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Ionising Radiation Exposure of the UK Population: 2010 Review

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Ionising Radiation Exposure of the UK Population: 2010 Review

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Abstract

Periodic reviews published by Public Health England (PHE) and predecessor organisations since 1974 have estimated the exposure of the UK population from naturally occurring and anthropogenic sources of ionising radiation. In this review, the eighth in this series, the per caput dose to the UK population in 2010 from all significant sources of ionising radiation was estimated to be about 2.7 mSv. This dose is the same as the per caput dose reported in the previous review for exposures occurring in 2003.

The per caput dose to the UK population from exposure to ubiquitous radiation in the environment in 2010 was about 2.3 mSv, or about 84% of the dose from all sources of radiation. This was dominated by exposure to natural sources of radiation, particularly radon gas. Anthropogenic radiation in the environment, from the historic testing of nuclear weapons in the atmosphere and from the routine discharge of radioactivity by industry, contributed less than 0.2% to the per caput dose to the UK population.

The per caput dose to the UK population not due to exposure to ubiquitous radiation in the environment was about 0.4 mSv, or about 16% of the dose from all sources of radiation. This was almost entirely the result of patient exposure during diagnostic medical examinations. Occupational exposure continued to contribute significantly less than 1% to the per caput dose to the UK population.

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Executive Summary

Since 1974 Public Health England (PHE) and predecessor organisations, the Health Protection Agency (HPA) (2005–2012) and the National Radiological Protection Board (NRPB) (1970–2005), have published reviews of the levels of exposure of the UK population to sources of ionising radiation. These sources of radiation include naturally occurring radiation in the environment, radioactivity discharged into the environment by human processes, medical use of radiation, radiation used in industry, and radiation in items used by members of the UK population. This is the eighth review in the series and estimated the dose to the UK population for exposures occurring in 2010, a summary of which is given in the table below.

Exposure of the UK population in 2010 from all sources of ionising radiation

Source of exposure	Collective dose (man Sv)	Per caput dose (mSv)
Ubiquitous radiation in the environment		
Radon and thoron	82,000	1.3
Intake of natural radionuclides (excluding radon)	17,000	0.27
Terrestrial gamma radiation	22,000	0.35
Cosmic radiation	20,000	0.33
Weapons fallout	310	0.005
Other anthropogenic radioactivity in the environment*	50	0.0008
Total dose from ubiquitous radiation in the environment	**140,000**	**2.3**
Exposure from the use of radiation		
Patient exposure from the medical use of radiation	27,000	0.44
Occupational exposure from the use of radiation†	26	0.0004
Total dose from the use of radiation	**27,000**	**0.44**
Total dose from all sources of radiation	**170,000**	**2.7**

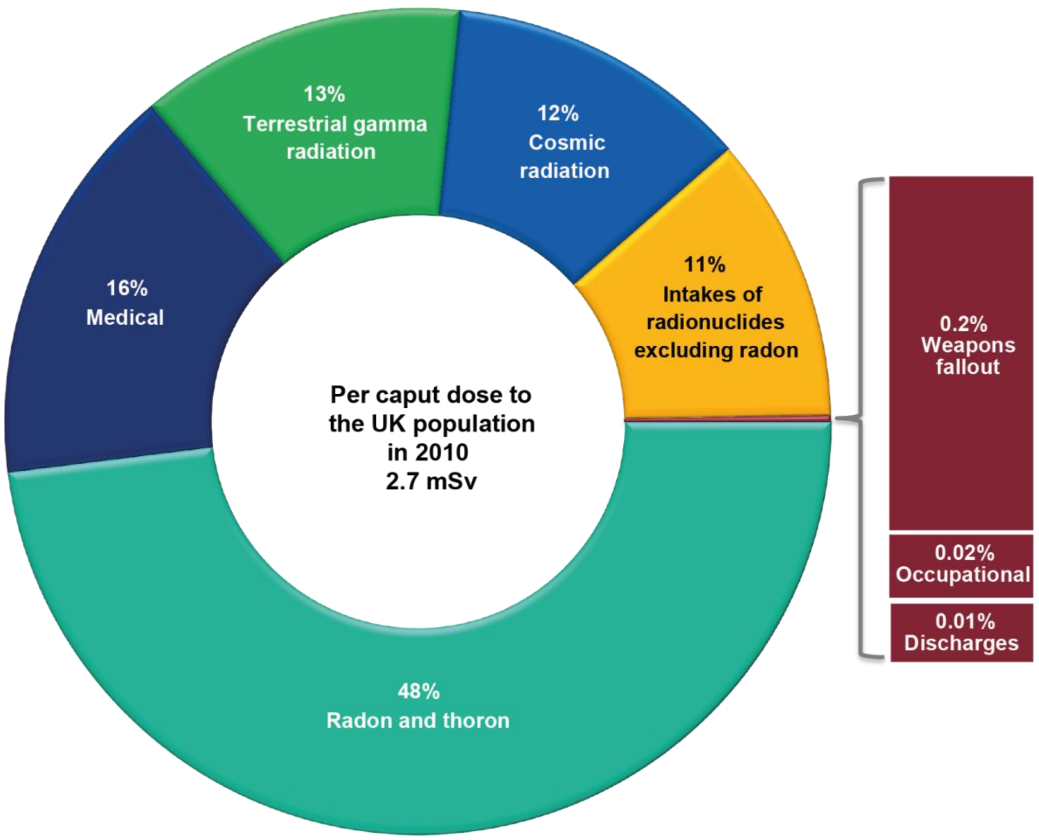
* Includes exposure to radionuclides routinely discharged or accidentally released into the environment.

† Includes occupational exposure to radiation which is not ubiquitous in the environment within the nuclear fuel cycle and during nuclear power production, application of radiation within medicine, and use of radiation in general industry and research. The contributions to the collective dose to the UK population from occupational exposure to radon and cosmic radiation are included within the 'radon and thoron' and 'cosmic radiation' sources, respectively.

The estimated per caput dose to the UK population in 2010 from exposure to all significant sources of ionising radiation was about 2.7 mSv, the same as that reported in the previous review for exposures occurring in 2003. The per caput dose to the UK population in 2010 from exposure to ubiquitous radiation in the environment was about 2.3 mSv, or about 84% of the per caput dose to the UK population for exposure to all sources of radiation. Exposure to ubiquitous radiation in the environment was dominated by exposure to natural sources of radiation, particularly radon gas. Anthropogenic radiation in the environment contributed less than 0.2% to the per caput dose to the UK population; the majority of this was from radionuclides released during historic testing of nuclear weapons in the atmosphere, with exposure to radionuclides routinely discharged by industry contributing less than 0.01% to the total.

The per caput dose to the UK population not due to exposure to ubiquitous radiation in the environment was about 0.4 mSv, or about 16% of the exposure from all sources of radiation. This was almost entirely the result of patient exposure during diagnostic medical examinations. Occupational exposure contributed significantly less than 1% to the per caput dose to the UK population.

The figure below shows a breakdown of the per caput dose to the UK population in 2010 by source of exposure.



Breakdown of the per caput dose to the UK population in 2010 by source of exposure

Contents

1 Introduction

Since 1974 Public Health England (PHE) and predecessor organisations, the Health Protection Agency (HPA) (2005–2012) and the National Radiological Protection Board (NRPB) (1970–2005), have reviewed the dose received by the UK population from exposure to all significant sources of ionising radiation (Webb, 1974; Taylor and Webb, 1978; Hughes and Roberts, 1984; Hughes et al, 1989; Hughes and O'Riordan, 1993; Hughes, 1999; Watson et al, 2005a). In this current review, the eighth in the series, the collective and per caput doses* received by the UK population† in 2010 from exposure to natural and anthropogenic sources of radiation in the environment, medical sources of radiation, and sources of radiation used in industry have been estimated. Although the dose to individual members of the UK population from exposure to radioactivity in consumer items is discussed, the contribution made by this source of exposure to the per caput dose to the UK population has not been estimated as the number of exposed individuals is not known.

For this review, doses to the UK population have been estimated for exposures occurring in 2010 as that was the last year for which a reasonably complete set of data was available. For more recent years, doses have been estimated for some exposure sources, but not all. Discussion of doses received by the UK population after 2010 is therefore left to the next review.

In addition to presenting the estimated dose to the UK population due to exposures occurring in 2010, occupational exposure to radiation received between 2004 and 2010 is presented for information, as it is currently not published elsewhere.

It is recognised that doses presented in this review often have relatively large uncertainties associated with them. These uncertainties arise from having to use partially complete datasets to estimate doses as either the data was not collected in sufficient detail to allow an accurate estimate of the dose to all exposed individuals to be made, or the data was not made available for use in this assessment. For example, it is not known precisely what dose each individual received when flying as this is dependent on the flight profile which varies with weather; the dose rate can therefore vary even between aircraft flying the same route.

In previous reviews the possible range in dose received by members of the UK population from different sources of radiation was presented to illustrate this uncertainty. As the per caput dose already accounts for any variation in exposure across the UK population, discussion of the variation in the dose from different sources of radiation is omitted from this review for simplicity.

Section 2 discusses exposure to radiation in the environment, including that from naturally occurring radiation as well as from anthropogenic sources of radiation which are ubiquitous in the environment. Section 3 discusses patient exposure from the medical use of radiation, while Section 4 discusses occupational exposure to radiation. Section 5 discusses exposure to members of the public from radioactivity used in consumer items and from the transport of radioactive material. Section 6 discusses the dose to the UK population in 2010 from all significant sources of ionising radiation.

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* In this review 'dose' represents the effective dose as defined by the International Commission on Radiological Protection (ICRP) (ICRP, 2007) unless otherwise stated.

† To estimate the per caput dose the UK population in 2010 was assumed to be 62.3 million (ONS, 2011a).

2 Exposure to Ubiquitous Radiation in the Environment

Radioactivity is present in the environment due to many different processes. Isotopes of uranium and thorium in the environment today, for example, were created billions of years ago in stars and subsequently incorporated into rocks when the Earth was formed. Other radionuclides, including tritium (^{3}H) and carbon-14 (^{14}C), are created continuously from the interaction of cosmic radiation with atoms in the atmosphere. In addition to these natural processes, humans have also introduced radionuclides into the environment – for example, in discharges made during nuclear power production.

All members of the UK population are exposed to radiation in the environment to some extent, the magnitude of that exposure depending on the location of the individual and their habits. This section discusses the dose to the UK population from exposure to all significant sources of radiation that are ubiquitous in the environment, including radiation of natural origin as well as anthropogenic radioactivity.

For exposure to ubiquitous radiation in the environment, where possible this review made use of data published by UK organisations – for example, the Environment Agency (EA) and the Scottish Environment Protection Agency (SEPA) – and international organisations – for example, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Where the dose estimates to the UK population from radiation in the environment could not be found in the literature, values were estimated using modelling. In this review, modelling was used to estimate the dose to the UK population from exposure to radioactivity taken into the body with food and when breathing. The appendix describes the approach used to estimate the dose from ingesting and inhaling naturally occurring radionuclides, while the approach used to estimate the dose from exposure to anthropogenic radiation in the environment is discussed in this section.

2.1 Exposure to radiation of natural origin

Radionuclides of natural origin are present in all environmental media, including soil, air and water. This section describes exposure to the UK population from the inhalation of radioactivity in air, ingestion of foods that have incorporated radionuclides from soil, water and air, and external irradiation from radionuclides present in soil and from radiation emitted by processes occurring in space.

2.1.1 Exposure from the inhalation of radon and thoron

Radon is a radioactive gas in the radioactive decay chains headed by uranium and thorium isotopes. The most radiologically significant radon isotopes are ^{222}Rn, which is in the ^{238}U decay chain and has a radioactive half-life of about 3.8 days, and ^{220}Rn, which is in the ^{232}Th decay chain and has a radioactive half-life of about 55 seconds. The name radon is generally attributed to ^{222}Rn, while ^{220}Rn is generally known as thoron.

How much radon is present in air inside a building depends on many factors, such as the activity concentration of radium-226 (^{226}Ra) in the underlying geology and its porosity, permeability and fracturing, how the building connects with the ground, the construction materials used in the building, and the method used for heating and ventilation. In addition, radon dissolved in potable water also contributes to the total radon activity concentration in indoor air, although that contribution is generally small (AGIR, 2009). As a result of all of these factors, large geographical variations exist in the activity concentration of radon in air in buildings (Wrixon et al, 1988; Rees et al, 2011). These variations in activity concentration result in large variations in the dose received by members of the UK population as illustrated in Figure 1.

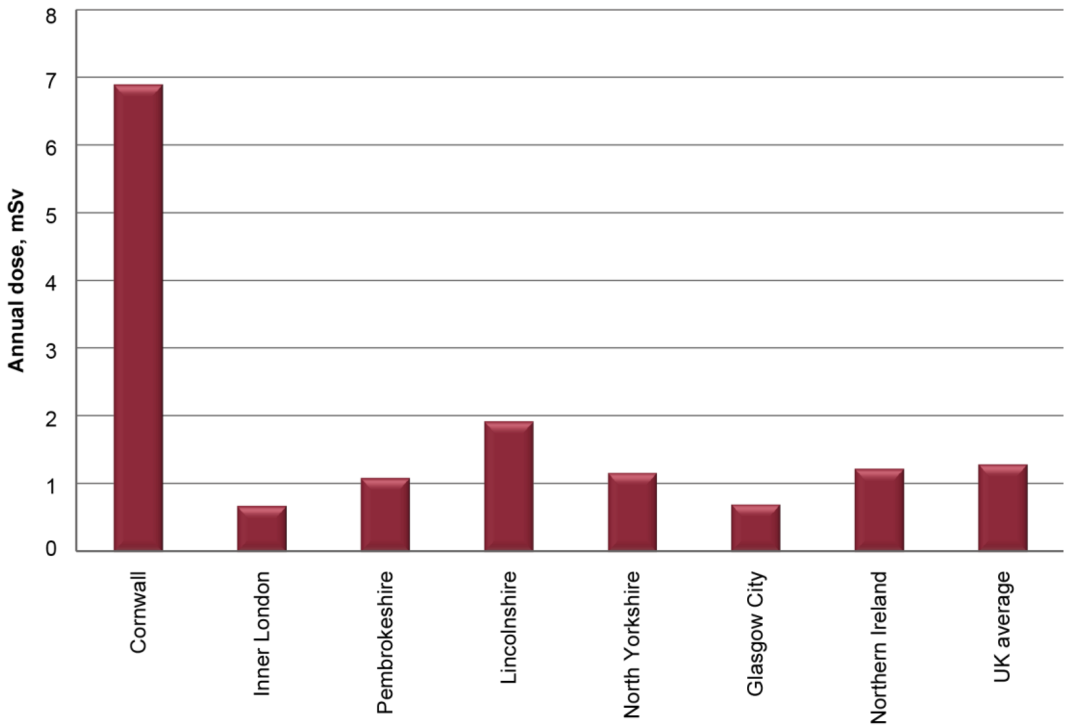

Figure 1: Illustrative annual doses from inhaling radon in different parts of the UK

In the mid-1980s a national survey was carried out to determine the level of radon in residential buildings across the UK (Wrixon et al, 1988). From this national survey the population weighted average radon activity concentration in indoor air was estimated to be 20 Bq m^{-3}. Since the 1988 national survey was published, further measurements have been made, although these were mostly targeted at buildings within areas of the UK that were likely to have relatively high radon levels and would not, therefore, represent typical values with respect to the UK as a whole. Consequently, Wrixon et al (1988) is considered still to provide the best estimate for the UK average indoor radon concentration in air.

To convert activity concentration to a dose requires the use of a dose coefficient and associated parameters. For this, and previous reviews, use was made of the convention that exposure to an average indoor radon concentration in air of 20 Bq m^{-3} results in an effective dose of about 1 mSv y^{-1} (NRPB, 1987). The International Commission on Radiological Protection (ICRP) is undertaking work on radon dosimetry; future reviews may make use of the results of that work.

Thoron also exists in air inside buildings and inhaling this gas also produces a radiation dose. Wrixon et al (1988) estimated that the mean equilibrium equivalent thoron concentration in UK housing was about 0.3 Bq m^{-3}. Using a conversion coefficient of 0.04 µSv per Bq h m^{-3} (UNSCEAR, 2000), Wrixon et al (1988) estimated that the average annual dose to the UK population from inhaling thoron while indoors was about 0.095 mSv.

The total collective dose to the UK population from inhaling both radon and thoron in the home was estimated to be about 68,000 man Sv, mostly from the inhalation of ^{222}Rn and its short-lived progeny. The annual per caput dose to the UK population from inhaling radon and thoron in the home was estimated to be approximately 1.1 mSv.

The same processes that retain radon inside dwellings also retain radon inside buildings and enclosed spaces used for occupational purposes. While inhaling radon in above-ground workplaces, Wrixon et al (1988) estimated that the average person in the UK receives a dose of about 0.2 mSv a year. The corresponding annual collective dose to the UK population from inhaling radon in above-ground workplaces is about 12,000 man Sv.

In mines, the enclosed atmosphere allows radon to build up in the air, exposing miners. Some miners, particularly those in smaller mines, are classified workers due to the potential dose they could receive; a summary of the CIDI (Central Index of Dose Information) data for classified underground mine workers is given in Table 1 (CIDI, 2004, 2005, 2006, 2007, 2008, 2009, 2010). However, the majority of miners in the UK work in larger mines which, because of better ventilation, have much lower activity concentrations of radon in air. The average annual individual and collective doses to miners from inhaling radon in large mines were estimated to be 0.6 mSv (Hindmarsh, 1992) and 3 man Sv, respectively, assuming that there are approximately 4,000 such miners in the UK (HSE, 2011).

Table 1: Exposure of classified underground workers to natural sources of radiation

	Number of workers in dose range (mSv)					
Year	<1	1–6	6–20	>20	Collective dose (man Sv)	Average dose (mSv)
2004	14	13	32	0	0.30	5.1
2005	6	34	24	0	0.32	4.9
2006	7	30	30	0	0.34	5.1
2007	15	27	30	0	0.33	4.5
2008	10	35	23	0	0.31	4.6
2009	2	19	33	0	0.32	6.0
2010	11	11	30	0	0.31	5.9

In outdoor air, radon and thoron are quickly diluted and therefore their activity concentration is relatively low compared with that inside buildings or enclosed spaces. The population weighted average concentrations of radon and thoron in outdoor air were estimated to be about 4 Bq m^{-3} (Wrixon et al, 1988) and 0.1 Bq m^{-3} (UNSCEAR, 2000), respectively. The doses received by an average member of the UK population from inhaling radon and thoron when outside were estimated to be approximately 0.02 mSv and 0.01 mSv a year, respectively (Wrixon et al, 1988). Based on these average individual doses, the collective dose to the UK population from inhaling radon and thoron while outside was estimated to be approximately 2,000 man Sv.

2.1.2 Exposure following intake of natural radionuclides other than radon

Radioactivity in the environment may be taken up by plants and animals which are then ingested by humans. In addition, some radionuclides are also present in the atmosphere and can be taken into the body by inhalation. The most significant of these radionuclides, with respect to contributing to the collective dose of the UK population, are ^{14}C, potassium-40 (^{40}K), rubidium-87 (^{87}Rb) and members of the uranium and thorium radioactive decay chains other than radon and thoron; exposure following the intake of other naturally occurring radionuclides is insignificant in comparison. The appendix presents the dose to individual age groups following the intake of these radionuclides and the methodology used to estimate that dose.

After production in the atmosphere through interaction of cosmic radiation with nitrogen atoms, ^{14}C is taken up by plants and becomes incorporated into human foodstuffs. The annual collective and per caput doses to the UK population from naturally produced ^{14}C ingested with food were estimated to be approximately 600 man Sv and 0.009 mSv, respectively.

Potassium is distributed throughout the body, its concentration held relatively constant by metabolic processes. On average, about 0.18% of the mass of an adult, and about 0.2% of the mass of a child, is potassium, with about 0.012% of this potassium being the radioactive isotope ^{40}K. The average annual doses to an adult and a child from ^{40}K in the body have been estimated to be 0.165 mSv and 0.185 mSv, respectively (UNSCEAR, 2010a). Over the entire UK population, the annual collective and per caput doses from ^{40}K in the body were estimated to be approximately 11,000 man Sv and 0.17 mSv, respectively.

Radioactive rubidium (^{87}Rb) constitutes 27.8% by mass of rubidium found in the Earth's crust and is readily taken up by plants and animals due to its similarity to potassium. The total annual collective and per caput doses to the UK population from intakes of ^{87}Rb in the diet were estimated to be approximately 100 man Sv and 0.002 mSv, respectively.

Members of the uranium and thorium radioactive decay series are present in very low concentrations in most foodstuffs. The total annual collective and per caput doses to the UK population from the intake of radionuclides in the uranium radioactive decay chain were estimated to be approximately 4,700 man Sv and 0.08 mSv, respectively. Following intake of radionuclides in the thorium radioactive decay chain, the annual collective and per caput doses to the UK population were estimated to be approximately 700 man Sv and 0.01 mSv, respectively.

Some foodstuffs contain relatively high levels of radioactivity due to processes that naturally concentrate certain radioactive isotopes within the food, or because those foods are grown in parts of the world that have high natural levels of radionuclides in the soil. Brazil nuts are an example of such a foodstuff which contain elevated levels of radium isotopes (Turner et al, 1958). The dose from the consumption of 100 g of Brazil nuts, assuming isotopes of radium are present with an activity concentration of 0.1 Bq g^{-1} (Martins et al, 2012), is about 0.01 mSv. Another example is the concentration of polonium-210 (^{210}Po) in marine animals including fish and mussels (FSA, 2002; EA et al, 2011). The average annual dose to the UK population from ingesting naturally occurring radionuclides in marine animals could be up to 0.02 mSv (Watson et al, 2005a).

In addition to becoming incorporated into plants used for foods, radionuclides from the uranium and thorium radioactive decay chains, principally lead-210 (^{210}Pb) and ^{210}Po, can become incorporated within or on tobacco leaves. This radioactivity is not removed during cigarette manufacture and can be inhaled when a cigarette is smoked. The US National Council on Radiation Protection and Measurements (NCRP) has estimated that smoking a cigarette a day causes an annual radiation dose of about 0.018 mSv (NCRP, 2009).

2.1.3 Exposure to terrestrial gamma radiation

External irradiation from gamma emitting radionuclides present in all geologies, including soils and rocks, occurs continuously. The most significant radionuclides are ^{40}K and radionuclides from the uranium and thorium radioactive decay chains.

Measurements of the external dose rate from terrestrial gamma emitting radionuclides have been made across the UK (Wrixon et al, 1988; Green et al, 1989). From these measurements the mean annual dose from terrestrial gamma radiation was estimated, after accounting for time spent inside and outside buildings, to be about 0.35 mSv. The corresponding annual collective dose to the UK population from exposure to terrestrial gamma radiation was estimated to be about 22,000 man Sv.

2.1.4 Exposure to cosmic radiation

The Earth is continually bombarded by high energy particles that mostly originate from events beyond the solar system, with a lower energy component originating from the sun. Although cosmic radiation is able to reach the ground, its intensity is considerably reduced by absorption in the atmosphere. In addition, the Earth's magnetic field acts to deflect the radiation away from the Earth, causing a variation in the cosmic radiation flux at ground level with respect to latitude, longitude and azimuth angle. The overall effect is that the dose rate due to cosmic radiation increases with an increase in both altitude and latitude, peaking close to the magnetic poles. The activity of the sun, which varies on an 11-year cycle, also affects the dose rate due to cosmic radiation. However, for simplicity, only the average dose rate due to cosmic radiation from being exposed at ground level and while flying is considered in this review.

At latitudes corresponding to those of the UK, UNSCEAR (2010a) estimated that, for times spent outside and at sea level, the annual dose from cosmic radiation is approximately 0.37 mSv. For time spent inside, the dose rate due to cosmic radiation is reduced due to the shielding effects of building materials. UNSCEAR (2010a) has suggested that the average dose rate inside buildings could be about 80% of that outside. Taking into account people in the UK spend on average 90% of their time indoors, the average annual dose to the UK population from cosmic radiation at ground level was estimated to be approximately 0.3 mSv. The collective dose to the UK population from ground-level exposure to cosmic radiation was estimated to be about 19,000 man Sv.

The cosmic radiation dose rate is significantly higher at the altitudes at which commercial passenger aircraft fly when compared to the dose rate at ground level. The European

Commission (EC, 2004) reported a measured average dose rate, for all types of flights in the northern hemisphere, of 0.0038 mSv h^{-1}. For this review an average dose rate of 0.004 mSv h^{-1} was used to estimate the dose received during all flights to and from the UK. In this review two groups of fliers were assessed: the first being people from the UK who flew as passengers in 2010 and the second being people who worked as flight and cabin crew.

The Office for National Statistics (ONS, 2011b) reported that, in 2010, approximately 46 million 'UK residents' flew as passengers; these passengers were taken to be members of the UK population for this review. Table 2 shows some destinations flown to by people living in the UK, with the approximate number of passengers flying to each destination in 2010 (ONS, 2011b). The dose people may have received from exposure to cosmic radiation during those flights is presented in Table 2, although they are for illustrative purposes only as actual flight times vary and the dose rate for specific flights depends on many factors including the flight profile and flight path taken.

The annual collective and average individual doses to people from the UK flying as passengers in 2010 were estimated to be approximately 1,600 man Sv and 0.03 mSv, respectively. This collective dose is slightly higher than that estimated in the previous review (Watson et al, 2005a) due to an increase in the number of passengers flying in 2010 compared to 2002.

Table 2: Estimated doses for a return flight from the UK to various destinations worldwide

Destination	Number of people flying in 2010	Approximate flight time (h)	Approximate dose (mSv)
Madrid (Spain)	10,059,000	5	0.02
Paris (France)	2,969,000	2.5	0.01
US	3,233,000	20*	0.08
Delhi (India)	850,000	17.75	0.07
Sydney (Australia)	453,000	42	0.2
Cape Town (South Africa)	371,000	24	0.1
Mexico City (Mexico)	315,000	21.5	0.09
Tokyo (Japan)	101,000	24.25	0.1

* The shown flight time is an average of that between London to New York (16 hours) and London to Los Angeles (24 hours) for a return journey.

Although exposure to aircrew from cosmic radiation is an occupational exposure, due to the source of the exposure the doses to aircrew from cosmic radiation is presented in this section. In 2010, the Civil Aviation Authority (CAA, 2011) reported that 39,907 aircrew worked for UK registered airlines. For this review it was assumed that all of these aircrew were UK citizens and each flew for an average of 600 hours a year (Warner-Jones et al, 2003). The collective and average individual doses to UK aircrew flying in 2010 were estimated to be approximately 100 man Sv and 2.4 mSv, respectively. These are similar to the doses estimated in the previous review (Watson et al, 2005a).

2.2 Exposure to anthropogenic radionuclides in the environment

Humans use the properties of radionuclides for many different processes, including energy production and diagnosis of medical problems. Waste produced by industrial or medical use of radioactivity is disposed of by releasing it to atmosphere, to the marine environment, to rivers, or to landfill or other suitable facilities. Once in the environment, these radionuclides can expose the UK population through, for example, being taken up into foods.

Only discharges of radionuclides to atmosphere and the marine environment during normal operations contribute significantly to the per caput dose to the UK population and have been included in this review; disposal of material containing radionuclides to landfill or to rivers are generally small in comparison and expose only a limited number of individuals.

2.2.1 Exposure to radionuclides discharged by the civil nuclear industry

The civil nuclear industry in the UK includes nuclear power stations, nuclear fuel cycle facilities, and research and development facilities. As of 2010 the nuclear power generation industry in the UK consisted of ten operating nuclear power stations, of which two operate Magnox reactors, seven operate advanced gas-cooled reactors (AGR) and one operates a pressurised water reactor (PWR). Eight nuclear power stations are presently in the defueling or decommissioning stage of the facilities life cycle. Fuel cycle facilities are located at Capenhurst, Springfields and Sellafield where uranium enrichment, fuel fabrication, fuel reprocessing and spent fuel storage are carried out. In addition, the UK civil nuclear industry includes two sites involved in the manufacture of radiopharmaceuticals.

The collective dose to the UK population from exposure to all significant discharges of radionuclides by the civil nuclear industry, from the time each site started operating until 2010, was assessed using the computer model PC CREAM 08® (Smith and Simmonds, 2009; Smith et al, 2009). For radionuclides released to the atmosphere, PC CREAM 08® assesses doses due to external irradiation from, and intake by inhalation of, radionuclides in the air, external irradiation following deposition of radionuclides, and ingestion of deposited radionuclides in terrestrial food. For exposure to radionuclides released to the marine environment, PC CREAM 08® assesses doses due to external irradiation from radionuclides in beach sediment and from the consumption of radionuclides in marine foods.

A summary of collective and per caput doses to the UK population in 2010 from exposure to radionuclides discharged into the environment by UK civil nuclear sites is given in Table 3. The total annual collective and per caput doses to the UK population in 2010 from exposure to radionuclides released into the environment by the UK civil nuclear industry were estimated to be about 12 man Sv and 2 10^{-4} mSv, respectively. Radionuclides discharged to the atmosphere and to the marine environment contributed about 30% and 70% to these doses, respectively. Nearly the entire collective dose to the UK population from exposure to radioactivity discharged as a liquid was due to discharges made by the Sellafield site. The most significant radionuclides were americium-241 (^{241}Am) and plutonium-239 (^{239}Pu) in molluscs and ^{14}C and caesium-137 (^{137}Cs) in fish. Nuclear power production sites were the most significant source of radionuclides released to atmosphere with respect to the UK population dose in 2010. The most significant radionuclides released to atmosphere were ^{14}C, sulphur-35 (^{35}S) and iodine-129 (^{129}I) that had been incorporated in terrestrial foods, particularly milk and grain.

Table 3: Estimated collective and per caput doses to the UK population in 2010 due to discharges made by UK civil nuclear sites

	Collective dose (man Sv)			Per caput dose (mSv)		
Type of site	**Atmospheric**	**Liquid**	**Total**	**Atmospheric**	**Liquid**	**Total**
Fuel fabrication	$1.3\ 10^{-2}$	$2.6\ 10^{-3}$	$1.6\ 10^{-2}$	$2.1\ 10^{-7}$	$4.2\ 10^{-8}$	$2.5\ 10^{-7}$
Reactor operation	$2.6\ 10^{0}$	$1.5\ 10^{-2}$	$2.6\ 10^{0}$	$4.2\ 10^{-5}$	$2.4\ 10^{-7}$	$4.2\ 10^{-5}$
Fuel reprocessing*	$7.6\ 10^{-1}$	$8.2\ 10^{0}$	$9.0\ 10^{0}$	$1.2\ 10^{-5}$	$1.3\ 10^{-4}$	$1.4\ 10^{-4}$
Radiopharmaceutical production	$1.7\ 10^{-1}$	$2.9\ 10^{-2}$	$2.0\ 10^{-1}$	$2.7\ 10^{-6}$	$4.7\ 10^{-7}$	$3.2\ 10^{-6}$
Total	$3.6\ 10^{0}$	$8.2\ 10^{0}$	$1.2\ 10^{1}$	$5.8\ 10^{-5}$	$1.3\ 10^{-4}$	$1.9\ 10^{-4}$

* Discharges from the Low Level Waste Repository (LLWR) in 2010 could not be distinguished from discharges made by the nearby Sellafield site (EA et al, 2011).

Radionuclides discharged from nuclear facilities located in other countries also contribute to the UK population dose. While no specific assessment of the dose to the UK population in 2010 from such discharges has been made, an assessment by the European Commission (EC, 2013) implied such discharges would most likely result in a similar level of exposure as discharges made by UK civil nuclear facilities.

The collective dose to the UK population in 2010 from exposure to radionuclides discharged during the production of radiopharmaceuticals was estimated to be approximately 0.2 man Sv. The most important contribution to this dose was exposure to ^{14}C discharged to atmosphere.

2.2.2 Exposure to radionuclides discharged by non-nuclear industries

Until 2001 there was an industry in the UK manufacturing phosphoric acid from imported phosphate ore. The waste from that process, which included naturally occurring radionuclides present in source material, was discharged as a liquid to the marine environment. Although those discharges ceased in 2001, environmental surveys showed that some radionuclides, particularly ^{210}Pb and ^{210}Po, persisted in the marine environment for many years (EA et al, 2011). However, by 2010, it was difficult to distinguish the anthropogenic radionuclides discharged by the phosphate industry from those radionuclides naturally present in the environment (EA et al, 2011). For this review it was therefore assumed that the dose to the UK population in 2010 from exposure to radionuclides discharged by the phosphate industry was effectively zero.

Water produced during extraction of oil and gas, termed produced water, includes low levels of radium isotopes and their radioactive decay progeny. From offshore installations this water is discharged into the marine environment as a waste product. The collective and per caput doses to the UK population in 2010 due to these discharges, estimated using PC CREAM 08® (Smith and Simmonds, 2009; Smith et al, 2009), together with the annual discharges reported by Harvey et al (2010a), were approximately 50 man Sv and $6\ 10^{-5}$ mSv, respectively.

The defence industry discharges radioactivity to the environment as a result of its work designing, testing and maintaining nuclear reactors for the UK nuclear submarine fleet. Hospitals discharge radioactivity during and after nuclear medicine procedures, while other facilities release radioactivity into the environment as a byproduct of industrial processes. For example, coal contains low levels of radionuclides and when it is burnt, such as in coal-fired power stations or steel production facilities, some of these radionuclides are released into the environment as ash. For many of these organisations, the radioactivity annually released into the environment is not routinely recorded due to its low level; an assessment of the contribution to the collective dose to the UK population in 2010 from such discharges could therefore not be made. However, for those organisations where annual discharges were available, the amount of radioactivity released into the environment was several orders of magnitude lower than discharges made by civil nuclear sites (EA et al, 2011). As a result, the contribution to the collective dose to the UK population in 2010 from discharges made by non-nuclear industries, excluding the oil and gas industry, is expected to be low compared to that arising from exposure to radioactivity discharged by the civil nuclear industry.

2.2.3 Exposure to radionuclides produced during nuclear weapons testing

When testing of nuclear weapons started in 1945 the majority of tests were conducted in the atmosphere. Following an atmospheric nuclear detonation up to 50% of the fallout, the deposition on to the ground of radioactive dust taken into the atmosphere by the detonation, occurs around the test site. The remaining fallout deposits globally due to radionuclides being carried high into the atmosphere. Signing of the Limited Test Ban Treaty in 1963 significantly reduced the number of atmospheric tests being conducted. Since 1963 the majority of nuclear tests have been carried out underground, which releases significantly less radioactivity into the atmosphere when compared to an atmospheric detonation. Consequently, exposure to radionuclides released during weapons testing is dominated by radioactivity released by weapon tests carried out before the mid-1960s (UNSCEAR, 2010a).

In 2010, the worldwide average annual dose from exposure to radionuclides produced by nuclear weapons testing was estimated to be about 0.005 mSv (UNSCEAR, 2010a). For this review the dose to the UK population from exposure to radioactivity produced by nuclear weapon testing was assumed to equal the world average. The collective dose to the UK population in 2010 from exposure to radioactivity in fallout was estimated to be approximately 300 man Sv. The main exposure pathways were external irradiation from ^{137}Cs present in soils and ingestion of ^{14}C, strontium-90 (^{90}Sr) and ^{3}H incorporated within food.

2.2.4 Exposure from accidentally released radioactivity

The use of radiation or radioactive material is generally very well controlled and subject to many safety requirements. However, there is still the potential for accidents to occur; over the last 60 years over 600 events are known to have occurred worldwide that caused significant radiation exposure (Nénot, 2009). Most of these incidents only affected a limited number of people – for example, workers in the immediate vicinity of the incident – and there was no exposure of the UK public. However, two accidents did result in the release of significant amounts of radioactivity which affected large areas of the UK at the time of the accident.

In 1957 an accident occurred at the Windscale nuclear reactor facility and plutonium-production plant in Cumbria. During this accident, uranium cartridges ruptured and oxidised which caused a fire that burned for 16 hours. During this fire, sizable amounts of radioactive iodine were released to the atmosphere. As a consequence of the fire, the government banned the sale of milk produced in a 500 km^2 area around the reactor site for several weeks. The results of environmental monitoring in 2010 (EA et al, 2011) showed that the concentrations of all radionuclides around the Sellafield site (which incorporates the original reactor at Windscale) were low, with iodine isotopes being below the level of detection. The contribution of radionuclides released during the Windscale fire to the collective dose to the UK population in 2010 is expected to be negligible.

In 1986, an uncontained rise in the core temperature of one of the reactors at the Chernobyl nuclear site in Ukraine caused a steam explosion which partially removed the concrete reactor lid. After the explosion the reactor’s graphite caught fire and radionuclides were released to the atmosphere for at least 10 days. Radioactivity was then carried by the wind over most of northern Europe, including the UK. As the plume of radioactivity passed over the UK radionuclides were deposited on to the ground, the level of deposition being dependent on the prevailing weather. Once radionuclides were on the ground they entered the human food chain; in the UK this was principally by sheep ingesting contaminated grass, although some freshwater fish were also affected. In order to limit the ingestion of contaminated foods, restrictions were placed on the movement and marketing of sheep from 9,800 farms, mainly in Cumbria, north Wales and southern Scotland. Over time, monitoring showed that the levels of radioactivity in sheep meat had decreased to levels where the restrictions could be lifted. Consequently, although some restrictions were still in place in England in 2010, all restrictions were lifted in Northern Ireland in 2000 and in Scotland in 2010. Due to the restrictions in place, any food produced in the UK had little or no radioactivity within it as a result of the Chernobyl accident. The contribution of radionuclides released during the Chernobyl accident to the collective dose to the UK population in 2010 is expected to be insignificant.

In March 2011 an earthquake occurred near Japan, which led to a tsunami that caused releases of radioactive material into the environment from the Tokyo Electric Power Company’s Fukushima Daiichi nuclear power station. Traces of ^{131}I, associated with the release, were subsequently detected in the UK (HPA, 2011). Early measurements indicated that doses to the UK population from inhaling this radionuclide would be very much less than the annual background radiation dose. As this incident occurred outside the period covered by this review it is mentioned for completeness; the full radiological impact from this incident will be described in the next review.

3 Exposure of Patients from the Medical Use of Radiation

3.1 Diagnostic procedures

Conventional static imaging for diagnostic purposes is perhaps the most recognised type of X-ray procedure. Over the last few decades new technologies have been developed that enhance the use of X-rays for diagnostic purposes, including fluoroscopic imaging and computerised tomography (CT).

In 2008, the last year for which data is available, around 46 million medical and dental X-ray examinations were carried out in the UK (Hart et al, 2010). The collective and per caput doses to the UK population from all diagnostic examinations carried out in 2008 were estimated to be about 25,000 man Sv and 0.4 mSv, respectively (Hart et al, 2010). Table 4 shows the contribution to this total dose from broad categories of examination. Due to the higher dose for procedures delivered by CT examinations, these examinations were estimated to contribute about 68% to the UK annual collective dose from all diagnostic radiology procedures carried out in the UK in 2008, even though they made up only about 11% of all X-ray examinations (Hart et al, 2010).

The increasing contribution made by CT examinations to the collective dose to the UK population from the medical use of radiation is shown in Figure 2. This increase stems from the approximate three-fold rise in the number of examinations performed in the UK over the last decade (Slack, 2011). Mainly as a consequence of the increase in the collective dose received due to CT examinations, the annual collective dose to the UK population from diagnostic medical procedures was approximately 8% higher in 2008 than that reported in the previous review for examinations carried out in the financial year 2001/02 (Watson et al, 2005a).

About 90% of diagnostic nuclear medicine procedures obtain images that show either the structure or function of an organ. Other procedures obtain diagnostic information without imaging. In 2003/04, around 680,000 nuclear medicine procedures of all types were performed in the UK resulting in a collective dose to the UK population of about 1,600 man Sv (Hart and Wall, 2005).

Table 4: Estimated UK collective and per caput doses from all diagnostic examinations in 2008

Area	UK collective dose (man Sv) †	Per caput dose (mSv)
CT	16,723	0.27
Conventional radiology*	4,799	0.08
Angiography (non-CT)	1,187	0.02
Interventional (non-CT)	1,985	0.03
Total diagnostic radiology	24,694‡	0.40

* Includes dental examinations.
† As reported in Hart et al (2010).
‡ Includes a contribution of 626 man Sv from unassigned examinations.

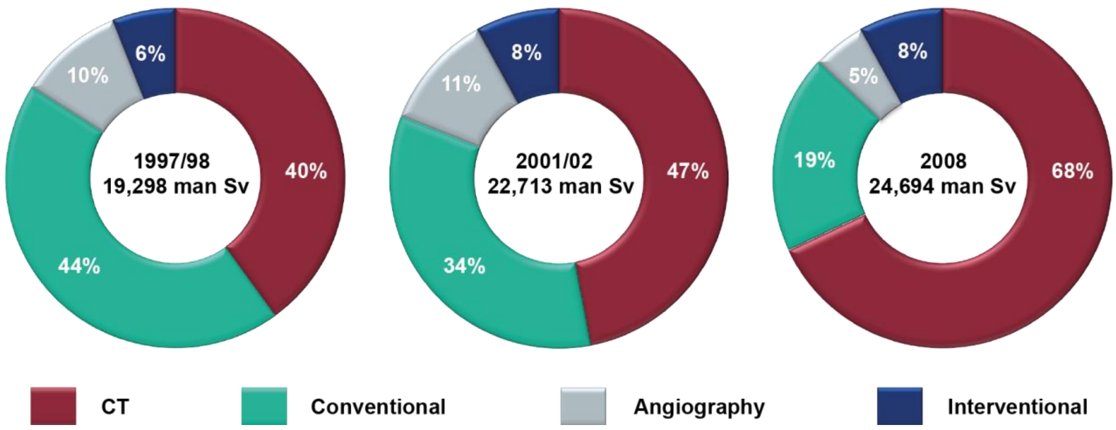

Figure 2: UK collective dose from different diagnostic radiology examinations carried out in the 1997/98 and 2001/02 financial years, and in the 2008 calendar year

Information on the number of nuclear medicine procedures carried out in the 2009/10 financial year was only available for England (Department of Health, 2010). Between 2003/04 and 2009/10, the total number of diagnostic examinations or tests involving radioisotopes in England increased by about 7% for imaging procedures and about 2% for other diagnostic procedures. Although the total number of nuclear medicine procedures performed across the UK in 2009/10 was not known, the increase in the number of procedures being performed throughout the UK between 2003/04 and 2009/10 was assumed to be the same as that which occurred in England. Based on this assumption, the collective and per caput doses to the UK population in 2009/10 from nuclear medicine procedures were estimated to be about 1,700 man Sv and 0.03 mSv, respectively.

3.2 Therapeutic procedures

In radiotherapy and therapeutic nuclear medicine the cell killing effects of radiation are harnessed using intentionally high doses delivered to specific tissues. The concept of effective dose is based on the addition of probabilities of stochastic effects, so it is inappropriate to include doses to the target organs in therapeutic procedures in the calculation of effective dose as the dose is so high that the possibility for stochastic effects is eliminated. However, during such procedures, organs other than the target organ are also irradiated. These non-target organs receive much lower doses than the target organ and stochastic effects may arise in them. Hart and Wall (2005) estimated that the collective dose to the UK population from exposure of non-target organs during the most common therapeutic procedures was about 740 man Sv. This equates to a per caput dose to the UK population of about 0.01 mSv.

4 Occupational Exposure to Radiation

In the UK, employers have a duty to assess and record the dose received by classified workers through the use of an approved dosimetry service (ADS). The UK Health and Safety Executive (HSE) annually collects information on occupational exposure to classified workers from the various ADSs and places that information within the Central Index of Dose Information, or CIDI, database (CIDI, 2004, 2005, 2006, 2007, 2008, 2009, 2010).

The CIDI database does not contain information on unclassified workers and therefore the number of unclassified workers exposed to radiation, and their doses, were obtained directly from employers or the ADSs. However, information on the level of exposure received by unclassified workers was not always systematically collected or kept in a form that made it readily available for review. In addition, any data collected was provided voluntarily. As a result, information collected on unclassified workers is likely to be incomplete and, to estimate the occupational exposure to some groups of workers, some assumptions regarding levels of exposure or the number of individuals exposed had to be made.

As occupational exposure is not currently published, all information collected for this review on the annual exposure to the UK workforce between 2004 and 2010 is given for information. In this section, only occupational exposure to radiation that is not ubiquitous in the environment is discussed; occupational exposure to ubiquitous radiation in the environment – for example, to radon in the workplace or to cosmic radiation – is discussed in Section 2.

4.1 Occupational exposure at UK civil nuclear licensed sites

This section reviews the dose to workers within those parts of the nuclear industry operating in the UK. The review is divided according to the different sectors of the nuclear industry and the classification system used by CIDI: fuel enrichment, fuel fabrication, power production, and reprocessing. Occupational exposure during decommissioning operations is also given. As the nuclear industry employs both classified and unclassified workers, this review made use of information both from CIDI and obtained through direct communication with employers and relevant ADSs.

URENCO UK Ltd operates a uranium enrichment facility at its Capenhurst site. A summary of the doses received by both URENCO UK Ltd employees and their contractors at this site is given in Table 5 (Armitage, 2012). Between 2008 and 2010 the average annual and collective doses received by workers at the Capenhurst site increased by approximately a factor of two, reaching 0.8 mSv and 0.3 man Sv, respectively. This increase was likely due to changes in monitoring practices rather than a genuine increase in occupational exposure (Armitage, 2012). The doses received by workers during 2010 were slightly higher than those reported in the previous review (Watson et al, 2005a).

Table 5: Occupational exposure in fuel enrichment facilities (Armitage, 2012)

	Number of workers in dose range (mSv)					
Year	0	0–1	1–6	>6	Collective dose (man Sv)	Average dose (mSv)
2004	9	326	7	0	0.10	0.29
2005	110	260	12	0	0.09	0.24
2006	23	353	15	0	0.15	0.38
2007	11	375	11	0	0.17	0.43
2008	39	369	14	0	0.13	0.27
2009	7	385	19	0	0.21	0.51
2010	4	309	97	0	0.34	0.83

Springfields Fuels Ltd, incorporated into the Nuclear Decommissioning Authority (NDA) since 2005, manufactures nuclear fuel for most types of nuclear reactor. Manufacture of mixed oxide fuel (MOX) was also carried out by Sellafield Ltd until 2010. A summary of the dose received by workers in fuel fabrication is given in Table 6. As CIDI included only a sum of the doses to workers in both fuel enrichment and fabrication, doses to workers in fuel fabrication were estimated by subtracting the dose reported by Armitage (2012) to workers in fuel enrichment from those in CIDI. The average annual effective and collective doses to classified workers in fuel fabrication in 2010 were approximately 0.6 mSv and 1 man Sv, respectively. These are comparable to those reported in the previous review (Watson et al, 2005a).

Table 7 summarises occupational exposures of classified workers at operating nuclear power stations, obtained from CIDI. These data include the CIDI categories of nuclear site radiographers, nuclear reactor operations, and nuclear reactor maintenance. The average annual effective and collective doses to classified workers at operating power production stations in 2010 were approximately 0.2 mSv and 1 man Sv, respectively. The average annual dose to these workers in 2010 was comparable with that reported in the previous review for all power production workers (Watson et al, 2005a). However, the collective dose to power production workers in 2010 was approximately two-thirds of that estimated in the previous review mainly due to the lower number of workers in 2010 compared to 2003.

A significant peak in the dose to workers at operating power production stations occurred in 2006 due to exposure received during extensive repair work carried out at two sites (British Energy, 2007). During this work a number of British Energy* staff exceeded the company dose restriction level (CDRL) of 10 mSv, for which approval was given.

Nuclear fuel reprocessing is carried out at the Sellafield site and a summary of the dose received by classified workers during this process is given in Table 8. In 2010 the average effective and collective doses to classified workers involved in nuclear fuel reprocessing were approximately 0.6 mSv and 2 man Sv, respectively. A comparison of the dose to workers involved in reprocessing in 2010 with that reported in the previous review could not be made as Watson et al (2005a) only reported the dose to all workers at the Sellafield site, which in 2003 included workers at the Calder Hall power station in addition to workers involved in fuel reprocessing.

Table 6: Occupational exposure of classified workers in fuel fabrication

	Number of workers in dose range (mSv)						
Year	0	0–1	1–6	6–10	>10	Collective dose (man Sv)	Average dose (mSv)
2004	226	1,332	343	0	0	1.2	0.64
2005	73	1,559	472	3	0	1.7	0.81
2006	87	1,447	644	0	0	2.0	0.89
2007	124	1,346	415	0	0	1.4	0.72
2008	103	1,365	376	0	0	1.3	0.72
2009	117	1,249	411	0	0	1.4	0.77
2010	175	1,329	284	0	0	1.1	0.60

Table 7: Occupational exposure of classified workers at operating nuclear power stations

	Number of workers in dose range (mSv)								
Year	0	0–1	1–6	6–10	10–15	15–20	>20	Collective dose (man Sv)	Average dose (mSv)
2004	4,543	2,715	266	7	0	1	0	1.3	0.18
2005	4,429	2,605	327	16	0	0	1	1.5	0.20
2006	4,075	2,809	437	36	14	0	0	2.2	0.30
2007	4,298	2,251	352	6	0	0	0	1.4	0.21
2008	4,361	2,042	332	57	1	0	0	1.8	0.26
2009	4,093	2,088	411	27	0	0	0	1.7	0.26
2010	4,432	1,989	287	13	0	0	0	1.2	0.18

* British Energy was taken over by EDF in 2009.

Table 8: Occupational exposure of classified workers in fuel reprocessing

Year	Number of workers in dose range (mSv)					Collective dose (man Sv)	Average dose (mSv)
	0	0–1	1–6	6–10	>10		
2004	492	2,862	539	9	0	2.3	0.59
2005	280	2,559	600	13	0	2.5	0.72
2006	195	2,442	855	4	0	3.0	0.84
2007	181	2,150	532	1	0	2.2	0.77
2008	208	2,069	556	3	0	2.0	0.71
2009	158	2,196	418	0	0	1.9	0.68
2010	145	2,285	384	1	0	1.8	0.64

Due to the complexity of the Sellafield site and the range of activities carried out which are likely to result in occupational exposure, Sellafield Ltd uses the CIDI category of 'other nuclear industrial work' for contracting companies and itinerant workers who perform work that could not fit within the specific categories used in CIDI (Wilson, 2011). Table 9 summarises the dose to workers recorded within this category. In 2010 the individual effective and collective doses to classified workers in this category were approximately 0.7 mSv and 4 man Sv, respectively. Although the average dose to these workers did not change significantly between 2005 and 2010, their collective dose declined by approximately 40%, primarily due to a decrease in the number of workers.

Table 9: Occupational exposure of classified workers not included in other categories

Year	Number of workers in dose range (mSv)							Collective dose (man Sv)	Average dose (mSv)
	0	0–1	1–6	6–10	10–15	15–20	>20		
2004	2,176	6,329	1,111	42	0	0	0	5.3	0.55
2005	1,861	6,052	1,249	98	0	1	0	6.1	0.66
2006	1,595	5,500	1,402	61	1	0	0	6.0	0.70
2007	1,491	3,209	1,116	66	0	1	0	4.7	0.79
2008	1,531	3,297	1,054	16	1	0	0	4.0	0.67
2009	1,484	3,263	1,069	20	0	0	0	4.2	0.72
2010	1,397	3,148	950	23	0	0	0	3.9	0.70

In the UK, the Nuclear Decommissioning Authority (NDA) oversees the decommissioning of a range of nuclear facilities located at a number of sites. Between 2003 and 2010 four nuclear power stations on sites owned by the NDA entered the decommissioning phase of their life cycle, bringing the total number of sites where decommissioning activities were underway to thirteen.

A summary of the doses received by classified workers involved in the decommissioning of nuclear facilities is given in Table 10. In 2010 the average annual effective and collective doses to classified workers involved in decommissioning were approximately 0.6 mSv and

2 man Sv, respectively. A peak in the dose received by these workers occurred in 2006; between 2006 and 2010 the annual effective and collective doses to these workers decreased by approximately 30% and 50%, respectively.

Within the period covered by this review there were approximately 14,000 unclassified nuclear industry workers in the UK (NDA, 2006; British Energy, 2007; Wilson, 2011; Gilvin, 2012). The average annual effective and collective doses to these workers were estimated to be approximately 0.32 mSv and 4.4 man Sv, respectively.

Table 10: Occupational exposure of classified workers involved in the decommissioning of nuclear facilities

	Number of workers in dose range (mSv)								
Year	0	0–1	1–6	6–10	10–15	15–20	>20	Collective dose (man Sv)	Average dose (mSv)
2004	1,190	2,296	669	43	1	0	0	3.0	0.72
2005	1,329	2,434	765	63	1	0	0	3.5	0.76
2006	1,513	2,306	942	53	59	0	0	4.4	0.90
2007	1,793	1,942	806	13	0	0	0	2.9	0.64
2008	1,514	1,845	810	120	0	0	1	3.4	0.80
2009	1,366	1,562	681	64	0	0	0	2.7	0.74
2010	1,292	1,371	640	24	0	0	0	2.1	0.64

4.2 Occupational exposure to materials with enhanced levels of natural radioactivity

Offshore production of oil and gas is accompanied by mobilisation of radionuclides of natural origin such as ^{226}Ra, ^{228}Ra and ^{210}Pb. Exposure of workers operating drilling platforms occurs from radium isotopes precipitated in production vessels, pipes and other equipment. Table 11 shows a summary of the dose to classified workers in the offshore oil and gas industry taken from the CIDI database. In 2010 the average annual effective and collective doses to classified oil and gas workers were approximately 0.2 mSv and 0.1 man Sv, respectively.

Table 11: Occupational exposure of classified workers in the offshore oil and gas industry

	Number of workers in dose range (mSv)					
Year	<1	1–6	6–20	>20	Collective dose (man Sv)	Average dose (mSv)
2004	596	24	0	0	0.11	0.18
2005	624	80	0	4	0.42	0.59
2006	698	26	0	0	0.15	0.20
2007	579	27	0	0	0.16	0.27
2008	627	23	1	0	0.13	0.20
2009	607	23	0	0	0.12	0.18
2010	587	33	1	0	0.14	0.22

Maintenance of equipment at facilities which burn coal – for example, air filters at coal-fired power stations or at blast furnaces – can result in workers being exposed to radionuclides in ash. The maximum annual doses to workers at a coal-fired power station and a steel production plant were estimated to be approximately 0.01 mSv and 0.09 mSv, respectively (Smith et al, 2001; Crockett et al, 2003). Although no estimate of the collective dose to workers at these facilities was made, as the number of workers who were exposed to ash is unknown, it is likely to be lower than the collective dose to workers in the nuclear power production industry.

Heavy mineral sands are a class of ore deposit which are an important source of various elements such as zirconium, titanium, thorium and tungsten. Although there are no natural deposits of mineral sands in the UK, several industries process imported ores. The imported ores contain radionuclides of the uranium and thorium radioactive decay series, usually in relatively high activity concentrations. Workers exposed to this material during processing have been estimated to receive a maximum annual dose of around 2 mSv (Oatway et al, 2004). However, this estimate was based on cautious assumptions and the majority of workers in this industry were estimated to receive annual doses below 1 mSv (Shaw, 2011). Although no estimate of the collective dose to workers at these facilities was made, as the number of workers who were exposed to these minerals is unknown, it is likely to be lower than the collective dose to workers in the nuclear power production industry.

4.3 Occupational exposure from the medical use of radiation

Medical staff in diagnostic radiology, radiotherapy, nuclear medicine and dentistry may receive a dose from working with sources of radiation. With the development of better techniques, exposure of medical staff has decreased with time. As a result of the low doses received by most medical staff, very few were classified in 2010 although many wore personal dosemeters to provide reassurance that doses remained low and as a means to monitor work procedures. As few medical staff were classified, CIDI was of limited use for this review and the majority of information on radiation exposure of medical staff was obtained by surveying the ADSs directly. The information collected from that survey is summarised in Table 12.

Most of the data collected in the survey was for exposures occurring in 2010, although some was for exposures occurring in 2009 (Mandeep, 2011; Moore, 2011; Temperton, 2011; Cords, 2012; Gilvin, 2012). Data was supplied for a mix of classified and unclassified workers. The information collected in the survey was assumed to be a reasonable representation of the typical range of doses received by all medical staff because responses were received from the majority of ADSs. A comparison of the average doses to workers in different medical disciplines is presented in Figure 3.

Almost every dental clinic in the UK routinely performs diagnostic X-ray imaging. Occupational exposure in dentistry was largely due to scattered radiation from the patient during these examinations. Since the previous review (Watson et al, 2005a), the average annual dose to dental workers fell from about 0.08 mSv to 0.007 mSv. The main reasons for this significant decrease are likely to be improvements to the equipment, such as better collimation, and changes in work practices. Due to the low dose received by most dental workers only three were classified as radiation workers in 2010.

Table 12: Reported occupational whole body exposures of UK medical workers in 2009/10

Work area	Number of workers in dose range (mSv)				Collective dose (man Sv)	Average dose (mSv)
	<0.1	0.1–1	1–6	>6		
Diagnostic radiology (DR)						
Radiologists	695	140	28	0	0.096	0.11
Cardiologists	392	127	9	0	0.063	0.12
Other clinicians	595	94	12	0	0.051	0.073
Radiographers	3,794	614	56	0	0.25	0.056
Nurses	1,827	281	27	1	0.14	0.064
Scientists and technicians	115	40	5	0	0.013	0.084
Other DR staff*	1,529	199	24	0	0.090	0.051
Total diagnostic radiology†	**8,947**	**1,495**	**161**	**1**	**0.70**	**0.066**
Dental practice	**1,721**	**86**	**1**	**0**	**0.012**	**0.0068**
Radiotherapy (RT)						
Beam radiographers	473	39	3	0	0.022	0.043
Radiotherapists	138	22	6	0	0.018	0.11
Nurses	199	14	7	0	0.019	0.088
Scientists and technicians	99	12	0	0	0.002	0.022
Other RT staff*	67	15	1	0	0.008	0.099
Total radiotherapy	**976**	**102**	**17**	**0**	**0.070**	**0.064**
Nuclear medicine (NM)						
Pharmacists	61	9	4	0	0.015	0.20
Radiographers and NM technicians	24	53	55	0	0.14	1.0
Scientists	31	20	3	0	0.011	0.21
Clinicians	13	4	0	0	0.005	0.27
Nurses	29	22	8	0	0.024	0.40
Other NM staff*	22	3	0	0	0.001	0.057
Total nuclear medicine	**180**	**111**	**70**	**0**	**0.19**	**0.53**
Unspecified workers	**19,142**	**4,041**	**665**	**108**	**3.9**	**0.17**
Total†	**29,245**	**5,749**	**913**	**109**	**4.9**	**0.14**

* Includes unspecified worker groups and non-medical workers within the indicated work area.
† Does not include data for dental practices which are discussed separately.

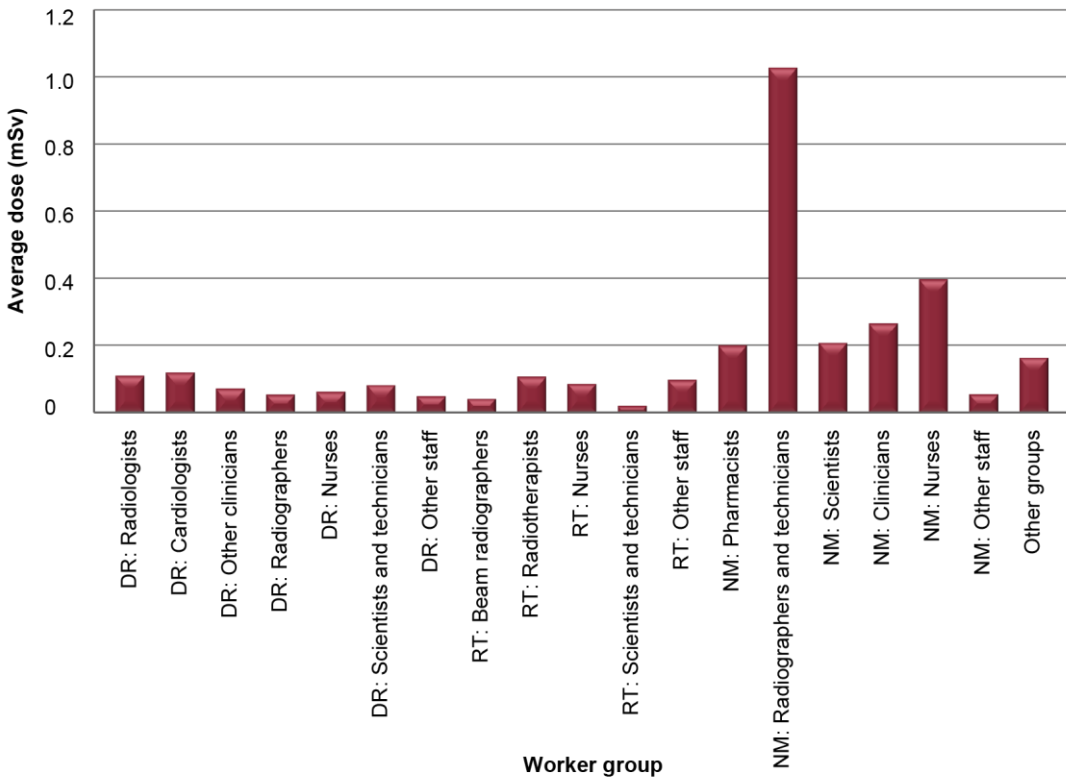

Figure 3: Reported average whole body occupational doses in medicine in the UK, 2009/10 (DR = diagnostic radiology, RT = radiotherapy, NM = nuclear medicine)

The General Dental Council (GDC) reported that there were around 38,000 dentists registered in the UK in 2010 (GDC, 2010). The result of the survey, shown in Table 12, therefore represents information on approximately 5% of the total workforce. The collective dose to UK dental workers, assuming they all performed diagnostic imaging, was estimated to be approximately 0.3 man Sv, further assuming an average annual dose of about 0.007 mSv (see Table 12). This collective dose is significantly lower than the dose reported in the previous review (Watson et al, 2005a) due to the lower annual dose assumed in this current review. Since the previous review, the average annual dose to workers in diagnostic radiology decreased slightly from 0.08 mSv to 0.07 mSv. Within diagnostic radiology, medical staff involved in interventional procedures guided by fluoroscopy – for example, cardiologists and interventional radiologists who work close to the X-ray field – were found to receive some of the highest individual doses. The only group of workers in diagnostic radiology who experienced an increase in their average annual dose between 2003 and 2010 were scientists and technicians whose average annual dose increased from 0.03 mSv to 0.08 mSv. Despite higher patient doses, CT imaging usually results in a relatively low occupational dose due to the collimation of the X-ray beam reducing levels of scattered radiation.

Occupational exposure within radiotherapy occurs in external beam therapy, brachytherapy and treatment planning/simulation using an X-ray machine. Since the previous review (Watson et al, 2005a) the average annual dose to workers involved in radiotherapy decreased slightly from 0.07 mSv to 0.06 mSv. Radiotherapists who are exposed during brachytherapy treatment, particularly when manually loading radioactive sources, received the highest average annual dose among all workers in radiotherapy.

Radionuclides administered to nuclear medicine patients are chosen for their gamma emitting properties. Consequently, external exposure of staff occurs when they work close to patients – for example, when positioning patients for imaging after the administration of the radionuclide, or while handling radionuclide generators and radioactive sources when preparing and giving injections to patients. Within nuclear medicine, the highest average annual dose was received by radiographers and technicians, followed by nurses. This was likely to be due to the time such staff spend close to patients during and after the administration of radioactive material. Although the average individual dose to radiographers and technicians increased since the last review (Watson et al, 2005a), from about 0.7 mSv to about 1 mSv, the average dose to nurses decreased from about 0.7 mSv to about 0.4 mSv. Since the previous review the average annual dose to workers in nuclear medicine has increased slightly from about 0.4 mSv to about 0.5 mSv.

The survey also collected information on staff who did not work exclusively in one particular area or whose area of work was unspecified. Information on such workers is included in Table 12 under ‘unspecified workers’. Of these workers, around 80% received an annual dose of less than 0.1 mSv, while around 0.5% received an annual dose above 6 mSv. The average individual annual dose to these workers in 2010 was about the same as that reported in the previous review (Watson et al, 2005a) for exposures occurring in 2003.

The survey of ADSs collected data on about 36,000 medical workers. However, using data collected by UNSCEAR (2010b) on the number of NHS staff in the UK, and after accounting for staff in independent hospitals, it was estimated that there were around 43,500 non-dental medical staff exposed to radiation in the UK. Table 12 therefore contains information on approximately 83% of the total exposed workforce. The collective dose to all non-dental medical workers in the UK was estimated to be approximately 6 man Sv, assuming an average annual dose of 0.14 mSv (see Table 12). This collective dose is similar to that estimated in the previous review (Watson et al, 2005a).

4.3.1 Occupational exposure in veterinary medicine

The use of radiation in veterinary practice has become commonplace. Diagnostic radiology is probably the most used specialism, but nuclear medicine and radiotherapy procedures are also known to be performed. The Royal College of Veterinary Surgeons (RCVS, 2010) estimated that there were around 15,000 veterinary surgeons in general practice in the UK. In addition, there were also around 7,000 veterinary nurses registered with the RCVS. Not all veterinary surgeons and nurses were occupationally exposed; for example, a survey carried out in 2010 for the RCVS indicated that only about 20% of veterinary surgeons and 55% of veterinary nurses performed diagnostic imaging (Robertson-Smith et al, 2010). Based on these figures it was estimated that approximately 7,000 veterinary workers were occupationally exposed to radiation.

Table 13 summarises the information held in CIDI on classified veterinary workers. The average annual dose to classified veterinary workers in 2010, about 0.5 mSv, is slightly less than that reported in the previous review for exposures occurring during 2003 (Watson et al, 2005a).

The 60 classified veterinary workers in 2010, shown in Table 13, represent less than 1% of the estimated number of occupationally exposed veterinary workers practising in the UK. Table 14 summarises information obtained from ADSs for exposure to both classified and unclassified veterinary workers (Mandeep, 2011; Moore, 2011; Temperton, 2011; Cords, 2012; Gilvin, 2012). Assuming that all classified and unclassified veterinary workers received an average dose equal to that given in Table 13 and Table 14, respectively, the annual collective and average doses to all UK veterinary workers in 2010 were estimated to be approximately 0.2 man Sv and 0.03 mSv, respectively. Both the collective and average individual doses to veterinary workers in 2010 were around an order of magnitude lower than those estimated in the previous review for exposures occurring in 2003 (Watson et al, 2005a).

Table 13: Occupational exposure of classified veterinary workers

	Number of workers in dose range (mSv)							Collective dose (man Sv)	Average dose (mSv)
Year	0	0–1	1–6	6–10	10–15	15–20	>20		
2004	52	62	4	0	0	0	0	0.034	0.29
2005	43	53	6	1	0	0	0	0.040	0.39
2006	23	53	2	1	0	0	0	0.024	0.30
2007	32	27	5	1	0	0	0	0.031	0.48
2008	28	28	12	0	0	1	0	0.057	0.83
2009	29	27	9	1	0	0	0	0.040	0.61
2010	32	17	11	0	0	0	0	0.031	0.52

Table 14: Reported occupational whole body exposures in UK veterinary medicine, 2009/10

Number of workers in dose range (mSv)				Collective dose (man Sv)	Average dose (mSv)
<0.1	0.1–1	1–6	>6		
996	82	5	0	0.025	0.023

4.4 Occupational exposure in the defence industry

The majority of occupationally exposed Army, Royal Navy and Royal Air Force personnel, as well as civilian contractors and staff seconded from non-Ministry-of-Defence establishments, were monitored by the Defence Science and Technology Laboratory (DSTL). A summary of the doses to staff monitored by DSTL is given in Table 15 (Perkins, 2011). The number of monitored personnel at sites covered by DSTL was lower than reported in the previous review (Watson et al, 2005a). This was partly due to a change in reporting procedure used by DSTL within the period covered by this current review, and partly due to a decrease in the number of workers. In 2010 the average annual effective and collective doses to all staff monitored by DSTL were about 0.3 mSv and 2 man Sv, respectively. The average annual individual dose was the same as that reported in the previous review, although the collective dose was around 70% of that reported in the previous review due to fewer workers being monitored.

Table 15: Occupational exposure at MoD sites

	Number of workers in dose range (mSv)					
Year	**<0.1**	**0.1–1**	**1–6**	**>6**	**Collective dose (man Sv)**	**Average dose (mSv)**
2004	3,124	4,082	412	0	2.2	0.29
2005	3,432	3,639	288	1	1.9	0.25
2006	3,065	3,709	312	0	1.9	0.26
2007	2,723	3,476	439	1	2.1	0.32
2008	2,998	3,309	236	1	1.7	0.25
2009	2,819	3,441	223	0	1.7	0.26
2010	2,764	3,479	224	0	1.6	0.25

A separate dosimetry service monitors personnel at Atomic Weapons Establishment (AWE) sites. A summary of occupational exposure at AWE sites is shown in Table 16 (Lawson, 2011). Since 2007, the average annual dose received by staff at AWE sites decreased by around a factor of two; it was not possible to determine the cause of this decrease. The annual collective dose to staff at AWE sites was approximately 0.2 man Sv, similar to that reported in the previous review (Watson et al, 2005a).

The Royal Navy operates a fleet of nuclear powered submarines whose pressurised water reactors are designed, supplied and supported by Rolls-Royce. These submarines carry the UK's nuclear arsenal whose warheads are designed, manufactured and supported by the AWE. Workers involved in operating or maintaining these systems could be occupationally exposed to radiation. Table 17 summarises the occupational exposure of employees and contractors at Rolls-Royce between 2004 and 2010 (Hales, 2011). Although exposure to both employees and contractors are shown in Table 17, contractors made up no more than 3% of the total workforce. The average annual effective and collective doses to Rolls-Royce workers in 2010 were around 0.003 mSv and 0.001 man Sv, respectively. The dose to workers at Rolls-Royce in 2010 was significantly lower than that reported in the previous review for exposures occurring in 2003 (Watson et al, 2005a).

Table 16: Occupational exposure at AWE sites

	Number of workers in dose range (mSv)					
Year	**<0.1**	**0.1–1**	**1–6**	**>6**	**Collective dose (man Sv)**	**Average dose (mSv)**
2004	2,141	749	25	0	0.26	0.089
2005	2,257	753	54	0	0.31	0.10
2006	2,521	724	67	0	0.35	0.11
2007	2,814	557	87	0	0.37	0.11
2008	3,205	354	53	0	0.22	0.060
2009	3,418	268	31	0	0.15	0.041
2010	3,430	295	32	0	0.15	0.040

Table 17: Occupational exposure at Rolls-Royce

Year	Number of workers in dose range (mSv)				Collective dose (man Sv)	Average dose (mSv)
	<0.1	0.1–1	1–6	>6		
2004	284	166	21	0	0.063	0.13
2005	284	138	22	0	0.062	0.14
2006	336	104	15	0	0.047	0.10
2007	370	45	13	0	0.036	0.083
2008	386	40	4	0	0.018	0.042
2009	385	34	2	0	0.010	0.023
2010	396	3	0	0	0.001	0.0025

4.5 Occupational exposure in radionuclide production industry

In the UK radionuclide production mainly occurs at two sites, both operated by GE Healthcare. These sites are at Amersham, which manufactures radiopharmaceuticals for diagnostic imagining, and Cardiff, which manufactures radiolabelled compounds. At Amersham, decommissioning of legacy facilities is underway, although production of radiopharmaceuticals continues. Production of radiolabelled compounds at the GE Healthcare site in Cardiff ceased in 2010, with the facilities now undergoing a decommissioning programme which will allow the bulk of the site to be de-licensed. Since 2010, Quotient Bioresearch has operated a radiolabelling division at a different site in Cardiff.

Table 18 presents doses to permanent staff at GE Healthcare (Tattam, 2012). In 2010, the average annual effective and collective doses to permanent staff at GE Healthcare were approximately 0.3 mSv and 0.2 man Sv, respectively. Between 2006 and 2010 the annual individual and collective doses to staff at GE Healthcare decreased by approximately 65%; this was a result of changes in monitoring practices rather than an actual reduction in the dose received (Tattam, 2012).

Table 18: Occupational exposure of permanent staff during radionuclide production

Year	Number of workers in dose range (mSv)				Collective dose (man Sv)	Average dose (mSv)
	0–5	5–10	10–15	15–20		
2004	909	19	0	0	0.59	0.64
2005	925	16	0	0	0.67	0.71
2006	924	16	0	0	0.72	0.77
2007	920	20	0	0	0.38	0.40
2008	796	20	0	0	0.33	0.40
2009	928	16	0	0	0.29	0.31
2010	856	11	0	0	0.23	0.27

In addition to permanent staff, GE Healthcare also employed contract workers. These contract workers receive lower doses than permanent staff, with their average annual dose being less than 0.2 mSv (Tattam, 2012). No estimate of the collective dose to contract staff was made as the number of such staff was not provided by GE Healthcare.

4.6 Occupational exposure in general industry

Ionising radiation has many applications in industry including the non-destructive testing of metals and concrete and the measurement of the properties of materials such as paper during manufacture. Doses to workers in general industry are generally low and many workers are not classified, although they may wear dosemeters for reassurance purposes or to monitor work practices.

Information on the dose received by classified industrial workers was obtained from CIDI, a summary of which is presented in Table 19. The number of classified workers in general industry fell by approximately 30% between 2003 (Watson et al, 2005a) and 2010. The annual collective dose to all classified workers in general industry in 2010 was approximately 1 man Sv, less than half that reported in the previous review (Watson et al, 2005a). The decrease in the collective dose was due to both the reduced number of classified workers and their lower average annual dose in 2010 compared with 2003. The relatively large number of workers involved in industrial radiography meant that this group continued to contribute most to the collective dose to all classified workers in general industry.

Table 19: Occupational exposure of classified workers in general industry in 2010

	Number of workers in dose range (mSv)							Collective dose (man Sv)	Average dose (mSv)
Type of work	0	0–1	1–6	6–10	10–15	15–30	>30		
Industrial radiography	1,579	627	156	8	1	0	0	0.68	0.29
Use and servicing of ionising radiation machinery	356	49	24	2	0	0	0	0.09	0.21
Application and manipulation of radioactive substances	306	149	25	5	0	0	0	0.15	0.31
Industrial research	235	93	6	0	0	0	0	0.03	0.090
Other industrial applications	421	144	32	0	0	0	1	0.16	0.27
Total	2,897	1,062	243	15	1	0	1	1.1	0.27

Table 20 summarises the doses to unclassified workers in general industry collected from an ADS (Gilvin, 2012). The number of workers in Table 20 represents about 40% of all UK unclassified workers in general industry (Gilvin, 2012). Assuming that the unaccounted for unclassified workers received the same average annual dose as the workers in Table 20, the collective dose received by all unclassified workers in general industry in 2010 was estimated to be approximately 0.5 man Sv.

Table 20: Occupational exposure of unclassified workers in general industry

Year	Number of workers in dose range (mSv)								Collective dose (man Sv)	Average dose (mSv)
	0	0–1	1–6	6–10	10–15	15–20	20–30	>30		
2004	538	281	59	13	7	3	3	4	1.02	1.1
2005	604	286	56	6	2	1	1	5	0.75	0.78
2006	546	312	94	6	4	7	1	4	1.50	1.5
2007	837	101	42	3	1	0	1	0	0.22	0.22
2008	904	73	18	0	4	0	0	1	0.19	0.19
2009	872	71	22	12	1	1	0	0	0.20	0.20

4.7 Occupational exposure in research and tertiary education

A number of university laboratories and research establishments use radioactive materials or X-ray sources in research work. It was estimated that there are around 10,000 workers in research and education in the UK who were exposed to radiation as part of their job. Although many workers may be issued with dosemeters, most will only wear them for intermittent periods – for example, when carrying out particular experiments. As the dose to such workers is generally low, only a small proportion were classified; in 2010 there were 468 classified workers in education and research who received an average annual dose of 0.2 mSv (CIDI, 2010).

For this review a survey was conducted by the Association of University Radiation Protection Officers (AURPO) of universities and research establishments. The survey supplied information on doses to workers for 31 establishments across the UK between 2004 and 2010 (Moseley, 2012). For exposures occurring in 2010 only, data covering an additional 10 establishments was supplied by a UK ADS (Cords, 2012). A summary of the information received from the survey is given in Table 21. The workers monitored by the ADS had a significantly higher average annual dose compared to those included in the AURPO survey.

Table 21: Occupational exposure in academic research and tertiary education

Year	Number of workers	Collective dose (man Sv)	Average annual dose (mSv)
2004*	4,198	0.065	0.015
2005*	3,940	0.063	0.016
2006*	4,034	0.078	0.019
2007*	3,771	0.041	0.011
2008*	3,611	0.040	0.011
2009*	3,476	0.050	0.014
2010†	4,307	0.23	0.053

* Data from Moseley (2012).

† Combined total from Moseley (2012) and Cords (2012).

Table 21 presents information on around 40% of the estimated number of workers who are thought to be exposed to radiation in research and tertiary education. Assuming all workers in research and education received an average annual dose of around 0.05 mSv, it was estimated that their annual collective dose was about 0.5 man Sv.

4.8 Occupational exposure during the transport of radioactive materials

A survey carried out by the HPA (Hughes and Harvey, 2009) estimated that the most exposed dock worker or ship crew member received an annual dose of around 0.2 mSv from radioactive materials transported by sea. The annual collective dose to these workers from exposure to radioactive materials being transported by sea was estimated to be approximately 0.002 man Sv (Hughes and Harvey, 2009).

A survey carried out by PHE (Harvey et al, 2014) estimated that the annual collective dose to workers exposed to radioactive material transported by air was about 0.15 man Sv. Harvey et al reported that the most exposed individuals were cargo handlers who could receive an annual dose of up to around 7 mSv, while the annual dose to individual aircrew was estimated to be a maximum of around 0.07 mSv.

A survey by the HPA (Watson et al, 2005b) estimated that the annual collective dose to workers exposed to radioactive material transported by road and rail was about 0.2 man Sv. This collective dose was dominated by exposure to workers involved in the transport of medical and industrial sources, whose average annual dose was estimated to be about 0.6 mSv.

5 Exposure of the UK Population from Items containing Radioactivity

5.1 Exposure from the use of radioactivity in consumer products

Many assessments have estimated the dose from the normal use of many different consumer products which contain radioactivity, including: antique glass and ceramics containing natural uranium (Watson and Hughes, 2010); irradiated gemstones (EC, 2007); electronic components (MoD, 2009); thoriated products (Taylor et al, 1983; NRPB, 1992; Gäfvert et al, 2003); and the keeping and examination of geological specimens (Dixon, 1983). Although the individual dose from using some of these items could exceed 0.1 mSv, the number of individuals regularly using such items, while not known precisely, is small and therefore the contribution to the collective dose of the UK population from using such items is not significant.

Some consumer products containing radioactivity are widely used in the UK and the dose that individuals may receive when using such items is given below. As the number of people in the UK exposed to these items is not known, the collective dose to the UK population from their use could not be estimated although it is expected not to be significant.

a Ionisation chamber smoke detectors (ICSDs) usually contain a small foil of ^{241}Am. The NRPB (1992) estimated that the maximum annual dose to residents of a house fitted with an ICSD was about 7 10^{-5} mSv

b Radionuclides, including ^{226}Ra, ^{3}H and promethium-147 (^{147}Pm), are used to produce luminescence on watches, dials and other items. The NRPB (1992) estimated that the maximum annual dose to someone wearing a timepiece containing radioactivity would be no more than a few tens of microsieverts

c Some lamps contain low levels of ^{3}H, krypton-85 (^{85}Kr) and isotopes of thorium (^{232}Th and ^{228}Th) which aid starting the lamp or are used as a component of the electrode. The maximum annual dose from the transport and disposal of fluorescent lamp starters was estimated to be less than 0.01 mSv (Harvey et al, 2010b; Jones et al, 2011); exposure during the normal use of such lamps was thought to result in lower doses

5.2 Exposure from transport of radioactive materials

Wherever possible, radioactive material transported by air travels on dedicated cargo flights to minimise exposure to passengers and aircrew. Harvey et al (2014) estimated that the maximum annual dose to a frequent flyer and the collective dose to all passengers from exposure to radioactive material transported by air were about 0.073 mSv and 5 man Sv, respectively.

Cargo vessels are used to transport the majority of radioactive packages moved by sea. Hughes and Harvey (2009) estimated that the annual dose to passengers from exposure to radioactive material transported by sea was less than 0.001 mSv. Although the annual collective dose to passengers on ships exposed to transported radioactive material was not estimated by Hughes and Harvey, it was thought to be less than that to passengers travelling by air.

Watson et al (2005b) estimated that the maximum dose to a member of the public from exposure to radioactive material transported by either road or rail was less than 0.02 mSv. The annual collective dose to the UK population from exposure to such material was about 0.02 man Sv.

6 Overall Radiation Exposure of the UK Population

This section summarises the estimated dose received by the UK population in 2010 from exposure to environmental sources of radiation, patient exposure from the medical use of radiation, and occupational exposure to radiation. Other sources of exposure – for example, to items containing radioactivity – were estimated to contribute an additional 5 man Sv to the total.

6.1 Exposure of the UK population to ubiquitous radiation in the environment

Table 22 and Figure 4 present a summary of the annual collective and per caput doses to the UK population in 2010 from exposure to all significant sources of ubiquitous radiation in the environment. The estimated collective and per caput doses to the UK population in 2010, from exposure to ubiquitous radiation in the environment, were approximately 140,000 man Sv and 2.3 mSv, respectively.

Table 22: Summary of the estimated collective and per caput doses to the UK population in 2010 from exposure to ubiquitous radiation in the environment

Source of exposure	Collective dose (man Sv)	Per caput dose (mSv)
Natural radiation		
Radon and thoron*	82,000	1.3
Intake of natural radionuclides (excluding radon)	17,000	0.27
Terrestrial gamma radiation	22,000	0.35
Cosmic radiation†	20,000	0.33
Total	**140,000**	**2.3**
Anthropogenic radiation		
Radionuclides discharged during normal operation	50	0.0008
Radiation from weapons testing	310	0.005
Total	**320**	**0.005**
Total dose due to radiation in the environment	**140,000**	**2.3**

* Includes occupational exposure to radon.

† Includes occupational exposure to cosmic radiation for aircrew.

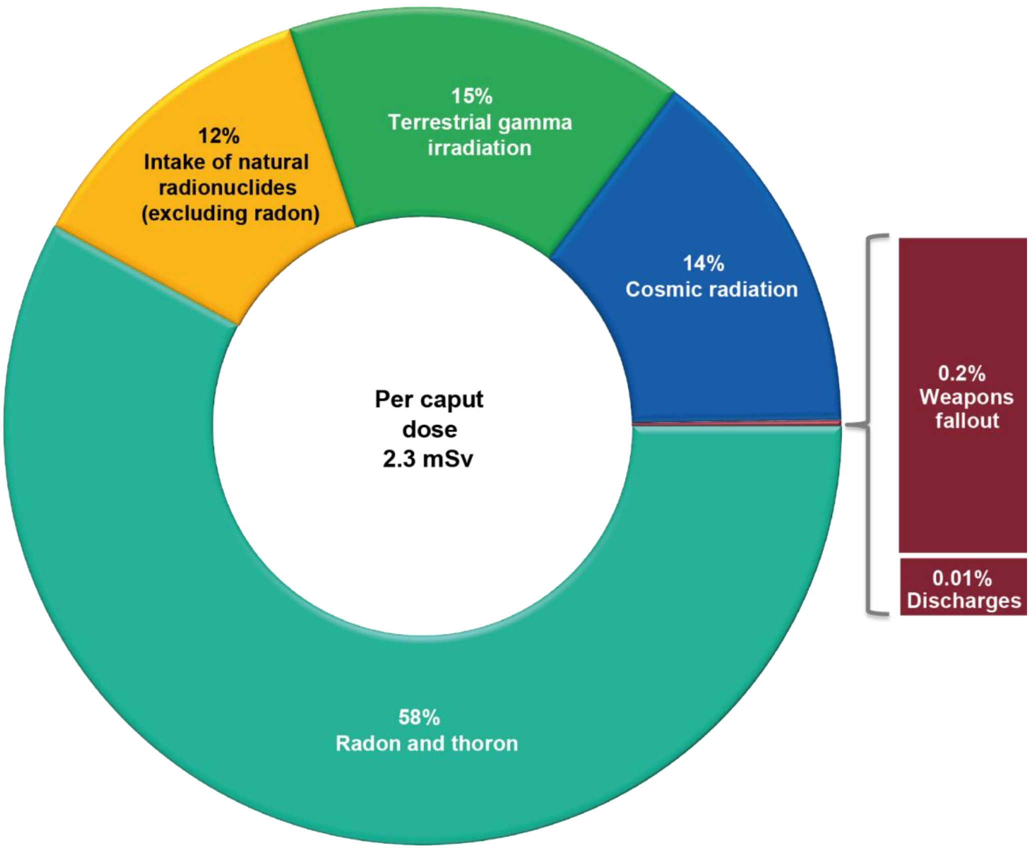

Figure 4: Breakdown of per caput dose to the UK population in 2010 from ubiquitous radiation in the environment by source of exposure

The estimated per caput dose to the UK population in 2010 was slightly higher than that in 2003 (Watson et al, 2005a). The estimated collective dose to the UK population was about 7% higher in 2010 than in 2003. The majority of this increase was due to a 6% increase in the UK population between 2003 and 2010. The remainder was mostly due to a reclassification of occupational exposure of aircrew and miners: in this review these exposures were summed with other sources of ubiquitous radiation in the environment; in the previous review they were summed with other occupational exposures. Changes in the dose assessment methodology to estimate exposure to radionuclides discharged during the normal operation of nuclear installations had minimal impact on the estimated dose.

The most significant source of exposure of the UK population from ubiquitous radiation in the environment was radon gas, the per caput dose from inhalation of which was estimated to be about 1.3 mSv. The per caput doses to the UK population from external irradiation by sources of radiation in the ground and from outer space, including during time spent flying, were about 0.4 mSv and 0.3 mSv, respectively. The per caput dose to the UK population from the ingestion of ^{40}K, ^{210}Pb and ^{210}Po in the diet was about 0.3 mSv.

The per caput dose to the UK population from exposure to anthropogenic radionuclides in the environment in 2010 was estimated to be about 0.005 mSv. Fallout from historic testing of nuclear weapons in the atmosphere was the most significant source of anthropogenic radiation in the environment; exposure to radionuclides released by industry contributed only about 5% to the per caput dose from exposure to anthropogenic radiation in the environment.

6.2 Exposure of patients from the medical use of radiation

Table 23 presents a summary of the collective and per caput doses to the UK population in 2010 due to exposure of patients during the medical use of radiation. The information in Table 23 is shown graphically in Figure 5.

Table 23: Summary of the estimated collective and per caput doses to the UK population in 2010 due to exposure of patients during the medical use of radiation

Type of procedure	UK collective dose (man Sv)	Per caput dose (mSv)
Conventional radiology	4,800	0.08
Angiography (non-CT)	1,200	0.02
Interventional (non-CT)	2,000	0.03
CT	17,000	0.27
Total diagnostic radiology	**25,000**	**0.40**
Diagnostic nuclear medicine	1,700	0.03
Therapeutic procedures	740	0.01
Total	**27,000**	**0.44**

The collective and per caput doses to the UK population from the medical use of radiation in 2010 were about 27,000 man Sv and 0.44 mSv, respectively. These doses are slightly higher than those received in 2003 (Watson et al, 2005a). This increase is due to the inclusion in this review of exposure to patients from therapeutic procedures as well as an increase in the number of high dose procedures, such as CT examinations, occurring in 2010 compared with 2003. Despite this increase, the per caput dose to the UK population in 2010 from the medical use of radiation was lower than in countries that have a similar level of health care as the UK (1.9 mSv) and the global average (0.6 mSv) (UNSCEAR, 2010a).

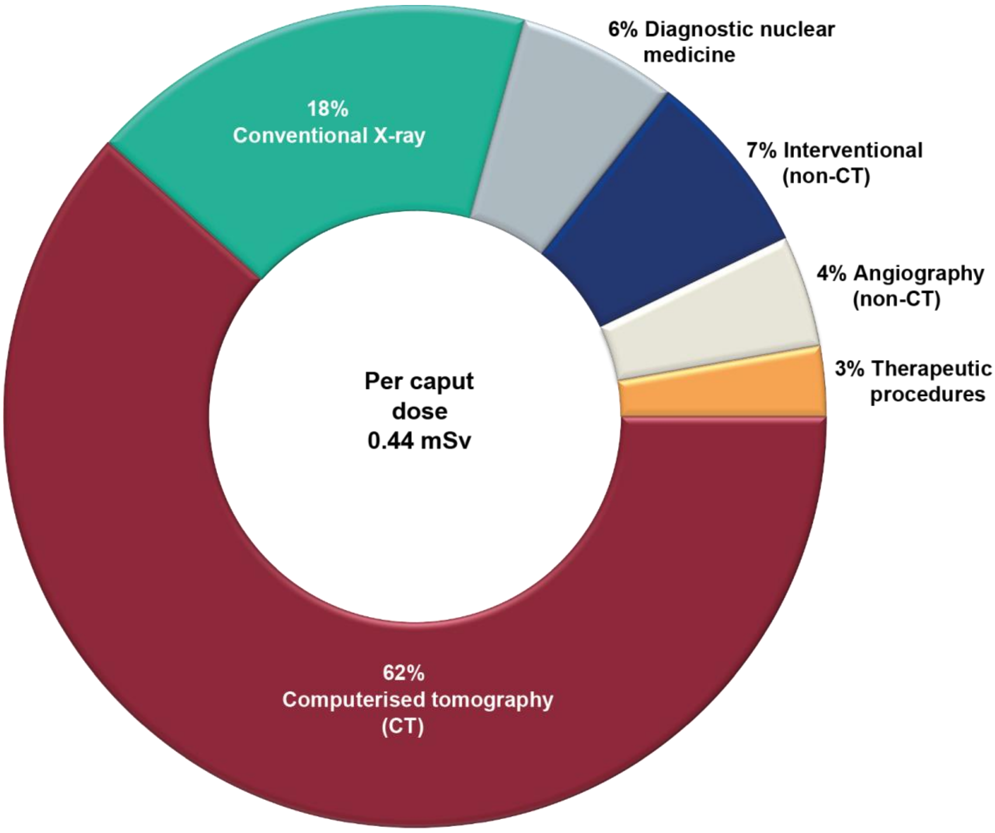

Figure 5: Breakdown by procedure of the per caput dose to the UK population in 2010 from exposure to patients during the medical use of radiation

6.3 Occupational exposure arising from the use of radiation

Table 24 presents a summary of the collective and per caput doses to the UK population in 2010 from occupational exposure to sources of radiation not ubiquitous in the environment. The information in Table 24 is shown graphically in Figure 6.

In 2010, the collective and per caput doses to the UK population from occupational exposure to sources of radiation not ubiquitous in the environment were about 26 man Sv and 0.0004 mSv, respectively. These doses are significantly lower than those estimated for exposures occurring in 2003 (Watson et al, 2005a), but it should be noted that occupational exposure to ubiquitous radiation in the environment, particularly cosmic radiation to aircrew, were included in this category of exposure in the previous review. In addition, most industries have fewer workers exposed to radiation in 2010 compared with 2003.

About 57% of the occupational dose to workers in the UK was from exposure to staff at nuclear licensed sites. Of staff at nuclear licensed sites, unclassified radiation workers received the highest collective dose followed by those classified staff labelled as ‘other classified workers' in CIDI (CIDI, 2010). The higher collective dose was due to the large number of staff exposed and, for the other classified staff category, their average annual dose.

Staff at non-nuclear licensed sites received approximately 43% of the occupational dose to UK workers. The majority of this dose was received by medical staff due to the large number of such workers in the UK.

Table 24: Summary of the estimated collective and per caput doses to the UK population in 2010 from occupational exposure to radioactivity not ubiquitous in the environment*

Type of worker	Collective dose (man Sv)	Per caput dose (mSv)
Staff at nuclear licensed sites		
Classified workers in:		
Fuel enrichment and fabrication	1.4	$2.3\ 10^{-5}$
Power production	1.2	$2.0\ 10^{-5}$
Reprocessing	1.8	$2.9\ 10^{-5}$
Other classified	3.9	$6.2\ 10^{-5}$
Decommissioning	2.1	$3.4\ 10^{-5}$
Unclassified workers	4.4	$7.1\ 10^{-5}$
Total for all nuclear licensed site staff	**15**	**$2.4\ 10^{-4}$**
Staff at non-nuclear licensed sites		
NORM industry staff	0.14	$2.2\ 10^{-6}$
Medical staff	6.3	$1.0\ 10^{-4}$
Veterinary staff	0.20	$3.2\ 10^{-6}$
Defence industry staff	1.8	$2.8\ 10^{-5}$
Radionuclide production industry staff	0.23	$3.7\ 10^{-6}$
General industry staff	1.60	$2.6\ 10^{-5}$
Research and education staff	0.50	$8.0\ 10^{-6}$
Transport staff	0.35	$5.6\ 10^{-6}$
Total for all non-nuclear licensed site staff	**11**	**$1.8\ 10^{-4}$**
Total occupational exposure	**26**	**$4.2\ 10^{-4}$**

* Occupational exposures to cosmic radiation or to radon are not included within this table; such exposures are included in the doses presented in Table 22.

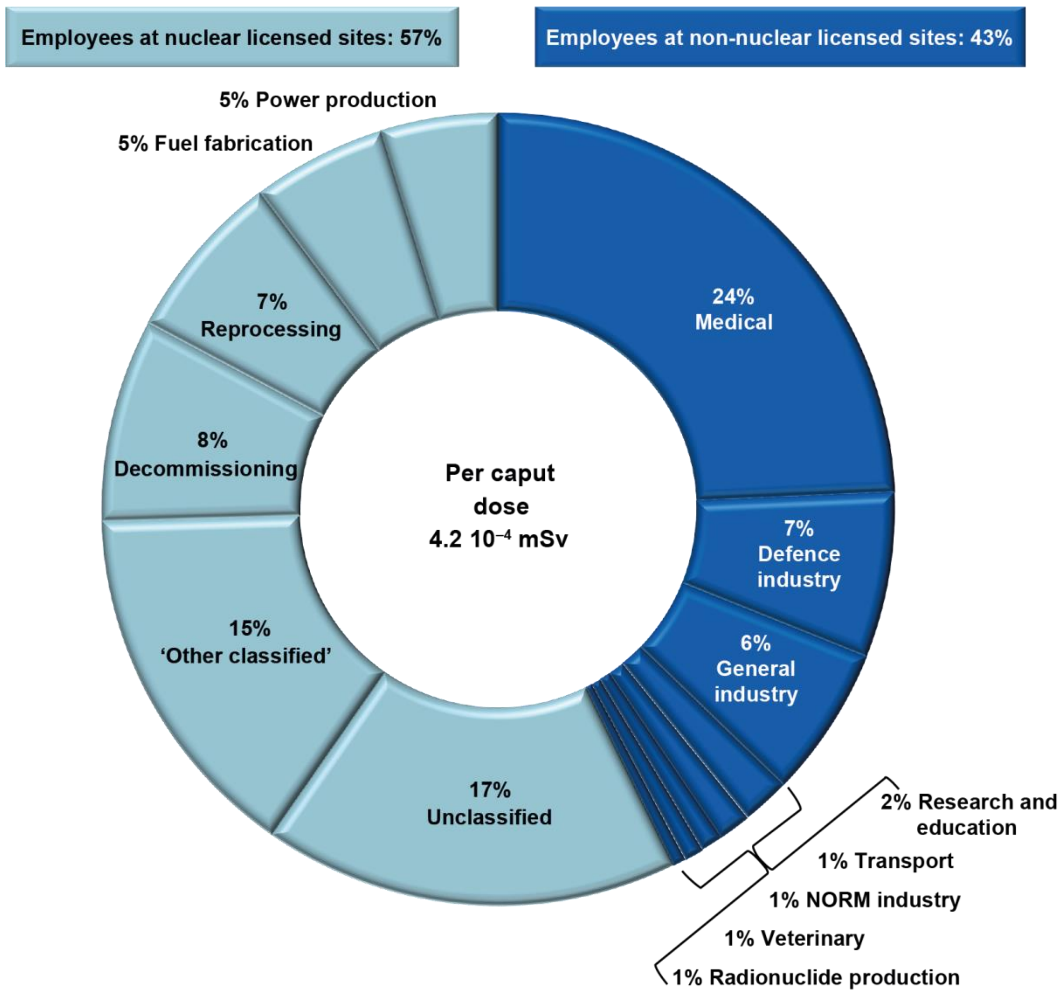

Figure 6: Breakdown by employment of the occupational dose to the UK population in 2010 from exposure to radiation not ubiquitous in the environment

6.4 Exposure of the UK population to all sources of ionising radiation

Table 25 presents the estimated collective and per caput doses to the UK population in 2010 from all significant sources of ionising radiation, with a breakdown of these doses by the main exposure route being shown in Figure 7. The per caput dose to the UK population in 2010, from all significant sources of ionising radiation, was estimated to be about 2.7 mSv, the same as that reported in the previous review for exposures occurring during 2003 (Watson et al, 2005a). In 2010 the collective dose to the UK population was estimated to be around 170,000 man Sv, about 6% higher than that estimated in 2003 (Watson et al, 2005a). The majority of this increase in the collective dose was due to the increase in the size of the UK population between 2003 and 2010.

The per caput dose to the UK population in 2010 from exposure to ubiquitous radiation in the environment was about 2.3 mSv, or about 84% of the per caput dose to the UK population from exposure to all sources of radiation. Inhalation of radon gas continued to contribute about half of the per caput dose to the UK population, while exposure to terrestrial gamma radiation, cosmic radiation, and from the intake of radionuclides in the diet each contributed between

Table 25: Exposure of the UK population in 2010 from all significant sources of ionising radiation

Source of exposure	Collective dose (man Sv)	Per caput dose (mSv)
Ubiquitous radiation in the environment		
Radon and thoron	82,000	1.3
Intake of natural radionuclides (excluding radon)	17,000	0.27
Terrestrial gamma radiation	22,000	0.35
Cosmic radiation	20,000	0.33
Weapons fallout	310	0.005
Other anthropogenic radioactivity in the environment*	50	0.0008
Total dose from ubiquitous radiation in the environment	**140,000**	**2.3**
Exposure from the use of radiation		
Patient exposure from the medical use of radiation	27,000	0.44
Occupational exposure from the use of radiation†	26	0.0004
Total dose from the use of radiation	**27,000**	**0.44**
Total dose from all sources of radiation	**170,000**	**2.7**

* Includes exposure to radionuclides routinely discharged or accidentally released into the environment.

† Includes occupational exposure to radiation which is not ubiquitous in the environment within the nuclear fuel cycle and during nuclear power production, application of radiation within medicine, and use of radiation in general industry and research. The contribution to the collective dose to the UK population from occupational exposure to radon and cosmic radiation are included within the 'Radon and thoron' and 'cosmic radiation' sources, respectively.

about 10% and 13%. Anthropogenic radiation in the environment, from the historic testing of nuclear weapons in the atmosphere as well as from the routine discharge of radioactivity by industry, contributed less than 0.2% to the per caput dose to the UK population in 2010.

The estimated per caput dose to the UK population from exposure to sources of radiation that are not ubiquitous in the environment was about 0.44 mSv, or about 16% of the per caput dose to the UK population in 2010 from exposure to all sources of radiation. The majority of this dose was from exposure of patients during medical procedures which used radiation or radioactivity. Occupational exposure contributed significantly less than 1% to the per caput dose to the UK population in 2010.

The most significant change in any exposure since the previous review (Watson et al, 2005a) was that, between 2003 and 2010, the per caput dose to the UK population from patient exposure during CT examinations increased from about 0.18 mSv to about 0.27 mSv. In 2010, patient exposure during CT examinations accounted for about 10% of the per caput dose to the UK population, or about 62% of the dose from all medical examinations. Despite the growing significance of CT examinations, their contribution to the per caput dose to the UK population in 2010 is still relatively low compared to that in some countries; NCRP (2009) reported that CT examinations in the US contributed about 24% to the per caput dose to the US population, equivalent to about 1.5 mSv.

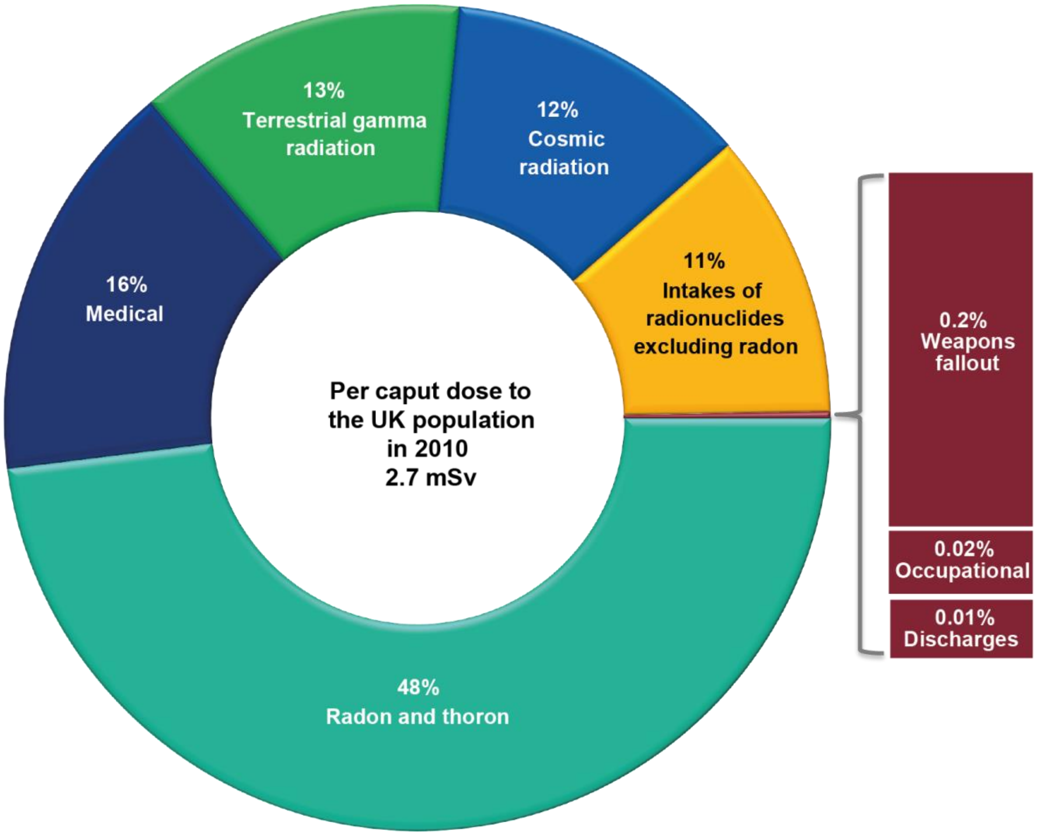

Figure 7: Breakdown of the per caput dose to the UK population in 2010 by source of exposure

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Appendix Methodology for Estimating the Dose due to Ingestion and Inhalation of Naturally Occurring Radionuclides

This appendix describes the methodology used in this review to estimate the annual dose to the UK population from ingesting and inhaling ^{14}C, ^{87}Rb and members of the uranium and thorium radioactive decay chains, excluding radon; the dose from inhaling and ingesting radon and ^{40}K were obtained from the literature as discussed in Section 2.1.

The dose following the ingestion of ^{14}C and radioisotopes in the uranium and thorium radioactive decay chains in the diet, D_{ing} (Sv y^{-1}), was estimated using the equation:

$$D_{\mathrm{ing}} = \sum_{\mathrm{f}} AC_{f,R}\, I_f\, DC_{\mathrm{ing},R}$$

where $AC_{f,R}$ is the activity concentration in food f of radionuclide R (Bq kg^{-1}), I_f is the average annual ingestion rate of food f (kg y^{-1}) (Smith and Jones, 2003), and $DC_{\mathrm{ing},R}$ is the dose coefficient for ingestion of radionuclide R (Sv Bq^{-1}) (ICRP, 2012). Doses were calculated for 1 year old infants, 10 year old children and adults for the ingestion of the following foods: fruit, nuts, potatoes, root and green vegetables, mushrooms, sugar, pork, beef, mutton, poultry, offal, milk, cheese and butter, eggs, fish, crustaceans and cereals. In addition, intake of radionuclides within water was also assessed. The activity concentration of radionuclides in each type of food and in water was assumed to be the same as that used in the previous review (Watson et al, 2005).

The dose to members of the UK population following inhalation of members of the uranium and thorium radioactive decay chains, excluding radon, D_{inh} (Sv y^{-1}), was estimated using the equation:

$$D_{\mathrm{inh}} = \sum_R AC_{\mathrm{air},R}\, B_{\mathrm{A}}\, DC_{\mathrm{inh},R}$$

where $AC_{\mathrm{air},R}$ is the activity concentration of radionuclide R in air (Bq m^{-3}), B_{A} is the average annual inhalation rate (1,900 m^3 y^{-1} for 1 year old infants, 5,600 m^3 y^{-1} for 10 year old children and 8,100 m^3 y^{-1} for adults) (Smith and Jones, 2003), and $DC_{\mathrm{inh},R}$ is the dose coefficient for inhalation of radionuclide R (Sv Bq^{-1}) (ICRP, 2012).

The annual dose from the ingestion of ^{87}Rb, $D_{\mathrm{ing,Rb}}$ (Sv y^{-1}), was estimated using the equation:

$$D_{\mathrm{ing,Rb}} = A_{\mathrm{Rb}}\, DC_{\mathrm{ing,Rb}}$$

where A_{Rb} is the activity of ^{87}Rb ingested annually (Bq y^{-1}) and $DC_{\mathrm{ing,Rb}}$ is the dose coefficient for ingestion of ^{87}Rb (Sv Bq^{-1}) (ICRP, 2012). The activity of ^{87}Rb ingested annually was estimated using the equation:

$$A_{\mathrm{Rb}} = \left(\frac{I_{\mathrm{D}}\, F\, D}{M}\right) N_{\mathrm{A}}\, \lambda$$

where I_{D} is the daily intake of rubidium (0.00435 g d^{-1}) (DCnutrition, 2012), F is the fraction of natural rubidium that is ^{87}Rb (27.8%), D is the number of days in a year (365 d y^{-1}), M is the atomic mass of rubidium (85.4678 g mol^{-1}), N_{A} is Avogadro constant (6.022 10^{23} atoms mol^{-1}), and λ is the radioactive decay constant for ^{87}Rb (4.5 10^{-19} s^{-1}), calculated using the radioactive half-life of ^{87}Rb (1.55 10^{18} s) (ICRP, 2008).

Table A1 presents the estimated dose to members of the UK population from the ingestion and inhalation of ^{14}C, ^{87}Rb and members of the uranium and thorium radioactive decay chains excluding radon. In 2010, approximately 4% of the UK population was under 5 years old, 14% were between the ages of 5 and 15 years, and 82% were older than 16 years (ONS, 2011). To estimate the collective dose to the UK population the dose to each age group, given in Table A1, was scaled by these fractions and then summed together.

Table A1: Estimated average annual dose to members of the UK population from the ingestion and inhalation of naturally occurring radionuclides other than radon

	Infants (mSv y^{-1})			Children (mSv y^{-1})			Adults (mSv y^{-1})		
	Ingestion	Inhalation	Total	Ingestion	Inhalation	Total	Ingestion	Inhalation	Total
^{14}C	8.9 10^{-3}	–	8.9 10^{-3}	1.1 10^{-2}	–	1.1 10^{-2}	8.8 10^{-3}	–	8.8 10^{-3}
^{40}K	1.7 10^{-1}	–	1.7 10^{-1}	1.9 10^{-1}	–	1.9 10^{-1}	1.7 10^{-1}	–	1.7 10^{-1}
^{87}Rb	2.0 10^{-3}	–	2.0 10^{-3}	2.0 10^{-3}	–	2.0 10^{-3}	2.0 10^{-3}	–	2.0 10^{-3}
^{238}U	9.9 10^{-5}	1.8 10^{-5}	1.2 10^{-4}	1.2 10^{-4}	2.2 10^{-5}	1.4 10^{-4}	1.2 10^{-4}	2.4 10^{-5}	1.4 10^{-4}
^{234}U	1.0 10^{-4}	2.1 10^{-5}	1.3 10^{-4}	1.2 10^{-4}	2.7 10^{-5}	1.5 10^{-4}	1.1 10^{-4}	2.8 10^{-5}	1.4 10^{-4}
^{230}Th	1.9 10^{-4}	3.3 10^{-5}	2.3 10^{-4}	3.3 10^{-4}	4.5 10^{-5}	3.7 10^{-4}	3.5 10^{-4}	5.7 10^{-5}	4.1 10^{-4}
^{226}Ra	2.9 10^{-3}	2.1 10^{-5}	2.9 10^{-3}	5.7 10^{-3}	2.7 10^{-5}	5.8 10^{-3}	2.7 10^{-3}	2.8 10^{-5}	2.7 10^{-3}
^{210}Pb	4.6 10^{-2}	1.4 10^{-3}	4.7 10^{-2}	4.4 10^{-2}	1.7 10^{-3}	4.5 10^{-2}	2.2 10^{-2}	1.8 10^{-3}	2.4 10^{-2}
^{210}Po	8.1 10^{-2}	2.5 10^{-4}	8.2 10^{-2}	4.7 10^{-2}	3.1 10^{-4}	4.7 10^{-2}	4.2 10^{-2}	3.2 10^{-4}	4.2 10^{-2}
^{232}Th	1.1 10^{-4}	4.8 10^{-5}	1.5 10^{-4}	1.9 10^{-4}	7.3 10^{-5}	2.6 10^{-4}	1.9 10^{-4}	1.0 10^{-4}	2.9 10^{-4}
^{228}Ra	1.6 10^{-2}	1.9 10^{-5}	1.6 10^{-2}	2.8 10^{-2}	2.6 10^{-5}	2.8 10^{-2}	6.2 10^{-3}	2.1 10^{-5}	6.3 10^{-3}
^{228}Th	1.3 10^{-4}	2.5 10^{-4}	3.8 10^{-4}	1.3 10^{-4}	3.1 10^{-4}	4.4 10^{-4}	1.3 10^{-4}	3.2 10^{-4}	4.5 10^{-4}
^{235}U	5.8 10^{-6}	2.5 10^{-6}	8.3 10^{-6}	7.4 10^{-6}	3.1 10^{-6}	1.1 10^{-5}	6.8 10^{-6}	3.4 10^{-6}	1.0 10^{-5}
Total	**3.2 10^{-1}**	**2.1 10^{-3}**	**3.2 10^{-1}**	**3.2 10^{-1}**	**2.5 10^{-3}**	**3.2 10^{-1}**	**2.5 10^{-1}**	**2.7 10^{-3}**	**2.5 10^{-1}**

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