines	—	—	—	—	—
Mining and milling - ISL mines	—	—	—	—	—
Power plants	7.0×10^{-5}	1.5×10^{-4}	1.2×10^{-3}	1.5×10^{-4}	5.0×10^{-5}
Reprocessing	—	—	6.9×10^{-4}	—	—
TOTAL FOR ALL DISCHARGES					
Mining and milling[c] - non-ISL mines	6.9×10^{-3}	6.9×10^{-3}	6.9×10^{-3}	6.9×10^{-3}	6.9×10^{-3}
Mining and milling - ISL mines	—	5.5×10^{-4}	5.5×10^{-4}	—	5.5×10^{-4}
Power plants	8.2×10^{-5}	2.0×10^{-4}	1.3×10^{-3}	2.6×10^{-4}	1.1×10^{-4}
Reprocessing	—	—	7.5×10^{-4}	—	—

[a] The characteristic individuals are those living 5 km from the points of discharge with behaviour indicative of the majority of people living the area.

[b] It is only appropriate to present the characteristic individual doses for discharges normalized to electricity generated and not summations of the various individual dose values, because the same individuals cannot be exposed to all discharges from the various sources in each region. Because collective doses are the sum of all individual doses, they can be presented both as total collective dose and as collective dose normalized to electricity generated.

[c] The radon emissions from mill tailings produced per unit of electricity generated are assumed to continue for 100 years.

69. Collective doses to the public for discharges from mining and milling, power plant operation and reprocessing in 2010 are summarized in table 15, and in table 16 normalized to the electricity generated by each process for that year. The local component (for the region-averaged or world-averaged population within 100 km) and the regional component (for the region-averaged or world-averaged population between 100 km and 1,500 km) of the collective doses due to the atmospheric releases are presented separately, integrated to 100 years (first pass). Radon emissions from mill tailings produced per unit of electricity generated are assumed to continue for 100 years. The global components of collective doses resulting from the globally-circulating radionuclides (^{3}H, ^{14}C, ^{85}Kr and ^{129}I) are also shown, integrated to 100, 500 and 10,000 years. For ease of comparison, table 17 shows the final

aggregated values for the total collective dose to the world public and for the collective dose normalized to electricity generated for each of the processes mining and milling, power plant operation and reprocessing.

70. The results in tables 15 and 16 indicate that for discharges from both power plant operation and reprocessing facilities, the global component of the collective doses due to globally-circulating radionuclides integrated to 100 years and longer exceed the local and regional components of the collective doses due to the initial discharge (first pass) integrated out to 1,500 km. It is important to recognize that global components are summed over the population of the entire world, which is taken as 10^{10} people to account for growth over the next 100 years (called "whole world population" in the tables 15 and 16). This component thus is the sum of a large number of very small doses with per caput values of the order of 10^{-8} Sv, and per caput values normalized to electricity generated of the order of 10^{-10} Sv/(GW a). Values for the collective doses in both tables 15 and 16 for the first-pass calculation are the doses integrated to 100 years and to a distance of 1,500 km for the local and regional components due to atmospheric discharges. Based on the results of the assessment, doses beyond this distance were assumed to be negligible.

71. For the nuclear industry, a significant fraction of the collective dose is due to radon discharges from mining and disposal of mill tailings. The importance of carbon-14 discharges from nuclear power plants and reprocessing is also evident. Table 18 shows the contribution from individual radionuclides to the collective doses to the public, and collective doses per unit of electricity generated, from reprocessing integrated to 100 years, not including contributions from globally-circulating radionuclides. Figure IV is derived from the data in table 18, showing collective doses per unit of electricity generated for individual radionuclides discharged from reprocessing. The importance of the carbon-14 contribution to dose is evident.

72. Figure V shows collective doses per unit of electricity generated due to the globally-circulating radionuclides (tritium, ^{14}C and ^{85}Kr) integrated to 100, 500 and 10,000 years, for each reactor type considered. Besides indicating the variation in the dose contribution from globally-circulating radionuclides for the different reactor types, the graphs also illustrate the importance of ^{14}C, whose contribution to collective dose increases with integration time. The global circulation for ^{129}I is not included in figure V because it is only discharged during the reprocessing phase.

73. Figure VI compares the collective doses to the public from all discharges, atmospheric and aquatic, from all nuclear power plants by region and by reactor type, not including contributions from globally-circulating radionuclides. The data indicate that HWRs and PWRs are the reactor types that contribute most to the collective doses. Table 19 shows the total collective dose for all nuclear reactor types summed and by region, with North America and Europe showing the highest values.

Table 15. Summary of collective doses to the public due to mining and milling, electricity generation from nuclear power reactors, and fuel reprocessing (in 2010)

Discharge type and source	*Collective dose[a, b] (man Sv)*					
	Africa	Asia and Pacific	Europe	Latin America	North America	World
LOCAL COMPONENT – ATMOSPHERIC RELEASES						
Mining and milling	No data by region					1.0×10^{1}
Power plants						
Inland	0	1.2×10^{0}	2.0×10^{0}	1.7×10^{-1}	2.2×10^{0}	5.3×10^{0}
Coastal	8.2×10^{-3}	2.7×10^{0}	1.2×10^{0}	1.5×10^{-2}	1.2×10^{-1}	3.8×10^{0}
Reprocessing	—	—	1.3×10^{0}	—	—	2.1×10^{0}
REGIONAL COMPONENT – ATMOSPHERIC DISCHARGES						
Mining and milling	No data by region					4.3×10^{1}
Power plants						
Inland	0	3.0×10^{0}	6.7×10^{0}	1.3×10^{-1}	5.8×10^{0}	1.6×10^{1}
Coastal	1.6×10^{-3}	6.8×10^{0}	3.5×10^{0}	2.9×10^{-2}	1.5×10^{-1}	8.4×10^{0}
Reprocessing	—	—	4.3×10^{0}	—	—	4.4×10^{0}
LOCAL AND REGIONAL COMPONENT – AQUATIC DISCHARGES						
Mining and milling	No data by region					—
Power plants						
Inland	0	1.4×10^{0}	1.4×10^{1}	8.1×10^{-1}	1.8×10^{1}	3.4×10^{1}
Coastal	9.3×10^{-5}	2.5×10^{-2}	6.8×10^{-2}	3.5×10^{-4}	1.3×10^{-3}	3.9×10^{-1}
Reprocessing	—	—	2.6×10^{-1}	—	—	1.1×10^{0}
LOCAL AND REGIONAL COMPONENTS (ATMOSPHERIC AND AQUATIC DISCHARGES)						
Mining and milling	No data by region					5.3×10^{1}
Power plants	9.9×10^{-3}	1.5×10^{1}	2.8×10^{1}	1.2×10^{0}	2.6×10^{1}	6.8×10^{1}
Reprocessing	—	—	5.8×10^{0}	—	—	7.6×10^{0}
TOTAL LOCAL AND REGIONAL COMPONENTS[c]	9.9×10^{-3}	1.5×10^{1}	3.3×10^{1}	1.2×10^{0}	2.6×10^{1}	1.3×10^{2}

GLOBAL COMPONENT – GLOBALLY-DISPERSED RADIONUCLIDES	
Source and integration time	*Collective dose (man Sv)*
	Whole world population
Mining and milling integrated to	
100 years	—
500 years	—
10 000 years	—
Power plants integrated to	
100 years	5.3×10^2
500 years	1.0×10^3
10 000 years	5.0×10^3
Reprocessing integrated to	
100 years	2.6×10^2
500 years	4.9×10^2
10 000 years	2.4×10^3

[a] Local and regional components of the collective doses (due to the first pass) are integrated to 100 years. The local and regional components are explained in chapter III. Per caput values are not given in the table, but are discussed in the text.

[b] For all tables in the annex, the calculations resulting from assessments are made to full precision and any discrepancies in the final sum of numbers in the tables are due to rounding.

[c] Total of the local and regional components due to mining and milling, power plants and reprocessing from the first-pass. The totals for each region include only discharges from power plants, except for Europe, which also has a value for reprocessing.

Table 16. Summary of collective doses to the public due to mining and milling, electricity generation from nuclear power reactors, and fuel reprocessing (in 2010) normalized to electricity generated

Discharge type and source	*Collective dose[a] per unit of electricity generated (man Sv/(GW a))*					
	Africa	*Asia and Pacific*	*Europe*	*Latin America*	*North America*	*World-average[b]*
LOCAL COMPONENT – ATMOSPHERIC DISCHARGES						
Mining and milling	No data by region					4.1×10^{-2}
Power plants						
Inland	0	8.0×10^{-1}	2.2×10^{-2}	2.2×10^{-1}	2.5×10^{-2}	2.9×10^{-2}
Coastal	5.6×10^{-3}	4.3×10^{-2}	3.2×10^{-2}	6.8×10^{-3}	8.5×10^{-3}	3.3×10^{-2}
Reprocessing	—	—	1.2×10^{-2}	—	—	8.6×10^{-3}
REGIONAL COMPONENT – ATMOSPHERIC RELEASES						
Mining and milling	No data by region					1.7×10^{-1}
Power plants						
Inland	0	2.0×10^{0}	7.2×10^{-2}	1.7×10^{-1}	6.5×10^{-2}	8.9×10^{-2}
Coastal	1.1×10^{-3}	1.1×10^{-1}	9.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	7.2×10^{-2}
Reprocessing	—	—	4.0×10^{-2}	—	—	1.8×10^{-2}
LOCAL AND REGIONAL COMPONENTS (AQUATIC DISCHARGES)						
Mining and milling	No data by region					—
Power plants						
Inland	0	9.3×10^{-1}	1.5×10^{-1}	1.1×10^{0}	2.0×10^{-1}	1.9×10^{-1}
Coastal	6.3×10^{-5}	4.1×10^{-4}	1.8×10^{-3}	1.6×10^{-4}	9.6×10^{-5}	3.3×10^{-3}
Reprocessing	—	—	3.0×10^{-3}	—	—	2.1×10^{-3}
LOCAL AND REGIONAL COMPONENTS (ATMOSPHERIC AND AQUATIC DISCHARGES)						
Mining and milling	No data by region					2.2×10^{-1}
Power plants	6.7×10^{-3}	2.4×10^{-1}	2.1×10^{-1}	3.9×10^{-1}	2.6×10^{-1}	2.3×10^{-1}
Reprocessing	—	—	5.5×10^{-2}	—	—	2.9×10^{-2}
TOTAL LOCAL AND REGIONAL COMPONENTS[c]	6.7×10^{-3}	2.4×10^{-1}	2.6×10^{-1}	3.9×10^{-1}	2.6×10^{-1}	4.3×10^{-1}

GLOBAL COMPONENT – GLOBALLY-DISPERSED RADIONUCLIDES	
Source and integration time	*Collective dose per unit of electricity generated (man Sv/(GW a))*
	Whole world population
Mining and milling integrated to	
100 years	—
500 years	—
10 000 years	—
Power plants integrated to	
100 years	1.8×10^{0}
500 years	3.4×10^{0}
10 000 years	1.7×10^{1}
Reprocessing integrated to[d]	
100 years	1.2×10^{0}
500 years	2.1×10^{0}
10 000 years	1.0×10^{1}

[a] Local and regional components of the collective doses (due to the first pass) are integrated to 100 years. The local and regional components are explained in chapter III. Per caput values are not given in the table, but are discussed in the text.

[b] World-average is used to qualify the calculations and data that are intended to represent a value averaged across the whole world. In this case the world average is the average of the population in each annulus for all nuclear sites for which data are available (annex A). Similarly, consumption rates for terrestrial and aquatic foods are average values for the world population. The world-average values can be used for comparative purposes including for comparison with the previous versions of the methodology for estimating public exposures due to radioactive discharges (annex A).

[c] Total of the local and regional components due to mining and milling, power plants and reprocessing from the first-pass. The totals for each region include only discharges from power plants, except for Europe, which also has a value for reprocessing.

[d] The normalized values were calculated as described in paragraphs 65 and 66.

Table 17. Comparison of the worldwide collective dose, and associated collective dose normalized to electricity generated, from mining and milling, power plant operation and reprocessing

Nuclear fuel cycle	*Collective dose (man Sv)*	*Normalized collective dose[a] (man Sv/(GW a))*
Local and regional component from mining and milling, power plants and reprocessing (first pass)[b]	130	0.43
Local and regional component (integrated to 100 years) plus global component integrated to		
100 years	910	3.0
500 years	1 700	5.5
10 000 years	7 600	25

[a] These values are averages for the whole world. The world average is the average of the population in each annulus for all nuclear sites for which data are available (annex A). Similarly, consumption rates for terrestrial and aquatic foods were average values for the world population. The results can be used for comparative purposes including for comparison with the previous versions of the methodology for estimating public exposures due to radioactive discharges (annex A).

[b] Local and regional components of the collective doses (due to the first pass) are integrated to 100 years. The local and regional components are explained in chapter III.

Table 18. Radionuclide contributions to the local and regional components of collective doses to the public from reprocessing integrated to 100 years

Radionuclide	*Collective dose per unit of electricity generated (man Sv/(GW a))*			*Collective dose (man Sv)*		
	Atmosphere	*Aquatic*	*Total*	*Atmosphere*	*Aquatic*	*Total*
^{3}H	1.3×10^{-3}	3.6×10^{-6}	1.3×10^{-3}	7.1×10^{-1}	8.0×10^{-4}	7.1×10^{-1}
^{14}C	2.0×10^{-2}	1.7×10^{-3}	2.2×10^{-2}	4.0×10^{0}	5.4×10^{-1}	4.5×10^{0}
^{41}Ar	0	0	0	1.7×10^{-3}	0	1.7×10^{-3}
^{54}Mn	0	8.4×10^{-7}	8.4×10^{-7}	0	1.7×10^{-4}	1.7×10^{-4}
^{58}Co	0	1.8×10^{-8}	1.8×10^{-8}	0	3.6×10^{-6}	3.6×10^{-6}
^{60}Co	3.4×10^{-7}	6.1×10^{-5}	6.1×10^{-5}	1.6×10^{-4}	3.0×10^{-2}	3.0×10^{-2}
^{85}Kr	4.5×10^{-3}	0	4.5×10^{-3}	1.1×10^{0}	0	1.1×10^{0}
^{90}Sr	0	5.8×10^{-7}	5.8×10^{-7}	3.0×10^{-2}	9.8×10^{-4}	3.1×10^{-2}
^{106}Ru	4.2×10^{-7}	9.0×10^{-5}	9.0×10^{-5}	1.2×10^{-3}	2.8×10^{-2}	2.9×10^{-2}
^{129}I	8.3×10^{-4}	2.3×10^{-5}	8.5×10^{-4}	5.1×10^{-1}	5.3×10^{-3}	5.2×10^{-1}
^{131}I	9.6×10^{-7}	1.3×10^{-9}	9.6×10^{-7}	1.1×10^{-3}	2.6×10^{-7}	1.1×10^{-3}
^{135}Xe	0	0	0	3.6×10^{-4}	0	3.6×10^{-4}
^{134}Cs	2.0×10^{-7}	1.7×10^{-6}	1.9×10^{-6}	3.9×10^{-5}	8.1×10^{-4}	8.5×10^{-4}
^{137}Cs	1.9×10^{-7}	1.7×10^{-5}	1.7×10^{-5}	6.5×10^{-3}	1.8×10^{-2}	2.5×10^{-2}
^{239}Pu	3.7×10^{-6}	8.3×10^{-5}	8.7×10^{-5}	1.6×10^{-1}	2.5×10^{-1}	4.2×10^{-1}
^{241}Am	0	5.7×10^{-5}	5.7×10^{-5}	1.2×10^{-2}	2.0×10^{-1}	2.2×10^{-1}
Total	2.7×10^{-2}	2.1×10^{-3}	2.9×10^{-2}	6.5×10^{0}	1.1×10^{0}	7.6×10^{0}

Table 19. Local and regional components of collective dose integrated to 100 years summed over all reactor types

	Africa	*Asia and Pacific*	*Europe*	*Latin America*	*North America*	*World*
Collective dose (man Sv)	9.9×10^{-3}	1.5×10^{1}	2.8×10^{1}	1.2×10^{0}	2.6×10^{1}	6.8×10^{1}

Figure IV. Contribution of radionuclides to the local and regional components of collective dose to the public from reprocessing integrated to 100 years and normalized to electricity generation

See data in table 18

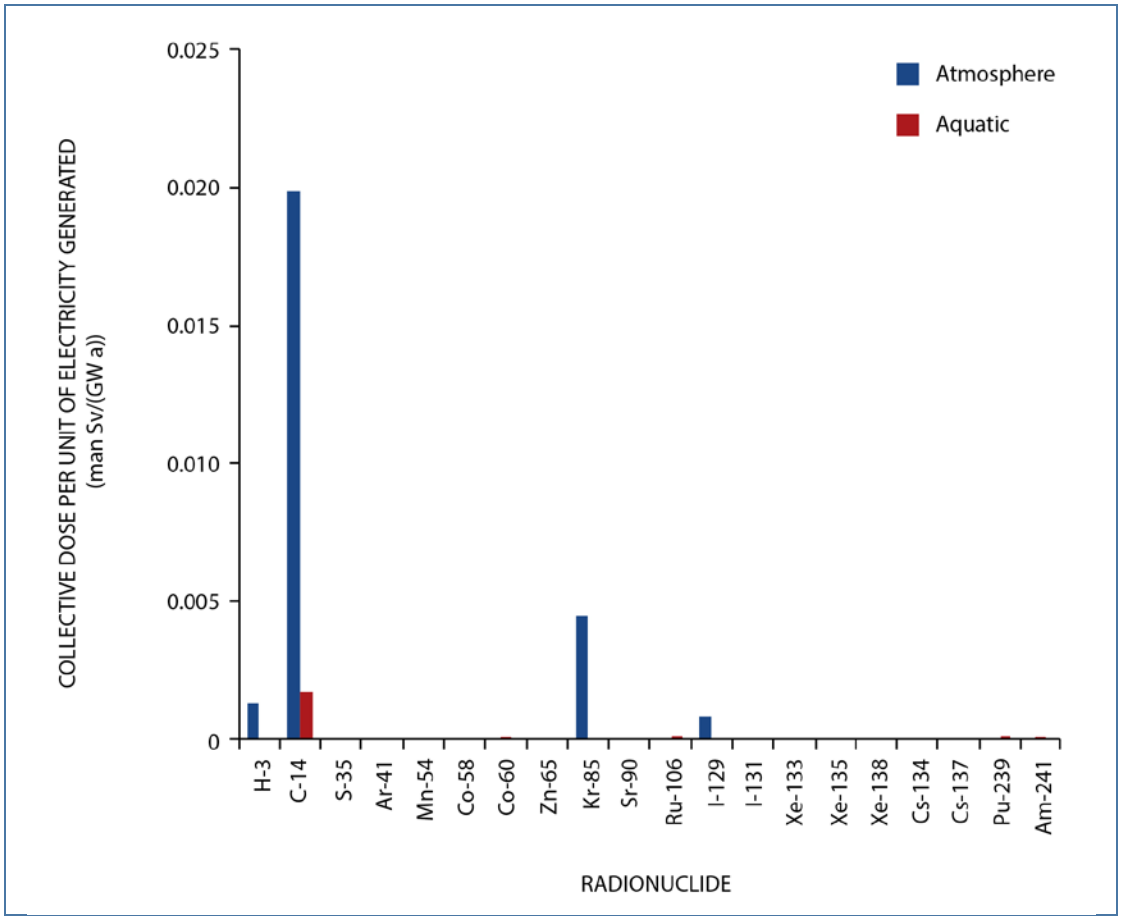


Figure V. Collective doses from globally-circulating radionuclides per unit of electricity generated

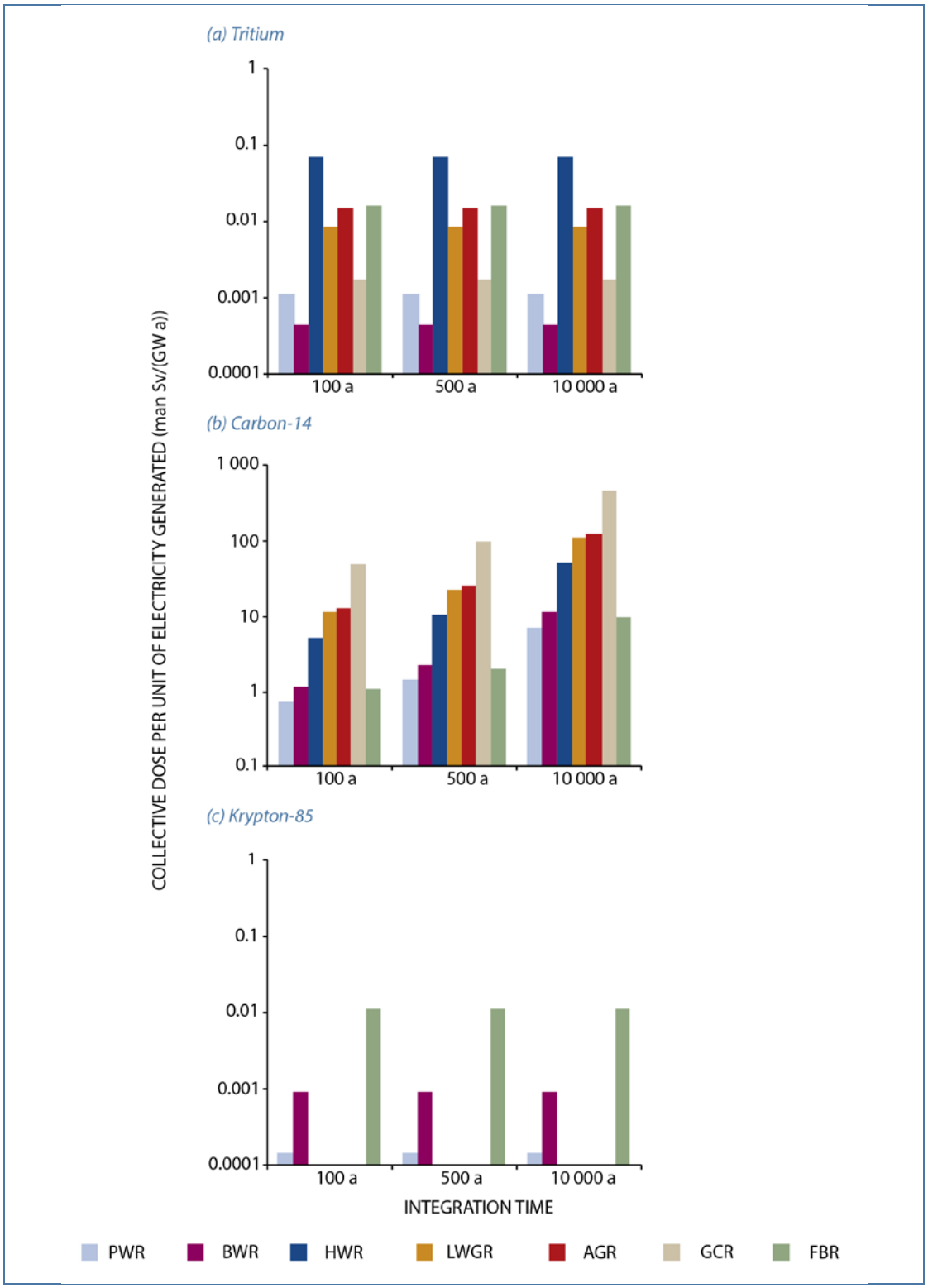
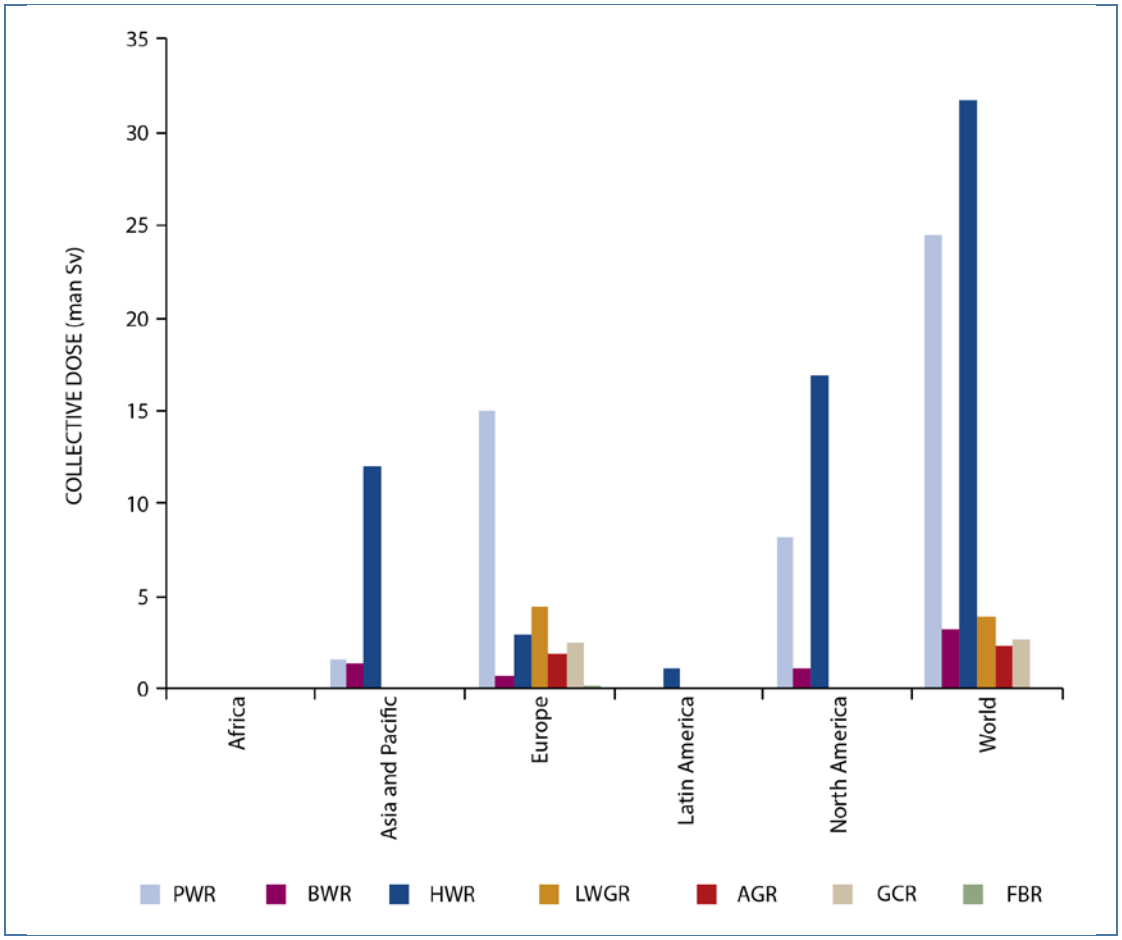


Figure VI. Local and regional components of the collective doses to the public due to total estimated discharges from nuclear power plants (2010) integrated to 100 years, by UNEP region and by reactor type



4. Uranium enrichment and fuel fabrication

74. The discharges from the processes of conversion, uranium enrichment and subsequent fuel fabrication needed for different reactor types have generally been determined in earlier studies to be relatively small, consisting mainly of radionuclides within the decay chains of uranium isotopes. The collective dose to the public estimated on the basis of the electricity generated, derived in the UNSCEAR 2000 Report [U9] and re-used in the UNSCEAR 2008 Report [U11], were used here to obtain an updated value based on the 2010 electricity generation from nuclear power. This value for uranium enrichment and fuel fabrication facilities is 0.003 man Sv/(GW a). The Committee earlier estimated the average annual collective dose to the public from all plants for the period 1998–2002 to be 0.8 man Sv [U11]. Updating this value to the electricity generated from nuclear power in 2010 from table 2, the average annual collective dose to the public due to uranium enrichment and fuel fabrication in the year 2010 is about 0.9 man Sv.

5. Solid waste disposal

75. Solid wastes arise at various stages in the nuclear fuel cycle. These include low- and intermediate-level wastes, mainly from reactor operations, high-level wastes from fuel reprocessing, and spent fuel for direct disposal. The activity concentrations of these wastes can range from just above natural background levels, as in mill tailings, to much higher levels, such as in spent reactor fuel.

76. Low- and intermediate-level wastes are generally disposed of by shallow burial in trenches or concrete-lined structures, but more advanced disposal sites also exist. Before disposal, all such material is manipulated and transported, which gives rise to both occupational and public exposures. For the nuclear fuel cycle, doses to members of the public from the transport of radioactive material have been earlier estimated using the factor of 0.1 man Sv/(GW a) for the collective dose per unit of electricity generated [U11]. Wastes from the nuclear fuel cycle also include large quantities of depleted uranium from uranium enrichment operations [U18]. High-level wastes and spent fuel are presently retained in interim storage facilities until adequate methods for disposal have been devised and disposal sites selected [U11].

77. Estimates of the doses due to solid waste disposal have been based on the projected eventual migration of radionuclides from the burial site into groundwater. The collective dose due to low- and intermediate-level waste disposal normalized to electricity generated is estimated to be approximately 0.5 man Sv/(GW a), due almost entirely to ^{14}C. The average worldwide per caput annual effective dose would be about 1 nSv per year of practice [U11].

C. Occupational exposure for the nuclear fuel cycle

78. The assessment of occupational exposures for the nuclear fuel cycle considers the practices of mining, milling, uranium enrichment and conversion, fuel fabrication, reactor operation, fuel reprocessing and research.

79. Collective doses due to occupational exposure for each practice in the nuclear fuel cycle that were reported in the UNSCEAR 2008 Report [U11] for the years 2000–2002 were used as the starting point to estimate the 2010 occupational exposures. This approach was taken since data were not readily available on the total number of, or the average annual effective dose to, monitored workers worldwide in 2010. As reported in the UNSCEAR 2008 Report, the Committee used the amount of electricity that can be generated from each practice (i.e. how much electricity can be generated from the uranium that is mined, milled, converted, and so on) to normalize collective doses to the electricity generated.

80. Table 20 summarizes the data on occupational exposure for the nuclear fuel cycle in the period 2000−2002 that are relevant for estimating occupational exposure for the nuclear fuel cycle in 2010.

81. The ratio from the 2000–2002 data for the average annual collective dose per unit of electricity generated was combined with the electricity generation for 2010 to estimate the annual collective dose for 2010. Similarly, the ratio obtained from 2002 for the average annual collective dose per unit mass of uranium mined, which can be further transformed to the collective dose per unit of electricity generated is assumed appropriate for the mining process. Actual data from the Canada, the United Kingdom and the United States for 2010 were obtained on the number of monitored workers and their average annual effective dose, and were compared with the respective country values for 2000−2002 in the UNSCEAR 2008 Report [U11]. These comparisons showed reasonable agreement with the scaled average annual effective dose, giving some confidence in the assumptions used.

Table 20. Worldwide average annual individual and collective doses to workers due to the commercial nuclear fuel cycle

From table 72 in the UNSCEAR 2008 Report [U11]; for the years 2000–2002[a]

Practice	*Monitored workers (thousands)*	*Average annual[b] collective dose (man Sv)*	*Average annual[b] collective dose per unit of electricity generated (man Sv/(GW a))*	*Average annual[b] effective dose to monitored workers (mSv)*
Mining	12	22	0.1	1.8
Milling	3	3	0.02	1.0
Enrichment	18	2	0.02	0.1
Fuel fabrication	20	31	0.1	1.6
Reactor operation	437	617	2.5	1.4
Reprocessing[c,d]	76	68		0.9
Research	90	36	0.1	0.4
Total	656	779	2.8	1.2

[a] Some values in the table have been corrected since table 72 was published in the UNSCEAR 2008 Report [U11]; for the years 2000–2002.

[b] The words "average annual" used in the table denote the annual dose averaged over the 2000-2002 year span.

[c] Also includes the reprocessing of some fuel associated with military application.

[d] The average annual collective dose per unit of electricity generated was not possible to obtain, because there were no data readily available on the amount of electricity generated from the reprocessed fuel.

82. Table 21 shows the current results for 2010 for the worldwide average annual collective dose compared to the 2000–2002 results. The procedure for estimating the values for each practice for 2010 is explained below.

– *Uranium mining*. The amount of uranium ore mined was assumed equal to the amount produced [U11]. Total uranium production in 2010 for 16 countries is shown in table 4 [O8]. Values were summed for all countries to give 54,100 t of uranium. Of this amount, 31,900 t was produced from open pit and underground uranium mines and 22,200 t was produced from in-situ leaching (ISL) processes. Assuming the same collective dose per unit mass of uranium extracted of 0.623 man Sv/kt as for 2000–2002 [U11], then the collective dose (rounded) is 20 man Sv. This value excludes uranium produced from ISL.

– *Uranium milling*. As for uranium mining, the total uranium production in 2010 was taken from table 4 [O8] and assumed to equal the total amount of uranium milled, 54,104 t. Applying the same simplifying assumptions used in the UNSCEAR 2008 Report [U11] (i.e. that all milled uranium is used in LWRs and that the uranium requirement is 220 t/(GW a) ([U11]; table 18-A)), the equivalent amount of electricity for 2010 is 246 GW a. The collective dose (rounded) for 2010 is then 5 man Sv. While ISL extract is not milled, it does go through some treatment to produce yellowcake. Thus the full amount of uranium mined, 54,100 t, is used here.

– *Uranium conversion and enrichment, and fuel fabrication*. UNSCEAR 2008 Report (table 15) shows the worldwide installed capacity for fuel cycle installations taken from the IAEA Nuclear Fuel Cycle Information System, NFCIS. Compiling the data from NFCIS for 2010 and comparing with table 15 from the UNSCEAR 2008 Report shows little has changed in the

capacity of these processes. All three processes show decreased capacities of between 8% and 9%. Using the assumption that these practices give the same collective dose per unit of electricity generated in 2010 as in 2002, the average annual collective dose for 2010 in table 21 has been adjusted to a lower value by 8%.

– *Reactor operation*. The normalized average annual collective dose for 2000–2002 was 2.5 man Sv/(GW a). Instead of using this value directly, as explained above, data from the OECD/NEA [O4] indicated a general decrease in the average annual collective doses. The reported average annual collective dose for operating nuclear power plants fell by 20% between 2002 and 2010, attributed to additional operating experience and the global exchange of best radiation protection practices. Using this, the normalized average annual collective dose for 2010 can be taken as 2.0 man Sv/(GW a). Assuming the total worldwide electricity generation in 2010 is 314 GW a, an average annual collective dose of 628 man Sv was calculated, about the same as that reported for 2002, as shown in table 21.

– *Reprocessing*. In the absence of updated data on occupational exposures during fuel reprocessing in 2010, it was assumed that reprocessing activities have remained more or less constant and the same collective dose was assigned as previously, i.e. no change. Data from UNSCEAR [U11] were not presented in terms of dose per unit of electricity generated.

– *Research*. In the absence of updated data on occupational exposures obtained during research for 2010, it was assumed that research activities have remained more or less constant and the same collective dose was assigned as previously. However, it should be noted that a slight downward trend in collective dose was observed over the previous two time periods in UNSCEAR [U11]. Data from UNSCEAR [U11] were not presented in terms of dose per unit of electricity generated.

Table 21. Worldwide levels of exposure of workers due to the commercial nuclear fuel cycle for 2010 and 2000–2002

Practice	*Average annual collective effective dose 2000–2002 (man Sv) (From [U11] for years 2000–2002)*	*Average annual collective dose 2010 (man Sv) (Estimates from this study)*	*Average annual collective dose per unit of electricity generated (man Sv/(GW a)) (From [U11] for years 2000–2002)*	*Remarks*
Mining	22	20	0.1	U production 2010=54.1 kt; of this 31.9 kt was the amount of U produced excluding ISL production (35 ktU average in 1998–2003)
Milling	3	5	0.02	246 GW a calculated using same simplifying assumption from UNSCEAR 2008 Report, table 18-A, that all milled uranium was used in LWRs, and that uranium requirement was 220 t/(GW a). Doses resulting from subsequent remediation activities were not accounted for
Enrichment	2	2	0.02	8% lower capacity than in 2000–2002 (not noticeable because numbers are rounded)
Fuel fabrication	31	29	0.1	8% lower throughput than in 2000–2002
Reactor operation	617	628	2.5	314 GW a total electricity generated by nuclear power plants in 2010 [I15, I16]
Reprocessing	68	68		Assumed constant collective dose–i.e. no change. Data were not presented [U11] in terms of dose per unit of electricity generated
Research	36	36	0.1	Assume constant collective dose–i.e. no change
Total	779	788	2.8	

D. Decommissioning

83. When a power company decides to close a nuclear power plant permanently, the facility must be decommissioned by safely removing it from service and reducing residual radioactivity to a level that permits release of the property and termination of the operating licence. As more commercial nuclear power reactors reach the end of their operating licence, there is a commensurate increase in decontamination and decommissioning activities that involve radiation exposure. These activities include decontamination of structures and components, dismantling of components and demolition of buildings, remediation of any contaminated ground, and removal of the resulting waste. As of 2015, 156 commercial and prototype reactors located in 19 countries with a total of 60.9 GW(e) capacity were permanently shut down [I8]. Most of these reactors were PWRs, GCRs and BWRs. The current assessment concentrated on occupational exposures during the decommissioning process.

84. The decommissioning process begins when a power company decides to permanently cease operations. The operator of a nuclear facility may choose between three decommissioning strategies: *(a)* immediate dismantling, *(b)* deferred dismantling after a safe storage period, and *(c)* entombment of the facility. Under immediate dismantling, decommissioning activities begin shortly after the permanent cessation of operations. This strategy implies prompt completion of the decommissioning project (approximately 10 to 20 years) and involves the removal of all radioactive material from the facility to another new or existing licenced facility.

85. Under deferred dismantling (sometimes called safe storage, safe store or safe enclosure), a nuclear facility is maintained and monitored in a condition that allows the radioactivity to decay and thus reduce occupational exposure. Parts of a facility containing radioactive contaminants are safely stored and maintained for upwards of 40 to 60 years until they can subsequently be decontaminated to levels that permit parts of the facility to be dismantled and released for unrestricted use.

86. Under entombment, radioactive contaminants are encased in a structurally long-lived material such as concrete until radioactivity decays to a level permitting the unrestricted release of the facility, or release with restrictions imposed by the regulatory body.

87. As of December 2015, the International Atomic Energy Agency/Nuclear Energy Agency Information System on Occupational Exposure (ISOE) database (http://www.isoe-network.net/) contained data on doses to workers from 84 reactors that were shut down, in some stage of decommissioning or fully decommissioned. These reactor units were generally of different types and sizes, and at different phases of their decommissioning programmes. At least 15 reactors had been fully dismantled, over 50 reactors were being dismantled, over 50 reactors were in deferred dismantlement, three had been entombed, and for others the decommissioning strategy was not specified yet.

88. Table 22 provides the average annual collective dose for occupational exposure per unit for up to 71 permanently shut down reactors by country and reactor type for 2008−2013, based on data recorded in the ISOE database and supplemented by individual country reports. Different decontamination and decommissioning strategies were being employed and each facility shown in the database was in a different stage of decommissioning, making definitive trends difficult to deduce from this information. Depending on the phase of decommissioning, there may be little or no worker exposure one year and the next year collective dose to workers may rise as much as 100-fold (adapted from [O5]). Considering the average collective doses for each of the reactor types, however, and the total average for all the units, the average values demonstrate some stability over these six years, with the total average for all units being about 0.06 man Sv per year and reactor.

89. Table 23 shows data from the whole decommissioning period for nuclear power plants that have been immediately decontaminated and decommissioned. The dose values given are the integrated doses for the whole decommissioning process. There may be some additional dose due to spent fuel storage until a permanent repository is opened, but these occupational exposures can be considered negligible compared to active decommissioning. For example, for five of the decommissioned units that reported to the REIRS database (Radiation Exposure and Information Reporting Systems) ([U24]; table 3.1), collective doses from occupational exposure due to spent fuel storage ranged from 0 to 1.86×10^{-3} man Sv annually. The values for electricity supplied were the total integrated electricity generation from the time the unit went on the grid until it ceased operation.

90. The relative quantity needed for the comparative study conducted here was an estimate of the collective doses from occupational exposure for decommissioning, integrated over the period of decommissioning. The fact that the annual collective dose varies from year to year is not relevant if a reasonable average can be obtained. Although limited, the Committee considered that the data on integrated doses for nuclear reactors shown in table 23 were sufficient for its use here.

91. The average total collective dose associated with the strategy of immediate decontamination and decommissioning of the commercial nuclear power plants shown in table 23 was less than 10 man Sv per reactor. While the alternative decommissioning strategies, deferred dismantling and entombment, may result in some reduction in the total collective dose per reactor from decommissioning, it may be another 10 to 20 years before any definitive conclusions can be documented.

92. Table 23 also shows the collective dose from occupational exposure normalized to the total integrated electricity supplied for each of the reactors, with an average for these 8 reactors of 1.80 man Sv/(GW a).

Table 22. Number of units and average annual collective dose from occupational exposure per reactor by country and reactor type for definitely shutdown reactors, 2008–2013

The columns headed dose give the average annual collective dose from occupational exposure in man-millisieverts per reactor (man mSv)

		2008		*2009*		*2010*		*2011*		*2012*		*2013*	
		No.	*Dose*	*No.*	*Dose*	*No.*	*Dose*	*No.*	*Dose*	*No.*	*Dose*	*No.*	*Dose*
PWR	France	1	23.2	1	62.1	1	117.2	1	264.1	1	275.6	1	189.3
	Germany	5	160.0	5	128.0	3	278.6	3	126.3	3	114.4	4	77.7
	Italy	1	1.1	1	1.7	1	3.2	1	1.8	1	3	1	5.2
	Spain	1	134.7	1	244.0	1	53.0	1	190.0	1	307.9	1	468.9
	United States	10	7.1	8	1.5	8	2.4	6	49.4	6	127.1	12	47.3
	Average	18	57.2	16	60.0	14	73.5	12	94.4	12	141	19	81.1
VVER	Bulgaria	4	31.0	4	29.4	4	11.3	4	9.2	4	10.1	4	3.3
	Germany	5	27.0	5	20.0	—	—	—	—	—	—	—	—
	Russian Federation	2	78.0	2	84.0	2	77.6	2	66.3	2	79.2	2	49.6
	Slovak Republic	1	48.2	2	106.0	2	12.4	2	10.0	2	4.3	—	—
	Average	12	38.6	13	46.0	8	28.2	8	23.7	8	25.9	6	18.7
BWR	Germany	3	179.0	3	138.0	1	427.1	1	289.5	1	88.2	1	72.0
	Italy	2	29.1	2	61.8	2	60.3	2	15.1	2	18.4	2	34.2
	Japan	—	—	—	—	2	123.8	2	48.4	2	41.2	2	64.2
	The Netherlands	1	0.3	1	0.6	n/a	n/a	1	10	—	—	—	—
	Sweden	2	39.1	2	27.0	2	6.2	2	27.2	2	20	2	3.45
	United States	3	13.4	4	5.1	5	21.8	4	30.7	4	59.4	5	55.7
	Average	11	64.9	12	51.1	12	76.3	12	50.3	11	44.1	12	46.2

		2008		2009		2010		2011		2012		2013	
		No.	*Dose*	*No.*	*Dose*	*No.*	*Dose*	*No.*	*Dose*	*No.*	*Dose*	*No.*	*Dose*
GCR	France	6	2.8	6	8.8	6	1.3	6	2.4	6	7.4	6	8.2
	Germany	2	13.0	2	17.0	—	—	—	—	—	—	—	—
	Italy	1	2.9	1	0	1	1.7	1	10.4	1	0.2	1	2.2
	Japan	1	20.0	1	20.0	1	50	1	50	1	70	1	10
	Spain	—	—	—	—	—	—	1	0	1	0	1	0
	United Kingdom	16	48.0	16	42.0	16	55	16	49	19	56	19	57.3
	United States	—	—	—	—	—	—	—	—	1	0	1	0
	Total number, average dose	26	32.1	26	30.0	24	39.1	25	34.4	28	42.1	28	41.1
HTGR	Germany	1	0	1	0	1	0	1	0	—	—	1	0
FBR	United States	—	—	1	80.14	1	77.9	1	294.9	1	2	1	0.1
LWGR	Lithuania	1	188.4	1	144.7	2	236.2	2	304.8	2	264.9	2	304.8
LWCHWR	Japan	1	431.3	1	114.6	1	111.6	1	126.6	1	148.8	1	134.1
All Units	Average	70	52.3	71	47.7	63	59.9	62	61.5	64	66.3	71	57.8

This table is adapted from table 4 in the 2012 ISOE annual report [O5]and table 5 from the 2010 ISOE annual report [O4]. Additional information was obtained from the individual country reports and the ISOE database, and the United States Nuclear Regulatory Commission Radiation Exposure and Information Reporting System (REIRS) [U24] database for United States definitely shut reactors. Data for 2013 were obtained from the 2013 ISOE country reports [O7] and the ISOE database [I20].

Dashes (—) represent missing or partial data in the data source. The acronyms for the reactor type used in tables 22 and 23 differ somewhat from those in the other tables in this annex (see paragraph 58). The acronyms in this table and table 23 are the designations used by the Nuclear Energy Agency.

The following explains the meaning of the acronyms that differ from previous tables:

LWCHWR (Light Water Cooled Heavy Water Reactor) also known as a CANDU reactor is the Canadian designed system. IAEA would refer to this as a PHWR.

VVER (water, water, energetic reactor) is a Soviet designed PWR.

HTGR, (also called HTGC, high temperature gas cooled) reactor. More of a prototype reactor but nuclear power plants include Peach Bottom and Fort Saint Vrain in the United States; Dragon reactor in the United Kingdom, and THTR-300 and AVR in Germany.

Table 23. Collective dose, and collective dose normalized to electricity supplied, due to the complete decommissioning process of immediately decontaminated and decommissioned commercial nuclear power plants

Reactor gross electrical capacity and total electricity supplied were obtained from the IAEA PRIS database [I7]. Collective doses were obtained from the ISOE database [I20] and REIRS reports [U24]

Reactor type	*Country*	*Plant*	*Gross Capacity (MW(e))*	*Collective dose (man Sv)*	*Electricity supplied (GW a)*	*Normalized collective dose (man Sv/ GW a)*
PWR	United States	Haddem Neck	603	8.457	12.1	0.70
		Maine Yankee	900	6.195	13.6	0.46
		Rancho Seco	917	2.345	5.1	0.46
		San Onofre 1	456	3.002	5.8	0.52
		Trojan	1 155	2.973	9.6	0.31
		Yankee Rowe	180	6.467	3.9	1.66
		AVERAGE		4.907	8.34	0.69
BWR	United States	Big Rock Point	71	5.703	1.45	3.93
HTGR	United States	Fort St. Vrain	342	3.961	0.62	6.39
All units	Average			4.900		1.80

V. RADIATION EXPOSURES ARISING FROM ELECTRICITY GENERATION BY COMBUSTION OF FOSSIL FUELS

A. Coal

1. Introduction

93. Coal is a family name for a variety of solid organic fuels and refers to a whole range of combustible sedimentary rock materials spanning a continuous quality scale. For convenience, this continuous series is often divided into two main categories: hard coal (which includes anthracite and bituminous coal) and brown coal (which includes sub-bituminous coal and lignite). The International Energy Agency [I15] makes use of two broad categories of coal; hard coal as having a gross calorific value not less than 23.9 GJ/t (5,700 kcal/kg) and brown coal with a gross calorific value less than 23.9 GJ/t (5,700 kcal/kg). Often coal data are presented in tonnes of coal equivalent (TCE) where one tonne of coal is equivalent to 7 million kilocalories. This description standardizes the carbon content and heat value of a particular type of coal. The International Energy Agency estimates that there are equal recoverable global reserves of both hard coal and brown coal [I14].

94. Combustion of coal for electricity generation is the largest contributor to worldwide electricity generation (figure I). Coal has maintained a share of about 40% of the total electricity generated for some decades, while the total electricity generation from coal and other sources has increased steadily as shown in figure I [I15]. The UNEP geographic region—Asia and the Pacific—accounted for 57% of the total electricity generation from coal in 2010, with China accounting for about 70% of this [U17]. In contrast, the geographic region—West Asia—used no coal for electricity generation in 2010 (table 2).

95. Electricity generation is not the only end-product of coal combustion, others being for example steel production and cement manufacturing. The largest 10 coal-producing countries are shown for the years 2008–2012 in table 24. China was the largest producer with a 30% increase in production over this five-year period. The total world primary coal production for this period had a 16% increased production in 2012 compared with 2008, and about a 60% increased production during the 10-year period since 2002 [U17].

96. Coal contains naturally occurring radionuclides from the uranium and thorium series (figure III) and potassium-40. The concentration of naturally occurring radioactive material in coal depends on the characteristics of the geological formation of the coal seams where it originated. Table 25 provides a representative overview of the range in concentrations, where large variations in the activity concentrations can be noted.

Table 24. Total primary coal production 2008–2012 (million metric tonnes, Mt)

Source: United States Energy Information Administration, International Energy Statistics 2008–2012, open source data [U17]

Country	*2008*	*2009*	*2010*	*2011*	*2012*
China	2 811	2 995	3 230	3 518	3 645
United States	1 063	975	984	994	922
India	517	558	562	575	589
Australia	392	408	424	402	421
Russian Federation	305	276	322	322	354
South Africa	252	249	255	253	259
Indonesia	249	291	325	360	443
Poland	143	135	133	139	144
Kazakhstan	111	101	111	116	126
Colombia	74	73	74	86	89
World	6 778	6 896	7 257	7 660	7 881

Table 25. Example ranges and/or averages of radionuclide activity concentrations in coal (Bq/kg) (table VII from IAEA [I2])

Country	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{40}K
Australia	8.5–47	21–68	19–24	20–33	16–28	11–69	11–64	23–140
Brazil[a]	72		72	72		62	62	
Egypt	59		26			8	8	
Germany Lignite (Former Democratic Republic of Germany)			10–145 32[a] <1–58 10[a]			10–63 21[a] <1–58 8[a]		10–700 225[a] <4–220 22[a]
Greece[b]	117–390		44–206	59–205			9–41	
Hungary	20–480					12–97		30–384
Italy[c]	23±3					18±4		218±15
Poland	<159 18[d]					<123 11[d]		<785
Romania	<415 80[a]		<557 126[a]	<510 210[a]	<580 262[a]	<170 62[a]		
United Kingdom	7–19	8.5–25.5	7.8–21.8			7–19		55–314
United States	6.3–73		8.9–59.2	12.2–77.7	3.3–51.8	3.7–21.1		

[a] Average.

[b] Lignite.

[c] Lignite, average.

[d] Average for all coal seams.

97. When coal is combusted the majority of the non-combustible matter remains in the bottom and fly ash. Because radionuclides are present in the mineral constituents, they also tend to remain in the ash, where the concentration of the radionuclides becomes enhanced [I2, S4, Z1]. However, radon is a noble gas and all the radon present in the coal is emitted through the flue-gas stack. As coal-fired power plants have modernized, the cleaning and filtering systems have become increasingly efficient and larger fractions of the particulate matter in the fly ash have been captured and removed from the discharge to atmosphere. The coal ash that is collected is either recycled for beneficial use or it is disposed of in landfills or impoundments.[6]

98. The components of the coal cycle that can lead to radiation exposures of the public are *(a)* discharges to atmosphere of radon from coal-mining activities and other wastes produced during mining, *(b)* radioactive discharges from the operation of coal-fired power plants, and *(c)* radiation exposures from the recycling and use of, or disposal of, coal ash. Occupational radiation exposures

[6] Coal ash can be disposed as a coal slurry in impoundments, a dammed reservoir that contains the coal slurry.

occur during *(a)* the mining for coal, and *(b)* work performed associated with power plant operation and disposal operations. In earlier studies, occupational exposures from work performed at the power plant were determined to be small [C5, G4, G5] in relation to the occupational radiation exposures incurred during coal mining. For this reason, combined with the relatively small number of workers involved compared to coal mining, this exposure source was not considered further in the current study. The following sections consider the other exposure sources and pathways.

2. Public exposure

(a) *Coal mining*

99. Radon emissions from coal mining contribute to exposure of the public from the coal cycle. Radon gas is emitted from the mines as a result of the coal mining activities, primarily through venting of the mines. Although data that could enable the assessment of this impact have earlier been scarce, new measurements on radon emissions from coal mining in China have become available. Radon emissions from 23 large-, medium- and small-sized coal mines in eight different provinces in China have been assessed, based on the monitoring results of radon activity in the mines. The large- and medium-sized coal mines are equipped with ventilation systems that are described as "good" or "relatively good." The smaller, privately owned coal mines generally are poorly ventilated, with radon concentrations 15 to 30 times higher than in the larger mines [L1]. The radon emissions have been normalized to the unit of coal output and per unit of electricity generated for each coal mine and for each size-class of coal mine. Typical values were obtained as shown in table 26 [W2].

Table 26. Radon emissions during one year from large-, medium- and small-sized coal mines in China [W2]

Type of coal mine	*Coal output (t/a)*	*Number of coal mines*	*Radon emissions per unit of coal output (Bq/t)*	*Radon emissions per unit of electricity generated (TBq/(GW a))*[a]
Large-sized	1.6×10^9	7	1.9×10^5	0.57
Medium-sized	5.7×10^8	4	1.3×10^6	3.6
Small-sized	3.9×10^8	12	3.5×10^6	11
Typical value			9.3×10^5	2.8

[a] From the data in table 26, obtained from the Chinese delegation to the Committee, the coal production per unit of electricity generation could be calculated as between 2.8 and 3.1×10^6 t/(GW a).

100. The radioactive content of coal-mine tailings do not differ significantly from background concentrations of natural radionuclides in soil; this situation is different from uranium mining and mill tailings, which have higher concentrations of the natural radionuclides [U9]. This exposure pathway is thus not considered further in this analysis.

101. The typical value for the radon emission (based on discharges of radon during one year) normalized to electricity generated obtained from the Chinese data, 2.8 TBq/(GW a), has been used with the electricity generation data from table 2 and the Committee's revised methodology for estimating public exposures due to radioactive discharges (annex A) to assess the radiological impact from this source. The default population distribution (see section III.A) was used and the radon was assumed to be released on its own with account taken of its short-lived progeny (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) in estimating the doses from inhalation.

(b) *Electricity generation from combustion of coal*

102. Coal combustion in power plants results in the direct release of gaseous radionuclides, and the production of ash with enhanced concentrations of natural radionuclides relative to those of coal [S4]. A fraction of the ash produced is released to atmosphere, dependent on the particulate collection devices used in the power plant. Modern coal-fired power plants have more efficient particulate collection devices than older coal-fired power plants.

103. To assess the doses due to atmospheric releases from coal-fired power plants, a representative case was considered. The coal (e.g. hard coal) was assumed to have an energy equivalent of 24 GJ/t with a power generation efficiency of 38% [I13]. Although the values of ^{238}U concentrations shown in table 25 show wide variations, an average ^{238}U concentration of 20 Bq/kg was chosen, based on typical values for Chinese coal reported as 10–25 Bq/kg [I10]. China is the largest producer of coal worldwide, so the value of 20 Bq/kg for the ^{238}U concentration in coal was considered reasonable as a typical average global value. Other studies have also found a normal range of 20–25 Bq/kg observed globally for good quality coal [S4, T1, U6]. A value of 20 Bq/kg for the ^{238}U concentration in coal had also been used in the UNSCEAR 1988 Report [U7]. It should also be noted that the resulting individual and collective doses calculated by the revised methodology for estimating public exposures due to radioactive discharges (annex A) are directly proportional to the ^{238}U concentration in coal.

104. Two different release rates were evaluated to represent the discharge characteristics of older coal-fired power plants and modern coal-fired power plants (table 27). The relative distribution among the different radionuclides in table 27 for the older plants were taken from Hedvall and Erlandsson [H2] while the same for the modern plants were based on Zeevaert et al. [Z1]. The key difference between the two data sets is that ^{222}Rn concentrations in the discharges are 100 times larger than ^{226}Ra in older plants and 1,500 larger than ^{226}Ra in modern plants that have more efficient filtering systems. However, in both cases the value for the discharge of lead and polonium particles has been chosen as twice that of uranium and radium [C4, T1]. Because radon is a noble gas, it is unaffected by filters. As seen from table 27, these releases are not in secular equilibrium. The distribution of older versus modern coal-fired power plants in the various regions of the world is not well-characterized so the results from both cases are included to illustrate the difference in the resulting doses.

105. The assessments presented in this annex using the Committee's revised methodology for estimating public exposures due to radioactive discharges (annex A) do not include dose contributions from ^{40}K or the ^{232}Th decay chain. The absorption of ^{40}K in humans is homeostatically controlled and therefore any doses from ^{40}K discharges have been neglected. The contribution of the ^{232}Th decay chain to exposures due to electricity generation from coal combustion has been studied by Zeevaert et al. [Z1]. They found that the concentrations of the radionuclides in the ^{238}U and ^{232}Th decay chains in flue gases discharged were similar. The largest contribution to individual doses came from deposition, with consumption of food crops dominating. In this category, the contribution from the ^{238}U decay series was one order of magnitude larger than the contribution from the ^{232}Th decay series. Although inclusion of the ^{232}Th decay series may lead to somewhat higher doses from electricity generation due to coal combustion, it was excluded from the analysis in this annex.

106. Aquatic discharges from coal-fired power plants may lead to additional exposure of local population groups, but this contribution has been found to be small and site-specific [L2, Z1], and were therefore not considered here.

Table 27. Releases to atmosphere (during one year) normalized to electricity generated from coal-fired power plants, based on a representative coal containing 20 Bq/kg of ^{238}U

Radionuclide	*Normalized release (TBq/(GW a))*	
	Older coal-fired power plants[a]	*Modern coal-fired power plants*[b]
^{222}Rn	0.07	0.07
^{210}Po	1.4×10^{-3}	9.3×10^{-5}
^{210}Pb	1.4×10^{-3}	9.3×10^{-5}
^{226}Ra	0.7×10^{-3}	4.7×10^{-5}
^{234}U	0.7×10^{-3}	4.7×10^{-5}
^{238}U	0.7×10^{-3}	4.7×10^{-5}
^{230}Th	0.7×10^{-3}	4.7×10^{-5}

[a] Relative radionuclide distribution source: [H2].

[b] Relative radionuclide distribution source: [Z1].

(c) *Radon discharges from coal ash disposed in landfills*

107. Coal ash is also referred to as coal combustion residuals (CCR) and coal combustion products (CCP) depending on the industry and the country, and is one of the larger streams of industrial waste generated in the United States [U21]. Coal ash includes a number of by-products from combustion of coal including: fly ash; (furnace) bottom ash; fluidized bed combustion ash; boiler slag; semi-dry absorption product; and flue gas desulphurization gypsum.

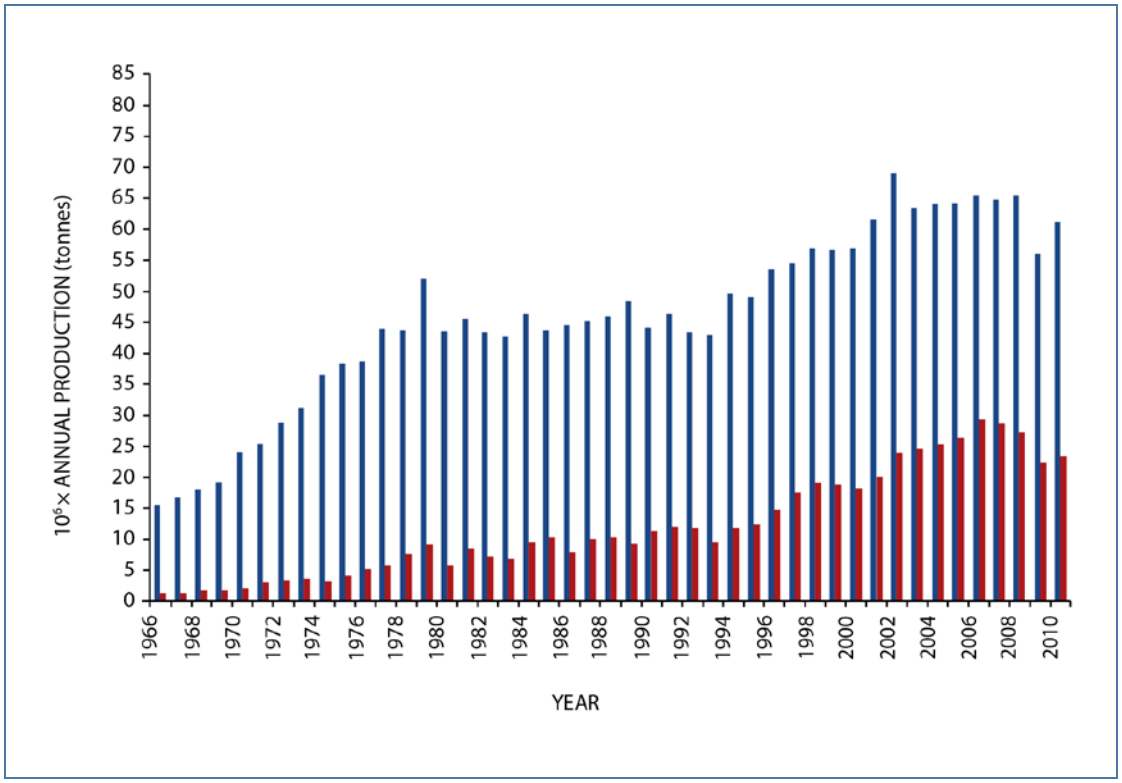
108. The coal ash collected from a power plant is either recycled for beneficial use or it is disposed of in landfills or impoundments. Figure VII shows a time history of fly ash production and the fraction used for construction in the period 1966–2010 in the United States [A1]. Approximately 40% was used commercially, leaving the remaining 60% for disposal. This does not include bottom ash, but the proportion sent for disposal was similar [A2].

109. Conventional back-filling or earthmoving operations are used to dispose of the coal combustion residues (CCR) in dry or slightly moist conditions. Impoundments represent a wet disposal method where the CCR is mixed with water at the power station and conveyed hydraulically through pipelines to artificial lagoons where the slurry is discharged. According to the Electric Power Research Institute [E3], about 60% of the disposed fly ash in the United States is managed dry in landfills, and 40% is managed wet in impoundments, and it noted that there was a long-term trend toward increased use of dry management practices [E3].

110. Earlier studies concluded that the individual doses to the public due to radioactive discharges from deposited coal ash were below values relevant from an individual radiation protection viewpoint (e.g. [U23]). The main reason was that the fraction of radon emanating from coal ash is small. This pathway was however considered relevant in the current assessment for collective doses given that the amount of coal ash produced is large and could be significant to the comparisons of collective doses. Also, a similar pathway was considered from the uranium mill tailings in the nuclear fuel cycle motivating a comparison between these two pathways.

Figure VII. Fly ash production and use in the United States (1966–2010) [A1]

(Blue = production, Red = used as a construction material in a variety of applications)



111. *Method for treating the radon discharge from coal ash deposits.* The amount of radon released to atmosphere from coal ash depends on the activity concentration of radon in the ash, which is related to the activity concentration of ^{226}Ra, and the extent to which the radon produced in the ash is emitted to atmosphere. A recent comprehensive review of radon emanation measurements for mineral, rock, soil, mill tailings and fly ash found the radon emanation fraction (the ratio of the radon emitted to that generated in the mill tailings (or ash deposits) per unit volume) for mill tailings (mostly uranium mill tailings) was 0.17 and for fly ash was 0.03 [S1]. In another study [S6] the radon emanation fraction for coal ash was found to be between 0.08 and 0.13 [S6]. In summary, the first cited study estimated a radon emanation from coal fly-ash of about 20% of the radon emanation from uranium mill tailings, and the second study estimated a value of about 50%. A representative average concentration of ^{226}Ra in coal ashes (fly- and bottom-ash) was taken as 100 Bq/kg [M2].

112. The ^{222}Rn flux (Bq/(m^2 s)) was studied using data from a repository for uranium residues in India [I5] and a linear relationship was found between the radon flux and the activity concentration of ^{226}Ra in the source:

$$^{222}\text{Rn flux (Bq/(m}^2\text{ s))} = 8.3 \times 10^{-4}\text{ kg/(m}^2\text{ s)} \times {}^{226}\text{Ra concentration (Bq/kg)} \quad (1)$$

113. Because the relationship between the radon flux and the radon emanation factor is linear, the constant in the above equation can be assumed to be proportional to the ratio of the radon emanation factors for different sources. Therefore, for fly ash the constant above could be reduced to between

20 and 50% of its value (comparable with the values from the studies cited above for the radon emanation from coal ash as compared to uranium mine tailings) to obtain an estimate of the ^{222}Rn flux from coal ash based on the ^{226}Ra concentration in coal ash. A value of 20% was used in this analysis, giving a linear constant in the above relationship of 1.7×10^{-4} kg/(m^2 s).

114. According to a survey in the United States regarding the disposal of solid waste from coal-fired power plants, a value for the area needed for disposing of solid wastes normalized to electricity generated was reported as 2–11 m^2/(GW h) [A9, F3]. A central value of 6 m^2/(GW h) was used for this analysis. Multiplying the radon flux during one year, obtained by using equation (1), with the linear constant adjusted for coal ash and a ^{226}Ra concentration of 100 Bq/kg, with the area needed for disposing of solid wastes normalized to electricity generated, gave the source term for the annual discharge of ^{222}Rn from deposited coal ashes of about 0.03 TBq/(GW a).

115. A similar value was reached by an independent method. This assessment used an annual discharge of 0.1 TBq/(GW a) as the source term for radon discharges from uranium mill tailings, one part of the nuclear fuel cycle. Using the source term 0.1 TBq/(GW a) for radon discharge from uranium mill tailings and reducing it to 20 to 50% gives an estimate for the annual discharge of radon from coal ash of 0.02–0.05 TBq/(GW a), agreeing well with the value 0.03 TBq/(GW a) obtained from the alternate assessment above.

116. The amount of ash placed in disposal was assumed to be 60% of the total ash produced in coal power plants, based on data cited earlier from the United States and the United Kingdom. The larger six coal-producing countries in table 24 are also countries with large land mass and therefore the value of 60% from the United States was assumed appropriate for use in this assessment. The remaining 40% of the ashes were assumed to be used in a variety of building-related activities and the resulting radiation exposures are discussed in subsection (e).

117. It was explained in paragraph 43 that radon discharges from one gigawatt-year of coal ash deposits were assumed to continue for 100 years and that allowance had to be made in the methodology for this continued discharge. This was done by multiplying the results for one year's discharge by 100 to allow for the discharge continuing for 100 years (see annex A, paragraph 17). Taking into account this multiplication by 100 years and that 60% of the total ash produced in coal-fired power plants was assumed placed in disposals, gave a value for the radon discharge from coal ash deposit normalized to electricity generation of 1.8 TBq/(GW a).

(d) *Results—public exposures due to discharges from coal mining, coal-fired power plants and ash deposits*

118. The annual discharges to atmosphere obtained as described above were used to derive individual and collective doses using the revised methodology for estimating public exposures due to radioactive discharges (annex A). The results of the calculation of the characteristic individual doses per unit of electricity generated integrated to 100 years due to atmospheric discharges from the three sources of public exposures from the coal cycle are shown in table 28. These three sources are *(a)* discharges from coal-fired power plants, *(b)* discharges from coal ash disposed in landfills and *(c)* discharges from coal mining. The radon discharges from one gigawatt-year of coal ash deposits were assumed to continue for 100 years. The results are presented for both older coal-fired and for modern coal-fired power plants. If the coal-fired power plants are older, then the individual doses from all three routes are similar, with those from the discharges from power plants being the highest. For newer power plants, the doses due to discharges from the plants are about 10% of those from the other two sources.

119. The values for each region that are shown in table 28 for the characteristic individual doses per unit of electricity generation due to radon discharges from coal mining and from coal ash deposits remain constant across the regions. This is because the discharges from mining and from ash deposits are from radon gas and therefore only result in inhalation doses. However, the discharges from coal-fired power plants include the other radionuclides from the ^{238}U series, as shown in table 27, and result in doses due to deposition and food consumption, which do have variations with geographical region. As described above, the ^{232}Th series was not considered in these calculations, and earlier assessments by [Z1], imply that this contribution is less than 10% of the contribution from ^{238}U.

120. The results also show a difference in the characteristic individual doses per unit of electricity generated due to coal-fired power plant discharges between the older and the modern coal-fired plants with the values for the modern plants being about 10% of those for the older plants. It could be expected that the values resulting from discharges from ash would differ between the older and the modern coal-fired power plants, but this is not reflected in table 28. This is because the actual difference in the amount that remains in the ash for an older versus a modern coal-fired power plant is very small, of the order of about 1%, and for both cases most of the radionuclides stay in the ash. This difference therefore does not show up in the results.

121. The collective doses to the public integrated to 100 years due to electricity generation from the coal cycle for each region and for the world as a whole are shown for the total electricity generated from coal in the year 2010 in table 29. Both cases, assuming *(a)* that all coal-fired plants are older and *(b)* that all coal-fired plants are modern, are compared. Considering the three discharge sources (from mining, power plants and ash deposits), the contribution to the collective dose from the discharges from coal-fired plants dominates for the older coal-fired plants, but is the smallest term for the modern plants where the contribution from mining is largest. To facilitate comparison, table 30 compares only the terms from the older versus modern coal-fired power plants.

Table 28. Summary of characteristic individual doses per unit of electricity generated integrated to 100 years due to atmospheric discharges from coal-fired power plant sources (mSv/(GW a))

Source	*Africa*	*Asia and Pacific*	*Europe*	*Latin America*	*North America*
From mining	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}
From older coal plants	3.8×10^{-4}	4.0×10^{-4}	4.2×10^{-4}	3.9×10^{-4}	4.2×10^{-4}
From modern coal plants	3.1×10^{-5}	3.2×10^{-5}	3.4×10^{-5}	3.2×10^{-5}	3.4×10^{-5}
From ash[a]	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}

[a] The annual discharges of radon from coal ash produced per unit of electricity generated are assumed to continue for 100 years.

Table 29. Summary of collective doses to the public integrated to 100 years for the total electricity generated from combustion of coal (in 2010) (man Sv)

Discharge type and source	*Africa*	*Asia and Pacific*	*Europe*	*Latin America*	*North America*	*World*
LOCAL COMPONENT[a] – ATMOSPHERIC DISCHARGES						
Mining	1.0×10^{0}	7.1×10^{1}	8.6×10^{0}	3.8×10^{-1}	3.4×10^{0}	7.0×10^{1}
Older coal plants	1.8×10^{0}	1.3×10^{2}	1.9×10^{1}	7.1×10^{-1}	7.4×10^{0}	1.4×10^{2}
Modern coal plants	1.5×10^{-1}	1.1×10^{1}	1.5×10^{0}	5.6×10^{-2}	5.8×10^{-1}	1.1×10^{1}
Ash[b]	6.7×10^{-1}	4.6×10^{1}	5.5×10^{0}	2.4×10^{-1}	2.2×10^{0}	4.5×10^{1}
Total (assuming all older coal plants)	3.5×10^{0}	2.5×10^{2}	3.3×10^{1}	1.3×10^{0}	1.3×10^{1}	2.5×10^{2}
Total (assuming all modern plants)	1.9×10^{0}	1.3×10^{2}	1.6×10^{1}	6.8×10^{-1}	6.2×10^{0}	1.3×10^{2}
REGIONAL COMPONENT[c] – ATMOSPHERIC DISCHARGES						
Mining	4.5×10^{0}	3.0×10^{2}	3.7×10^{1}	1.6×10^{0}	1.5×10^{1}	3.0×10^{2}
Older coal plants	8.7×10^{0}	6.4×10^{2}	9.0×10^{1}	3.4×10^{0}	3.5×10^{1}	6.4×10^{2}
Modern coal plants	6.9×10^{-1}	5.0×10^{1}	6.9×10^{0}	2.6×10^{-1}	2.7×10^{0}	5.0×10^{1}
Ash[b]	2.9×10^{0}	2.0×10^{2}	2.4×10^{1}	1.0×10^{0}	9.4×10^{0}	1.9×10^{2}
Total (assuming all older coal plants)	1.6×10^{1}	1.1×10^{3}	1.5×10^{2}	6.0×10^{0}	5.9×10^{1}	1.1×10^{3}
Total (assuming all modern plants)	8.0×10^{0}	5.5×10^{2}	6.7×10^{1}	2.9×10^{0}	2.7×10^{1}	5.5×10^{2}
TOTAL LOCAL AND REGIONAL COMPONENTS – ATMOSPHERIC DISCHARGES						
Mining	5.5×10^{0}	3.7×10^{2}	4.5×10^{1}	2.0×10^{0}	1.8×10^{1}	3.7×10^{2}
Older coal plants	1.1×10^{1}	7.7×10^{2}	1.1×10^{2}	4.1×10^{0}	4.3×10^{1}	7.8×10^{2}
Modern coal plants	8.3×10^{-1}	6.0×10^{1}	8.3×10^{0}	3.2×10^{-1}	3.3×10^{0}	6.0×10^{1}
Ash[b]	3.5×10^{0}	2.4×10^{2}	2.9×10^{1}	1.3×10^{0}	1.2×10^{1}	2.4×10^{2}
Total (assuming all older coal plants)	2.0×10^{1}	1.4×10^{3}	1.8×10^{2}	7.4×10^{0}	7.2×10^{1}	1.4×10^{3}
Total (assuming all modern plants)	9.9×10^{0}	6.8×10^{2}	8.3×10^{1}	3.6×10^{0}	3.3×10^{1}	6.7×10^{2}

[a] The local component of collective dose is calculated for people living between 0 and 100 km from the discharge point.

[b] The discharges of radon from coal ash produced in 2010 from electricity generation are assumed to continue for 100 years.

[c] The regional component of collective dose is calculated for people living between 100 and 1,500 km from the discharge point.

Table 30. Comparison of collective doses to the public integrated to 100 years from coal-fired power plants given alternative plant design (man Sv)

	Collective doses to the public integrated to 100 years (man Sv)					
Doses from coal-fired power plants	*Africa*	*Asia and Pacific*	*Europe*	*Latin America*	*North America*	*World*
LOCAL COMPONENT[a] – ATMOSPHERIC DISCHARGES						
Older coal plants	1.8×10^{0}	1.3×10^{2}	1.9×10^{1}	7.1×10^{-1}	7.4×10^{0}	1.4×10^{2}
Modern coal plants	1.5×10^{-1}	1.1×10^{1}	1.5×10^{0}	5.6×10^{-2}	5.8×10^{-1}	1.1×10^{1}
REGIONAL COMPONENT[b] – ATMOSPHERIC DISCHARGES						
Older coal plants	8.7×10^{0}	6.4×10^{2}	9.0×10^{1}	3.4×10^{0}	3.5×10^{1}	6.4×10^{2}
Modern coal plants	6.9×10^{-1}	5.0×10^{1}	6.9×10^{0}	2.6×10^{-1}	2.7×10^{0}	5.0×10^{1}
TOTAL LOCAL AND REGIONAL COMPONENTS – ATMOSPHERIC DISCHARGES						
Older coal plants	1.1×10^{1}	7.7×10^{2}	1.1×10^{2}	4.1×10^{0}	4.3×10^{1}	7.8×10^{2}
Modern coal plants	8.3×10^{-1}	6.0×10^{1}	8.3×10^{0}	3.2×10^{-1}	3.3×10^{0}	6.0×10^{1}

[a] The local component of collective dose is calculated for people living between 0 and 100 km from the discharge point.

[b] The regional component of collective dose is calculated for people living between 100 and 1,500 km from the discharge point.

(e) *Coal ash in building materials*

122. Coal combustion products (CCPs) are used as ingredients in a variety of construction materials including concrete, grouting, fill material, lightweight aggregate, road construction or maintenance materials, and in soil stabilization [U1].

123. Fly ash and furnace bottom ash are the main CCPs and the extent to which they are utilized varies by country. Approximately 40% of CCPs produced in the United States are utilized in construction materials [A2], and the percentage utilization was around 45% in the European Union [E2] for fly ash and bottom ash CCPs produced in 2010. China is the largest producer of electricity from combustion of coal and consequently the largest producer of coal ash. According to Tang et al. [T2], China produces proportionately more coal ash because it has a very low coal washing rate (51%). In 2010, the fly ash utilization rate in China was over 65% [T2]. In contrast, in 2009 less than 20% of CCPs produced in Australia were utilized [H3].

124. As noted previously, the activity concentration of natural radionuclides in coal ash is increased relative to coal by a factor of 5–10. However, the concentration is again diluted when the fly ash is mixed with other materials to form construction material. The presence of fly ash in building materials may increase indoor exposures to gamma radiation from ^{226}Ra, ^{232}Th and ^{40}K contained in the coal ash, and exposures due to inhalation of radon emanating from the building construction material such as concrete [D3, F1, T4].

125. The relationship between coal ash in construction material and exposure is not straightforward. The use of coal ash has been shown to either increase, decrease or have essentially no effect on exposures relative to traditional construction materials [T4]. This reflects differences in the source of the coal, the natural radionuclide content of the traditional construction materials, and to the changes in structural properties of the construction material. For example, the use of fly ash and furnace slag in concrete has been shown to reduce radon exhalation rates because it alters the porosity and chemistry of

the construction material [D3, D4]. As of the year 2016 there are no consistent or internationally accepted limits for radionuclides in building materials.

126. A population-weighted average annual effective dose of 0.41 mSv from indoor exposure to gamma rays mainly determined by construction materials was reported by UNSCEAR [U9]. The results for individual countries generally ranged between 0.3 and 0.6 mSv. A more recent analysis by de Jong et al. [D3] calculated an annual effective dose of 0.32 mSv for the Netherlands, which is at the lower end of the range given by UNSCEAR [U9]. In both evaluations, the results included dwellings where fly ash was used in the construction material.

127. Collective doses either for geographical region or for the world as a whole due to the use of coal ash in building materials have not been analysed further in this study. Although the individual doses that have been assessed are very low, some contribution to the total collective dose can be expected from the use of coal ash in construction materials. However, the various factors causing variability in the exposure characteristics cause major uncertainty in the assessments.

3. Occupational exposures from coal mining

128. Previous UNSCEAR studies have estimated the collective doses due to occupational exposure from coal mining. In the UNSCEAR 1988 Report [U7], based on exposure data from British coal mining and the worldwide coal production rate, the worldwide collective dose was estimated as 2,000 man Sv. The UNSCEAR 2000 Report [U9] updated this value to an estimated 2,600 man Sv. The UNSCEAR 2008 Report estimated the worldwide collective dose to workers from coal mining in 2002-2004 at 16,560 man Sv in a year [U11]. Most of the data on occupational exposure from coal mining that were used in the UNSCEAR 2008 Report came from China. A study on radiation levels in China reported the annual average collective dose to underground coal miners in 2003–2004 as 16,500 man Sv [L1]. In addition, occupational exposures from coal mining in the United Kingdom in 2002 were reported in the UNSCEAR 2008 Report [U11] as 3 man Sv for 5,000 coal miners and an average individual dose of 0.6 mSv.

129. The worldwide collective dose to coal miners in 2010 could be estimated from the 2002 collective dose value assuming that the increase in electricity generation from coal in the period 2002–2010 was proportional to the increase in occupational exposure due to coal mining for the same time span. This assumed that the same collective dose normalized to electricity generation that was assessed for 2002-2004 [U11] was applicable for 2010 and that the efficiency of coal mining remained the same, i.e. the same number of coal miners was needed to obtain the same amount of coal. The electricity generated from coal-fired power plants in the reference year of 2010 was 992 GW a (table 2). The corresponding number for the period of 2002–2004 considered in the UNSCEAR 2008 Report was 720 GW a [I12]. This gave a rounded worldwide estimate of the collective dose to coal miners of 23,000 man Sv, as a first approximation.

130. Table 31 shows results from a Chinese study [L1], together with data on the number of coal miners in three categories of mines in China for 2010 [W2]. No new values of the average annual effective dose to coal miners have been published since the 2010 values in table 31.

131. Chinese coal production between 2004 and 2010 increased by approximately 50%. During this period, there was an increase in the number of underground miners working at medium- and large-sized coal mines and a significant decrease in the number working in small-sized township and privately-owned coal mines [W2]. The last column in table 31 uses the average annual effective dose from 2004 and the number of coal miners in 2010 to estimate the collective dose in 2010 in China for the three

coal-mine categories: small, medium and large. This can be compared to the collective dose in 2002-2004, also shown in the table. (The number of bone-coal miners in China in 2010 was not available, although this group represented a small fraction of the total in the 2004 data.) This approach gave an estimated collective dose in 2010 for coal miners in China of about 10,000 man Sv.

132. During the period 2002–2004, China accounted for almost 90% of the underground coal miners in the world. Assuming that the proportion of underground coal miners from countries worldwide was about the same in 2010 as in 2002–2004, the total world collective dose to coal miners was estimated to be about 11,000 man Sv (compared to 23,000 man Sv obtained using the simpler approach above). This can also be compared to the value 16,560 man Sv that was reported in the UNSCEAR 2008 Report [U11]. The implied decrease would be due to more efficient coal-mining technology for underground coal extraction and to the closing of many of the smaller, less efficient coal mines with poor ventilation [W2].

133. The dose contribution for thorium and its decay products and aerosols containing long-lived alpha-emitting radionuclides were not assessed in this study [L1]. In the past, the effective dose from aerosols containing long-lived alpha-emitting radionuclides was roughly estimated by using the contents of radioactive material in the coal and the concentrations of dust in underground coal mines. The estimation indicated that the annual individual dose ranges from several to ten microsieverts, which has been assumed to be of little significance in this comparative study.

Table 31. Annual doses to underground coal miners in China [L1]

The information in the table for number of miners for the year 2010 was obtained from an official communication from the Chinese delegation to the Committee

Type of coal mine	*Average annual effective dose (2004) (mSv)*	*Number of miners in 2004 (millions)*	*Number of miners in 2010 (millions)*	*Collective dose 2002–2004 (man Sv)*	*Collective dose in 2010, using average annual effective dose from 2004 and number of miners in 2010 (man Sv)*
Large-sized	0.32	1	1.26	315	403
Medium-sized	0.63	1	1.31	630	825
Small-sized	3.78	4	2.27	15 100	8 581
Bone-coal	11.3	0.05	Not available	567	Not available
Total	2.75 (weighted average)	6.05	4.84	16 612	9 809

B. Natural gas

134. According to table 2 the global combustion of natural gas produced 544 GW a of electrical energy in 2010. This amount of electrical energy was second only to that due to the combustion of coal at 992 GW a and was 1.7 times the amount of electricity generated by nuclear power plants. The generation of 1 kW h of electrical energy has been estimated to require the combustion of 0.286 m^3 of natural gas [U20].

135. Natural gas is essentially methane (CH_4) with trace amounts of other materials. The most important radionuclide released during the combustion of natural gas is ^{222}Rn. Several authors have

reported on the concentration of ^{222}Rn in natural gas as measured at the wellhead or at various other locations in the gas-delivery system. In developed countries, natural gas is typically not used directly from the wellhead, but is processed to remove moisture and refrigerated to condense and remove higher chain gases, including ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}). The condensation process is important, because radon tends to condense with ethane and propane [D6, G2]. Gesell [G2] studied nine gas-processing plants and found that, on average, the ^{222}Rn content of gas ready to be sold for combustion (the sales gas) was 34% of that at the wellhead (the input gas) with a range of 4 to 90%. Further, natural gas may be transported by pipeline over long distances and is also typically stored at locations near its end use. Because the half-life of ^{222}Rn is 3.8 days, appreciable decay can occur between the production and combustion of natural gas.

136. Measured values of ^{222}Rn in natural gas are summarized in table 32. The range of individual values was large; the weighted average of 879 samples was 625 Bq/m^3. Most of the values in table 32 were for samples taken at the wellhead. Considering the processes that reduce the concentration of radon from the gas at the wellhead to the gas sold for combustion [V2], a value of 300 Bq/m^3 was considered to be a reasonable estimate.

Table 32. Summary of reported concentrations of ^{222}Rn in samples of natural gas

Unless noted otherwise, the samples were taken at or near the wellhead. Concentration values are in units of Bq/m^3

Source	*Area*	*Number of samples*	*Minimum value*	*Maximum value*	*Mean*
[B9]	NW New Mexico SW Colorado	307	7.4	5 880	910
[M4]	NW New Mexico SW Colorado	42	11.8	2 130	610
[G2]	Texas, Oklahoma, Louisiana	15	37	4 400	1 330
[V1]	Netherlands, Germany, North Sea, Borneo, Nigeria	~200	33	1 650	74[a]
[K2]	N. Germany	196	—	4 000	580
[V2]	British Columbia	~32	7	921	272
[O9]	Ireland	8[b]	116	918	638
[A4][c]	Syrian Arab Republic	36	15	1 142	400
[R4]	Pennsylvania	21	37	2 920	1 370
[P2]	Pennsylvania	22	110	5 476	1 770
	Weighted average	879			625

[a] Average results for the Netherlands only.

[b] Same field sampled at various times.

[c] Taken at many locations, including those in gas-processing plants.

137. The calculation of the activity of ^{222}Rn released normalized to electricity generated is thus given as

$$0.2860\frac{\mathrm{m}^3}{\mathrm{kW}\cdot\mathrm{h}}\times 300\frac{\mathrm{Bq}}{\mathrm{m}^3}\times 8760\frac{\mathrm{h}}{\mathrm{a}}\times 10^6\frac{\mathrm{kW}}{\mathrm{GW}}\times 10^{-12}\frac{\mathrm{TBq}}{\mathrm{Bq}}=0.75\frac{\mathrm{TBq}}{\mathrm{GW}\cdot\mathrm{a}} \quad (2)$$

This value for the release of ^{222}Rn normalized to electricity generated was used with UNSCEAR's revised methodology for estimating public exposures due to radioactive discharges (annex A). The 2010 data on electricity generation from natural gas for each region, shown in table 2, were used, and the default population distribution based on population densities for 2010 was used for the collective doses (see paragraph 34). The resulting characteristic individual and collective doses are compared with those for other electricity-generating technologies in table 33 (for characteristic individual doses) at the end of this chapter and in table 46 (for collective doses) in chapter VIII.

138. Other radionuclides can appear in natural gas. One of them is ^{220}Rn, but its half-life (55.6 s) is too short for it to appear at the point of end use of the gas for combustion. If water is co-produced with natural gas, the water may contain soluble amounts of radium. Radium-226 is the parent of ^{222}Rn and is a decay product of ^{238}U; ^{224}Ra is the parent of ^{220}Rn and is a decay product of ^{228}Ra and ultimately of ^{232}Th (see figure III). The progeny of the three radium isotopes and ^{222}Rn can also be present in natural gas, but typically in small amounts. Lead-210 is a longer-lived (half-life of 22.2 years) decay product of ^{226}Ra and ^{222}Rn, and van der Heijde et al. noted that the activities of ^{210}Pb and its decay product ^{210}Po in natural gas are more than can be accounted for by the decay of ^{226}Ra and ^{222}Rn [V1]. These authors concluded that the additional ^{210}Pb and ^{210}Po had been produced from the natural gas reservoir. In general, these radionuclides other than radon do not reach the end point of combustion of natural gas, but they typically plate out within the gas-distribution system fairly close to the point of withdrawal and/or treatment. Because the radionuclides are contained within equipment, workers can incur external exposure to radiation. Organo and Fenton [O9] concluded after investigations in Ireland that workers at offshore locations would be exposed "at most" to around 100 μSv in a year. The Pennsylvania Department of Environmental Protection [P2] measured the external ambient dose rate at several locations within gas production and processing sites and estimated a maximum annual average dose of 270 μSv. The Committee has assumed a reasonably realistic estimate of 100 μSv in a year.

139. A problem in estimating the collective effective dose to workers is determining the number of workers in the industry apportioned to the amount of natural gas used to generate electricity. An indirect method was used to make this determination. According to the United States Bureau of Labor Statistics [U16], there were 89,000 production and non-supervisory workers in the oil- and gas-extraction subsector. Most of these workers were not working directly in support of natural gas production for electricity generation, but there was no further breakdown in the data. In order to estimate the fraction of workers supporting the generation of electrical energy by combustion of natural gas, data from [I17] for the OECD countries for 2010 were used. In terms of energy produced, these data indicated that 12% of the energy produced from oil and natural gas together was used for electricity generation due to combustion of natural gas. Thus, it was estimated that 10,700 workers were employed in the United States to produce natural gas for the generation of electricity.

140. According to [U19] 209.2 billion cubic metres of natural gas were used in 2010 to produce electricity in the United States. With the use of previously mentioned conversion factors this was equivalent to 83.5 GW a of electrical energy. Thus, the normalized collective dose for workers based on the data originating in the United States was 0.013 man Sv/(GW a).

C. Oil

141. The combustion of oil for electricity generation accounted for less than 5% of the world's electricity generation in 2010, but accounted for more than 30% of electrical energy generated in West Asia. The generation of 1 kW h of electrical energy is estimated to require the combustion of 0.278 L of petroleum [U20]. Most of the "petroleum" combusted to generate electricity in 2010 in the OECD countries consisted of fuel oil [I17], which has an approximate density of 0.95 kg/L.

142. Petroleum is produced from underground reservoirs in the presence of geological formations that contain the primordial radionuclides ^{40}K, ^{238}U and ^{232}Th; the latter two are parents of chains that produce a series of radionuclides usually present in secular equilibrium (see figure III). A process that can perturb the secular equilibrium is the dissolution of some members of the chain in water, which at depth can be at high temperature. Water containing dissolved radium is typically co-produced with oil. Radium-226 is a member of the chain headed by ^{238}U; ^{226}Ra is the parent of ^{222}Rn and an additional series of decay products including ^{210}Pb and ^{210}Po. Radium-228 is a member of the chain headed by ^{232}Th; ^{228}Ra is the parent of ^{224}Ra and ^{220}Rn. Both ^{226}Ra and ^{224}Ra are parents of additional short-lived beta or gamma-emitting radionuclides.

143. Apparently some power plants can burn crude (or heavy) oil with its associated natural gas [A5], but it is more typical that associated natural gas and water produced in the process must be removed from petroleum before delivery to a pipeline or refinery [S5]. Radon is more typically associated with natural gas and the soluble isotopes of radium are typically associated with the produced water. As produced water is withdrawn from depth, it cools and dissolved minerals, including radium, can form precipitates and deposit on the production tubing and on various other production equipment. These deposits are known as scale or sludge. With time the radium contained within scale and sludge will come into equilibrium with gamma-emitting decay products and give rise to external exposure of workers.

144. There are many studies of the presence of radionuclides in scale, sludge, (e.g. [I1, R3]) and produced water [S5], and of radon in natural gas (see section V.B above), but there are few measurements of radium or radon in crude oil or its subsequent products. Crude oil generally contains some remaining water within a water-in-oil emulsion and this water contains dissolved radium [S5]. Radon is also quite soluble in oil [B2].

145. The report by Bell et al. [B2] appears to be the only one that reports measurements of both ^{222}Rn and ^{226}Ra in the same samples of crude oil. Because the half-life of ^{222}Rn is 3.82 days, the samples had to be delivered quickly and correction made for decay in transit. Seven samples of crude oil from wells in Texas and Oklahoma were measured. The results for ^{222}Rn varied from a minimum of 3.2 Bq/kg to a maximum of 17 Bq/kg and had an average of 7 Bq/kg. The results for ^{226}Ra had a minimum of 0.2 Bq/kg, a maximum of 13 Bq/kg and an average of 0.7 Bq/kg. The ratio of ^{222}Rn to ^{226}Ra had a minimum of 4, a maximum of 38, and an average of 15. Thus, most of the ^{222}Rn in fresh samples of crude oil was unsupported, that is, it was far in excess of the activity that was in equilibrium with ^{226}Ra. Except for those power plants that burn crude oil directly, this excess ^{222}Rn would decay or be removed in the refining and/or transportation processes.

146. Hamlat et al. [H1] reported concentrations of ^{226}Ra in an unspecified number of samples of crude oil collected in Algeria. The range of values was from 6 Bq/kg to 20 Bq/kg; these values are reasonably consistent with those reported by Bell et al. [B2]. Al-Saleh and Al-Harshan [A7] measured radionuclides in 14 petroleum-product samples, including crude oil drawn from the Riyadh City Refinery. The detection limit for ^{226}Ra was 0.014 Bq/kg; the only products with detectable amounts of ^{226}Ra were "sweet naphtha" (0.65±0.40 Bq/kg) and "flushing oil" (0.45±0.20 Bq/kg).

147. The limited amount of data indicated above suggests a cautious approach in estimating the release of radionuclides from the combustion of oil products. For this procedure the Committee estimated that there was a concentration of ^{226}Ra in all oil products of 1 Bq/kg. Further, it assumed that unsupported amounts of ^{222}Rn decayed or otherwise were eliminated in the process, so that the concentration of ^{222}Rn in all oil products was also 1 Bq/kg.

148. Then, the normalized release of ^{222}Rn was calculated as

$$0.278\frac{\mathrm{L}}{\mathrm{kW}\cdot\mathrm{h}}\times 0.95\frac{\mathrm{kg}}{\mathrm{L}}\times 1\frac{\mathrm{Bq}}{\mathrm{kg}}\times 8760\frac{\mathrm{h}}{\mathrm{a}}\times 10^{6}\frac{\mathrm{kW}}{\mathrm{GW}}\times 10^{-12}\frac{\mathrm{TBq}}{\mathrm{Bq}}=0.002\frac{\mathrm{TBq}}{\mathrm{GW}\cdot\mathrm{a}} \qquad (3)$$

This value for the release of ^{222}Rn normalized to electricity generated was used with the revised methodology for estimating public exposures due to radioactive discharges (annex A). The 2010 data on electricity generation from oil for each region, shown in table 2, were used, and the default population distribution based on population densities for 2010 was used for the collective doses (see paragraph 34). The resulting characteristic individual and collective doses are compared with those for other electricity-generating technologies in table 33 (for characteristic individual doses) at the end of this chapter and in table 46 (for collective doses) in chapter VIII.

149. There may be other radionuclides emitted by the combustion of oil products; Al-Masri and Haddad [A5] reported values of about 60 Bq/kg of ^{210}Po in heavy oil fuel used in three power plants in the Syrian Arab Republic. The same authors [A6] also reported that soil in the vicinity of the three power plants contained enhanced levels of ^{210}Pb and ^{210}Po. Other authors have not reported measurements of ^{210}Pb and ^{210}Po associated with oil-fired power plants.

150. As mentioned above, ^{226}Ra and ^{228}Ra and their decay products accumulate in scale and sludge around wellheads and processing equipment. This gives rise to occupational exposure, when workers are in the vicinity of these elements. Kvasnicka [K4] estimated that the maximum effective dose on offshore platforms could be managed to be below 1 mSv in a year. It is expected that the doses to workers on offshore platforms would be higher than on onshore platforms, because of more substantial problems with scale formation and the limited space in the working environment on the platforms. Hamlat et al. [H1] measured ambient dose rates in the vicinity of onshore oil and natural gas production equipment. They estimated that annual effective doses around oil extraction equipment might range from 40 to 600 μSv for normal activities. A value of 300 μSv was adopted for this analysis.

151. There were no direct data on the number of workers in the oil industry apportioned to the combustion of oil for the generation of electricity, so an indirect method was used. According to the United States Bureau of Labor Statistics [U16], there were 89,000 production and non-supervisory workers in the oil- and gas-extraction subsector in the United States in 2010. In order to estimate the fraction of workers who were supporting the generation of electrical energy by the combustion of oil, data from [I17] were used. In terms of energy produced these data indicated that only 1.7% of energy produced from oil and natural gas was used for the generation of electricity by the combustion of oil in 2010. Thus, it was estimated that 1,520 workers in the United States could be apportioned to generation of electrical energy by the combustion of oil.

152. According to [U19] 7.02×10^9 kg of oil were used in 2010 to generate electricity in the United States. Using the conversion factors given above, this is equivalent to 3.03 GW a of electricity. Thus, the collective dose to workers normalized to the electricity generated, based on data from the United States, was estimated to be 0.15 man Sv/(GW a).

D. Comparisons of exposures from fossil-fuel electricity generation

153. Table 33 shows characteristic individual doses integrated to 100 years per unit of electricity generated for the UNEP regions. These doses are due to atmospheric discharges from the coal cycle and the combustion of gas or oil in power plants generating electricity. Although the doses resulting from the modern coal plants are about 10% of the doses from the older plants, in total the characteristic individual doses per unit of electricity generated from both the older and the modern coal plants are larger than from the gas or the oil combustion technologies. See chapter VIII for further comparisons between these and other electricity-generation technologies.

Table 33. Summary of characteristic individual doses per unit of electricity generated integrated to 100 years due to atmospheric discharges from the coal cycle and the combustion of gas and oil (mSv/(GW a))

Showing results from both older and modern coal plants

Electricity generation technology	*Release*	*Africa*	*Asia and Pacific*	*Europe*	*Latin America*	*North America*	*West Asia*
Coal							
- From mining	Radon	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	2.4×10^{-4}	0
- From older coal plants	Natural radionuclides including radon	3.8×10^{-4}	4.0×10^{-4}	4.2×10^{-4}	3.9×10^{-4}	4.2×10^{-4}	0
- From modern coal plants		3.1×10^{-5}	3.2×10^{-5}	3.4×10^{-5}	3.2×10^{-5}	3.4×10^{-5}	0
- From ash	Radon	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	1.5×10^{-4}	0
Gas	Radon	6.3×10^{-5}	6.3×10^{-5}	6.3×10^{-5}	6.3×10^{-5}	6.3×10^{-5}	6.3×10^{-5}
Oil	Radon	1.7×10^{-7}	1.7×10^{-7}	1.7×10^{-7}	1.7×10^{-7}	1.7×10^{-7}	1.7×10^{-7}

VI. RADIATION EXPOSURES ARISING FROM ELECTRICITY GENERATION FROM GEOTHERMAL ENERGY

154. Geothermal energy is derived from the heat of the earth at locations where magma is closer than normal to the earth's surface. The generation of electricity from geothermal sources presently depends upon the use of steam or hot water from wells drilled into underground reservoirs. As shown in table 2 [I17], geothermal energy in the reference year 2010 generated 7.77 GW a of electricity and accounted for 0.3% of the total world's electricity generation in 2010.

155. Electricity generation from geothermal sources first began in 1904 at Larderello, Italy, with an experimental 10 kW generator. At the present time the installed capacity is in excess of 9,000 MW in 25 countries [L3]. The larger power plants are at The Geysers, California; Larderello, Italy; Cerro Prieto, Mexico; Leyte, Philippines; Salton Sea, California; Hellisheidi, Iceland; Tiwi and Malitbog, Philippines; and Wayang Windu and Darajat, Indonesia [K1].

156. Different approaches can be taken to generate electricity from geothermal sources. If dry steam is available, the simplest is to run the steam through a turbine and exhaust to the atmosphere. Efficiency is improved if the dry steam is condensed, with heat dissipated through cooling towers. Most reservoirs, however, do not produce dry steam, but some combination of steam and hot water or hot water alone. In this situation, it is necessary to separate steam from water, or, if hot water alone is produced, to flash the water to steam through single, double, or even triple passes. A binary process is in use at some sites that use water of lower temperature; hot water is run through a primary loop and a fluid with a lower boiling point through a secondary loop. As of the year 2016, most electrical energy generation is through the flash process with single or double flash; the other major technology is the use of dry steam with condensation [M3].

157. During the 1970s there was substantial interest in evaluating the potential impact of the release of ^{222}Rn from gases vented during the operation of geothermal electricity-generating plants. The more complete evaluations were reported for The Geysers and the Larderello Plants. Anspaugh [A10] reported that 19.3 TBq/a were being released from The Geysers during the operation of 11 dry steam condensing units with 502 MW of electrical power; the daily rate was noted to be equivalent to the average daily background emission of ^{222}Rn from about 40 km^2 of soil. For the Larderello geothermal complex, the emission rate per unit energy was 38.5 TBq/(GW a) according to George et al. [G1]. This was based on measurements performed by D'Amore [D1], who calculated that 300 GBq/d were being released from the Larderello geothermal complex, which had an installed capacity of about 420 MW [P1]. Thus, the emission rate per unit energy at Larderello was 260 TBq/(GW a).

158. The above represent the two situations where data were complete enough to estimate emissions per unit of electricity generated. Based on this limited set of data, the Committee assumed an average value of 150 TBq/(GW a). There are measurements of radon in steam or hot water from other locations, and samples of such data are given in table 34; at the time of the assessment no data were available for the amount of ^{222}Rn that might be released from geothermal sites using binary circle systems. A reason that data are scarce on radon related to geothermal energy is that, following the measurements in the 1970s, it was generally concluded that this source of radon was not significant compared to the natural exhalation of radon from soil. Measurements of ^{222}Rn and ^{220}Rn in geothermal fluids do continue, but are mainly related to understanding of the dynamics of resources [W6].

Table 34. Reported concentrations of ^{222}Rn in fluids produced from geothermal wells

Location	*Activity of ^{222}Rn per unit of produced fluid (Bq/kg)*	*Reference*
The Geysers, weighted average	520	[A10]
The Geysers	620	[K3]
Larderello	1 280	[K3]
Larderello, weighted average	3 100	[G1]
Salton Sea, California	110	[K3]
East Mesa, Imperial Valley, CA	1.1	[K3]
Wairakei, New Zealand	630	[W6]

159. The value of 150 TBq/(GW a) for the release of ^{222}Rn normalized to electricity generation from geothermal energy was used with the electricity generation data by region from table 2 and with estimates of population density to give an estimate of the characteristic individual and collective doses. There is substantial uncertainty regarding the population density around geothermal power plants, as it is necessary to locate the plants within the narrow confines of the resource. The Geysers and the Cerro

Prieto plants are in isolated locations, but large metropolitan areas are within 1,500 km. The other extremes are geothermal power plants located on islands. Because of these discrepancies and the lack of specific population data on each power plant, the Committee made two calculations for geothermal: one with the assumption of low-density population, as in the assessments for uranium mining and milling, and one with the default population density.

160. Table 46 in chapter VIII compares the collective doses to the public for the discharges from the nuclear fuel cycle, coal cycle, gas, oil and geothermal electricity-generating technologies. As explained in the previous paragraph, two values are given for geothermal energy. The normalized discharge of radon for geothermal electricity generation is the largest of the electricity-generating technologies shown in table 46. However, the impact of geothermal electricity generation remains small because of the limited use of this technology. Further, there is substantial uncertainty regarding the discharge of radon from geothermal power plants; data are available for only two plants, and the estimated discharges from these two plants vary substantially.

161. There are even fewer data on occupational exposure in the geothermal industry. Anspaugh [A10] reported no evidence of increased external gamma exposure, but did note increased levels of radon and short-lived progeny at several locations normally inaccessible except during maintenance. In general, moderate to severe disequilibria were found, and an average excess amount of exposure was 0.05 Working Levels[7] (WL) (1 μJ m^{-3}). Razzano and Cei [R1] indicated that 36 persons work over three shifts to operate the Larderello complex. From data in the same paper, the electricity generated in 2013 at Larderello was 5,659 GW h with 767 MW of "efficient" installed capacity. The combination of these data leads to an annual occupational exposure of 5 man WLM/(GW a). According to [I11] 1 WLM is equivalent to an effective dose of 10–20 mSv, but the higher values are associated with mines and homes. A more reasonable value for outdoor exposure is 10 mSv, which would also be consistent with [U10]. Thus, the normalized collective dose to workers in geothermal electricity generation would be 0.05 man Sv/(GW a).

VII. ASSESSING DOSES FROM THE CONSTRUCTION PHASE OF ELECTRICITY-GENERATING TECHNOLOGIES

162. All electricity-generating technologies considered by the Committee have a construction phase during which the facilities and infrastructure are established. Although in general there are no significant radiation exposures associated with the construction, there may be radiation exposures associated with obtaining the materials for construction such as in mining activities.

163. Industries not directly linked to electricity generation, such as mining, milling and processing of metal ores, contribute to occupational and public exposure because of the presence of natural radionuclides [U11, U22]. While public exposures from the mining industry may be negligible on an individual basis, typical occupational doses in the mining industry may be up to a few millisieverts in a year. The collective dose from occupational exposures during the mining of metals was evaluated for this study on the basis of the dose per unit mass of metal ore mined for each electricity-generating technology, as discussed in the UNSCEAR 2008 Report [U11], and on recent data from 2012 on radiation exposure of miners of rare earth metals in China [W3].

[7] A working level (WL) is a unit of potential alpha energy per unit of air. In the SI system of units, one WL is equal to 2.08×10^{-5} J m^{-3}. A working level month is a unit of exposure to 1 WL for a month. For occupational personnel one month is considered to be 170 hours.

164. Aggregate is also used extensively in the construction of electricity-generating plants. Aggregate in building and construction refers to the material used for mixing with cement, bitumen, lime, gypsum and other additives to form concrete or mortar. Commonly used aggregates include sand, crushed or broken stone, gravel, and blast-furnace slag. In some cases, the amount of aggregate used is similar to the total mass of all other materials.

165. The relative volumes of concrete required to construct various nuclear and coal-fired power plants are tabulated in tables 35 and 36. Typical radionuclide concentrations in raw and processed materials and in wastes of the mineral processing industry, including the cement industry, were reviewed in the UNSCEAR 2000 Report (see table 27 in [U9]). Typical radionuclide concentrations in metal ores were reported to be about three orders of magnitude higher than of materials in the cement industry. For this assessment, only the occupational exposures from the mining of metal ores needed for metals used in construction of electricity-generating technologies were evaluated.

Table 35. Estimates of the amounts of construction materials used in nuclear power plants

Plant	*Mass of metals (t)*	*Volume of concrete (m^3)*
PWR, 1 000 MW(e) [D5]	61 000	169 000
BWR, 1 000 MW(e) [D5]	66 000	200 000
PWR, 1 000 MW(e) [B8][a]	38 000 (estimated)	75 000 (estimated)
Nuclear power plant [W5]	36 000	75 000

[a] The amount presented for specific metals: Al, Cr, Cu, Ag, Fe, Pb, Mg, Mn, Mo, Ni, Sn, Zn.

Table 36. Estimates of the amounts of construction materials used in coal-fired power plants

Plant[a]	*Mass of metals (t)*	*Comments*	*Volume of concrete (m^3)*
Coal-fired power plant [S7]	50 000 steel	Amount presented in generic terms as "steel" and expressed in kg/MW(e)	380 000
Coal-fired power plant [W5]	41 000 metals	Amount presented for specific metals: Al, Cr, Cu, Mn, Mo, Ni, steel (low alloy and stainless) and V and expressed in t/GW(e)	31 000

[a] 1,000 MW(e) plant assumed.

166. The mass of metal ore required to produce the metals in the building materials has been estimated from information on the total metal inventory required and from the metal ore grade used. It was assumed that steel was the primary metal used. Iron is alloyed with carbon to produce plain carbon steel. Alloy steels also contain various alloying metals. The category of steel used in the different electricity-generating technologies and the contents of alloying metals were considered. Plain carbon steels were assumed to contain iron and 0.16–0.59% carbon. Low-alloy steels were assumed to contain less than 0.25% carbon, as well as small amounts of nickel, chromium, molybdenum, manganese and silicon. High-alloy stainless steels were assumed to contain molybdenum, chromium and/or nickel and other elements. These assumptions are based on the information in [C1, G3].

167. For high-alloy stainless steel, type S316 was used as the basis for this assessment, because it is widely used in industrial applications. Type S316 contains around 2% by mass of molybdenum [A3, S3]. Other steel types may contain different levels of molybdenum, or none at all, which could influence the results. This is because molybdenum is a low-grade metal ore and therefore extraction of molybdenum may make a larger contribution to occupational exposures [A3, S3].

168. Based on the above, the composition of typical steels for each category (plain, low-alloyed and high-alloyed stainless) was assumed as shown in table 37. If the type of steel was not known, the proportions given in table 38 were assumed.

Table 37. Composition of different types of steel (based on [C1, G3])

Material	*Composition (% by weight)*
PLAIN STEEL	
Iron	99.62
Carbon	0.38
LOW-ALLOY STEEL	
Iron	99.63
Molybdenum	0.33
Carbon	0.05
HIGH-ALLOY STAINLESS STEEL	
Iron	65.35
Chromium	17.00
Nickel	12.00
Molybdenum	2.50
Manganese	2.00
Other non-metallic elements	1.07
Carbon	0.08

Table 38. Assumed mix of steel types used in construction where details were not specified (based on [C1, G3])

Steel type	*Proportion of total (%)*
High-alloy stainless steel	10
Low-alloy steel	30
Plain steel	60

169. *Assumptions on ores.* The amount of ore required for the construction of an electricity-generating facility also depends on the ore grade. The assumptions made regarding ore grades are shown in table 39 [A8, C3, M1].

Table 39. Metals and their assumed ore grades

The data presented here are typical values taken from [A8, C3, M1], and the numbers have been rounded

Resource	*Ore grade at mine (%)*
Tin	79
Manganese	47
Zirconium	47
Iron	46
Magnesium	41
Tantalum	31
Chromium	26
Aluminium	11
Zinc	7
Lead	6
Nickel	2
Copper	1.4
Vanadium	0.3
Molybdenum	0.18
Silver	0.01
Gold	0.0005

170. *Recycling of metals.* Recycling is an important part of the metal industry from both an economic and energy-saving point of view. In the United States, approximately two thirds of the steel produced in 2008 was made from recycled material [U15]. Around 43% of the total crude steel production worldwide is made from recycled steel, with the main sources for steel recycling typically being discarded cars, household appliances and steel cans, as well as old buildings and structures [W4]. Typical building construction uses approximately 60–65% recycled metal [B1], while in the United Kingdom about 94% of construction steel is recovered [T3].

171. Special rules apply to the re-use of scrap steel and other metals from nuclear power plants; authorities establish limits on the activity concentrations of radionuclides in materials that can be released for recycling. There is, however, no indication that there are significant differences in the degree of recycling between the various electricity-generating technologies.

172. The effect of recycling metals has not been included in the present study, because of insufficient data for large portions of the world. By not explicitly considering recycling, the collective dose per unit of electricity generated due to the extraction and processing of the metals used in the construction of a facility is likely to be overestimated by around a factor of two on average, and possibly a factor of five or more for some regions of the world with developed recycling processes. This should not affect the relative comparisons of occupational exposures from mining metals between technologies, but would affect comparisons of the total exposures (public and occupational) among the electricity-generating technologies.

173. *Dose assessment.* To estimate the radiation exposure of workers in the mining industry (occupational exposure) from ore extraction and processing, the following assumptions were made:

(a) The ores are extracted only through underground mining. The use of above-ground mining would give rise to smaller radiation doses than underground mining [U11]. Consequently, this assumption leads to an overestimation of collective dose.

(b) The presence of several metals in an ore was not considered. Each ore was assumed to contain only one metal type, and thus the contribution to occupational doses from the extraction and processing of the various minerals was evaluated independently and summed. In reality some metals will be extracted together and consequently the resulting collective doses may have been overestimated.

(c) Occupational exposures from mining and processing of raw materials were inferred from data on uranium mining and processing, and on mining other minerals. Mining data for underground copper mines in Australia (Mount Isa), Canada (Kidd Creek), South Africa (Palabora), and Portugal (Neves Corvo) show annual production rates of 1–5 kilotonnes of ore per employee [I19]. The denoted employees included all workers at the mines. Based on these data, the Committee selected a mid-range value of 3 kt of metal ore per employee for use in this assessment (table 40).

(d) The average annual effective dose to non-uranium miners, including those involved in mineral processing, given in the UNSCEAR 2008 Report [U11] was 3.0 mSv, with a range of 1.3 to 5.0 mSv. Using an annual average value of 3.0 mSv for all workers associated with the mining industry, and the value of 3 kt of metal ore per employee given in *(c)*, the collective dose per unit mass of ore extracted was estimated at 1×10^{-9} man Sv/kg (table 40). The data for *(c)* and *(d)* were obtained from different worker populations and this introduces some uncertainty in the estimation of the collective dose per unit mass of ore extracted.

(e) In a recent study in China [W3] data were collected on radiation levels, and dose assessments were performed for workers of the rare earth industry in the Baotou area and Sichuan Province, two large mining districts in China. These regions account for about 77% of the total annual output of rare earth mines in China; the reported annual production rates were 0.01 and 0.02 kt of rare earth metal per mining employee, respectively.

(f) The Chinese study has estimated the collective dose per unit mass of rare earth metal extracted. The typical value for the whole rare earth industry that was obtained in the Chinese study on radiation exposure of Chinese workers in mining, crushing, beneficiation and refining is about 150×10^{-9} man Sv/kg. This value relates to the mass of metal extracted, which differs from the value 1×10^{-9} man Sv/kg given in *(d)* which relates to mass of metal ore. The Committee used the latter value in the analysis in order to account for the different metal requirements with associated metal ore grades of each electricity-generating technology.

(g) As a check, an alternative estimate was obtained by comparing with the data on uranium mining. The collective dose per unit mass of uranium extracted given in the UNSCEAR 2008 Report [U11] was 1 man Sv/kt (based on 2000–2002 data). Assuming (from information in [I4, O8]) an average grade for uranium ore of 0.3%, the collective dose per unit mass of uranium ore extracted is 3×10^{-9} man Sv/kg.

174. Although the assumptions in paragraph 173 affect the absolute values of the assessed collective dose, the relative importance of the different electricity-generating technologies with regards to the construction phase remains.

Table 40. Collective effective dose per unit mass of ore mined used in this study

Estimate based on	*Annual production rate of ore per person (kt)*	*Average annual occupational dose (mSv)*	*Collective dose per unit mass of metal ore extracted (man Sv/kg)*
[U11]	3	3	1×10^{-9}

175. *Nuclear power plants.* For the current assessment, the assumed design lifetime of a nuclear power plant was 40 years and the capacity factor[8] was 90% (table 41).

176. Three different studies of the use of materials in nuclear power plants have been published. Dones et al. [D5] studied the material used in two Swiss nuclear power plants—the pressurized-water reactor (PWR) at Gösgen and the boiling-water reactor (BWR) at Leibstadt. Both were of the 1,000 MW(e) type, but the capacity of the Leibstadt plant was increased to 1,190 MW(e) following construction. For the latter, the total amount of metals used was 66,000 tonnes, of which two thirds were unalloyed steel/iron. In addition, 200,000 m^3 of concrete were used. Bryan and Dudley [B8] considered the quantities of different materials used in a typical 1,000 MW(e) PWR with river water cooling. The total mass of metals used was estimated at 38,000 tonnes but the proportions of each metal were not specified. The total amount of concrete used was estimated as 210,000 tonnes (~87,260 m^3). White and Kulcinski [W5] gave the amount of material needed for four power plants, including a nuclear power plant, where values of 36,000 tonnes of metals and 180,000 tonnes (~75,000 m^3) concrete were given. The study focused on the energy payback ratio[9] and CO_2 emissions, and it was not in that sense a full life cycle assessment. Furthermore, the study did not consider potential radiation exposure. The data from the three studies are presented in table 35.

Table 41. Assumed plant sizes, life times and capacity factors for the different electricity-generating technologies

* Assumed to be the same as coal

Electricity-generating technology	*Typical plant gross capacity (MW(e))*	*Lifetime (years)*	*Capacity factor (%)*
Nuclear [I3]	1 000	40	90
Coal [F3, I18]	1 000	40	80
Natural gas [O1, S8]	505	25	80
Solar PV [F3, N3]	—	30	9.4
Wind turbine [D2, N4, O10]	25	20	24
Biomass [W5]	1 000*	20	75
Geothermal [R5, S9]	NA	30	NA

[8] Capacity factor (net) is the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period [U25].
[9] Energy payback ratio is the ratio of total electrical energy produced during a system's normal lifespan, divided by the electrical energy required to build, maintain and fuel it.

177. *Example of a dose calculation for a nuclear power plant.* Specifications of the typical plant gross capacity, lifetimes and capacity factors (can also be called load factor) used in the calculations are shown in table 41. Table 42 shows an example of the details of a dose calculation for a nuclear power plant. The collective dose was estimated based on occupational exposures related to metal ore mining and processing of the metal ore for metals needed to construct the power plants.

Table 42. Example calculation of collective dose from occupational exposure during construction phase of a nuclear power plant

Type: PWR Gösgen, 970 MW(e), capacity factor 90% [D5]

Resource/Elements	*Metal needed for construction* (kg/kWh)	*Ore grade at mine* (%)	*Amount of ore needed at mine* (kg/kWh)	*Collective dose* (manSv/(GW a))
Stainless steel				
Iron	4.7×10^{-5}	46	1.0×10^{-4}	8.9×10^{-4}
Manganese	1.4×10^{-6}	47	3.1×10^{-6}	2.7×10^{-5}
Chromium	1.2×10^{-5}	26	4.8×10^{-5}	4.2×10^{-4}
Molybdenum	1.8×10^{-6}	0.18	9.9×10^{-4}	8.7×10^{-3}
Nickel	8.6×10^{-6}	2	4.3×10^{-4}	3.8×10^{-3}
Low-alloyed				
Iron	1.8×10^{-5}	46	3.9×10^{-5}	3.5×10^{-4}
Molybdenum	5.9×10^{-8}	0.18	3.3×10^{-5}	2.9×10^{-4}
Unalloyed steel				
Iron	1.1×10^{-4}	46	2.4×10^{-4}	2.1×10^{-3}
Other				
Copper	4.7×10^{-6}	1.4	3.3×10^{-4}	2.9×10^{-3}
Aluminium	6.3×10^{-7}	11	5.6×10^{-6}	4.9×10^{-5}
Total				1.9×10^{-2}

178. *Coal-fired power plants.* There are a number of different designs of coal-fired power plants. However, the amounts of material used in their construction do not differ significantly. Spath et al. [S7] conducted a full life cycle assessment of a coal-fired power plant covering the construction and decommissioning of the plant. The amount of steel used in the construction of a 1,000 MW(e) plant was 50,000 tonnes, but no data were given on the other metals. Also, the proportions of plain carbon steel, low-alloy steel and stainless steel were not specified. White and Kulcinski [W5] described a total amount of 41,000 tonnes of metals in their study. In both studies [S7, W5], the analysed units had an assumed capacity factor of 80% and a lifetime of 40 years. The information from these studies is summarized in table 36.

179. *Natural gas power plant.* The designs of natural gas power plants also vary. Spath and Mann [S8] presented a full life cycle assessment for a 505 MW(e) natural gas power plant covering its construction and decommissioning. The study is similar in approach to the one they used for coal-fired power plants [S7]. Again, potential radiation exposure was not considered and no specific data were provided on the particular metals used to construct the plant. The amount of steel used was 31 t/MW(e) and the amount of concrete used was 98 t/MW(e). The Committee assumed that the average capacity of a natural gas

power plant was 505 MW(e) to estimate the amount of each metal using the assumptions shown in table 37 and table 38.

180. *Solar energy power plant.* Solar energy is by far the largest energy resource available on earth. Two different technologies contribute to solar electricity generation: solar photovoltaics (PV) and concentrating solar power (CSP).

181. Solar PV systems convert direct and diffused solar radiation into electricity through a photovoltaic process using semiconductor devices. Solar PV systems can be used anywhere in the world on suitable land and on buildings. Solar PV technology is also very adaptable to being used in a modular fashion, which means that systems can be installed close to centres of demand.

182. Silicon-based PV solar cells contain small amounts of rare earth elements. Crystalline-silicon PV cells are the most common PV cells in use today [U14].

183. Concentrating solar power (CSP) systems are designed to produce high-temperature heat for electricity generation or for co-generation of electricity and heat. CSP systems are capable only of exploiting direct normal irradiation, which is the energy received directly from the sun (i.e. not scattered by the atmosphere) on a surface tracked perpendicular to the sun's rays. Areas suitable for CSP development are those with strong sunshine and clear skies, usually arid or semi-arid areas. Parabolic mirrors or troughs are used in CSP[10] technology. The parabolic mirrors are designed to concentrate solar radiation onto linear heat collection elements [N2].

184. A solar energy power plant does not have a fuel cycle in the same way that most other energy technologies do, consequently any potential human exposure to ionizing radiation is related to the use of natural resources for manufacturing the centralized CSP plants or the PV solar cells. The largest contribution to the collective dose is from the acquisition of raw materials, especially minerals used for manufacturing the CSP plants or PV solar cells.

185. Silicon-based PV solar cells contain small amounts of rare earth elements, which are of particular interest because the ores from which they are obtained have relatively high contents of uranium and thorium. Thus, the mining of the ores and their subsequent processing lead to occupational radiation exposures.

186. Because relevant data on the use of metals and other natural resources were only readily available for the PV solar systems, the assessment was only carried out for this type of solar energy production.

187. The metals required to construct a solar PV system and amount of ore required are shown in table 43. The results are based on data for a life cycle assessment of a 3 kWp[11] multicrystalline–silicon PV solar panel mounted on a slanted roof in Switzerland [J1]. The solar panel efficiency was 9.4%. The solar PV system lifetime was assumed to be 30 years, with the exception of the power inverter that changes direct current to alternating current. In this case a lifetime of 15 years was assumed. The parts included were mainly PV panels, mounting structures, inverter and electric installations. Metals used for the solar panels included small amounts of rare earth elements, which are derived from ores with high contents of thorium or uranium.

188. The amount of ore required per unit of electricity generated depends on the ore grade. In table 43, the values were based on published ore grades [A8, C3, J1].

[10] Also called concentrated solar power and concentrated solar thermal (CST).

[11] The symbol, kWp, stands for the peak power (kW) of the solar PV system—the basic unit for the characterization of the capacity of PV plants measured in a standardized test at a temperature of 25 °C and an irradiation of 1,000 W/m^2.

Table 43. Ore usage at mine for the production of energy by a PV solar system mounted on a slanted roof in Switzerland

Figures are for production of 1 kWh by a 3 kWp[a] PV solar system; ore grade values provided in table 38

Resource	*Amount of metals required per unit electricity produced*[b] *(kg/kW h)*	*Amount of ore required per unit electricity produced (kg/kW h)*
Aluminium	1.7×10^{-3}	1.5×10^{-2}
Chromium	2.6×10^{-6}	1.0×10^{-5}
Copper	4.2×10^{-4}	3.0×10^{-2}
Iron	1.3×10^{-3}	2.7×10^{-3}
Lead	1.3×10^{-6}	2.2×10^{-5}
Magnesium	5.4×10^{-5}	—
Manganese	4.4×10^{-6}	9.3×10^{-6}
Molybdenum	4.2×10^{-6}	8.3×10^{-3}
Nickel	5.0×10^{-8}	2.5×10^{-6}
Silver	2.9×10^{-6}	2.9×10^{-2}
Tantalum	7.8×10^{-7}	2.5×10^{-6}
Tin	1.6×10^{-6}	2.1×10^{-6}
Zinc	3.1×10^{-6}	4.4×10^{-5}

[a] The symbol, kWp, stands for the peak power (kW) of the solar PV system—the basic unit for the characterization of the capacity of PV plants measured in a standardized test at a temperature of 25 °C and an irradiation of 1,000 W/m^2.

[b] Calculated based on data in Jungbluth et al. [J1].

189. *Wind power plant.* The kinetic energy of wind is exploited in wind turbines for electricity generation. Wind speeds suitable for electricity generation range from 4 to 25 metres per second. These are attainable practically all over the world, with the exception of some equatorial regions. Wind power is exploited not only onshore but also offshore, where wind speeds are higher and the wind is typically available more regularly and for longer periods of time. The depth of water and distance from centres of demand onshore are major factors influencing the siting of offshore developments [O3].

190. An assessment of materials used to build an onshore wind power unit was conducted by White and Kulcinski [W5]. The assessment was for a three-blade wind turbine and assumed a 25 MW(e) unit, with a capacity factor of 24% and a lifetime of 20 years. The data on construction materials is summarized in table 44.

Table 44. Estimates of the amounts of construction materials used in wind power plants

Data in White and Kulcinski [W5] and references therein. Amount presented is for low-alloy and stainless steel and expressed in t/GW(e)

Plant[a]	*Mass of metals (t)*	*Volume of concrete (m^3)*
Wind power plant [S7]	85 000 steel	130 000

[a] 25 MW(e) plant assumed.

191. *Biomass power plant.* Biomass fuel includes straw, wood or wood residues from forests, and wood waste from wood-processing plants, such as sawmills or pulp and paper mills. Biomass fuel can contain varying amounts of radionuclides associated with past emissions or accidents. One example of this is fuel containing varying amounts of ^{137}Cs in wood that has been obtained from forested regions affected by fallout from past nuclear power plant accidents. The ^{137}Cs can be emitted in the flue gases or concentrated in the ash from the combustion of biomass containing ^{137}Cs and possibly lead to exposures. In some areas filters are currently in use to decrease the ^{137}Cs in the flue gases, and treatment or proper burial of the ashes can reduce or prevent exposures. Exposures via these pathways are not treated further here since the ^{137}Cs originates from nuclear power plant accidents and are concentrated in the forested areas that have received significant fallout from past accidents.

192. In general terms, biomass fuel has a lower energy density than coal and is more challenging to handle. As a consequence, the fuel handling equipment is heavier than that for a coal-fired power plant of equivalent capacity. Technically, biomass power plants can be as large as coal-fired power plants in terms of installed capacity, but, in general, biomass units are not built as large as coal units, mostly because of the significant difficulties with supply and storage associated with materials of lower energy density [R2].

193. The design of a biomass power plant is not very different from that of a coal-fired power plant. The main difference is that the ash handling equipment is generally smaller in a biomass plant, depending on the type of fuel used (biomass typically generates less ash than coal). However, this difference may be neglected to a first approximation, and therefore the Committee assumed that the materials required per kilowatt to build a biomass power plant were the same as those given by White and Kulcinski for a coal-fired power plant [W5]. For the biomass power plant, the capacity factor was assumed to be 75% and plant lifetime 20 years.

194. *Summary*. Table 45 shows occupational collective effective doses normalized to energy production due to mining for ores and the processing needed for construction of the electricity-generating plants or devices, as estimated in this study. Electricity-generating technologies using coal, natural gas and biomass have the lowest collective doses normalized to electricity generated, followed by slightly higher values for nuclear power. Wind power shows a larger collective dose by about a factor of 10 compared to the lowest values, and solar power shows the largest value by about a factor of 80. The differences between the various electricity-generating technologies are connected to various plant facilities using different types and amounts of steel and metals. Another reason is the differences in the capacity factors and lifetime of the plants, with a higher capacity factor and longer lifetime implying a lower collective dose per unit of electricity generation.

Table 45. Collective effective dose normalized to unit of electricity generation for construction of electricity-generating plants or devices

Electricity-generating technology	*Normalized occupational collective dose due to mining and processing of ores needed for construction (manSv/(GW a))*
Nuclear	0.02
Coal	0.01
Natural gas	0.01
Solar PV	0.8
Wind	0.1
Biomass	0.01

VIII. COMPARISON OF RADIATION EXPOSURES FROM ELECTRICITY-GENERATING TECHNOLOGIES

195. Sources of radiation exposure from electricity-generating technologies based on the *(a)* nuclear fuel cycle, *(b)* coal cycle, the combustion of natural gas, oil and biofuels, *(c)* geothermal energy, *(d)* wind power and *(e)* solar energy have been investigated in this annex. Two electricity-generating technologies, the nuclear fuel cycle and the coal cycle have been substantially investigated using the same methodology, the Committee's revised methodology for estimating public exposures due to radioactive discharges (annex A). This same methodology was also used to investigate public exposures derived with more rudimentary assessments based on less available data for the electricity-generating technologies that employ combustion of oil and natural gas, and geothermal energy.

196. Occupational exposures for all of these technologies were also estimated, relying mainly on data from dosimetric records of worker exposures. In addition, new assessments on occupational exposures from *(a)* decommissioning of nuclear power reactors and *(b)* the mining of rare earth metals needed for the construction phase in different electricity-generating technologies have been presented, adding for the first time solar energy, wind power and combustion of biomass to the electricity-generating technologies assessed by the Committee.

197. This chapter compares the results for the different electricity-generating technologies investigated by applying the revised methodology for estimating public exposures due to radioactive discharges (annex A). This is followed by a comparison of all results for both occupational and public exposures.

A. Comparison of public exposures due to radioactive discharges from the electricity-generating technologies based on the nuclear fuel cycle, coal cycle, combustion of natural gas and oil, and use of geothermal energy

198. Table 46 shows results from applying the revised methodology for estimating public exposures due to radioactive discharges (annex A). The results represent the sum of all discharges assessed in this annex for the electricity-generating technologies based on the *(a)* nuclear fuel cycle, *(b)* coal cycle and combustion of natural gas and oil, and *(c)* use of geothermal energy.

199. The table provides estimates of collective doses to the worldwide public, and associated collective doses normalized to electricity generation in 2010, integrated to 100 years. Collective doses normalized to electricity generation are the sum of the collective doses for each process in the nuclear fuel cycle, or the coal cycle, divided by the total electricity generated in 2010 for that cycle. For the coal cycle, the doses were estimated assuming all discharges were either from older coal plants or from modern ones. Both results are shown and represent a range of values for the coal cycle. Although the assessments of the nuclear fuel cycle and coal cycle were more substantive than those for the combustion of oil and natural gas, and geothermal energy, the Committee considered that comparing the magnitudes of the total and normalized collective doses was still valid.

Table 46. Collective dose to the worldwide public, and associated normalized collective dose for 2010, integrated to 100 years [a,b]

Except where otherwise specified, the collective doses given are for the local and regional components. Shown also is the percentage of total world electricity generation in 2010 for each electricity-generating technology and the discharges for ^{222}Rn normalized to the electricity generation in 2010

Electricity-generating technology	*Collective dose (man Sv)*	*Normalized collective dose (man Sv/(GW a))*	*% of total world electricity generation in 2010*	*Normalized ^{222}Rn discharges (TBq/(GW a))*
NUCLEAR FUEL CYCLE				
Nuclear, total from mining and milling, power plants and reprocessing, excluding global component	130	0.43	13	Uranium mining – 66 Milling – 3 Operational mill tailings – 3 Mill tailings[c] – 10
Adding global component integrated to				
100 years	910	3.0		
500 years	1 700	5.5		
10,000 years	7 600	25		
COAL CYCLE				
Coal, older coal plants	1 400	1.4	40	Coal mining – 2.8 Power plants – 0.07 Ash[c] – 1.8
Coal, modern coal plants	670	0.7		
OTHERS				
Natural gas	55	0.10	22	0.75
Oil	0.03	0.000 3	4.6	0.002
Geothermal (low-density population – default population)	5–160	1–20	0.3	150

[a] Projections of any health effects using collective doses in the table are not recommended.

[b] All estimates are calculated based on best estimates; site- and location-specific collective doses are not presented.

[c] The values of the normalized ^{222}Rn discharges (TBq/(GW a)) shown in table 46 for uranium mine mill tailings (Mill tailings) and for coal ash deposits (Ash) were multiplied by 100 to account for radon emanating for 100 years from these surfaces. The value for coal ash deposits was also multiplied by a factor of 0.6 since only 60% of the ashes produced are deposited.

200. Excluding the global component from the globally-circulating nuclides, electricity generation from the coal cycle gave the highest collective dose to the public integrated to 100 years—both for the total generation in 2010 and when normalized to unit of electricity generated—for both older and modern coal plants. When the global component resulting from the globally-circulating radionuclides originating from the nuclear fuel cycle was taken into account, integrated to 100 years, the total collective dose from the nuclear fuel cycle was of the same order as from the coal cycle, about in the middle range of the values for modern versus older coal plants. Because of ongoing global exposures from the globally-circulating radionuclide ^{14}C discharged from nuclear power plants and from

reprocessing facilities, the collective dose from the nuclear fuel cycle slowly increases over centuries as shown in figure V, in section IV. This is also evident in the doses shown in table 46 for the global circulation integrated to 100, 500 and 10,000 years. The total collective dose normalized to electricity generated for the nuclear fuel cycle, including the globally-circulating nuclides and integrated to 10,000 years, is 25 man Sv/(GW a) as shown in table 46. Comparing with earlier UNSCEAR assessments, the UNSCEAR 2000 Report [U9] estimated the same quantity as 40 man Sv/(GW a). As described earlier, the collective dose from globally-circulating radionuclides is the sum of very small doses to the entire world's population. The local and regional components of collective dose assessed for the nuclear fuel cycle excluding globally-circulating radionuclides, and for the coal cycle, are for the local and regional populations exposed to the respective discharges of the source (see paragraph 34).

201. The magnitude of collective doses resulting from the coal cycle, for both the older and the modern coal plants, is due in large part to *(a)* the amount of electricity generated from coal (40% of the world's electricity generation in 2010), *(b)* the greater number of coal mines compared to uranium mines and *(c)* the contribution to the collective dose from the discharge of radon and other radionuclides from the ^{238}U series arising from the combustion of coal at the power plants. Another important factor is that a larger population base lives near coal plants and coal mines compared to nuclear plants and uranium mines.

202. Natural gas accounted for 22% of the world's electricity generation in 2010, which led to a larger contribution to the collective dose than oil, but was still small in relation to coal. Combustion of oil for electricity generation contributed only marginally to collective doses. These relatively small doses from natural gas and oil combustion were however the dominant contribution to collective dose for West Asia where, as shown in table 2, natural gas and oil accounted for most of the electricity generation in that region in 2010.

203. Discharges of ^{222}Rn normalized to the electricity generated are also shown in table 46; the largest value is estimated for geothermal energy. This finding is based on few existing data. However, because of the process for generating electricity from geothermal energy discussed in section VI, it is reasonable that the impact of ^{222}Rn discharges from gases vented during the operation of geothermal electricity-producing plants is relatively significant. The resulting doses from geothermal energy shown in table 46 are assessed using two different population densities, low-density and the default population density (see chapter III), where the available population data discussed in chapter VI suggest the low-density population distribution may be more realistic. The range in results for the collective dose demonstrates the strong dependence on the population data. However, the impact of geothermal electricity generation remains small because of the limited use of this technology.

204. The next largest value for the normalized ^{222}Rn discharge is for uranium mining, which is a factor of about 20 larger than the value for coal mining. This is also reasonable because uranium mining occurs where there are high levels of uranium and therefore of its progeny products such as ^{222}Rn. Shown in table 47 is a comparison of estimated doses to the public from the mining of coal and the mining of uranium. The assessments resulted in a larger estimate for the characteristic individual dose per unit of electricity generated for uranium mining (non-ISL) than for coal mining, consistent with the larger normalized ^{222}Rn discharge. However, values for both the worldwide collective dose (essentially comprising local and regional components alone) and of the associated values normalized to unit of electricity generated in 2010 are larger for coal mining than uranium mining. This is because of the larger number of coal mines in the world and because the population density is higher around coal mines compared to uranium mines.

Table 47. Comparison of doses to the public from mining of coal and mining of uranium

	Coal mining	*Uranium mining*	
		non-ISL	*ISL*
Characteristic individual dose per unit of electricity generated (Sv/(GW a))	2.4×10^{-7}	5.5×10^{-6}	2.5×10^{-7}
Worldwide collective dose (man Sv)	3.7×10^{2}	4.0×10^{1}	1.3×10^{0}
World-average collective dose per unit of electricity generated (man Sv/(GW a))	3.8×10^{-1}	2.8×10^{-1}	1.3×10^{-2}

205. Figure VIII shows graphically the contribution each electricity-generating technology considered makes to the worldwide collective dose to the public. Two distinct values are presented for the nuclear fuel cycle: the first is the local and regional component for the population exposed directly to the discharges, and the second includes the global component for the population of the world as a whole due to globally circulating radionuclides. The values for both the coal cycle and geothermal energy are deemed to represent boundary values, assuming either all modern or all older coal plants for the coal cycle, and for geothermal energy assuming two different population distributions. Figure IX shows the same sources as figure VIII but for the total collective dose normalized to electricity generated. The values for the nuclear fuel cycle without global circulation are slightly less than for the coal cycle, which lies somewhere between the two values given for the modern and older coal plants. Including the global circulation to the nuclear fuel cycle results in the larger value for these two technologies. Comparing these data with figure VIII shows how the magnitude of electricity generated for each technology results in the collective dose to the public. Figure IX also shows the magnitude of the upper bound for the collective dose normalized to electricity generation for geothermal energy.

206. Table 48 breaks down the comparison of collective doses—and collective doses normalized to electricity generated in 2010—for each of the source components of the nuclear fuel cycle and coal cycle technologies that have been assessed. These components are coal mining, discharges from coal combustion during power plant operation and from coal ash deposits associated with the coal cycle for electricity generation. For the nuclear fuel cycle, these components are uranium mining and milling including mill tailings, discharges during electricity generation from the nuclear power plant and discharges from reprocessing. Collective doses normalized to electricity generated in 2010 for each of the source components for the nuclear fuel cycle shown in table 48 use the electricity produced as a result of each process in the normalizations.

207. Although the differences in collective doses normalized to electricity generation for the various sources are not very large, (with the exception of old-style coal plants, which have the largest value), the total collective doses in 2010 show significant differences. For both sets of results, the largest values are from old-style coal combustion power plants. Collective doses for the different components associated with the coal cycle are all larger than collective doses for the components associated with the nuclear fuel cycle, except for modern coal plants compared to nuclear power plants. The categories shown in table 48 make clear the importance of radon discharges from coal mining and from coal ash deposits, which—with the assumptions made in this study—make significant contributions to the total collective doses even when the coal combustion power plant is modern. The differences in the dose values for the old-style compared with the modern coal combustion power plant are due to the nuclides in the ^{238}U decay chain other than radon, because the radon discharge from the flue-gas stack is the same in both cases. Table 49 shows this difference between modern versus old-style coal combustion power plants regarding dose contribution per radionuclide from the ^{238}U decay chain.

208. Table 49 shows local and regional components of collective doses assessed from discharges of radionuclides in the ^{238}U decay chain from the flue-gas stack of a coal plant during the combustion of coal for electricity generation in a modern compared to an old-style coal plant. The ^{222}Rn discharges are the same for both types of coal plant; consequently the doses from ^{222}Rn are also the same in table 49. It is clear from the breakdown of the radionuclides shown in table 49 that the large differences in the doses assessed for the old-style versus modern coal plants are due to the other radionuclides shown, with ^{210}Pb and ^{210}Po giving the largest contribution.

Figure VIII. Local and regional components of the collective doses to the public integrated to 100 years, for the electricity-generating technologies based on the nuclear fuel cycle, coal cycle, combustion of gas and use of geothermal energy

Data from table 46

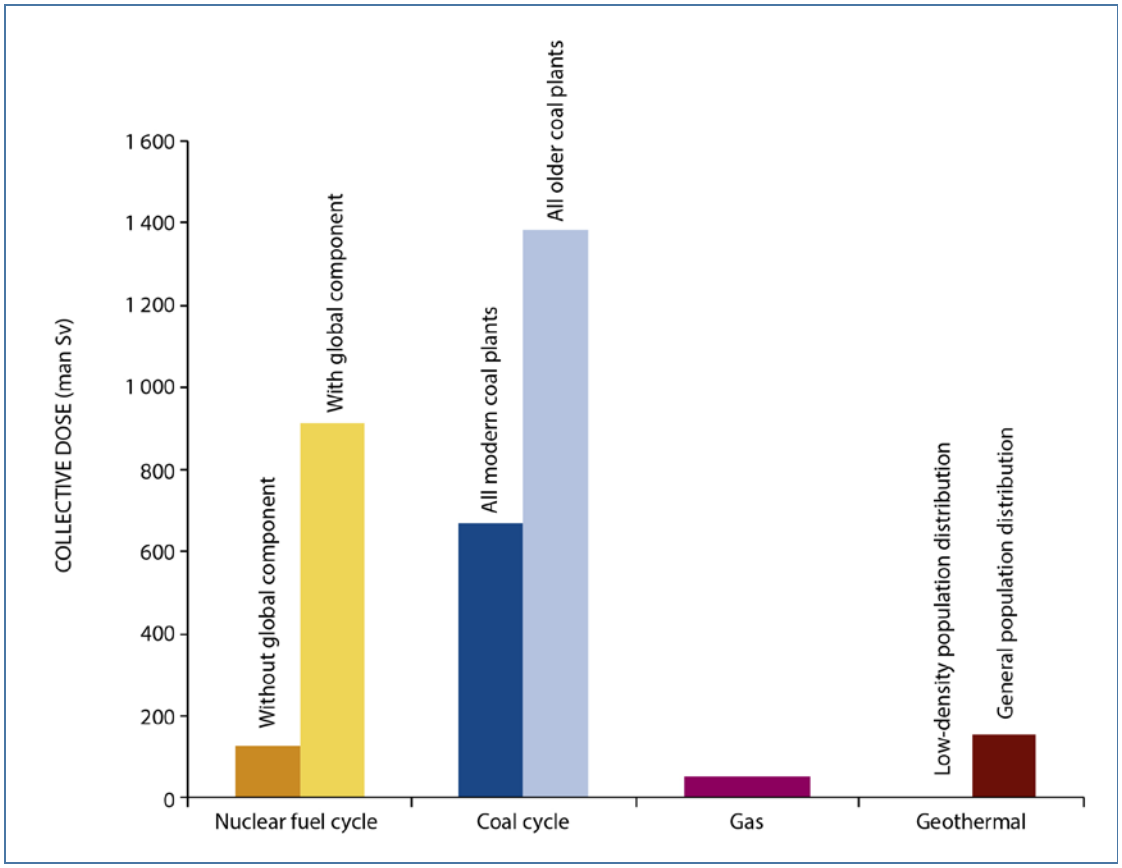


Figure IX. Local and regional collective doses to the public integrated to 100 years, normalized to electricity generated for the technologies based on the nuclear fuel cycle, coal cycle, combustion of gas and use of geothermal energy

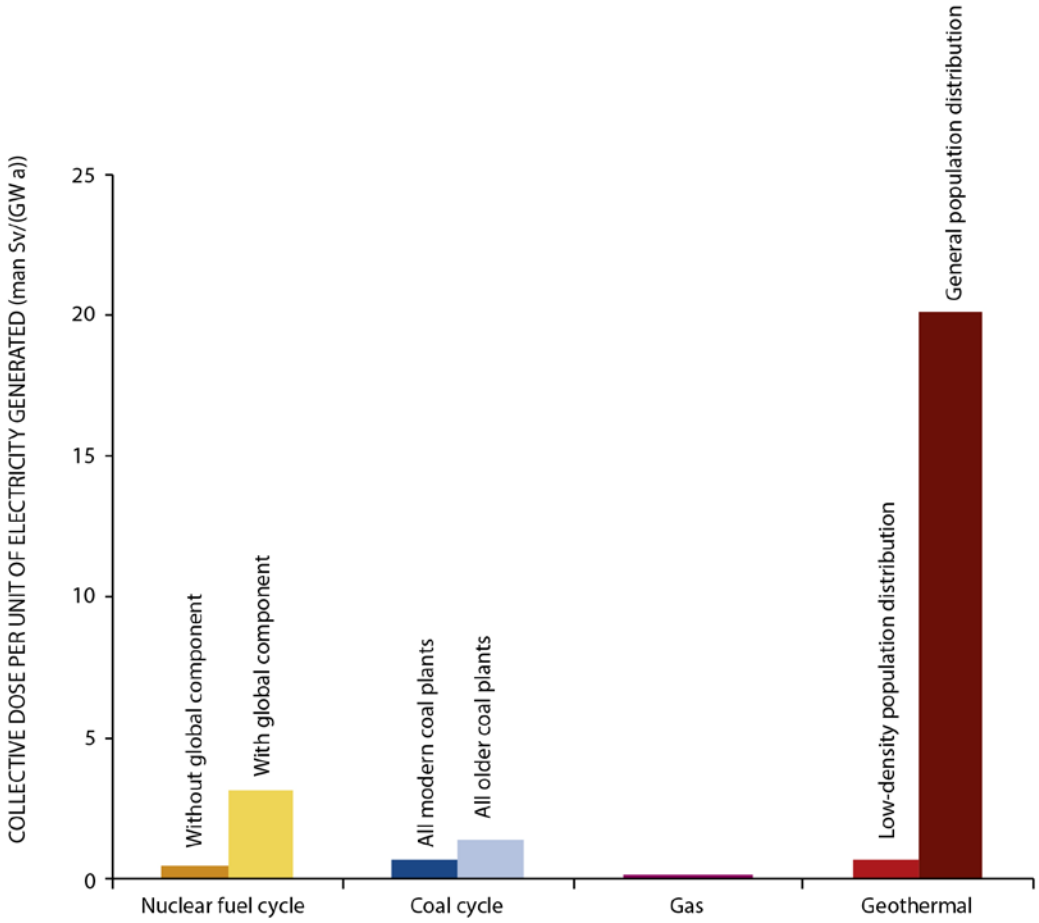


Table 48. Comparison of collective doses to the public, and collective doses normalized to electricity generation in 2010, integrated to 100 years, to the world-average population within a 1,500 km radius of each source for the electricity-generating technologies based on the coal cycle and the nuclear fuel cycle

Coal			*Nuclear*		
Source	*Collective dose (man Sv)*	*Normalized collective dose (man Sv/(Gw a))*	*Source*	*Collective dose (man Sv)*	*Normalized collective dose (man Sv/(Gw a))*
Coal mining	370	0.4	Uranium mining[a] and milling	53	0.2
Older coal plants	780	0.8	NPP generation	68	0.2
Modern coal plants	60	0.1			
From coal ash deposits	240	0.2	Reprocessing	7.6	0.03

[a] Of the 53 man Sv for uranium mining and milling, 40 man Sv is from mining only.

Table 49. Local and regional components of collective dose, integrated to 100 years, due to discharges from modern and old-style coal combustion power plants

Radionuclide	*Collective dose from modern coal plants (man Sv)*		*Collective dose from old-style coal plants (man Sv)*	
	Local	*Regional*	*Local*	*Regional*
^{210}Pb	2	9	28	135
^{210}Po	3	14	46	216
^{222}Rn	2	8	2	8
^{226}Ra	1	7	20	98
^{230}Th	2	8	26	122
^{234}U	0.5	2	7	34
^{238}U	0.4	2	6	29
Total[a]	11	50	135	641

[a] Slight differences between the totals shown here and those in table 48 are due to rounding performed on the values in table 48. The values in table 49 are left as generated in the assessment to avoid inconsistent rounding of individual radionuclides for the purpose of attaining the same total rounded value as shown in table 48. It should also be recalled that in this table, as in all tables in the annex resulting from assessments, the calculations are done to full precision and any discrepancies in the final sum of numbers in the tables are due to rounding.

209. Doses assessed from the radon emanation from coal ash versus uranium mill tailings, using ^{222}Rn discharges normalized to electricity generated given in table 46, are compared in table 50. As described in chapter IV and more extensively in annex A, a low population density was used in the assessments on uranium mill tailings whereas a default population density was used in the assessment on coal ash. The characteristic individual dose per unit of electricity generated is larger for uranium mill tailings compared to coal ash, reflecting the greater activity concentrations of naturally occurring radionuclides, including radon, in mill tailings. However, when the total electricity generation is taken into account, collective doses assessed from coal ash are greater than those from mill tailings. The results show the effect of the continued emanation of radon centuries into the future.

Table 50. Collective dose per unit of electricity generated to world-average population within 1,500 km and integrated to 100 years, also integrated for two different times since disposal, and characteristic individual dose per unit of electricity generated from emanation of radon from coal ash and mill tailings

Time since disposal	*Collective dose per unit of electricity generated (man Sv/(GW a))*		*Characteristic individual dose per unit of electricity generated (Sv/(GW a))*	
	Coal ash	*Mill tailings*	*Coal ash*	*Mill tailings*
100 years	0.2	0.04	1.5×10^{-7}	8.4×10^{-7}
500 years	1.2	0.2		

210. *Significant radionuclides from nuclear power plant discharges.* The importance of ^{14}C and the globally circulating radionuclides, and ^{222}Rn and the ^{238}U series, is discussed in other sections. The following concentrates on comparing other significant radionuclides discharged from different nuclear power plant types.

211. Table 51 shows the world-average collective dose per unit of electricity generated for the nuclear power plant types assessed in this annex. The table illustrates the relative importance to the world-average collective dose per unit of electricity generated of ^{90}Sr, ^{137}Cs and ^{35}S from the GCR-type reactor, and tritium from the HWR reactor.

Table 51. Local and regional components of collective doses, integrated to 100 years, normalized to electricity generation in 2010, shown for all nuclear power plant types considered

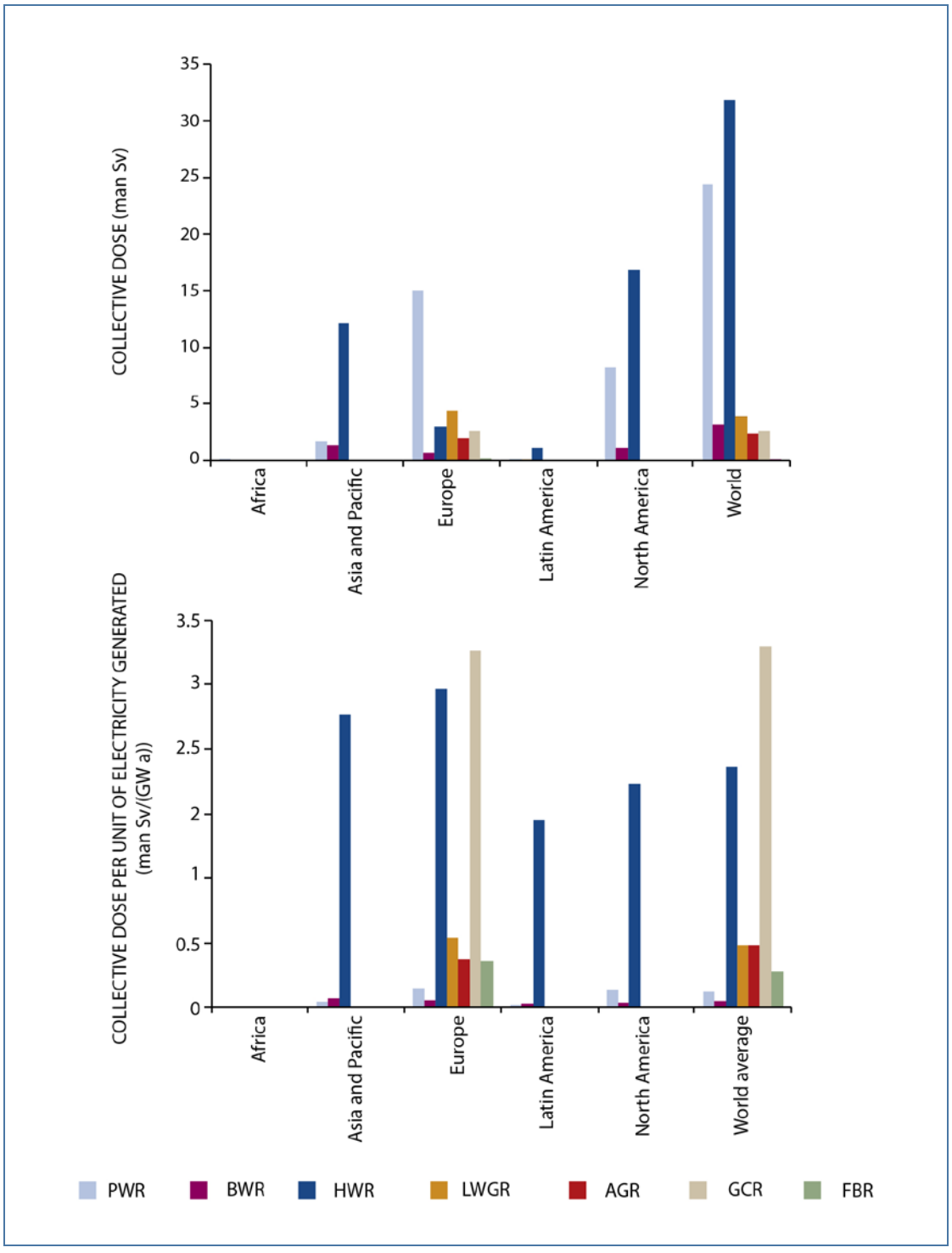
See chapter IV for details on the power plant types

Discharged radionuclide	*World-average collective dose per unit of electricity generated for each nuclear power plant type (man Sv/(GW a))*						
	PWR	*BWR*	*HWR*	*LWGR*	*AGR*	*GCR*	*FBR*
^{3}H	7.2×10^{-2}	8.6×10^{-3}	1.7×10^{0}	1.2×10^{-1}	1.9×10^{-2}	3.3×10^{-2}	2.3×10^{-1}
^{14}C	4.6×10^{-2}	3.2×10^{-2}	1.4×10^{-1}	3.1×10^{-1}	3.5×10^{-1}	1.3×10^{0}	2.8×10^{-2}
^{35}S	0	0	0	0	4.5×10^{-2}	2.4×10^{-1}	0
^{41}Ar	4.5×10^{-5}	4.6×10^{-5}	1.3×10^{-3}	3.4×10^{-3}	8.4×10^{-4}	7.0×10^{-2}	0
^{54}Mn	2.3×10^{-5}	1.0×10^{-4}	0	4.0×10^{-5}	0	0	1.8×10^{-4}
^{58}Co	3.7×10^{-5}	4.0×10^{-5}	0	5.9×10^{-6}	0	0	1.7×10^{-4}
^{60}Co	2.0×10^{-4}	5.6×10^{-3}	1.5×10^{-4}	8.8×10^{-3}	7.0×10^{-2}	3.5×10^{-3}	2.3×10^{-3}
^{65}Zn	0	5.0×10^{-4}	0	1.6×10^{-4}	7.0×10^{-5}	0	0
^{85}Kr	2.2×10^{-6}	1.4×10^{-5}	0	0	0	0	1.7×10^{-4}
^{90}Sr	7.0×10^{-5}	1.2×10^{-3}	0	1.2×10^{-2}	3.4×10^{-5}	4.7×10^{-1}	0
^{106}Ru	3.7×10^{-5}	1.0×10^{-6}	0	0	0	0	0
^{131}I	6.0×10^{-5}	3.2×10^{-4}	1.7×10^{-5}	7.5×10^{-3}	2.5×10^{-5}	0	1.5×10^{-4}
^{133}Xe	1.2×10^{-4}	1.5×10^{-4}	0	1.1×10^{-2}	0	0	0
^{135}Xe	3.4×10^{-5}	3.4×10^{-4}	0	2.4×10^{-3}	0	0	0
^{138}Xe	1.5×10^{-9}	3.1×10^{-7}	0	1.1×10^{-6}	0	0	0
^{134}Cs	3.2×10^{-4}	2.6×10^{-4}	0	3.4×10^{-4}	7.4×10^{-4}	3.8×10^{-2}	1.1×10^{-2}
^{137}Cs	4.2×10^{-4}	1.0×10^{-3}	4.6×10^{-2}	6.6×10^{-3}	6.6×10^{-4}	6.2×10^{-1}	7.7×10^{-3}
Total	1.2×10^{-1}	5.0×10^{-2}	1.9×10^{0}	4.8×10^{-1}	4.9×10^{-1}	2.8×10^{0}	2.8×10^{-1}

212. Figure X shows estimated collective doses by world region and totalled for the world by nuclear reactor type, with the values taken from table 51. Both collective doses, and collective doses normalized to electricity generated in 2010 are shown. The collective doses show a different profile than that shown in the figure displaying the collective doses normalized to electricity generated. Two nuclear power plant types, GCRs and HWRs, dominate the collective doses normalized to electricity generated. However it is the power plant types PWRs and HWRs that dominate the contribution to the collective doses; this is because of a combination of the number of reactors that exist in each region coupled with the discharged amounts of significant radionuclides for each reactor type.

Figure X. Local and regional collective doses to the public integrated to 100 years, and associated values normalized to electricity generation, by world region and nuclear reactor type

Results shown for collective doses from all discharges (man Sv) and for collective dose from all discharges normalized to electricity generation (man Sv/(GW a)) in 2010. Note that the order of the individual reactor types is according to their world share of electricity generated in 2010, as shown in table 9



B. Comparison of public and occupational exposures

213. Table 52 summarizes the results from all occupational and public exposures that have been presented in this annex. The table shows collective doses normalized to electricity generated in 2010, followed by collective doses for the same year. The local and regional components of doses to the public are for world-average populations out to 100 km and between 100 km and 1,500 km from a facility respectively, integrated over 100 years. Other conditions are as stated earlier in this chapter. This section considers the total exposure from each electricity-generating technology, i.e. public plus occupational exposures.

214. The occupational exposures from coal mining dominate collective doses, so that the total exposure of the public and occupational exposures combined is largest from the coal cycle. This is true even considering the public exposures from the nuclear fuel cycle including the global circulation integrated out to 10,000 years. The next largest is the total exposure from the nuclear fuel cycle, where public exposure including global circulation gives the highest dose followed by occupational exposures. The same trend is observed for the associated collective doses normalized to electricity generated, with the exception of the public exposures from the nuclear fuel cycle normalized to electricity generated integrated out to 10,000 years, which gave the largest value.

215. The comparisons of public doses shown in table 52 that have been assessed using the revised methodology for estimating public exposures due to radioactive discharges (annex A) have been described in section A of this chapter. They are provided in this table to facilitate comparison with occupational exposures and view the entire exposure, public and occupational, from each electricity-generating technology. One comparison of interest noticeable in table 52 is that collective doses to the public resulting from radon discharges from natural gas power plants are about the same as collective doses to the public resulting from the discharges from operation of nuclear power plants (55 versus 68 man Sv, respectively). However, the collective dose to the public normalized to electricity generated in 2010 is about a factor of four larger for the nuclear fuel cycle than for the combustion of natural gas (not including global circulation). The relatively large actual collective dose assessed for combustion of natural gas results from the larger amount of electricity produced by natural gas than nuclear power in 2010.

216. The assessments on collective dose provided in the annex can be put in perspective by considering natural exposure to background radiation from ^{222}Rn. All doses to the public from natural gas, oil, and geothermal energy are calculated from the release of ^{222}Rn. A significant fraction of the doses from the coal and nuclear cycles are also due to the release of ^{222}Rn. Radon-222 occurs naturally in nature and is a major fraction of the dose to man from all naturally occurring sources of radiation. Wilkening et al. [W7] have estimated that the average exhalation rate of ^{222}Rn from soil is 1.6×10^{-2} Bq $(m^2\ s)^{-1}$. As a result of this exhalation from soil and the additional exhalation of ^{222}Rn from building materials, the Committee [U9] has previously estimated that the average effective dose from ^{222}Rn is 1.15 mSv a^{-1}. For the world population considered here, the collective dose due to exposure to naturally occurring radon is 11,500,000 man Sv a^{-1}, a value much larger than any given in table 46.

217. Total occupational collective doses are significantly greater than public collective doses for the coal cycle and combustion of oil, from a factor of about ten for coal plants to about five hundred for combustion of oil, although the values for combustion of oil are in comparison small. For natural gas and geothermal energy, total public collective doses were assessed to be larger than total occupational collective doses. Total occupational collective doses for the nuclear fuel cycle are of about the same order as the total collective dose to the public when including the global circulation to 100 years.

218. The largest occupational collective dose normalized to energy generated in 2010 resulting from the mining for metals for construction materials was from solar photovoltaic (PV) technology, which was a factor of forty and eighty larger than for the nuclear fuel cycle and coal cycle, respectively. This was followed by the occupational collective dose for wind power, which was also larger than the values for the nuclear fuel cycle and coal cycle. These differences come from the different metal requirements for solar PV and wind power technologies, discussed in chapter VII.

Table 52. Comparison of the public and occupational exposures assessed in this annex[a,b]

	Nuclear fuel cycle		*Coal*	*Modern coal plant*	*Older coal plant*	*Natural gas*	*Oil*	*Geothermal*	*Solar PV*	*Wind*	*Biomass*
COLLECTIVE DOSES NORMALIZED TO ELECTRICITY GENERATION (man Sv/(GW a))											
Public	U mining and milling	0.2	Coal mining (Rn discharge)	0.4	0.4						
	Nuclear power plant operation	0.2	Coal plant operation	0.1	0.8						
	Reprocessing	0.03	Ash, radon emanation	0.2	0.2						
Total public (not including globally circulating radionuclides)		0.43		0.7	1.4	0.1	0.000 3	1–20			
Total public (including globally circulating radionuclides)	100 years	3.0									
	500 years	5.5									
	10 000 years	25									
Occupational		2.7[c]		11	11	0.01	0.15	0.05			
Occupational - decommissioning, nuclear		1.8									
Occupational - mining for construction		0.02		0.01	0.01	0.01			0.8	0.1	0.01
COLLECTIVE DOSES (man Sv)											
Public	U mining and milling	53	Coal mining (Rn discharge)	370	370						
	Nuclear power plant operation	68	Coal plant operation	60	780						
	Reprocessing	8	Ash, radon emanation	240	240						
Total public (not including globally circulating radionuclides)		130		670	1 400	55	0.03	5–160			

	Nuclear fuel cycle		*Coal*	*Modern coal plant*	*Older coal plant*	*Natural gas*	*Oil*	*Geothermal*	*Solar PV*	*Wind*	*Biomass*
Total public (including globally circulating radionuclides)	100 years	910									
	500 years	1 700									
	10 000 years	7 600									
Occupational		788		11 000	11 000	7	17	0.4–0.8			
Decommissioning (occupational) per nuclear reactor		5									
Occupational - mining for construction		6		7	7	3			3	4	0.4

[a] Projections of any health effects using collective doses in the table are not recommended.

[b] All estimates are calculated based on best estimates; site- and location-specific collective doses are not presented.

[c] From UNSCEAR 2008 Report.

C. Commentary on significance of accidents

219. While this annex has focused on comparing the exposures from normal operations of the various electricity-generating technologies, a commentary is needed regarding the risk of serious accidents that give rise to radiation exposure. This is clearly only significant for nuclear power. While it is beyond the competence of the Committee to assess the probability of any future accident, the Committee has assessed information on past accidents that have exposed the public and workers, notably the 1986 accident at the Chernobyl nuclear power plant in the former Soviet Union (UNSCEAR 2008 Report, annexes C and D [U12]). Moreover since that report, the Committee has conducted an assessment of the levels and effects of radiation exposure due to the 2011 nuclear accident at the Fukushima Daiichi nuclear power station (FDNPS). The UNSCEAR 2013 Report [U13] gave estimates of the collective doses to the population of Japan due to the FDNPS accident. These estimates were compared with the previous estimates by the Committee for populations of European countries exposed to radiation following the 1986 Chernobyl accident in the former Soviet Union. This comparison is shown in table 53.

Table 53. Estimates of the collective effective doses from the FDNPS and Chernobyl accidents [U13]

Accident	*Collective effective dose (thousand man Sv)*		
	Over first year	*Over ten years*	*Up to age 80 years*[a]
Fukushima Daiichi nuclear power station	18	36	48
Chernobyl Unit 4			400

[a] Summing the dose to all exposed individuals integrated from their age at the time of the accident until they reach age 80 years.

220. Comparing radiation doses alone, it is clear that serious accidents give rise to collective doses that are very many times greater than collective doses due to normal operations. For example, the collective dose from the single accident at Chernobyl Unit 4 is more than 400 times the annual global collective dose to the public from all nuclear power. Such a comparison of collective doses can be made only in order to gain perspective on the magnitude of the radiological impact. However, great care must be taken when assimilating these comparisons, because there are obviously many major non-radiological differences between accidents and normal operations for electricity generation. While collective doses from such accidents have been much larger than those from annual normal operations, the distribution of doses is more localized geographically, whereas the collective doses from normal operations for electricity generation are population-averaged over geographical regions or the world as a whole.

IX. RESEARCH NEEDS

221. The use of electricity is ubiquitous throughout the world and the demand for electricity continues to grow. Because of the prevalence of different types of electricity-generating technologies coupled with the diversity inherent in the countries of the world, standard data on exposures to radioactive discharges or materials is non-uniform or non-existent. Thus, any study comparing different electricity-generating technologies will suffer from inconsistent or incomplete databases. This annex has used consistent methodologies together with sound judgement on the use and interpretation of available data to assess public and occupational exposures from electricity-generating technologies. Some specific areas of interest that would improve understanding or that would increase the certainty of this work are included in this section.

222. *Data.* Consistent data on radioactive discharges across all electricity-generating technologies, including how they change with time and changing practices across all electricity-generating technologies, would improve the ability to assess and compare these technologies. Data on occupational exposures and their change with time and practice for each technology would also help. The following lists some specific needs that have been identified:

(a) Decommissioning of coal power plants generates NORM wastes, the magnitude of which should be quantified (NORM wastes are naturally occurring radionuclides such as lead and polonium which in this case become plated out in pipes and the boiler, and other mechanical parts of the plant [M5]). Occupational exposures received during decommissioning of coal power plants need to be monitored in a representative manner in order to allow assessment of this exposure route for workers. This is also true regarding occupational exposures of workers decommissioning nuclear power plants.

(b) The combustion of natural gas and oil for electricity generation causes naturally occurring radionuclides to accumulate in the pipes. Assessment of any occupational or public exposures from this source is dependent on representative data on the activity concentrations that occur. There are some data available on this, however the measured external gamma exposure rates are of more significance.

(c) In order to assess the occupational doses resulting from the management of radioactive waste generated in nuclear power plants, representative data on doses received by workers needs to be collected or compiled [M5].

(d) Information on the proportion of nuclear fuel reprocessed for peaceful (i.e. electricity generation) versus non-peaceful (i.e. military applications) has only been available for the La Hague, France reprocessing facility and therefore the assessment of the doses due to discharges from reprocessing activities was compromised by the lack of open information. Also, some of the occupational doses at reprocessing facilities, such as Sellafield in the United Kingdom, are from the reprocessing of historical wastes so it is very hard to relate occupational doses to just nuclear fuel that has been reprocessed, or to electricity generation. Actual data on reprocessing activities related to electricity generation are needed to improve the exposure assessments.

(e) Storage, transmission and distribution of electricity are not included in the assessments of dose from electricity generation presented in this annex. These infrastructures are used regardless of the type of electricity generation (although there are differences between centralized and distributed grid systems that are optimal for different technologies), and these kinds of dose assessments could be included in any future update of the evaluations presented in the annex.

223. Databases could be consistent and standardized; these types of efforts are currently conducted by various international organizations. The success of these efforts, however, depends on the volunteer compliance of member countries submitting annual reports to these organizations, such as UNSCEAR, IAEA and NEA, and on funding and interest to keep the programmes current. These programmes would benefit from extending the data-collection schemes to include all relevant technologies, and investing in research to identify significant parameters to help design streamlined data-collection schemes that would further decrease the burden on member countries and data-collecting organizations.

224. *Uranium mining using the ISL process.* Explanations were given in chapter IV of the assumptions made about radon releases during uranium mining using the ISL process. Existing data are inconclusive, and radon could be released in varying quantities from the lixiviant used to dissolve the uranium in the underground ore body, depending on the specifics of the process. Determining more precisely the amount of radon releases from ISL uranium recovery, and how to better generalize them, requires additional research and a more complete understanding of the variation in the global processes and procedures currently in use for mining of uranium using the ISL process.

225. *Recycling of metals.* In chapter VII on assessing doses from the mining of metals needed in the construction phase, several assumptions were made in the assessments. Although the assumptions affect the absolute value of the assessed collective doses, the relative importance when comparing the different electricity-generating technologies with regards to the construction phase should remain relevant. However, these assumptions make a difference when comparing to the other components in the full cycle of electricity generation, such as in table 52. One area of importance that could be studied further is the effect of recycling metals, which has not been included in the present study because of insufficient data for large portions of the world. By not explicitly considering recycling, the collective dose per unit of electricity generated due to the extraction and processing of the metals used in the construction of a facility is likely to be overestimated by around a factor of two on average, and possibly a factor of five or more for some regions of the world with developed recycling processes (assuming the recycled metal is not contaminated with radioactive material). Also, recycling may affect the different technologies somewhat differently because it is more difficult and costly to recycle electronics and components (such as in solar panels) than larger bulk metal objects (such as in more conventional power plant components).

226. *Reference year.* This annex concentrates on the reference year 2010 for the assessments. Lifetime commitments would be relevant for comparing the full impact of the different electricity-generating technologies. Confounders in this type of extrapolation are associated with the changes in the respective electricity-generating technologies over time, caused by, for example, improving effectiveness of each technology in both economic and environmental terms and in radiation protection practices.

227. *Suess effect.* The displacement of ^{14}C in atmospheric CO_2 discharges during the coal cycle and other fossil fuel releases of CO_2 (which are depleted in ^{14}C) is known as the Suess effect. Research into this effect would improve knowledge of the global carbon cycle and could help clarify the role of ^{14}C in human exposures in the modern world.

X. CONCLUSIONS

228. This annex provides estimates of exposures from the various electricity-generating technologies that *(a)* may be used by researchers and policy-makers in their own more comprehensive assessments for developing energy policy; *(b)* can be used to help inform the media and the public on these matters in a balanced perspective; and *(c)* can highlight possible emerging issues or opportunities for improvement that may warrant more attention and scrutiny, or future research. The following summarizes the findings.

229. The Committee has updated its methodology for estimating public exposures due to radioactive discharges, which is now more flexible for use in evaluating radiation exposures to the public from diverse electricity-generating technologies. This methodology along with extensive data collection and analyses has provided the Committee with a sounder basis for comparative studies than was possible earlier. The Committee has also re-evaluated occupational exposures arising from different electricity-generating technologies relying on data mainly from dosimetry records of worker exposures. These evaluations comprised the basis for the current comparative study on radiation exposures of both the public and of workers from electricity generation. To compare exposures, the Committee has focused on two metrics. These were *(a)* the collective doses to defined population groups integrated over specific time periods resulting from one year's electricity generation by each technology in each geographical region and for the world as a whole, and *(b)* the relevant collective doses divided by the amount of electricity generated by each technology. The year 2010 was used as the reference year for the comparisons.

230. The Committee has conducted this comparative study by investigating sources of radiation exposure from electricity-generating technologies based on the *(a)* nuclear fuel cycle, *(b)* coal cycle, the combustion of natural gas, oil and biofuels, and *(c)* geothermal, wind and solar power. Two electricity-generating technologies (nuclear fuel cycle and coal cycle) were investigated in detail because a more robust database existed for these technologies. The Committee evaluated the main sources of radioactive discharges from the life cycle of these electricity-generating technologies. For the nuclear fuel cycle, these were uranium mining, milling and mill tailings, power plant operation, spent fuel reprocessing, and decommissioning activities. For the coal cycle, they were the mining for coal, power plant operation for both a modern coal plant and an older-style coal plant, and coal ash deposits.

231. The Committee estimated that, excluding long-lived globally circulating radionuclides, the contribution from the coal cycle, assuming discharges from a modern coal plant, was more than half of the total collective dose to the global public from the discharges due to a single year's global electricity generation, while the nuclear fuel cycle contributed less than a fifth. The contribution from the coal cycle comes from discharges of natural radionuclides (primarily radon and its radioactive progeny) during coal mining, combustion of coal at the power plant and from coal ash deposits. Similarly, almost half of the contribution to public exposures from the nuclear fuel cycle also comes from discharges of natural radionuclides during uranium mining and milling activities. These values depend on the amount of electricity generated by each technology; in 2010, the coal cycle produced the largest amount of total electricity generated, about 40%. Although radon and its progeny are relatively important contributors to collective doses to the public for both the nuclear fuel cycle and the coal cycle, the associated individual doses are small compared with doses due to inhalation of naturally occurring radon [U9, W7].

232. The Committee found, however, that the contribution to the collective dose to the public from each electricity-generating technology was not only because of how much electricity each technology generated. There were differences due to the collective doses per unit of electricity generated. In normal operations, the coal cycle gives a higher collective dose per unit of electricity generated than electricity generation from nuclear power plants, and significantly higher than the other technologies evaluated—with the exception of geothermal energy. Based on the limited information on radon discharges from geothermal power plants, the collective dose per unit of electricity generated by geothermal energy could be significant. However, because the use of geothermal technology is not widespread, its contribution to radiation exposures of the global public is smaller than that of the coal cycle.

233. Previous investigations on electricity generation from the nuclear fuel cycle have examined the contribution to human exposures made by long-lived radionuclides, such as carbon-14, which are discharged, circulate globally and continue to contribute to radiation exposures of the public centuries into the future, albeit as extremely small individual doses. The Committee found that public exposures from these globally-circulating radionuclides, for one year of discharge and integrated to 100 years, result in a contribution to exposures from the nuclear fuel cycle that are about the same as the coal cycle. Over long integration times such as hundreds of years, the contribution from these radionuclides results in larger collective doses to the global public from the nuclear fuel cycle than the coal cycle.

234. The Committee also assessed the occupational exposures for these technologies. The largest collective dose to workers per unit of electricity generated resulted from coal mining, because of exposures to naturally occurring radionuclides. Of all the collective doses evaluated, to both the public and workers, the exposure of workers from coal mining gave the largest contribution, although it has fallen over time because of better mining conditions. Regarding the mining of rare earth metals needed for construction, by far the largest collective dose to workers per unit of electricity generated assessed in this study came from solar power, followed by wind power. This is because the workers are exposed to natural radionuclides during mining, and the amount of low-grade ore required to be mined for these technologies is high.

235. The total collective dose (i.e. to the global public and all exposed workers combined) per unit of electricity generated by the coal cycle was larger than that generated by the nuclear fuel cycle, even when considering the long-lived globally-circulating radionuclides integrated out to 500 years. When considering the amount of electricity generated in the year 2010 by each technology, the coal cycle resulted in the largest collective dose to the global public and workers combined, followed by the nuclear fuel cycle. Of the remaining technologies, geothermal energy and combustion of natural gas were the next largest contributors.

236. Great care should be taken when interpreting and using these results, because this analysis only gives a perspective on the magnitude and differences of radiation exposures, and cannot be used to determine whether one form of energy generation is preferable to another. As stated earlier, a number of factors determine why a certain mix of energy generation technologies may be selected by countries. Radiation exposure is only one of them.

237. Moreover, when comparing collective doses for the various electricity-generating technologies, it is important to note that the collective dose from serious accidents, such as those that occurred at the Chernobyl and Fukushima-Daiichi nuclear power stations, were orders of magnitude larger than the collective doses to the world population from one year's normal operation of all the technologies of electricity generation that were assessed in the annex. More significantly, the distribution of doses after an accident is more localized geographically (local populations receive higher doses than the average), whereas the collective doses from normal operations for electricity generation are often averaged over populations within each geographical region or the world as a whole.

XI. ACKNOWLEDGEMENTS

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