United Nations Scientific Committee on the Effects of Atomic Radiation

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

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SCIENTIFIC ANNEX D:

Evaluation of occupational exposure to ionizing radiation

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SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

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NOTE

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The attachments cited in this annex are electronically available for download from
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ANNEX D

EVALUATION OF OCCUPATIONAL EXPOSURE TO IONIZING RADIATION

CONTENTS

The attachment cited in this annex includes 23 tables with supplementary information and is electronically available for download from the UNSCEAR website *http://www.unscear.org/unscear/en/publications/2020_2021_4_Attachment.html*

LIST OF ABBREVIATIONS

AFAN	African Alara Network
AGR	Advanced gas-cooled reactor
BSS	Basic safety standards
BWR	Boiling water reactor
CARI	Computer and Automation Research Institute
EPCARD	European Program Package for the Calculation of Aviation Route Doses
FBR	Fast-breeder reactor
FDG	Fluorodeoxyglucose
GCR	Gas-cooled reactor
GDP	Gross domestic product
GNI	Gross national income
GSD	Geometric standard deviation
HTGR	High-temperature graphite reactor
HWR	Heavy water reactor
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
ILO	International Labour Organization
ISEMIR	Information System on Occupational Exposure in Medicine, Industry and Research
ISL	In situ leaching
ISO	International Organization for Standardization
ISOE	Information System on Occupational Exposure
ISR	In situ recovery
ISS	International Space Station
JISCARD	Japanese internet system for calculation of aviation route doses
LET	Linear energy transfer
LLRD	Long-lived radionuclide dust
LWGR	Light-water-cooled, graphite-moderated reactor
MDL	Minimum detectable level
NASA	National Aeronautics and Space Administration
NORM	Naturally occurring radioactive material

OECD/NEA	Organization for Economic Co-operation and Development/Nuclear Energy Agency
PCAIRE	Predictive code for aircrew radiation exposure
PRIS	Power Reactor Information System
PWR	Pressurized water reactor
RnP	Radon and its progeny
SPECT	Single-photon emission computed tomography
SI units	International System of units
UMEX	Information System on Uranium Mining Exposure
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organization
WLM	Working level month
WNA	World Nuclear Association

I. INTRODUCTION

1. Radiation exposure can occur as a result of occupational activities utilizing sources of ionizing radiation. It is incurred by workers using radiation or radioactive substances in industry, medicine, education and research. Occupational exposure can also occur from natural sources of radiation, e.g., crews exposed to cosmic radiation during air travel and space flights or workers in coal, uranium or other mineral mining exposed to radon and other natural radioactive substances. The average level of occupational exposure is generally similar to the global average level of natural radiation exposure, but some workers can receive exposure several times higher than this [U10].

2. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reviews the sources of occupational exposure and estimated distributions of individual annual effective doses and annual collective effective doses from occupational exposure in various industry sectors in accordance with the source types. It is of particular interest to examine the changes that have taken place over time with the introduction of improved practices, new technology, and revised regulations. Radiation sources and exposure estimates are, therefore, periodically reviewed and updated by the Committee to evaluate prevailing trends in occupational exposure and to identify new worker groups receiving significant radiation doses.

3. This annex supplements and updates previous UNSCEAR publications on occupational exposure [U2, U3, U4, U6, U8, U10]. Differences exist between countries in the procedures for monitoring and reporting occupational exposure; reflecting, for example, differences in regulatory requirements and practices. As a result, comparisons of data on doses are not always straightforward and may be somewhat limited in scope.

4. The outcome of the Committee’s assessments is the scientific basis for national and international organizations to evaluate the necessity for developing radiation protection standards, recommendations or guidance. The Committee’s assessments are used also by the relevant agencies of the United Nations system in formulating international safety standards for protection of the public and of workers against ionizing radiation; those standards, in turn, are linked to important legal and regulatory instruments in Member States. Governments and organizations throughout the world rely on the Committee’s assessments of the sources and effects of radiation as the scientific basis for estimating radiation risk, establishing radiation protection and safety standards and regulating radiation sources.

5. The analysis of worldwide occupational exposure presented in this annex is based primarily on data submitted by the United Nations Member States in response to the UNSCEAR Occupational Exposure Survey for the period 2003–2014. The survey is supplemented by data from peer-reviewed literature and reports from national competent authorities. Where appropriate, reference is made to summaries of earlier evaluations by the Committee for completeness and comparison.

6. In the current annex, the Committee has updated its evaluations of occupational exposure from natural and human-made sources of radiation. The annex is subdivided into sectors according to the types of exposure and sources. The subsectors associated with occupational exposure to natural sources of radiation included in the evaluation are: *(a)* radiation exposure of aircrew and space crew; *(b)* exposure in extractive and processing industries (mining of coal, of minerals other than coal and of uranium); *(c)* exposure from oil and natural gas extraction industry; and *(d)* radon exposure in workplaces other than mineral extraction industries. The subsectors associated with occupational exposure to human-made sources of radiation are: *(a)* exposure within the nuclear fuel cycle; *(b)* exposure due to medical uses of

radiation; *(c)* exposure due to industrial uses of radiation; *(d)* exposure for military purposes; and *(e)* exposure from miscellaneous uses of radiation, consisting of groups of exposed workers not included in the subsectors described previously. The current annex addresses veterinary medicine in the subsector on medical uses of radiation; previously, it was included in miscellaneous uses of radiation.

7. The Committee began collecting data on occupational exposure due to natural radiation sources in connection with the preparation of the UNSCEAR 2000 Report [U7, U8]. Until the implementation of the former International Basic Safety Standards (BSS) [I1] in the 1990s, most countries had not been particularly concerned with assessing occupational exposure to natural sources of radiation. Over the past two decades, exposure to enhanced levels of natural radiation has become a focus of attention for radiation protection. The European BSS [E2] and related guidance [E3] established requirements to evaluate the levels of occupational exposure to natural sources of radiation. The current international safety standards on radiation protection, such as the BSS [I12] and the European BSS [E8] further develop such recommendations and requirements and may influence the content and data collection for future UNSCEAR assessments of occupational exposure. Regarding data collection and compared to earlier evaluations, the Committee had expected and hoped for a greater response rate to the UNSCEAR Occupational Exposure Survey from United Nations Member States for periods evaluated in this annex.

8. The Committee's assessment of occupational exposure due to human-made sources of radiation includes exposure within the subsectors of nuclear fuel cycle, medical uses of radiation, industrial uses of radiation, uses of radiation sources for military purposes, and miscellaneous uses of radiation. The following information regarding the collection of data for the Committee's assessment of occupational exposure due to human-made sources of radiation should be noted:

- For the nuclear fuel cycle sector, the Committee requested data on occupational exposure for the same work activities evaluated in its previous reports: uranium mining and milling, uranium conversion and enrichment, fuel fabrication, reactor operation (permanent staff and contractors), spent fuel reprocessing, and research in the nuclear fuel cycle. In addition, data were also requested for the subsectors on decommissioning, management of radioactive waste and spent nuclear fuel, safety and safeguards inspections, and transport within the nuclear fuel cycle;
- For the medical sector, the identified work activities and division into subsectors are similar to those used in the previous evaluation [U10]. The Committee requested data on occupational exposure in diagnostic radiology (and separately for conventional and interventional diagnostic radiology), nuclear medicine, radiation therapy, dental practice, and veterinary medicine. The Committee also requested data for different work categories (physicians, nurses, technicians, and others) in most work subsectors in medical use of radiation;
- For the industrial sector, the Committee collected data and evaluated the level of occupational exposure in industrial irradiation, industrial radiography, luminizing, radioisotope production and distribution, well logging, accelerator operation, use of industrial gauges, and all other industrial uses of radiation. These are the same subsectors that were previously used;
- For the sector on military use of radiation sources, the Committee assessed available data on occupational exposure due to manufacture of weapons, the use of nuclear ships and their support facilities, and other relevant military activities (e.g., research, transport and non-destructive testing);
- For the miscellaneous sector, the Committee included use of radioactive material in educational establishments and research applications, management of disused radioactive sources from industrial activities, transport of radiation sources outside the nuclear fuel cycle, and other non-specified occupational groups.

A. Scope and objectives of analysis

9. The principal scope and objectives of this evaluation of occupational exposure remain, largely, as in the previous assessments of the Committee, as follows:

- To assess average annual effective doses to workers (both the average dose and the distribution of doses within the workforce) for each of the major work sectors and subsectors involving the use of ionizing radiation;
- To assess the average annual collective effective doses to workers for each of the major work sectors and subsectors involving the use of ionizing radiation;
- To estimate the worldwide level of occupational exposure for different sectors involving exposure to natural sources and to human-made sources of radiation;
- To identify and analyse temporal trends in occupational exposure in order to evaluate the effects of changes in regulatory standards or requirements, e.g., changes in dose limits, new technological developments and modified work practices;
- To identify possible new groups of workers receiving higher doses due to implementation of new techniques in applying radiation sources;
- To address the level of exposure to the lens of the eye;
- To identify research needs, and implications for future analysis of occupational exposure.

10. This analysis does not address occupational exposure due to radiological accidents (e.g., Chornobyl and Fukushima) as the Committee published dedicated evaluations on this topic, including occupational exposure aspects [U9, U11, U16].

B. Sources of occupational exposure to radiation

11. According to the International Labour Organization (ILO), the definition of occupational exposure to any hazardous agent includes all exposure incurred at work, regardless of source [I47]. The term *occupational exposure* is used in this annex to denote all radiation exposure incurred by workers in the course of their work, with the exception of: *(a)* exposure to the normal local natural background radiation; *(b)* exposure from exempt activities involving radiation or exempt sources; and *(c)* any medical exposure of patients [I29]. Occupational exposure is usually measured by individual monitoring; when this is not feasible, data from monitoring of the workplace are used to assign individual doses. The doses are usually assessed and recorded for radiation protection purposes by licensees and competent authorities. This annex uses two different categories of workers: *(a)* monitored workers, which refers to all workers subject to individual or workplace monitoring; and *(b)* measurably exposed workers, which refers to the workers who have received doses equal to or above the administratively established recording level used in the monitoring programme.

12. The International Commission on Radiological Protection (ICRP) and the International Atomic Energy Agency (IAEA) have previously distinguished between "practices", human activities that increase exposure or likelihood of exposure, and "interventions", actions that reduce exposure or likelihood of exposure [I1, I25]. However, since its Publication 103 [I29] published in 2007, ICRP has used a situation-based approach to characterize the circumstances where radiation exposure may occur as "planned", "emergency", and "existing" exposure situations. ICRP considers that it is appropriate to

limit the use of the term "intervention" to describe protective actions that reduce exposure, while the terms "emergency" and "existing" exposure situations should be used to describe radiological situations, where such protective actions to reduce exposure are needed [I29]. Although the term "practice" can still be and is used, especially in regulatory text and in the International BSS [I12] and European BSS [E2], to describe regulated sources within planned exposure situations, the Committee decided to avoid the term "practice" and replace it in this evaluation by work sectors. Occupational exposure occurs in the workplace as a result of exposure to external sources of radiation only, or as a result of a combination of exposure to external sources and of intake of radioactive substances (radionuclides) to the body by inhalation, ingestion or skin absorption. Some workplaces have a potential risk for external exposure only, others have potential risk for both types of exposure (internal and external).

13. Occupationally exposed workers, who have recognized rights and duties in relation to occupational radiation protection, are subject to controls established by the national regulatory authorities. To enable an assessment of their exposure, they are mostly monitored individually through a routine and continuing measurement programme, the alternative being workplace monitoring. A substantial number of workers, mostly those exposed to ionizing radiation, are not individually monitored. The exposure situations for these workers differ considerably with regard to such influences as the type of industry, conditions in the workplace, radionuclides involved and their physical and chemical forms. There are also workers who are not classified as occupationally exposed and are not subject to regulatory control; nonetheless, they are monitored for reassurance purposes. However, obtaining a comprehensive set of exposure data for such workers is difficult.

14. The criteria for selecting the workers to be monitored and for exposure to be recorded differ considerably between countries. Some regulatory authorities or operators/employers monitor only exposed workers while others, for various reasons, include non-exposed workers in their individual monitoring programmes. Also, countries use different approaches for recording doses and related exposure data. As demonstrated in table A.1 in the electronic attachment, some countries report that calculated radiation doses below the established minimum detectable level (MDL) are recorded, while others state that only doses above a certain defined level of exposure are registered. This may lead to bias and additional uncertainties in the results when comparing levels of exposure between different countries and sectors.

II. METHODOLOGY AND SOURCES OF DATA

A. Dose assessment methodology for occupational exposure

15. The principal dosimetric quantities in radiation protection as defined by the International Commission on Radiation Units and Measurements (ICRU) in its Report 51 are the following [I44]:

- Absorbed dose in a tissue or organ T, D_T, is defined as the mean energy absorbed per unit mass averaged over the entire tissue or organ. The International System of units (SI unit) for absorbed dose is joule per kilogram (J/kg) and its distinctive name is Gray (Gy);

- Equivalent dose in a tissue or organ T, H_T, is defined as the sum of the absorbed doses in that tissue or organ, weighted by the relevant radiation weighting factor, w_R, for each radiation type

R, $D_{T,R} \times w_R$. The radiation weighting factors reflect the higher biological effectiveness of charged particle radiation with high linear energy transfer (LET) per unit length as compared with low-LET radiation. Since w_R is dimensionless, the SI unit for the equivalent dose is the same as for the absorbed dose, J/kg, and its distinctive name is Sievert (Sv);

– Effective dose, *E,* is the tissue-weighted sum of the equivalent doses ($H_T \times w_T$) in all specified tissues and organs, T, of the body. The tissue weighting factor, w_T, is selected to represent the relative contribution of that tissue or organ to the health detriment in a reference population resulting from uniform irradiation of the body. The sum of the tissue weighting factors is 1. The unit for the effective dose is the same as for absorbed dose, J/kg, and its symbol is also Sv;

– Committed equivalent dose, $H_T(\tau)$, is the time integral of the equivalent dose rate in a particular tissue or organ that will be received by an individual following intake of radioactive material into the body by a *reference person*, where τ is the integration time in years. The committed period is taken to be 50 years for adults;

– Committed effective dose, $E(\tau)$, is the sum of the products of the committed organ or tissue equivalent doses and the appropriate weighting factors, w_T, that will be received by an individual following intake of radioactive material into the body by a *reference person*, where τ is the integration time in years, which is 50 years for adults.

16. The *reference person* referred to here is a hypothetical person for whom the organ or tissue equivalent doses are calculated by averaging the corresponding doses of the *reference male* and *reference female*. The equivalent doses of the *reference person* are used for the calculation of the effective dose by multiplying these doses by the corresponding tissue weighting factors [E11].

17. Operational quantities are used in practical application for monitoring and investigating situations involving external exposure. For area monitoring, two quantities: namely, the ambient dose equivalent, H^*(d), and the directional dose equivalent, H'(d, Ω), are used to assess the exposure to external radiation. The ambient dose equivalent, H^*(d), at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded field in the "ICRU sphere" at a depth, *d*, on the radius opposing the direction of the aligned field. The directional dose equivalent, H'(d, Ω), at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned field in the "ICRU sphere" at a depth, *d*, on the radius in a specified direction Ω. The personal dose equivalent $H_p(d)$ is the dose equivalent in soft tissue (commonly) interpreted as the sphere of 300 mm in diameter; at an appropriate depth, *d*, below a specific point on the human body. This point is usually given by the position where the individual's dosimeters are worn. The depth for $H^*(10)$ or $H_p(10)$, for monitoring of effective dose is 10 mm depth in soft tissue. The depth for $H'(0.07, \Omega)$ or $H_p(0.07)$, for monitoring of equivalent dose to local skin is 0.07 mm. The depth for $H'(3, \Omega)$ or $H_p(3)$, equivalent dose to the lens of the eye is 3 mm. The unit of ambient, directional dose equivalent and personal dose equivalent is J/kg, and its distinctive name is Sievert (Sv) [I44].

18. The basic quantity used herein to express radiation exposure is the effective dose. This derived quantity is developed for radiation protection purposes but cannot be directly measured. The Committee uses it to compare radiation doses in different work activities and exposure scenarios. An estimate of the effective dose, *E*, needs to take the contribution from external and also from internal exposure into account, as appropriate. *E* is usually reported in millisievert (mSv). It can be calculated from an annual dose using the following expression:

$$E = E_{\text{external}} + \Sigma e_{j,\text{inh}}(50).\, I_{j,\text{inh}} + \Sigma e_{j,\text{ing}}(50).\, I_{j,\text{ing}} \quad (1)$$

where $E_{external}$ is the effective dose due to external exposure received during a year (often the period of study), which is calculated on the basis of the operational quantity $H_p(10)$; $e_{j,inh}(50)$ — the committed effective dose per unit activity intake by inhalation of radionuclide *j*, integrated over 50 years; $I_{j,inh}$ is the activity intake of radionuclide *j* by inhalation during the year; $e_{j,ing}(50)$ is the committed effective dose per unit activity intake by ingestion of radionuclide *j*, integrated over 50 years; and $I_{j,ing}$ is the activity intake of radionuclide *j* by ingestion during the year. For most forms of intake, the dose coefficients provided by ICRP are for intakes by inhalation and ingestion and do not take account of uptakes through the skin although it is well known that such may occur. The ICRP occupational intake of radionuclides series has provided dose coefficients for injection of some radionuclides which could be used as a surrogate for rapid absorption through skin [I35] using a specific ICRP Data Viewer [I42]. However, these coefficients were published after the period selected for this evaluation.

1. Assessment of effective dose from exposure to external sources of radiation

19. For dose assessment of exposure to external sources of radiation, three operational quantities are used: *(a)* the ambient dose equivalent $H^*(10)$; *(b)* the directional dose equivalent $H'(d, \Omega)$; and *(c)* the personal dose equivalent $H_p(d)$ [I44]. Both the ambient and directional dose equivalent are applied to area monitoring, while the personal dose equivalent is reserved for individual monitoring of workers (via personal dosimeters worn on the body). The effective dose cannot be measured because of the computational values needed for each organ dose and the personal dose equivalent is used for estimation of the effective dose. For assessment of the radiation protection quantity *effective dose*, a depth d=10 mm is selected, and for assessment of the equivalent dose to the skin, hands, wrists, and feet, a depth d=0.07 mm is used. In special cases of monitoring, such as the dose to the lens of the eye, a depth d=3 mm is used. The SI unit for these three operational quantities are J/kg and the corresponding distinctive name is Sievert (Sv).

20. A factor that contributes to the uncertainty in the external dose assessment is the placement of the personal dosimeters. Most often, the dosimeter is placed on the front of the body, which is satisfactory provided that the dosimeters have been designed to measure $H_p(10)$. In radiology, where lead aprons are frequently used, various approaches have been adopted. In some cases, the assessment of effective doses to workers is carried out by means of a dosimeter worn on the trunk, under the apron. Where exposure is likely to be greater, for example in interventional radiology, two dosimeters are sometimes used, one placed under the apron and a second outside. The purpose of the second dosimeter is to assess the contribution to the effective dose due to the irradiation of unshielded parts of the body [N3]. When monitoring is intended to give only an upper estimate of an exposure, a single dosimeter is worn outside the apron. Understanding the placement of dosimeters, particularly with regard to protective aprons, is important to properly characterize the dose received and to minimize the uncertainties.

21. The IAEA conducted a survey covering cardiologists from 56 countries, which found that 76% of the studied interventional cardiologists stated that they always used their personal dosimeter (77% in developed countries and 70% in developing countries); and 45% of the interventional cardiologists stated that they always used two dosimeters (50% in developed countries and 24% in developing countries) [C12, I9]. The comparison of doses between countries is complex due to the lack of harmonization in how personal dosimeters should be used. Another study with cardiologists from 11 countries in Latin America showed that only 64% of the cardiologists used their personal dosimeters regularly, only 36% were aware of their personal dose values, only 41% used protective ceiling-suspended screens, only 14% had detailed knowledge of the X-ray system they were using and only 27% knew the quality control results [C13, V3, V4].

22. ICRU recommendations on the acceptable levels for total uncertainty in measured radiation doses in Reports 47 and 66 [I43, I45] are broadly consistent with similar statements made by ICRP. ICRU recommends that, for single measurements of the operational quantities, "in most cases, an overall uncertainty of one standard deviation of 30% should be acceptable". The error of instruments may substantially exceed this limit at some energies and for certain angles of incidence but conform to it when they occur in a radiation field with a broad energy spectrum and broad angular distribution [I43, I45].

23. A distinction should be recognized between the accuracy of a measurement with a dosimeter under laboratory conditions in a well-known radiation field and that of a measurement in the workplace [A14, V1, V2]. The EC Radiation Protection 160 report [E7] recommends that, for a measurement of the operational quantity $H_p(10)$ for a single field component and for a quantity value equal to or greater than 1 mSv (equals the recommended annual effective dose (E) limit for the members of the public) in proportion to the wear period, the combined uncertainty should be less than 30% for photon/electron workplace fields and less than 50% for neutron fields. From considerations of the response characteristics of neutron personal dosimeters currently used, and from the results of intercomparisons, there are difficulties meeting a 30% combined uncertainty criterion for whole body doses from neutrons. Even with a relaxation of the criterion to 50%, it is not possible with any current design of neutron dosimeters to meet the criterion over the full range of neutron energies possibly present in the workplace [E7].

2. Assessment of effective dose from cosmic radiation

24. Aircrew personnel are exposed to primary and secondary fields of cosmic radiation in the atmosphere, which are very complex in terms of particle composition and energies. The various components of the cosmic radiation field have been thoroughly discussed in the UNSCEAR 2008 Report [U10]. Individual monitoring by measurement is impractical, as instruments that can assess the entire spectrum of the radiation field considerably exceed the size and weight of ordinary personal dosimeters. As a consequence, aircrew dose, in terms of effective dose, E, is calculated by means of computer programs, thus following the recommendations of ICRP Publication 132 [I37]. This approach is feasible, since the radiation field at aircraft locations is accurately calculated, except in extremely rare cases of sudden increases of intensity and energy due to solar particle events, which can lead to much higher doses. Solar particle events and the associated doses are of concern to space crews operating outside the earth's protecting atmosphere. Individual monitoring of aircrew personnel based on computer programs relies on knowledge of geographic location (latitude/longitude), flight altitude, solar cycle phase, and pilot and aircrew information. Software codes are generally validated by comparing the calculated values of E with the measured values of the operational quantity ambient dose equivalent $H^*(10)$. The agreement between calculated and measured values should be within ±30% at a 95% confidence level, as recommended by ICRU [I43, I45].

3. Assessment of effective dose for radionuclide intake

25. In its UNSCEAR 2008 Report [U10], the Committee provided a detailed overview of effective dose assessment for intakes of radionuclides, on which the most recent ICRP recommendations were published in ICRP Publication 103 [I29]. However, the release of a set of companion publications for occupational intakes of radionuclides are started in ICRP Publications 130, 134, 137 and 141 [I35, I36, I38, I40]. The revised dose coefficients were calculated using the human alimentary tract model [I28] and a revision of the human respiratory tract model that takes account of more recent physiological data [I35]. In addition, information is provided on absorption into blood following inhalation and ingestion of different chemical

forms of elements and their radioisotopes [I33, I35, I36]. The most recent ICRP recommendations were, however, not applied in 2003–2014, the period of data collection for the current assessment. The reported effective doses provided in the current evaluation were calculated on the basis of earlier methodologies for calculating doses due to intakes of radionuclides as provided in ICRP Publications 26 and 60 and the publications under their umbrella [I24, I25].

4. Assessment of effective dose for radon inhalation

26. As early as 1988, the International Agency for Research on Cancer (IARC) classified radon as a proven human carcinogen because studies of miners occupationally exposed to radon were noted to provide a direct basis for assessing lung cancer risk to miners [I22]. The Committee also concluded that inhaled radon and its progeny have been established as carcinogens for the lung in several comprehensive evaluations [U7, U9, U14].

27. In line with the International BSS recommendations [I12], employers are required to ensure that the activity concentrations of radon in workplaces are below a suitable reference level, and that protection is optimized. This reference level should not be set higher than 1,000 Bq/m^3. It is, therefore, often the case that annual effective dose data for exposure to radon are available only if at workplaces the radon concentrations in air exceed 1,000 Bq/m^3 for 2,000 working hours in a year.

28. The health risk due to exposure to radon comes mainly from the inhalation of its short-lived decay products and the resulting alpha particle irradiation of the bronchial airways. The radiation dose delivered to the respiratory system and the resulting potential health detriment are a complex function of the radon decay products' aerosol characteristics and the physiological parameters of the exposed individual [H4, I27, I35, I46, U7, U9, W4]. Quantities and units used for the assessment of effective dose resulting from inhalation of radon and its progeny are given in UNSCEAR reports [U9, U10, U14].

29. There are several workplaces where doses from radon can be high enough to justify monitoring or protective action (e.g., in mining, mineral processing) and in some underground and above-ground workplaces (e.g., show caves, spas, underground laboratories or stores, water treatment plants, storage facilities or even some office buildings and schools).

30. For workers in mining (especially uranium mining) and mineral processing, radiation exposure is normally under regulatory control. Most regulatory bodies follow the radiation protection recommendations of ICRP. For radon exposure, ICRP Publication 65 adopted the dose conversion factor of 5 mSv per working level month (WLM) (1 WLM = 6.38×10^5 h Bq/m^3 EEC) [I26]. ICRP recently revised the dose conversion factor to 12 mSv per WLM for mines, 20 mSv per WLM for an indoor workplace and 24 mSv per WLM for a tourist cave [I38]. However, these new conversion factors were not implemented for the review period analysed in this assessment.

31. For workplaces other than mines, most workers exposed to radon are not monitored. In the literature, many radon measurements taken in these workplaces are reported. The majority of the studies have measured radon gas concentrations in units of Bq/m^3, and subsequently assessed radon doses to workers by using the UNSCEAR dose conversion factor of 9 nSv per (h Bq/m^3), assuming the total annual working hours ($\leq$2,000 hours) and a radon equilibrium factor (typically F=0.4). Because several different dose conversion factors are available, the UNSCEAR Occupational Exposure Survey has requested the participating Member States to specify the dose conversion factor used in their calculations (adopted in their country).

32. For the purpose of evaluating average effective doses from radon inhalation by public and worker, the Committee adopted a dose conversion coefficient of 9 nSv per (h Bq/m^3) in 1982 [U4]. This value was retained by the Committee in its assessments [U8, U9, U10]. Recently, the Committee reviewed epidemiological studies of lung cancer risk from radon exposure published since 2006 [U14]. The evidence reviewed by the Committee is compatible with its previous dose assessments of lung cancer risk due to radon exposure and it concluded that there was no reason to change the established dose conversion factor for its dose assessments.

5. Assessment of doses to lens of eye

33. In the past couple of decades, new and relevant information has appeared regarding the understanding of the radiation risk of cataract formation. As a result, in its Publication 118 [I32], ICRP revised the former threshold for tissue reactions of the lens of the eye and reduced it from 1.5 to 0.5 Gy. The recommended annual equivalent dose limit for the lens of the eye for occupational exposure in planned exposure situations was reduced from 150 to 20 mSv averaged over five consecutive years and 50 mSv in any single year. The development of sensitive methods for monitoring eye exposure has thus become increasingly important. To assist in computational assessments of radiation dose to the lens of the eye for exposed persons, ICRP Publication 116 [I30] provides approved reference data on conversion coefficients for the lens of the eye for estimating the absorbed dose to the lens. These new ICRP conversion coefficients were, however, not applied in 2003–2014, the period of data collection for the Committee's assessment presented in this annex.

34. ICRP, in Publication 139 [I39], describes the challenges in monitoring the exposure of the lens of the eye. The difficulties in placing a device to which the dosimeter can be attached near the eyes are the main challenge. While the quantity $H_p(3)$ has been used or proposed for control and evaluating the dose to the lens of the eye in relation to the ICRP dose limits, few physical dosimeters have been constructed/calibrated to assess these operational quantities properly for d=3 mm. In principle, the reading of a dosimeter over the apron at collar level is a reasonable indicator of the dose to the lens of the eye when protective glasses are not worn, but when protective glasses are used, the collar dosimeter may grossly overestimate the dose to the lens of the eye [D7, I10, R3, S5, V5]. In addition, with the significant uncertainties involved in the dosimetry of the lens of the eye and the fact that actual doses to the lens of the eye may be of the same order as the annual equivalent dose limit to the lens of the eye, the important task of assessing compliance with the annual equivalent dose limit has become a challenge [I30, I34, I39, N5].

35. An intercomparison exercise dedicated to lens of the eye dosimeters used in medical practice gave an overview of the different dosimetric systems currently available in Europe for lens of the eye dose monitoring [C13]. The observed results were satisfactory overall since, among the 20 participant countries, 17 were able to provide 90% of their responses in accordance with the standard requirements of the International Organization for Standardization (ISO) [I50]. For a minority of participants, some discrepancies compared with the reference doses were observed for irradiation set-ups characterized by large angles and/or low energies. Some improvements could be achieved by applying calibration of the devices used [C13].

B. Dose recording

36. In order to ensure the reliability of dose assessments, some countries have implemented systems to authorize monitoring services based on a set of requirements established by the national regulatory

authority, while others apply criteria based on the quality management system for accrediting individual monitoring services. In most countries, dose reporting and recording are regulated by national laws or norms and may differ for various categories of workers depending on their exposure. The IAEA, in its publications [I2, I3, I4] and more recently [I15], has provided guidelines for how monitoring data and results are to be reported, which dose levels are to be recorded, and which documents and records of radiation exposure are to be maintained.

37. Despite guidelines for dose recording, variations from country to country may significantly affect the reported values of average annual collective effective dose. This will increase the uncertainty in comparisons between data compiled in different countries. The approaches used in measuring and reporting occupational exposure in each country for which data were reported are summarized in table A.1 in the electronic attachment. If major differences in used approaches are obvious, caution should be exercised when directly comparing data. The main differences arise because of the following factors:

- The protocol for determining whom in the workforce should be monitored and for whom doses should be recorded in specific categories;
- The recording level used;
- The recording of dose values less than recording level or the minimum detection limit (MDL);
- The techniques used for measurement of external radiation exposure (e.g., thermoluminescence dosimeter or optically stimulated luminescence dosimeter);
- The approach adopted to fill missing monitoring periods in the records;
- The evaluation of anomalous results, such as unexpectedly high dose values;
- Whether or not internal exposure is included or treated separately;
- Whether natural background is subtracted from the recorded dose;
- The reliability of the individual monitoring data.

C. Dose distribution

38. The dose distributions presented in this annex follow the same approach as the ones used in previous UNSCEAR reports [U8, U10]. For the purpose of comparing dose distributions and of evaluating trends, three characteristics of dose distributions were identified as being particularly useful: *(a)* the average annual effective dose (*E*); *(b)* the average annual collective effective dose (*S*); and *(c)* the average annual collective effective dose distribution ratio for certain doses (SR_E) [U10], which is given by:

$$SR_{\mathrm{E}} = \frac{S(>E)}{S} \quad (2)$$

where *S(>E)* is the average annual collective effective dose delivered at annual individual doses that exceed *E* (mSv).

Similarly, the distribution ratio for the number of exposed workers for certain doses (NR_E) is given by:

$$NR_{\mathrm{E}} = \frac{N(>E)}{N} \quad (3)$$

where *N* is the total number of workers, *N(>E)* is the number of workers receiving annual doses exceeding *E* (mSv).

D. Sources of data

1. Literature review

39. A comprehensive database search of published literature related to occupational exposure was conducted, covering the period 2003–2017, with inclusion of additional relevant recent articles and reports. Pre-screening sought to identify publications that might demonstrate changes of trends and updates in work sectors since the UNSCEAR 2008 Report [U10]. Publications were deemed suitable for pre-screening if there was a match on one or more of the following search terms: "ionizing radiation and occupational exposure or radiation exposure"; "radiation worker" and "occupational exposure". A more detailed search was conducted for six broad sectors identified for occupational exposure (natural sources, nuclear fuel cycle, medical uses, industrial uses, military activities and miscellaneous use of ionizing radiation). This process was followed by screening and evaluation of the relevant literature from 2003 onwards through the PubMed and ScienceDirect databases, including studies and reports provided by international or governmental organizations. About 700 articles and reports were identified for review, of which about 50% were assessed as meeting the selection criteria following the UNSCEAR 2017 Report, annex A [U13].

2. UNSCEAR Occupational Exposure Survey

40. The purpose of the Committee's current evaluation of worldwide occupational exposure is to provide more detailed and updated information on exposure to ionizing radiation related to different work activities, e.g., to identify job functions and categories of work within each practice that lead to more relevant exposure, to identify the contributions of external versus internal exposure to the total effective dose, and to obtain information about the reliability of measurements associated with the accreditation or authorization of monitoring services.

41. The current evaluation is based on data from the UNSCEAR Occupational Exposure Survey, launched in 2016 and completed in 2019. The evaluation follows the same procedure as that for former evaluations: a formal request to all Member States of the United Nations for data to be submitted via the UNSCEAR online platform. Two questionnaires were prepared for the survey, a simplified and a detailed questionnaire. In the simplified questionnaire, essential data on the number of workers and the average annual effective dose for each work sector, subsector, work category and subcategory were requested. The detailed questionnaire requested data on the number of monitored workers, average annual effective dose for all monitored workers, average annual collective effective dose and dose distribution for the period 2003–2014. In order to be able to perform a more detailed analysis of the data, some additional information was also requested. The data obtained by the questionnaires were supplemented by data from the literature review and also data obtained from other international organizations. By September 2019, a total of 57 Member States had responded to the simplified questionnaire, providing data on numbers of workers in different work sectors. Forty-four countries responded to the detailed questionnaire, providing data on numbers of workers along with average annual effective doses and/or average annual collective effective doses. The list of countries responded to the UNSCEAR Occupational Exposure Survey is presented in table A.2 in the electronic attachment and the list of national contact persons in the acknowledgement.

42. The detailed questionnaire was designed in such a way that it could be answered by countries with either a limited national database or with a comprehensive national database. It comprises:

- *Basic questions*: value of MDL, value of recording level, information about accreditation/ authorization of dosimetry services; number of monitored workers; number of measurably exposed workers; average annual effective dose for all monitored workers; average annual effective dose for measurably exposed workers; dose distribution for the effective dose intervals: *E*<MDL; MDL–1; 1–5; 5–10; 10–15; 15–20; 20–30; 30–50; *E*>50 in mSv; average annual collective effective dose for each subsector or worker category;

- *Detailed questions*: for work sectors, subsectors and work categories and subcategories, the contribution made by internal (inhalation of radon and its progeny and intakes of other radionuclides) and external dose to the total effective dose and also the factor used to convert radon exposure to effective dose; percentage of females in the workforce; and doses to the lens of the eye and hands, when appropriate. Also, where possible, occupational data by work category were requested for some medical subsectors.

43. The simplified questionnaire was designed to obtain essential data from countries not prepared to respond to the detailed questionnaire. The questionnaire also asked for data on average annual effective dose and its standard deviation, and the uncertainty in the number of workers expressed as a percentage. Additional data were requested about the availability of the national dose register database for radiation dose records; the annual dose limit for effective dose adopted by the country; the recording dose; the value of MDL in mSv per measurement interval and the recorded dose quantity (*E* or $H_p(10)$). The mandatory requested data were the number of workers involved in each subsector.

44. The 44 countries that responded to the detailed UNSCEAR Occupational Exposure Survey and provided additional methodology information had external dose monitoring services available. About 68% of these had internal monitoring in operation. About 80% of the countries had a central occupational dose register.

E. Estimation of worldwide levels of exposure

45. The worldwide annual number of monitored workers, the worldwide average annual collective effective dose and the worldwide average annual effective dose were estimated for most of the sectors of occupational exposure, including natural and human-made sources of radiation. The determination of the number of monitored workers and the average annual effective dose per worker in all sectors could not be derived directly from data obtained from the UNSCEAR Occupational Exposure Survey because of lacking information. Moreover, not all State members of the Committee provided data for the current assessment. Where collected data were not sufficient to derive quantitative estimates, regression-based models were derived for the association between the annual number of workers or average annual effective dose and available predictor variables. These models were then used to estimate (extrapolate) the number of workers or the average annual effective dose for countries where no reported data except for predictor variables were available. Table 1 presents a list of predictor variables used in this assessment.

46. The quality of the Committee’s global evaluations of occupational exposure depended on the availability of samples of representative data and on the quality of the data collected from the countries surveyed. In addition, the use of extrapolation models necessarily introduced uncertainty and potential bias to the estimates because the methods were limited to statistically derived predictions using only the available data, but with limited knowledge of their adequacy, precision, and representativeness. The overriding limitation was the low rate of participation by United Nations Member States in providing occupational exposure monitoring data.

Table 1. Predictor variables by sector and subsector used in the UNSCEAR extrapolation models

Sector	*Subsector*	*Job category*	*Predictor variables*
NATURAL SOURCES OF RADIATION			
Coal extraction and processing			Average total primary coal production for each period
Mineral other than fuel mineral extraction and processing			Average annual total mineral other than fuel mineral production for each period
Oil and gas extraction			Average total petroleum production for each period, annual GDP for each period
HUMAN-MADE SOURCES OF RADIATION			
Nuclear fuel cycle	Uranium mining and milling		Average total of extracted ore for each period
	Reactor operation		Average energy generated per type of reactor for each period
	Fuel fabrication		
	Other subsectors		No predictor parameter used
Medical	Diagnostic radiology	Physicians	Annual GDP, physician density, computer tomograph density, and gamma camera or nuclear medicine unit density within a period. Other medical parameters should be used (i.e., interventional radiology systems density), but data not available worldwide
		Nurses	
		Technicians	
		Other jobs	
		Combined job categories	
	Conventional radiology	Physicians	Same predictor variables as applied in diagnostic radiology
		Nurses	
		Technicians	
		Other jobs	
		Combined job categories	
	Interventional radiology	Physicians	Same predictor variables as applied in diagnostic radiology
		Nurses	
		Technicians	
		Other jobs	
		Combined job categories	
	Nuclear medicine	Physicians	Same predictor variables as applied in diagnostic radiology
		Nurses	
		Technicians	
		Other jobs	
		Combined job categories	

Sector	*Subsector*	*Job category*	*Predictor variables*
	Radiation therapy	Physicians	Same predictor variables as applied in diagnostic radiology
		Nurses	
		Technicians	
		Other jobs	
		Combined job categories	
	Dental radiology		Same predictor variables as applied in diagnostic radiology
	Veterinary medicine		Same predictor variables as applied in diagnostic radiology
	Other medical uses		
Industrial	Industrial irradiation		Annual GDP for each period and number of irradiators or sterilization facilities for industrial irradiation
	Industrial radiography		Annual GDP for each period and average annual petroleum production
	Luminizing		Annual GDP for each period
	Radioisotope production and distribution		Annual GDP for each period and number of research reactors
	Well logging		Annual GDP for each period and average annual petroleum production
	Accelerator operation		Annual GDP for each period
	Industrial gauges		Annual GDP for each period and average annual petroleum coal and other mineral production
	Other industrial uses		Annual GDP for each period
Miscellaneous	Educational establishments		Annual GDP for each period and number of research reactors
	Disused radioactive sources		Annual GDP for each period
	Transport of radiation sources outside the nuclear fuel cycle		
	Other occupational groups		

47. Ideally, information on national practices and the sophistication of local radiation protection could be used to predict unknown values for the number of monitored workers and the average annual effective dose (or, alternatively, the national average annual collective effective dose). However, for occupational exposure to radiation from sectors other than the nuclear fuel cycle, summaries of the national practices were not readily available. A variety of approaches were possible for extrapolation (e.g., scaling by population size, by employment rates in industrial or medical sectors). Until now, the Committee has based its approach on presumed proportionality to the average gross domestic product (GDP) over a

specified time interval [U6, U8, U10]. Several considerations have influenced the choice of this quantity in preference to others, notably the availability of reliable worldwide statistics on GDPs and their potential for general application; the latter because a GDP can be reasonably correlated with a country's level of industrial activity and of medical care, characteristics unlikely to be reflected in any other single quantity. To make the extrapolation more reliable, it should be applied not globally but separately by country or within geographic regions, economic regions or economic classes, followed by summation over those groups. Such a strategy would result in extrapolations of available data within groups of countries with broadly similar levels of economic activity and would allow for general geographical comparisons. However, the poor participation of many countries—in particular, those in low economic classes—in the UNSCEAR Occupational Exposure Survey, necessitated extrapolations to be made globally rather than within economic classes, which might have afforded better precision.

48. Notwithstanding the problems of sparse data encountered in this evaluation, some improvement in extrapolation has been expected due to the use of multiple predictors (table 1). For example, for the medical sector, the predictors used were the GDP per capita (GDP at current prices in USD [U1]) in each year within each period and other likely correlated variables (when available), e.g., the physician density (number of physicians per 1,000 persons), computed tomographs (number of computer tomographs per million persons), and gamma camera or nuclear medicine unit density (number of nuclear medicine machines per million persons). As discussed below, some improvements are also expected as a result of using statistical modelling techniques in which the best fit model was selected from a range of alternative models.

1. Methodology of extrapolation and uncertainty assessment

49. The intermediate goals for estimating the total number of workers worldwide in all sectors and the worldwide average annual effective dose over all sectors were to estimate the number of monitored workers in each subsector in each country and the average annual effective dose within each occupational subsector in each country. However, estimates of the average annual effective dose and the number of workers were available only from a small fraction of the world's countries, particularly those of higher economic status. Because estimates were not available from many countries, strategies were devised to extrapolate the data from those countries providing data to those not providing data, so that a worldwide estimate of the average annual effective dose (within a subsector), and a worldwide estimate of the total number of workers (in the same subsector) could be derived. Because extrapolation was involved, a strategy for assessing the uncertainty was also developed so as to give approximate confidence bounds of the estimates.

50. For the present evaluation, a number of assumptions were made in order to develop a strategy that could be applied systematically within and across the occupational work subsectors. First, it was assumed that the reported values from the countries were average values, but not absolutely precise, i.e., the true value was uncertain. Second, it was assumed that the values submitted by each country reporting data were equally likely to be greater or smaller than the true average value. This assumption implied that the values provided by each country were approximately the 50th percentile of a distribution of the uncertainty on the true average value. Third, the distribution of uncertainty around the reported average value was assumed to be a right-skewed so that the lower bound of the uncertainty distribution would not be less than zero. For convenience, the distribution of uncertainty around the estimate was assumed as log-normal implying that the reported average value was also approximately equal to the median or geometric mean of the uncertainty distribution.

51. Because the data sets that were used in each country to derive their reported values were not available, there was no means to estimate the precision of each reported value. Hence, a decision was

made to subjectively characterize the uncertainty of the reported values to be within 15% of the true value (at the one-sigma confidence level). For a log-normal distribution, this level of uncertainty translates to a geometric standard deviation (GSD) of the uncertainty distribution of about 1.15.

52. For those countries not reporting any data, a strategy was necessary to estimate, i.e., extrapolate, a value from data reported from countries with data, and to estimate the uncertainty of the extrapolated values. To extrapolate values for countries not reporting data, a strategy based on regression models that could be used for predictive purposes was developed. Because of computational difficulties in using the results of individual model fittings to estimate the uncertainty of each extrapolated value, a decision was made to subjectively estimate the uncertainty of each extrapolated value to be ±40% of the true value (at the one-sigma confidence level). For a log-normal distribution, this level of uncertainty translates to a GSD of the uncertainty distribution of about 1.4.

53. In summary, an uncertainty of each country's estimate of average annual effective dose and the number of workers, in the form of a GSD, was subjectively assigned to be 1.15 for countries that reported data, and to be 1.4 for the estimates from countries for which an extrapolation model to make estimates was used.

54. The extrapolation models to estimate the average annual effective dose and the number of workers for countries not reporting data were derived using the reported data for model development. The modelling approach was to use available covariate data such as GDP and other variables presented in table 1 for the countries that reported values to develop multivariate regression equations that could be used for predictive purposes. Using the derived model and the covariate data from each country not reporting data, values of the average annual effective dose and the number of workers could be estimated for those countries not reporting.

55. The form of the multivariate extrapolation model was:

$$Y = \beta_0 + \beta_1 z_1 + \beta_2 z_2 + \beta_3 z_3 + \beta_4 z_4 + \epsilon \quad (4)$$

where Y was either the number of monitored workers in a specific country or the average annual effective dose in that country, β_0 was the intercept and β_l the fitted regression coefficients, and ϵ was the error vector for the four predictor variables. The z_l values were the parameters for fitting, e.g., GDP in a specific year as presented in table 1 for a listing of predictor variables for each occupational subsector.

56. In this work, stepwise multivariate linear regression was used to fit predictive models with various combinations of covariates. To prevent over-fitting, the maximum number of predictor variables allowed was four but could also be fewer, depending on the data available (table 1). Although other statistical techniques besides linear regression, e.g., Poisson regression, could theoretically be used and might be preferred, linear regression of the reported values was used for reasons of simplicity and transparency. To ensure consistent results with Poisson regression models, predicted values from the linear regression models, when negative (i.e., physically impossible values), were set equal to zero.

57. The extrapolation models were applied to each country not providing data as a means for predicting the number of workers and the average annual effective dose for that country. While the model development process resulted in several possible models, each was based on slightly different combinations of the available covariate data. The model chosen for use was the one with the largest adjusted coefficient of correlation (R^2) where the "adjustment" was the standard statistical implementation to account for the number of predictor variables.

58. While development of extrapolation models was originally intended for both *(a)* the number of workers and *(b)* the average annual effective dose, model derivation efforts indicated that the available

covariate data were unsatisfactory for predicting the average annual effective dose, i.e., the adjusted R^2 values of the prediction models for average annual effective dose were too low for the models to be reliable. Hence, the regression-based extrapolation models were used only for estimating the number of workers in countries that did not report data, but not for the average annual effective dose, which required a different strategy, as described in the paragraphs below.

59. Extensive fitting models for the number of workers showed that models for individual occupational subsectors either fit relatively well (adjusted $R^2>0.7$) or very poorly (adjusted $R^2<0.1$). For this reason, the extrapolation of the number of workers was conducted only for those subsectors for which the derived extrapolation models had adjusted $R^2\geq 0.7$. Fortunately, those subsectors for which adequate models could not be developed are known to be relatively small contributors to the worldwide workforce. The occupational subsectors where the extrapolation models were not deemed to be reliable included oil and gas extraction, radioactive waste management, transport within the nuclear fuel cycle, safety and safeguards inspections, the "other categories" of the nuclear fuel sector, veterinary medicine, military uses, disused radioactive sources, transport of radiation sources outside nuclear fuel cycle, and other occupational groups.

60. While the worldwide total number of workers is probably underestimated because extrapolation models for some subsectors could not be developed, the underestimation does not appear to be large because those subsectors are known to have far fewer workers. The derived uncertainty interval, described in a later section, attempts to account for any underestimation.

61. The regression-based modelling procedure allowed for an estimation of the number of workers for each country within each participating occupational subsector. To achieve the goal of estimating the worldwide total number of workers in each subsector, the country-specific estimates of the number of workers (determined either as a reported value or an extrapolated value) were simply summed:

$$N_{\mathrm{T}} = \sum_{i=1}^{n} N_i \qquad (5)$$

where N_{T} is the worldwide total number of workers in a single occupational sector, N_{i} is the reported or extrapolated number in country i, and n is the number of countries worldwide that conducted the particular occupational subsector.

62. The total uncertainty on the worldwide number of workers, expressed as a GSD, was determined as a weighted average of the country-specific GSD values over all countries participating in the subsector:

$$GSD_{\mathrm{NT}} = \exp\left(\sqrt{\sum_{i=1}^{n}[ln(GSD_i)^2 \times w_i]}\right) \qquad (6)$$

where GSD_{NT} is the total GSD for the estimated number of workers for all countries participating in the subsector, n is the number of countries with workers in the particular subsector, and the weighting factor w_i for each country i, was determined as the fraction of the total worldwide number of workers (N_{T}) in the subsector contributed by country i, i.e., $w_i = N_i/N_T$. As noted, the GSD values used in the summation were assumed as 1.15 for countries providing data, and 1.4 for the countries for which, in assigning a value, model extrapolation was necessary.

63. Extrapolation models for the average annual effective dose required a different strategy because the regression-based models were found not to be satisfactory due to an absence of correlations between available covariate data and the reported average annual effective doses. Hence, for this purpose, the

average annual effective dose was based solely on a weighted average of the estimates from the subset of countries providing data on dose per worker (within each occupational subsector) with weighting factors equal to the fraction of the workers from each country participating in the subsector:

$$D_{\mathrm{w}} = \sum_{i=1}^{n} D_{w,i} \times w_{E,i} \tag{7}$$

where D_w is the estimate of the worldwide average annual effective dose (for a given subsector), n is the number of countries responding to the UNSCEAR Occupational Exposure Survey for the subsector, $D_{w,i}$ is the reported average annual effective dose in country i, and $w_{\mathrm{E},i}$ is the weighting factor for each country i, determined as the fraction of the total number of workers from countries providing values of average annual effective dose (N_{TE}) contributed by country i, i.e., $w_{E,i} = N_i/N_{TE}$.

64. One acknowledged weakness of this method is that some countries were not represented in the weighted average because they had not reported an average annual effective dose for workers and because no suitable extrapolation model for the dose per worker could be derived. However, as described below, the derived uncertainty interval attempts to allow for that possible underestimation.

65. Here, the overall GSD of the average annual effective dose was derived as a weighted average of the GSD for all countries, including those countries for which no estimates could be made, i.e.:

$$GSD_{\mathrm{E}} = \exp\left(\sqrt{\sum_{i=1}^{n} [ln(GSD_i)^2 \times w_i]}\right) \tag{8}$$

where GSD_{E} is the uncertainty for the average annual effective dose considering for all the world's countries participating in the subsector, and n is the total number of countries with workers in the particular subsector regardless if extrapolation estimates were possible for the country. As described above, for the estimation of average annual effective dose, the *GSD*-value for countries providing data was assumed as 1.15, and 1.4 for the countries for which no extrapolation could be made. The weighting factor w_i for each country i, was determined as the fraction of the total worldwide number of workers (N_{T}) contributed by country i, i.e., $w_i = N_i/N_T$.

66. While the described strategy to estimate the uncertainty on the worldwide total number of workers is only an approximation, it is worthy to note that the method attempts to derive a subjective confidence interval to account for the possible underestimation of the number of workers. While the estimate of the worldwide average annual effective dose was based on a weighted average of data from countries reporting data, the uncertainty (expressed as a GSD) was based on a weighted average of all countries. The GSD derived by considering all countries, including those for which no extrapolation could be made, contributed to a more realistic uncertainty estimate that attempts to account for any underestimation.

67. To interpret the derived uncertainty for the worldwide estimates for number of workers and for average annual effective dose, the overall (worldwide) GSD for each of the two estimated quantities was used to derive an interval or range in which the true value was expected to lie — on the basis of the available information and the extrapolation strategy described. The interval, consistent with log-normal theory, was derived with the lower bound equal to the ratio of the estimate and the squared GSD (estimate divided by GSD^2) and an upper bound equal to the product of the estimate and the squared GSD (estimate times the GSD^2). Under the assumption that the uncertainty distribution is log-normal, this interval would encompass approximately 95% of the range in which the true value would be expected to lie. Here we refer to this interval as a "subjective confidence interval".

68. The worldwide number of workers was estimated as a sum of the number of workers in all subsectors:

$$N_{\text{WN}} = \sum_{i=1}^{s} N_i \tag{9}$$

where N_{WN} is the worldwide number of workers, N_i is the number of workers in subsector i, and s is the number of subsectors.

69. The uncertainty on the worldwide number of workers across all subsectors, expressed as a GSD, was determined as a weighted average of the subsector-specific GSD values:

$$GSD_{\text{WN}} = \exp\left(\sqrt{\sum_{i=1}^{s}[ln(GSD_i)^2 \times w_i]}\right) \tag{10}$$

where GSD_{WN} is the worldwide GSD for the estimated number of workers over all countries and all subsectors, s is the number of subsectors, and the weighting factor w_i for each subsector i, was determined as the fraction of the total worldwide number of workers (N_{WN}) in the subsector i.

70. The worldwide average annual effective dose over all countries and all subsectors was estimated as the average value weighted by the number of workers in each subsector:

$$D_{\text{WE}} = \sum_{i=1}^{s} D_{WS,i} \times w_{S,i} \tag{11}$$

where D_{WE} is the estimate of the worldwide average annual effective dose over all countries and all subsectors, s is the number of countries responding to the UNSCEAR Occupational Exposure Survey for the subsector, $D_{WS,i}$ is the average annual effective dose in subsector i, and $w_{S,i}$ is the weighting factor for each subsector i, determined as the fraction of the total number of workers in each subsector.

71. The uncertainty on the worldwide average annual effective dose across all subsectors, expressed as a GSD, was determined as a weighted average of the subsector-specific GSD values:

$$GSD_{D_W} = \exp\left(\sqrt{\sum_{i=1}^{s}[\ln{(GSD_i)}^2 \times w_i]}\right) \tag{12}$$

where GSD_{Dw} is the GSD for the worldwide average annual effective dose across all countries and all subsectors, s is the number of subsectors, and the weighting factor w_i for each subsector i, was determined as the fraction of the total worldwide number of workers (N_{WN}) in the subsector i.

2. Practical implementation of model and uncertainty estimation

72. The worldwide level of occupational exposure from natural sources was estimated for civilian aviation, coal extraction and processing, and minerals other than fuel minerals. For civilian aviation, the extrapolation was not needed for number of workers since the International Civil Aviation Organization (ICAO) provided the data for the countries that did not respond to the UNSCEAR Occupational Exposure Survey; the average annual effective dose is weighted by the number of workers. For coal extraction and processing, the extrapolation of number of workers was based on the linear regression model applying the average annual total primary coal production for each period as an independent variable; the average

annual effective dose is weighted by the number of workers. For mineral other than fuel mineral extraction and processing, the extrapolation of number of workers was based on the linear regression model applying the average annual mineral other than fuel mineral production for each period as an independent variable; the average annual effective dose is weighted by the number of workers. However, the worldwide level of occupational exposure for gas and oil extraction could not be derived because of lack of correlation between dependent variables and the independent variables applied in the linear regression model, which are GDP and petroleum production. The same was true for radon exposure in workplaces other than mines; the complexity of the subject along with the lack of data did not allow an extrapolation for this work sector.

73. Five sectors are associated with human-made sources of radiation: *(a)* nuclear fuel cycle; *(b)* medical; *(c)* industrial; *(d)* military; and *(e)* miscellaneous groups of workers not included in the sectors described previously. The predictor variables used to extrapolate the dependent variables are presented in table 1. An updated evaluation for exposure to human-made sources of radiation for military uses was not conducted because of lack of data.

74. Limitations of methodology as implemented are summarized below:

- The representativeness of the countries was evaluated on the basis of the World Bank classification of the world's economies. There are four income groups: high, upper-middle, lower-middle and low income used in this evaluation. The assignment of each country is based on gross national income (GNI) per capita (currency: USD). The updated threshold for each (in July 2020) is: GNI below or equal to 1,045 USD for low income, GNI in a range from 1,046 to 4,125 USD for lower-middle income, GNI in a range from 4,126 to 12,745 USD for upper-middle income, and GNI above 12,745 USD for high income. For the period 2010–2014, 76 countries were classified as high income, 55 countries as upper-middle income, 48 countries as lower-middle income and 36 countries as low income. The data were obtained from the World Bank database for 2014 [W15];
- For this assessment, the proposed extrapolation procedure was found not to be viable for each of the conventionally defined income groups because of inadequate participation by United Nations Member States and the resulting lack of data for several classes that allowed to derive the 49 mathematical models to determine the number of workers for sectors, subsectors and job categories. As shown directly below, there were no data on the number of workers in low income and lower-middle income countries and few data from upper-middle income countries. Only the high income countries provided adequate data for extrapolation of the number of workers:
  - Zero of 49 subsectors and job categories (0%) in the low income group;
  - Zero of 49 subsectors and job categories (0%) in the lower-middle income group;
  - Eight of 49 subsectors and job categories (16%) in the upper-middle income group;
  - Thirty of 49 subsectors and job categories (61%) in the high income group.

75. The same problem of lack of data existed for estimating the average annual effective dose per worker by economic class, as is shown below. Only the high income countries provided adequate data:

- Zero of 49 subsectors and job categories (0%) in the low income group;
- Zero of 49 subsectors and job categories (0%) in the lower-middle income group;
- One of 49 subsectors and job categories (2%) in the upper-middle income group;
- Twenty-two of 49 subsectors and job categories (45%) in the high income group.

76. The analysis indicated that extrapolation by economic class was not possible and, for that reason, extrapolation using data of all Member States with data pooled together was the only alternative. The preventing analysis by economic classes significantly restricts the ability of the extrapolated values to be tailored to any specific economic class. Technical limitations imposed by sparse data also included limiting the ability to check and satisfy statistical assumptions on linearity, equality of variance across predictor variables (homoscedasticity), and normality.

77. Lack of knowledge about which countries were carrying out the activities of the subsectors in medical, industrial and miscellaneous sectors was also a challenging problem. Both the number of workers and the average annual collective effective dose per country could potentially be exaggerated in the extrapolation if a given country did not conduct such activities.

78. To assist in disregarding countries from extrapolation that did not have each subsector, a survey was conducted with the assistance of the IAEA in 2019 (table A.3 in the electronic attachment). This survey was a simple (yes or no) questionnaire asking if the country had conducted studies of the subsectors listed in those three sectors. The IAEA survey also had inadequate participation by countries, which prevented a systematic use of the survey results. A total of 31 countries responded to the survey, 14 countries from Africa, 12 countries from Asia, one from South America, and four from Europe. For the current analysis, the critical data are those from Africa since there was no contribution from this region to the UNSCEAR Occupational Exposure Survey. On the basis of the data obtained in the IAEA survey, it was assumed that all countries used diagnostic radiology (conventional radiology and interventional radiology), dental practices, and radiation therapy. However, only countries with per capita GDP higher than 500 USD were assumed to practice nuclear medicine and veterinary medicine using ionizing radiation.

III. LEVELS AND TRENDS OF EXPOSURE TO NATURAL SOURCES OF RADIATION

79. Exposure of workers to enhanced natural background related radiation is encountered in many occupational settings. Until implementation of the International BSS [I1, I12], most countries had not been particularly concerned with assessing occupational exposure to natural sources of radiation. Over the past years, this has become a focus of attention in radiation protection. The European Union has established safety standards for the protection of workers exposed to radiation from natural sources [E1, E8]. Since 2002, 19 European Union countries and three additional associated countries (Iceland, Norway and Switzerland) have regularly recorded the associated doses in an occupational exposure database [P6].

80. Besides the European Union countries, some countries have already implemented radiation protection legislation for workers to natural sources of radiation. The great majority of workers exposed to such sources are not individually monitored. They include aircrew, workers involved in mineral sand and processing industries (e.g., mining and milling of ore, physical mineral separation processes and thermal processes for extraction, processing and combustion of minerals) and in the oil and gas industry, and workers exposed to radon in various workplaces.

A. Cosmic ray exposure of aircrew and space crew

1. Civilian aviation

81. The exposure of aircrew has already been presented in previous UNSCEAR reports [U6, U8, U10]. Aircrew are exposed to cosmic radiation, which is composed of primary and secondary radiation. The former consists of high-energy particles of galactic and solar origin, whereas the latter consists of scatter products resulting from interaction processes in the atmosphere and in the aircraft structure. The intensity of the dose rate during a flight predominantly depends on three physical factors: *(a)* it increases with the altitude above sea level; *(b)* the geomagnetic shielding reduces the dose rates by deflecting parts of the charged cosmic and solar particles, particularly in the region ±30º around the equator. However, between 60° latitude and the geomagnetic poles, increasingly more charged particles intrude along the geomagnetic field lines into the atmosphere and cause a rise in the ambient dose equivalent rate. An exception is the South Atlantic Anomaly, a geographic region that extents from about −50° to 0° latitude and from −90° to 40° longitude, where—due to the asymmetry between the magnetic and rotation axes of the earth—the flux of energetic particles is increased; and *(c)* in phases of high solar activity the flux of galactic particles towards the earth is scattered, leading to a reduction of the ambient dose equivalent rate in the atmosphere. In times of low solar activity, the protecting effect of the solar wind is weak, and the ambient dose equivalent rates are higher. The solar activity changes more or less periodically in a cycle of 11 years. The route dose of a flight thus depends physically on the altitude profile, the latitude, the date and the duration of the flight. The individual annual dose of an aircrew member also depends on the flown route mix and on the number of block hours, both of which are influenced by a number of work arrangement factors.

82. In the past decades, extended experimental studies of the monitoring methodology for estimating the low- and high-LET components have been performed and continuously advanced [B22, B23, F10, H9, L6, V10, V11, V12]. Since the radiation field at aviation altitudes is very complex, different types of dosimeters and spectrometers have to be used in order to assess every component. The most common detectors delivering a comprehensive picture of the radiation field at flight altitudes are tissue equivalent proportional counters and semiconductor dosimeters and spectrometers. Other typical detection devices for measurements of the different field components are, for instance, thermoluminiscent dosimeters for the non-neutron component, bubble dosimeters for low-energy neutrons and etched track detectors for charged particles. Also, electronic personal dosimeters, delivering real-time doses, are occasionally used and have proved to be in satisfying agreement with the above-mentioned passive detectors [B23, F10].

83. The period which was analysed regarding occupational exposure in the present annex covers the decreasing phase of solar cycle 23 from its maximum in the year 2000 to its minimum in 2009, followed by the increasing phase of solar cycle 24 to its maximum in 2014. The measured ambient equivalent dose rates during minimum solar activity are larger than those measured during maximum solar activity. Also, high altitudes and latitudes are associated with higher dose values. The comparison of the effective route doses between the middle of the decreasing phase of solar cycle 23 (January 2004) and its minimum (January 2009) showed an increase from 25 to 30 µSv on the trans-equatorial route Frankfurt–Johannesburg, and from 50 to 78 µSv on the polar route Frankfurt–New York [F9]. Earlier experiments performed during maximum solar activity (1991–1992) measured an average dose rate of 3.0 µSv/h on a flight from Paris to Buenos Aires at an average flight altitude of 10,070 m [B22]. In contrast, the average dose rate measured during the solar minimum phase (1996–1998) and a higher latitude (Paris–Tokyo) was 6.6 µSv/h at an average flight altitude of 10,700 m. The influence of flight altitude on the dose rate is demonstrated by a Concorde-flight from Paris to New York during the solar maximum and minimum and at an average flight altitude of 15,400 m (maximum flight altitude: 18,000 m). During the solar

maximum and minimum, the average dose rates were 8.5 and 9.5 μSv/h, respectively, which are significantly higher values than those measured at lower altitudes.

84. Established experimental monitoring systems have been successfully used in order to measure the differences in the ambient dose equivalent, $H^*(10)$, in different positions within the aircraft. The ambient dose equivalent rate in the front and back of the cabin has been found to be up to 19% higher than in the middle part [K12]. Moreover, the measured ambient dose equivalent rate is higher with a full tank (up to 25%), in particular in the middle part of the cabin, which is due to an increased contribution of moderated neutrons produced within the full tank.

85. The detector response of a tissue equivalent proportional counters has been simulated and the findings concerning detector characteristics have been used to simulate the radiation field outside the aircraft. Thus, conclusions concerning the shielding effect of the aircraft could be drawn. The measured ambient dose equivalent rate within the aircraft is reduced by up to 25% when compared with calculations in free atmosphere [B7].

86. A particular subject of research interest is the investigation of the radiation exposure at high altitudes during solar storm periods and solar particle events, which are indirectly measured as ground level enhancements by ground-based neutron monitors and registered an increase of the number of high-energy charged particles striking the earth's atmosphere. In-flight measurements during solar storm periods have been evaluated and indicated an increase of up to about 80% of the total dose for flights crossing the polar region [B11]. Another study estimated a maximum dose rate of 1.7 mSv/h during a single flight [C17]. In the context of dose increase, the equator region is less affected by ground level enhancements. A variety of models aiming to predict the increase of radiation exposure due to solar particle events has been developed on the basis of very limited experimental data on ground level enhancements. The comparison of calculations and measurements of the ambient dose equivalent rates showed good agreement with a discrepancy between the model and measurements of typically less than ±25% [A7, A8]. However, some investigated models disagreed with each other by an order of magnitude, which might be due to the fact that the analysis of ground level enhancements during geomagnetically disturbed conditions is quite complex [B10].

87. Dose assessment based on measurement is a complex task due to the aforementioned complexity of the radiation field at aviation altitudes. Therefore, effective doses, *E,* for aircrew are not derived by individual monitoring using dosimeters; instead, they are routinely calculated using special computer programs that take flight parameters such as altitude, geographic position, and solar activity into account. The average annual effective dose is, therefore, usually estimated using codes that are validated by experimental data of the ambient dose equivalent $H^*(10)$ [B24, E5].

88. Several computer programs[1] have been developed in different countries for route dose calculation. Some of these have been approved by civil aviation authorities and serve as official national monitoring tools and some have purely scientific purposes. Comparisons for periods close to the solar minimum and maximum and for selected flights covering major commercial routes show an overall agreement between the codes within ±20% from the median [B24, B25, M3]. Furthermore, most of the mentioned codes have previously been validated by measurements showing an agreement between calculated and measured values better than ±20% [E4].

89. For the purpose of official dose monitoring of aircrew personnel, typically the calculated values of effective dose *E* are periodically verified by measurements of ambient dose equivalent $H^*(10)$, which is

[1] For example: CARI, EPCARD, JISCARD, and PCAIRE.

generally used as a surrogate for *E*. Various studies evaluating actual flight profiles concluded that, depending on the measuring method and calculation technique of the used program code, the deviation between experimental data and calculated values of $H^*(10)$ ranges between 10% and 30% [B8, B9, B28, G3, H9, L4, L6, W6].

90. For the purpose of continuous code validation with experimental data, an open access database was built up from records of the mixed field dosimetry device LIULIN placed on board Czech Airlines aircraft since 2001. For the monitoring period 2001–2011, calculated results by computer codes used for routine dosimetry of aircrew were compared with long-term measurement results from the database [P9]. It comprises records of energy deposition spectra, absorbed dose rates, and ambient dose equivalent rates. Moreover, it offers calculated values for effective dose and ambient dose equivalent [B24, O1]. The relative differences between measured and calculated values were mostly within ±30%. In contrast to other sources of measured dose values, this database presents relatively recent values of long-term measurements that are publicly available.

91. Data from the UNSCEAR Occupational Exposure Survey for aircrew are presented in table A.4 in the electronic attachment. The table includes values for the periods 2000–2004, 2005–2009 and 2010–2014, which were subject of the survey, whereas values for the periods 1990–1994 and 1995–1999, have been presented in former UNSCEAR reports [U6, U8]. For the period 2000–2004, the data for three countries, Czechia, Lithuania and the Netherlands, were used from the UNSCEAR 2008 Report [U10], as for these countries no updated values were provided via the UNSCEAR Occupational Exposure Survey. For the civilian aviation subsector, 22 countries replied to the survey, of which 12 countries provided only their most recent information regarding the number of aircrew (not included in table A.4 in the electronic attachment). More detailed responses on the number of workers, the average annual collective effective dose, and the average annual effective dose, regarding the periods of interest, were provided by 10 countries: Denmark, Finland, France, Germany, Greece, Iceland, Japan, Slovenia, United Kingdom and United States.

92. According to the responses to the UNSCEAR Occupational Exposure Survey, the average annual collective effective doses of monitored workers in civilian aviation reported in the periods 2000–2004, 2005–2009 and 2010–2014 were 734, 773 and 738 man Sv, respectively. The respective reported average annual effective dose was 2.7, 2.8 and 2.7 mSv, ranging from 1.3 to 3.1 mSv for the period 2000–2004, from 2.1 to 3.1 mSv for the period 2005–2009, and from 1.0 to 3.1 mSv for the period 2010–2014. The average annual effective dose weighted by the total numbers of monitored workers for 2000–2014 was 2.7 mSv. Due to a lack of data, dose data could not be evaluated separately for cockpit and cabin crew. It must be stressed that these numbers were derived on the basis of information provided by the 10 countries that replied to the survey in varied detail. For a worldwide estimate, additional sources of data were considered. The uncertainty interval for the average annual effective dose ranges from 1.5 to 4.6 mSv.

93. An estimate for the worldwide numbers of aircrew personnel was derived on the basis of numbers provided by ICAO [I23]. ICAO forecasts future traffic and capacity using panel regression and econometric modelling. Then, for this forecast, the needed fleet was estimated, and the number of aircraft determined. Given the worldwide number of aircraft, the number of pilots and cabin crew members was derived. Since no personnel data for the years earlier than 2015 were available from ICAO, an estimate was made on the basis of the total number of monitored workers as presented in the UNSCEAR 2000 Report [U8] for 1995–1999, and of the total number of workers for the years 2015–2019 as provided by ICAO, who estimated an average total number of 898,200 workers. Assuming linear growth for all periods since 1995–1999, the number of aircrew personnel was estimated to be 400,000–500,000 for the period 2000–2004, 550,000–650,000 for the period 2005–2009, and 700,000–800,000 for the period 2010–2014. As for the numbers of cockpit and cabin crew, the data provided by ICAO for the years

2015–2019 show a constant ratio of 38% (cockpit) vs. 62% (cabin), which–due to their consistency–is assumed to be about the same for earlier periods.

94. ICAO also provided information concerning worldwide aircraft traffic for the period 2010–2014 [I23]. A differentiation between long-, medium- and short-haul flights has become challenging in recent decades, since cabin crew personnel, in particular, are increasingly distributed to all categories of flights. Due partly to very large inter-country heterogeneity with regard to different categorizations, retrospective estimations based on worldwide volume of traffic alone are insufficient for the derivation of reliable values. However, it can be stated that, on average, 4% of worldwide flights have flight durations of more than six hours, 13% have flight durations of one–six hours, and 83% have flight durations of less than one hour.

95. The worldwide information about number and radiation exposure of aircrew personnel as collected and derived from the sources mentioned above is presented in table 2 and in table A.4 in the electronic attachment. If a linear increase is assumed, the number of aircrew personnel has steadily grown by a factor of about 2.5 from 300,000 (1995–1999) to ~750,000 workers (2010–2014). Due to the lack of sufficient information, the average annual collective effective dose was estimated roughly for the three periods under investigation using the average annual effective dose from the survey data and the number of aircrew provided by ICAO. Noticeable effects on the average annual effective dose due to solar activity are not to be expected, since the periods under consideration comprise solar minimum and maximum phases and should therefore even out (for 2000–2014, the only solar minimum occurred in 2009 and two solar maxima in 2001 and 2014). The uncertainty interval for the worldwide number of workers, for 2010–2014, ranges from 570,000 to 990,000.

Table 2. Estimates of worldwide levels of annual occupational exposure for civilian aviation workers

Period	*Number of workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		
			All flights	*Short-haul flights*	*Long-haul flights*
1990–1994	[a]	800[b]	[a]	1–2[b]	3–5[b]
1995–1999	300[b]	900[b]	3[b]	2[b]	3[b]
2000–2004	450[c]	1 220[d]	2.7[e]		
2005–2009	600[c]	1 680[d]	2.8[e]		
2010–2014	750[c]	2 030[d]	2.7[e]		

[a] Not enough data to estimate the worldwide level of exposure.

[b] Values taken from earlier UNSCEAR reports [U6, U8].

[c] Estimates values based on data provided by ICAO [I23].

[d] Estimated from data referred to in footnotes *c* and *e*.

[e] Average dose values as provided by 10 countries via the UNSCEAR Occupational Exposure Survey.

96. Deriving the worldwide exposure of aircrew personnel on the basis of the dose information of only 10 countries is subject to uncertainties for three main reasons: internationally different limits on working hours, heterogeneous definitions of short/medium/long haul, and location of operation, i.e., latitude. All except one of the countries that reported dose values to the UNSCEAR Occupational Exposure Survey were European countries, which are legally regulated by the European Union. According to these regulations, crew members should not exceed 900 block hours in a calendar year [E6]. For the United States, the only non-European country reporting on dose, the number of annual block hours for pilots is limited by the Federal Aviation Administration to 1,000 hours, whereas for cabin crew members no limitations are defined, yielding an imbalance in average dose values between cockpit and cabin crew

members [N4]. Given these discrepancies, a worldwide extrapolation considering regulations of all countries requires more information of the respective countries in order to reduce the uncertainties. Another source of uncertainty is introduced via the varying definitions of short-, medium- and long-haul flights, which differ from country to country and airline to airline. The classifications can be based on flight distance, flight time, or whether a flight is intercontinental, international or domestic. Especially the latter classification strongly depends on country location and size and, therefore, cannot be used for international comparisons. The latitude where the airlines operate also influences the national average annual effective dose values. Aircrew on domestic flights in equatorial countries receive a lower dose than aircrew flying on polar routes. Additional uncertainties which cannot be easily assessed on a worldwide basis are airline specific agreements in order to compensate for stress factors (flight duration, number of crossed time zones) and agreements concerning individual route preferences due to factors such as gender, age, family status, and other social ties.

97. Regarding the number of female personnel working in the aviation sector, Germany and Greece in the UNSCEAR Occupational Exposure Survey reported that the proportion of female workers was about 60%. Even though the number of female pilots had increased, the majority of female workers were cabin crew [F9]. Another source reporting on female workers in the period 1992–1996 found that in the United States, about 84% of flight attendants were female [G2]. According to an ILO report, the gender ratio in the civil aviation has, on average, remained relatively unchanged [S8]. It identifies a multitude of reasons for a prevailing gender imbalance, from differing career paths due to maternity to national legislation preventing women from entering the transport sector.

98. The European Union has established standards for the protection of workers exposed to natural radiation [E1]. Since 2002, several Member States of the European Union calculate and record aircrew doses as occupational exposure in their national dose registers. In addition, thanks to continuous research regarding the radiation exposure of civilian aircrew personnel, many peer-reviewed studies provide comprehensive dose information from many countries, also outside the European Union. In the following, dose estimates for aircrew for various countries, as published in these studies, are presented.

99. In Canada, a year-long study of the cosmic radiation exposure of Air Canada pilots during the solar minimum phase in 2009 was carried out. It showed that the estimated annual effective doses received by pilots were higher than the annual general public limit of 1 mSv, with the majority receiving about 3 mSv, although none exceeded the recommended intervention level of 6 mSv [B14]. Another study focusing on the cosmic radiation exposure for crew members of a transport squadron in the Canadian Air Force within a period of 30 months (2007–2009) found that more than half of the aircrew received higher annual effective doses than the general public limit of 1 mSv per year, with some crew members receiving an effective dose of almost 4 mSv. The dose distribution over all crew members exhibits two maxima, one at 0.5 mSv and the other at 2.5 mSv [B13]. Both studies were based on the dose calculation code PCAire and the calculations were supported by on-board measurements.

100. In Czechia, individual dosimetric monitoring of aircrew has been required by law since 1998. A study presents the effective dose values of Czech aircrew covering 20 years of dose collection [K13]. All dose values were calculated using the computer code Computer and Automation Research Institute (CARI). In the years 1998–2017, the average annual effective doses ranged from 1.3 to 2.1 mSv; the collective effective doses ranged from 1.3 to 5.1 man Sv, depending on the solar activity. The overall mean value of the average annual effective dose over the investigated 20 years was 1.6 mSv. Table 3 summarizes the mean, median, minimum and maximum values for the average annual effective dose of the Czech study [K13].

Table 3. Exposure of Czech civilian aircrew members for the period 1998–2017 [K13]

Year	*Number of workers*	*Mean (mSv)*	*Median (mSv)*	*Minimum value (mSv)*	*Maximum value (mSv)*
1998	857	1.5	1.7	~0.01	2.8
1999	1 055	1.5	1.6	~0.01	2.5
2000	1 042	1.5	1.7	~0.01	2.5
2001	1 245	1.4	1.5	~0.01	2.9
2002	1 202	1.5	1.6	~0.01	3.2
2003	1 309	1.7	1.8	~0.01	3.0
2004	1 484	2.0	2.1	~0.01	3.4
2005	1 765	2.0	2.1	~0.01	3.4
2006	1 865	2.0	2.2	~0.01	3.8
2007	1 902	2.1	2.3	~0.01	4.4
2008	2 158	1.9	2.2	~0.01	3.8
2009	2 111	1.8	2.1	~0.01	3.9
2010	2 044	1.6	1.8	~0.01	3.3
2011	1 865	1.6	1.8	~0.01	3.7
2012	2 065	1.5	1.6	~0.01	4.1
2013	2 353	1.4	1.2	~0.01	3.7
2014	2 208	1.4	1.2	~0.01	5.3
2015	1 815	1.4	1.2	~0.01	5.4
2016	1 922	1.4	1.3	~0.01	5.7
2017	1 881	1.4	1.2	~0.01	4.9

101. In an investigation in Finland of the radiation dose to Finnish aircraft cabin attendants, the average cosmic radiation dose was calculated (CARI-6) as 3.2 mSv (range: 0.0–9.5 mSv) per active work year [K7]. The analysis was based on questionnaire data obtained from 544 flight attendants. Another study examining the dose to cabin crew in Finland made use of individual flight timetables and calculated the annual dose with the European Program Package for the Calculation of Aviation Route Doses (EPCARD) software. The annual effective radiation dose of cabin crew members increased linearly from 0.7 mSv in 1960 to 2.1 mSv in 1995 [K8]. Since these values are lower than the 3.2 mSv of the previous study, the authors assume that the result of the previous study was overestimated. A more recent study examined the annual dose values of cabin and cockpit crew members by means of the dose estimation programs CARI-6 and EPCARD. In total, 1,535 cockpit crew members (5% female) and 3,487 cabin crew members (87% female) of Finnish airline personnel were included in the study. The average age of the study participants was 44 years and over 60% were between 30 and 50 years [T1].

102. In Germany, a cohort study covering 6,000 male pilots from 1960 until 2004 was performed by Hammer et al. [H2]. The study was based on a job-exposure matrix and calculations for individual flight profiles using CARI-6. In the group of subjects still active by the end of 2004, the median cumulative effective dose over the occupational lifetime per person was 29.4 mSv and the first and third quartile and the maximum value were 23.0, 40.5 and 71.4 mSv, respectively. For persons no longer employed, the values for the median, first and third quartiles and the maximum cumulative effective dose were 31.3, 12.3, 45.3 and 73.9 mSv, respectively. The cumulative effective dose was strongly correlated with duration of employment and flight hours. In a more recent work by Wollschläger et al. [W14], the same cohort was investigated, using a job-exposure matrix and EPCARD for individual dose calculations. According to this analysis, the average annual effective dose was 2.25 mSv (range 0.01–6.39 mSv). Male cabin crew had a higher average annual effective dose (2.63 mSv) than female cabin crew (2.15 mSv). Similarly, male cockpit crew showed a higher average annual effective dose (2.29 mSv) than female cockpit crew (1.85 mSv). Radiation exposure of all German aircrew was also investigated on the basis of data from the national dose register from 2004–2009 by Frasch et al. [F9]. The respective dose values for pilots, cabin crew, female, and male workers are summarized in table 4. The category “Other” consists mainly of loadmasters and special air force staff. In 2004, at the middle of the decreasing phase of solar activity, the average annual effective dose was 1.9 mSv and increased until the solar minimum in 2009 to 2.3 mSv. With the decreasing protection by solar activity the frequency distributions of annual doses stretch towards higher dose values. These accounts in particular for doses above the median. Also, the annual doses of pilots and flight attendants vary significantly with age and gender due to age-dependent phases of professional career and family status.

Table 4. Doses of all monitored aircraft crew personnel in Germany [F9]

Job category year	*Number of workers*	*Collective dose (man Sv)*	*Mean (mSv)*	*Median (mSv)*	*Maximum value (mSv)*	*Standard deviation (mSv)*
All aircraft crew						
2004	29 852	58.21	1.9	1.9	6.1	1.0
2009	36 596	85.88	2.3	2.4	7.0	1.3
Cockpit, female						
2004	313	0.49	1.6	1.4	5.6	1.1
2009	609	1.09	1.8	1.6	6.8	1.3
Cockpit, male						
2004	7 982	15.58	2.0	1.7	5.7	1.0
2009	9 853	21.81	2.2	2.0	6.7	1.3
Cabin, female						
2004	16 626	32.29	1.9	2.0	6.1	1.0
2009	20 426	48.35	2.4	2.3	6.9	1.2
Cabin, male						
2004	4 098	9.21	2.2	2.4	5.3	0.9
2009	4 822	13.84	2.9	3.0	7.0	1.2
Other						
2004	871	0.65	0.7	0.8	2.8	0.4
2009	953	0.78	0.8	0.8	3.0	0.5

103. In Ireland, during the years 2002–2005, there was a 75% increase in the number of aircraft personnel receiving doses >1 mSv, due to an increase of the total number of flights flown per year [C16]. The percentage of aircrew receiving doses in the range 4.0–6.0 mSv increased from 0.2% (2002) to 4.5% (2005). In 2004 and 2005, the average annual effective doses received by Irish aircrew were 1.8 and 2.0 mSv, respectively. Route doses were calculated with CARI-6 and validated with EPCARD.

104. A study from Japan calculated the effective doses for the round-trip flights from Tokyo Narita International Airport to 12 cities (Auckland, Bangkok, Frankfurt, Hong Kong, Honolulu, London, Madrid, Moscow, New York, San Francisco, Singapore and Sydney) using the CARI-6 code under conservative conditions. The highest estimated dose for the round trip was that to New York with 210 μSv and the lowest estimated dose was to Hong Kong with 26 μSv [Y2]. Another study obtained the annual effective doses for pilots and cabin crew of Japanese Airlines in 2007 using JISCARD [Y3]. According to this study, the annual crew doses were 1.7 mSv on average, and 3.8 mSv at maximum for pilots, whereas for cabin crew the average annual effective doses were 2.2 mSv, and 4.2 mSv at maximum.

105. The aim of a study in Lithuania from 2003 was to evaluate potential doses that could be received by aircrew of Lithuanian Airlines. Measurements and calculations (CARI-6) were performed in the period of modest solar activity. Therefore, and despite the fact that only short-haul flights are operated by Lithuanian Airlines, the study concludes that the annual dose of 1 mSv may be exceeded under some circumstances [M7].

106. In Portugal, the annual effective dose for aircrew in military transport missions has been estimated at 1.5–1.8 mSv [A13]. Assuming a six-month period of pregnancy in which female crew members are still working, the dose equivalent to the fetus may vary between 0.8 and 1.0 mSv. Another assessment of occupational cosmic radiation exposure of Portuguese airline pilots showed that all investigated pilots received more than 1 mSv per year of service [S12]. The authors analysed medium-haul flights, which were defined as flights within Europe, and long-haul flights, which were defined as flights between Europe and other continents. The average dose rates estimated for medium-haul pilots (3.29 ± 0.24 μSv/h) were larger than those for long-haul pilots (2.66 ± 0.33 μSv/h).

107. In Saudi Arabia, aircrew are not considered to be radiation workers and, hence, are not occupationally monitored. In a one-year study, the radiation exposure of Saudi Aramco aircrew was measured or estimated using CARI-7 program and thermoluminiscent dosimeters [S9]. Of all monitored aircrew, the minimum annual effective dose was about 0.4 mSv and the maximum annual value was 0.8 mSv. However, from a total number of 2,767 investigated flights, only 11 flights were “out-of-kingdom” flights, i.e., flights of relatively long duration and high altitudes. With 1,595 flights, the majority of flights were domestic flights of short duration (≤1 hour) and low altitude. The study showed, depending on flight duration and altitude, pregnant aircrew may reach the annual pregnancy radiation dose limit of 1 mSv.

108. In Spain, an investigation of the radiation exposure of aircrew working for Iberia performed in 2001 yielded an average annual effective dose of 1.4 mSv, ranging between 0.4 and 2.7 mSv [S1]. The average value for short-haul flights was considerably lower (1.7 mSv) than the value for long-haul flights (2.2 mSv). However, the average annual effective doses can increase by 5–20% since the values presented in this study were obtained when solar activity had reached a maximum value, which is associated with low dose values.

109. In Taiwan, China, occupational exposure of aircrew to cosmic radiation is currently neither regulated nor monitored. A recent study, based on publicly accessible civilian aviation statistical reports, proposes a comprehensive approach for estimating the average annual collective and the average annual

effective dose received by Taiwanese pilots [Y1]. For the period 2006–2018, the average annual effective doses varied between 1.7 and about 3.0 mSv, with a mean value of 2.2 mSv.

110. In Turkey, cosmic radiation doses for aircrew of Turkish Airlines were estimated using CARI-6 software on board 137 flights (60 domestic and 77 international) [P3]. The doses for each flight varied from 1.2 to 83 µSv. Annual effective doses for short-haul flights from Istanbul to domestic airports covering 800 hours on each route were calculated to range from 1.0 to 1.7 mSv. In contrast, annual effective doses of international flight routes for 800 hours were calculated to range from 1.8 to 4.8 mSv.

111. In the United States, using the methodology for the retrospective exposure assessment for flight crew of the former Pan American World Airways company, the average annual flight attendant effective dose was estimated to 2.4 mSv (career dose range 0.33–100 mSv) [W2]. Another study by Anderson et al. [A16] analysed radiation exposure of female crew members of the Pan American company by means of questionnaire data. Completed work history questionnaires were received from 5,898 living cohort members. Mean employment time as flight attendant was 7.4 years at the Pan American company and 12 years in total. The estimated average annual effective dose of occupational cosmic radiation exposure was 2.5 ± 1.0 mSv, with a mean career dose of 30 mSv [A16].

112. Assessing the contribution to radiation dose from exposure to solar particle events, a computer model was developed by the National Aeronautics and Space Administration (NASA) and solar storm data were provided by the National Oceanic and Atmospheric Administration Space Weather Prediction Center from two study periods (1992–1996 and 1999–2001) [A17]. As a result, seven solar particle events were identified to have the potential to significantly increase the radiation exposure for US flight personnel on commercial routes. For a flight of a couple of hours during a solar particle event, the authors estimated a maximum effective dose of 1.2 mSv for aircrew personnel. That means that during solar particle events, pregnant crew members could potentially exceed the ICRP recommended dose limit of 1 mSv during pregnancy.

113. Using the same cohort as in Waters et al. [W2], Yong et al. [Y4] estimated the cosmic radiation exposure of 5,964 former United States commercial cockpit crew members. The average annual effective dose was calculated to be 1.4 mSv (median = 1.4; range 0.0042–2.8) but varied from 0.081 mSv (range 0.00072–0.14) in 1940 to 1.6 mSv (range 0.059–1.8) in 1980 [Y4]. The career dose was strongly correlated with the duration of employment (Spearman correlation coefficient: 0.90). The average career dose was 28 mSv (median = 31; range 0.0047–71). Exposure to cosmic ionizing radiation and circadian rhythm disruption was estimated for a time range between 1963 and 2003 for 83 male pilots from a major United States airline by Grajewski et al. [G1]. Pilots flew a median of 7,126 flight segments and 14,959 block hours for 27.8 years. The median of the annual radiation exposure from cosmic radiation was estimated to be 1.92 mSv. Another study by Grajewski et al. [G2] evaluated data of 764 female flight attendants resulting in an annual average effective dose of 0.36 mSv within the period 1992–1996.

2. Space crew

114. The naturally occurring radiation environment in space differs substantially from that experienced on earth, in both type and intensity. Three main sources generally affect exposure to ionizing radiation while in the space environment: *(a)* galactic cosmic rays; *(b)* solar particle events; and *(c)* radiation from particles trapped in the earth's magnetic field. Both galactic cosmic rays and radiation from particles trapped in the magnetic field are fairly constant sources of exposure while solar particle events are sporadic and transient events. All these sources are composed of accelerated particles with velocities near the speed of light [B1, B16, B17, T4].

115. The majority of crewed spaceflight missions have been conducted in low-earth orbit where exposure to galactic cosmic rays and solar particles from solar particle events are limited to trajectories that cross regions of polar latitudes and exposure to radiation from particles trapped in earth's magnetic field is limited to trajectories that traverse the South Atlantic Anomaly. These range in duration from a few hours to the current record for consecutive time in space – 438 days [B16, B17, M2]. Historically, the only missions to go beyond the protection of the earth's magnetic field were the Apollo missions conducted in the 1960s and 1970s. Crews on these missions were exposed to galactic cosmic rays as well as varying contributions of radiation from particles trapped in earth's magnetic field due to different trajectories through the Van Allen belts. Total absorbed radiation doses experienced during these short duration missions (1–13 days) were relatively low (1.6 to 11.4 mGy) [B16, B17]. In space, humans are always surrounded by different material which can act as shielding. Due to the nature of high-energy particle interactions with matter, the amount of available shielding alters the radiation environment experienced by humans in space, which impacts the ultimate radiation dose [N9]. To date, a total of 336 NASA astronauts have flown in space and have had their cumulative dose recorded using thermoluminescent dosimeters. The mean total badge dose (estimated absorbed dose) for these astronauts was 16.8 mGy with a standard deviation of 23.6 mGy [N12].

116. Radiation monitoring during long-term space missions aboard the Mir space station and International Space Station (ISS) demonstrates that the crew member's effective dose can be as high as 100–300 mSv after a one year space mission, i.e., 0.4–0.8 mSv per day [B15, P11].

117. In order to better understand radiation doses to sensitive organs inside the human body, Sihver et al. [S10] reported various phantom experiments performed in space. The results from the measurements in these phantoms have shown that the crew member effective dose on the ISS is in the order of 0.4–0.8 mSv per day, depending on solar cycle, shielding and the orbit.

118. Biodosimetry of astronaut lymphocyte samples, taken prior to- and post-flight (two samples), provides an important in vivo measurement of radiation-induced damage incurred during space flight, which can be included in the astronauts' medical records. Between 2007 and 2015, Health Canada analysed samples from seven astronauts who had stayed on the ISS for approximately six months [B6]. The estimates of the incurred absorbed dose for the astronauts were all less than 0.25 Gy.

119. Biological doses determined by chromosome aberration frequency from pre- and post-flight blood sample analysis and physical doses measured in flight using thermoluminescent dosimeters worn by ISS crew members were analysed by Cucinotta et al. [C20]. Physical and biological doses for 19 ISS crew members yielded an average effective dose for the approximately six-month missions of 72 mSv. Analyses showed that 80% or more of organ dose equivalents incurred on the ISS are from galactic cosmic rays and only a small contribution is from trapped protons and that the galactic cosmic ray dose contribution decreased due to the high level of solar activity in recent years [C20, Z1].

B. Exposure in extractive and processing industries

120. The extraction and processing of natural resources from soil or rocks is common across the world for the production of a variety of products. As radioactive substances are found in variable quantities in all natural material, extraction and processing can result in significant exposure to workers. Protection can be optimized through raising awareness and applying controls. Mining and processing industries employ a predominantly male workforce. Although more women are now working in mining in some countries, any increase in female employment is generally very low.

121. All rocks, soil and water on earth contain varying concentrations of the radioactive nuclides ^{40}K, ^{238}U and ^{232}Th and radioactive daughter nuclides in their decay series. Disturbance of any material (e.g., mining) and its processing to extract specific target material (e.g., smelting) or the modification of natural distributions (e.g., mineral sand separation) can result in exposure to ionizing radiation. Radiation exposure of workers is usually dependent on the radionuclide concentration, extraction and processing method, and exposure duration. For mining operations, the main source of exposure is typically radon in underground operations. In mineral processing activities, mineral dust and accumulation of gamma radiation emitting radionuclides can contribute to significant exposure. A number of new assessments in these areas have been made since the UNSCEAR 2008 Report [U10].

1. Coal mining

122. The main potential sources of occupational exposure in the extractive industries are the natural radionuclides arising from the radioactive decay of the ^{238}U and ^{232}Th series. Exposure may occur via three main routes: *(a)* inhalation of radon and its progeny; *(b)* inhalation and ingestion of ore dust; and *(c)* external irradiation with gamma rays.

123. Between 2000 and 2014, the coal production industry was concentrated primarily in 12 countries (Australia, China, Colombia, Germany, India, Indonesia, Kazakhstan, Poland, Russian Federation, South Africa, Turkey, and United States). These 12 countries contributed 90–94% to worldwide coal production. In the period 2010–2014, China contributed up to 48%, and the United States contributed about 12% to the worldwide production. The average annual total coal production for each period (2000–2004, 2005–2009 and 2010–2014) is shown in table 5 for those 12 major producers along with four other countries (Islamic Republic of Iran, Japan, Philippines and United Kingdom) that are not major producers but have responded to the UNSCEAR Occupational Exposure Survey, submitting data on number of workers. The worldwide total primary coal production increased by a factor of 1.6 (from 5.07×10^3 million metric tonnes in the period 2000–2004 to 7.88×10^3 in the period 2010–2014). The worldwide increase is driven by production in China, which increased by a factor of 2.3 (from 1.67×10^3 million metric tonnes in the period 2000–2004 to 3.80×10^3 in the period 2010–2014).

124. Data from the UNSCEAR Occupational Exposure Survey on coal mining are included in table A.4 in the electronic attachment. For coal mines, three countries provided data for the periods 2000–2004 and 2005–2009 (Poland, United Kingdom and United States). Data from China [L7, U10] and Turkey [F7] were added for the extrapolation analysis. For the latter period (2010–2014), only two countries responded to the detailed questionnaire (Poland and United Kingdom) providing data for the number of workers and average annual effective dose. Four countries responded to the simplified questionnaire (Islamic Republic of Iran, Japan, Philippines, and the United States), providing data on workforce only.

Table 5. Average annual amount of total primary coal production [U17]

Country	*Average annual of total primary coal production (million metric tonnes)*		
	2000–2004	*2005–2009*	*2010–2014*
Australia	334	387	447
China	1 673	2 744	3 796
Colombia	46	67	85
Germany	208	198	190
India	364	471	547
Indonesia	116	226	389
Iran (Islamic Republic of)	1.1	1.3	1.1
Japan	1.9	1.3	1.2
Kazakhstan	77	95	116
Philippines	1.8	3.5	7.1
Poland	162	147	139
Russian Federation	248	288	326
South Africa	231	248	257
Turkey	55	71	70
United Kingdom	29	18	16
United States	994	1 031	940
World	**5 075**	**6 548**	**7 881**

125. The predictor variable used to extrapolate the coal mining workforce was the average total primary coal production given in table 5 and the number of workers were obtained from the survey (table A.4). The average total primary coal production accounted for by the countries that responded to the survey corresponded to 56, 60 and 62% for 2000–2004, 2005–2009 and 2010–2014, respectively. The worldwide number of workers was calculated on the basis of the relationship of the number of workers per production of total primary coal. According to the reported data, the number of workers per production of one million metric tonnes decreased over time: 2,138 (2000–2004), 1,350 (2005–2009) and 995 (2010–2014). The estimated worldwide number of workers are presented in table 6 and table A.4 in the electronic attachment for each period and were about 10.9, 8.8 and 8.0 million in the three periods, respectively.

Table 6. Number of workers for total primary coal production reported to UNSCEAR Survey

Countries	*Number of workers (10^3)*		
	2000–2004	*2005–2009*	*2010–2014*
China	6 005[a]	5 100	4 700
Poland	103	92	84
United Kingdom	6.0	6.0	5.2
United States	101	120	125
Total reported	6 215	5 318	4 914
Worldwide	**10 900**	**8 800**	**8 000**

[a] Value from UNSCEAR 2008 Report [U10].

126. The worldwide average annual effective dose represents the average annual effective dose weighted by the number of workers for each country that provided data through the detailed questionnaire of UNSCEAR Occupational Exposure Survey and additional data obtained from the literature review. The estimated worldwide average annual effective doses are 2.3, 2.1 and 1.6 mSv for the periods 2000–2004, 2005–2009 and 2010–2014, respectively. The uncertainty interval for the number of workers for 2010–2014 ranges from 4.9 to 13 million and the uncertainty interval for the worldwide average annual effective dose from 1.0 to 2.6 mSv. The estimated worldwide average annual collective effective doses are 25,070, 18,480, and 12,800 man Sv for the periods, respectively. These data are presented in table 7 and table A.4 in the electronic attachment. All worldwide estimates should be used with caution, since they were primarily derived from data for the single country that accounts for 95% or more of the reported number of workers and collective effective dose, as shown in table 8. However, this country represents about 33, 42, and 48% of the average worldwide total primary coal production for the periods, respectively.

Table 7. Estimates of worldwide levels of annual occupational exposure for coal mining

Period	*Average total primary coal production (million metric tonnes)*	*Number of workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1990–1994[a]		3 910	2 737	0.7
1995–1999[a]		6 900	16 560	2.4
2000–2004	5 072	10 900	25 070	2.3
2005–2009	6 544	8 800	18 480	2.1
2010–2014	7 934	8 000	12 800	1.6

[a] Values from earlier UNSCEAR reports [U6, U8].

127. Occupational exposure data for coal mining workers obtained from the literature review have been used to supplement the data obtained from the UNSCEAR Occupational Exposure Survey. Three countries have published data related to national surveys: China, Poland and Turkey (table 8). The Chinese data for the average annual effective dose for coal mining, obtained through the literature review, have been used in estimating the worldwide average annual effective dose for coal mining.

Table 8. Occupational exposure data for coal mining workers obtained from literature review

Country	*Year*	*Number of workers (10^3)*	*Average annual effective dose (mSv)*	*Average annual collective effective dose (man Sv)*	*Notes*	*Reference*
China	2002–2004	6 005	2.4	14 412		[U10]
	2005–2009	5 100	2.2	11 335		[L7]
	2010–2014	4 700	1.7	7 982		[L7]
Poland			2.0		Nose breather	[S13]
			2.7		Mouth breather	[S13]
Turkey	2000–2004		4.9			[F7]

2. Mineral mining and processing

128. The sources of radiation exposure for mineral extraction discussed in this section are basically as described in the coal mining section above. The evaluation of occupational exposure in mineral mining and processing comprises the following group of commodities: iron/steel-alloys, non-ferrous metals, precious metals and industrial minerals. The extraction and processing industries of these commodities account for about 14% of the total extraction industry in the period 2010–2014. Mineral fuel (coal, petroleum, natural gas and uranium), which is not included in this subsector, accounts for about 86% of the total mineral extraction in the period 2010–2014 [R7]. Of the group of commodities studied here, iron/steel-alloys comprise about 63% of commodities production in the period 2010–2014. It is followed by industrial minerals, which comprise about 32% of the production during this period. The production of these commodities worldwide was concentrated primarily in six countries: China (about 28%), Australia (17%), Brazil (11%), India (7%), the United States (5%) and the Russian Federation (4%). The data are presented in table 9.

Table 9. Average annual total mineral production other than mineral mining per country in the period 2010–2014 [R4, R5, R6, R7]

Values reported to the UNSCEAR Occupational Exposure Survey are given in bold

Country	*Average annual total production (million metric tonnes)*					*Total production (%)*
	Iron, steel-alloys [a]	*Non-ferrous metals* [b]	*Precious metals* [c]	*Industrial minerals* [d]	*Total*	
Australia	338	5.0	0.0021	19.1	362	16
Bangladesh				**1.5**	**1.5**	**<0.1**
Brazil	**222**	**1.8**	**0.0001**	**18**	**242**	**11**
Canada	**25**	**4.1**	**0.0008**	**31.6**	**61**	**2.7**
China	**432**	**30**	**0.0038**	**184**	**647**	**28**
Germany	0.05	0.5		33.3	34	1.5
India	**109**	**2.7**	**0.0003**	**38.5**	**150**	**6.5**
Iran (Islamic Republic of)	**21.1**	**0.7**	**0.0001**	**27.3**	**49**	**2.1**
Iraq				**0.2**	**0.2**	**<0.1**
Kazakhstan	18.7	1.1	0.0009	4.5	24	1.0
Kenya	**0.1**			**0.1**	**0.2**	**<0.1**
Madagascar	**0.4**			**0.1**	**0.5**	**<0.1**
Mexico	9.5	1.3	0.0053	22.6	33	1.4
Philippines	**0.7**	**0.1**	**0.0001**	**0.9**	**1.7**	**<0.1**
Poland		**0.6**	**0.0012**	**6.6**	**7.2**	**0.3**
Russian Federation	59	4.9	0.0018	29	91	4.0
South Africa	55	0.9	0.0005	3.1	59	2.6
Sweden	**17**	**0.5**	**0.0003**	**0.05**	**18**	**0.7**
United Kingdom		**0.1**		**9.7**	**9.8**	**0.4**

Country	*Average annual total production (million metric tonnes)*					*Total production (%)*
	Iron, steel-alloys [a]	*Non-ferrous metals* [b]	*Precious metals* [c]	*Industrial minerals* [d]	*Total*	
United States	**34**	**4.2**	**0.0014**	**88.8**	**127**	**5.5**
All countries above	1 339	53.9	0.0185	519	1 917	83
Survey countries [e]	862	45	0.011	407	1 215	53
Worldwide	1 460	83	0.028	760	2 300	100

[a] Includes iron, chromium, cobalt, manganese, molybdenum, nickel, niobium, tantalum, titanium, tungsten and vanadium.

[b] Includes aluminium, antimony, arsenic, beryllium, bismuth, cadmium, copper, gallium, germanium, indium, lead, lithium, mercury, rare earth minerals, rhenium, selenium, tellurium, tin and zinc. Bauxite is not included.

[c] Includes gold, palladium, platinum, rhodium and silver.

[d] Includes asbestos, baryte, bentonite, boron minerals, diamonds (gem/industrial), diatomite, feldspar, fluorspar, graphite, gypsum and anhydrite, kaolin (China clay), magnesite, perite, phosphates, potash, salt (rock salt, brines, marine salt), sulphur (elemental/industrial), talc (including steatite and pyrophyllite), vermiculite.

[e] From the UNSCEAR Survey, data on workers involved in other mineral extraction and processing are included in table A.4 in the electronic attachment. For the period 2003–2004, two countries responded to the detailed survey (United Kingdom and United States). For the period 2005–2009, three countries responded to the detailed survey (Slovenia, United Kingdom and United States). For the period 2010–2014, seven countries replied to the simplified questionnaire, providing data on number of workers for the latest period (Bangladesh, Brazil, China, India, Sweden, United Kingdom and United States). Three of those countries also replied to the detailed questionnaire (Brazil, India and United Kingdom).

129. The predictor variable used to extrapolate the workforce was based on the total mineral production other than fuel minerals given in table 9, and the number of workers obtained in the UNSCEAR Occupational Exposure Survey, given in table A.4 in the electronic attachment. The worldwide average production of these minerals increased by a factor of 1.8 from 2000–2004 to 2010–2014. The countries responding to the survey for the period 2010–2014 are responsible for about 52% of the total production of the minerals grouped as iron/steel-alloys, non-ferrous metals, precious metals, and industrial metals. There is a statistically significant correlation between the production of the minerals and the number of workers. The worldwide number of workers was calculated on the basis of the relationship of the number of workers per production of those four groups of minerals. According to the reported data for 2010–2014, the number of workers per production of one million tonnes during that period was 1,628. Because of the lack of data for the two previous periods (2000–2004 and 2005–2009), the number of workers per production could not be derived reliably. The estimated worldwide number of workers for 2010–2014 is 3.8 million. This value may be underestimated because the production of bauxite was not considered in the calculation, which represents about 10% of the total production of non-ferrous metals. Only three countries provided average annual effective dose for the period 2010–2014. The weighted average annual effective dose is 2.5 mSv. This value is a rough global estimate because of the small sample size and the three countries reporting average annual effective dose data account for only 17% of the total production. Average annual effective dose data for different types of mines, available from the literature (2003–2014), are presented in table 10. A large variation (range of values) in the reported values for average annual effective dose can be observed. The average annual collective effective dose is estimated as 9,500 man Sv. As described in section II.E.2, the uncertainty interval calculated for the worldwide number of workers is from 2.3 to 6.2 million and the uncertainty interval for the worldwide average annual effective dose is from 1.3 to 4.9 mSv.

Table 10. Summary of average annual effective dose for mineral production other than fuel mineral

Country	*Type of mining*	*Average annual effective dose (mSv)*	*Reference*
Brazil	Granite industry	0.0003–0.2	[E13]
	Sandblasters	1.2–16.5	[E13]
Democratic Republic of Congo	Columbite-tantalite	12 (0.008–18)	[M10]
Egypt	Phosphate (radon daughters)	27 (0.69–80.99)	[K3]
	Phosphate (external exposure)	12 (6–56)	[K3]
Ghana	Gold	0.7 (0.22–1.9)	[D6]
	Gold (open pit mines)	0.2–0.3	[D1]
	Gold (underground mines)	1.7–2.0	[D1]
Hungary	Manganese	2.6–3.6	[K1]
Iran (Islamic Republic of)	Twelve different types of mines	<0.1–31	[F2]
Nigeria	Granite	0.25	[A1]

C. Oil and gas extraction

130. Naturally occurring radioactive material (NORM) found in the earth's crust, largely in the form of ^{226}Ra and ^{228}Ra and their associated radionuclides, is brought to the surface during gas and oil production processes. NORM represents a potential internal radiation exposure hazard to workers from the inhalation and ingestion of natural radionuclides (^{238}U, ^{228}Th and ^{232}Th progenies), particularly during maintenance, transport of waste and contaminated equipment, decontamination of equipment and processing of waste. The short-lived progeny of the radium isotopes, in particular of ^{226}Ra, emit gamma radiation capable of penetrating the walls of internally contaminated pipes and vessels. Therefore, the deposition of contaminated scales and sludge in these components produces enhanced dose rates outside these components. The values depend on the amount and activity concentrations of radionuclides present inside and the degree of shielding provided by pipe or vessel walls.

131. The average annual effective dose was estimated as 3.2 mSv for workers in an oil refinery in Egypt, assuming exposure to external gamma radiation sources, inhalation of particulates, and skin exposure due to beta radiation. The assessment was derived from activity concentration measurements of samples taken throughout the plant [B2]. The average annual effective dose for workers at the oil and gas facilities in Argentina was estimated to be in a range from 0.02 to 1.6 mSv. Only the external radiation exposure pathway was considered in the dose estimate [C5].

132. The average annual effective dose for workers exposed to radium in natural gas extraction from shale rocks in the United States was estimated to range from 0.002 to 0.36 mSv. Exposure to external gamma radiation and inhalation of radon and particles were considered in the dose assessment [Z2].

133. The exposure of maintenance personnel who perform pipe scale rattling operations has been reported by Hamilton et al. [H1] in a comprehensive study on that specific task. Under controlled conditions using personal air samplers and dosimeters on operators, coupled with a significant number of area samplers, the external, inhalation and ingestion exposure was determined. On the basis of an

assessment of cleaning 20 pipes per day for 250 days per year, the average annual effective doses for the operator and helper were assessed to be 3.3 and 4.9 mSv, respectively [H1].

134. Data from the UNSCEAR Occupational Exposure Survey on gas and oil extraction are included in table A.4 in the electronic attachment. For the period 2000–2004, only the United States responded to the simplified survey, providing number of workers. For the period 2005–2009, only the United Kingdom responded to the detailed questionnaire and the United States responded to the simplified questionnaire. For the period 2010–2014, three countries—Brazil, United Kingdom and United States—replied to the detailed survey. Another five countries responded to the simplified survey through 2017, providing number of workers (China, Islamic Republic of Iran, Iraq, Kenya, and the Philippines).

135. An estimation of the global oil and gas extraction workforce was not possible by extrapolation due to the lack of statistically significant correlation between number of workers and oil production. The lack of correlation may be due to differences in data provided, such as submission of total number of workers in the oil extraction industry or submission number of workers involved in tasks such as maintenance. For future analysis, the requested data should be specific for the workforce involved in maintenance. The total number of workers reported by the countries responding to the UNSCEAR Occupational Exposure Survey for the period 2010–2014 is around one million; the average annual effective dose is 0.2 mSv and the average annual collective effective dose is about 200 man Sv.

D. Radon exposure in workplaces other than mines

136. The levels of radon in workplaces are exceptionally variable, and high radon doses to workers can occur also in places other than underground mines. In the UNSCEAR 1993 Report [U6], the exposure to radon progeny was considered only in underground mines. The UNSCEAR 2000 Report [U8], in addition to mines and below-ground workplaces, included radon spas, subways, show caves and tourist mines, and also underground water treatment plants and underground stores. Above-ground workplaces such as factories, shops, offices and schools were also considered in the UNSCEAR 2000 Report [U8]. Exposure to radon in these workplaces was, therefore, usually regarded as essentially unamenable to control. However, there has been increasing interest in some workplaces, including underground ones, where radon levels are expected to be high and there is some scope for reducing the radon levels.

137. Before 2000, there were very few data on which to base an estimate of worldwide exposure to radon in workplaces. In the United Kingdom, radon concentrations were measured in 4,800 workplaces in areas of the country where levels were expected to be above average radon concentration of 210 Bq/m^3, and in 710 cases the concentration exceeded 400 Bq/m^3. Of the estimated 1.7 million workplaces in the United Kingdom, 5,000 with about 50,000 workers are expected to exceed 400 Bq/m^3. Their collective effective doses and average individual doses were 270 man Sv and 5.3 mSv in a year [U7, U8]. On the basis of the United Kingdom data and with extrapolation on the basis of GDP, a crude estimate was that the worldwide average annual collective effective dose would be about 6,000 man Sv and the average annual effective dose 4.8 mSv for workplaces exceeding 400 Bq/m^3 [U10].

138. In workplaces other than mines, radon concentration is measured in Bq/m^3 instead of WLM as in mines. To evaluate the average annual effective dose from radon inhalation in those workplaces, the Committee's radon dose conversion factor of 9 nSv per (h Bq/m^3) of radon equilibrium equivalent concentration is used [U14].

139. The assessment of average annual effective dose due to exposure to radon depends not only on radon concentration in workplaces but also on the location-specific radon equilibrium factor, *F*, and actual

working hours per year. In indoor workplaces, *F*=0.4 is commonly used. However, due to different ventilation rates and variation in solid particle concentrations, *F* values vary widely, from as low as 0.15 to as high as 0.89, with a mean of 0.44 [C8]. In underground show caves and tourist mines, the *F* values can also vary from 0.10 to 0.85 with an overall average value of 0.40 [C11]. The average *F* values in thermal spas vary from 0.10 to 0.45 with an overall average of 0.30, somewhat lower than the overall average *F* value for show caves and tourist mines [C11].

140. Any scientific work referenced in this annex and used to perform a dose assessment will respect the local *F* value where reported. For example, site-specific *F* values were used to assess occupational exposure to radon in Australian tourist mines and caves [G4, S14], where the *F* values varied from 0.19 to 0.75 with an average of 0.39. The *F* value of 0.57 was used to assess radon exposure for workers in Spanish and Romanian show caves [A12, C21]. In thermal spas, the average local *F* values were reported to be 0.1 in Hungary [K2], 0.15 in China [L8], and 0.2 in Greece [N6]. If no local *F* value is reported, a default value of 0.4 is used to obtain a dose from radon exposure.

141. For average annual effective dose assessment, normal time spent in workplaces is commonly assumed to be 2,000 hours per year. However, in many underground workplaces or in some storage rooms or water treatment plants where radon concentrations are significantly elevated, this is not the case. For example, annual working hours for seasonal tour guides in Australian tourist mines and caves varied from 650 to 1,500 hours [G4, S14], significantly lower than commonly assumed 2,000 working hours per year. For different rooms in a thermal spa resort in South Africa, Botha et al. [B20] applied different occupancy hours (varying from 414 to 1,932 hours per year) to assess workers' annual effective doses from exposure to radon in the air. Some underground workplaces are used by workers as offices or storage rooms with no regular occupancy. For example, bank staff spent less than 130 hours per year in underground safe deposit rooms in Italy where radon concentrations were significantly elevated [T5]. In three fish culture stations in Pennsylvania, United States, radon concentration varied from 44 to 600 Bq/m^3 [L5]. Working hours in the hatch houses were limited due to the overall process of maintaining fish cultures; the occupancy time for workers varied from 4 to 629 hours per year. If location specific working hours are not given in an article, the typical 2,000 hours per year is conventionally used in the dose assessment.

142. The spectrum of workplaces other than mines where radon can present a hazard is wide. Underground workplaces can accumulate high radon levels in the same way as underground mines. Such workplaces include subways, tunnels, underground parking, caves, spas, close-out mines open to visitors and some underground stores/offices. Results of the literature review are summarized in table 11. The average values for workplace categories in this table are simple averages of reported values from literature review without population weighting (due to lack of information on numbers of workers in different workplaces). Table 11 shows the occupational radon exposure in different workplaces, which all have a wide range of average annual effective dose varying from 0.2 to 5.1 mSv. Radon exposure is generally higher in underground than in above-ground workplaces. The table also shows the complexity of the matter, with several factors influencing the occupational radon exposure.

143. Workers in the category of above-ground workplaces are the second largest group identified in annex B of the UNSCEAR 2000 Report [U8]. As shown in table 11, except in some storage rooms and certain parts of water treatment plants, radon concentrations in above-ground workplaces are generally low, and the resulting average annual effective dose is generally less than 1 mSv.

Table 11. Summary of radon exposure in workplaces other than mines

Source	*Practice*	*Average Rn (Bq/m^3) (range)*	*Average annual effective dose (mSv), (range)*	*References*
Underground	Show-cave/tourist-mine	3 090 (20–>30 000)	5.1 (0.01–50)	[A12, A15, C21, F6, F8, G4, L2, L8, S2, S14, T3, W1]
	Thermal spa/hot spring	250 (30–2 810)	3.4 (0.2–18)	[B20, C2, K2, L8, N6, N7, N10, S4, V8]
	Subway/tunnel/ parking garage	28 (5–85)	0.2 (0.04–0.6)	[F8, H10, H11]
	Laboratory/storage/ winery/office	400 (20–8 660)	2.7 (0.1–8.4)	[C6, F5, L8, R10, T5, V7]
Above-ground	School/university/ hospital	180 (10–1 360)	1.3 (0.1–9.8)	[A10, A18, B3, C7, C9, C15, I51, K11, M1, O10, S18, V8, V9, Z3]
	Office/business building	74 (23–273)	0.5 (0.2–2.0)	[A3, B3, B26, C6, C9, C14, C15, C18, E12, I51, O10, T5, W3, W5]
	Factory	66 (10–220)	0.43 (0.1–1.3)	[A6, I51, I52, M5, O10]
	Storage/wine cellar	190 (10–860)	1.4 (01–6.2)	[A10, B21, D3, S4]
	Water plant/fish hatchery	793 (20–2 720)	1.4 (0.01–4.7)	[A5, J2, R9, L5]

144. Even though information on numbers of workers in different above-ground workplaces is generally not available, one can expect that most workers are in factories or office/business buildings where average radon concentrations are generally below 100 Bq/m^3 and the associated annual effective doses below 1 mSv. From 2007 to 2017, more than 7,600 federally owned indoor workplaces in Canada were tested for radon [W5]. For a total of 255,557 public servants, the average radon concentration in federal workplaces was 34.3 Bq/m^3; the corresponding annual radon effective dose was 0.25 mSv (with F=0.4 and 2,000 working hours). A study by Whicker and McNaughton [W3] reported radon concentrations in the offices of Los Alamos National Laboratory with a mean value of 24.3 Bq/m^3 and an annual effective dose from radon exposure of 0.3 mSv (based on 2,000 working hours and F=0.4). In a national radon survey of bank companies in Italy, Trevisi et al. [T5] reported on more than 342,000 employees working in 311 bank workplaces. The radon levels in underground workplaces ranged from 27 to 4,851 Bq/m^3 with an overall mean value of 153 Bq/m^3.

145. With labour statistics in 2017, time statistics and more than 7,600 long-term radon measurements in various workplaces, occupational radon exposure in workplaces other than mines was assessed by Chen [C10] for a total of 18,709,820 workers in Canada. The assessment showed that the average annual effective dose due to radon exposure in workplaces other than mines was 0.21 mSv in Canada, significantly lower than the earlier, crude global estimate of 4.8 mSv, which was based on experience from the United Kingdom for workplaces exceeding 400 Bq/m^3 [U8, U10].

146. The available data from the current UNSCEAR Occupational Exposure Survey for radon in workplaces other than mines are given in table A.4 in the electronic attachment. Four countries have

reported data for the period 2003–2014. Even with these very limited data, the responses demonstrate considerable variation for the average annual effective dose, from 1.0 to 6.0 mSv.

147. Clearly, elevated levels of radon have been found in a number of countries, but the levels of exposure vary considerably according to the workplace. So far, owing to lack of information, the Committee has performed only crude estimates of the worldwide levels of exposure. Although the quantity of data available for the last two periods has increased, the sample sizes are still very small, and the levels of exposure depend on factors that vary from country to country, such as geology, building material, working conditions and regulatory regimes.

148. Although the data received by the UNSCEAR Occupational Exposure Survey are very limited, extensive new data have been reviewed from the literature as summarized in table 11. These data show that the average annual effective doses vary from 0.2 to 5.1 mSv for underground workplaces and from 0.4 to 1.4 mSv for above-ground workplaces. For workplaces other than mines, the majority (likely more than 99% according to Canadian labour statistics [C10]) are above ground. In view of this (i.e., above-ground factories and business buildings for the majority of workers), the average annual effective dose from radon exposure in workplaces other than mines is estimated to be 1.0 ± 0.5 mSv.

E. Conclusions on occupational exposure to natural sources of radiation

149. Because of the limited data available, the evaluation of the worldwide level of radiation exposure to natural sources has been possible for only some sectors. Civilian aviation, coal mineral extraction and processing, and mineral other than fuel minerals are the sectors for which the worldwide evaluation was conducted for the period 2010–2014. No evaluation for the gas and oil extraction sectors nor for radon exposure in workplaces other than mines was conducted.

150. The evaluation of occupational exposure due to cosmic radiation for civilian aviation is based on data from the UNSCEAR Occupational Exposure Survey and supplemented by data provided by ICAO. The additional personnel data have improved the evaluation compared to previous UNSCEAR reports [U8, U10]. For the periods 2000–2004, 2005–2009 and 2010–2014, the worldwide number of civilian aviation personnel is estimated to be ~450,000, ~600,000 and ~750,000, respectively. It has, thus, increased by a factor of about 2.5 compared to the period 1995–1999 [U10]. The average annual effective dose for workers is estimated to be 2.7, 2.8 and 2.7 mSv for the mentioned periods, respectively. This is in the same order of magnitude as previously estimated by the Committee [U8, U10]. The estimated global average annual collective effective dose for civilian aviation is 1,220, 1,680 and 2,030 man Sv for the periods 2000–2004, 2005–2009 and 2010–2014, respectively. The uncertainty interval for the worldwide number of workers ranges from 567,000 to 990,000 and the uncertainty interval for the worldwide average annual effective dose from 1.5 to 4.6 mSv.

151. Mining is an extensive industry. Employment in the mining industry is changing for a variety of interrelated reasons: commercial, political, technological, demographic and social. The net effect, however, has been a steady fall in the number of people employed in mining. According to the ILO, since the early 1990s, when about 25 million people were estimated to be employed in mining (including some 10 million in coal mining), the decline in employment has ranged from steady to more rapid at different times in different regions [I48]. Mining is still a male-dominated industry. Although more women are now working in all aspects of mining in some countries, any increase in female employment is generally very low.

152. The level of exposure in mines depends on a number of factors, including type of mine, geology, working conditions, technology and engineered controls such as ventilation systems. For coal mining, the UNSCEAR 1988 Report [U5] estimated the global average annual collective effective dose for mining as 2,000 man Sv. The UNSCEAR 2000 Report [U8] estimated worldwide average annual collective effective dose for coal mining as 2,700 man Sv, which is about 16% of the estimate value of 16,560 man Sv in the UNSCEAR 2008 Report [U10].

153. The estimated worldwide average annual collective effective dose is about 12,800 man Sv for the period 2010–2014. For coal extraction and processing, the estimated number of workers is about 10.9 million for 2000–2004, 8.8 million for 2005–2009 and 8.0 million for 2010–2014. The extrapolation of the workforce data is based on data for countries responsible for 56, 60 and 62% of the average total primary coal production for the periods 2000–2004, 2005–2009 and 2010–2014, respectively. For coal extraction and processing, the estimated average annual effective dose is about 2.3 mSv for 2000–2004, 2.1 mSv for 2005–2009 and 1.6 mSv for 2010–2014. There is gradual decrease in the average annual effective dose, from 2.4 mSv (1990–1995) [U10] to 1.6 mSv (2010–2014). The uncertainty interval for the worldwide number of workers for coal extraction and processing for the period 2010–2014 ranges from 4.9 to 13 million and the uncertainty interval for the worldwide average annual effective dose from 1.0 to 2.6 mSv. For extraction and processing industries other than fuel extraction industries, the estimated number of workers is about 3.8 million for 2010–2014. The estimated average annual effective dose is about 2.5 mSv and the estimated average annual collective effective dose is about 9,500 man Sv. The uncertainty interval for the worldwide number of workers for extraction and processing industries other than fuel extraction industries for the period 2010–2014 ranges from 2.3 to 6.2 million and the uncertainty interval for the worldwide average annual effective dose from 1.3 to 4.9 mSv. The current worldwide estimate of the workforce for mining and processing industries seems to be more solid than the previous ones since it is based on data of countries responsible for about 60% of the average annual total primary coal production and total mineral production other than uranium and oil. The level of radiation exposure in coal mining has declined compared to the UNSCEAR 2008 Report [U10], which is mainly due to decreasing levels of radiation exposure in China. It is probably due to the improvement of ventilation in government owned mines and the closing of smaller township and private mines. Despite the improvement in the data provided, there are still limitations regarding their representativeness.

154. The worldwide number of workers exposed to natural sources of radiation for the period 2010–2014 is estimated at a minimum of 12.6 million workers; 24,300 man Sv for the average annual collective effective dose; and about 1.9 mSv for the average annual effective dose weighted by the number of workers. The uncertainty interval for the worldwide number of workers for all three sectors of natural sources of radiation for the period 2010–2014 ranges from 7.8 to 20 million and the uncertainty interval for the worldwide average annual effective dose from 1.1 to 3.3 mSv. This is a rough estimate of the level of exposure to natural sources of radiation. Since the contributions of radiation exposure to oil and gas extraction and radon exposure in workplaces other than mines have not been estimated in the current analysis, the estimated values presented in table 12 are certainly an underestimate. The level of radiation exposure has decreased over time. This may reflect the radiation protection measures implemented in the concerned countries. A vast majority of workers exposed to natural sources of radiation are not individually monitored. In order to compare exposure estimations in table 12, the values for the period 1995–1999, were taken from table 91 of the UNSCEAR 2008 Report [U10], on total number of monitored workers, total average annual collective effective dose and total average annual effective dose, excluding the contribution from radon at workplaces other than mines.

155. Although the data received by the UNSCEAR Occupational Exposure Survey are very limited for radon exposure in workplaces other than mines, new data have been reviewed from the literature, as summarized in table 11. Extensive reviewed data from literature showed that the average annual effective doses vary from 0.2 to 5.1 mSv for underground workplaces and from 0.4 to 1.4 mSv for above-ground

workplaces. For workplaces other than mines, the majority (likely more than 99% according to Canadian labour statistics [C10]) are above-ground workplaces, such as factories and business buildings. In view of this fact, the average annual effective dose from radon exposure in workplaces other than mines is estimated to be 1.0 ± 0.5 mSv.

156. The worldwide level of occupational exposure for oil and gas extraction was not estimated due to the limited available data. Although an increasing number of countries responded to the simplified UNSCEAR Occupational Exposure Survey, no statistically significant correlation was found between the independent variables (GDP and oil production) and the dependent variable (workforce). The lack of correlation may be due to discrepancies in data provided by the countries, such as submission of total number of workers in the oil extraction industry or submission of data for the number of workers involved in tasks, e.g., maintenance. For future analysis, such data should be included.

Table 12. Summary of estimates of worldwide levels of annual occupational exposure for workers exposed to natural radiation sources, excluding oil and gas extraction, and radon exposure in workplaces other than mines

Categories	*1995–1999*	*2000–2004*	*2005–2009*	*2010–2014*
NUMBER OF MONITORED WORKERS (10^3)				
Civilian aviation	300	450	600	750
Coal extraction/processing	6 900	10 900	8 800	8 000
Mineral extraction/processing	4 600	[a]	[a]	3 800
Total	**11 800**[b]	[a]	[a]	**12 600**
AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE (man Sv)				
Civilian aviation	900	1 220	1 680	2 030
Coal extraction/processing	16 560	25 070	18 480	12 800
Mineral extraction/processing	13 800	[a]	[a]	9 500
Total	**31 260**[b]	[a]	[a]	**24 300**
AVERAGE ANNUAL EFFECTIVE DOSE (mSv)				
Civilian aviation	3.0	2.7	2.8	2.7
Coal extraction/processing	2.4	2.3	2.1	1.6
Mineral extraction/processing	3.0	[a]	[a]	2.5
Total	**2.7**[b]	[a]	[a]	**1.9**

[a] No worldwide estimation was possible because of limited data or no reliable data.

[b] These data, taken from table 91 of UNSCEAR 2008 Report [U10], exclude the contribution from radon at workplaces other than mines for reason of comparison.

IV. LEVELS AND TRENDS OF EXPOSURE TO HUMAN-MADE SOURCES OF RADIATION

A. Nuclear fuel cycle

157. A major source of occupational exposure is the operation of nuclear reactors to generate electrical energy. This involves a complex cycle of activities, including uranium mining and milling, uranium conversion and enrichment, fuel fabrication, reactor operation, decommissioning, spent fuel reprocessing, research and development activities, radioactive waste management, safeguards inspections, and transport. Occupational exposure arising from this sector was discussed and quantified in previous UNSCEAR reports: 1972 [U2], 1977 [U3], 1982 [U4], 1988 [U5], 1993 [U6], 2000 [U8], and 2008 [U10], with comprehensive evaluation in the UNSCEAR 1977, 1982, 2000 and 2008 Reports. In comparison with many other sources of exposure, the activities in the nuclear fuel cycle are well documented, and considerable quantities of data on occupational dose distributions are available, in particular for reactor operation. This annex considers occupational exposure arising at each main stage of the fuel cycle.

158. Each stage in the fuel cycle involves different types of workers and work activities. In some cases, e.g., for reactor operation, the data are well segregated while, in others, the available data span several activities, e.g., for uranium mining and milling. The data on occupational exposure for each activity is derived primarily from the UNSCEAR Occupational Exposure Survey [U3, U4, U5, U6, U8, U10]. Other sources exist, particularly the joint Organization for Economic Co-operation and Development's Nuclear Energy Agency (OECD/NEA) and IAEA Information System on Occupational Exposure (ISOE) [O3], which serves as a key source of occupational exposure data for reactor operation in the period 2000–2014, as do the Joint Reports by OECD/NEA and IAEA [O4, O5, O6, O7, O8].

159. For each stage of the fuel cycle, this annex provides estimates of the magnitude of and temporal trends in the average annual collective effective dose and per capita effective doses, and the numbers of monitored workers. The average annual collective effective doses are also expressed in normalized terms, i.e., per unit practice relevant to the particular stage of the cycle. For uranium mining and milling, uranium conversion and enrichment, fuel fabrication and spent fuel reprocessing, the normalization is initially presented in terms of unit mass of uranium or fuel produced or processed. An alternative way to normalize is in terms of the equivalent amount of energy that can be (or has been) generated by the fabricated (or enriched) fuel. The basis for the normalizations, i.e., the amount of mined uranium, the separation work during enrichment and the amount of fuel required to generate a unit of electrical energy in various reactor types, that were given in UNSCEAR 2008 Report, annex B [U10]. For reactors, the data may be normalized in several ways, depending on how they are to be used. In this annex, normalized average annual collective effective doses are given for each reactor type and per unit electrical energy generated.

1. Uranium mining

160. Previously, the mining of uranium generally involved underground or open-pit techniques to remove uranium ore from the ground followed by ore processing. The milling process involves the crushing and grinding of raw ores followed by chemical leaching, separation of uranium from the leachate and precipitation of yellowcake [K5], and drying and packaging of the final product for shipment.

161. Uranium ore can be extracted 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) or in situ recovery (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 generally a cost-effective method for extracting large volumes of lower-grade ore. These techniques may then be combined with other bulk extraction techniques (such as conventional milling, leaching and extraction, or alternative techniques such as heap leaching) that 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. ISL 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 [O9, U10, U18].

162. ISL for uranium has expanded rapidly since the 1990s, and is now the predominant method for mining uranium, accounting for 45% of the uranium mined worldwide in 2012. ISL extraction, also known as solution mining, or ISR in North America, involves leaving the ore where it is in the ground, and recovering the minerals from it by dissolving them and pumping the solution to the surface. A suitable leach solution (acidic or alkaline) is injected into the ore zone below the water table; thereby oxidizing, complexing, and mobilizing the uranium. Subsequently, the uranium bearing solution is brought to the surface through extraction or recovery wells for further processing [I13, I16].

163. Workers in the mining and milling of uranium ores are exposed to both external sources of radiation and intake of radionuclides. Mining operations such as drilling, blasting, loose-dressing, mucking, crushing, boulder-breaking, loading and dumping generate ore dust of different particle sizes, which become dispersed in the mine environment and give rise to an inhalation hazard. Concentrations of the ore dust are quite variable with time and location. Extremely high values can be reached during blasting and ore dumping. In general, these workplaces are very dusty and, consequently, there is a potential risk of inhalation of aerosol particles containing radionuclides from the ^{238}U decay chain. Doses due to intake of radionuclides depend on workplace conditions, which vary considerably according to the type of mine (underground or above ground), the ore grade, the airborne concentrations of radioactive particles (which vary depending on the type of mining operation and the quality of ventilation) and the particle size distribution. In underground mines, the main source of doses due to intake of radionuclides is radon and its decay products. Because of the confined space underground and practical limitations to the degree of ventilation that can be provided, the total committed dose is of greater consequence in underground mines than in open-pit mines. In open-pit mines, the inhalation of radioactive ore dust is generally the largest source of committed dose, although the doses tend to be low. Higher doses resulting from this source would be expected in ore milling and in the production of yellowcake. Intake of radionuclides makes the greatest contribution to the total effective dose resulting from underground mining.

164. Most natural uranium is mined for electrical energy production in fission reactors, but it is also used in nuclear research reactors and in military activities. Commercial uranium use is determined primarily by the fuel consumption requirements of power reactors and continues to increase steadily, while the requirements for research reactors remain modest by comparison.

165. Between 2000 and 2014, uranium production was concentrated in 22 countries. Global uranium production increased by a factor of 1.6 between 2000 and 2014, mainly as the result of rising production in Kazakhstan and Namibia. The five-year average of annual uranium production in the world increased from 37 kt (in 2000–2004) to 57 kt (in 2010–2014) [O4, O5, O6, O7, O8, O9]. The average of annual uranium production is shown in table 13 for each country included in the subsector. The 10 countries with the largest production (Kazakhstan (37%), Canada (16%), Australia (11%), Niger (8%), Namibia (7%), Russian Federation (5%), Uzbekistan (5%), China (3%), United States (3%) and Ukraine (2%)) account for 96% of the world production in 2010–2014.

Table 13. Average worldwide uranium production [O9, U10]

OP: Open pit; ISL: In situ leach; CoP: Co-product/by-product; UG: Underground

Countries	*Types of mining*	*Average annual uranium production for each period (tonnes U)*		
		2000–2004	*2005–2009*	*2010–2014*
Australia	OP, ISL, CoP	7 742	8 415	6 062
Brazil	OP	146	257	197
Canada	OP, UG	11 373	10 028	9 277
China	UG, ISL	718	836	1 450
Czechia	UG, ISL	458	325	216
France	CoP	103	4	5
Germany		101	40	34
Hungary	CoP	7	2	3
India	UG	225	250	391
Iran (Islamic Republic of)	OP		5	12
Kazakhstan	ISL	2 771	7 758	20 757
Malawi	OP		18	825
Namibia	OP	2 472	3 607	4 066
Niger	OP, UG	3 051	3 239	4 407
Pakistan		37	43	45
Romania		88	84	80
Russian Federation	ISL, UG	3 013	3 395	3 109
South Africa	CoP	803	575	540
Spain		62		
Ukraine	OP, UG	791	817	920
United States	OP, ISL, UG	1 030	1 562	1 712
Uzbekistan	ISL	1 904	2 354	2 575
Total		**~36 900**	**~43 600**	**~56 700**

166. uranium mining workforce may be exposed externally to gamma rays emitted from ore, process material, products, and tailings, and exposed internally from the inhalation of long-lived radionuclide dust, radon and radon progeny, and through ingestion and wound contamination. A detailed dose assessment was conducted for each type of uranium mining through the Information System on Uranium Mining Exposure (UMEX). The survey contains official data provided by 36 countries and 5 national reports prepared by the IAEA. The average annual effective dose for each type of mining and processing method and for the components of each pathway of exposure derived from the UMEX survey are presented in table 14. Extraction by ISL results in higher average annual effective dose (3.9 mSv) followed by underground mining (1.8 mSv), open-pit (open cut) mining (1.5 mSv), open pit (open cut) processing (1.4 mSv), underground processing (0.5 mSv) and other techniques (0.9 mSv) [I16].

The exposure from external gamma radiation for the ISL technique is not corrected for natural background exposure, and the annual effective dose may be overestimated by some 0.5 to 1 mSv.

167. The ISL extraction technique has become the dominant uranium mining and processing method, increasing from 17% (2000–2004) to 46% (2010–2014). Underground mining has decreased over time: 42% (2000–2004) to 28% (2010–2014). Open-pit mining has also decreased over time: 28% (2000–2004) to 19% (2010–2014), as presented in table 15. Most uranium mining in Kazakhstan, Uzbekistan and the United States uses ISL extraction methods, also used in Australia, China and the Russian Federation [O4, O5, O6, O7, O9].

Table 14. Average annual effective dose components of each pathway of exposure in different types of mining and processing derived from the UMEX survey [I16]

LLRD: Long-lived radionuclide dust; RnP: Radon and its progeny

Types of mining	*Average annual effective doses (mSv)*			
	External gamma irradiation	*LLRD*	*RnP*	*Total*
Underground mining	0.85	0.18	0.80	1.83
Underground milling	0.24	0.18	0.12	0.54
Open pit mining	0.74	0.45	0.28	1.47
Open pit milling	0.52	0.54	0.38	1.44
In situ leaching (extraction and processing)	2.50[a]	0.36	1.07	3.93
Other	0.49	0.23	0.21	0.93

[a] Not corrected for background exposure, which could lead to an overestimation of 0.5–1 mSv per year.

Table 15. Distribution of worldwide uranium production [O4, O5, O6, O7, O8, O9]

Type of mining	*Percentage distribution of world uranium production (%)*		
	2000–2004	*2005–2009*	*2010–2014*
Open pit	28	26	19
Underground	42	36	28
In situ leaching	17	27	46
Heap leaching (stope or block)	2	2	0.6
In-place leaching	<0.1	<0.1	0.0
Co-product/by-product	10	9	7
Other methods[a]	0.5	0.1	0.5

[a] Includes mine water treatment and environmental restoration.

168. Occupational exposure data from the current UNSCEAR Occupational Exposure Survey for uranium mining in the nuclear fuel cycle are given in table A.5 in the electronic attachment. For uranium mining, three countries provided occupational exposure data for 2000–2004 (Australia, Canada and Czechia), which account for 53% of the total average annual uranium production for 2000–2004. Additional workforce data for countries responsible for 45% of the world uranium production were

obtained from the Joint Reports by OECD/NEA and IAEA [O4, O5]. For the period (2005–2009), five countries responded to the UNSCEAR Occupational Exposure Survey (Australia, Canada, China, Czechia and France). These countries account for 45% of the total average annual uranium production for the period 2005–2009. The workforce data for countries responsible for another 46% of uranium production were obtained from the Joint Reports by OECD/NEA and IAEA [O6, O7]. For the period 2010–2014, seven countries responded to the UNSCEAR Occupational Exposure Survey (Australia, Canada, China, Czechia, France, India and Russian Federation). These countries are responsible for 36% of the total average annual uranium production for the period 2010–2014. The workforce data for countries which account for 56% of uranium production were obtained from the Joint Report by NEA and IAEA [O9]. The number of workers obtained from this Joint Report includes the workforce from the mining and processing industries. Therefore, the current evaluation of occupational exposure in uranium production industry does not separate the uranium mining and uranium milling subsectors.

169. The workforce data obtained from the UNSCEAR Occupational Exposure Survey and from the Joint Reports by OECD/NEA and IAEA cover 99% of the worldwide average uranium production for the period 2000–2004, 91% of the uranium production for the period 2005–2009 and 95% of the uranium production for the period 2010–2014. Therefore, no extrapolation was needed. The number of workers from the countries that reported occupational exposure data in the period 2000–2004 represents 12% of the global workforce and for the period 2010–2014 even 46%. On the basis of a trend of greater global workforce representation in the survey, the average annual effective dose for monitored workers obtained from the survey was applied to the entire global workforce. The analysis is complicated by a shift in the mineral extraction process (from open pit and underground mining to a greater use of ISL technique) between the periods 2000–2004 and 2010–2014 (table 15). As illustrated in table 14, mining using ISL technique may result in significantly greater individual exposure than open pit or underground mining, however an accurate background correction was not performed for these data. While production and workforce data are considered to have acceptable representativeness, there may be no correlation with monitored worker exposure and the global estimate.

170. The estimation of worldwide exposure in uranium mining activities is based on the average annual effective dose reported by countries in the UNSCEAR Occupational Exposure Survey: 2.7 mSv for 2000–2004, 2.5 mSv for 2005–2009 and 2.8 mSv for 2010–2014, with the assumption that the values are representative averages for all such activities, and using data on the size of workforce also from the Joint Report by NEA and IAEA [O8].

171. Trends of exposure in mining are presented in table 16 and figure I. Uranium production has gone through three cycles over the past 40 years, which includes an initial period (1975–1989) of moderate growth followed by a period of significant reduction of about 40% (2000–2004). Recently (2010–2014), uranium production again increased to 57 kt, similar to the levels experienced in the 1970s and 1980s. During the same 40-year period, the estimated annual number of monitored workers substantially decreased (from 240,000 in 1975–1979 to a low of 22,000 in 1995–1999); in the three latest five-year periods (2000–2014), the estimated annual number of workers increased again to 44,000. Over the initial 25 years of evaluation (1975–1999), the average annual effective dose was around 4 to 5 mSv. During the past three periods, the average annual effective dose is estimated to have been fairly constant at a level somewhat less than 3 mSv. The average annual collective effective dose coupled with mining followed the same pattern of number of workers, decreasing from 1,300 man Sv (1975–1979) to around 80 man Sv (2000–2004) and then increasing again to around 120 man Sv (2010–2014). Over the 40 years of evaluation, the average annual collective effective dose per unit uranium produced significantly decreased from 26 to 2 man Sv/kt U, (table 16 and figure I). Further, the average annual collective effective dose per unit energy generated significantly decreased from 5.9 to 0.5 man Sv/GWa (table A.5 in the electronic attachment).

Table 16. Estimates of worldwide levels of annual exposure in uranium mining

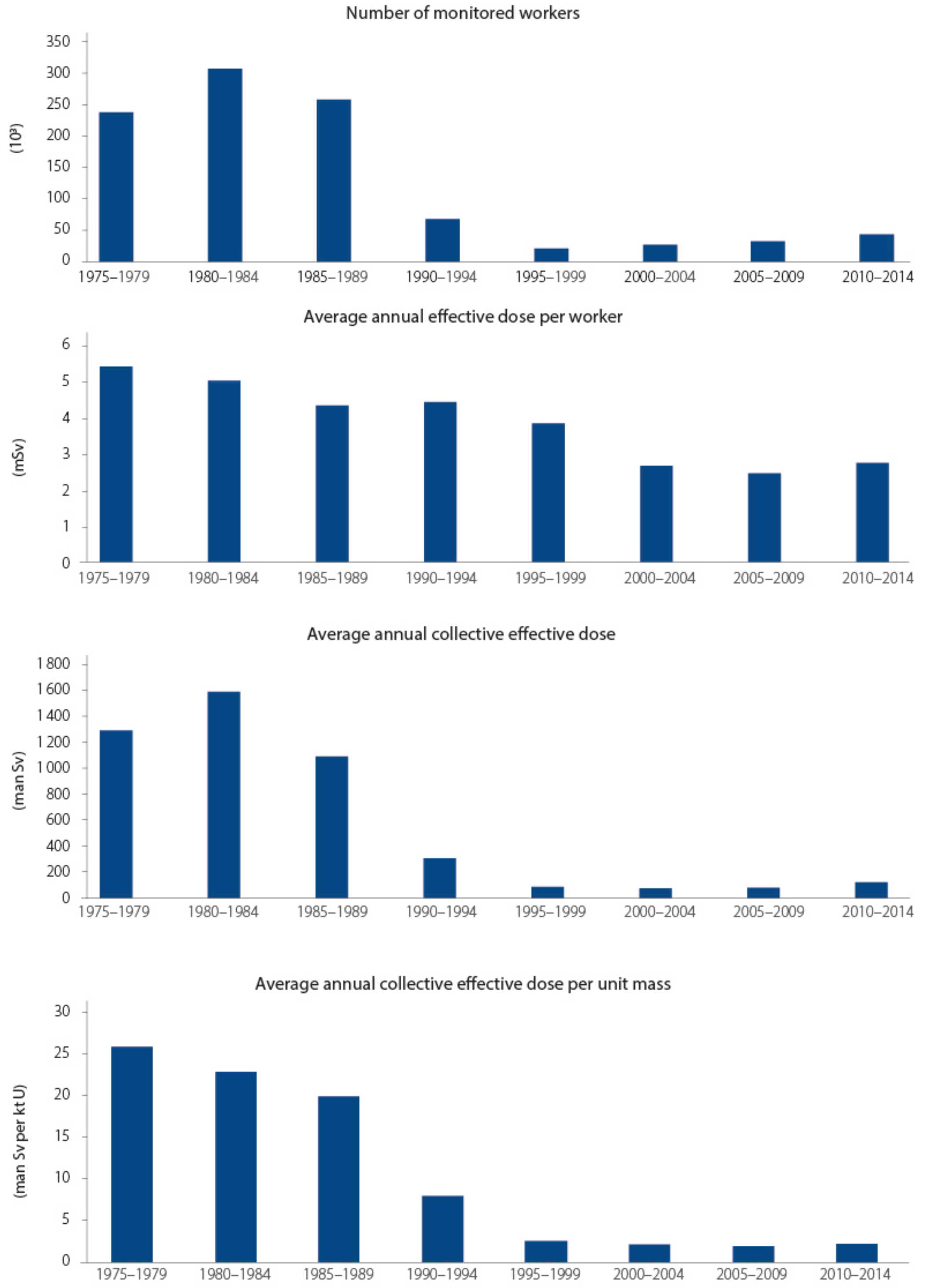
Period	*Annual amount of U production (kt U)*	*Average annual collective effective dose per unit mass (man Sv/kt U)*	*Number of monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979[a]	52	26	240	1 300	5.5
1980–1984[a]	64	23	310	1 600	5.1
1985–1989[a]	59	20	260	1 100	4.4
1990–1994[a]	39	8	69	310	4.5
1995–1999[a]	34	2.5	22	85	3.9
2000–2004	37	2.1	28	77	2.7
2005–2009	44	1.9	33	82	2.5
2010–2014	57	2.2	44	123	2.8

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

172. According to the UMEX survey, during most of the milling process the material is wet so usually gamma exposure will dominate. However, during final product drying and packaging, the material is dry and inhalation of long-lived radionuclide dust is likely to dominate the dose. Generally, it is in the final product area that the highest occupational doses are recorded in a processing facility. Table 14 presents the average annual effective doses obtained from the UMEX survey: 3.93 mSv for ISL (extraction and processing), 1.44 mSv for open-pit milling and 0.54 mSv for underground milling [I16].

173. Occupational exposure data from the current UNSCEAR Occupational Exposure Survey for uranium milling in the nuclear fuel cycle are given in table A.6 in the electronic attachment. Five countries reported exposure data within the period 2000–2014. The average annual effective dose for monitored workers ranges from 0.41 mSv (India, 2010–2014), to 3.8 mSv (Czechia, 2010–2014). In the survey, Australia and Canada reported that for uranium milling, the contribution to the total effective dose from internal exposure (inhalation of dust and radon) was larger than the contribution from external exposure. One country, Canada, reported that 6% of monitored workers were female in uranium milling. The total average annual collective effective dose for the countries that responded to the survey for the period 2010–2014 was 4.2 man Sv (table A.6 in the electronic attachment).

Figure I. Estimated worldwide trends in occupational exposure due to uranium mining



2. Uranium conversion and enrichment

174. Uranium conversion and enrichment is the process by which the final product from the milling process (e.g., U_3O_8, UO_4, UO_2 or $(NH_4)_2U_2O_7$) is converted to a gaseous form before the concentration of ^{235}U is enriched. Most light water reactors (LWRs) use fuel slightly enriched in ^{235}U (generally about 3–5%). In contrast, gas-cooled reactors (GCRs) and heavy water reactors (HWRs) use natural (unenriched) uranium, which contains about 0.7% of ^{235}U. Some older research reactors use high-enriched uranium (up to 98% of ^{235}U). For example, the U_3O_8 from the milling process is converted to UO_2 by a reduction reaction with an acid. The UO_2 is converted to uranium tetrafluoride (UF_4) by the addition of hydrofluoric acid and then to uranium hexafluoride (UF_6) using fluorine gas (F_2). The enrichment process requires the uranium to be in a gaseous form, since most enrichment is performed by gas centrifugation techniques which use thousands of rapidly spinning vertical tubes that separate ^{235}U from the slightly heavier ^{238}U isotope. The global uranium conversion capacity summarized in table 17 are based on data from the World Nuclear Association (WNA) [W7, W8, W9, W10, W11, W12].

Table 17. Global conversion capacity for the period 2005 to 2015 [W7, W8, W9, W10, W11, W12]

Country	*Location*	*Year*	*Nameplate capacity (tU)*	*Capacity utilization (%)*	*Capacity utilization (tU)*
Brazil	Sao Paulo	2005–2011	90		
		2013	40	70	28
		2015	100	70	70
Canada	Port Hope	2005–2015	12 500	70	8 750–14 000
China	Lanzhou & Hengyang	2005	1 000		
		2007–2011	3 000		3 650
		2013–2015	3 650–4 000		4 000
France	Pierrelatte	2005–2014	14 000–15 000	70	14 000
Russian Federation	Angarsk Seversk	2005–2007	15 000		
		2009–2013	25 000	55	12 000–18 000
		2015	12 500		12 500
United Kingdom	Springfields	2005–2013	6 000		5 000
United States	Metropolis	2005	14 000		
		2007	17 600		13 000
		2009–2013	15 000	70	
		2015	15 000	70	10 500
Total		**2005**	**62 590**		
		2007	**68 690**		**64 590**
		2009	**76 090**		**64 590**
		2011	**75 590**		**55 531**
		2013	**76 190**	**68**	**51 478**
		2015	**59 100**	**78**	**46 320**

175. Uranium conversion plants are operating commercially in Canada, China, France, the Russian Federation, and the United States (table 17). As a result of low demand for commercial nuclear power plant fuel and excess inventories of uranium, four primary producers have either reduced (Cameco) or

suspended production at their conversion facilities (ConverDyn) or closed permanently (Springfields Fuels, United Kingdom) and two out of three Rosatom facilities (Russian Federation), while only one new conversion plant (Orano's Philippe Coste) has started operation to replace equivalent shuttered capacity at the same site. Large commercial enrichment plants are in operation in France, Germany, the Netherlands, the Russian Federation, the United Kingdom, and the United States, and a few smaller plants are operating elsewhere (e.g., Argentina, Brazil, India, Islamic Republic of Iran and Pakistan).

176. Exposure data for uranium enrichment are given in table A.7 in the electronic attachment. For 2003–2014, the reported data represent merely 20–40% of the world enrichment activities and cannot be said to be globally representative. Consequently, the Committee was unable to estimate worldwide numbers due to a lack of data. According to the reported data, the average annual effective dose to monitored workers was low and remained at a level of about 0.1 mSv between 1990 and 2014. The total average number of reported monitored workers and the resulting total collective dose were somewhat lower during 2003–2014 than during 1995–2002, about 10,000 monitored workers and about 1 man Sv. However, as stated in table A.7, since data are missing from some major enrichment facilities, care should be taken in drawing global conclusions or comparisons. Nevertheless, it can be concluded that the individual and collective doses arising from uranium conversion and enrichment remain relatively low.

177. Occupational exposure (external and internal) occurs during the conversion and enrichment stages of the fuel cycle. Inhalation of yellowcake, UF_4, uranium dioxide (UO_2), uranium trioxide (UO_3), uranyl fluoride (UO_2F_2), and UF_6 gases may occur at different stages of the uranium conversion process. The activities with the greatest potential for inhalation exposure are yellowcake sampling, removal of ash waste following purification, and maintenance activities. Inadvertent release of UF_6 may occur during sampling, UF_6 cylinder loading and unloading, and maintenance activities [S16]. External radiation exposure generally contributes more to occupational worker exposure than internal radiation exposure does for these stages. Limited worker exposure data was obtained for the conversion stage. Average annual collective effective dose for the Honeywell International facility (United States) varied between 1.5 and 1.6 man Sv between the 2006–2009 and 2010–2014 periods. The average annual effective dose to monitored workers decreased from 1.95 to 1.33 mSv for the 2006–2009 and 2010–2014 periods. The average annual effective dose for measurably exposed workers decreased from 2.11 to 1.42 mSv for these same periods. The Cameco facility in Port Hope, Canada, is both a conversion and fabrication facility. As such, occupational exposure for the conversion stage at Port Hope is reported under the fuel fabrication stage in table A.8 in the electronic attachment.

3. Fuel fabrication

178. Fuel fabrication facilities convert natural or enriched uranium into fuel for nuclear reactors. Fuel fabrication for LWRs typically begins with the receipt of low-enriched uranium (UF_6) from an enrichment plant. The UF_6 is heated to form a gas, and then the UF_6 gas is chemically processed to form uranium dioxide (UO_2) powder. This powder is then pressed into pellets, sintered into ceramic form, loaded into zircaloy tubes, and constructed into fuel assemblies. In the case of HWRs that use natural uranium as fuel, the fabrication process does not entail the handling of enriched ^{235}U (e.g., UF_6 or uranyl nitrate solutions). Following the conversion of the final product from the milling process into UO_3, further processing converts this into ammonium diuranate ($(NH_4)_2U_2O_7$), or ammonium uranyl carbonate ($UO_2CO_3 \cdot 2(NH_4)_2CO_3$), which is then reduced to form reactor grade (high purity) UO_2. Dry natural UO_2 powder is pressed into pellets, sintered, and loaded into zircaloy tubes. The global fuel fabrication capacity is summarized in table 18 for LWRs and table 19 for HWRs.

179. The major process safety concerns at nuclear fuel fabrication facilities are those of fluoride handling. Workers may be exposed to ammonium diuranate, ($(NH_4)_2U_2O_7$), UO_2F_2, and UO_2 powder. The primary inhalation hazard is from uranium dioxide powder during packaging and unpackaging, powder handling and pellet production, and maintenance activities. The risk of exposure is managed through the rigorous control of material.

Table 18. World fuel fabrication capacity of light water reactors [W13]

tHM: tonnes of heavy metal

Country	*Location*	*Fuel fabrication capacity (tonnes per year)*		
		Conversion	*Pelletizing*	*Rod/assembly*
Brazil	Resende	160	120	400
China	Yibin	800	800	800
	Baotou [a]	200	200	600
France	Romans	1 800	1 400	1 400
Germany	Lingen	800	650	650
India	Hyderabad	48	48	48
Japan	Kumatori	0	383	284
	Tokai-Mura [a]	450	690	690
	Kurihama	0	620	630
Kazakhstan	Oskemen	0	108	0
Republic of Korea	Daejeon	700	700	700
Russian Federation	Elektrostal [b]	1 500	1 500	1 560
	Novosibirsk	450	1 200	1 200
Spain	Juzbado	0	500	500
Sweden	Västeras	787	600	600
United Kingdom	Springfields [c]	950	600	860
United States	Richland	1 200	1 200	1 200
	Wilmington	1 200	1 000	1 000
	Columbia	1 600	1 594	2 154
Total		**12 645**	**13 913**	**15 276**

[a] Includes fuel fabrication capacities of two companies.

[b] Includes approximately 220 tHM for high-power channel reactors.

[c] Includes approximately 200 tHM for advanced gas-cooled reactors.

Table 19. World fuel fabrication capacity of pressurized heavy water reactors [W13]

Country	*Location*	*Rod/assembly (tonnes per year)*
Argentina	Cordoba and Eizeiza	160
Canada	Port Hope	1 500
	Peterborough	1 500
China	Baotou	246
India	Hyderabad	1 000
Pakistan	Chashma	20
Republic of Korea	Taejon	400
Romania	Pitesti	250
Total		**5 076**

180. The estimated exposure data for fuel fabrication are given in table 20 and table A.8 in the electronic attachment. This information was provided by countries that responded to the UNSCEAR Occupational Exposure Survey and represents approximately 80% of the fuel fabrication workforce. Exposure data were not obtained from several countries, but the information submitted is considered representative of the entire subsector and a global estimate was made with relatively good confidence on the basis of the amount of reactor fuel produced and that this fuel was fabricated for LWRs and HWRs. The average annual number of monitored workers has been reasonably constant for all five-year periods since 1975 at about 20,000 but with a small peak of 28,000 in the 1985–1989 period. The worldwide average annual number of measurably exposed workers in the periods 1990–1994 and 1995–1999 was estimated to be approximately 10,000—about half the number of monitored workers. On the basis of the current survey, this estimation remains valid. The estimated average annual collective dose showed a decline, from 36 to 21 man Sv, between the first two five-year periods, and little change over the next two periods, with the value for 1990–1994 being approximately 22 man Sv, and then increased to about 30 man Sv for 1995–1999. It then gradually decreased during the last three periods, to a value below 20 man Sv. The average annual effective dose to monitored workers showed an initial decline, from 1.8 to 1.0 mSv, during the first 5-year periods, increased to 1.4 mSv at the end of the 1990s, and then finally decreased again to about 0.9 mSv.

Table 20. Estimated worldwide levels of annual occupational exposure due to fuel fabrication

Period	*Number of monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose to monitored workers (mSv)*
1975–1979[a]	20	36	1.8
1980–1984[a]	21	21	1.0
1985–1989[a]	28	22	0.8
1990–1994[a]	21	22	1.0
1995–1999[a]	22	30	1.4
2000–2004	23	26	1.2
2005–2009	21	19	0.9
2010–2014	20	17	0.9

[a] Values from earlier UNSCEAR reports [U6, U8].

181. The increase in the average annual effective dose for measurably exposed workers in the 1995–1999 period could have been because some countries began to include the dose due to internal exposure in their dose records. There are two main sources of exposure in the fabrication of nuclear fuel: external exposure to gamma radiation and internal exposure resulting from the inhalation of airborne material. Beginning in 1994, the United States combined internal and external radiation exposure data in their national reporting for nuclear fuel cycle workers. According to the report of the United States Nuclear Regulatory Commission [U19], the annual collective dose increased threefold due to the inclusion of internal dose from the inhalation of uranium. This change in national reporting accounted for 80% of the increase in average annual collective effective dose for the 1995–1999 period. In Sweden, the monitoring method for internal exposure to uranium was improved in 2008, which then revealed significantly higher effective doses to specific workers, and a higher annual collective effective dose for related five-year periods.

182. The internal dose component depends also on the type of nuclear fuel. Occupational exposure in the production of nuclear fuel is expected to be lower for fuel involving only natural uranium than for that involving enriched uranium. The type of dose recorded in the national database can be a source of discrepancy between countries. Some countries record only doses due to external exposure and others record doses due to both internal and external exposure. Moreover, some countries include workers who do not work in controlled areas in their individual monitoring programme. The variation in types of nuclear fuel also influences the comparison of doses between countries.

183. In summary, the average annual collective effective dose and effective dose for monitored and measurably exposed workers related to fuel fabrication in the nuclear sector has decreased since the 1995–1999 period. The countries included in table A.8 in the electronic attachment account for 75–80% of the annual global production capacity for uranium pelleting and fuel rod assembly [W13].

4. Nuclear power reactor operation

184. Reactors used for electrical energy generation are characterized by their coolant system and moderator: light-water-moderated and cooled pressurized water reactors (PWRs); light-water-moderated and cooled, boiling water reactors (BWRs); pressurized heavy-water-moderated and –cooled reactors (HWRs); gas-cooled graphite-moderated reactors (GCRs), in which the gas coolant, either carbon dioxide or helium, flows through a solid graphite moderator; and light-water-cooled, graphite-moderated reactors (LWGRs). These are all thermal reactors, in which the moderator material is used to slow down fast fission neutrons to thermal energies. Fast-breeder reactors (FBRs) at present make a minor contribution to electrical energy production.

185. Occupational exposure can vary significantly from reactor to reactor and is influenced by such factors as reactor size, age and type. Several broad categories for commercial nuclear power reactors currently in operation include PWRs, BWRs, GCRs (which include older Magnox reactors) and also newer generation reactors, advanced gas-cooled reactors (AGRs), HWRs and LWGRs. Within each category, much diversity of design and diversity in the refuelling schedule can be seen, which may contribute to differences in occupational exposure. In addition, changes in operating circumstances can alter the exposure at the same reactor from one year to the next. Some of these variations will be discussed in this section.

186. Thirteen countries responded to the UNSCEAR Occupational Exposure Survey and provided occupational exposure data for operating commercial nuclear power reactors (2000–2014). In addition, data on exposure of workers at operating nuclear power reactors are available from ISOE. These data

have been published annually as ISOE reports from the OECD/NEA since 1992. The ISOE report [O3] contains information on average annual collective effective dose trends for the nuclear power industry in the OECD Member States. These trends include those related to occupational exposure from operating reactors and from definitely shutdown reactors. They also include occupational exposure data (e.g., average annual collective effective dose, average annual effective doses and number of workers per reactor by country and type of reactor). The ISOE report [O3] also contains occupational exposure data from 76 participating utilities from 29 Member States. This includes data from the database for a total of 377 operating reactor units and 57 shutdown reactors, covering about 90% of the world's operating commercial reactors. The data provided in response to the UNSCEAR Occupational Exposure Survey and ISOE data are presented in table A.9 in the electronic attachment.

187. The average number of operating reactors over the evaluated period is 440 for 2000–2004, 439 for 2005–2009 and 451 for 2010–2014. The average number of PWRs increased from 263 to 274 from 2000–2004 to 2010–2014. The average number of BWRs increased from 91 (2000–2004) to 94 (2005–2009) and then decreased to 87 (2010–2014). The average number of HWRs progressively increased from 37 (2000–2004) to 59 (2010–2014). However, the number of GCRs and LWGRs has decreased from 31 to 17 and from 19 to 15 over the past three periods, respectively. The average number of nuclear power reactors in operation and the average electrical energy generated per country and type of reactor for each period (2000–2004, 2005–2009 and 2010–2014) are presented in table A.9 in the electronic attachment. The average annual electrical energy generated during 2000–2004 was 288 GWa; during 2005–2009 297 GWa, and during 2010–2014 279 GWa.

188. Data on occupational exposure for reactors of each type and a worldwide summary by reactor type and generated energy are given by country in table A.9 in the electronic attachment. Worldwide levels of exposure have been estimated from the data obtained from the UNSCEAR Occupational Exposure Survey and from ISOE. The extrapolations are based on the generated electrical energy per type of reactor in operation. Very little extrapolation was needed, as the data on annual collective effective dose were substantially complete; close to 100% for PWRs and GCRs, about 94% for BWRs, and 88% for HWRs. However, for LWGRs, exposure data were provided from only 6% of the operating reactors. Previous UNSCEAR evaluations treated FBRs and high-temperature graphite reactors (HTGRs) separately. No data were provided on these either in the ISOE database or in response to the UNSCEAR Occupational Exposure Survey, and only two FBRs (Beloyarsk-3 and -4) were in operation between 2000 and 2014. The UNSCEAR 1993 and 1988 Reports [U5, U6] concluded that they made a negligible contribution to occupational exposure and, hence, would not be considered further.

189. The procedures for the recording and inclusion of doses incurred by workers who regularly carry out their work on the premises or site of another employer and who may be exposed due to the site operator's use of radiation or who may take onto a site their own source of radiation (such workers, referred to as itinerant or outside workers, are often employed by contractors) may differ from utility to utility and country to country [I15]. This may influence the respective statistics in different ways. In some cases, itinerant/outside workers may appear in the annual statistics for a given reactor several times in one year (whereas they should rather appear, with the summed dose recorded, once only). If appropriate corrections are not made, then statistics so compiled will inevitably overestimate the size of the exposed workforce and underestimate the average individual dose and also the fractions of the workforce and the average annual collective effective dose arising from individual doses above the prescribed levels. This will be important only where transient itinerant workers are used extensively and where no central point for the collection and maintenance of dose records (e.g., national dose registry) is used. For example, this may be important for reactor operations when itinerant workers are hired to assist with reactor refuelling and maintenance (i.e., outages). Many hundreds of itinerant workers will augment the permanent workforce at an operating reactor for several weeks or months until the maintenance and refuelling activities are completed.

190. Countries differ in how they present information on the exposure of workers at nuclear installations. The majority present statistics for the whole workforce, i.e., employees of the utility and itinerant workers, often with separate data for each category; some provide data for utility employees only, whereas others present the average annual collective effective dose for the total workforce but individual doses for the utility workers only.

191. The type of reactor is just one factor influencing the doses received by workers. Other basic features of the reactor play a role, including the piping and shielding configuration, fuel failure history, reactor water chemistry, and work procedures and conditions at the reactor. All of these can differ from site to site, even between reactors of the same type, contributing to the differences seen in occupational exposure. At all reactors, external irradiation by gamma rays is the most significant contributor to occupational exposure. The exposure occurs mostly during scheduled maintenance/refuelling outages. For the most part, such exposure is due to activation products (^{60}Co, ^{58}Co, ^{110m}Ag, ^{124}Sb); however, when fuel failures occur, fission products (^{95}Zr, ^{137}Cs) may also contribute to external exposure. At BWRs, workers in the turbine hall incur some additional external exposure due to ^{16}N, an activation product with energetic gamma radiation (6.13 and 7.11 MeV), carried by the primary circulating water through the turbines. In HWRs, heavy water is used as both coolant and moderator. Neutron activation of deuterium produces a significant amount of tritium in these reactors so, in addition to the usual external exposure, workers receive internal exposure due to tritium, which is a pure beta-emitter with low electron energy, on average only 5.7 keV.

192. The estimation of workforce exposure worldwide in reactor operation is based on the average generated energy, per type of reactor, per country, and on reported data on average annual collective dose. The average annual effective dose for monitored workers is calculated for countries with a reported number of workers and is assumed to be representative for all the workforce for each reactor type and period. The total number of workers is estimated using collective dose and average annual effective dose for each reactor type. The data are presented in table A.9 in the electronic attachment.

193. PWRs constitute the majority of installed nuclear generating capacity for the period 2000–2014, followed by BWRs (table A.9 in the electronic attachment). Averaged over the whole period, 89% of the total energy was generated in LWRs (of this 68% was from PWRs and 21% from BWRs), with contributions of 5.7% for HWRs, 2.3% for GCRs and 2.9% for LWGRs. FBRs contribute only about 0.1% of the total energy generated. There are significant differences between occupational exposure at PWRs and that at BWRs, therefore, each type of reactor is considered separately.

(a) *Light water reactors*

Pressurized water reactors

194. External exposure due to gamma radiation is the main source of occupational exposure at PWRs. Since, in general, only a small contribution comes from internal exposure, it is rarely monitored. The contribution of neutrons to the overall level of external exposure is insignificant. Most occupational exposure occurs during scheduled plant shutdowns, when planned maintenance and other tasks are undertaken, and during unplanned maintenance and safety modifications. Activation products and, to a lesser extent, fission products within the primary circuit and coolant, are the main source of external exposure. The material used in the primary circuit, the primary coolant chemistry, the reactor's design, and operational features, and the extent of unplanned maintenance all influence the magnitude of the exposure resulting from this source. Significant changes over time in many of these areas have affected the levels of exposure. One of the main non-standard maintenance operations associated with significant dose is the replacement of steam generators [U8]. By far the largest numbers of operating PWRs are

located in the United States, France and Japan. These three countries operate about 55% of the operating PWRs. In general, more than half of the energy (55%) generated by PWRs in the 2010–2014 period was produced in the United States and France. Another 30% was generated in the Republic of Korea (7%), China (6%), the Russian Federation (5%), Ukraine (5%) and Germany (5%). Electricity generation by PWRs in Japan decreased to 5.8 GWa during the 2010–2014 period due in part to the shutdown of their PWR fleet in 2011.

195. The average worldwide number of PWRs increased from 78 in 1975–1979 to 274 in 2010–2014. The corresponding average annual electrical energy generated increased much more, from 27 to 195 GWa. The number of monitored workers at PWRs increased from about 63,000 to 230,000 in 1985–1989. Between the periods 1985–1989 and 2005–2009, the numbers ranged from 230,000 to 310,000. In the recent period 2010–2014, the number of monitored workers increased to 370,000 (figures II and III, table 21 and table A.9 in the electronic attachment) [U10]. Overall, the number of measurably exposed workers is about 40% of that for monitored workers during 2010–2014. Between the first two periods, the average annual collective effective dose increased by a factor of about two, from 220 to 450 man Sv. Between 1985 and 1999, the estimated average annual collective effective dose fluctuated in a range from 400 to 500 man Sv. In the last three periods, it decreased by a factor of three: 227 man Sv in 2000–2004, 192 in 2005–2009 and 146 in 2010–2014. Over the past three decades, annual collective effective dose has been decreasing at PWRs. This decrease in collective dose is best demonstrated by examining average annual collective effective dose per operating reactor and per electrical energy generated in a year (table 21). The gradual decrease in the average annual collective effective dose per reactor and average annual collective effective dose per energy generated is most likely the result of continual improvement of protection measures with improved reactor design and operational procedures, and of measures to reduce the source term in the reactor primary cooling system.

196. The five- to tenfold reduction in the normalized average annual collective effective dose during the past three decades is associated with the substantial decrease in the average annual effective dose to monitored workers. The average annual effective dose decreased by a factor of 10 between the periods 1975–1979 and 2010–2014, from 3.5 to 0.4 mSv, respectively. The worldwide average annual effective dose to measurably exposed workers, 0.91 mSv in 2010–2014, is about twofold higher than that for all monitored workers. The occupational exposure data for PWR workers submitted in response to the UNSCEAR Occupational Exposure Survey, when supplemented with exposure information from the ISOE database, is almost 100% complete for the period 2000–2014. While one country did not provide average annual effective dose data for their individual workers, average annual collective effective dose data for these workers was obtained. The distribution ratios of number of monitored workers, NR_E, and of average annual collective effective dose, SR_E, have not been evaluated because of a lack of data.

Boiling water reactors

197. External exposure due to gamma radiation is also a main source of occupational exposure in BWRs, with most exposure occurring during scheduled shutdowns, when planned maintenance is undertaken, and during unplanned maintenance and safety modifications. At BWRs, workers engaged in maintenance in the turbine hall incur some additional external exposure due to the decay of ^{16}N. In the period 2010–2014, the largest numbers of BWRs were located in the United States (35) and Japan (24). Overall, 60% of the electrical energy generated by BWRs in the 2010–2014 period occurred in the United States. Electricity generation by BWRs in Japan decreased from 16.0 to 3.74 GWa between the periods 2005–2009 and 2010–2014 in part due to the shutdown of their BWR fleet in 2011.

198. The average worldwide number of BWRs consistently increased from 51 in 1975–1979 to 94 in 2005–2009; and decreased to 87 reactors in 2010–2014 [U10]. The corresponding increase in the average annual electrical energy generated worldwide was somewhat greater, from about 15 GWa in 1975–1979 to

64 GWa in 2005–2009, decreasing to 52 GWa in 2010–2014. The number of monitored workers at BWRs worldwide increased from about 59,000 to about 160,000 between the 1975–1979 and 1990–1994 periods and has remained between 130,000 and 150,000 since 1994 as presented in figures II and III as well as in table 21 and table A.9 in the electronic attachment. Overall, the number of measurably exposed workers has been 40–65% of the number of monitored workers for the past 20 years. The average annual collective effective dose has decreased from about 450 man Sv during the 1980–1984 period to about 85 man Sv during the 2010–2014 period. Over this same time interval, there has been a twofold increase in the energy generated. The normalized average annual collective effective dose per reactor and the average annual collective effective dose per GWa electricity produced have both consistently decreased during every five-year period since 1984. Both sets of values indicate significant reductions over the past 30 years, indicating that the efficiency of protection measures from design and operational procedures, and measures to reduce the source term (e.g., ^{60}Co at cooling system surfaces) has improved over time.

199. Eight countries responded to the UNSCEAR Occupational Exposure Survey. These data were supplemented by those obtained from the IAEA Power Reactor Information System (PRIS) and the NEA/IAEA ISOE databases. The combined data represent over 90% of the BWRs in global operation between 2000 and 2014. The global estimate of occupational exposure due to BWR reactor operation is based on average annual collective effective dose for measurably exposed workers and annual energy generated. The data are presented in table A.9 in the electronic attachment.

200. The substantial reduction of the average annual collective effective dose over time is associated with an eightfold decrease in the average annual effective dose to monitored workers over the past 40 years (table 21). The worldwide average annual effective dose to measurably exposed workers, 1.2 mSv in 2010–2014, is about twofold higher than that for monitored workers. The distribution ratios of the number of monitored workers, NR_E, and of the average annual collective effective dose, SR_E, have not been evaluated because of a lack of data. Occupational exposure data for BWRs submitted in response to the UNSCEAR Occupational Exposure Survey and supplemented with information from the IAEA PRIS [I7] and the NEA/IAEA ISOE databases are representative of all operational BWRs.

(b) *Heavy water reactors*

201. The worldwide average number of HWRs increased from 12 in 1975–1979 to 59 in 2010–2014 [U10]. The corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 3 to 19 GWa. The number of monitored workers in HWRs worldwide increased from about 7,000 to about 58,000 over the 40 years of evaluation, as shown in figures II and III, table 21 and table A.9 in the electronic attachment. Overall, the number of measurably exposed workers was about 40% of the number of monitored workers. The average annual collective effective dose varied between 30 and 60 man Sv in the periods between 1975 and 1999, and increased from 40 to 60 man Sv during the last three periods. The normalized average annual collective effective dose per reactor was around 2.4 man Sv in the first three periods, but then dropped to 1.1 man Sv and has remained relatively constant over the past 25 years. The corresponding values normalized to the electrical energy generated have fallen by a factor of more than three, from 11 to 3 man Sv per GWa, over the past 40 years. Both sets of values suggest significant improvement in the efficiency of radiation protection measures for both design and operational procedures.

202. The average annual effective dose to monitored workers has constantly decreased over the past 40 years. There has been about a fivefold reduction overall. The worldwide average annual effective dose to measurably exposed HWR workers, 2.2 mSv in 2010–2014, is about twofold higher than that to monitored workers. The doses due to the intake of tritium (as tritiated water) may have provided an major contribution, around 20%, to the total effective dose [H6] The occupational exposure data for HWR

workers submitted in response to the UNSCEAR Occupational Exposure Survey, when supplemented with exposure information from the ISOE database, is representative of up to 96% of the operational HWRs reporting, annual electricity generated, and average annual collective effective dose. The distribution ratios of the number of monitored workers, NR_E, and of average annual collective effective dose, SR_E, have not been evaluated because of a lack of data.

(c) *Gas-cooled reactors*

203. There are two main types of GCRs: Magnox reactors, including those with steel pressure vessels and those with pre-stressed concrete pressure vessels, and AGRs. Another type, HTGRs, reported previously [U5], is no longer in operation. Most of the experience with GCRs has been gained in the United Kingdom, where they have been installed and operated for many years. Initially, the GCRs were of the Magnox type, but throughout the 1980s, the contribution of AGRs, both in terms of their installed capacity and energy generated, increased. The contribution from AGRs to occupational exposure will increase as Magnox reactors are decommissioned.

204. In its UNSCEAR 1993 Report [U6], the Committee investigated the differences in occupational exposure between the Magnox reactors and AGRs. These arise mainly from the use of concrete (as opposed to steel) pressure vessels in the AGRs (and the later generation of Magnox reactors) and the increased shielding they provide against external radiation, the dominant source of occupational exposure. That report identified significant differences between the various types, with the average annual effective dose in first-generation Magnox steel-pressure-vessel reactors remaining uniform at about 8 mSv, whereas the corresponding values for Magnox reactors with concrete pressure vessels and for AGRs were less than 0.2 mSv. During the 1990–1994 period, significant dose reductions were achieved at the Magnox reactors, with further reductions during the next two periods. More detailed information can be found in the reviews of radiation exposure in the United Kingdom [U10]. In this annex, no distinction has been made between the various types of GCRs.

205. The worldwide number of GCRs averaged over five-year periods decreased significantly from 40 in the period 1975–1979 to 17 in the latest period (2010–2014) [U10]. Several Magnox reactors have been shut down. With the permanent shutdown of Tokai-1 (Japan) in 1998, the only operating GCRs are in the United Kingdom. There has been a corresponding decrease in both the average annual energy generated worldwide and the number of monitored workers, as shown in figures II and III, table 21 and table A.9 in the electronic attachment. Over eight five-year periods, the average annual collective effective dose decreased from 36 to 1 man Sv. The normalized average annual collective effective dose per reactor decreased from 0.9 to 0.05 man Sv, while the corresponding values per amount of generated energy also decreased, from 6.6 to 0.14 man Sv per GWa. Both sets of values indicate significant reductions over the eight periods, showing that the efficiency of protection measures from both design and operational procedures has improved over time.

206. The average annual effective dose to monitored workers worldwide, averaged over five-year periods, fell progressively from 2.8 to 0.06 mSv over time. The global occupational exposure data for operational GCRs is complete since the only operational ones for 2000 to 2014 are in the United Kingdom. The distribution ratios of the number of monitored workers, NR_E, and of average annual collective effective dose, SR_E, have not been evaluated because of a lack of data.

(d) *Light-water-cooled graphite-moderate reactors*

207. LWGRs were developed in the former Union of Soviet Socialist Republics and installed only in what is now the Russian Federation, Ukraine and Lithuania. Data equivalent to only 11% of the total energy generated by LWGRs were available from the ISOE database and from the UNSCEAR Occupational Exposure Survey, provided by Lithuania. The Russian Federation has provided data through the UNSCEAR Survey; however, these data were not specific to LWGRs.

208. The overall number of operating LWGRs increased from 12 in the first period to 20 in 1985–1994. Since then, it has slowly decreased to 15 in 2010–2014 [U10]. The corresponding average annual energy generation increased from 4.4 to 10 GWa in the period 1985–1999, and has since then been fairly constant, around 8–9 GWa. In the UNSCEAR 2008 Report [U10] the estimate of the number of monitored workers showed an increase from about 5,000 (1978–1979) to 13,000 (1985–1989), but with no data available for the periods from 1990–1994. The estimated average annual collective effective dose increased significantly over the periods, from 36 to 62 to 173 to 190 man Sv for the four periods from 1978 and 1994. Over these periods, the normalized average annual collective effective dose per reactor increased from 3 man Sv in 1978–1979 to 9 man Sv in 1985–1994. The corresponding normalized values per electricity energy generation also increased from 8 man Sv per GWa in 1978–1979 to 20 man Sv per GWa in 1985–1994.

209. In its UNSCEAR 1993 Report [U6], the Committee suggested that the large increase in average annual collective effective dose between the second and third periods (62 to 170 man Sv) was artificial in that the data included a major component from the after-effects of temporary work at Chornobyl. However, the data for 1990–1994 showed a continued high exposure (190 man Sv).

210. The estimated worldwide exposure is uncertain due to uncertainties in the estimates for the periods up to 1994, the lack of data in the period 1995–1999, and the limited exposure data for the three recent periods (2000–2014). Exposure data were obtained from only two reactors in Lithuania in operation up to 2009, but no exposure data were available for the 15 operational LWGRs in the Russian Federation. Therefore, the estimate is based on expert judgement by the Committee, using the available reported exposure data. The assumption was to use an average annual effective dose of 1 mSv and 2,500 workers per reactor as representative for all LWGRs, together with the information from the IAEA PRIS database [I7] on the number of operating reactors and generated energy. This global estimate should be treated with caution since it is based on very few exposure data.

(e) *Radiation exposure according to job category*

211. Information on doses according to job category has been provided through ISOE (table A.10). To account for some non-homogeneity in the statistical recording systems, these data have been aggregated into five broad categories: refuelling, maintenance, inspection, servicing, and all other tasks.

212. In general, the doses associated with most annual jobs, regardless of reactor type, have decreased from the 2000–2004 period to the 2010–2014 period. For PWRs, the average annual collective effective dose per reactor showed a 37% decrease for refuelling jobs, a 35% decrease for inspection jobs, a 27% decrease for servicing jobs and a 49% decrease for other jobs. For maintenance jobs, the average collective dose per reactor remained stable. For BWRs, the average annual collective effective dose per reactor associated with annual inspection and servicing remained stable from the 2000–2004 period to the 2010–2014 period. However, the average annual collective effective dose per BWR increased for refuelling and maintenance operations by 40 and 80%, respectively, between these same periods.

(f) *Summary for nuclear power reactors*

213. Data on occupational exposure at reactors worldwide are summarized in table 21 and table A.9 in the electronic attachment. The worldwide number of power reactors averaged over the eight five-year periods increased from 193 in the first period to 451 in the 2010–2014 period. A corresponding increase in average annual energy generation also occurred, from 55 to 279 GWa. Averaged over the whole period, about 89% of the total energy was generated in LWRs (of this about 68% was from PWRs and 21% from BWRs), with contributions of about 5.7% for HWRs, 2.3% for GCRs, and 2.9% LWGRs.

214. The summary below on estimates of worker exposure in the three recent periods include information received from the UNSCEAR Occupational Exposure Survey and from the ISOE database. The information is at least 90% complete for BWRs and HWRs and essentially 100% complete for PWRs and GCRs. The number of monitored workers increased from about 150,000 to 630,000 during the studied periods. The 1990–1994 period is the first for which there is a reasonably robust estimate of the number of measurably exposed workers, some 260,000, which represents about 50% of the number of monitored workers. The percentage of monitored workers with measurable effective doses has varied between 40 and 50% over time.

215. The average annual collective effective dose averaged over five-year periods has decreased fourfold over the last three decades (1985 to 2014). The trends in annual values are shown in table 21, table A.9 in the electronic attachment and figures II and III. Averaged over the three recent periods, about 77% of the average annual collective effective dose was received by workers at LWRs. The estimated contribution from workers at HWRs was 12%, at GCRs 0.5% and at LWGRs 10%.

216. The normalized average annual collective effective dose per reactor averaged over all reactors decreased by about a factor of five from 3.7 man Sv per operating reactor to 0.7 man Sv per operating reactor between the periods 1980–1984 and 2010–2014. The normalized average annual collective effective dose per unit of electrical energy generated (man Sv per GWa) decreased tenfold over the same timeframe. A generally decreasing trend is apparent for normalized figures for most reactor types.

217. The average annual effective dose to monitored workers averaged over all reactors fell steadily between the periods 1975–1979 and 2010–2014, from 4.1 to 0.5 mSv. This downward trend in annual dose to monitored workers is evident for each operating reactor type, although there are some differences between reactor types in the magnitude of the doses and in their rate of decline.

Table 21. Summary of worldwide estimates of occupational exposure due to reactor operation

PWR: Pressurized water reactor; BWR: Boiling water reactors; HWR: Heavy water reactor; GCR: Gas-cooled reactors; LWGR: Light-water-cooled, graphite-moderated reactor

Period	*PWR*	*BWR*	*HWR*	*GCR*	*LWGR*[a]	*All reactors*
AVERAGE NUMBER OF MONITORED WORKERS (10^3)						
1975–1979[b]	63	59	7	13	5	147
1980–1984[b]	140	102	14	25	10	291
1985–1989[b]	230	139	18	31	13	431
1990–1994[b]	310	160	20	30		520
1995–1999[b]	265	144	18	21		448
2000–2004	278	132	34	11	47	501
2005–2009	309	149	43	14	40	555
2010–2014	370	148	58	14	38	627

Period	*PWR*	*BWR*	*HWR*	*GCR*	*LWGR*[a]	*All reactors*
AVERAGE ANNUAL EFFECTIVE DOSE TO MONITORED WORKERS (mSv)						
1975–1979[b]	3.5	4.7	4.8	2.8	6.6	4.1
1980–1984[b]	3.1	4.5	3.2	1.4	6.4	3.5
1985–1989[b]	2.2	2.4	3.4	0.8	13.2	2.5
1990–1994[b]	1.3	1.6	1.7	0.5		1.4
1995–1999[b]	1.9	1.6	1.6	0.3		1.7
2000–2004	0.8	1.1	1.2	0.3	1.0	0.9
2005–2009	0.6	0.9	1.1	0.1	1.0	0.7
2010–2014	0.4	0.6	1.0	0.06	1.0	0.5
AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE (man Sv)						
1975–1979[b]	220	279	32	36	36	603
1980–1984[b]	450	454	46	34	62	1 046
1985–1989[b]	500	331	60	24	173	1 088
1990–1994[b]	415	240	35	16	190	896
1995–1999[b]	504	237	29	7		777
2000–2004	227	143	41	3	47	461
2005–2009	192	127	48	2	40	409
2010–2014	146	86	58	1	38	328
NORMALIZED AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE PER UNIT ELECTRICAL ENERGY GENERATED (man Sv/(GWa)						
1975–1979[b]	8.1	18.3	11.0	6.6	8.2	10.9
1980–1984[b]	8.0	18.0	8.0	5.8	8.3	10.4
1985–1989[b]	4.3	7.9	6.2	3.2	16.7	5.7
1990–1994[b]	2.8	4.8	3.0	2.0	20.3	3.9
1995–1999[b]	3.0	3.8	2.4	0.71		3.1
2000–2004	1.2	2.2	2.9	0.4	5.3	1.6
2005–2009	1.0	2.0	2.8	0.3	4.8	1.4
2010–2014	0.75	1.7	3.1	0.1	4.8	1.2
NORMALIZED AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE PER REACTOR (man Sv per reactor)						
1975–1979[b]	2.8	5.5	2.6	0.90	3.0	3.1
1980–1984[b]	3.3	7.0	2.4	0.84	3.8	3.7
1985–1989[b]	2.3	4.0	2.3	0.54	8.7	2.4
1990–1994[b]	1.7	2.7	1.1	0.44	9.4	1.9
1995–1999[b]	2.0	2.6	1.2	0.21		1.9
2000–2004	0.86	1.6	1.1	0.09	2.5	1.0
2005–2009	0.72	1.4	1.1	0.10	2.5	0.9
2010–2014	0.53	1.0	1.0	0.05	2.5	0.7

[a] The estimates in the periods (2000–2004, 2005–2009 and 2010–2014), are based on the number of operational reactors, energy generated for each reactor and occupational exposure data for reactors in Lithuania up to 2009. The estimate is highly uncertain.

[b] Values from earlier UNSCEAR reports [U6, U8].

Figure II. Worldwide trends in average annual collective effective dose due to reactor operation, and in normalized average annual collective effective dose per unit electrical energy and per reactor

PWR: Pressurized water reactor; BWR: Boiling water reactors; HWR: Heavy water reactor;
GCR: Gas-cooled reactors; LWGR: Light-water-cooled, graphite-moderated reactor

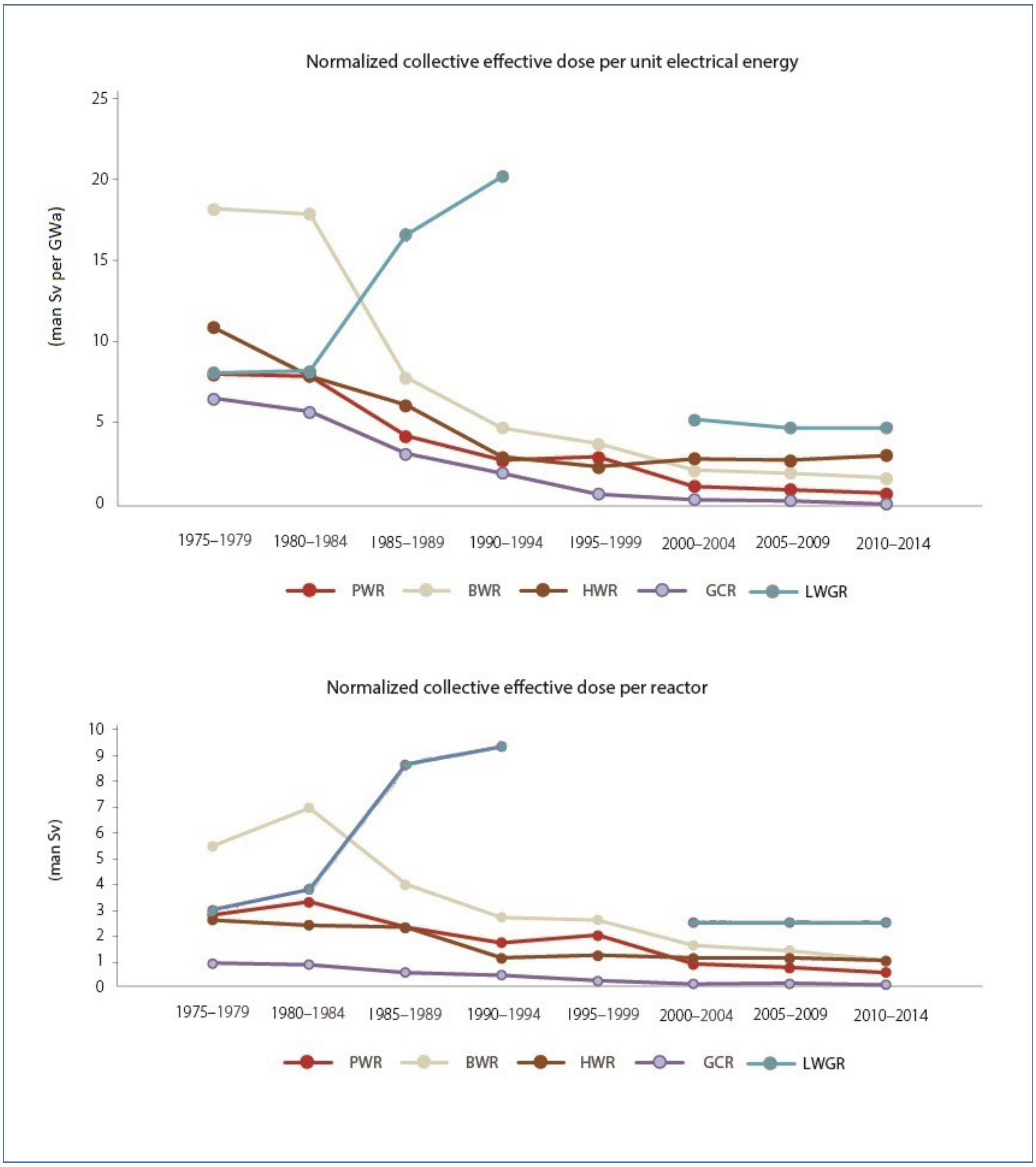
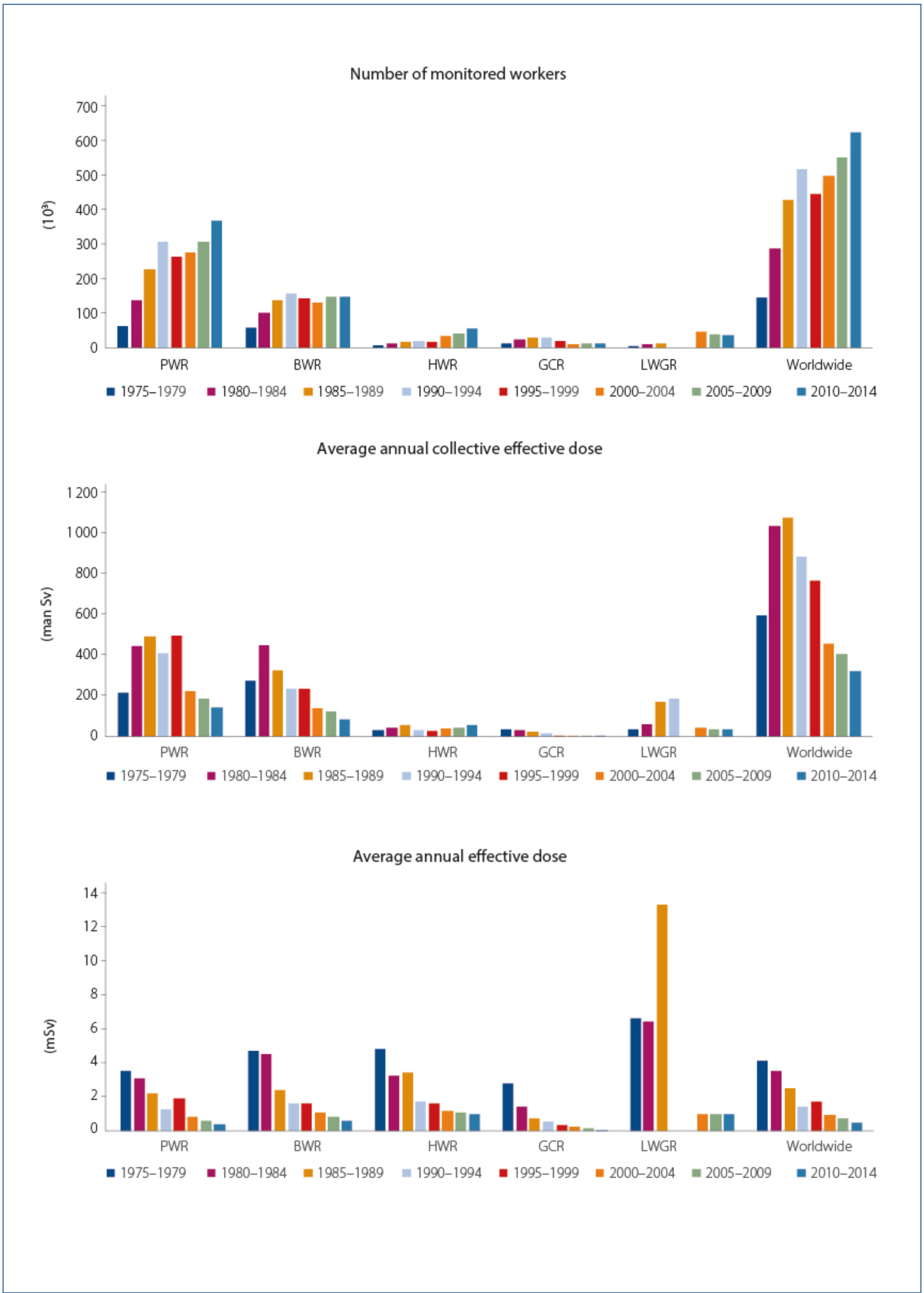


Figure III. Worldwide trends in occupational exposure from nuclear power reactors

PWR: Pressurized water reactor; BWR: Boiling water reactors; HWR: Heavy water reactor;
GCR: Gas-cooled reactors; LWGR: Light-water-cooled, graphite-moderated reactor



5. Decommissioning

218. When a nuclear facility is permanently closed, it must be decommissioned by safely removing it from service and reducing the residual content of radioactive material to a level that permits release of the property and termination of the operating licence. During decommissioning, there is an increase in work activities that involve occupational exposure. Such 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.

219. Occupational exposure during decommissioning activities is influenced by several factors, such as type of facility, and operational history. The type of exposure differs from that during the operational phase. In addition to external exposure, there may also be an increased risk of internal exposure due to radioactive substances in dust (e.g., demolition). The choice of decommissioning strategy may affect occupational exposure. Decommissioning of a nuclear facility involves one of three strategies: *(a)* immediate dismantling; *(b)* deferred dismantling after a safe storage period; or *(c)* entombment of the facility.

220. The immediate dismantling strategy involves the initiation of decommissioning activities shortly after the permanent cessation of reactor 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) licensed facility. Under the deferred dismantling strategy (sometimes called safe storage, safe store, or safe enclosure), reactor operation ceases, reactor fuel is unloaded and placed in spent fuel storage pools and the nuclear facility is maintained and monitored in a condition that allows the radioactivity to decay and with the potential to 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. Under the entombment strategy, 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.

221. Since decommissioning work activities are conducted, step by step, throughout several years, exposure of workers may occur at different times during the whole process and will depend on the type of work conducted. While most occupational exposure comes from external exposure, radioactive dust may be generated when nuclear reactor facilities are dismantled. If this radioactive dust is inhaled, it will result in an internal exposure.

222. Assessments presented in table 68 of UNSCEAR 2008 Report [U10], using data from 13 nuclear power plants in the United States, showed that about 2,000 workers were involved in the decommissioning process in the period 1995–2002, with an average annual effective dose for measurably exposed workers of around 2 mSv and an average annual collective dose around 4 man Sv. The data were not considered sufficient for evaluating the worldwide level of exposure.

223. In UNSCEAR 2016 Report [U12], an assessment of integrated exposure for a whole decommissioning process for reactors that have been immediately decommissioned is presented. The exposure was less than 10 man Sv per reactor. Exposure normalized to the total integrated electricity supplied for each reactor was also assessed for eight of the reactors with an average of 1.8 man Sv per GWa, (table 24 in UNSCEAR 2016 Report, annex B [U12]). Using deferred dismantling or entombment decommissioning strategies may result in some reduction in the total collective dose per reactor, but there is insufficient data to support such a conclusion.

224. In the present assessment on occupational exposure during decommissioning in the nuclear fuel cycle, available exposure data from the UNSCEAR Occupational Exposure Survey, the ISOE database, and the assessments in UNSCEAR 2016 Report [U12] conducted as part of radiation exposure from electricity generation are used. The data in the UNSCEAR Occupational Exposure Survey do not distinguish between nuclear facility types whereas the ISOE database contains data from decommissioning of power reactors only. The ISOE database for decommissioning of power reactors for the period 2000 to 2014 is not complete. Numerous annual reports for individual reactors undergoing decommissioning activities were not submitted to ISOE, either by the utility or the Member State as part of their annual report. Gaps in annual occupational exposure reports cannot be bridged due to unique decommissioning tasks and scheduling for each reactor. Consequently, a global estimate of average annual effective dose and collective effective dose is not projected.

225. Table 22 shows a summary of exposure data for the periods 2000–2004, 2005–2009 and 2010–2014 from both the UNSCEAR Occupational Exposure Survey and from ISOE. The average annual number of monitored workers reported in the three periods vary between 18,000 and 24,000. The average annual effective dose to monitored workers has decreased from 0.6 and 0.1 mSv during these periods. The total collective doses for the respective periods were 13.77, 3.37 and 3.43 man Sv, where decommissioning activities in Ukraine in the period 2000–2004 account for 7.84 man Sv. The average annual collective effective dose per reactor was 0.29 man Sv in the first period and decreased to 0.07 in the last period. However, it is difficult to draw any conclusions because occupational exposure may differ depending on the decommissioning activities at any given time for any given reactor. More specific data on decommissioning of nuclear power reactors are presented in table A.11 in the electronic attachment. Additional data on average annual collective effective dose for occupational exposure per unit for shut down reactors by country and reactor type for 2008−2013 were presented in table 23 in annex B of the UNSCEAR 2016 Report [U12]. While workforce data presented in table A.11 in the electronic attachment may be representative of the type of activities and exposure for similar scheduled activities, there are no correlations between the number of workers, the type of plant being decommissioned, the specific task undertaken in a particular year or the individual and collective effective exposure received.

226. In 2014, the Fukushima Daiichi nuclear power station entered into decommissioning phase. The exposure data from this station are excluded from the average occupational exposure for decommissioning due to the unique conditions compared to standard decommissioning strategies for planned shutdown reactors.

Table 22. Estimated occupational exposure due to decommissioning from ISOE data

Period	*PWR*	*BWR*	*HWR*	*GCR*	*LWGR*	*All reactors*	*Survey*[a]
AVERAGE ANNUAL NUMBER OF MONITORED WORKERS (10^3)							
2000–2004	6.54	4.70		0.79	10.85	22.88	11.3
2005–2009	11.02	3.12		0.18	3.76	18.08	12.0
2010–2014	18.30	6.93		0.56	4.59	23.45	20.7
AVERAGE ANNUAL EFFECTIVE DOSE TO MONITORED WORKERS (mSv)							
2000–2004	0.53	0.34		0.17	0.72	0.57	0.45
2005–2009	0.15	0.26		0.23	0.07	0.15	0.35
2010–2014	0.08	0.09		0.06	0.12	0.09	0.39

Period	PWR	BWR	HWR	GCR	LWGR	All reactors	Survey[a]
AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE (man Sv)							
2000–2004	3.47	1.78		0.68	7.84	13.77	5.1
2005–2009	1.71	0.84		0.56	0.25	3.37	4.2
2010–2014	1.91	0.84	0.03	0.09	0.57	3.43	8.0
NORMALIZED AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE PER REACTOR (man Sv per reactor)							
2000–2004	0.19	0.19		0.04	4.36	0.29	
2005–2009	0.07	0.08		0.03	0.25	0.06	
2010–2014	0.08	0.05	0.02	0.01	0.28	0.07	

[a] Data reported from six countries to the UNSCEAR Occupational Exposure Survey and include the whole nuclear fuel cycle.

6. Spent fuel reprocessing

227. The principal reason for reprocessing spent fuel from an LWR has been to recover unused uranium and plutonium in the spent fuel elements. The practice is conducted in only a few countries: France and the United Kingdom operate commercial-scale facilities, Japan and India have experimental facilities, and the Russian Federation has been reprocessing spent fuel for reactors developed in that country [U8].

228. Spent fuel assemblies removed from a reactor are highly radioactive and produce heat. They are therefore put into large spent fuel storage tanks or “ponds” of water, which cool them and, with three metres of water over the assemblies, shield the radiation they emit. They remain in the spent fuel storage tanks for a number of years either at the reactor site or at the reprocessing plant, and the level of radioactivity decreases considerably with time. For most types of spent fuel, reprocessing occurs at any time from 5 to 25 years after the fuel has been unloaded from the reactor.

229. The used fuel assemblies from LWRs can be dismantled and refabricated into fuel assemblies that are compatible for use in an HWR reactor. In some instances, depleted uranium may be added to the recovered uranium to attain a natural uranium equivalent fuel with 0.71% ^{235}U. For re-use in an LWR, the uranium needs to be converted, enriched, and fabricated into new fuel pellets. A significant amount of plutonium recovered from used fuel is currently recycled into mixed oxide fuel. Reprocessing to recover uranium and plutonium avoids wasting a valuable resource, saving some 30% of the natural uranium that would otherwise be required.

230. Several European countries and others, e.g., China, India, Japan, and the Russian Federation, have policies to reprocess used nuclear fuel. The exposure data for spent fuel reprocessing are given in table A.12 in the electronic attachment. Reprocessing in Japan did not restart after the closure of the Tokai reprocessing plant in 2007 and China had not started any reprocessing during the studied periods. India and the Russian Federation have not provided any information on the amount of used nuclear fuel reprocessed or the occupational exposure associated with this reprocessing in 25 to 30 years. The IAEA estimates that the Russian Federation has reprocessed a total of 6,000 tonnes of spent nuclear fuel [I19]. While the United States has reprocessed some used nuclear fuel, none has been from civilian nuclear power plants. The collected data are, therefore, not representative of worldwide reprocessing activities. Since the period 1990–1994, the reported number of monitored workers and the average annual collective dose generally decreased between the successive periods, as evidenced by the countries with complete data in the UNSCEAR Occupational Exposure Survey. The increase observed for the 1990–1994 period

is explained by the fact that the information from the Russian Federation is available for only that period. The average annual effective dose for monitored workers has, in general, decreased since 1980.

231. The estimate for the worldwide level of exposure between 1995 and 2002 in the UNSCEAR 2008 Report [U10] was based on the trends in the data from the reporting countries for earlier periods. The Committee no longer believe that these extrapolations, leading to substantial increase in the number of workers and the average annual collective effective dose for the periods 1995–1999 and 2000–2002, are valid and, therefore, these estimates have been removed from this annex. Although the reprocessing data from France and the United Kingdom, supplemented by data on naval propulsion fuel reprocessing from the United States, are believed to be representative for European countries, no attempts to estimate global values were made. Nevertheless, “total values” for the three periods 2000–2004, 2005–2009 and 2010–2014 are assumed to be reliable enough for inclusion in the worldwide global values for all nuclear activities (table 27). It is clear, as evidenced from the reporting countries, that both incurred radiation doses and staff numbers show decreasing trends during the studied periods. This is a natural and expected result due to the closure of older reprocessing facilities, improved radiation protection measures, and a general decrease in reprocessing activities.

7. Nuclear fuel cycle research

232. Nuclear research and development are essential for maintaining the safe and efficient operation of existing nuclear power plants and fuel cycle facilities, and also for ensuring the emergence of new and innovative nuclear energy systems. Global research and development efforts are striving to improve uranium resource utilization, maximize energy generation, minimize waste generation, improve safety, and limit proliferation risk. There has been, however, a significant decline in nuclear research and development expenditures in recent years, which is reflected in a decrease in the number of monitored workers conducting nuclear fuel cycle research (table 23).

233. For the Committee’s UNSCEAR 2008 Report [U10] it was difficult to estimate the levels of occupational exposure that could unequivocally be attributed to research and development related to the commercial nuclear fuel cycle. Only few data were available separately for this category; even if this had not been the case, uncertainties as to their proper interpretation exist. There was considerable variation in the levels of collective dose associated with research activities in each country, reflecting, inter alia, the relative role of nuclear energy in the national energy supply and the extent to which nuclear technology was developed domestically or imported. These difficulties remain also for this assessment. Exposure data between 1975 and 2014 for research in the nuclear fuel sector are shown in tables 23 and A.13 of the electronic attachment. The response to the recent UNSCEAR Occupational Exposure Survey was lower than in previous surveys.

234. The reported average annual number of monitored workers for the period 2000–2004 is about 33,000. A total of 22,000 workers reported by the United States for the period 2000–2002 and earlier were conducting general research and most likely not nuclear fuel cycle research, so they are excluded in the summary of 2000–2004. The reported annual average number of monitored workers is lower for the two recent periods compared to all previous periods and reflects a decrease in the number of reporting countries. The average annual effective dose for monitored workers decreased between the periods 1975–1979 and 1995–1999, from 1.5 to 0.3 mSv. Since then, the average annual effective dose has remained at the same level of 0.3 mSv per year.

235. The Committee estimated the worldwide level of exposure in its UNSCEAR 2008 Report [U10] on the basis of the trends in data from reporting countries. The estimated number of monitored workers

decreased by about 25%, from 120,000 in 1990–1994 to 90,000 in 2000–2002, and the estimated average annual collective effective dose dropped by a factor of four over six periods, from 170 man Sv in 1975–1979 to 36 man Sv in 2000–2002 (table A.13 in the electronic attachment). This decrease was similar to the reduction in the average annual effective dose from 1.4 to 0.4 mSv during the same periods.

236. An estimation of the worldwide level of exposure in nuclear fuel cycle research for 2003–2014 would not be reliable because of limited data and lack of an appropriate predictive parameter. The average annual collective effective dose would be based on very few reporting countries. It is unclear whether the decrease in the number of monitored workers is due to a decrease in activities in nuclear fuel cycle research, a consequence of less data reporting, or both. From table A.13 in the electronic attachment, some exposure trends for reporting countries can be identified. In Argentina and France, the average numbers of monitored workers have decreased over the past 40 years with the exception of 2010–2014, where the number of monitored workers increased in France. In China and India, the number has increased, while for the Republic of Korea and Sweden, the number remains at the same level.

Table 23. Data on occupational exposure in nuclear fuel cycle research reported to UNSCEAR Survey

Years	*Number of reporting countries*	*Average annual number of monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose for monitored workers (mSv)*
1975–1979[a]	13	63.4	96.3	1.5
1980–1984[a]	15	75.5	89.4	1.2
1985–1989[a]	15	82.6	66.0	0.80
1990–1994[a]	15	46.3	35.9	0.77
1995–1999[a]	13	48.3	14.6	0.30
2000–2004[b]	18	32.9	10.7	0.33
2005–2009	8	5.1	2.3	0.45
2010–2014	11	14.7	4.3	0.29

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

[b] Twelve countries reported data for 2000–2002, four countries for 2003–2004 and two countries for the whole period 2000–2004.

8. Radioactive waste management

237. Radioactive waste is produced at all stages of the nuclear fuel cycle. It is classified as low-, intermediate- and high-level waste [U10]:

(a) Low-level waste includes paper, rags, tools, clothing, filters, which contain small amounts of mostly short-lived radioactive material. In order to reduce its volume, it is often compacted or incinerated (in a closed system) before disposal. Worldwide it makes up 90% of the volume but only 1% of the radioactivity of all radioactive waste;

(b) Intermediate-level waste contains larger amounts of radioactive material and handling may require special shielding. It typically includes resins, chemical sludges and reactor components, and contaminated material from reactor decommissioning. Worldwide it makes up 7% of the volume and 4% of the radioactivity of all radioactive waste;

(c) High-level waste may be the spent fuel itself or the principal waste from its reprocessing. While making up only 3% of the volume of all radioactive waste, it contains 95% of the radioactive material. It includes highly radioactive fission products and some heavy elements with long-lived radioactivity. It generates a considerable amount of decay heat and requires cooling and also special shielding during storage, handling and transport. If the spent fuel is reprocessed, the separated waste is vitrified by incorporating it into borosilicate glass which is sealed inside stainless-steel canisters for eventual disposal deep underground. On the other hand, if spent reactor fuel is not reprocessed, all the highly radioactive isotopes remain in it, and so the whole fuel assemblies are treated as high-level waste. This spent fuel takes up about nine times the volume of the vitrified high-level waste that would result from reprocessing and encapsulating an equivalent amount of spent fuel, which is then ready for disposal.

238. The doses incurred by personnel managing radioactive waste depend on the scope of the activities performed. The average annual effective dose for workers involved in the safe management of spent fuel is in the range 0.2–11 mSv. The level of exposure is lower for workers involved in radioactive waste management (disposal), where the average annual effective dose is in the range 0.2–3 mSv [U10]. Eleven countries responded to the UNSCEAR Occupational Exposure Survey with information for waste management workers monitored from 2003 to 2014. Summary data from the survey and the UNSCEAR 2008 Report [U10] is presented in table 24. The number of monitored waste management workers increased from about 8,950 in the 2000–2004 period to 13,470 in the 2005–2009 period to 16,440 in the 2010–2014 period. The average annual collective effective dose also increased during each of these three periods. The average annual effective dose associated with radioactive waste management for all monitored workers decreased slightly from the 2000–2004 period to the 2010–2014 period. The average annual effective dose for measurably exposed workers, however, increased slightly between the two periods. The total reported values for radioactive waste management for the three periods 2000–2004, 2005–2009 and 2010–2014 are assumed to be reliable enough for inclusion in the worldwide global values for all nuclear activities (table 27), but they are not regarded as either representative or inclusive (e.g., legacy sites, storage of spent nuclear fuel, or decommissioning waste) of all the activities associated with the nuclear fuel cycle sector.

Table 24. Data on occupational exposure due to nuclear fuel cycle radioactive waste management reported to UNSCEAR Survey

Country	*Period*[a]	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
					Monitored workers	*Measurably exposed workers*
China	2003–2004	1 059		1 942	1.84	
	2005–2009	1 831		1 870	1.02	
	2010–2014	2 437		2 390	0.98	
Czechia	2003–2004	7	2.5	1	0.21	0.58
	2005–2009	14	9.6	30	2.21	3.22
	2010–2014	61	30	20	0.31	0.63
France	2010–2014	64	2.7	0	0.01	0.14

Country	*Period*[a]	*Monitored workers (10³)*	*Measurably exposed workers (10³)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
					Monitored workers	*Measurably exposed workers*
Germany	2003–2004	613	132	86	0.14	0.66
	2005–2009	621	84	110	0.17	1.26
	2010–2014	998	94	130	0.13	1.43
India	2010–2014	1 493	638	680	0.45	1.07
Poland	2003–2004	48	44	27	0.56	0.61
	2005–2009	46	24	20	0.33	0.62
	2010–2014	49	23	10	0.25	0.53
Spain	2003–2004	252	34	16	0.07	0.48
	2005–2009	215	28	10	0.04	0.30
	2010–2014	220	14	4.4	0.02	0.31
Sweden	2003–2004	526	100	95	0.18	0.95
	2005–2009	723	104	110	0.15	1.06
	2010–2014	1 194	123	200	0.17	1.64
Switzerland	2003–2004	51	15	3	0.05	0.17
	2005–2009	91	27	20	0.21	0.70
	2010–2014	141	30	20	0.12	0.55
United Kingdom	2000–2004	460		160	0.35	
	2005–2009	1 660		860	0.52	
	2010–2014	1 966		690	0.35	
United States	2000–2004	5 930	1 940	1 220	0.20	0.63
	2005–2009	8 272	2 634	1 660	0.20	0.63
	2010–2014	7 819	2 367	1 900	0.24	0.80
Total reported	**2000–2004**	**8 950**	**2 270**	**3 550**	**0.40**	**0,64**
	2005–2009	**13 470**	**2 910**	**4 690**	**0.35**	**0.67**
	2010–2014	**16 440**	**3 320**	**6 040**	**0.37**	**0.89**

[a] The period 2000–2004 includes data from United Kingdom and United States for the period 2000–2002, taken from table 71, UNSCEAR 2008 Report [U10] and reported data for the period 2003–2004. Data from all other countries for the period 2000–2004 contain reported data for the period 2003–2004 only.

9. Transport within nuclear fuel cycle

239. The significant majority – about 95% – of radioactive consignments are not related to nuclear power generation. As one example, Canada transports about one million packages of radioactive material each year [N11]. Transport is an integral part of the nuclear fuel cycle; from the transport of uranium ore to a conversion and enrichment facility to the disposal of spent fuel and components from a decommissioned nuclear power plant. Most material used in nuclear fuel cycle is transported several times during its progress through the cycle. Transport of radioactive sources outside the nuclear fuel cycle is discussed in section IV.E.3.

240. Many countries have experience transporting nuclear fuel cycle material. In the United States, nearly 3,000 shipments of commercially used fuel have been moved over 2.5 million kilometres in the past 40 years, mostly over roads and some by rail. The United Kingdom and France transport a combined average of 550 shipments of high-level radioactive waste every year, primarily by rail. Sweden makes approximately 40 shipments per year, while Japan has made around 200 shipments per year [N11].

241. Workers who transport radioactive material include equipment operators and truck drivers. The radiation exposure that these workers receive is generally very low (<1 mSv); hence, they are treated as members of the public, i.e., with regard to the system regulating exposure to ionizing radiation. A French report on occupational exposure found that the average annual effective dose to transportation workers was 0.1 mSv for 1,002 monitored workers and 0.32 mSv for 310 measurably exposed workers [F4]. A review of the annual occupational exposure reports published by the United States Department of Energy found that monitored workers responsible for the movement and transportation of radioactive material received average annual effective doses of less than 0.1 mSv (table 25). Approximately 10 to 15% of these workers, however, received measurable exposure and their average annual effective doses gradually increased from 0.4 mSv for the 2000–2004 period to 0.9 mSv for the 2015–2018 period [M8, M9].

242. Only few countries have provided occupational exposure information for transport in the nuclear fuel sector in the UNSCEAR Occupational Exposure Survey. The average annual effective dose for measurably exposed workers is in the range of 0.3–0.7 mSv, which is in agreement with the data reported from the United States (table 25). While the data are informative, they are dominated by activities at the United States Department of Energy for the three periods in 2000–2014 and, thus, are not representative of worldwide occupational exposure in transport within the nuclear fuel cycle. These data are not included in the worldwide assessment of average annual exposure due to the nuclear fuel cycle.

Table 25. Data on occupational exposure in transport within nuclear fuel cycle reported to UNSCEAR Survey

Country	Period	Monitored workers (10^3)	Measurably exposed workers (10^3)	Average annual collective dose (man Sv)	Average annual effective dose (mSv)	
					Monitored workers	Measurably exposed workers
China	2005–2009	44		32	0.7	
	2010–2014	84		38	0.4	
France	2010–2014	896	234	94	0.1	0.4
United Kingdom	2003–2004	7	7	3	0.4	0.4
	2005–2009	18	18	5	0.3	0.3
	2010–2012	24	24	10	0.4	0.4
United States[a]	2000–2004	1 323	200	85	0.06	0.4
	2005–2009	1 823	254	140	0.08	0.5
	2010–2014	1 514	179	147	0.1	0.8
	2015–2018	1 038	124	90	0.09	0.9

[a] Data from annual reports of United States Department of Energy [M8, M9].

10. Safety and safeguards inspections

243. Occupational exposure also occurs for workers taking part in safety and safeguards inspections. Such activities are conducted by regional and national authorities in Member States and by the IAEA. Information on exposure within this subsector was introduced as part of the present UNSCEAR Occupational Exposure Survey and just a few countries provided data. The number of monitored workers in Germany was about 2,600, in the Republic of Korea 200–300, in Algeria 200–300, and in Czechia 20–30. About 10–20% of monitored workers were classified as measurably exposed. The average annual effective dose for monitored workers was less than 0.3 mSv.

11. Other work categories in nuclear fuel sector

244. Exposure data for workers in the nuclear fuel sector not related to the above work categories and reported in the UNSCEAR Occupational Exposure Survey are summarized in table 26. The United Kingdom reported an average annual collective dose between 4 and 6 man Sv, the United States about 2–3 man Sv and Czechia about 0.3 man Sv. India and China reported about 1 man Sv for the period 2010–2014. France reported an annual collective dose of about 16 man Sv for this category of workers. With regard to the French data, reported by the Institute for Radiological Protection and Nuclear Safety for 2011, additional subsectors are used, e.g., logistics and maintenance (contractors), outfitting, nuclear propulsion, and others [F4]. For the reported monitored workers in the period 2010–2014, about 54,000, an average collective dose of 24.1 man Sv was reported, which gives an average annual effective dose of 0.4 mSv but with large variations between the reporting (0.1–1.9) countries.

Table 26. Data on occupational exposure in work categories in nuclear fuel cycle not included in specific subsectors and reported to UNSCEAR Survey

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective dose (man Sv)*	*Average annual effective dose (mSv)*	
					Monitored workers	*Measurably exposed workers*
China	2005–2009	0.44		0.32	0.72	
	2010–2014	0.66		0.83	1.26	
Czechia	2003–2004	0.14	0.12	0.30	2.12	2.54
	2005–2009	0.15	0.12	0.29	2.02	2.39
	2010–2014	0.14	0.11	0.27	1.93	2.50
France	2005–2009	30.3	9.55	16.0	0.53	1.67
	2010–2014	31.3	10.15	15.5	0.50	1.53
India	2011–2014	0.97	0.69	1.30	1.33	1.89
Slovenia	2010–2014	0.023	0.023	0.04	1.54	1.54
United Kingdom	2003–2004	8.24	8.18	5.81	0.71	0.71
	2005–2009	7.25	7.24	5.67	0.78	0.78
	2010–2014	6.46	6.46	4.24	0.66	0.66
United States	2003–2004	17.0	3.16	3.01	0.18	0.95
	2005–2009	13.6	2.29	1.74	0.13	0.76
	2010–2014	14.5	2.48	1.92	0.13	0.78

12. Summary

245. The trends in worldwide occupational exposure arising from each stage of the commercial nuclear fuel cycle are summarized in table 27. The displayed data constitute annual averages over five-year periods. For the period 2000–2004, averages are calculated on the basis of data (2000–2002) from the UNSCEAR 2008 Report and data (2003–2004) in the recent UNSCEAR Occupational Exposure Survey. Both uranium production and the related average annual collective effective dose increased during the three studied periods. The uranium enrichment data include somewhat larger uncertainties. Occupational exposure associated with fuel fabrication is little changed. Reactor operation is the main source of the number of workers and incurred radiation doses in the nuclear fuel cycle. Although the average number of workers increased, both the average annual effective dose and the average annual collective effective doses decreased over the three most recent periods. Decommissioning, spent fuel reprocessing, research in nuclear fuel cycle, radioactive waste management, transport of fuel, and safety and safeguards inspection all had a less impact on the overall exposure in the nuclear fuel cycle.

Table 27. Estimated worldwide levels of annual exposure due to nuclear fuel cycle[a]

Practice/work sector	*Monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv/GWa)*	*Average annual effective dose to monitored workers (mSv)*
2000–2004				
Mining	28	77	0.5	2.7
Enrichment	18	1.8		0.1
Fuel fabrication	23	26	0.1	1.2
Reactor operation[b]	501	461	1.6	0.9
Reprocessing[c]	16	7.9		0.5
Decommissioning[c]	23	14		0.6
Research[c]	33	11		0.3
Radioactive waste management[c]	9	3.6		0.4
Total[d,e]	**652**	**602**	**2.2**	**0.9**
2005–2009				
Mining	33	82	0.4	2.5
Enrichment	8	1.2		0.1
Fuel fabrication	21	19	0.1	0.9
Reactor operation[b]	555	409	1.4	0.7
Reprocessing[c]	6	1.9		0.3
Decommissioning[c]	18	3.4		0.2
Research[c]	5	2.3		0.4
Radioactive waste management[c]	13	4.7		0.4
Total[d,e]	**660**	**523**	**1.8**	**0.8**
2010–2014				
Mining	44	123	0.5	2.8
Enrichment	10	1.2		0.1
Fuel fabrication	20	17	0.1	0.9
Reactor operation[b]	627	328	1.2	0.5
Reprocessing[c]	6	1.4		0.2
Decommissioning[c]	23	3.4		0.1
Research[c]	15	4.3		0.3
Radioactive waste management[c]	16	6.1		0.4
Total[d,e]	**762**	**483**	**1.7**	**0.6**

[a] Data are annual values averaged over the indicated periods.
[b] Does not include data for FBRs and HTGRs.
[c] Numbers represent the total collected data.
[d] Totals are presented to illustrate trends and do not reflect true values.
[e] Data from IAEA PRIS database [I7] are used to estimate average annual collective effective dose per unit energy generated.

246. The number of workers increased during the recent three periods, due to an increase in both nuclear power reactor operation and uranium mining. Reactor operation is the dominant sector with regard to the number of monitored workers and accounts for about 627,000 in the recent period, which corresponds to about 80% of the estimated total. Mining accounts for about 44,000 and fuel fabrication for about 20,000. The estimated average annual number of workers is based on both collected good quality data (uranium mining and milling, fuel fabrication and reactor operation) but also data that contain different levels of uncertainty. Therefore, all total estimates should be treated with caution, and are best used to compare trends within the different subsectors. National procedures for the recording and inclusion of doses incurred by transient or contract workers during reactor refuelling and maintenance activities can significantly influence the annual statistics (e.g., number of monitored workers and average annual effective dose) reported for operational reactors. Some, but not all, respondents to the UNSCEAR Occupational Exposure Survey adjusted their annual statistics to account for itinerant workers and their occupational exposure.

247. The estimated worldwide number of monitored workers in the nuclear fuel cycle for the period 2010–2014 is 0.76 million, and the estimated average annual effective dose is 0.6 mSv. The average annual collective effective dose is estimated at about 483 man Sv in the most recent period, which represents a decrease of about 100 man Sv during the three reported periods. The main reason for the decreasing trend is the decrease in exposure in reactor operation.

248. The average annual effective dose received by monitored workers in the nuclear fuel cycle, which was estimated to 4.4 mSv in the first period (1975–1979), has since then continually decreased and is estimated as 0.9, 0.8 and 0.6 mSv, respectively during the three recent periods. However, there are large variations in these averages depending on activity type in the nuclear fuel cycle, e.g., in reactor operation the average annual effective dose decreased from 0.9 to 0.5 mSv during the three reported periods, whereas in mining and milling operations the average annual effective dose varied between 2.5 and 2.8 mSv.

249. The UNSCEAR Occupational Exposure Survey also include exposure data (from 20 countries) for the total nuclear fuel sector. The survey shows a 17% increase in average annual number of monitored workers between the periods 2000–2004 and 2010–2014. Moreover, the average annual effective dose estimated from the survey data shows a decrease from 0.9 to 0.6 mSv during the same periods.

250. The estimated worldwide levels of average annual collective effective dose are fairly certain for much of the nuclear fuel cycle. Data for operating nuclear reactors are essentially complete for LWRs, HWRs, and GCRs. Estimates for LWGRs are based on the number of operational reactors, the average annual energy generated for each reactor, and historical data obtained for Lithuania's operational LWGRs. This later estimate is based on expert judgment and is highly uncertain. Nevertheless, the number of workers and the occupational exposure associated with operating reactors account for the vast majority of data collected for the nuclear fuel cycle. Similarly, the data collected are essentially complete for fuel enrichment, fuel fabrication, and reprocessing. Uncertainties associated with uranium mining will improve with increased environmental monitoring, especially at ISL sites. While the underreporting and uncertainties associated with decommissioning, research activities, and radioactive waste management may be considerable, the number of workers and their associated individual and collective doses are small relative to the rest of the nuclear fuel cycle. The global number of nuclear fuel cycle workers, and their individual and collective doses, could be underestimated by as much as 10%.

B. Medical uses of radiation

251. Radiation and radioactive sources are used in medicine for both diagnostic and therapeutic purposes. Medical uses of radiation increase yearly as the benefits of procedures become more widely disseminated. The wide range of applications, procedures and techniques used in the context of patient exposure are described in the Committee's recent evaluation of medical exposure from ionizing radiation [U15], which also discusses changes in practice and current trends. Usually, medical staff (physicians, technicians, nurses, medical physicists, technologists and other personnel) constitute the largest group of workers exposed to human-made sources of ionizing radiation. The exposure of those who support or comfort patients undergoing radiation treatment or diagnostic procedure, often referred to as "carers and comforters" [I12], is considered to be medical exposure and is not considered in this annex.

252. The Committee evaluated occupational exposure for each practice, using average values for all workers over five-year periods without previously highlighting the influences of job function and medical procedure on staff exposure. Providing relevant information on occupational exposure related to the different practices by identifying job functions and categories of work within each practice was one of the tasks the Committee was facing. It covered the estimation of effective doses and equivalent doses to hands and to the lens of the eye. However, the insufficient data provided by countries to the UNSCEAR Occupational Exposure Survey burdened many of the estimated values with a large uncertainty. The contribution of female workers in the medical sector was also assessed.

253. The estimate of worldwide average annual effective doses is based on data from the UNSCEAR Occupational Exposure Survey and supplemented by data from the literature. For this analysis, it was assumed that the dosimetry had used the right algorithm to calculate the effective dose. The design and use of lead aprons were considered: i.e., dosimeter position, in particular whether the dosimeters were worn outside the apron or under it, or whether one dosimeter was worn under the apron and a second worn outside it. For the assessment of the doses to hands and to lens of the eye, it was assumed that these were estimated using the appropriate dosimeter and appropriate evaluation algorithms and procedures. Data for the UNSCEAR Occupational Exposure Survey involved in the different subsectors of medical uses of radiation are presented in tables A.14 to A.19 of the electronic attachment.

1. Diagnostic radiology

254. Diagnostic radiology refers to the analysis of images obtained using predominately X-rays and includes conventional diagnostic radiology and computed tomography. Diagnostic examinations with X-rays have been used in medicine for over a century, with increasing sophistication and new techniques.

255. Exposure data from the UNSCEAR Occupational Exposure Survey (2003–2004, 2005–2009, 2010–2014) in diagnostic radiology are given in table A.14 in the electronic attachment. Twenty-four countries responded to the survey within the period 2003–2014, which represents about 12% of the worldwide number of countries. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the new survey data for the period 2003–2004 to form the broader period 2000–2004. On the basis of the reported data, female workers constitute about 60% of the workforce (table A.15 in the electronic attachment); however, the variation in this percentage between the few countries that reported data is high.

256. In general, the Committee is evaluating diagnostic radiology, which includes conventional diagnostic radiology and interventional radiology, as one pooled subsector. Although the UNSCEAR Occupational Exposure Survey enabled data to be separately reported, most national databases still

combine data from conventional and interventional radiology. It is well known that occupational exposure to conventional diagnostic radiology is significantly lower than to interventional radiology; this is because interventions require the operator and assisting personnel to remain close to the patient and thus close to the primary beam of radiation. However, there are limitations in the analysis because very few countries provided specific data for each one of these subsectors. Only 14 countries provided data separately for conventional diagnostic radiology and 13 countries for interventional radiology. Because of the smaller sample of data compared to those 24 countries that provided pooled data, and also in order to evaluate the worldwide trend of occupational exposure, the analysis of occupational exposure in diagnostic radiology did not separate data from conventional and interventional radiology in this evaluation. There is a wide variation in the average annual effective dose and percentage of measurably exposed workers to monitored workers. These observed variations may be explained by many factors, including the way data are recorded in national databases, the mixture of procedures performed by medical staff, and differing protective measures implemented by each country.

257. Due to scattered radiation, the doses to the hands and lens of the eyes for interventional radiology operators can potentially be very high. Only three countries provided data on equivalent doses for lens of the eye, for which the recorded average annual equivalent doses were less than 4.4 mSv. Seven countries provided data on equivalent doses to the hands; the recorded average annual equivalent doses vary between 1 and 37 mSv. The detailed data provided are presented in table A.15 in the electronic attachment.

258. Occupational exposure data on diagnostic radiology obtained from the literature review were used to supplement the data obtained from the UNSCEAR Occupational Exposure Survey. Three countries have published data related to national surveys: Bosnia and Herzegovina, Ghana and Pakistan (table 28). These data were also used in the estimation of the worldwide exposure.

Table 28. Occupational exposure data for diagnostic radiology obtained from the literature

Country	*Period*	*Number of monitored workers (10^3)*	*Number of measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Reference*
					Monitored workers	*Measurably exposed workers*	
Bosnia and Herzegovina	1999–2003	0.824	0.484	1.3	1.6	2.4	[B4]
	2004–2008	1.156	0.721	1.9	1.6	2.3	[B4]
Ghana	2008–2009	0.278		0.12	0.42		[A2]
Pakistan	2003–2007	1.432		2.1	1.5		[J1]

259. The worldwide number of monitored workers is estimated on the basis of the methodology described in section II.E.1. The number of workers involved in diagnostic radiology is estimated to be about 8 million for the period 2010–2014. The total estimate is derived from the sum of estimated numbers of workers in job categories of physicians, nurses, and technicians. Another job category called "others" consists of the job categories not mentioned above. The workforce of "others" was not included in the sum due to its high uncertainty, which likely results in an underestimation of the number of workers in diagnostic radiology. The worldwide estimate for the periods 2000–2004 and 2005–2009 were not derived because of limited data and lack of reliable correlation between the number of workers and the predictor parameters used to derive the mathematical models. The worldwide occupational exposure data in diagnostic radiology are presented in table 29. The estimate number of monitored workers has increased over time, from 0.6 million (1975–1979) to more than 8 million (2010–2014). The uncertainty interval for the worldwide number of workers ranges from 3.9 to 14 million. The UNSCEAR 2008 Report

[U10] presented a workforce increase by a factor of seven from 1990–1994 to 1995–1999. The significant increase of workforce is a result of a more reliable estimate based on data from the World Health Organization. Although the workforce for 2010–2014 is underestimated, the uncertainty interval accounts for that underestimation. The worldwide estimated average annual effective dose for monitored workers is the average annual effective dose weighted by the number of workers of each country that provided average annual effective dose data (0.2 mSv), which is estimated as 0.4 mSv for the 2010–2014 period. The uncertainty interval for the worldwide average annual effective dose ranges from 0.2 to 0.8 mSv. There is a slight reduction to the average annual effective dose for monitored workers of 0.5 mSv (1994–1999) and an important decrease from 0.9 mSv (1975–1979). The estimated average annual collective effective dose for the 2010–2014 period is 3,200 man Sv, which is slightly lower compared to the period 1995–1999. The average annual collective effective dose increased substantially from 600 to 3,200 man Sv over the 40-years period of analysis.

Table 29. Estimated worldwide levels of occupational exposure in diagnostic radiology

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	630		600	0.9	
1980–1984[a]	1 060		720	0.7	
1985–1989[a]	1 350		760	0.6	
1990–1994[a]	950	350	470	0.5	1.3
1995–1999[a]	6 670		3 335	0.5	
2010–2014	8 000	[b]	3 200	0.4	[b]

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

[b] No worldwide estimation was possible because of limited data or no reliable data.

260. The Committee has evaluated occupational exposure for various job categories within the field of diagnostic radiology (for conventional and interventional radiology pooled together): physicians, nurses, technicians, other job categories in this subsector. The limited data provided by the countries that responded to the UNSCEAR Occupational Exposure Survey resulted in lack of statistically significant correlation between the data and the predictor parameters. The majority of countries presented data for the workforce in conventional and interventional radiology only. Out of the 33 countries which provided occupational exposure data for different job categories, as presented in table A.16 in the electronic attachment, 13 provided summarized data for all job categories. The size of the workforce for different job categories were unfortunately the only reliable estimates that could be established. The data for the periods 2000–2004 and 2005–2009 have not been used due to lack of reliable correlation between the available data and the predictor parameters used to derive the mathematical models. The numbers of monitored physicians and nurses for the period 2010–2014 are 0.5 and 0.6 million, respectively. The number of monitored technicians for the same period is about 6 million. Physicians and nurses represent about 10% of the estimated workforce each and technicians represent about 80% ("others" job category is not included in the total estimate).

(a) *Conventional diagnostic radiology and computed tomography*

261. Conventional X-ray examination involves static imaging; the various techniques applied (radiography, mammography and bone densitometry) and computer tomography are described in detail in UNSCEAR 2020/2021 Report, annex A [U15]. For radiography, which is the most widely used X-ray application, the average doses depend on the equipment used. For computer tomography, occupational doses are generally very low, and the technique does not represent a significant source of occupational exposure. For mammography, the doses are generally similar to those in computer tomography. In general, the techniques used in conventional diagnostic radiography do not represent a major influence on the level of occupational exposure.

262. Exposure data from the UNSCEAR Occupational Exposure Survey (2003–2004, 2005–2009, 2010–2014) on occupational exposure in conventional diagnostic radiology are given in table A.14 in the electronic attachment. Fourteen countries have responded to the survey for the period 2003–2014, which represents about 7% of the worldwide number of countries. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. Female workers represent about 65% of the workforce.

263. The equivalent doses to the lens of the eye and to the hands are evaluated for workers carrying out conventional diagnostic radiology procedures. Only two countries have provided data on average annual equivalent dose to the lens of the eye; the recorded doses vary from 1.7 to 1.9 mSv. Four countries provided data on the average annual equivalent dose to the extremities (hands); the measurable doses vary from 0.5 to 27 mSv. The data are presented in table A.15 in the electronic attachment. The fact that very few countries provided data on average annual equivalent doses to the lens of the eye and to the hands results in a poor reliability of any attempt at deriving global dose estimates. However, the available literature data support the values of the UNSCEAR Occupational Exposure Survey [H7, O2, S19].

264. Occupational exposure data for conventional diagnostic radiology obtained from the literature review have been used to supplement the data obtained from the UNSCEAR Occupational Exposure Survey. Basić et al. [B4] published national survey data for Bosnia and Herzegovina on occupational exposure for conventional diagnostic radiology (table 30). The data were also used in the estimation of the worldwide occupational exposure.

265. The worldwide number of monitored workers is estimated on the basis of the methodology described in section II.E.1. The worldwide estimates were performed only for the 2010–2014 for conventional diagnostic radiology, which was due to the limited data and also due to the lack of correlation of the available data and the predictor parameters for the other periods (2000–2004 and 2005–2009). The number of workers involved in conventional diagnostic radiology is estimated to be about 8 million for the period 2010–2014. The uncertainty interval for the worldwide number of workers ranges from 4.0 to 15 million. The average annual effective dose for monitored workers is the average annual effective dose weighted by the number of workers of each country that responded to the UNSCEAR Occupational Exposure Survey, which is estimated as 0.4 mSv. The uncertainty interval for the worldwide average annual effective dose ranges from 0.2 to 0.8 mSv.

Table 30. Occupational exposure data for conventional diagnostic radiology in Bosnia and Herzegovina [B4]

Period	*Number of monitored workers (10^3)*	*Number of measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1999–2003	0.773	0.447	1.1	1.5	2.3
2004–2008	1.070	0.667	1.7	1.6	2.3

(b) *Interventional radiology*

266. Interventional radiology is the use of X-ray imaging techniques to facilitate the introduction and guidance of devices in the body for diagnostic or treatment purposes [E8]. Such procedures may be performed also by clinicians other than radiologists, such as cardiologists, orthopaedists, gastroenterologists, urologists and vascular operators.

267. The radiation exposure of staff can be attributed to the type and complexity of procedure, radiation protection barriers, staff experience, radiological equipment used, and workload. Knowledge of these various parameters and their effect on scatter radiation levels can help to understand the fluctuation of the average doses between countries, such as effect of the collimation of the beam, of detector distance, of height of table, of magnification, and of the position of the X-ray tube (above or below the table) [H3, I39, P4, P5].

268. Currently, several radiation protection measures are implemented on a regular basis worldwide, e.g., radiation protection barriers, spectral filtration, pulsed fluoroscopy, low frame rates, and X-ray systems with dose reduction post-processing algorithms [I31, I49, K6, K10, M6]. The implementation of such radiation protection measures results in a reduction of exposure for operators at interventional theatres. Also, it explains the trend of dose reduction and the large variation of doses between countries or even between medical facilities in the same country.

269. A worldwide evaluation of radiological protection in interventional cardiology carried out by the IAEA using the Information System on Occupational Exposure in Medicine, Industry and Research (ISEMIR) showed that there was a large difference in radiological protection policies between countries. Of the 191 regulatory bodies contacted, only 81 replied. Some noteworthy results are: *(a)* just over 50% of the regulatory bodies mandate radiological protection training for personnel in order to be able to perform interventional cardiology procedures; *(b)* there is a spectrum of radiation protection licensing systems in use throughout the world, ranging from the physician not needing a licence to use radiation in interventional cardiology to the physician needing such a licence; *(c)* many regulatory bodies have limited access to these data and, even if they do have access, the data are often not detailed enough to provide the required information; and *(d)* a further complicating factor, namely that recorded doses may underestimate true occupational exposure because compliance by interventional cardiology personnel can be poor and because an individual's exposure from different intervention cardiology facilities may not be summed [I9, P1].

270. Exposure data from the UNSCEAR Occupational Exposure Survey (2003–2004, 2005–2009, 2010–2014) on occupational exposure for interventional radiology are given in table A.14 in the electronic attachment. Thirteen countries responded to the survey for the years 2003–2014. The data provided in the

UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. Female workers represent about 55% of the workforce.

271. The equivalent doses to the lens of the eye and hands are evaluated for workers carrying out interventional radiology procedures. Only one country provided data for the lens of the eye; the average annual equivalent dose was 7 mSv. Four countries provided data on equivalent dose to extremities (skin of the hands) ranging between 0.7 and 37 mSv. The respective data are presented in table A.15 in the electronic attachment. The available literature data support the survey's values. An investigation in Poland showed that for a three-month evaluation of equivalent doses to the hands and to the lens of the eye, 87% of these were lower than 0.1 mSv and only 0.03% of the recorded doses were higher than the annual dose limit of 500 mSv. The same study showed that only 32% of the recorded equivalent doses to the lens of eye were lower than 0.1 mSv and about 5% of the doses were higher than 5 mSv, which may indicate that it is likely that a number of annual equivalent doses to the lens of eye may exceed the value of 20 mSv [S19]. Another study concluded that the annual median equivalent dose to the lens of eye in computer tomography guided interventions did not exceed 20 mSv assuming 50 to 200 computer tomography guided intervention procedures per year [H7]. These and additional data indicate that the equivalent dose to the lens of the eye has the potential to exceed 20 mSv per year in specific interventional procedures and working conditions, in particular for interventional radiologists and cardiologists [O2].

272. Equivalent doses to the lens of the eye of urologists during interventional procedures have been compared with values measured during interventional radiology, cardiology, and vascular surgery. The measurements were taken in a surgical theatre using a mobile C-arm system and electronic personal dosimeters (worn over the lead apron). Measurements were collected during 34 urology interventions (nephrolithotomies). The median values of the effective doses (in terms of $H_p(10)$) measured over the apron were 393 µSv/procedure for urologists and 21 µSv/procedure for nurses. The 3rd quartile of the recorded values was 848 µSv/procedure for urologists and 39 µSv/procedure for nurses. Median values of over-apron dose per procedure for urologists were 19 times higher than those measured for radiologists and cardiologists working with proper protection (using ceiling suspended screens) in catheterization departments [V6].

273. An evaluation of equivalent doses to the lens of the eye for staff in an interventional cardiology department in Spain showed that doses for physicians ranged between 8 and 60 mSv, for a workload of 200 procedures per year. Lower doses were collected for nurses, with estimated annual equivalent doses to the lens of the eye (in terms of $H_p(3)$) between 2 and 4 mSv [P10]. Effective doses from five interventional cardiology centres in Spain were collected in the national registry programme of the Spanish Society of Cardiology. Measurements were performed over the apron at a chest level using electronic dosimeters. An average effective dose (in terms of $H_p(10)$) of 46 µSv/procedure was estimated for cardiologists. Lower doses were noted in other professionals such as assistant cardiologists, nurses, or anaesthetists. Procedures for valvular and other structural heart diseases involved the highest occupational doses, averaging over 100 µSv/procedure. The new limit for the occupational equivalent dose for the lens of the eye (20 mSv) is likely to be exceeded by those interventionalists who do not use protection tools (e.g., ceiling suspended screen, goggles) even with standard workloads [S6].

274. The worldwide number of monitored workers is evaluated on the basis of the methodology described in section II.E.1. The estimated number of monitored workers for interventional radiology is about 0.8 million for 2010–2014, which is about 10% of the estimated number of workers involved in conventional diagnostic radiology. The uncertainty interval for the worldwide number of workers ranges from 0.4 to 1.3 million.

275. The average annual effective dose for monitored workers is calculated as the reported average annual effective dose weighted by the number of monitored workers for each country that responded to

the UNSCEAR Occupational Exposure Survey, which is estimated as 0.6 mSv. The uncertainty interval for the worldwide average annual effective dose ranges from 0.3 to 1.2 mSv. Assuming that the weighted average annual effective dose represents the worldwide value, the average collective effective dose is about 500 man Sv.

276. Occupational exposure for staff performing interventional procedures in different institutions in Bosnia and Herzegovina in 2009 showed that the highest average annual effective dose assessed was 1.6 mSv for the interventional operators at one institution. The study covers four out of five institutions that perform interventional procedures. The results in table 31 present a large variation of doses between the five hospitals [B5].

Table 31. Occupational exposure data for interventional procedures in different institutions in Bosnia and Herzegovina in 2009 [B5]

Institution	*Number of monitored workers*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
INTERVENTIONAL OPERATORS			
Clinical Centre of Sarajevo University	16	0.021	1.4
University Clinical Centre of Tuzla	10	0.004	0.52
Clinical Hospital Mostar	3	0.001	0.38
Special Heart Clinic of Bosnia and Herzegovina	8	0.013	1.6
All institutions	**37**	**0.039**	**1.1**
NURSES			
Clinical Centre of Sarajevo University	11	0.009	0.98
University Clinical Centre of Tuzla	16	0.006	0.39
Clinical Hospital Mostar	3	0.0008	0.28
Special Heart Clinic of Bosnia and Herzegovina	11	0.006	0.55
All institutions	**41**	**0.021**	**0.58**
RADIOGRAPHERS			
Clinical Centre of Sarajevo University	4	0.003	0.79
University Clinical Centre of Tuzla	3	0.0009	0.31
Clinical Hospital Mostar	2	0.0007	0.44
Special Heart Clinic of Bosnia and Herzegovina	3	0.002	0.72
All institutions	**12**	**0.007**	**0.59**
Total	**90**	**0.066**	**0.81**

277. Interventional radiology specialists used to receive individual effective doses notably higher than those observed in conventional diagnostic radiology. An appreciable difference is not expected when new radiological protection measures and techniques, such as the robotic catheter systems gaining favour in many centres both for vascular intervention and cardiac electrophysiological ablation, have been implemented. It is important to notice that the majority of the countries responding to the UNSCEAR Occupational Exposure Survey are classified as high-income countries according to the World Bank classification [B18, H3, H12, I31, I39, I49, K6, K10, M6, P4, P5].

278. The doses for the operators performing 25 fenestrated endovascular aortic repair or branched endovascular aortic repair were assessed in a hospital in the United Kingdom. The results showed that the average annual doses to the head, to the thorax over-lead apron, and to the thorax under-lead apron were 2.3, 3.0, and 0.4 mSv, respectively. The radiation doses associated with these procedures are likely to be higher compared with standard, infrarenal aortic interventions [A9].

279. The average annual effective doses of the operators performing hip arthroscopy procedures, femoroacetabular impingement procedures and soft-tissue pathology procedures in a hospital in the United States was estimated at about 0.3 mSv. The dose assessment was based on data collected over four months of performing hip arthroscopy procedures, and the operator was exposed to approximately 0.09 mSv. These data were extrapolated for 12 months (156 procedures) [C4].

280. The radiation exposure for a team of vascular operators was prospectively monitored in a 12-month period in a hospital in China. The staff performed 30 endovascular aortic repairs, 58 arteriograms with and without embolization, and 61 percutaneous transluminal angioplasty and stent. The average annual effective dose was estimated at 0.20 mSv (range, 0.13 to 0.27 mSv); the average annual equivalent dose to the lens of the eye was estimated at 0.19 mSv (range, 0.10 to 0.33 mSv) and the average annual equivalent dose to the hand was estimated at 0.99 mSv (range, 0.29 to 1.84 mSv). These doses per procedure for the chief operator were highest for endovascular aortic repairs. Significant differences were observed for the average hand dose per minute of fluoroscopy among different surgeons [H8].

(c) *Dental practice*

281. Dental radiology is a part of diagnostic radiology; however, it has usually been presented separately as occupational exposure is typically very low. Diagnostic X-ray machines are widely available and are used frequently in almost every dental practice or clinic. The total number of X-ray devices used in dentistry is thus extremely large. Occupational exposure in dentistry is caused mainly by scattered radiation from the patient and leakage from the tube head (although the latter should be insignificant with modern equipment). The general trend over the past 30 or more years has been an increase in the number of personnel involved in dental radiology, coupled with a steady decrease in average annual collective effective dose. The majority of dental practitioners do not receive doses higher than the MDL and, indeed, some regulatory authorities do not require routine individual monitoring, except for high workload.

282. National data on occupational exposure arising from dental practice over the periods 2003–2004, 2005–2009 and 2010–2014 are provided in table A.14 in the electronic attachment. Only 28 countries responded to the UNSCEAR Occupational Exposure Survey within the period 2003–2014. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. The reported average annual effective doses range between values below the MDL and 2.3 mSv. The high values of the average doses in some countries may arise from the fact that dosimetry in these countries is implemented only for those workers for whom received doses ≥MDL or higher than the recording level were expected (equal data for exposed and monitored workers). Female workers represent about 75% of the workforce.

283. The worldwide number of monitored workers is estimated on the basis of the methodology described in section II.E.1. The best estimates of the worldwide number of workers involved in dental practice is about 350,000 for the period 2000–2004, 400,000 for the period 2005–2009 and 450,000 for the period 2010–2014. The uncertainty interval for the estimates of the worldwide number of workers ranges from 300,000 to 680,000.

284. The worldwide occupational average annual effective doses arising from dental practice over the periods 2000–2004, 2005–2009 and 2010–2014 are estimated as the average annual effective dose for monitored workers weighted by the number of workers in each country that responded to the UNSCEAR Occupational Exposure Survey. The estimated value is 0.2 mSv in each period. The uncertainty interval for the worldwide average annual effective dose ranges from 0.1 to 0.3 mSv. Assuming that the weighted average annual effective dose represents the worldwide values, the average annual collective effective doses are about 70 man Sv for the period 2000–2004, 80 man Sv for the period 2005–2009 and 90 man Sv for the period 2010–2014.

285. The trends for occupational exposure in dental practice from 1975 to 2014 are presented in table 32 and figure IV. The previous estimates of the number of workers were in the range of 260,000 to 500,000 within the period 1975–1999. In the current evaluation, the workforce in dental practice slightly increased to 404,000 in the period 1995–1999 to 450,000 in the period 2010–2014. The average annual effective dose decreased from 0.3 mSv (1975–1979) to 0.1 mSv (1990–1994, and 1995–1999), and then increased to 0.2 mSv in three latter periods. The estimated average values are close to those reported by countries as MDL over all the periods.

286. The estimated level of exposure is in agreement with the published data. Dose assessment for dental personnel in different institutions in Bosnia and Herzegovina in 2009 showed that no personnel received an annual effective dose higher than 1 mSv [B4]. Evaluation of the effective doses over three years (2011–2013) in 90 dental health professionals, 72 oral radiologists and 18 radiographic assistants (technicians or dental assistants), of 14 dental colleges in Karnataka state in India showed that the effective doses are lower than 1.5 mSv per year [R2]. A total of 658 dentists were surveyed from April 2012 to May 2013 in the Republic of Korea. The results showed that the annual effective doses were consistently low, below 0.2 mSv [K4].

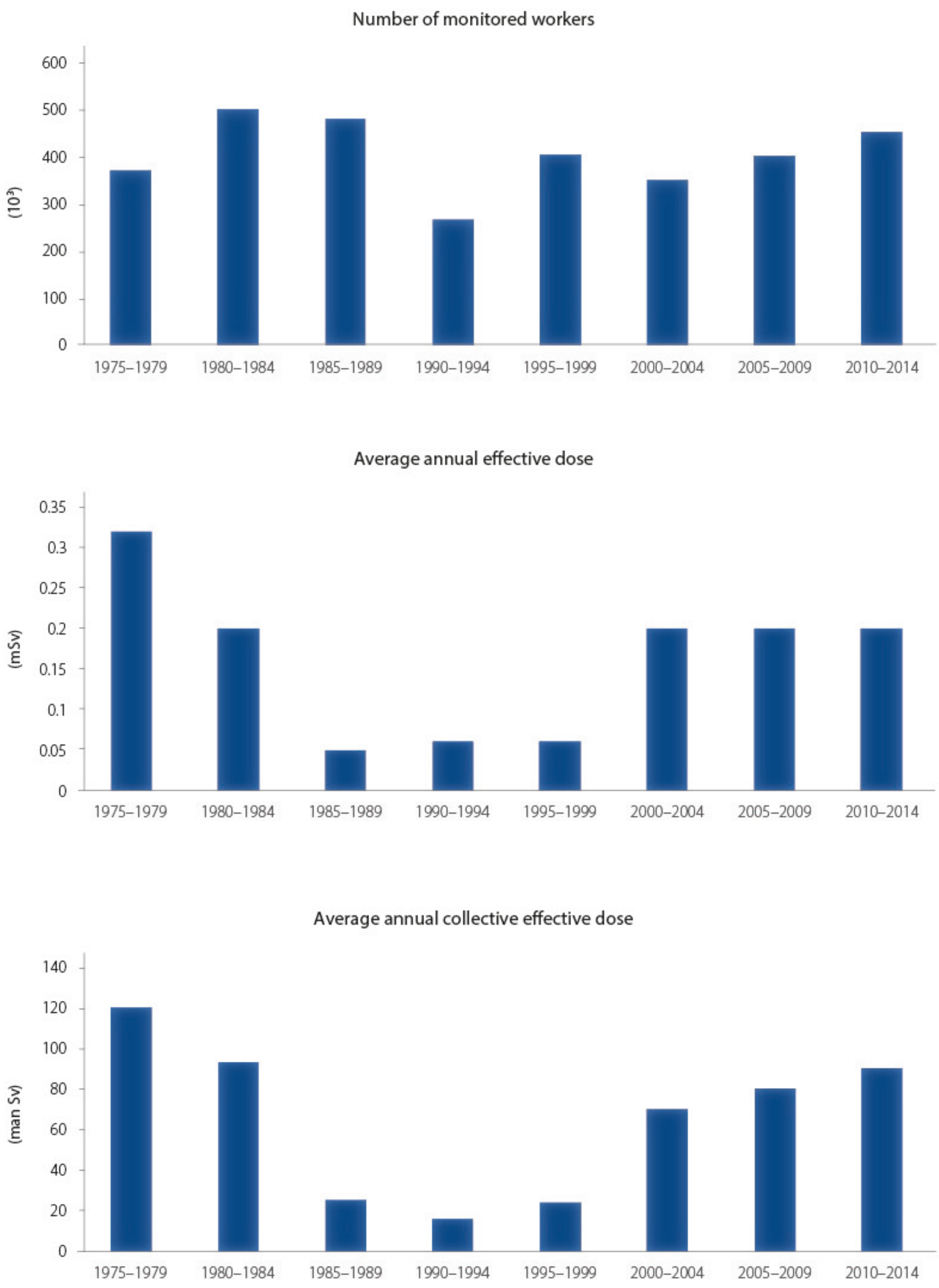
Table 32. Estimated worldwide levels of occupational exposure in dental practice

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	370		120	0.3	
1980–1984[a]	500		93	0.2	
1985–1989[a]	480		25	0.05	
1990–1994[a]	265	17	16	0.0.6	0.9
1995–1999[a]	404		24	0.06	
2000–2004	350	[b]	70	0.2	[b]
2005–2009	400	[b]	80	0.2	[b]
2010–2014	450	[b]	90	0.2	[b]

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

[b] No worldwide estimation was possible because of limited data or no reliable data.

Figure IV. Worldwide trends in occupational exposure at dental practices



2. Nuclear medicine

287. Nuclear medicine procedures involve the introduction of unsealed radioactive substances into the body, most commonly to obtain images that provide information on either organ structure or function. The radioactive substance may, in most instances, be administered intravenously, orally, by inhalation or into a cavity (e.g., intrathecally or intra-articularly). A radionuclide is usually combined with a targeting chemical to form a radiopharmaceutical to be distributed in the body according to physical or chemical characteristics (e.g., a radionuclide incorporated in a phosphate will localize in the bone, making a bone scan possible). The radiation emitted from the body is subsequently acquired to produce diagnostic images. Less commonly, unsealed radionuclides are administered to treat certain diseases such as hyperthyroidism and thyroid cancer, bone metastasis, primary or metastatic liver cancer, lymphomas, and neuroendocrine tumours. The use of radionuclide generators, particularly ^{99m}Tc generators, requires handling substantial amounts of radioactive material during the elution process. The magnitude of exposure while performing clinical nuclear medicine procedures depends on the precautions taken, including the use of syringe shields when performing injections. When personnel are close to the patient while giving injections and positioning the patient and camera, the imaging process makes the largest contribution to their exposure. The use of automatic injectors and dispensers, in the case of positron emission tomography (PET), may reduce the occupational exposure [L1].

288. Tasks involving the preparation and assay of radiopharmaceuticals are associated with the highest occupational exposure in nuclear medicine and can give annual doses of up to 5 mSv [N2]. There is a potential risk for intake of radiopharmaceuticals, especially for personnel involved in their preparation and assay. Internal exposure of personnel is usually much lower than external exposure and is controlled by monitoring work surfaces and airborne concentrations. However, the level of occupational exposure will depend on the level of radiological protection measures applied in the workplace. There are studies showing that annual effective dose can reach values up to 9 mSv, arising from the intake of ^{131}I [K9].

289. National data on occupational exposure arising from nuclear medicine over the periods 2003–2004, 2005–2009 and 2010–2014 are provided in table A.14 in the electronic attachment. Twenty-five countries responded to the UNSCEAR Occupational Exposure Survey for the years 2003–2014. The data provided in the UNSCEAR 2008 Report for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. The sample does not separate workers involved in diagnostic or therapeutic procedures only. There is a wide variation in the average annual effective dose, ranging from 0.2 to 1.8 mSv. Female workers represent about 70% of the workforce.

290. Nuclear medicine staff may receive high equivalent doses to the skin of the hands, especially to the fingers in contact with the syringe, if adequate radiological protection measures are not implemented. Only eight countries have provided equivalent dose data for the hands (skin dose); the reported average annual equivalent doses are 6 mSv (ranging from 1 to 11 mSv) in the period 2000–2004; average dose of 9 mSv (ranging from 1 to 18 mSv) in the period 2005–2009; and 14 mSv (ranging from 1 to 48 mSv) in the period 2010–2014. Trend analysis suggests that extremity doses have increased over time. The average annual equivalent doses to the lens of the eye were reported by only three countries. The equivalent doses range from below the MDL to 7 mSv (table A.15 in the electronic attachment).

291. Data from six European countries (ORAMED Project) showed that if radiation protection standards are low, the extremity (skin) doses can exceed the annual skin dose limit of 500 mSv for technicians, physicians and nurses administering therapy with ^{90}Y/Zevalin and ^{177}Lu labelled peptides [R8]. The total exposure of radiochemists or technicians during labelling procedures is almost threefold that received by physicians or nurses when administering ^{90}Y/Zevalin and involves more working steps and higher activity. The non-dominant hand receives the highest doses. In the majority of cases, the tip of the index finger or the thumb of the non-dominant hand was found to receive the maximum dose. The maximum

skin dose can be underestimated by a factor of about six if it is estimated using dosimeters worn on the wrist or on the ring finger [R8]. The high frequency of the preparation of radiopharmaceuticals for diagnostic procedures may result in high extremity doses. Nevertheless, the specific dose rates for ^{99m}Tc and ^{18}F are comparatively lower and the measurements in glass vials exhibit only insignificant contributions of beta and gamma mixed radiation fields [S17]. The highest doses for ^{90}Y are in the fingertips. The doses estimated used ring dosimeters may be underestimated [B12]. The doses can be reduced with implementation of optimized procedures [M4, O11, P2].

292. The European Good Manufacturing Practice guideline [E9] defines a number of quality control tests that must be performed prior to the release of fluorodeoxyglucose (^{18}FDG), among them measuring the energy spectrum of the sample to detect other radionuclide impurities and measuring the half-life of the radioisotopes in the sample. Significant differences in doses, depending on the hand and operator, can be noticed. The difference in equivalent doses measured for each hand (average left-hand dose 1.5 mSv; average right-hand dose 0.85 mSv) is probably due to the fact that all operators were predominately right-handed. If one operator was responsible for performing all quality control in a facility, the total annual finger equivalent dose would be 392 mSv on the basis of the average dose received five times a week for 52 weeks of the year. However, this has the potential to be as high as 525 mSv annually, using the highest individual operator average finger dose of 2.0 mSv per session. There is the potential for operators to exceed the legal dose limits [F3]. Actually, any tasks that involve handling ^{18}FDG result in finger doses that can reach the dose limit if radiological protection measures are not applied [L3].

293. The assessment of the equivalent doses to the fingers of workers conducting different tasks in 54 major institutions in India showed that the maximum equivalent doses were 0.35 mSv/GBq for elution of ^{99m}Tc in radiopharmacy work; 1 mSv/GBq during injection of the radiopharmaceutical, and 0.95 mSv/GBq for scintigraphy. Results are presented in table 33 [T2].

294. Results of a survey of occupational exposure over two years (2008 and 2009) in a nuclear medicine department in Kuwait showed that the average annual effective dose (in terms of $H_p(10)$) and equivalent dose to skin (in terms of $H_p(0.07)$) are both about 1 mSv for physicians and technicians [A4]. Although the authors have reported the operational quantities instead of effective dose and equivalent dose, these data were considered for comparison purposes.

Table 33. Maximum equivalent dose to fingers during different nuclear medicine procedures [T2]

Procedure	*Maximum equivalent dose to fingers (mSv/GBq)*
NUCLEAR MEDICINE PROCEDURE USING ^{99m}Tc	
Elution and radiopharmacy	~0.35
Injection	1
Scintigraphy	0.95
NUCLEAR MEDICINE PROCEDURE USING ^{18}FDG	
Dispensing	0.097
Injection	0.324
Scintigraphy	0.56
NUCLEAR MEDICINE PROCEDURE USING $^{188/186}$Re and ^{153}Sm	
Angiosplasty due to $^{188/186}$Re	3.92
Preparation of ^{153}Sm for synovectomy	6.5

295. In Czechia, a survey of occupational exposure in a nuclear medicine department provided average annual effective dose for physicians, technicians and radiopharmacists during the period 2001–2006. The doses were significantly reduced over the six-year period for all three work categories, about twofold for physicians and technicians and tenfold for radiopharmacists. Table 34 presents doses for staff working in a nuclear medicine department with a tendency of decreasing radiation exposure for all professional categories, even though the administered activity of ^{131}I increased during the six-year period [D4].

Table 34. Average annual effective dose of occupationally exposed staff in a nuclear medicine department in Czechia [D4]

Year	*Average annual effective dose (mSv)*		
	Physicians (n=5)	*Technologists (n=9)*	*Radiochemists (n=2)*
2001	1.9±0.6	1.9±0.8	3.2
2002	1.8±0.8	1.7±1.4	1.8
2003	1.2±0.8	1.0±1.0	0.6
2004	1.4±0.8	1.1±1.2	1.3
2005	1.3±0.6	0.9±0.4	0.6
2006	0.8±0.4	0.7±0.2	0.3

296. The use of high-efficiency cadmium zinc telluride detectors in single-photon emission computed tomography (SPECT) cameras has demonstrated the ability to reduce the radiation exposure of staff and of patients undergoing myocardial perfusion imaging studies. An evaluation of occupational doses conducted before and after the implementation of high-efficiency SPECT in a New York hospital in 2007–2008 was published by Duvall et al. [D8]. Table 35 presents the occupational doses by staff category for a total of 3,539 patients tested before and 3,898 after the implementation of high-efficiency SPECT. It is estimated that about 39% of the dose reduction was due to the new technology used, and related to the reduction of administered activity [D8].

Table 35. Average annual effective dose for staff of New York nuclear cardiology laboratory [D8]

SPECT: Single-photon emission computed tomography

Staff category	*Average annual effective dose (mSv)*	
	Before the implementation of high-efficiency SPECT[a]	*After the implementation of high-efficiency SPECT*[b]
DEEP-DOSE EQUIVALENT		
Nurse	4.9	2.9
Technologist	5.3	3.3
Administrative	0.43	0.27
SHALLOW-DOSE EQUIVALENT		
Nurse	4.9	2.9
Technologist	5.6	3.3
Administrative	0.43	0.34

Staff category	*Average annual effective dose (mSv)*	
	Before the implementation of high-efficiency SPECT[a]	*After the implementation of high-efficiency SPECT*[b]
LENS-DOSE EQUIVALENT		
Nurse	5.0	2.9
Technologist	5.5	3.3
Administrative	0.47	0.30

[a] October 2007–September 2008.

[b] October 2010–September 2011.

297. The worldwide number of monitored workers is estimated on the basis of the methodology described in section II.E.1. The worldwide occupational exposure data in nuclear medicine are presented in table 36 and figure V. The number of workers involved in nuclear medicine is estimated to be around 200,000 for the three latter periods: 2000–2004, 2005–2009 and 2010–2014. The uncertainty interval for the worldwide number of workers ranges from 110,000 to 370,000.

298. The average annual effective doses arising from nuclear medicine over the periods 2000–2004, 2005–2009 and 2010–2014 are estimated as the average annual effective dose for monitored workers weighted by the number of workers of each country that responded to the UNSCEAR Occupational Exposure Survey. The estimated values are 1.1 mSv for 2000–2004, 0.7 mSv for 2005–2009 and 0.4 mSv for 2010–2014. For the worldwide average annual effective dose, the uncertainty interval for the period 2010–2014 ranges from 0.2 to 0.8 mSv.

299. Assuming that the weighted average annual effective dose represents the worldwide values, the average annual collective effective doses are about 220 man Sv for the period 2000–2004, 140 man Sv for the period 2005–2009 and 80 man Sv for the period 2010–2014.

300. The average annual effective dose was about 1.0 mSv during the first six five-year periods (1975–2004), then a decrease in the average annual effective doses was observed in the two latter periods up to about 0.4 mSv. A similar trend was observed in a study involving more than 6,000 Chinese nuclear medicine workers for whom the annual effective dose decreased from about 0.8 mSv in 2010 to 0.4 mSv in 2016 [D2].

301. The Committee has attempted to evaluate the occupational exposure for various job categories within the nuclear medicine subsector: physicians, nurses, technicians, and other job categories. The worldwide level of exposure could not be derived because of limited available data and, therefore, the unacceptable high uncertainty of the predicted values. The data obtained from the UNSCEAR Occupational Exposure Survey are presented in table 36 and table A.17 in the electronic attachment.

302. Although new SPECT radiopharmaceuticals are continually being developed, there is a major trend to extend positron emission tomography procedures. Nowadays, ^{18}FDG is the most used tracer but research on other ^{18}F-labelled molecules has resulted in several new radiopharmaceuticals, including ^{11}C. Furthermore, the search for new radionuclides introduced ^{62}Cu, ^{68}Ga, ^{86}Y, ^{94}Tc and ^{223}Ra. Many of these radionuclides emit positrons with relatively high energies combined with high-energy gamma emission. The future number of procedures and the nature of these radionuclides can, consequently, increase whole body exposure and exposure to the extremities [C19, S15].

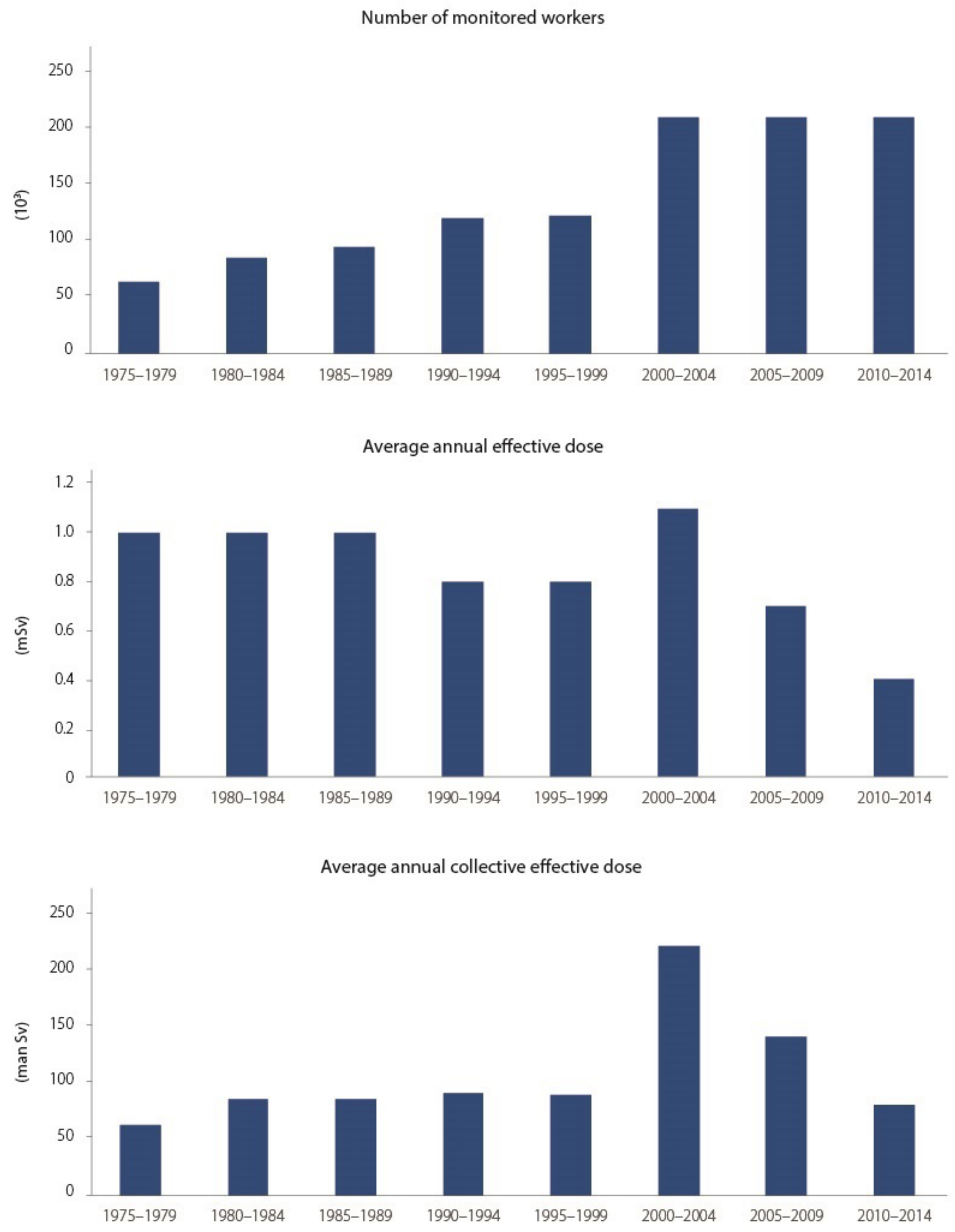
Table 36. Estimated worldwide levels of occupational exposure in nuclear medicine

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	61		62	1.0	
1980–1984[a]	81		85	1.0	
1985–1989[a]	90		85	1.0	
1990–1994[a]	115	65	90	0.8	1.4
1995–1999[a]	117		89	0.8	
2000–2004	200	[b]	220	1.1	[b]
2005–2009	200	[b]	140	0.7	[b]
2010–2014	200	[b]	80	0.4	[b]

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

[b] No worldwide estimation was possible because of limited data or no reliable data.

Figure V. Worldwide trends in occupational exposure at nuclear medicine



3. Radiation therapy

303. Radiation therapy refers to the use of ionizing radiation produced by a sealed source or a radiation generator to treat various diseases (usually cancer). Sometimes radiation therapy is referred to as radiation oncology; however, selected benign diseases may also be treated. Radiation therapy is delivered through external beams of radiation (teletherapy) or by placing sealed radioactive sources in or near the tumour tissue (brachytherapy). External radiation beams may consist of high-energy X-rays or gamma rays, electrons, protons, neutrons, or heavier charged particles. Gamma-ray beams are often produced by high activity sources of ^{60}Co while all other external radiation beams are produced by electrical equipment such as X-ray machines and particle accelerators.

304. Brachytherapy, with a manual loading of the radioactive treatment sources, is usually the most significant source of personnel exposure [I41, N2]. This may occur during the receipt and preparation of the sources, during their loading and unloading, and during treatment. Treatments with an external beam do not usually require personnel to be present in the treatment room when the beam is administered. The possible exception may be made for low-energy (50 kV and less) X-ray contact therapy units, which are sometimes used for intracavitary treatment. Radiation therapy staff of medical accelerators operating with energies of above about 10 MeV are also exposed to radiation due to activated material in the treatment rooms. The activation arises primarily from photonuclear reactions and neutron capture. The assessments of an annual dose received by staff due to activated material during typical operations are in the range of 0.7–5 mSv. These numbers demonstrate that this dose is not negligible; however, they strongly depend on the chosen model and applied approach [A11, D5, P7, R1].

305. The evaluation of the average annual effective dose of a group of 20 radiation therapy workers in Egypt showed that the average annual effective dose for the radiation therapy group (n=20) working on a linear accelerator was 3.1 ± 1.5 mSv (range from 1.5 to 6 mSv/a) [E10].

306. Occupational exposure data for radiation therapy obtained via the literature review have been used to supplement the data obtained from the UNSCEAR Occupational Exposure Survey. Two countries have published data related to national surveys, Bosnia and Herzegovina, and Pakistan (table 37). These data were added to the data obtained from the UNSCEAR Occupational Exposure Survey to estimate the worldwide occupational exposure level.

Table 37. Data on occupational exposure for radiation therapy from literature review

Country	*Period*	*Number of monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	*Reference*
Bosnia and Herzegovina	1999–2003	0.038	0.045	1.2	[B4]
	2004–2008	0.045	0.071	1.6	[B4]
Pakistan	2003–2007	0.367	0.43	1.17	[J1]

307. National data on occupational exposure arising from radiation therapy over the periods 2003–2004, 2005–2009 and 2010–2014 are provided in table A.14 in the electronic attachment. Twenty-six countries have reported to the UNSCEAR Occupational Exposure Survey within the period 2003–2014. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. The average annual effective dose ranges from below MDL to 3.5 mSv. Female workers represent about 65% of the workforce.

308. Staff carrying out brachytherapy procedures may receive high doses to the hands. Five countries have provided data on average equivalent dose to hands (skin dose) and then for brachytherapy and teletherapy pooled together. The average equivalent dose was 1.2 mSv (ranging from 1 to 1.4 mSv) in the period 2000–2004, 7.1 mSv (ranging from 0.2 to 37 mSv) in the period 2005–2009 and 1.6 mSv (ranging from 1 to 22 mSv) in the period 2010–2014. Germany provided a recorded value of 0.1 mSv for the average annual equivalent dose to the lens of the eye (table A.15 in the electronic attachment).

309. The worldwide number of monitored workers is evaluated on the basis of the methodology described in section II.E.1. The worldwide occupational exposure data in radiation therapy are presented in table 38 and figure VI. The number of workers involved in radiation therapy is estimated to be about 200,000 for the periods 2000–2004 and 2005–2009 and about 300,000 for the period 2010–2014. The data indicate a stable number of monitored workers involved in this practice since 1995. The uncertainty interval for the period 2010–2014 of the worldwide number of workers ranges from 170,000 to 540,000.

310. The average annual effective doses arising from radiation therapy over the periods 2000–2004, 2005–2009 and 2010–2014 are estimated as the average annual effective dose for monitored workers weighted by the number of workers of each country that responded to the UNSCEAR Occupational Exposure Survey. The estimated values are 0.4 mSv for 2000–2004, and 0.3 mSv each for 2005–2009 and 2010–2014. The uncertainty interval for the period 2010–2014 on the average annual effective dose ranges from 0.1 to 0.5 mSv. Assuming that the weighted average annual effective dose represents the worldwide values, the average annual collective effective doses are about 80 man Sv (2000–2004), 60 man Sv (2005–2009) and 90 man Sv (2010–2014). The average annual effective dose decreased from 2.2 mSv (1975–1979) to 0.3 mSv (2010–2014), which is close to reported MDLs by countries.

311. The Committee has attempted to evaluate the occupational exposure for various job categories within the radiation therapy subsector: physicians, nurses, technicians, other job categories. The worldwide level of exposure could not be derived because of limited available data and, therefore, the high uncertainty of the predicted values. The data obtained from the survey are presented in table A.18.

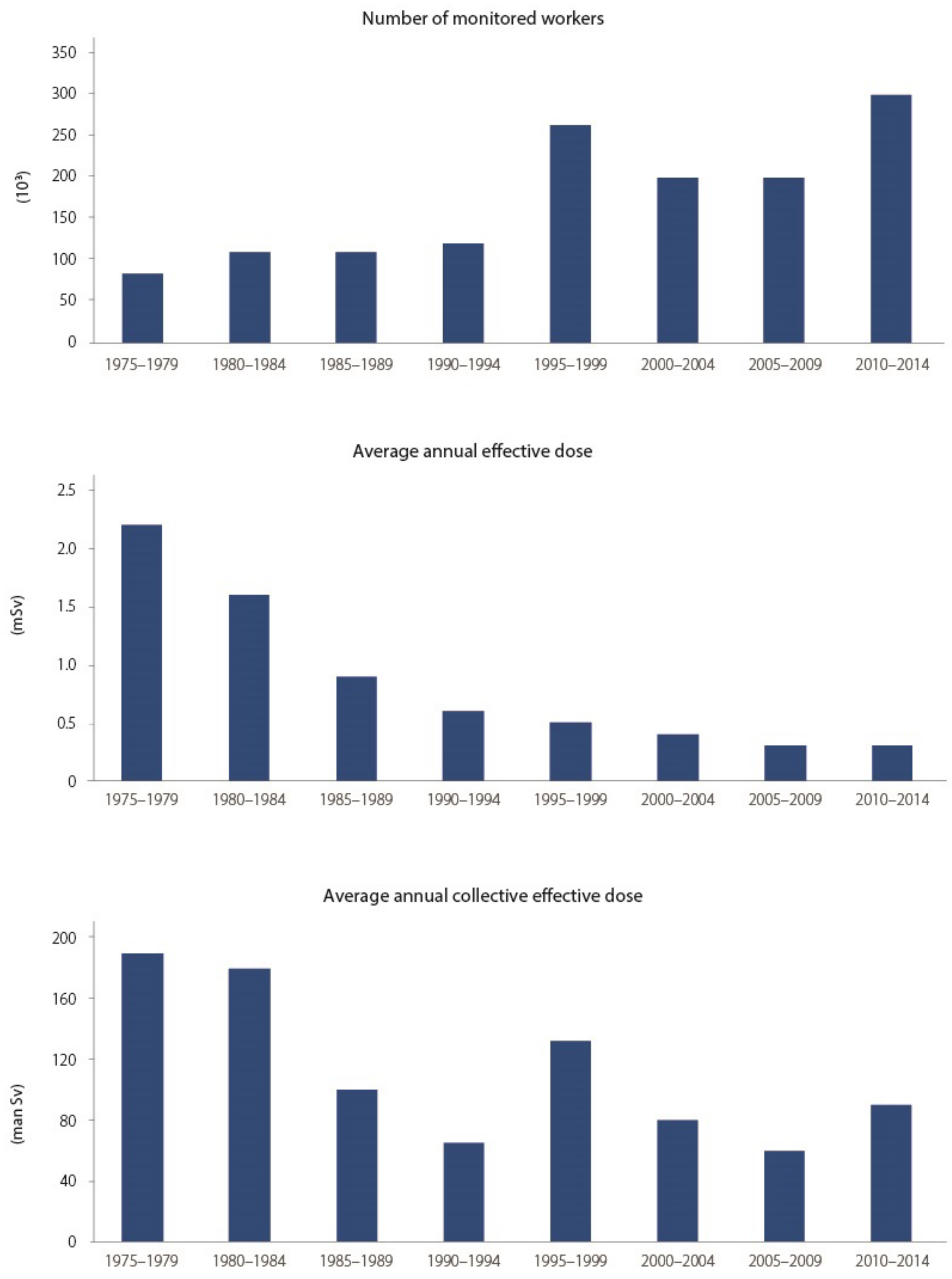
Table 38. Estimated worldwide levels of occupational exposure in radiation therapy

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	84		190	2.2	
1980–1984[a]	110		180	1.6	
1985–1989[a]	110		100	0.9	
1990–1994[a]	120	48	65	0.6	1.3
1995–1999[a]	264		132	0.5	
2000–2004	200	[b]	80	0.4	[b]
2005–2009	200	[b]	60	0.3	[b]
2010–2014	300	[b]	90	0.3	[b]

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

[b] No worldwide estimation was possible because of limited data or no reliable data.

Figure VI. Worldwide trends in occupational exposure at radiation therapy



4. Veterinary medicine

312. Veterinary radiological practice refers to essential diagnostic radiography and the application of nuclear medicine tools used by veterinary practitioners. Although the technology associated with the generation of X-rays is similar to conventional diagnostic radiology, doses to personnel depend largely on the type of animal examined. Most veterinary radiological examinations are conducted with conventional diagnostic radiography systems but there are also special veterinary computer tomography scanners and veterinary scintigraphy systems; the isotope ^{99m}Tc is widely used (90% of all examinations) in nuclear-medicine-type examinations. In general, the average annual effective doses to individuals should be low, because they arise essentially from scattered radiation. Some practices may, however, result in the additional exposure of extremities if, for example, assistants hold animals in position while the examination is being performed [C3].

313. National data on occupational exposure arising from veterinary medicine over the periods 2003–2004, 2005–2009 and 2010–2014 are provided in table A.14 in the electronic attachment. Twenty-six countries have responded to the UNSCEAR Occupational Exposure Survey within the period 2003–2014. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. There is a wide variation in the average annual effective dose, and it is very likely that the doses are below 1 mSv. On average, female workers represent about 55% of the workforce.

314. Staff carrying out veterinary medicine may receive high doses to the hands because of the nature of nuclear-medicine-type procedures and having to hold animals during an exposure. Only four countries provided average annual equivalent dose data for hands (skin dose) for the period 2010–2014; the reported average equivalent dose is 0.7 mSv (ranging from 0.2 to 1 mSv) as presented in table A.15 in the electronic attachment.

315. The worldwide occupational exposure data in veterinary medicine are presented in table A.14 in the electronic attachment. The worldwide level of occupational exposure was evaluated on the basis of the methodology described in section II.E.1. However, due to the lack of statistically significant correlation between the occupational data and the predicted parameters applied to derive the mathematical models, it was not possible to predict global estimates with suitable reliability. Therefore, the worldwide occupational exposure levels were not estimated for the periods 2000–2004, 2005–2009 and 2010–2014.

5. All other medical uses

316. The category “all other medical uses of radiation” was intended to cover new/expanding uses of radiation within the medical sector that did not fit into the categories of diagnostic radiology, dental radiology, nuclear medicine, radiation therapy and veterinary medicine.

317. The number of workers potentially exposed in these other uses may substantially exceed those in the few occupations for which data have been separately presented in this section. The average exposure levels of workers involved in other uses of radiation are in general very low. However, the way in which the doses are aggregated may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, that receive doses significantly above the average is for the data to be examined periodically.

318. National data on occupational exposure arising from “all other medical uses” over the periods 2003–2004, 2005–2009 and 2010–2014 are provided in table A.14 in the electronic attachment. Twenty-three countries responded to the UNSCEAR Occupational Exposure Survey and supplied data for the period

2003–2014. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2003–2004 to form the broader period 2000–2004. On average, female workers represent about 65% of the workforce.

319. The worldwide level of occupational exposure is evaluated on the basis of the methodology described in section II.E.1. Due to the poor statistically significant correlation between the occupational data and the predicted parameters applied to derive the mathematical models, the global estimate may be calculated for the period 2010–2014 only. The worldwide occupational exposure data were not estimated for the three periods 2000–2004, 2005–2009 and 2010–2014. The reported number of monitored workers is around 200,000. The average annual effective dose is below 1 mSv as in the previous evaluated periods.

6. Summary

320. There is a wide variation in the reported effective doses and the number of exposed workers. This may be explained by many factors, including the way data are recorded in the national databases, the mixing of doses related to monitored and measurably exposed workers, the mixing of procedures performed by the medical staff, workload, and protective measures implemented by each country. On average, female workers represent about 60% of the workforce in the medical sector.

321. All worldwide estimates of occupational exposure are evaluated on the basis of the methodology described in section II.E.1. The insufficient data supplied to the UNSCEAR Occupational Exposure Survey resulted in a weak correlation between the original data and predicted global estimates and, thus, some of them are statistically insignificant and were not presented in this annex.

322. Diagnostic radiology includes conventional diagnostic radiology and interventional radiology pooled together. The worldwide number of monitored workers was estimated to be 8 million, with uncertainty interval from 3.9 to 14 million. The worldwide average annual effective dose was estimated as 0.4 mSv, with uncertainty interval from 0.2 to 0.8 mSv. The average annual collective effective dose was estimated as 3,000 man Sv. A trend observed was an increase in the numbers of workers and the average annual collective dose over the 40 years of analysis. The average annual effective dose has gradually decreased by a factor of two, from 0.9 mSv (1975–1979) to 0.4 mSv (2010–2014). The estimated worldwide number of workers represents about 90% of the total number of monitored workers involved in the medical uses of radiation (excluding veterinary medicine).

323. On the basis of the data reported by the countries that responded to the UNSCEAR Occupational Exposure Survey, the value for annual equivalent dose to the hands of an individual worker is unlikely to exceed 500 mSv. The derived average equivalent dose to the lens of the eyes in all medical subsectors is 7 mSv, but because of the limited data obtained through the survey, the derived value should not be assumed as representative. Some literature data indicate that the annual equivalent dose to the lens of the eye may exceed 20 mSv for some workers.

324. In dental practices, the estimated values for the workforce varied from about 270,000 to 500,000 in the period 1975–1999; no clear trend was observed. In the current evaluation, the number of workers increased from 350,000 in the period 2000–2004 to 450,000 in the period 2010–2014, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average annual effective dose is 0.2 mSv while the average annual effective dose in the period 1995–1999 was 0.1 mSv. Both values are close to the MDL reported by countries. The uncertainty interval for the worldwide number of workers for the period 2010–2014 ranges from 300,000 to 680,000 while the interval for the worldwide average annual effective dose ranges from 0.1 to 0.3 mSv.

325. For nuclear medicine, no statistically significant changes in workforce were observed during the three periods under consideration (2000–2004, 2005–2009 and 2010–2014). The estimated global number of monitored workers for these periods is about 200,000 each, which represents about 2% of the total number of monitored workers involved in the medical sector. The average annual effective dose decreased consecutively over these periods down to 0.4 mSv. The threefold increase in monitored workers between the periods 1977–1999 and 2000–2014 is likely to be a consequence of the introduction of new radiopharmaceuticals and new equipment for nuclear medicine diagnostics and therapy. Positron emission tomography (and its hybrid solutions) and SPECT are effective sources of diagnostic information and often replace traditional X-rays. The uncertainty interval for the worldwide number of workers ranges from 110,000 to 370,000 and the interval for the worldwide average annual effective dose from 0.2 to 0.8 mSv.

326. For radiation therapy, the number of workers exposed varies between 200,000 and 300,000 over the periods 1995–1999, 2000–2004, 2005–2009 and 2010–2014. The estimated number of workers for the period 2010–2014 is 300,000, which represents about 4% of the total number of monitored workers involved in the medical uses of radiation. The estimated average annual effective dose for the same period is 0.3 mSv; and the estimated average annual collective effective dose is 90 man Sv. The uncertainty interval for the worldwide number of workers ranges from 170,000 to 540,000 and the interval for the worldwide average annual effective dose from 0.1 to 0.5 mSv. An increase in average annual equivalent dose to the hands from 1 mSv in 2000–2004 to 6 mSv in 2010–2014 was observed in data reported through the UNSCEAR Occupational Exposure Survey. However, the trend cannot be taken as globally representative since too few countries provided data.

327. Because of the lack of correlation between the reported survey data and the predictor parameters, the worldwide level of occupational exposure in veterinary medicine and “all other medical uses” were not derived. According to the reported data, the average annual effective dose seems to be below 0.5 mSv, similar to previous evaluated periods.

328. The estimated number of workers involved in medical uses of ionizing radiation is about 9 million workers worldwide; the average annual collective effective dose is estimated to be about 4,500 man Sv and the average annual effective dose is 0.5 mSv. The uncertainty interval for the worldwide number of workers ranges from 5.0 to 17 million and the interval for the worldwide average annual effective dose from 0.26 to 1.0 mSv. Although the workforce for 2010–2014 is underestimated because it does not include veterinary medicine and all other medical uses of radiation, the uncertainty interval accounts for that underestimation. The evaluation of the trends in occupational exposure for all medical uses together showed an increasing number of monitored workers, dominated by those involved in diagnostic radiology, while the annual average annual effective dose has been stable or more likely decreasing since the 1985–1989 period. The increasing number of workers correlates with the substantial increase in average annual collective effective dose presented in table 39. The relevant increase in the workforce from 1990–1994 to 1995–1999 was due to an improvement of data collection through collaboration with the World Health Organization (WHO).

Table 39. Estimated worldwide levels of annual occupational exposure from all medical uses

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	1 280	650	1000	0.8	1.5
1980–1984[a]	1 890	520	1 140	0.6	1.7
1985–1989[a]	2 220	590	1 030	0.5	1.7
1990–1994[a]	2 320	550	760	0.3	1.4
1995–1999[a]	7 440	[b]	3 540	0.5	[b]
2010–2014	9 000	[b]	4 500	0.5	[b]

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

[b] No worldwide estimation was possible because of limited data or no reliable data.

C. Industrial uses of radiation

329. Radiation sources, including sealed sources, X-ray machines, particle accelerators and unsealed sources, are used in a number of industrial applications. Among these are industrial irradiation, industrial radiography, luminizing, radioisotope production and distribution, well logging, accelerator operation, and industrial gauges. Because of the many different occupations involved and the ways in which exposure is categorized, it is difficult to obtain comparable statistics for different countries. Most radiation exposure in industrial uses of radiation is low, a fact that contributes to the lack of detail in recorded data for occupational exposure.

1. Industrial irradiation

330. The most widespread uses of industrial irradiation are the sterilization of medical and pharmaceutical products, the preservation of foodstuffs, polymer synthesis and modification, and the eradication of insect infestation. Usually, the irradiators use gamma emitting sources (such as ^{60}Co) or electron beams (e-beams). The required product doses are extremely high, and the involved source activities or beam currents are correspondingly high. The highest used electron energy in commercial irradiation is 10 MeV in order to avoid induced activity. Dose rates in a typical irradiation chamber would be of the order of 1 Gy/s while e-beams are capable of delivering up to about 100 kGy/s; however, gamma rays can penetrate deeper into studied material than electrons.

331. A survey conducted by the IAEA between 2004 and 2008 to assess the worldwide number of sterilization facilities showed that over 200 gamma irradiators were in operation for a variety of purposes in 55 countries: 100–120 gamma irradiators were located in Europe and the United States [I6]. The IAEA reported the number of workers for 30 operating gamma irradiators from 12 countries and the number of workers for 16 operating e-beam irradiators from six countries. These data are presented in table 40 and showed when using linear regression analysis and excluding e-beam irradiators that there is a statistically significant correlation between the number of gamma irradiators and number of workers for each country (adjusted $R^2 = 0.65$). Therefore, the number of gamma irradiators and the number of workers for each country were used to derive a mathematical model to estimate the total number of

workers worldwide. Using the IAEA data, in 2008 the total number of irradiators was estimated to be 6,249, and the total number of gamma irradiators 6,182 [I18].

332. On the basis of the total cumulative sale of ^{60}Co by all suppliers, the IAEA survey estimated that the installed capacity of cobalt was increasing by about 6% per year. It was further noticed that the worldwide use of disposable medical devices was growing at approximately the same rate (5–6%), an observation that could corroborate the estimated growth in installed capacity. The yearly increasing rate of 6% was applied to estimate the total number of gamma irradiators for the years 2009 to 2014.

Table 40. International Atomic Energy Agency survey results for industrial irradiation [I18]

Country	*Gamma irradiators*		*Electron beam irradiators*	
	Number of irradiators	*Number of workers*	*Number of irradiators*	*Number of workers*
Argentina	3	35		
Belarus	2	25	3	16
Brazil	3	12		
Croatia	1	4		
Czechia	1	7		
Denmark	1	5	1	5
Germany	1	15		
Hungary	2	13	1	2
India	6	98		
Mexico	5	57		
Philippines			2	27
Republic of Korea	4	8	6	24
United States	1	22	3	33

333. A total of 14 countries responded to the UNSCEAR Occupational Exposure Survey in the period 2003–2014. Nine other countries provided data within the period 2015–2018. The data available over the three periods are provided in table A.20 in the electronic attachment. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. The average annual effective dose for monitored workers ranges from <MDL to 0.65 mSv in the latest period, 2010–2014. According to the survey data, female workforce represents about 10% of the monitored workers.

334. The worldwide level of occupational exposure is evaluated on the basis of the methodology described in section II.E.1. As described before, the mathematical model was derived on the basis of the number of gamma irradiators as predictor parameters to estimate the number of workers for industrial irradiation. The worldwide occupational exposure arising from industrial irradiation over the periods 2005–2009 and 2010–2014 are presented in table 41 and table A.20 in the electronic attachment. Assuming that the average number of gamma irradiators was 6,182 for the period 2005–2009, the worldwide number of monitored workers was estimated as 82,000 for that period. Assuming that the annual increasing rate of ^{60}Co installed capacity was 6% since 2008, as predicted, the average number of gamma irradiators was estimated as 7,830 for the period 2010–2014. Applying the same model derived for the period 2005–2009, the estimated number of monitored workers worldwide was 110,000 for the period 2010–2014. There is

no statistically significant correlation between the number of irradiators and the average annual effective dose. The estimated average annual effective dose is the average values weighted by the workforce of the countries that responded to the UNSCEAR Occupational Exposure Survey: 0.6 mSv for 2005–2009 and 0.4 mSv for 2010–2014. Assuming that the derived average annual effective dose represents the worldwide average annual effective dose, the average annual collective effective doses are 49 and 44 man Sv for 2005–2009 and 2010–2014, respectively. The estimates for the period 2000–2004 were not made because of lack of data for the predictor parameter. The Committee recognized that the number of monitored workers and the average annual collective effective dose is underestimated, which is because the estimated values were based on the number of gamma irradiators; the e-beam irradiators were not included in the calculation. The IAEA survey [I6] conducted between 2004 and 2008 estimated the worldwide number of sterilization facilities and showed that the number of e-beam irradiators represented only 1% of the total number of irradiators.

Table 41. Estimated worldwide levels of annual occupational exposure from industrial irradiation

Period	*Number of monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose of monitored workers (mSv)*
2005–2009	82	49	0.6
2010–2014	110	44	0.4

2. Industrial radiography

335. Industrial radiography uses non-destructive testing to inspect material and components with the objective of locating and quantifying defects and degradation in material properties that would lead to the failure of engineering structures. In general, industrial radiography uses X-rays or gamma emitters. The most commonly used gamma emitter is ^{192}Ir but other radionuclides, such as ^{75}Se, are also used on a smaller scale. After crossing the specimen to be investigated, photons are captured by a detector such as a silver halide film, a phosphor plate or a flat panel detector. The examination can be performed in static 2D set-up (radiography), in real time 2D set-up (fluoroscopy), or in 3D set-up after image reconstruction (by computer tomography). It is also possible to perform tomography in nearly real time (4-dimensional computer tomography). Detectors can also be used to analyse the X-ray spectrum. Techniques such as X-ray fluorescence, X-ray diffractometry and several others complete the range of tools that can be used in industrial radiography.

336. Industrial radiography is performed in two quite different situations. In the first, it is carried out at a single location, usually in a permanent facility that has been designed and shielded for the purpose, in which case, items to be radiographed are brought to the facility. In the second situation, the radiography is conducted at multiple locations in the field, in which case the radiographic equipment is brought to the location where the radiograph is required, often referred to as “site radiography”. There are usually significant differences in the degree of control that can be exercised in the two situations. Site radiography with mobile sources is often performed under challenging environmental circumstances such as difficult access to the object to be radiographed, bad weather conditions, night-time when few people are in the vicinity of the controlled area. Thus, radiological incidents with high exposure could occur more often in mobile radiography [U10].

337. The IAEA established ISEMIR, a web-based tool for companies performing non-destructive testing by industrial radiography. ISEMIR is used to regularly collect and analyse occupational radiation dose data for industrial radiography workers and to use this information to improve and optimize their radiation

protection. A total of 423 radiographers provided data to the ISEMIR-IR database. Over 200 radiographers provided a value for their effective dose in 2009: the average annual effective dose was 3.4 mSv, with a reported maximum annual effective dose of 30 mSv. The majority of radiographers (76%) stated that they received an annual effective dose of less than 5 mSv in 2009, nearly one-quarter received a dose between 5 and 20 mSv, and a small percentage (2%) received a dose greater than 20 mSv. The data on average effective doses for different regions are shown in table 42. On the basis of data from 141 radiographers who provided both annual doses and workloads, the estimate (at the 95% level) of the mean occupational dose per exposure was 4.8 ± 2.3 µSv. Data for radiographers with workloads of less than 100 instances of exposure per year were excluded from the analysis shown in table 42. Data from 129 radiographers were used to estimate the average occupational dose per exposure, which was 2.9 ± 1.2 µSv. There was no statistically significant difference in the mean dose per exposure for radiographers using only gamma radiation sources and those using only X-ray sources [I8, I11, I20].

Table 42. Information on occupational exposure for radiographers in different regions [I11]

Regions	*Number of responses with data*	*Number of responses without data*	*Effective dose (mSv)*					
			Mean	*Min*	*Q1*[a]	*Median*	*Q3*[b]	*Max*
Africa	9	8	1.9	0.0	0.0	0.6	2.4	8.5
Asia-Pacific	24	25	4.5	0.0	0.1	1.4	5.3	30
Europe	92	74	2.4	0.0	0.1	1.4	4.1	8.9
Central and South America	41	31	3.0	0.0	0.3	1.6	2.9	20
North America	68	60	5.0	0.0	0.7	3.1	8.0	30
Global	234	198	3.4	0.0	0.3	1.8	4.7	30

[a] 25th percentiles.

[b] 75th percentiles.

338. The available data over the periods are given in table A.20 in the electronic attachment. Twenty-five countries responded to the UNSCEAR Occupational Exposure Survey within the period 2003–2014. Three other countries provided data within the period 2015–2018. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. Data obtained from the literature have been used to supplement the available data for the periods 2005–2009 and 2010–2014 [B4, B27, E10, U10]. The average annual effective dose, reported by the countries for the studied five-year periods between 2000 and 2014, ranges from 0.04 to 8.7 mSv.

339. The worldwide level of occupational exposure is evaluated on the basis of the methodology described in section II.E.1. An attempt was made to use two predictor parameters, GDP per capita and petroleum production, to estimate the worldwide level of exposure for industrial radiography. There was no statistically significant correlation between the average number of workers and average annual effective dose for each period of the analysis and parameters. No other worldwide data are available that can be used as a predictor parameter specific to industrial radiography. Due to the lack of an appropriate predictor parameter to estimate reliable levels of occupational exposure, the estimated average number of monitored workers for the 2005–2009 and 2010–2014 periods is assumed to be the same as for the period 2000–2002 previously estimated for the UNSCEAR 2008 Report [U10]. This assumption was applied because the analysis of the trends for the number of monitored workers in the countries that responded to the UNSCEAR Occupational Exposure Survey showed that, in general, there was no change

in the number of workers over time. According to the reported data, the female workforce represents about 5% of the number of monitored workers.

340. The average annual effective dose assumed in the current analysis is the average annual effective dose of the countries that responded to the UNSCEAR Occupational Exposure Survey weighted by the number of monitored workers in each country. The average annual effective dose values are 1.5, 1.7 and 1.1 mSv for 2000–2004, 2005–2009 and 2010–2014, respectively. The average annual effective doses are similar to the global median value estimated by the ISEMIR for 2009, which was 1.8 mSv [I20]. Additionally, there is a significant decreasing trend in the average annual effective dose for the years 1975–2014 for monitored workers' average annual effective dose (from 2.6 to 1.1) as reported by their countries. In order to estimate the average annual collective effective dose, the average annual effective dose weighted by the number of workers will be assumed as the global estimate.

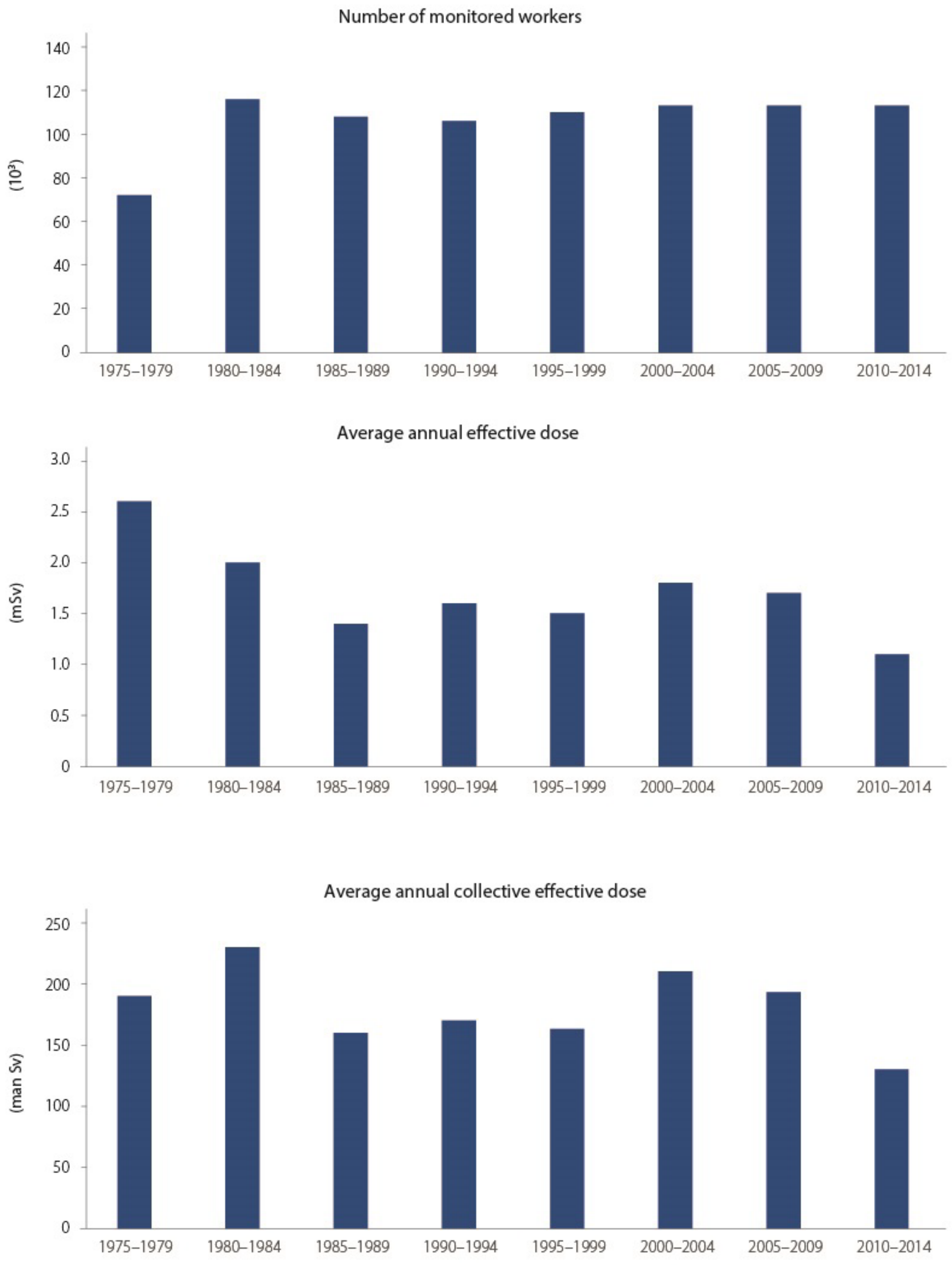
341. The worldwide estimated levels of occupational exposure are shown in table 43, table A.20 in the electronic attachment and figure VII. There was an increase in the number of monitored workers from 72,000 (1975–1979) to 116,000 in the first two periods (1975–1979 and 1980–1984) and then the number of monitored workers remained about the same in the last six periods until 2014, at approximately 113,000. Assuming that the average annual effective dose estimated for the three last periods represents the worldwide average values, it seems that the average annual effective dose dropped from 2.6 to 1.1 mSv from 1975–1979 to 2010–2014. The average annual collective effective dose follows the same pattern as the number of workers, increasing from 190 to 230 man Sv in the first two periods, then dropping to 126 man Sv for the period 2010–2014 because of the decreasing average annual effective dose. According to the UNSCEAR Occupational Exposure Survey conducted with IAEA assistance, several countries in Africa use industrial radiography; however, no African countries responded to the survey. Uncertainties on the estimates were not evaluated because of the lack of data.

Table 43. Estimated worldwide levels of annual occupational exposure in industrial radiography

Period	*Number of monitored workers (10^3)*	*Number of measurably exposed workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	72		190	2.6	
1980–1984[a]	116		230	2.0	
1985–1989[a]	108		160	1.4	
1990–1994[a]	106	53	170	1.6	3.2
1995–1999[a]	110	50	163	1.5	3.3
2000–2004	113	50	210	1.8	
2005–2009	113		190	1.7	
2010–2014	113		130	1.1	

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

Figure VII. Trends in number of monitored workers, average annual effective dose and average annual collective effective dose for industrial radiography



3. Luminizing

342. Luminizing is one of the oldest industrial uses of ionizing radiation. For many years radioluminous paint has been used in products where the ability to see an indication in the dark was considered useful. Radionuclides have been used in the luminous paint industry for many years, the radiation emitted being converted into light by a scintillator (usually zinc sulphide). For much of the 20th century, ^{226}Ra was the most widely used radionuclide, but in recent years, for various reasons, this has been replaced by ^{3}H (tritium) and ^{147}Pm (promethium). In addition, improved technology has, in some cases, enabled manufacturers to reduce the amount of radioactive material used in certain products.

343. More recently, gaseous tritium light sources have also been incorporated into products to provide a source of illumination. Some examples of widely available radioluminous products are timepieces, map illuminators, navigational instruments (e.g., compasses), exit signs, torches, novelty items (e.g., key rings) and fishing floats. Examples of radioluminous products available to only a small number of specialists are weapon sights, signs, dials and switches (e.g., on boats and aircraft). When compared to products containing radioluminous paint, significantly greater activities of tritium gas are required to produce the same degree of brightness.

344. Some fluorescent lamps have small quantities of a variety of radionuclides in order to provide initial ionization for the arc that energizes the phosphor coat on the inside surface of the lamp to produce visible light. In addition, thoriated electrodes and thorium iodate are often used in halogen vapour lamps.

345. The available data for the periods of interest are shown in table A.20 in the electronic attachment. Four countries responded to the UNSCEAR Occupational Exposure Survey within the period 2003–2014. Due to the limited occupational data provided, the worldwide levels of occupational exposure in the luminizing subsector were not estimated. The average annual effective dose for monitored workers provided from the survey ranged from 0.01 to 0.69 mSv. According to the reported data, the female workforce represents about 30% of the number of monitored workers.

346. The data from the countries that responded to the UNSCEAR Occupational Exposure Survey for 2010–2014 showed that there are at least 1,700 monitored workers, 3% of whom are exposed to measurable doses. The average annual effective doses decreased over time, from 7.4 mSv in the period 1975–1979 to 0.05 mSv in the period 2010–2014.

4. Radioisotope production and distribution

347. Radioisotopes are produced for a great variety of industrial and medical purposes. The main source of occupational exposure in radioisotope production and distribution is external irradiation; in some cases, internal exposure may make a slight contribution to the effective dose. In general, however, internal exposure has not been included in reported statistics for occupational exposure except in more recent years and, even then, their inclusion is far from universal. Reporting conventions for workers involved in radioisotope production may also vary from country to country (e.g., with regard to whether the reported doses include only those arising during the initial production and distribution of radioisotopes or whether they include also those arising in the subsequent processing, encapsulation, packaging and distribution of radionuclides that may have been purchased in bulk elsewhere), and this may affect the validity of comparisons between reported doses.

348. The number of cyclotrons dedicated to the production of positron-emitting radionuclides is increasing in medical institutions/hospitals owing to the well-established role of positron emission tomography imaging in clinical practice. The radiation safety issues in a cyclotron facility are much

different from those in conventional nuclear medicine production facilities because of the presence of penetrating gamma radiation of 511 keV, higher specific gamma ray constant of positron emitters and the secondary neutrons from the cyclotron during production. The radiation protection issues at such a facility are complex and the radiation and safety controls should be stringent.

349. A study on the risks of radiation exposure during cyclotron maintenance activities noted that maintenance of high workload cyclotrons may involve a potentially high risk of inhalation of strongly activated particulate matter [C1]. The average annual effective dose for workers of the Cyclotron Center in Taiwan, China, was estimated as 2.1 mSv for $H_p(10)$ and the average equivalent dose (skin) to fingers as 96.2 mSv for $H_p(0.07)$ [K14].

350. The exposure of workers at a cyclotron accelerator radioisotope production facility in Brazil was recorded for the years 2007–2011. The average annual effective doses for three workgroups are presented in table 44 [S11]. The target group receiving the highest exposure was described as being responsible for the maintenance, preparation and switching of targets, and also for intervention in cyclotron beam lines, which happens when the cyclotron must be turned off so that potential flaws can be repaired.

Table 44. Average annual effective dose for cyclotron facility workers in Brazil [S11]

Workgroup	*Average annual effective dose by year (mSv)*				
	2007	*2008*	*2009*	*2010*	*2011*
Target	15.7	11.1	9.4	7.4	11.4
Operation	5.7	1.9	3.3	1.9	4.1
Radioprotection	7.0	5.2	6.1	3.9	5.0

351. National data on occupational exposure arising from radioisotope production and distribution over the period 2000–2014 are given in table A.20 in the electronic attachment. Fourteen countries responded to the detailed UNSCEAR Occupational Exposure Survey within the period 2003–2014. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. Data obtained from the literature have been used to supplement the available data for the period 2005–2009. The average annual effective dose from the survey data ranges for monitored workers from 0.10 to 4.53 mSv. Data obtained from the literature [S3] provided a maximum average annual dose for the “target” working group of 12 mSv. According to the reported data, the female workforce represents about 8% of all monitored workers.

352. Two predictor parameters, GDP per capita and number of research reactors, were used in an attempt to estimate the worldwide level of exposure for radioisotope production. The number of research reactors were obtained on the IAEA Research Reactor Database [I21]. There was no statistically significant correlation between the average number of workers and average annual effective dose for each period of the analysis and parameters. No other worldwide data are available that can be used as a predictor parameter specific for radioisotope production, which prevented worldwide extrapolation.

353. The data from the countries that responded to the UNSCEAR Occupational Exposure Survey for 2010–2014 showed that there are at least 4,400 monitored workers, 40% of whom are exposed to measurable doses. The average annual effective doses have decreased over time, from 2.2 mSv in the period 1975–1979 to 0.8 mSv in the period 2010–2014.

5. Well logging

354. Mining, ground engineering and water industries, and oil and gas exploration and production (conventional and unconventional, e.g., fracking) make extensive use of radioactive sources, and in some cases radiation generators, for characterizing and evaluating geological formations and borehole and well constructions (IAEA SSG-57) [I17]. Well logging techniques are used to explore geological formations by using sealed gamma ^{137}Cs or neutron ^{241}Am-Be sources to measure and record the density or porosity of geological strata along a borehole.

355. Exposure data from the UNSCEAR Occupational Exposure Survey (2000–2004, 2005–2009, 2010–2014) for the well logging subsector are shown in table A.20 in the electronic attachment. Nine countries responded to the detailed survey for the period 2003–2014. A total of 21 countries, including those nine, responded to the simplified survey for the period 2011–2018; these data were added to the extrapolation. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. The average annual effective dose of monitored workers from the survey data for the period 2000–2014 ranges <MDL to 2.7 mSv. According to the reported data, the female workforce represents 5% of the number of monitored workers.

356. The predictor parameters to estimate the worldwide level of occupational exposure in the well logging subsector were petroleum production, mineral production and GDP per capita. There is no statistically significant correlation between these parameters and the number of monitored workers and the average annual collective effective dose. The adjusted R^2 values stemming from the correlation attempts were all below 0.5, and such correlations are not appropriate to use in deriving reliable predicted values. Because of lack of worldwide predictor parameter data, no further attempt was made to extrapolate the level of occupational exposure in the well logging subsector. The data from the countries that responded to the UNSCEAR Occupational Exposure Survey for 2010–2014 showed that of at least 11,290 monitored workers, 12% are classified as measurably exposed. The average annual effective dose decreased over time, from 1.3 mSv in the period 1975–1979 to 0.3 mSv in the period 2010–2014.

6. Accelerator operation

357. Consideration is limited here to occupational exposure arising from accelerators used for nuclear physics research at universities and at national and international laboratories. Accelerators (generally of somewhat smaller size) are increasingly being used for medical, therapeutical and radiopharmaceutical purposes. However, exposure arising from those uses is more appropriately considered under medical uses of radiation in section IV.B. Similarly, accelerators are also found in radiography and commercial radioisotope production but, again, these are dealt with under those work categories. Most exposure resulting from accelerators arises from induced radioactivity and occurs mainly during the repair, maintenance, and modification of equipment. The exposure results mainly from gamma rays from the activation of solid surrounding material by leakage penetrating radiation such as neutrons, high-energetic gamma rays and, in some cases, secondary induced heavy particles. The potential committed effective dose from internal exposure in the normal operation mode of accelerators is usually negligible in comparison with the effective dose due to external irradiation.

358. Exposure data from the UNSCEAR Occupational Exposure Survey (2000–2004, 2005–2009, 2010–2014) on occupational exposure in accelerator operation are given in table A.20 in the electronic attachment. Seven countries responded to the detailed survey for the period 2003–2014. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. The average annual effective dose of monitored workers from the survey data ranges from <MDL to

1.63 mSv. According to the reported data, the female workforce for the three periods is 1–20% of the number of monitored workers.

359. The predictor parameter to estimate the worldwide level of occupational exposure in the accelerator operation subsector was GDP per capita. There is statistically significant correlation between the predictor parameter and the number of monitored workers, the number of measurably exposed workers and the average annual collective effective dose for the period 2010–2014. The adjusted R^2 values were all 0.9. However, the extrapolation model was derived from data of only six countries. In addition, the challenge here is to define the countries that should be included in the extrapolation calculation. Because of limited information, the results of the extrapolation were not used here. The data from the countries that responded to the UNSCEAR Occupational Exposure Survey for 2010–2014 showed that of at least 10,000 monitored workers, 10% are classified as measurably exposed. The average annual effective dose decreased over time from 1.6 mSv (1975–1979) to about 0.1 mSv (2000–2014).

7. Industrial gauges

360. Industrial gauges are mechanical tools used to measure, monitor, and control the thickness of sheet metal, textiles, paper napkins, newspaper, plastics, photographic film, and other products as they are manufactured. Non-portable gauging devices (i.e., gauges mounted in fixed locations) are designed for measurement or control of material density, flow, level, thickness, or weight. The gauges contain sealed sources that radiate through the substance being measured to a readout or controlling device. Portable gauging devices, such as moisture density gauges, are used at field locations. These gauges contain a gamma-emitting sealed source, usually ^{137}Cs, or a sealed neutron source, usually ^{241}Am-Be [U20].

361. Industrial gauges are required for industries where pressure and temperature are critical parameters. Growing industrialization is one of the factors driving the demand for industrial gauges. The global market for industrial gauges is divided into seven regions, namely North America, Latin America, Asia Pacific excluding Japan, Western Europe, Eastern Europe, Japan and the Middle East and Africa. North America and Western Europe account for a major share of the global industrial gauges market. This is attributed to the presence of vast manufacturing bases such as those for chemicals, food, dairy products, and paper & pulp, which require industrial gauges in the manufacturing plants. In the Pacific excluding Japan region, the industrial gauge market is expected to be boosted by western companies shifting their manufacturing facilities there because of its cheap labour and raw material resources. The Middle East and Africa industrial gauge market is driven mainly by the oil and gas industry [P8].

362. Exposure data from the UNSCEAR Occupational Exposure Survey (2000–2004, 2005–2009, 2010–2014) on the use of industrial gauges are given in table A.20 in the electronic attachment. Nine countries responded to the survey for the period 2003–2014. Another 15 countries responded to the simplified survey for the period ranging from 2011 to 2018. The average annual effective dose of monitored workers from the survey data ranges from <MDL to 0.84 mSv. According to the reported data, the female workforce represents 10–15% of the number of monitored workers.

363. The predictor parameters applied to estimate the worldwide level of occupational exposure in the industrial gauge subsector were petroleum production and GDP per capita. There is no statistically significant correlation between these predictor parameters and the number of monitored workers and the average annual collective effective dose. The adjusted R^2 values were all below 0.5, which are not appropriate for deriving any reliable predicted value. Because of lack of worldwide predictor parameter data, no further attempt was made to extrapolate the level of occupational exposure in this subsector. The data from the countries that responded to the UNSCEAR Occupational Exposure Survey for 2010–2014

showed that there are at least 610 monitored workers. The average annual effective dose of monitored workers from countries that reported data is 0.2 mSv. According to survey conducted with IAEA assistance, several countries in Africa carry out practices involving industrial gauges [I18].

8. All other industrial uses

364. The many other uses of radiation in industry include those in soil moisture gauges, thickness gauges and X-ray diffraction but their occupational exposure data are, in general, not separately identified or reported. The number of workers potentially exposed in these other uses may substantially exceed the number in the few occupations for which data have been separately presented in this section. The average exposure levels of workers involved in "other uses of radiation" is generally low.

365. Exposure data from the UNSCEAR Occupational Exposure Survey (2000–2004, 2005–2009, 2010–2014) on all other industrial uses are given in table A.20 in the electronic attachment. Twenty countries responded to the survey for the period 2003–2014. A total of 26 countries, including 13 who completed the detailed survey, responded to the simplified survey for the period 2011–2018. Data obtained from the literature were used to supplement the available data for all periods [A2, B5, F1, H5, U10]. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. The average annual effective dose of monitored workers from the survey data ranges from 0.03 to 1.4 mSv. Japan, Germany, and France represent about 70% of the reported monitored workers for the period 2000–2004. Feedback indicates that national systems for data collecting do not allow the data to be readily separated into the categories used in this review.

366. The predictor parameter applied to estimate the worldwide level of occupational exposure in the "all other industrial uses" subsector was GDP per capita. No statistically significant correlation between this predictor parameter and the number of monitored workers or the average annual collective effective dose could be established. The data from the countries that responded to the UNSCEAR Occupational Exposure Survey for 2010–2014 showed that there are at least 120,000 monitored workers classified in the category. The average annual effective dose of monitored workers from countries that reported data is about 0.3 mSv, while the average annual effective dose of measurably exposed workers is 1.2 mSv for the period 2010–2014. According to the reported data, the female workforce represents 15–20% of the number of monitored workers.

9. Summary

367. The national data on all industrial uses of radiation grouped together are presented in table A.21 in the electronic attachment. The data are more complete than for the separate categories. Because of the lack of a reliable predictor to estimate the worldwide level of occupational exposure in the industrial sector, the estimate for all industrial uses was based on the trends for all countries. The same approach was applied in the UNSCEAR 2008 Report [U10]. The estimate of the worldwide workforce in the industrial sector was 1.1 million for the period 2010–2014. The uncertainty interval of the worldwide number of workers ranges from 0.56 to 2.2 million. The workforce increased by a factor of two over the 40-year period of evaluation, from 0.5 to 1.1 million. This value may be an underestimation due to the limited representativeness of reported data. The estimated value for the average annual effective dose decreased by a factor of four over the 40-year period of evaluation (1.6 to 0.4 mSv). The uncertainty interval of the worldwide average annual effective dose ranges from 0.2 to 0.8 mSv. The estimated average annual collective effective dose was 440 man Sv for the period 2010–2014; it decreased by a factor of two over the 40-year period of evaluation. The worldwide level of exposure for the total industrial sector is

presented in table 45, table A.21 and figure VIII. Because the estimate of the worldwide level of exposure is based on trends that countries reported to the UNSCEAR Occupational Exposure Survey, no assessment of uncertainties was conducted.

368. There is a wide variation in the average annual effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in national databases, and the radiation protective measures implemented by each country.

369. For industrial irradiation, it is the first time that the Committee had enough information to derive the worldwide number of monitored workers. This was carried out for the periods 2005–2009 and 2010–2014, using the number of gamma irradiators as a predictor parameter. The total number of workers in the industrial irradiation subsector for the period 2010–2014 is estimated as 110,000, which represents about 10% of the total number of monitored workers in the industrial sector. The average annual collective dose is estimated to be 44 man Sv for the period 2010–2014, which represents about 9% of the average annual collective dose for the total industrial sector. The estimated average annual effective dose is below 1 mSv. The Committee recognizes that the number of monitored workers and average annual collective effective dose are underestimated. That is because the estimated values were based on the number of gamma irradiators; the e-beam irradiators were not included in the calculation. An IAEA Survey conducted in 2004–2008 to estimate the worldwide number of sterilization facilities showed that the number of e-beam irradiators represented about 1% of the total number of irradiators [I6].

370. For industrial radiography, the Committee has estimated the worldwide level of occupational exposure since the period 1975–1979. Due to lack of statistically significant correlation between the occupational parameters and the predictor parameter, the worldwide number of monitored workers for the respective periods 2000–2004, 2005–2009 and 2010–2014 was derived on the basis of the observed trend in the number of monitored workers for the countries that responded to the UNSCEAR Occupational Exposure Survey. It was assumed that the size of the workforce was the same during the period 2000–2014. The industrial radiography subsector represents about 10% of the total number of monitored workers in the industrial sector. The estimated number of monitored workers increased from 72,000 (1975–1979) to 113,000 (2010–2014). The average annual collective effective dose is estimated as 126 man Sv for the period 2010–2014, which represents about 30% of the average collective dose for the total industrial sector. It decreased from 190 man Sv (1975–1979) to 126 man Sv (2010–2014). The estimated average annual effective dose was below 1.1 mSv, decreasing from 2.6 mSv (1975–1979) to 1.1 mSv (2010–2014). Since the trends of countries was the parameter applied to extrapolate the data, the estimate of the uncertainty was not feasible.

371. For luminizing, the worldwide number of monitored workers was not estimated due to the limited number of countries responding to the UNSCEAR Occupational Exposure Survey. On the basis of the data reported for 2010–2014, the number of monitored workers was approximately 1,700. The average annual effective dose was 0.05 mSv. The average annual effective dose from the countries that responded to the survey decreased significantly over time, from 7.4 mSv (1975–1979) to below 1 mSv during the last three periods (2000–2014).

372. For radioisotope production, the worldwide number of monitored workers was not estimated due to the limited number of countries responding to the UNSCEAR Occupational Exposure Survey and lack of statistically significant correlation between the data and the predictor parameters (GDP and number of research reactors). The data reported for 2010–2014 show that there were at least 4,470 monitored workers, 40% of whom were exposed to measurable doses. The average annual effective doses decreased over time, from 2.2 mSv in the period 1975–1979 to 0.8 mSv in the period 2010–2014.

373. For the well logging subsector, the worldwide number of monitored workers was not estimated due to the lack of an appropriate predictor parameter for the extrapolation model. On the basis of the data reported by the countries that responded to the UNSCEAR Occupational Exposure Survey, the number of monitored workers increased over time. The reported total number of monitored workers for the period 2010–2014 was approximately 11,000. The average annual effective dose decreased over time from 1.3 mSv (1975–1979) to 0.3 mSv (2010–2014).

374. For accelerator operation, the worldwide number of monitored workers was not estimated because no suitable correlations for extrapolations could be established. On the basis of the data reported by the responding countries, the number of monitored workers increased over time. The reported total number of monitored workers for the period 2010–2014 was approximatively 10,000. The average annual effective dose was below 1 mSv for 2010–2014; it decreased over time from 1.6 mSv (1975–1979) to 0.06 mSv (2010–2014).

375. For the industrial gauge subsector, the worldwide number of monitored workers was not estimated due to the lack of an appropriate predictor parameter for the extrapolation model. On the basis of the data reported by the countries that responded to the UNSCEAR Occupational Exposure Survey, the total number of monitored workers for the period 2010–2014 was approximately 600 and the average annual effective dose was about 0.2 mSv.

376. For the "other industrial uses of radiation" subsector, the worldwide number of monitored workers was not estimated due to the inability to establish an appropriate predictor parameter. Based on the data reported, the number of monitored workers decreased over time. The reported total number of monitored workers was 127,000 for the period 2010–2014; approximately 50% of the reported workforce. The estimated average annual effective dose during that period was about 0.3 mSv.

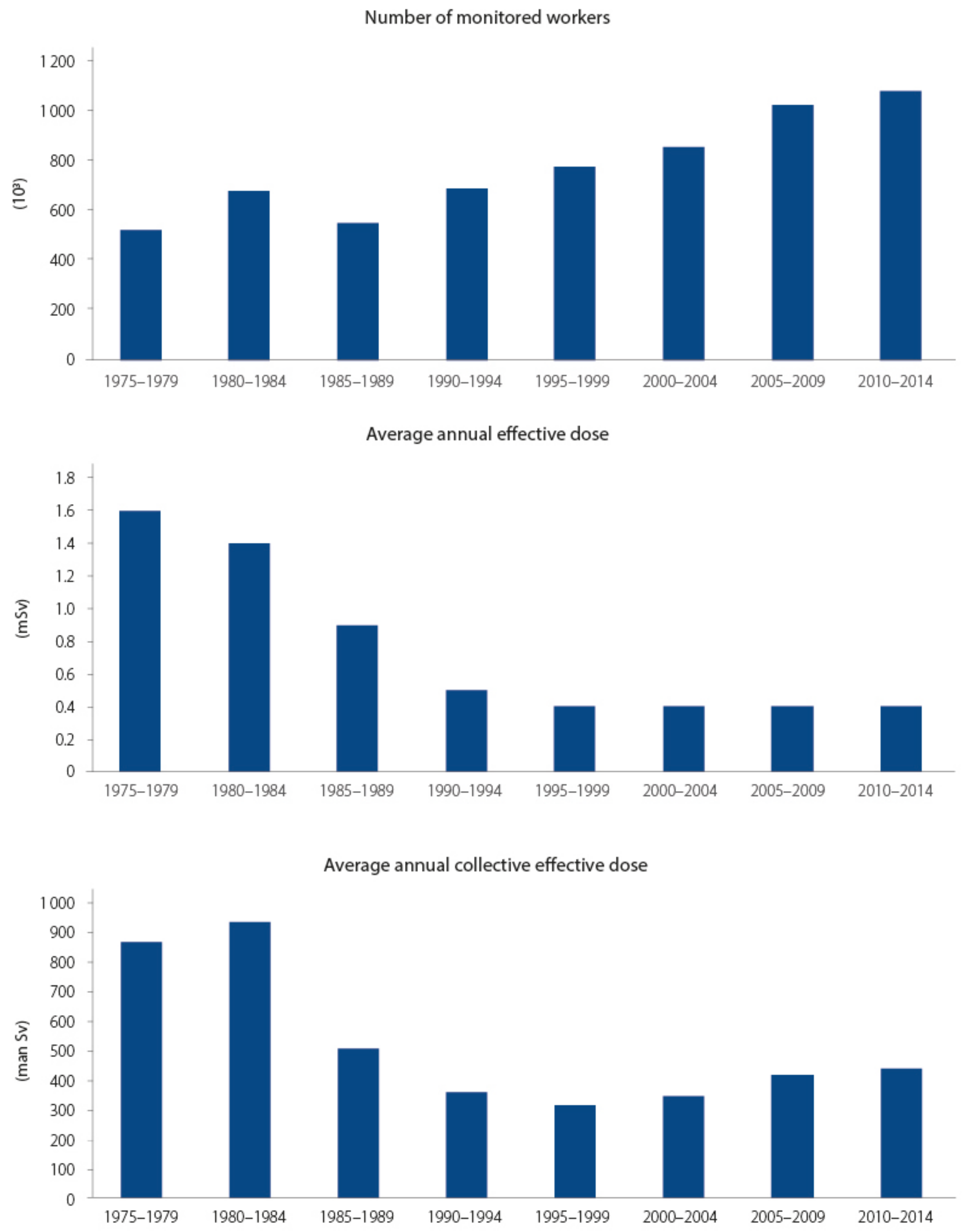
377. The summary of the estimated worldwide levels of occupational exposure in the industrial sector is presented in table 45, table A.21 and figure VIII. The number of monitored workers has doubled over the past four decades. The average annual effective doses to monitored workers involved in industrial uses of radiation consistently decreased to a level of around 0.5 mSv since the 1990s. The largest contribution to the occupational exposure comes from industrial radiography, industrial irradiation and the "other industrial uses of radiation" subsectors. The occupational exposure data presented in table 45 are rough estimates of the number of workers, average annual effective dose and average annual collective effective dose. The estimated values were derived on the basis of trends in the countries that provided data.

Table 45. Estimated worldwide levels of occupational exposure in industrial sector

Period	*Number of monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose to monitored workers (mSv)*
1975–1979[a]	530	870	1.6
1980–1984[a]	690	940	1.4
1985–1989[a]	560	510	0.9
1990–1994[a]	700	360	0.5
1995–1999[a]	790	315	0.4
2000–2004	869	348	0.4
2005–2009	1 043	419	0.4
2010–2014	1 100	440	0.4

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

Figure VIII. Trends in number of monitored workers, average annual effective dose and average annual collective effective dose for all industrial uses



D. Military uses

378. Radiation exposure of workers in military activities can be grouped into three broad categories: *(a)* those arising from the production and testing of nuclear weapons and associated activities; *(b)* those arising from the use of nuclear energy as a source of propulsion for naval vessels; and *(c)* those arising from the use of ionizing radiation for the same wide range of purposes for which it is used in civilian spheres (e.g., research, transport and non-destructive testing).

379. According to the information published in 2014, the United States military has effectively employed ionizing radiation since it was first introduced during the Spanish-American War in 1898. Currently, the military annually monitors 70,000 persons for occupational exposure, about 2% of its workforce. In recent years, the Departments of the Navy (including the Marine Corps), the Army, and the Air Force all have a low collective dose that remains close to 1 man Sv annually. Only a few coast guards are now routinely monitored. As with the nuclear industry as a whole, the Naval Nuclear Propulsion Program records a higher collective dose than the remainder of the United States military. The average annual collective effective doses for 2006 are presented in table 46. Responsible for measuring the individual radiation exposure are the Army, Naval, and Air Force Dosimetry Centers, and various naval reactor sites comprising more than 50% of the National Voluntary Laboratory Accreditation Program's accredited radiation dosimeter processors [N8]. External exposure is monitored for whole body exposure and extremity exposure. The measurement techniques include thermoluminescent and optically stimulated luminescent dosimeters, and electronic pocket dosimeters. Individual monitoring to evaluate the intake of radionuclides is performed for the personnel in Army, Navy, Air Force, and the naval reactor sites. The internal monitoring techniques include in vivo and in vitro bioassays. The United States military maintains occupational exposure records on over two million individuals from 1945 through the present. These records are controlled in accordance with the Privacy Act of 1974 but are available to affected individuals or their designees and other groups performing sanctioned epidemiology studies [B19].

Table 46. Radiation occupational exposure data for United States military personnel in 2006 [B19]

Armed services	*Number of monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
Naval reactors	46	20	0.44
Army	12	1.0	0.08
Air Force	6.6	0.6	0.09
Navy and Marine Corps	6.0	1.3	0.22
Total	**70.6**	**22.9**	**0.32**

380. The occupational exposure data of the military personnel assigned to tenders, bases, and nuclear-powered ships from operation and maintenance of naval nuclear propulsion plants and to ship ward personnel are evaluated annually by the United States Department of Navy. The annual data for number of monitored workers, dose distribution and total effective dose are presented for 64 years (from 1954 to 2018). The data presented in the reports provide a good picture of the trend of occupational exposure showing that, despite the significant increase of the number of ships being overhauled, there is a substantial decrease in effective doses [M8].

381. Radiation exposure at the prototype naval nuclear propulsion plants originates primarily from PWRs. In this type of reactor, water circulates through a closed piping system to transfer heat from the reactor core to a secondary steam system isolated from the reactor cooling water. Trace amounts of corrosion and wear products are carried by reactor coolant from reactor plant metal surfaces. Some of

these corrosion and wear products are deposited on the reactor core and become radioactive from exposure to neutrons. Reactor coolant carries some of these radioactive products through the piping systems where a portion of the radioactivity is removed by a purification system. Most of the remaining radionuclides transported from the reactor core are deposited in the piping systems. The reactor core is installed in a heavy-walled pressure vessel within a primary shield [M9].

382. The primary shield limits radiation exposure from the gamma rays and neutrons produced when the reactor is operating. Reactor plant piping systems are installed primarily inside a reactor compartment that is itself surrounded by a secondary shield. Access to the reactor compartment is permitted only after reactor shutdown. Most radiation exposure to personnel comes from inspection, maintenance, and repair inside the reactor compartment. The major source of the radiation exposure is ^{60}Co deposited inside the piping systems. Radiation exposure to personnel from neutrons during reactor operation is much less than from gamma radiation. After reactor shutdown, when maintenance and other support work is executed, no neutron exposure is detectable. Therefore, the radiation exposure at prototypes is primarily from gamma radiation [M9].

383. Radiation exposure at the expended core facility at the naval reactor facility is due primarily to gamma rays emitted by irradiated reactor fuel and structural components that were inside the reactor vessel during operation and became radioactive by exposure to neutrons. Work on these components is performed remotely in specially designed shielded cells, in deep water pits that shield personnel, or with shielded equipment used to place spent fuel into interim dry storage [M9].

384. Radiation exposure at the naval reactor’s laboratories is basically external, attributable to examination and analysis of irradiated fuel and other material, and to decontamination and decommissioning of obsolete facilities. Gamma rays is the significant contributor to dose. Although alpha and beta radiation are present, they are generally well shielded. Neutron radiation contributes very little to doses at the laboratories [M9].

385. The UNSCEAR 1993 Report [U6] addressed the potential for extrapolation based on normalized collective dose, with the normalization performed in terms of unit explosive yield for weapons, and per ship or installed nuclear capacity for the Naval Nuclear Propulsion Program. It concluded that such extrapolation was not viable. Pending the acquisition of further data, the UNSCEAR 1993 Report [U6] proposed adopting a very simple approach for estimating worldwide exposure from this source, namely that the worldwide collective dose from military activities is greater by a factor of three than the sum of the collective dose in the United Kingdom and the United States. Four assumptions underlay the choice of this factor. First, the levels of military activities in the former Soviet Union and the United States were broadly comparable. Second, the levels of exposure in the former Soviet Union were greater than in the United States by an indeterminate amount thought to exceed a factor of 2 in 1975–1989. Third, the levels of exposure in France have been comparable to those in the United Kingdom. Fourth, the exposure in China was not as high as that in the former Soviet Union or in the United States.

386. Until its UNSCEAR 2000 Report [U8], the Committee reviewed the occupational exposure separately for weapon fabrication and associated activities and for nuclear ships and their support facilities. This approach was not applied in the UNSCEAR 2008 Report [U10] because the data provided by countries were pooled together. Based on the described assumptions, the estimated worldwide number of monitored workers has been roughly constant, at between 300,000 and 400,000. The average annual collective effective dose from military activities would have been about 400 man Sv in 1975–1979, falling to about 250 man Sv in 1985–1989, 100 man Sv in 1990–1994, 58 man Sv in 1995–1999 and 52 man Sv in 2000–2002. Given the crudeness of the underlying assumptions, it was not possible to give a precise estimate of the collective dose: the worldwide average annual collective dose during the evaluated period was about 50–150 man Sv.

387. Exposure data from the UNSCEAR Occupational Exposure Survey (2000–2004, 2005–2009, 2010–2014) for military activities are given in table A.23 in the electronic attachment. For weapon fabrication and associated activities, only three countries (France, United Kingdom and United States) responded to the detailed survey within the period 2003–2014. The same countries also provided data for the subsector covering nuclear ships and their support facilities for the period 2003–2014. Twelve countries responded to the simplified survey providing data for total military activities. Most of them reported only data on the number of monitored workers. Some countries provided data for 2015 and 2017. There has been an improvement in data collection since the Russian Federation provided the number of workers for the year of 2016 for its total military activities.

388. The total number of monitored workers reported by the countries that responded to the UNSCEAR Occupational Exposure Survey in the period 2010–2014 is about 80,000. The Russian Federation, the United Kingdom and the United States account for 98% of the total reported workforce. The United States accounts for 66%, the Russian Federation for 19% and the United Kingdom for 13%.

389. On the basis of the trend of occupational exposure in the United Kingdom and in the United States, the number of monitored workers involved in weapon fabrication and associated activities decreased from about 21,000 during the period 1975–1979 to 14,200 during 2010–2014. The average annual effective dose decreased from 0.7 mSv during 1975–1979 to 0.1 mSv during 2010–2014. The average annual collective effective dose decreased from 14 man Sv (1975–1979) to 1.4 man Sv (2010–2014).

390. On the basis of the trend of occupational exposure in the United Kingdom and in the United States, the average number of monitored workers involved in nuclear ships and their support facilities increased from about 42,000 to 47,000 in the period 1975–1979 and 2010–2014. The average annual effective dose decreased from 2.1 mSv during the period 1975–1979 to 0.2 mSv during 2010–2014 and the average annual collective effective dose decreased from 92 to 8 man Sv in the same periods.

391. On the basis of the trend of occupational exposure in the United Kingdom and in the United States, it is shown that the number of monitored workers involved in all military activities decreased from about 104,000 during the period 1975–1979 to 64,000 during the period 2010–2014. The average annual effective dose decreased from 1.3 mSv (1975–1979) to 0.15 mSv (2010–2014) and the average annual collective effective dose decreased from 137 to 9.7 man Sv between the same periods.

392. Because very little occupational exposure data were available, the Committee was unable to derive worldwide levels of occupational exposure from sources for military use. The occupational data collected through the UNSCEAR Occupational Exposure Survey are few and insufficient for extrapolation. The data would also need to be qualified in terms of completeness, in particular as to whether they cover all significant occupational exposure related to military activities. For example, they do not include occupational exposure arising in the mining of uranium used in either nuclear weapon or nuclear naval programmes; nor is it clear to what extent the reported data include exposure arising during the enrichment of uranium for the weapon and naval programmes or exposure arising in the chemical separation and subsequent treatment of plutonium.

393. In summary, data provided by the countries that responded to the UNSCEAR Occupational Exposure Survey do not allow the derivation of a reliable estimate of the worldwide level of occupational exposure to sources used in military activities. However, data from the United States and the United Kingdom showed a substantial decrease in the average annual collective effective dose over time, due to the reduction in both the workforce and the average annual effective dose.

E. Miscellaneous uses of radiation

394. There are a number of occupations where radiation exposure may be involved that are not covered by other categories. These include research in educational establishments, the management of spent radioactive sources, and transport of radioactive material outside the nuclear fuel cycle. The data reported by countries are given in table A.22 in the electronic attachment.

1. Educational establishments

395. Research workers in educational establishments use radioactive sources, X-ray equipment, irradiators using ^{60}Co or ^{137}Cs sealed sources, training research reactors and unsealed radioactive sources for a wide range of activities. Examples of uses include X-ray crystallography and radioactive labels (e.g., ^{3}H, ^{14}C, ^{32}P, ^{35}S, and ^{125}I). Also, preclinical, multimodal imaging equipment (such as micro-computer tomography, and micro-positron emission tomography equipment) for small animals, using radionuclides such as ^{18}F and ^{99m}Tc.

396. Exposure data from the UNSCEAR Occupational Exposure Survey (2000–2004, 2005–2009, 2010–2014) in educational establishments are given in table A.22 in the electronic attachment. Nineteen countries responded to the detailed survey for the period 2003–2014. Several other countries responded to the simplified survey, providing data on the number of monitored workers for the period 2013–2018. Data obtained from the literature have been used to supplement the available data for all periods [U10]. The data provided in the UNSCEAR 2008 Report [U10] for 2000–2002 were added to the survey for the period 2000–2004. The average annual effective dose of monitored workers from the survey data ranges from ≤MDL to 2 mSv.

397. The predictor parameters applied to estimate the worldwide level of occupational exposure in educational establishments subsector were GDP per capita and the number of training research reactors. No statistically significant correlation was found between these predictor parameters and the number of monitored workers and the average annual collective effective dose. The estimated worldwide number of workers for all educational establishments was based on the trends in increase in the sector for all countries, which is the same approach applied in the analysis of the reported data for the UNSCEAR 2008 Report [U10]. According to the collected data, the average increase in the number of monitored workers from 2000–2004 to 2005–2009 was 8% and from 2005–2009 to 2010–2014 it was 12%. For measurably exposed workers, the corresponding increase from 2000–2004 to 2005–2009 was 6%, while no change was observed from 2005–2009 to 2010–2014.

398. The estimated worldwide workforce in educational establishments increased by a factor of four over 40 years of evaluation, from 140,000 during the period 1975–1979 to 540,000 during 2010–2014. This number may be an underestimation due to the possible limited representativeness of the reporting countries. The average annual effective dose was below 1.0 mSv and it decreased from 0.6 mSv (1975–1979) to 0.07 mSv (2010–2014). The estimated average annual collective effective dose decreased by a factor of two, from 74 man Sv in the period 1975–1979 to 38 man Sv in 2010–2014. The worldwide level of exposure for the educational establishment subsector is presented in table 47 and table A.22.

Table 47. Estimated worldwide levels of annual occupational exposure in the educational sector

Period	*Number of monitored workers (10³)*	*Number of measurably exposed workers (10³)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979[a]	140		74	0.55	
1980–1984[a]	180		43	0.24	
1985–1989[a]	160		22	0.14	
1990–1994[a]	310	30	33	0.11	1.1
1995–1999[a]	372	29	36	0.10	1.2
2000–2004	446	30	27	0.06	0.9
2005–2009	482	32	34	0.07	
2010–2014	540	32	38	0.07	1.2

[a] Values from earlier UNSCEAR reports [U3, U4, U6, U8, U10].

2. Disused radioactive sources

399. Radioactive sources are used worldwide in various applications in medicine, agriculture, industry, transportation, construction, geology, mining, and research. Disused sources are those that are no longer used and with no intention of being used again in the practices for which they were authorized. Spent sources, which can no longer be used for their intended purposes as a result of radioactive decay, are a subset of disused sources.

400. Short-term storage of a disused source is not itself a management option but rather a necessary interim step in implementing one or more of the management options, such as reuse, recycling, return to a supplier and long-term storage and disposal. When a radioactive source is declared disused, it is often stored at the user's site pending further management. Another example is the interim storage of orphan sources (i.e., those outside regulatory control), found at a border control point of a State or in a facility within the metal recycling industries. The appropriate duration for short-term storage is likely to depend on the national strategy applicable to the disused source and the capability of the user to provide safe and secure storage. A disused source with a relatively short half-life (e.g., less than 100 days) could be stored in a safe and secure facility for a period necessary to allow for radioactive decay to decrease the activity concentration to a level at which it can be released from regulatory control and managed as non-radioactive material [I14].

401. According to the IAEA definition, a disused radioactive source is no longer used, and is not intended to be used, for the practice for which an authorization has been granted; however, the source may be suitable for other uses (e.g., research and training activities, calibration of radiation detection equipment). Management options for disused sources, therefore, include reuse or recycling, long-term storage and disposal, and return to supplier [I14]:

(a) Reuse, in some cases, may be as simple as transferring the device to another user, whereas recycling is always a technically demanding task that requires particular expertise and authorization;

(b) Reuse of a disused source is normally subject to source integrity and quality verification according to regulatory standards;

(c) Reuse and recycling may require the removal of the radioactive source from the device in which it is housed and its emplacement in a new device, which are potentially hazardous operations. If these operations are required, they should be carried out only with appropriate authorization, knowledge, equipment, facilities, and skills;

(d) Long-term storage of disused sources, even if planned for an extended period, is not meant to be a permanent solution but rather a stage prior to disposal. Where disposal facilities are available, consideration should be given for disused sources to be disposed of, rather than stored in a long-term storage facility. Disposal of disused sources declared as radioactive waste (i.e., their emplacement in an appropriate facility with no intention of retrieval) is the final step in secure management.

402. Six countries responded to the detailed UNSCEAR Occupational Exposure Survey for the period 2003–2014. Additionally, five countries responded to the simplified survey for the period between 2016–2017. Due to the limited data, the Committee was unable to estimate the worldwide level of occupational exposure to disused radioactive sources. About 1,000 workers were reported for the period 2010–2014. The average annual effective dose for monitored workers is of the order of 0.1 mSv during the period 2010–2014.

3. Transport of radioactive sources outside nuclear fuel cycle

403. Radioactive substances are used extensively in medicine, agriculture, research, manufacturing, non-destructive testing, and mineral exploration. Globally, about 20 million consignments of radioactive material are transported each year on public roads, railways, and ships. The significant majority – about 95% – of radioactive consignments are not related to the nuclear fuel cycle. Most radioactive material packages transported emit some penetrating ionizing radiation, and radiation exposure of transport workers and the public may occur during their transport. The radiation exposure incurred by transport workers can vary significantly depending on a number of factors: most important is the type of radiation emitted (primarily gamma rays and neutrons), the radiation field intensity in the surrounding of a package and conveyance, and the duration of exposure. However, if the international transport regulations are followed, the levels of exposure to the public are low during normal transport and the average annual effective doses to transport workers are typically of the order of less than 1 mSv. Nevertheless, a few workers, usually involved in the distribution of medical, research and industrial isotopes, could occasionally receive somewhat higher doses [S7].

404. Ten countries responded to the UNSCEAR Occupational Exposure Survey for the period 2003–2014. Twelve countries responded to the simplified survey for the period 2010–2017. Consequently, the Committee was unable to estimate worldwide levels of occupational exposure in transport of radiation sources due to lack of data. For the period 2010–2014, about 6,200 monitored workers were reported by the countries responding to the survey. About 8% of the workers were classified as measurably exposed. The average annual effective dose during this period was 0.3 mSv and for measurably exposed workers it was 1.6 mSv.

4. Other occupational groups

405. The "other occupational groups" category was included in the UNSCEAR Occupational Exposure Survey to ensure that no sizeable group of exposed persons was overlooked. The data cover disparate groups that often cut across the other categories.

406. Nineteen countries responded to the detailed UNSCEAR Occupational Exposure Survey for the period 2003–2014. Additionally, 14 countries responded to the simplified survey for the period 2003–2017. Data from the literature were used to supplement the supplied data [I5, N1, U10]. The tentative predictor parameters applied to estimate the worldwide level of occupational exposure for the “other occupational groups” subsector was GDP per capita. No statistically significant correlation between the predictor parameter and the number of monitored workers or the average annual collective effective dose or effective dose was found. The adjusted R^2 values were not appropriate for deriving reliable estimates. For the period 2010–2014, about 35,000 workers were reported in this category by the data reported to the survey. The average annual effective dose during the period is reported to be in the order of 0.1 mSv.

5. Summary

407. The national data from all miscellaneous uses of radiation are presented in table A.22 in the electronic attachment. An estimate of the worldwide level of exposure could be performed only for the category of educational establishments. Extrapolation for other categories was not performed due to the limited data provided by countries participating in the UNSCEAR Occupational Exposure Survey and the lack of statistically significant correlations between the studied occupational exposure variables and the tentative predicted parameter, GDP per capita.

408. For educational establishments, the number of monitored workers was about 90% of the total workforce for all miscellaneous uses of radiation. The average annual collective effective dose represents about 87% of the collective dose for all miscellaneous uses. The average annual effective dose estimated for monitored workers is less than 1 mSv for all studied five-year periods. The estimate of the size of the worldwide number of monitored workers is 540,000, and the corresponding average annual collective effective dose is calculated as 38 man Sv.

409. The reported number of monitored workers, obtained through the UNSCEAR Occupational Exposure Survey, in the category of “spent sources” or disused radioactive sources was 540, 500 and 900 for the periods 2000–2004, 2005–2009 and 2010–2014, respectively. The average annual effective dose reported for these monitored workers was for all periods below 0.5 mSv. The average annual collective effective dose for the period 2010–2014 was 0.1 man Sv.

410. The number of monitored workers reported in the category of transport of radiation sources (excluding transport in the nuclear fuel cycle) was 2,330, 2,400 and 6,210 for the periods 2000–2004, 2005–2009 and 2010–2014, respectively. The average annual effective doses reported for monitored workers during all studied five-year periods were below 1 mSv. The reported average annual collective effective dose during the period 2010–2014 was 2.1 man Sv.

411. Finally, the number of monitored workers reported through the UNSCEAR Occupational Exposure Survey in the “other occupational groups” category was 82,800, 42,000 and 35,600 for the periods 2000–2004, 2005–2009 and 2010–2014, respectively. The average annual effective doses reported for monitored workers during all periods were about 0.1 mSv. The reported average annual collective effective dose during the period 2010–2014 was 3.8 man Sv.

F. Conclusions on occupational exposure to human-made sources

412. The category of human-made sources of radiation includes the subsectors of the nuclear fuel cycle, medical uses of radiation, industrial uses of radiation, military activities, and miscellaneous uses of radiation. The Committee has been evaluating the level of occupational exposure for the sectors included in the category of human-made sources of radiation since 1975. The trends in worldwide occupational exposure arising from each sector are summarized in table 48, except for military uses, for which a reliable estimate of the worldwide level of exposure was not possible. The table presents the estimates of the worldwide number of monitored workers, average annual collective effective dose, and average annual effective dose; the data represent the annual averages during five-year periods over 40 years, from 1975–1979 to 2010–2014. In comparison with many other sources of exposure, the activities in the nuclear fuel cycle are well documented, and considerable amounts of data on occupational dose distributions are available, in particular for reactor operation. The same is not true for the subsectors of medical, industrial, and miscellaneous uses of radiation, where uncertainties of the estimated values are higher than the ones for reactor operation and even for uranium mining.

413. The number of monitored workers was not estimated for several subsectors, such as veterinary medicine from medical sector; for most of the subsectors of the industrial sector (luminizing, radioisotope production and distribution, well logging, accelerator operation, industrial gauges and all other industrial uses); several subsectors of miscellaneous use of radiation (disused radioactive sources, transport of radiation sources outside the nuclear fuel cycle and other occupational groups). The reason is either the limited available data obtained from the UNSCEAR Occupational Exposure Survey, or the lack of appropriate predictor parameters needed to derive the extrapolation mathematical model. This leads to the conclusion that the number of monitored workers is underestimated for the medical, industrial, and miscellaneous sectors. The total number of workers for the industrial sector was derived from a different set of data, and not a sum of the number of monitored workers of the subsectors. A large number of countries have provided the occupational data for industrial sector, pooling together all the subsectors. For some subsectors, no estimates for the periods 2000–2004 and 2005–2009 were made. Again, this was due to the limited available data or lack of appropriate predictor parameters to derive the model although several attempts to derive the mathematical models were made using the parameters available worldwide. Thus, the period 2010–2014 has a more complete set of analysis.

414. On the basis of the analysis for the period 2010–2014, the total number of monitored workers for the category of human-made sources of radiation is estimated as at least 11.4 million. The uncertainty interval of the worldwide number of workers ranges from 6.2 to 21 million. The number of monitored workers in the medical sector represents about 79% of the total workforce of the sectors comprising the human-made sources of radiation. The industrial sector represents about 10%, the nuclear fuel cycle sector about 7% and the miscellaneous sector about 4% of the total workforce in the category of human-made sources of radiation. The number of monitored workers increased over the course of the reported 40-year period (1975–1979 to 2010–2014) for all sectors. The nuclear fuel cycle had a different pattern: it increased by a factor of 1.6 from 1975–1979 to 1987–1989, then decreased by a factor of about 1.5 up to 2000–2004, when it started to increase slightly. It seems that the workforce for the medical sector was underestimated in the UNSCEAR evaluations previous to the UNSCEAR 2008 Report. The total number of monitored workers consistently increased over the 40-year period, from 2.8 to 11.4 million. The Committee recognizes that the total number of monitored workers for all sectors, except for the nuclear fuel cycle, has been underestimated.

Table 48. Estimated worldwide occupational exposure due to human-made sources of radiation

Sectors	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1995–1999*	*2000–2004*	*2005–2009*	*2010–2014*
NUMBER OF MONITORED WORKERS (10^3)								
Nuclear fuel cycle	560	800	888	800	670	652	660	762
Medical	1 280	1 890	2 220	2 320	7 440			9 000
Industrial	530	690	560	700	790	870	1040	1 100
Miscellaneous	140	180	160	360	476	446	482	540
Total	**2 820**	**3 910**	**4 228**	**4 600**	**9 754**			**11 400**
AVERAGE ANNUAL COLLECTIVE EFFECTIVE DOSE (man Sv)								
Nuclear fuel cycle	2 300	3 000	2 500	1 400	1 000	602	523	483
Medical	1 000	1 140	1 030	760	3 540			4 500
Industrial	870	940	510	360	315	348	419	440
Miscellaneous	70	40	20	40	53	38	34	38
Total	**4 660**	**5 370**	**4 310**	**2 660**	**4 960**			**5 460**
AVERAGE ANNUAL EFFECTIVE DOSE (mSv)								
Nuclear fuel cycle	4.4	3.7	2.6	1.8	1.4	0.9	0.8	0.6
Medical	0.8	0.6	0.5	0.3	0.5			0.5
Industrial	1.6	1.4	0.9	0.5	0.4	0.4	0.4	0.4
Miscellaneous	0.5	0.3	0.2	0.1	0.1	0.1	0.1	0.1
Total	**1.7**	**1.3**	**1**	**0.6**	**0.5**			**0.5**

415. The average annual effective dose for the category of human-made sources of radiation is estimated as 0.5 mSv for the period 2010–2014. The uncertainty interval on the average annual effective dose ranges from 0.3 to 0.9 mSv. In the nuclear fuel cycle sector, the workers' higher exposure is due mainly to the exposure in the uranium mining industry and estimated as 0.6 mSv for the period 2010–2014. The average annual effective dose for the medical sector is estimated as 0.5 mSv and for the industrial sector as 0.4 mSv. The average annual effective dose for the miscellaneous sector is estimated as 0.1 mSv. The average annual effective dose for the whole category of human-made sources consistently decreased over the 40-year period from 1.7 to 0.5 mSv. The main contribution of the reduction of dose comes from the nuclear fuel cycle sector, which decreased from 4.4 to 0.6 mSv over that period. It is followed by the industrial sector, which decreased from 1.6 to 0.4 mSv over the same period. The average annual effective doses for medical and miscellaneous sectors were, in general, below 1 mSv.

416. The average annual collective effective dose for human-made sources of radiation is estimated as 5,460 man Sv for the period 2010–2014. The average annual collective effective dose for the medical sector represents about 83% of the total average annual collective effective dose for human-made sources of radiation. The nuclear fuel cycle and the industrial sectors represent about 16% (8% for each sector). The miscellaneous sector represents about 1% of the average annual collective effective dose for human-made sources of radiation. There is no trend in the average annual collective dose over the 40-year period. It fluctuated between 5,500 and 4,500 man Sv; this excludes the period 1990–1994, which was estimated as 2,660 man Sv. Since the estimated total number of monitored workers for all sectors of the category of human-made sources of radiation is underestimated, the same statement is true for the average annual collective effective dose.

V. ASSESSMENT OF GLOBAL PRACTICES

417. This annex supplements and updates the previous UNSCEAR publications on the subject of occupational exposure [U3, U4, U6, U8, U10]. Occupational exposure has been evaluated for two broad categories of work: natural sources of radiation and human-made sources of radiation. There are four sectors associated with exposure to natural sources of radiation: *(a)* cosmic ray exposure of aircrew and space crew; *(b)* exposure in extractive and processing industries; *(c)* gas and oil extraction; and *(d)* radon exposure in workplaces other than mines. There are five sectors associated with human-made sources of radiation: *(a)* nuclear fuel cycle; *(b)* medical sector; *(c)* industrial sector; *(d)* military purposes; and *(e)* miscellaneous applications. The last sector includes educational establishments, disused radioactive sources resulting from industrial research applications, transport of radiation sources outside the nuclear fuel cycle, and other specific occupational groups.

418. The estimate of the worldwide levels of occupational exposure improved in comparison to the previous evaluations. In the previous UNSCEAR reports, due to the limited data for the sectors of natural sources of radiation category, the Committee was unable to extrapolate the data for those sectors (civilian aviation, mineral extraction, and processing (of minerals other than coal and uranium), oil and gas extraction and radon exposure in workplaces other than mines). In the current evaluation, the extrapolation of the levels of occupational exposure was significantly improved for civilian aviation, extraction and processing of coal and extraction and processing of minerals other than coal and uranium. However, for the extraction and processing industry, the improvement is related to the estimate of the number of workers. The average annual effective dose might be underestimated because it is not clear if the available data include the contribution of exposure to radon and its progeny. No improvement was seen for oil and gas extraction, which was due to limited data obtained from the UNSCEAR Occupational Exposure Survey and the lack of a statistically significant correlation between the data and the predictor parameter (petroleum production). Due to the complexity of the exposure and the lack of appropriate data, the Committee was unable to estimate the level of occupational exposure for the sector of radon exposure in workplaces other than mines.

419. The estimate of the worldwide level of exposure for the subsector of civilian aviation has improved in comparison to previous analyses. This is due to the detailed information on worldwide air traffic and civilian aviation personnel provided by ICAO. However, because there were only few responses to the UNSCEAR Occupational Exposure Survey, the worldwide estimation of the average annual effective dose could not be improved in the same way. The uncertainties in the estimation arise from internationally different limits on working hours, heterogeneous definitions of short/medium/long haul, and location of operation, i.e., latitude and altitude. Estimations are also hampered by a lack of information about the route nets that are predominantly covered by each country's airlines and the number of executed flights.

420. The estimate of the worldwide level of exposure for the subsectors of the nuclear fuel cycle has improved in comparison to the previous analyses. The methodology applied for the extrapolation was the same as the one applied in the previous UNSCEAR reports. For uranium mining, the amount of extracted ore is used as predictor variable. The variable used for fuel fabrication and reactor operation is the average energy generated. A wide coverage of data meant that just small adjustments were required to derive the worldwide level of exposure for these subsectors of the nuclear fuel cycle. Moreover, the available data to conduct the analysis from the UNSCEAR Occupational Exposure Survey were supplemented with detailed information from IAEA, OECD/NEA and WNA. These data resulted in an improved understanding of the radiation exposure to workers employed in the sectors of uranium mining, nuclear fuel fabrication, spent fuel reprocessing, and nuclear power plant decommissioning. While the global estimate of occupational exposure within the nuclear fuel cycle is more robust, it is likely underestimated. The lack of national registries for occupational exposure, differences in national requirements for

monitoring of occupational exposure, incomplete dosimetry records for active and decommissioned nuclear fuel cycle facilities, lack of records for occupational exposure to radon and radon progeny radionuclides and incomplete responses to the UNSCEAR Occupational Exposure Survey by United Nations Member States have contributed to the underestimation of global exposure to occupational radiation in the nuclear fuel cycle.

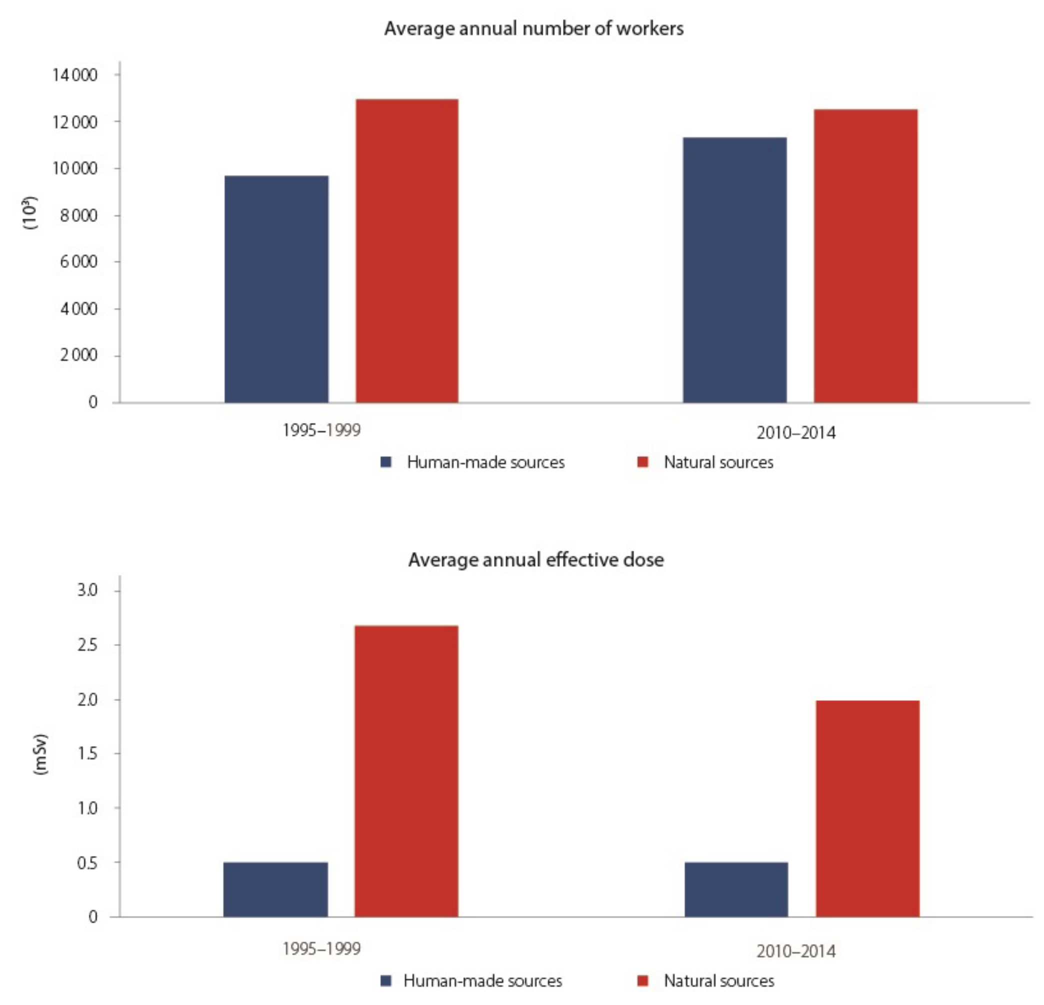
421. The estimate of the worldwide level of exposure for the subsectors of the medical sector was also improved for the estimate of the number of monitored workers. The method applied for the current analysis is based on multivariate regression modelling. The predictor parameters applied to derive the extrapolation mathematical models are described in table 1. The model was not applied for the calculation of the average annual effective dose and the collective effective dose because the quality of fit to the data of the model with predictor parameters was not high enough (i.e., the coefficient of determination, adjusted R^2, was below 0.7) between the data and the predictor parameters. The application of derived mathematical models resulted in the estimation of reliable values for the number of monitored workers. However, the methodology has a limitation: the mathematical models are appropriate for estimating the parameters only for countries classified as having high and upper-medium GNI, according to the World Bank classification [W15]. The reason is that the model was derived on the basis of data from countries that belong to those two GNI categories. The developed model was not applied to derive the worldwide average annual effective dose because of lack of statistically significant correlation between the data and the predictor parameters. The worldwide average annual effective dose was derived as the average effective dose weighted by the number of workers in each country. In order to estimate the average annual collective effective dose, it was assumed that the weighted average annual effective dose reflected the worldwide value.

422. The estimate of the worldwide level of exposure for the subsectors of the industrial and miscellaneous sectors used the same methodology described for the medical sector. However, due to limited data obtained from the UNSCEAR Occupational Exposure Survey and the lack of statistically significant correlation between the data and the predictor parameters, the estimate of the worldwide level of exposure was made for only few subsectors, resulting in an underestimation of the number of monitored workers.

423. It is difficult to compare doses between countries because of different national approaches to defining the doses recorded in their databases. For example, the way doses below the recording level are recorded and criteria for including workers in the individual monitoring programme differ between countries. Some countries include workers who do not work in controlled areas, resulting in an increase of the monitored workforce and a decrease in the average annual effective dose.

424. The worldwide levels of occupational exposure are presented in table 12 for workers exposed to natural sources (excluding oil and gas extraction and radon exposure in workplaces other than mines), and in table 48 for workers exposed to the human-made sources of radiation. A comparison of the worldwide levels of occupational exposure due to exposure to natural and human-made sources of radiation for the periods 1995–1999 and 2010–2014 is illustrated in figure IX.

Figure IX. Comparison of worldwide levels of occupational exposure due to exposure to natural and human-made sources of radiation between 1995–1999 and 2010–2014



425. The total number of monitored workers exposed to ionizing radiation is estimated to be approximately 24 million in the period 2010–2014. About 52% are employed in the sectors that include exposure to natural sources of radiation (12.6 million workers) and about 48% in the sectors that include exposure to human-made sources of radiation (11.4 million workers). The Committee recognizes that the number of monitored workers is underestimated for both categories: natural sources and human-made sources of radiation, and could be as high as 41 million workers. No estimation of the total number of workers was made for the periods 2000–2004 and 2005–2009 due to limited available data or lack of appropriate predictor parameters to derive the extrapolation mathematical models for several subsectors in human-made sources and natural sources. In the period 1995–1999, the estimated number was about 21.5 million workers, excluding the contribution from radon at workplaces other than mines for reason of comparison. This increase is due to the large number of workers exposed to both natural sources and human-made sources of radiation.

426. For exposure to natural sources of radiation during the period 2010–2014, the extraction and processing of coal and minerals other than coal and uranium accounts for 94% of the number of workers. About 11.8 million were employed in mining operations: 70% in coal mining and 30% in other mining operations, excluding uranium mining. The estimated number employed in civilian aviation (mainly exposed to cosmic radiation) was about 0.7 million. The estimated number of workers for the sector "radon exposure in workplaces other than mines"—which includes industries (e.g., food industries, breweries, laundries), waterworks, shops, public buildings and offices, schools, subways, spas, caves and closed mines open to visitors, underground restaurants and shopping centres, tunnels (construction and maintenance) and sewerage facilities—was not estimated due to its complexity and also because of limited available data.

427. For exposure to human-made sources of radiation, the greatest contribution comes from medical uses of radiation (80% of the number of workers). About 9 million workers are involved in the medical sector, 0.76 million in the nuclear fuel cycle sector, 1.1 million in the industrial sector and 0.5 million (underestimated number) in the miscellaneous sector. Due to the limited data obtained from the UNSCEAR Occupational Exposure Survey and lack of predictor parameters, the worldwide number of monitored workers was not estimated for military activities.

428. The worldwide average annual collective effective dose to workers exposed to radiation during the period 2010–2014 is estimated to be around 30,000 man Sv. The worldwide average annual collective effective dose to workers exposed to natural sources of radiation (in excess of the average levels of natural background radiation) is estimated to be around 24,300 man Sv, which represents about 80% of the average annual collective effective dose. The largest component of this, 22,300 man Sv, comes from extraction and processing: about 57% in coal mining and about 43% in other mining operations (excluding uranium mining, which is dealt with as part of the nuclear fuel cycle). The estimated average annual collective effective dose for the civilian aviation sector, due to exposure to cosmic radiation, is about 2,000 man Sv. The estimation of the average annual collective effective dose for the sector "workplaces other than mines" was not calculated for the reasons described in the estimation of the workforce. However, the estimated collective dose due to exposure to natural sources of radiation is associated with much greater uncertainty than that due to human-made sources of radiation. This is because of the limited data obtained from the UNSCEAR Occupational Exposure Survey, which restricted the estimate of the worldwide number of workers, especially for oil and gas extraction and radon exposure in workplaces other than mines. The other limitation is the scarce available data for average annual effective dose because the majority of the workers exposed to natural sources of radiation are not individually monitored.

429. The worldwide average annual collective effective dose to workers exposed to human-made sources of radiation during the period 2010–2014 is 5,460 man Sv. The average annual collective effective dose to workers in the nuclear fuel cycle sector for the period is estimated to be about 480 man Sv. The contribution of medical sector is estimated to be 4,500 man Sv, and 440 man Sv for the industrial sector. The average annual collective effective dose to workers in the miscellaneous sector is about 38 man Sv. The Committee recognizes that the value is underestimated. This is because of the limited data obtained from the UNSCEAR Occupational Exposure Survey, which restricted the estimate of the worldwide number of workers, especially for most medical subsectors. A challenge is to obtain worldwide data for the appropriate application of predictor parameters for each subsector to derive mathematical estimation models. Another limitation is the scarce available data for the average annual effective dose. On the basis of the current estimate, the medical uses of radiation contribute about 82% of the average annual collective effective dose due to exposure to human-made sources of radiation.

430. The worldwide average annual effective dose to workers exposed to radiation during the period 2010–2014 is estimated to be around 1.2 mSv. The uncertainty interval for the worldwide average annual

effective dose is from 0.7 to 2.1 mSv. In the period 1995–1999, the estimation was 1.8 mSv. The worldwide average annual effective dose to workers exposed to natural sources of radiation (in excess of the average levels of natural background radiation) is roughly estimated to be around 2 mSv. The average annual effective dose to monitored workers varies widely from occupation to occupation and also from country to country for the same occupation. On the basis of the reported data, the average annual effective dose to monitored workers from human-made sources of radiation are around 0.5 mSv. The average annual effective doses to workers in the nuclear fuel cycle sector are, in most cases, higher than the doses to those in other occupations. For the period 2010–2014, the estimated worldwide average annual effective dose for the nuclear fuel cycle is about 0.6 mSv (table 48). Uranium mining contributes to the higher exposure, the average annual effective dose is 2.8 mSv. Fuel fabrication is ranked as the second sector that delivers high radiation exposure; the average annual effective dose is 0.9 mSv. Reactor operation is the third sector with high radiation exposure: the average annual effective dose is 0.5 mSv. All estimations for the nuclear fuel sector are summarized in table 27. The average annual effective dose in the medical sector is estimated as 0.5 mSv, in the industrial sector is estimated as 0.4 mSv.

A. Trends in occupational exposure

431. For exposure to natural sources of radiation, the evaluation of the level of exposure was first introduced in the period 1990–1994. Due to limited data available at that time, the Committee was unable to derive the worldwide levels of exposure in its previous evaluations. However, the data available for the current evaluation, especially for the period 2010–2014, enabled a reliable assessment of the number of workers in civilian aviation, mining operations and mineral processing. As a result, the estimated worldwide number of workers is greater than the estimate in previous UNSCEAR evaluations, but might still underestimate the actual number of workers because it was not possible to derive the worldwide estimates for oil and gas extraction and for radon exposure in workplaces other than mines.

432. The worldwide average annual number of monitored workers exposed to human-made sources of radiation consistently increased from 1975–1979 to 1990–1994, then it increased by a factor of two in the following period (1995–1999) due to a more realistic estimate of the workforce for the medical sector derived for that period. An increase in the workforce of about 20% was observed from 1995–1999 to 2010–2014. The estimated workforce increased from about 2.8 million to about 11.4 million over the 40-year period of evaluation (table 48). The greatest increase (from about 1.3 million to about 9.0 million) was in the number of workers in the medical sector, which represents about 79% of the workforce.

433. The number of monitored workers for the nuclear fuel cycle also increased significantly in the first three periods (1975–1989), from about 0.6 million in the first period to about 0.9 million in the third period, but it dropped to 0.8 million in 1990–1994 and to about 0.76 million in 2010–2014. The average annual collective effective dose averaged over the five years for each of the first three periods (1975–1989) for all operations in the nuclear fuel cycle varied little around the average value of 2,500 man Sv, despite a factor of 3–4 increase in electrical energy generated by nuclear means. The amount of electrical energy generated continued to increase, but the average annual collective effective dose decreased by a factor of about 2, to 1,400 man Sv, in 1990–1994. Since then, it consistently decreased to around 480 man Sv (2010–2014). A relevant part of this decrease came from the reduction in the reactor operation component, from 1,100 man Sv in 1985–1989 to 328 man Sv in 2010–2014. The average annual effective dose to monitored workers in the nuclear fuel cycle was consistently reduced over the whole period, from 4.4 to 0.6 mSv. There are some variations between parts of the nuclear fuel cycle and between countries.

434. The worldwide number of monitored workers in the medical sector increased by a factor of almost seven over the 40-year period, from 1.3 million to 9.0 million. This number is probably underestimated and could be as high as 17 million. The largest increase, from 2.3 million to 7.4 million, was observed in the two periods within 1990–1999 because then the estimate was based on more complete information from the UNSCEAR Global Survey of Medical Exposure. The worldwide average annual collective effective dose due to all medical uses of radiation, about 1,000 man Sv, changed little over the first three five-year periods. It then dropped significantly, to 760 man Sv, in 1990–1994, but increased to 3,500 man Sv following the increase of the workforce in 1995–1999, which increased by about 25% over the last periods. Some downward trend is seen in the worldwide average annual effective dose to monitored workers, as the uncertainties of the estimates are rather high. The worldwide average annual effective dose decreased from about 0.8 mSv in 1975–1979 to about 0.5 mSv in 1985–1989, and this value has been steady since then. On the basis of the data obtained from the UNSCEAR Occupational Exposure Survey for diagnostic radiology, conventional diagnostic radiology represents about 90% of the workforce of diagnostic radiology; the other 10% is related to interventional radiology. The "veterinary medicine" subsector was part of the miscellaneous sector in previous UNSCEAR reports.

435. The worldwide number of monitored workers in the industrial sector increased by a factor of two over the 40-year period, from 0.5 million to 1.1 million. The worldwide average annual collective effective dose due to all industrial uses of radiation was fairly uniform over the period 1975–1984 at about 900 man Sv. It decreased, however, by a factor of almost two in the second half of the 1980s to 510 man Sv and then decreased further, to about 360 man Sv in 1990–1994, and to about 315 man Sv in 1995–1999. The last two periods of analysis showed an increase: 419 man Sv (2005–2009) and 440 man Sv (2010–2014). Because of the lack of statistically significant correlation between the data and the predictor parameters applied to extrapolate the data for several subsectors of the industrial sector, it is difficult to identify which subsector is responsible for the increase in the average annual collective effective dose. The average annual effective dose decreased by a factor of almost four from 1975–1979 to 1995–1999, from 1.6 and 0.4 mSv, and the average annual effective dose values did not change over the last three periods. It should be noted that in UNSCEAR reports prior to 1990–1994, "industrial uses" included a component reflecting "educational uses", which tended to distort the data. Since then, educational uses have been dealt with in a separate subsection, and the industrial data for earlier years have been adjusted to remove the educational component.

436. The worldwide levels of occupational exposure for the miscellaneous sectors were underestimated due to the limited data available and also to the lack of statistically significant correlation between the data and the predictor parameters available to derive the mathematical models. Further, the worldwide levels of occupational exposure for human-made sources of radiation for military uses were not estimated due to the limited data available.

B. Dose to lens of eye

437. The analysis of occupational doses to the lens of the eye is a new, challenging task. It is a consequence of the ICRP recommendations published in 2012 [I32], which proposed lowering the annual limit of the equivalent dose to the lens of the eye in occupational exposure from 150 to 20 mSv averaged over five consecutive years but not more than 50 mSv in a single year. In 2013, the reduced dose limit was introduced in the European Union Member States [E8], and in 2014 it was recommended by the International BSS [I12]. The available topical literature indicates many challenges in the implementation of the new limit due to the lack of dosimetry data and to the problems relating to the dose estimation at high angles and at low energies.

438. A literature review showed that lowering the annual limit of the equivalent dose to the lens of the eye makes it possible that some workers (in medical and industrial sectors) may receive annual equivalent doses above this limit. This applies, in particular, to personnel in interventional radiology (more than 5 mSv per quarter) and in industrial radiography (up to 60 mGy per year in terms of absorbed dose). Failing to use goggles and personal shields can obviously lead to an increase in the equivalent dose to the lens of the eye. On the other hand, a decrease in the dose can be expected with the introduction of new technologies and protocols, and also with wider recognition of workplaces where the possibility of such exposure may occur.

439. Data on the equivalent doses to the lens of the eye derived from the UNSCEAR Occupational Exposure Survey are limited. Thus, they could not be used in a mathematical model described in section II.E.1 to determine global estimates. Data on occupationally exposed workers to whom questionnaires on the annual equivalent doses to the lens of the eye were assigned were provided by only a few countries: in diagnostic radiology (3 of 24 countries that provided data), conventional diagnostic radiology (2 of 14 countries), nuclear medicine (3 of 25 countries), radiation therapy (1 of 25 countries) and veterinary medicine (1 of 25 countries). The reported average annual equivalent doses to the lens of the eye for diagnostic radiology, radiation therapy, and veterinary medicine are the average annual equivalent doses for these sectors. These average annual values are lower than 20 mSv. In diagnostic radiology (interventional and conventional) doses are lower than 7 mSv, in radiation therapy (brachytherapy) about 0.1 mSv, and in veterinary medicine 1 mSv. In nuclear medicine the provided maximum equivalent dose was 7 mSv.

VI. IMPLICATIONS FOR FUTURE EVALUATIONS

440. The global assessment of occupational exposure is a complex task. The most important issue for the assessment is to have relevant and sufficient data provided by United Nations Member States. As indicated in various chapters above, this assessment was based mainly on data collected through the UNSCEAR Occupational Exposure Survey, which was not sufficient to ensure representative data for robust and reliable evaluations and predictions in many sectors. Based on experiences from this assessment, the following observations and recommendations are intended to facilitate the data collection process to enable improved robustness and coverage of future global evaluations by the Committee.

441. Since most United Nations Member States do not have a national dose registry or a central point for the collection and maintenance of dose records, the Committee recommends the use of its survey questionnaire (especially for the essential data sets) to collect occupational exposure data on a regular basis. With involvement of national contact persons and more frequent data collection, the Committee intends to update its evaluations more frequently with a focus on essential data. These include annual total numbers of occupationally-exposed workers (with breakdown into monitored workers and female workers, when possible) nuclear fuel cycle, medical uses of radiation, industrial uses of radiation, civilian aviation, and industrial processes involving NORM (e.g., mining, processing, oil and gas extraction).

442. In the radon at workplaces other than mines subsector, there are large variations in the average annual effective dose that depend on the workplace and ventilation. As monitoring of worker exposure is not a requirement in many countries, it will continue to be a challenge in future evaluations. It is, nevertheless, important to continue collecting information, and a way forward may be that in future surveys, in addition to exposure data, information on the type of workplaces where radon may be a potential source of exposure will be requested.

443. A review and revision of the present version of the questionnaire is necessary, to include developments in work activities with different sectors and subsectors. In the reactor operation subsector, the type of reactor needs to be included. For the uranium mining subsector, the current work activities in the questionnaire (mining and milling) may need to be changed. Moreover, due to a general improvement in occupational radiation protection, the number of workers receiving high doses is decreasing and a review of the current dose intervals in the questionnaire may be needed. To facilitate future evaluation of occupational exposure in the gas and oil industry, it is recommended that the relevant work tasks be specified in the survey.

444. Initiatives for future assessments should focus on motivating submission, of even partial data sets of the identified essential data, from countries not represented in this assessment. For the broad range of occupations where workers are exposed to natural and human-made sources of radiation, the collection and collation of national data is not a simple process. The Committee recommends targeting countries with large populations (and so potentially significant contributions to global workforce). The Committee suggests approaching regional organizations, such as the African Regional Cooperative Agreement for Research, Development and Training related to Nuclear Science and Technology, regional networks (e.g., AFAN)[2] with the objective of improving data collection from regions underrepresented in this evaluation. The current collaboration with international organizations, e.g., IAEA, ICAO, ILO, OECD/NEA, WHO and WNA has been important for the evaluation. The Committee recommends expanding these collaborations to support Member States in the collection of occupational exposure data for future UNSCEAR surveys.

445. Due to lack of data, worldwide levels of exposure can only be roughly estimated. For the most part, quantitative estimation requires the use of available predictor variables (independent variables of the mathematical models) to derive the mathematical models to extrapolate the worldwide estimates. Since extrapolation is an inevitable task, the Committee recommends including essential predictor parameters in the survey questionnaires. Also, it suggests conducting a thorough review of the outreach process and focusing the request for data on the most needed information and parameters presented in table 1.

446. The global assessment of occupational exposure has focused on the estimation of average annual effective doses to workers and temporal dose trends in various sectors. This approach assesses the overall collective exposure but does not provide information on the distribution of doses to individual workers. Collection of data on cumulative doses to workers is important for improved analysis of trends and for the implications for management of radiation exposure in workplaces.

[2] https://african-alara.net.

VII. SUMMARY AND CONCLUSIONS

447. The Committee has been collecting and evaluating sources and levels of occupational exposure since 1975. Occupational exposure to ionizing radiation can occur as a result of activities utilizing radiation or radioactive substances in industry, medicine, education and research and can also occur when workers are exposed to natural sources of radiation. The Committee's evaluations of worldwide occupational exposure to ionizing radiation provide information relevant for policy- and decision-making regarding the safe use of radiation. The resulting dose distributions and trends provide insight into the main sources and situations of exposure and information about the main factors influencing exposure. The evaluations assist in identifying emerging issues and may identify situations that should be subjected to more attention and scrutiny by relevant stakeholders.

448. The Committee's assessment of worldwide occupational exposure levels and trends is based on two sources: *(a)* data from the UNSCEAR Global Survey of Occupational Radiation Exposure; and *(b)* reviews and analyses published in peer-reviewed literature. Its evaluation of occupational exposure to ionizing radiation is based on the individual monitoring of workers or their workplaces and the recording of their exposure. Data on occupational radiation exposure in Member States are generally collected in terms of effective dose as it is used for radiation protection purposes. Therefore, occupational exposure is expressed in operational terms like "effective dose" and "collective effective dose". These are the radiation protection quantities used by the international safety standards established under the aegis of the IAEA with the co-sponsorship of relevant international intergovernmental organizations.

449. In this assessment, the Committee has analysed new available data collected for the period 2003–2014 and considered the results of the evaluation on occupational exposure in comparison with the results in previous UNSCEAR reports and it has reached the following conclusions.

450. The worldwide annual number of workers exposed to natural and human-made sources of ionizing radiation is estimated by the Committee to be approximately 24 million in the period 2010–2014. About 52% of those were employed in the sectors that involve exposure to natural sources of radiation (12.6 million) and about 48% were employed in sectors that involve exposure to human-made sources of radiation (11.4 million). The total number of workers showed a slight increase compared with the period 1995–1999, when the annual number estimated by the Committee was about 21.5 million workers for both sources combined.

451. For exposure to natural sources of radiation during the period 2010–2014, the extraction and processing of coal and minerals other than coal and uranium accounted for 94% of the annual number of workers. About 11.8 million were employed in mining operations: 70% in coal mining and 30% in other mining operations, excluding uranium mining. The estimated number of people employed in civilian aviation (who are exposed mainly to cosmic radiation) was about 0.7 million. The annual collective effective dose for natural sources was about 24,300 man Sv (excluding oil and gas extraction and radon exposure in workplaces other than mines, due to lack of data).

452. The average annual collective effective dose for the period 1995–1999 in UNSCEAR 2008 Report [U10] was estimated as 31,260 man Sv, of which 30,360 man Sv was due to extraction and processing of coal and minerals other than coal and uranium, and 900 man Sv due to the exposure of civilian aviation exposed to cosmic radiation. In the current evaluation, the estimate for the collective dose has decreased to 24,300 man Sv, the largest contribution coming from mining operations—12,800 man Sv from coal mining and processing and 9,500 man Sv from other minerals extraction and processing of coal and mineral other than coal and uranium mining. About 2,000 man Sv is due to the exposure of aircrew to cosmic radiation. Due to lacking data, the Committee was unable to derive the average annual collective

effective dose for workers exposed to elevated levels of radon and its progeny in workplaces other than mines; however, the average annual effective dose was estimated based on data from the literature.

453. The estimated worldwide annual number of monitored workers exposed to human-made sources increased to over 11.4 million in 2010–2014 compared with about 10 million in the period 1995–1999. The medical sector dominated the workforce exposed to human-made sources, accounting for about 80% of the total workforce and about 75% of the collective dose. The average annual effective dose for the period 2010–2014 for all human-made sources was about 0.5 mSv, a substantial decrease from 1.7 mSv some 40 years ago, and the average annual collective effective dose was about 5,500 man Sv (about 480 man Sv to workers in the nuclear fuel cycle, about 4,500 man Sv to workers in medical uses and about 440 man Sv to workers in industrial uses).

454. Occupational exposure from human-made sources has changed greatly since 1970, when it was dominated by the practices in the nuclear fuel cycle. Except for medical uses, all other practices have shown a reduction in the level of exposure. A significant part of the reduction of the average annual effective doses is observed in the nuclear fuel cycle and industrial sectors. In the nuclear fuel cycle, reactor operation continues to be the major contributor to occupational exposure. In the future, decommissioning of reactors will increase and, therefore, the collection of data started during this evaluation period. However, it was not possible to make a worldwide estimation for this annex.

455. The worldwide average annual effective dose for all workers during the period 2010–2014 was estimated to be around 1.2 mSv—about two thirds of the value estimated for the period 1995–1999. The annual effective dose was estimated to be around 2 mSv for workers exposed to natural sources and 0.5 mSv for workers exposed to human-made sources. In the period 1995–1999, the estimated annual effective dose to workers exposed to natural sources was 2.7 mSv (excluding radon exposure in workplaces other than mines), while the dose from exposure from human-made sources remained at 0.5 mSv. The Committee’s current estimate of the worldwide average annual collective effective dose is around 30,000 man Sv.

456. The Committee’s estimates presented in this annex for natural and human-made sources are based on a process of mathematical and statistical extrapolation using the limited available data provided by the countries in response to the UNSCEAR Global Survey of Occupational Radiation Exposure. Uncertainty estimates for occupational exposure are provided to characterize the precision and accuracy of the reported estimates of number of workers, expressed as a range of the average annual effective dose, and the annual collective effective dose. Occupational sectors with more data generally have a narrower range, clearly demonstrating the value of having more data, from more countries, available for analysis.

457. Improvements for the period 2010–2014 were possible for several reasons, including the cooperation of international organizations and use of improved mathematical and statistical techniques. For example, *(a)* improvement in the estimation of crew exposure in civilian aviation was due to the detailed information on worldwide air traffic and civilian aviation personnel provided by ICAO; *(b)* improvement in the estimates for the subsectors of the nuclear fuel cycle was due to availability of information from the ISOE database (jointly maintained by the IAEA and NEA/OECD); and *(c)* improvements in the medical sector estimates due to use of mathematical multivariable models with mathematical derivation of uncertainties.

458. While some improvements were possible, the limited data received through the UNSCEAR Global Survey of Occupational Radiation Exposure and the lack of correlation between the data and available predictor variables resulted in the estimation of the worldwide level of exposure for many subsectors but not all. Relatively complete data submission for the nuclear fuel cycle worker sectors and the reliability of this information is well documented. There is a likely underestimation of the number of workers and

estimated collective effective doses, owing to the lack of data for some occupational sectors in the reported periods. For most of the subsectors of the industrial sector, military, occupations involving exposure to radon and several subsectors of the nuclear fuel cycle, the reported data did not allow the Committee to make sufficiently robust worldwide estimates, and this remains an area for its future work.

459. Data on the equivalent doses to the lens of the eye are limited. It is expected that for the Committee's next evaluation of occupational exposure, more countries will be able to provide reliable data on the equivalent doses to the lens of the eye due to the implementation of new radiation protection regulations. Radiation exposure of the hands and of the lens of the eye due to scattered radiation can potentially be high, which could be the case for operators conducting interventional radiology procedures.

460. The current evaluation of occupational exposure has not identified any group of workers receiving high average annual effective doses due to implementation of new techniques in applying radiation sources. However, it has been noticed that the average annual equivalent dose values for the skin of the hands of the nuclear medicine workforce have increased over the last three periods. The high equivalent doses to the skin of the hands, especially to the fingers in contact with the syringe, may be explained by the increasing use of high-energy beta-emitting radioisotopes, also due to high workload combined with the poor implementation of adequate radiological protection measures.

461. Although the data received from the UNSCEAR Occupational Exposure Survey are in some cases very limited, extensive new data have been reviewed. Essential data collection from a larger number and broader representation of Member States (e.g., regions, income levels, and activities in subsectors) is an area that the Committee has identified as a future area of work in order to reduce uncertainties, allow extrapolation of estimated occupational exposure doses (e.g., for gas and oil extraction, for subsectors of the industrial sector and for miscellaneous uses of radiation) and enhance estimates of trends in different work sectors and for different organs (e.g., hands and lens of the eye). This will require further clarification and harmonization of the required data.

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[a] ISO 3-digit country code was used in this annex and its electronic attachment for presenting country data in tables.

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VOLUME IV

Scientific annex with appendices
Annex D: Evaluation of occupational exposure to ionizing radiation

EVALUATING RADIATION SCIENCE FOR INFORMED DECISION-MAKING

In 1955 the United Nations General Assembly established the Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in response to concerns about the effects of ionizing radiation on human health and the environment. At that time fallout from atmospheric nuclear weapons tests was reaching people through air, water and food. UNSCEAR was to collect and evaluate information on the levels and effects of ionizing radiation. Its first reports laid the scientific grounds on which the Partial Test Ban Treaty prohibiting atmospheric nuclear weapons testing was negotiated in 1963.

Over the decades, UNSCEAR has evolved to become the world authority on the global levels and effects of exposure to ionizing radiation. UNSCEAR's independent and objective evaluations of the science are to provide for—but not address—informed policymaking and decision-making related to radiation risks and protection.

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