Ionising Radiation Exposure of the UK Population: 2005 Review

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ABSTRACT

Since 1974, periodic reviews have been published by NRPB (now the Health Protection Agency - Radiation Protection Division) which have provided estimates of the exposure of the UK population from sources of ionising radiation, both natural and artificial. This is the latest review in that series and gives estimates of individual doses based predominantly on data collected for the years 2001 to 2003. The average levels of natural radiation show little or no variation with time, and revised estimates of average annual doses from these sources are due to better or more complete data or changes in occupancy times or other habit data. The average annual dose from natural radiation was found to be 2.23 mSv and about half of this is from radon exposure indoors. Artificial (anthropogenic), sources of radiation are subject to variations and trends that reflect current technology and radiological protection practices. The average annual dose from artificial radiation was found to be a little over 0.42 mSv and mainly derived from the use of X-rays in medical procedures. The overall average annual dose is therefore almost 2.7 mSv. This is a slight increase over that found in the previous review, mainly due to an increased contribution from medical irradiation. The non-medical artificial sources include consumer products, fallout from weapons testing in the past, and discharges of radioactive wastes from industrial and nuclear sites. Exposures to members of the public from these sources remain at a very low level. Individual annual doses to members of the public from practices, other than medical procedures, are generally much less than the annual dose limit of 1 mSv. There has been a long-term trend towards lower occupational doses in the nuclear industry, and worker doses in medicine, general industry and research tend to be low. However, some small groups of workers in general industry occasionally receive annual doses up to around the annual dose limit for workers. In recent years many more homes and places of work have been identified as having high radon levels that require remediation, and radon exposure at work continues to make the largest contribution to all occupational exposure.

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EXECUTIVE SUMMARY

Since 1974 the National Radiological Protection Board (now the Health Protection Agency - Radiation Protection Division) has produced reviews of the levels of exposure to ionising radiation in the UK, from sources of natural and artificial origin. This report describes the latest review in the series, and gives estimates of individual doses based predominantly on data collected for the years 2001 to 2003. The average levels of natural radiation show little or no variation with time, and revised estimates of average annual doses from these sources are due to better or more complete data, or changes in occupancy times or other habit data. The average annual dose from natural radiation is 2.2 mSv. The overall average annual dose was found to be 2.7 mSv, which represents a slight increase on that found in the previous review, carried out in 1999. This increase is due to a larger contribution from medical irradiation. A larger number of procedures and increased use of computed tomography in recent years have increased this contribution by some 10% over that found in the previous review. Natural sources account for about 84% of the overall average annual dose. Estimates of the average annual dose from natural and artificial sources are given in the table below.

Annual exposure of the UK population from all sources of ionising radiation

Source	Annual collective dose, man Sv	Average annual dose, μSv*
Natural:		
Cosmic	19,400	330
Gamma	20,600	350
Internal	14,700	250
Radon	76,400	1,300
Artificial:		
Medical	24,300	410
Occupational	385	6
Fallout	350	6
Disposals	50	0.9
Consumer products	4	0.1
Total (rounded)	157,000	2,700

* 1,000,000 μSv = 1 Sv

The main findings were as follows:

a) radon is found to be the largest contributor to radiation exposure, and comprises about half of the overall average annual dose;

b) radon also gives rise to the largest variation in individual dose, and annual doses in some homes can approach 100 mSv (100,000 μSv);

c) while cosmic radiation at ground level has remained constant, there has been a slight increase in the overall dose to the population from cosmic radiation exposure from air travel, due to the increased number of flights made by UK residents;

d) the average annual dose from natural terrestrial gamma radiation has remained the same as assessed in previous reviews;

e) a reassessment of the intakes of natural radionuclides in foodstuffs has resulted in a slightly lower estimate of the average annual dose from internal radiation;

f) medical irradiation has been found to be the largest artificial source of radiation exposure, and the contribution from this source has increased by about 10% in recent years;

g) the collective dose from occupational exposure in the nuclear industry has decreased significantly;

h) the highest individual annual doses from routine occupational exposure are from radon in workplaces;

i) average annual exposures from consumer products, weapons fallout and discharges of radioactive wastes all remain at very low levels;

j) individual annual doses to the public from non-medical artificial sources are less than the annual dose limit for members of the public.

CONTENTS

1 INTRODUCTION

Since 1974 the National Radiological Protection Board (now HPA-RPD*) has produced reviews of the levels of exposure to ionising radiation in the UK, from sources of natural and artificial origin (Webb, 1974; Taylor and Webb, 1978; Hughes and Roberts, 1984; Hughes, Shaw and O'Riordan, 1989; Hughes and O'Riordan, 1993; Hughes, 1999). As noted in the Government response (GB Parliament, 1977) to the report of the Royal Commission on Environmental Pollution (Royal Commission, 1976), it is the intention of the NRPB / HPA-RPD to report periodically on the radiation exposure of the UK population. These reviews are made available to national and international organisations and are a source of information on dose comparisons and trends. This is the seventh review in this series and covers the period from 1998 to 2003, with the main data reflecting the levels of exposure in the later years of this period. The average levels of natural radiation show little or no variation with time and revised estimates of average annual doses are the result of better or more complete data, or changes in occupancy times or other habit data. Artificial sources are largely controllable and trends are apparent for some of these. These trends are from the introduction of new technology, or developments in radiological protection policy and techniques. This report gives estimates of the average, and range, of doses to the UK population from all sources of ionising radiation. The resident population of the UK in 2001 was 58.8 million (Laverty, 2003).

During the period of this review the radiological protection philosophy and standards were those established by the recommendations of the International Commission on Radiological Protection (ICRP) (ICRP, 1991). These recommendations form the basis of the European Union Basic Safety Standards (BSS) Directive (European Commission, 1996) on the hazards of ionising radiation, and the requirements of that Directive are applied in the UK, for example through the Ionising Radiations Regulations (IRR99) (GB Parliament, 1999a), the Radioactive Substance Act (RSA93) (GB Parliament, 1993) and The Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR) (GB Parliament, 2001a). The dose quantity used throughout this review is effective dose, unless otherwise specified, and is abbreviated to dose unless the full term is required for clarity. Sub-multiples of the unit of dose, the Sievert, are described in the Glossary.

Exposure to radiation has been divided into six categories and these are discussed in turn.

* On April 1st 2005, NRPB merged with the Health Protection Agency to form its Radiation Protection Division (HPA-RPD)

2 NATURAL RADIATION

Natural radiation originates from sources beyond the Earth's atmosphere (cosmic radiation) and from primordial radionuclides within soil and rocks. Sources have been divided into four categories.

2.1 Cosmic radiation

Primary cosmic radiation consists of very energetic charged particles moving through space. They originate mostly from events beyond our solar system, with a lower energy component originating from the sun. Cosmic radiation that interacts with the atmosphere mainly consists of very high-energy protons, with a small component of alpha particles and electrons. When these particles enter the Earth's atmosphere they collide with, and disrupt, atoms in the upper atmosphere, producing secondary radiation. By the time the cosmic radiation reaches the ground its intensity has been considerably reduced, by absorption in the atmosphere. The secondary particles from solar protons are only detectable in high altitude aircraft, but their intensity can increase during periods of increased solar activity. The nuclear reactions initiated by cosmic particles in the atmosphere give rise to a number of radionuclides, such as carbon-14 (^{14}C). The intensity of the cosmic radiation is also affected by the Earth's magnetic field and there is some variation of the dose rate with latitude. The minimum dose rate is found at the equator, and is a few percent lower than at the poles.

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) (UN, 2000) has produced an estimate of the cosmic radiation dose rate. UNSCEAR divides the radiation component into two parts: directly ionising radiation and neutron radiation. The estimates of dose rate from directly ionising radiation is little changed between the UNSCEAR reports published in 1988 (UN, 1988) and 2000 (UN, 2000), being represented by an average of around 280 μSv per year at sea level in latitudes between 50^0 and 60^0 (corresponding to the UK). This dose is mainly from muon radiation. In addition to this exposure, UNSCEAR estimates (UN, 2000) that the dose rate from cosmic neutron radiation at sea level with a latitude corresponding to that of the UK is approximately 90 μSv per year. Thus the total dose to the population in the UK from cosmic radiation from exposure outdoors is around 370 μSv per year.

For exposure inside buildings, the dose rate quoted above will be reduced due to the shielding effects of building materials. An exact value for this reduction is not possible as it depends on the type of building (for example, shielding is more effective when living at the bottom of a set of flats than at the top) and materials (concrete, wood, etc) used. Cosmic ray muons and neutrons are very energetic and can easily penetrate buildings. For occupancy inside a building, UNSCEAR recommends an average reduction in the dose rate of 20% compared to the dose rate when outside (UN, 2000). The amount of time people spend inside buildings also must be taken into account, and this is estimated to be about 90% in the UK (Smith and Jones, 2003). Taking these factors into account the estimated average dose to the UK population from cosmic radiation at ground level is about 300 μSv per year, and is the same as that estimated in the previous review (Hughes, 1999). The value received by an individual depends on altitude, latitude, type of building and the building's construction material.

In the UK the effect on the average resident of increasing dose rate with altitude is small, such that there is little difference in the dose rate for someone living at sea level compared to someone living in a mountainous area. However, the difference in dose rate between sea level and the altitude at which aircraft fly is more significant. The dose received during a particular flight varies with altitude, latitude and flight time, but some typical values can be determined using computer codes developed for this purpose (FAA, 2004). For altitudes of between 9-12 km and a latitude of 50^0 (corresponding to a flight from Northern Europe to North America), the dose rate is generally in the range of 4-8 μSv per hour. However, the dose rate during long haul flights at lower latitudes is generally lower and so a dose rate of 4 μSv per hour may be used to represent the average dose rate for all long haul flights. For short haul flights, taken to represent journeys between European countries, the flight altitude is generally less than that considered for long haul (for example, transatlantic) flights, being between 7.5-10.5 km. At this altitude the dose rate is typically around 3 μSv per hour. These dose rates correspond to those estimated by British Airways (Irvine and Flower, 2002), and take account of the climb and descent phase of the flight.

For illustrative purposes, Table 1 contains some approximate doses from a return flight from London to various destinations, calculated using a computer code (FAA, 2004). These doses are in addition to any doses that the individuals receive on the ground. For aircrew the time spent in the air can be considerably higher than that for passengers. Aircrew doses are discussed in the occupational exposure section (see Section 4.11).

TABLE 1 Approximate doses from a return journey by air

Destination, from London:	Approximate flight time*, h	Approximate dose for a return journey[#], μSv
Paris	2	4
Glasgow	2.5	6
Malaga	5	15
Athens	7	25
Moscow	8	40
New York	15	100
Los Angeles	22	160
Johannesburg	23	75
Hong Kong	26	140
Sydney	40	160

Notes:

* Total time in the air for a direct return flight from London to the indicated destination

The values in this table are approximate values for illustration only. Actual flight times may vary and the doses will depend on many factors including flight profile and the specific route taken

In the previous review it was estimated that the average annual dose to the UK population from air travel was about 20 μSv (Hughes, 1999). This was based on the number of flights made by UK residents in 1996, which was some 28 million. In 2002 this had risen to 44 million (Summerfield and Babb, 2004), giving an increase in the average annual dose to about 30 μSv. The overall average annual dose in the UK from all cosmic radiation exposure is therefore about 330 μSv. The overall range in annual dose at ground level is from about 200 to 400 μSv, mainly depending on variations in the shielding provided by buildings.

2.2 Intakes of natural radionuclides

Natural radionuclides in the environment may be taken up by plants and hence may be taken into the body. Average annual doses to adults, children and infants were calculated from average intakes of foodstuffs and reported radionuclide concentrations in those foodstuffs. These estimates of annual dose are described in the following sections.

2.2.1 Cosmogenic radionuclides

The interactions of cosmic radiation with atoms in the atmosphere produce a range of radionuclides that can give rise to human exposure by inhalation, or by ingestion after their uptake by plants. These radionuclides include tritium (^{3}H), beryllium-7 (^{7}Be), carbon-14 (^{14}C) and sodium-22 (^{22}Na). The most significant cosmogenic radionuclide is ^{14}C, which is taken up by plants and becomes incorporated into human foodstuffs. The Food Standard Agency and Scottish Environment Protection Agency (FSA and SEPA, 2002) have an extensive programme of monitoring of radionuclides in the environment from authorised discharges and, for the purposes of comparison, measurements are also carried out on some natural radionuclides in seafood and terrestrial foodstuffs. Activity concentrations of natural ^{14}C in foodstuffs from those measurements are used in this study to estimate average annual doses from ^{14}C intakes.

2.2.2 Primordial radionuclides

Natural radionuclides of terrestrial origin have very long half-lives or derive from a very long-lived parent radionuclide. These primordial radionuclides were created in stellar processes before the Earth was formed and are still present in the earth's crust. The main primordial radionuclides are listed in Table 2, the most radiologically significant being those of uranium, thorium and potassium. Uranium-238 (^{238}U), uranium-235 (^{235}U) and thorium-232 (^{232}Th) undergo radioactive decay through a series of decay products, shown in Table 3, eventually producing stable isotopes of lead. All these radionuclides are present in rocks and soils and can be taken up by plants, and thus enter the food chain. During the process of radioactive decay these radionuclides can emit alpha (α), beta (β) and gamma (γ) radiation. Therefore when these radionuclides are ingested or inhaled they give rise to an internal radiation dose. The presence of these radionuclides in rocks, soils and building materials can also give rise to a radiation dose from direct external irradiation, see Section 2.3. Radiation exposures from ^{40}K, ^{87}Rb and the radionuclides of the uranium and thorium series are assessed here. The exposures from the other radionuclides listed in Table 2 are insignificant.

TABLE 2 Primordial radionuclides

Radionuclide	Relative abundance, %	Half-life, y	Decay
^{40}K	0.0117	1.3 10^{9}	β
^{50}V	0.25	1.4 10^{17}	β
^{76}Ge	7.44	1.5 10^{21}	β
^{82}Se	8.73	1.1 10^{20}	β
^{87}Rb	27.8	4.7 10^{10}	β
^{90}Zr	2.80	3.9 10^{10}	β
^{100}Mo	9.63	1.2 10^{19}	β
^{113}Cd	12.22	9.0 10^{15}	β
^{115}In	95.7	4.4 10^{14}	β
^{116}Cd	7.49	2.6 10^{19}	β
^{123}Te	0.91	1.2 10^{13}	β
^{128}Te	31.69	7.2 10^{24}	β
^{130}Te	33.8	2.7 10^{21}	β
^{138}La	0.09	1.3 10^{11}	β
^{144}Nd	23.8	2.3 10^{15}	α
^{147}Sm	15.0	1.1 10^{11}	α
^{148}Sm	11.3	7.0 10^{15}	α
^{150}Nd	5.64	1.7 10^{19}	β
^{152}Gd	0.2	1.1 10^{14}	α
^{174}Hf	0.162	2.0 10^{15}	α
^{176}Lu	2.6	3.8 10^{10}	β
^{180}Ta	0.012	1.0 10^{15}	α
^{186}Os	1.58	2.0 10^{15}	α
^{187}Re	62.6	5.0 10^{10}	α
^{187}Re	62.6	5.0 10^{10}	β
^{190}Pt	0.01	6.5 10^{11}	α
^{190}Pt	0.01	6.5 10^{11}	α
^{232}Th	100	1.4 10^{10}	α
^{234}U	0.0055	2.5 10^{5}	α
^{235}U	0.72	7.0 10^{8}	α
^{238}U	99.3	4.5 10^{9}	α

Previous reviews in this series have shown that the largest source of exposure of the UK population is from radon gas (^{222}Rn). Table 3 shows that ^{226}Ra, which is present in the ground, decays to ^{222}Rn, which gives rise to an inhalation dose. Exposures from radon are described separately in Section 2.4.

2.2.2.1 Potassium-40

Potassium-40 (^{40}K) constitutes 0.012% of natural potassium by weight and potassium is distributed throughout the body. The concentration in the body is held relatively constant by metabolic processes. An average annual dose to adults of 165 μSv has been estimated from measurements of average body content of this radionuclide (UN, 2000). The average annual dose in younger age groups (10 y old) is higher, at 185 μSv, due to a higher ^{40}K concentration (UN, 2000). Infants have ^{40}K concentrations similar to adults (ICRP, 1975), and have therefore, as an approximation, been ascribed the same annual dose as adults. Lower ^{40}K concentrations in elderly females (ICRP, 1975) give rise to an annual dose about half that of young male individuals (UN, 1982).

2.2.2.2 Rubidium-87

Radioactive rubidium (^{87}Rb) constitutes 27.8% of rubidium found in the earth's crust and decays to stable strontium-87 (^{87}Sr). It occurs naturally in igneous rocks in varying amounts depending on the rock type. Normal human adults contain about 300 mg in all tissues (www.dcnutrition.com, 2003). It is estimated that the average annual dose to an adult is about 2 μSv. The same average annual dose is assumed for other age groups.

2.2.2.3 Uranium and thorium

The longer lived members of the uranium and thorium series are present in very low concentrations in most foodstuffs. Some of these radionuclides can be more concentrated in certain foodstuffs as a result of natural processes and some examples of these are given below. It has been established by many studies (Bradley, 1993; Ham et al, 1998; Young et al, 2002; UN, 2000; Defra, 1999; Dale, 2000, 2001 and 2002) that, of the radionuclides in the uranium and thorium series, ^{210}Pb and ^{210}Po provide the main contribution to the annual dose.

Other members of the uranium and thorium series have been measured in foodstuffs in a number of studies. These make a small but important contribution to the total dose. Typical uranium and thorium series activity concentrations in foodstuffs are given in Appendix A, Table A1. Activity concentration values are given for the foods that make up the total diet, including drinking water. Average annual intakes of foodstuffs for adults, children and infants (Smith and Jones, 2003) are given in Appendix A, Table A1, and are used to calculate the doses for each radionuclide. The doses are given in Appendix A, Tables A2-A4, and summarised in Table 4.

The average annual doses from radionuclides in the uranium and thorium series from intakes of different foodstuffs, are illustrated in Figures 1 and 2. Figures 1 and 2 show that in the case of infants, the largest single contribution, from radionuclides of the uranium and thorium series is from dairy products. Contributions to adult dose from these radionuclides are distributed relatively evenly between the main food groups. The contributions to the average annual dose due to inhalation of different radionuclides are illustrated in Figure 3 and Table 4. These were calculated from the data on air concentrations of radionuclides, dose coefficients and breathing rates given in Table A1 of Appendix A. Radionuclides of the uranium series give average annual doses from ingestion and inhalation of about 67 μSv and 2 μSv respectively. The average annual doses from ingestion and inhalation of radionuclides of the thorium series are about 7 μSv and 0.4 μSv respectively.

TABLE 3 Decay series of natural radionuclides

Uranium series			Actinium series			Thorium series		
Radionuclide	Half-life	Decay*	Radionuclide	Half-life	Decay*	Radionuclide	Half-life	Decay*
^{238}U	$4.5\ 10^{9}$ y	α	^{235}U	$7.0\ 10^{8}$ y	α	^{232}Th	$1.4\ 10^{10}$ y	α
^{234}Th	24 d	β	^{231}Th	25 h	β	^{228}Ra	5.7 y	β
^{234m}Pa	1.2 min	β	^{231}Pa	$3.3\ 10^{4}$ y	α	^{228}Ac	6.1 h	β
^{234}U	$2.5\ 10^{5}$ y	α	^{227}Ac	22 y	β	^{228}Th	1.9 y	α
^{230}Th	$7.7\ 10^{4}$ y	α	^{227}Th	19 d	α	^{224}Ra	3.7 d	α
^{226}Ra	$1.6\ 10^{3}$ y	α	^{223}Ra	11 d	α	^{220}Rn	56 s	α
^{222}Rn	3.8 d	α	^{219}Rn	4.0 s	α	^{216}Po	0.15 s	α
^{218}Po	3.0 min	α	^{215}Po	$1.8\ 10^{-3}$ s	α	^{212}Pb	11 h	β
^{214}Pb	27 min	β	^{211}Pb	36 min	β	^{212}Bi	61 min	β
^{214}Bi	20 min	β	^{211}Bi	2.1 min	α	^{212}Po (64%)	$3.0\ 10^{-7}$ s	α
^{214}Po	$1.6\ 10^{-4}$ s	α	^{207}Th	4.8 min	β			
^{210}Pb	22 y	β	^{207}Pb	(stable)		^{208}Tl (36%)	3.0 min	β
^{210}Bi	5 d	β				^{208}Pb	(stable)	
^{210}Po	138 d	α						
^{206}Pb	(stable)							

Note

* Only the main decay modes are shown. Most of these radionuclides also emit gamma radiation.

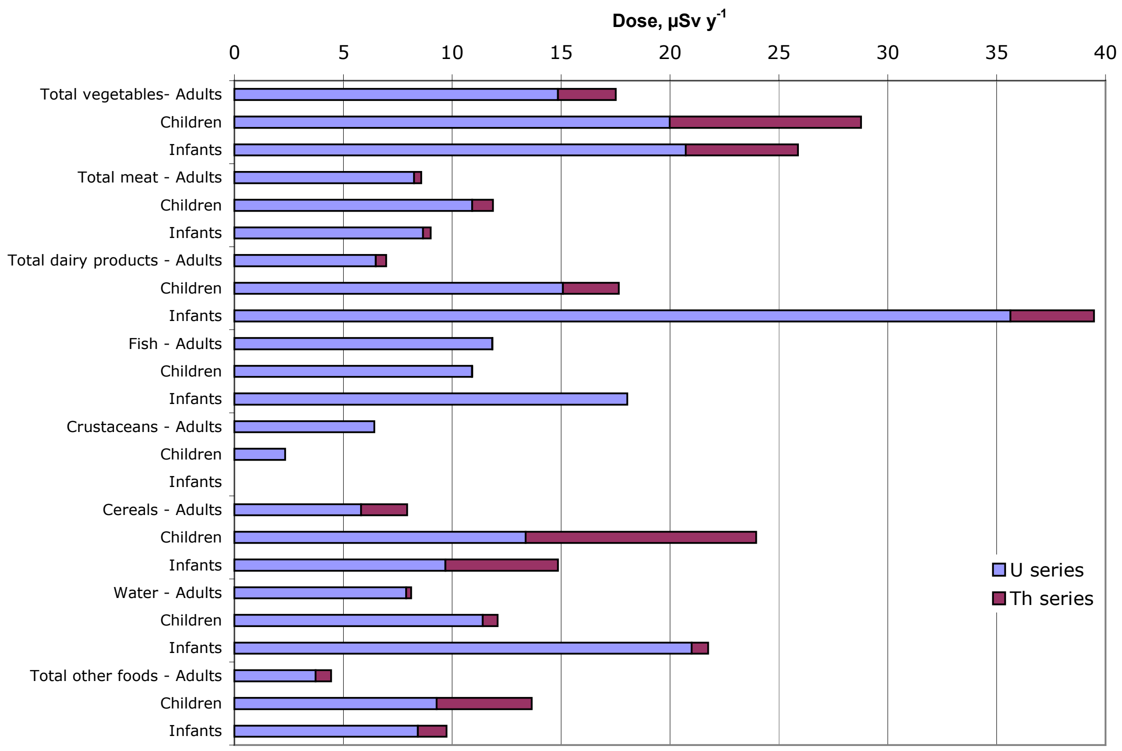


Figure 1. Annual dose to each age group from natural radionuclides of the ^{238}U and ^{232}Th series in foodstuffs.

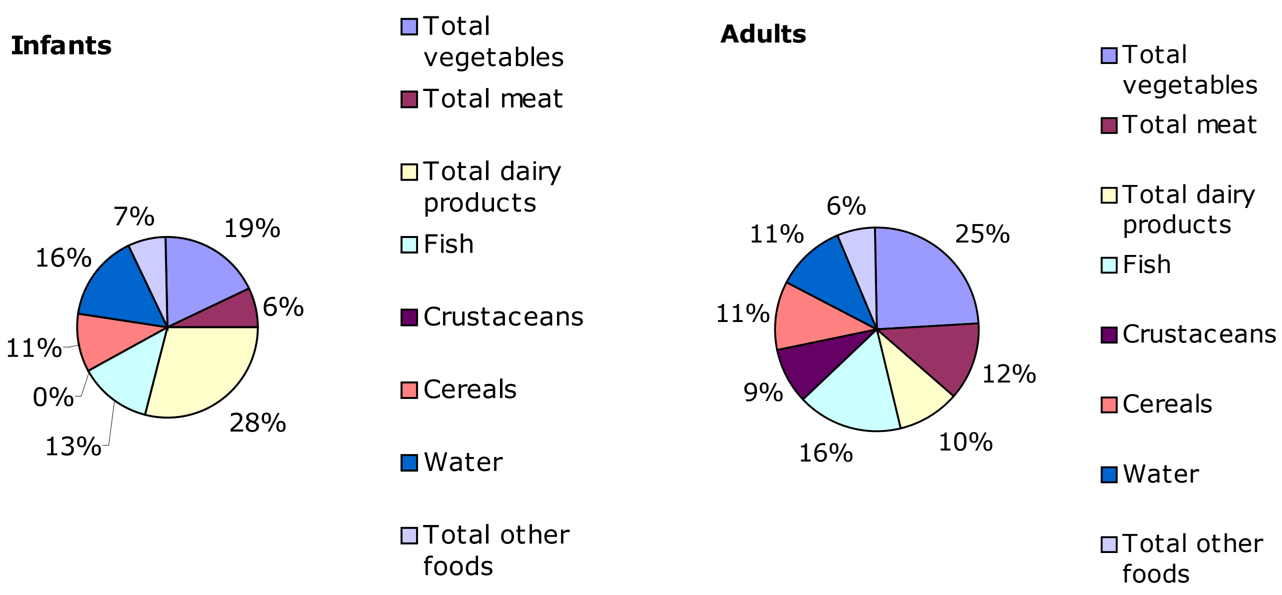


Figure 2. Contributions to the annual dose to an adult and an infant from radionuclides of the uranium and thorium series in a typical diet.

Apart from radon, it is the longer-lived radionuclides of the uranium and thorium series that make the main contributions to inhalation dose from naturally occurring radionuclides. In particular ^{210}Pb makes the largest contribution, as shown in Figure 3. The exposures from inhalation of radon and its short-lived decay products are described in Section 2.4.

TABLE 4 Annual doses to three age groups from ingestion and inhalation of natural radionuclides

	Infants, μSv y^{-1}			Children, μSv y^{-1}			Adults, μSv y^{-1}		
Nuclide	Ingestion	Inhalation	Total	Ingestion	Inhalation	Total	Ingestion	Inhalation	Total
^{238}U	9.93 10^{-2}	1.79 10^{-2}	1.17 10^{-1}	1.22 10^{-1}	2.24 10^{-2}	1.44 10^{-1}	1.18 10^{-1}	2.35 10^{-2}	1.42 10^{-1}
^{234}U	1.04 10^{-1}	2.09 10^{-2}	1.25 10^{-1}	1.20 10^{-1}	2.69 10^{-2}	1.47 10^{-1}	1.10 10^{-1}	2.84 10^{-2}	1.38 10^{-1}
^{230}Th	1.92 10^{-1}	3.33 10^{-2}	2.25 10^{-1}	3.26 10^{-1}	4.48 10^{-2}	3.71 10^{-1}	3.49 10^{-1}	5.67 10^{-2}	4.06 10^{-1}
^{226}Ra	2.89 10^{0}	2.09 10^{-2}	2.91 10^{0}	5.73 10^{0}	2.74 10^{-2}	5.76 10^{0}	2.71 10^{0}	2.84 10^{-2}	2.74 10^{0}
^{210}Pb	4.58 10^{1}	1.41 10^{0}	4.72 10^{1}	4.35 10^{1}	1.68 10^{0}	4.52 10^{1}	2.22 10^{1}	1.78 10^{0}	2.40 10^{1}
^{210}Po	8.13 10^{1}	2.52 10^{-1}	8.16 10^{1}	4.66 10^{1}	3.11 10^{-1}	4.69 10^{1}	4.17 10^{1}	3.23 10^{-1}	4.20 10^{1}
^{232}Th	1.06 10^{-1}	4.75 10^{-2}	1.54 10^{-1}	1.90 10^{-1}	7.28 10^{-2}	2.63 10^{-1}	1.90 10^{-1}	1.01 10^{-1}	2.91 10^{-1}
^{228}Ra	1.64 10^{1}	1.90 10^{-2}	1.64 10^{1}	2.76 10^{1}	2.58 10^{-2}	2.76 10^{1}	6.24 10^{0}	2.11 10^{-2}	6.26 10^{0}
^{228}Th	1.29 10^{-1}	2.47 10^{-1}	3.76 10^{-1}	1.30 10^{-1}	3.08 10^{-1}	4.38 10^{-1}	1.27 10^{-1}	3.24 10^{-1}	4.51 10^{-1}
^{235}U	5.78 10^{-3}	2.47 10^{-3}	8.25 10^{-3}	7.42 10^{-3}	3.08 10^{-3}	1.05 10^{-2}	6.84 10^{-3}	3.44 10^{-3}	1.03 10^{-2}
^{14}C	8.87 10^{0}	-	8.87 10^{0}	1.05 10^{1}	-	1.05 10^{1}	8.84 10^{0}	-	8.84 10^{0}
^{40}K	1.65 10^{2}	-	1.65 10^{2}	1.85 10^{2}	-	1.85 10^{2}	1.65 10^{2}	-	1.65 10^{2}
^{87}Rb	2.00 10^{0}	-	2.00 10^{0}	2.00 10^{0}	-	2.00 10^{0}	2.00 10^{0}	-	2.00 10^{0}
Total*	3.23 10^{2}	2.07 10^{0}	3.2 10^{2}	3.22 10^{2}	2.52 10^{0}	3.2 10^{2}	2.50 10^{2}	2.69 10^{0}	2.5 10^{2}

* Overall totals rounded, radon excluded

2.2.3 All internal exposure from intakes

The average annual dose to both 1 y and 10 y olds from intakes of natural radionuclides, excluding radon, is estimated to be around 320 μSv. For adults it is estimated to be around 250 μSv. This average annual dose is based mainly on UK estimates of radionuclide intakes and results in a slightly lower average dose than was derived in the previous review, which relied more on international data. Almost all this dose is from ingestion, with 1% or less being from inhalation of the relatively long-lived radionuclides considered. The largest contribution to the average annual adult dose is 165 μSv (66%), from ^{40}K. The next largest contribution, about 76 μSv (30%) is from radionuclides of the uranium and thorium series. The average adult annual dose from cosmogenic ^{14}C is estimated to be about 9 μSv (3.6%), and the remainder, about 2 μSv, is mainly from ^{235}U and ^{87}Rb intakes. Consumption of foods with elevated activity concentrations, or at elevated rates (Smith and Jones, 2003), can lead to annual doses a few times higher than the UK average; that is approaching 1000 μSv. The contribution from ^{40}K is highest in children and young adults, and diminishes with age. In elderly females, annual doses from ^{40}K are about half that of young males (UN, 1982). Those of the elderly with low intakes of radionuclides will therefore have annual doses slightly above 100 μSv. The rounded range of annual doses is therefore from about 100 μSv to 1000 μSv. Note that radon is not included in this range – see Section 2.4.

2.2.4 Examples of elevated intakes

2.2.4.1 Natural radioactivity in drinking water

Current legislation (GB Parliament, 1999b) sets out the maximum levels of radioactivity in spring water and bottled drinking water in the UK. These regulations do not apply to natural mineral waters. A maximum total indicative dose (TID) is defined in the regulation as 0.1 mSv per year per person, not including contributions from ^{40}K, radon decay products or tritium. A limit for tritium is set separately at 100 Bq l^{-1}.

An analysis of natural radioactivity in bottled waters was carried out by the Food Standards Agency (FSA) (FSA, 2004). Gross alpha activity in the samples ranged from below the limit of detection to 8.4 Bq l^{-1}; gross beta activity ranged from below the limit of detection to 6.1 Bq l^{-1}. Doses were calculated by FSA, assuming a consumption rate of 2 litres per day (730 litres per year) and ranged from 0.002 – 0.484 mSv y^{-1} (FSA, 2004). The radionuclides giving the significant proportion of these doses are ^{234}U and ^{226}Ra. However, it should be noted that it is unlikely that the general population consumes this amount of bottled water per day, hence the estimated dose is likely to be an overestimation.

The ingestion of radon gas dissolved in tap water can lead to a small exposure, when consumed. However, it is unlikely that all the radon will remain in the water once released from the tap, and some will disperse into the surrounding air where it contributes to the radon in indoor air from other sources. If the tap water is boiled, almost all the radon will be removed. The dose to an adult member of the public ingesting 1 litre per day of tap water containing 1 Bq of radon would receive an annual equivalent dose to the stomach of about 30 μSv (Kursheed, 2000), giving an annual effective dose of almost 4 μSv. A UK-wide survey (Henshaw et al, 1993) found an average concentration of about 3 Bq l^{-1} in tap water. This could therefore result in an average annual effective dose of about 10 μSv, from drinking 1 l d^{-1} of tap water. There are some private water supplies in the UK where concentrations approaching 1000 Bq l^{-1} (Smith, D M et al, 1990) have been found, giving rise to annual doses in the order of 1 mSv. Relatively few individuals would receive such annual doses, and this dose is estimated on the cautious assumption that all the radon is retained within the water.

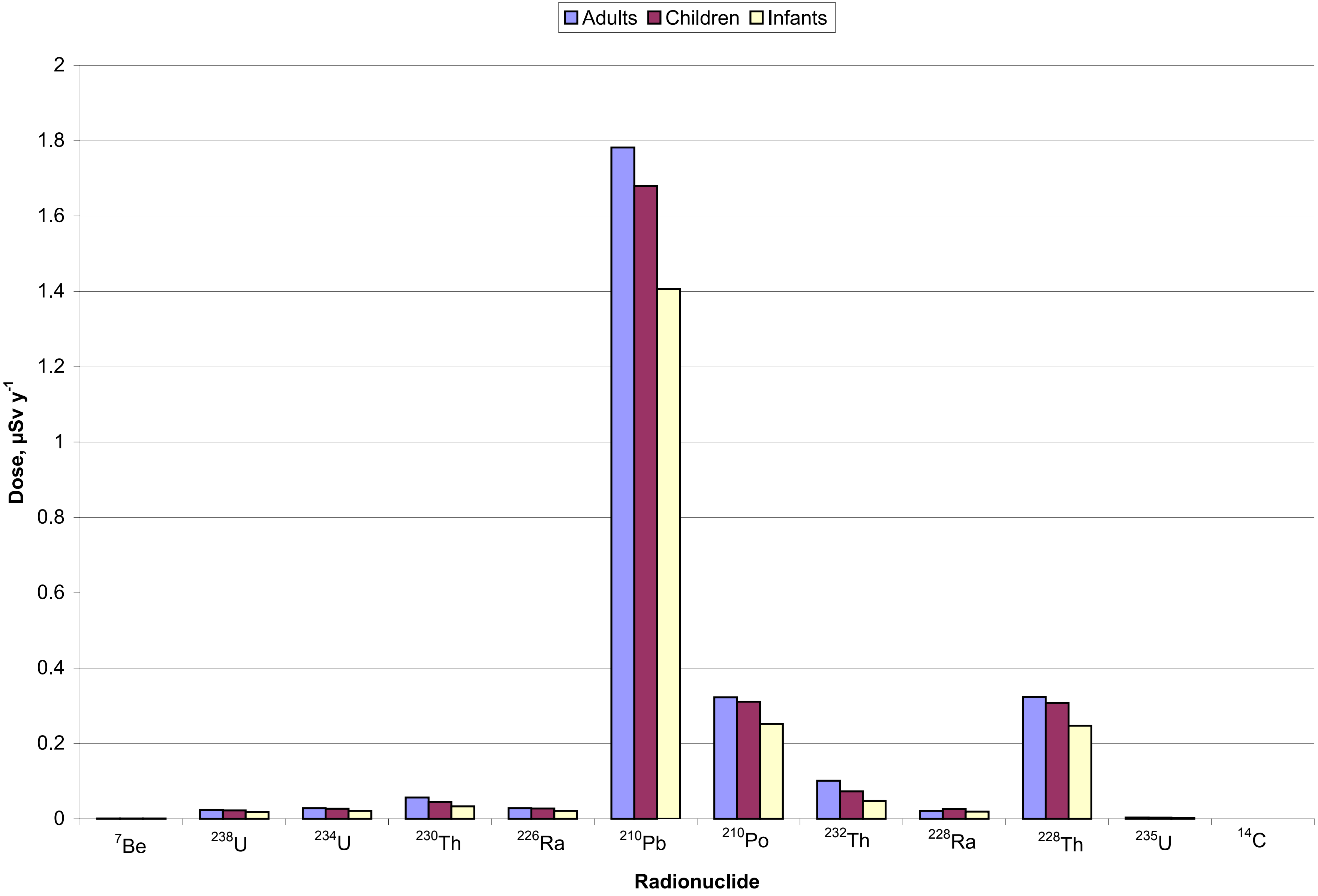


Figure 3 Inhalation doses to three age groups from naturally occurring radionuclides (excluding radon)

2.2.4.2 Foodstuffs

The consumption of foodstuffs containing elevated concentrations of natural activity will increase an individual's dose. Mussels contain relatively high concentrations of ^{210}Po and the average concentration found in a study carried out in 2001 was 42 Bq kg^{-1} (EA et al, 2004). The consumption of an 80g jar of mussels containing this concentration of ^{210}Po would lead to a dose of approximately 4 μSv. If a jar of mussels that contains the same activity concentration is consumed each week for a year the annual dose received would be about 200 μSv.

Brazil nuts can contain elevated levels of radium isotopes (Turner et al, 1958), sometimes up to a few hundred Becquerels per kilogram. A study (Hiromoto et al, 1996) found average concentrations of about 30 Bq kg^{-1} of both ^{226}Ra and ^{228}Ra, and lower activities of other radionuclides. The consumption of a 100g bag could give rise to a dose of about 4 μSv, or 200 μSv per annum if a bag is consumed each week. Since a bag usually contains some 30 to 40 nuts, this implies a dose of about 0.1 μSv per Brazil nut.

2.3 Gamma radiation

Most radionuclides in the uranium and thorium series, and ^{40}K, emit gamma radiation. A world-wide review (UN, 2000) of the concentrations of ^{40}K, ^{238}U and ^{232}Th in soil gave median values of 400, 35 and 30 Bq kg^{-1}, respectively. In the UK, levels of ^{238}U range from 2 to 330 Bq kg^{-1}, depending on the type of rock in the area, and ^{232}Th is present at an activity concentration of between 1 and 180 Bq kg^{-1}.

These radionuclides, which are present in soils and other natural materials, give rise to exposures from gamma radiation outdoors. Building materials, which also contain these radionuclides, also give rise to external gamma exposure indoors. The gamma contributions from the other radionuclides listed in Table 2 are insignificant. To determine the population dose from terrestrial gamma radiation in the UK, dose rate measurements were made throughout the country both indoors (Wrixon et al, 1988) and outdoors (Green et al, 1989). The average dose rate at a height of 1 m outdoors in the UK, weighted by the population distribution, was found to be 32 nGy h^{-1}. This gives an average annual dose outdoors of about 16 μSv (Green et al, 1989). The average indoor dose rate was found to be 60 nGy h^{-1}, varying by about a factor of 3 above and below this mean (Wrixon et al, 1988). This results in an average annual dose of almost 340 μSv (Wrixon et al, 1988). The average annual dose from both indoor and outdoor exposure was therefore found to be about 350 μSv (Wrixon, et al, 1988). No further surveys have been carried out that would require a revision of this average annual dose. The rounded range of individual annual doses is between 100 μSv and 1000 μSv, and derives mainly from the range in indoor dose rates.

2.4 Radon and Thoron

2.4.1 Introduction

Radon (^{222}Rn) gas emanates from the decay of ^{226}Ra in the ground. Radon has a half-life of 3.8 days and decays into a number of short-lived radionuclides, which give rise to a dose by inhalation. The decay chain of the thorium series, shown in Table 2, gives rise to thoron (^{220}Rn), which is another isotope of radon. Thoron gas is also present in indoor air; however it has a much shorter half-life and is present at lower activity concentrations than ^{222}Rn, so it contributes much less to the total dose compared to ^{222}Rn. The population weighted average concentration of radon in outdoor air has been estimated as 4 Bq m^{-3} (Wrixon et al, 1988). The doses resulting from inhalation of radon and thoron and their decay products are described in Section 2.4.4.

2.4.2 Radon in homes

Radon tends to concentrate in buildings due to the fact that indoor air pressure is normally lower than that outdoors, mainly due to indoor heating, and the action of wind passing over the building. The main source of indoor radon is from the ground below, but it can also be carried into homes in the water and natural gas supplies, and released when these are used. Also, uranium in building materials can be a minor source of radon.

Since the build up of radon gas indoors is mainly due to ingress of the gas from the ground below a building, this can be reduced or prevented in a number of ways, such as the provision of an impermeable membrane at ground level. One of the most effective methods is the construction of a sump below the ground floor from which air is pumped to the outside. This draws out radon gas before it enters inside the building. Such a system can be constructed and operated by the householder at a modest cost.

In 1990 NRPB recommended that an Action Level of 200 Bq m^{-3} should be established (NRPB, 1990). This is the level, averaged over a year, above which action should be taken to reduce radon concentrations in dwellings. This was part of a control strategy that involved identifying radon Affected Areas, which is an area with a 1% probability or more of present or future homes being above the Action Level. It was also advised that future homes be designed so that radon would be as low as reasonably practicable. The government accepted this advice (DoE, 1990) and since then a major survey programme has been supported by the Department for Environment, Food and Rural Affairs (Defra), the National Assembly for Wales, the Scottish Executive, the Department of the Environment for Northern Ireland, and many local authorities.

Information has been provided to the public through occasional publicity campaigns and NRPB offers a service to measure indoor radon levels using passive dosimeters supplied through the post. The radon control strategy can be summarised as:

- radon measurements should be made in existing homes in Affected Areas,

- radon concentrations at or above the Action Level should be reduced to as low as reasonably practicable, and
- new homes built within radon-prone localities should be constructed with precautions against the ingress of radon.

2.4.3 Radon surveys in the UK

In the early 1980s a national survey of the level of radon in homes was carried out, in which measurements were made in about 2000 homes throughout the UK (Wrixon et al, 1988). The national survey was carried out in such a way that the results would give a population weighted average for the UK as a whole and statistically representative averages for each county. Since then there has been a major programme to measure radon in homes and other buildings in the UK, in order to identify those premises with high indoor radon concentrations. Measurements have been made in some 500,000 homes using passive dosimeters. However, most of these measurements were targeted at premises in radon-prone areas. Therefore, despite the large number of results from these measurements, the best estimate of the average UK indoor concentration, and the distribution of concentrations, is still from the first national survey. This survey found that the average indoor concentration in the UK is 20 Bq m^{-3}.

About 0.5% of the housing stock, that is some 100,000 homes, are above 200 Bq m^{-3}, and about two thirds of these are predicted to be in Devon and Cornwall (NRPB, 1990). However, it was also found that homes with high concentrations could be found almost anywhere in the UK. Very few homes have concentrations that exceed 100 Bq m^{-3}, but a small number of homes can be expected to have very high levels. Two houses have been found in the Kerrier District of Cornwall, one with 17,000 Bq m^{-3}, and the other with 12,000 Bq m^{-3} (NRPB, 2004).

One of the objectives of the measurement programme was to produce maps of the UK, which show the probability of finding homes above the Action Level in each 5 km square. These maps assist in the provision of advice to government and allow the efficient allocation of measurement resources to find houses above the Action Level. These maps are occasionally updated and published, and the latest maps for England, Wales (Green et al, 2002) and Northern Ireland (Green et al, 1999) are shown in Figures 4 and 5. Those publications contain more detailed maps for the radon-prone areas. A similar map for Scotland has not yet been completed. The maps can provide information for house buyers and vendors in the Affected Areas on whether a radon survey may be advisable. The maps also provide a guide for the targeting of publicity campaigns for householders to encourage them to participate in the survey programme.

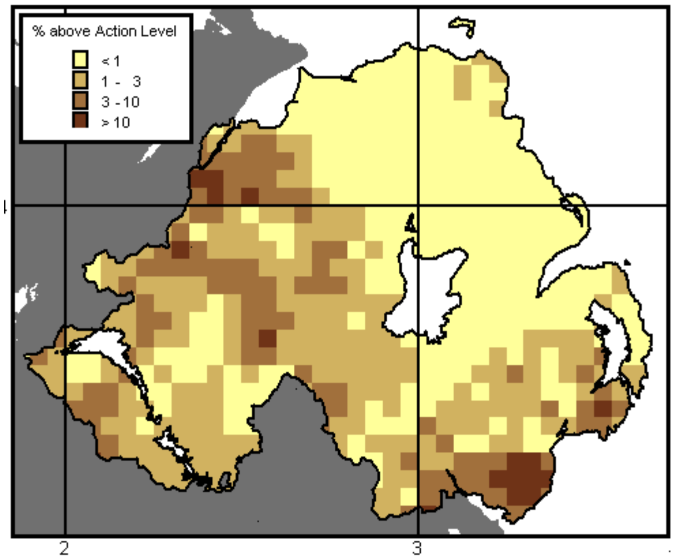


Figure 4 Estimated proportion of homes exceeding the Action Level in each 5 km grid square in Northern Ireland

The current survey data (Green, 2004) are summarised in Table 5, which gives the numbers of homes predicted to be in excess of the Action Level in each part of the UK. The numbers found up to mid 2004 over the whole UK are almost half of the predicted total.

TABLE 5 Radon measurements in the UK*

Survey data	England	Scotland	Wales	Northern Ireland	UK#
Total housing stock (millions)	20.7	2.2	1.28	0.61	25
Population weighted average radon concentration (Bq m^{-3})	21	16	20	19	20
Number of homes measured	426,000	9,200	12,900	21,400	470,000
Number of homes found to be at or above the Action Level	45,000	250	1,200	1,000	47,000
Total number of homes estimated to be at or above the Action Level	100,000	2,000	10,000	4,000	100,000
Homes found above the Action Level as a percentage of the estimated number above the Action Level.	45%	12.5%	12%	25%	47%

Notes:

* Data compiled to August 2004. The numbers of homes measured will increase as current radon programmes are completed.

Rounded totals.

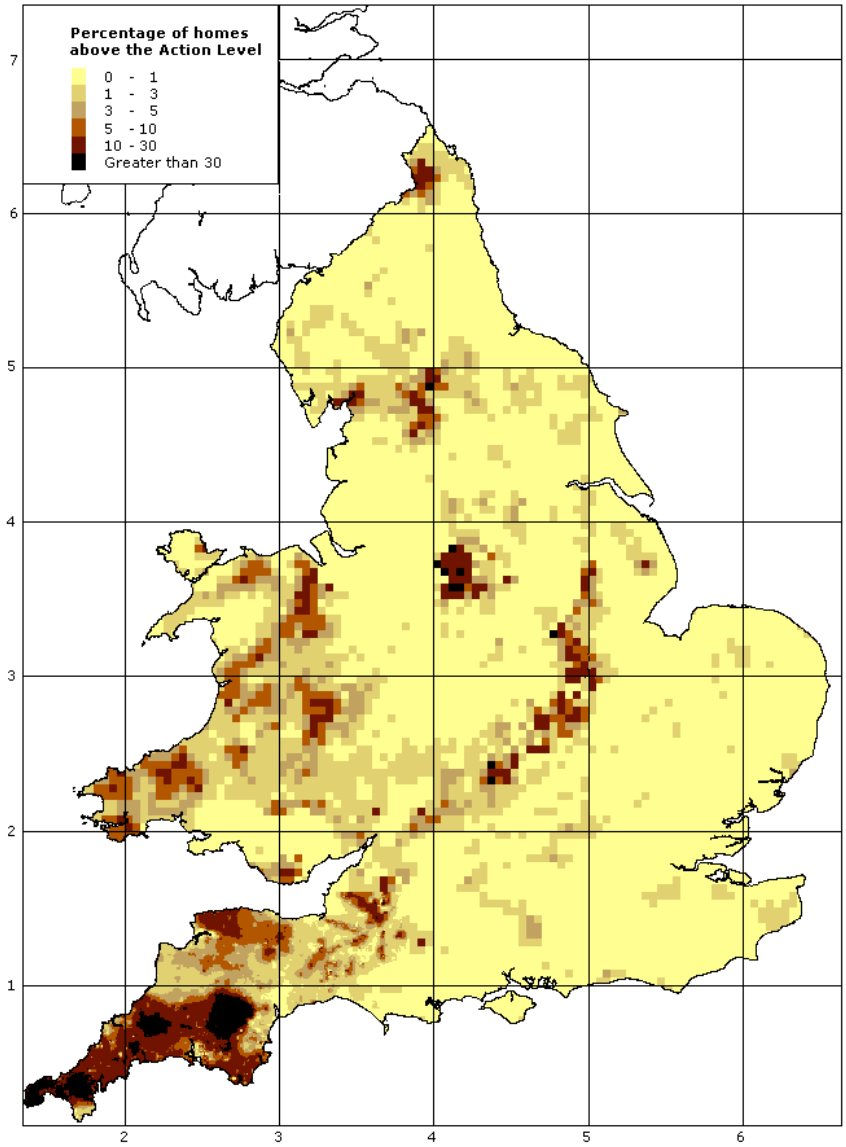


Figure 5 Overall map of radon Affected Area in England and Wales (axis numbers are the 100 km co-ordinates of the Ordnance Survey National Grid)

2.4.4 Doses from radon and thoron

Radon decays into a series of radionuclides that can become attached to particles of dust in indoor air. Inhalation of radon gas and its decay products gives rise mainly to a dose to the lungs, which is almost all from the decay products rather than radon gas itself. The dose to the lungs can be converted into an effective dose, using the appropriate weighting factor. This can then be expressed as an effective dose rate per unit of radon gas concentration. However, this quantity depends on many factors, such as the degree of equilibrium between radon gas and its decay products, the fraction of decay products that are attached to dust particles and the size of particles to which those radionuclides are attached.

For dwellings a conversion convention (NRPB, 1987) was adopted that gives rise to about 1 mSv y^{-1} at the UK average indoor concentration of 20 Bq m^{-3}. This conversion convention for dwellings was used in earlier reviews (Hughes, et al, 1989; Hughes and O'Riordan, 1993), and also in the previous review (Hughes, 1999) following the continued adoption of this conversion convention by NRPB (NRPB, 1998). For all indoor occupancy the average annual dose is about 1.2 mSv, (Wrixon et al, 1988) assuming radon concentrations in other buildings are similar to those in dwellings. The annual dose from exposure outdoors is negligible in comparison, due to the low outdoor occupancy in the UK and the lower radon concentrations outdoors. The average annual dose from radon (^{222}Rn) is therefore around 1.2 mSv, and individual annual doses vary from about 0.3 mSv to a few hundred millisieverts in homes with the highest radon levels. In the dwelling with the highest radon concentration found, at 17,000 Bq m^{-3}, the annual dose is estimated to be approximately 850 mSv.

In addition to radon exposure there is a small annual dose from thoron (^{220}Rn), which is estimated to be 0.1 mSv on average in the UK (Cliff, 1996), with a general range between about 0.05 to 0.5 mSv. Some recent measurements (Proctor, 2004) of thoron in homes at a number of locations in the UK support this general range, and suggest that in homes with the highest thoron levels, annual doses from this source can be around 1 mSv. The average annual dose from both radon isotopes in the UK is about 1.3 mSv (1,300 μSv), and this dose is mainly from the exposure of lung tissue by the inhalation of radon decay products.

2.5 All natural exposure

The average annual dose in the UK from all natural sources is therefore about 2,230 μSv, and the annual collective dose is about 131,000 man Sv. The contributions to the total are shown in Table 6. This estimate is slightly smaller than that in the previous review, due to a reduced estimate of the contribution from internal radionuclides, and despite a slight increase in the cosmic radiation component from airtravel. It should be noted that this average annual dose includes a contribution of 30 μSv from airtravel. However, not all of the population receives a dose from this source. Therefore the average annual dose from natural sources that everyone is exposed to is about 2,200 μSv. Radon provides the major contribution to the average dose and the cause of the large variation in the individual dose from all natural radiation - annual doses in some homes can reach a few hundred millisieverts.

TABLE 6 Summary of doses to the UK adult population from natural sources

	Average annual dose (µSv)		
Source	Previous estimate	Present estimate	Range
Cosmic radiation	320	330*	200 – 400#
Terrestrial gamma radiation	350	350	100 – 1000
Internal radionuclides	270	250	100 – 1000
Radon†	1,200	1,200	300 – 100,000
Thoron†	100	100	50 – 500
Total	2,240	2,230	1,000 – 100,000

Notes:

* Including an additional 30 µSv from airtravel, which is increased from 20 µSv in the previous review. It should be noted that not all of the population is exposed to this source.

Range does not include airtravel.

† Including decay products.

3 MEDICAL USES OF RADIATION

The announcement of Roentgen's discovery of X-rays in 1895 was almost immediately followed by medical use of X-rays. For over a century now the diagnostic use of X-rays has been routine, for example to view broken bones, to identify foreign bodies such as bullets, or to locate kidney stones. Shortly after the discovery of X-rays and their application to medicine, the dangers of excessive exposure to X-rays became apparent. The International Commission on Radiological Protection (ICRP) recommendations (ICRP, 1991), and the Ionising Radiation (Medical Exposure) Regulations (IR(ME)R, 2000) state that use of ionising radiation in medicine should be justified and optimised, including consideration of both the benefits and detriments of the exposure. Work by NRPB to establish reference levels of dose has contributed to patient dose reduction (see Section 3.2)

The largest contribution to the overall dose from artificial radiation in the UK has been shown in previous studies to come from medical procedures (Hughes, 1999). Most of this exposure is due to the use of X-rays and NRPB has carried out a number of surveys to assess the exposure from these procedures (Hart and Wall, 2002; Hart and Wall, 2004; Hart et al, 2002).

3.1 Some common types of medical X-ray imaging

3.1.1 Conventional

This is the standard X-ray examination familiar to most people. Conventional radiography involves recording images on film or, increasingly, digital images stored on computer. Static images may be recorded or moving x-ray images can be viewed in real-time on a display screen. This production of moving images is known as fluoroscopy. Angiography is an application of X-rays for the examination of blood vessels and usually involves fluoroscopy. Angiography is used in a range of procedures and the patient dose depends on the part of the body being investigated. Due to its importance, it is identified separately in the analysis of the dose contributions from all procedures in Section 3.2. Table 7 shows the typical effective dose from some common X-ray procedures conducted in the UK.

TABLE 7 Some common X-ray procedures in the UK, showing numbers and doses

Procedure	Annual number	Dose, mSv
Intraoral dental	9,562,500	0.005
Chest/ribs	8,273,369	0.02
Ankle	1,003,438	0.002
Lumbar spine	824,763	1.0
Barium enema	359,436	7.2
Data from Hart and Wall, 2002		

3.1.2 Interventional procedures

These are procedures involving X-ray guidance for minimally invasive therapeutic procedures. Interventional X-rays usually involve a combination of fluoroscopy, where moving images are viewed in real-time on a display screen, and "spot" pictures that record static images. If the fluoroscopy is prolonged, these procedures give relatively high patient doses. Table 8 shows the typical dose from some common interventional procedures conducted in the UK.

TABLE 8 Some common interventional X-ray procedures in the UK, showing numbers and doses

Procedure	Annual number	Dose, mSv
Insertion of pacemaker	28,688	0.7
Lithotripsy	23,672	1.3
PTCA (a coronary procedure)	22,440	15.1
Data from Hart and Wall, 2002		

3.1.3 Computed Tomography (CT)

In CT, special X-ray equipment is used to take cross-sectional images of the body. The X-ray generator and detector rotate around the body and computers construct two-dimensional images looking at a "slice" across the body, or even three-dimensional images. Soft tissues are clearly visualised in CT images but at the expense of relatively high patient doses. Table 9 shows the typical effective dose from some common CT procedures conducted in the UK.

TABLE 9 Some common CT procedures in the UK, showing numbers and doses

Procedure	Annual number	Dose, mSv
CT head	618,391	2
CT abdomen	297,244	10
CT chest	192,885	8
CT spine	63,183	4
Data from Hart and Wall, 2002		

3.1.4 General trends

Department of Health statistics on the number of imaging procedures conducted each year in English hospitals show that computed tomography (CT) and interventional radiology have shown a steady increase over the period 1997/1998 – 2001/2002, while conventional radiology and fluoroscopy have had little growth. The frequency of CT examinations has increased by 39% and interventional radiology by 55% during this period, while conventional radiology has only shown a 1% increase. Over this period, the total number of CT, radiographic and fluoroscopic examinations (ie all X-ray examinations) has increased by around 4% (Hart and Wall, 2004).

3.2 Overall dose from X-ray examinations

The collective dose for each type of examination is calculated by multiplying the number of examinations by the average dose per examination. These are then summed to give the total collective doses to the population from all types of X-ray examination. Results are presented in Table 10 and Figure 6. The annual collective dose from diagnostic radiology in the UK in the financial year 2001/ 2002 was approximately 22,700 man Sv, resulting in an average annual dose of 0.38 mSv (Hart and Wall, 2004). A previous survey (Hart and Wall, 2002) showed the average effective dose for the financial year 1997/98 to be 0.33 mSv, while in 1991 it was found to be 0.35 mSv (Hughes and O'Riordan, 1993). The current value of 0.38 mSv represents a slight increase over previous estimates but is low in comparison with other countries with similarly developed levels of health care. The average dose from diagnostic X-ray examinations in similarly developed countries is 0.73 mSv (UN, 2000). The lower average dose in the UK is probably due to both lower frequencies of examination and lower doses per examination in the UK (Hart and Wall, 2004).

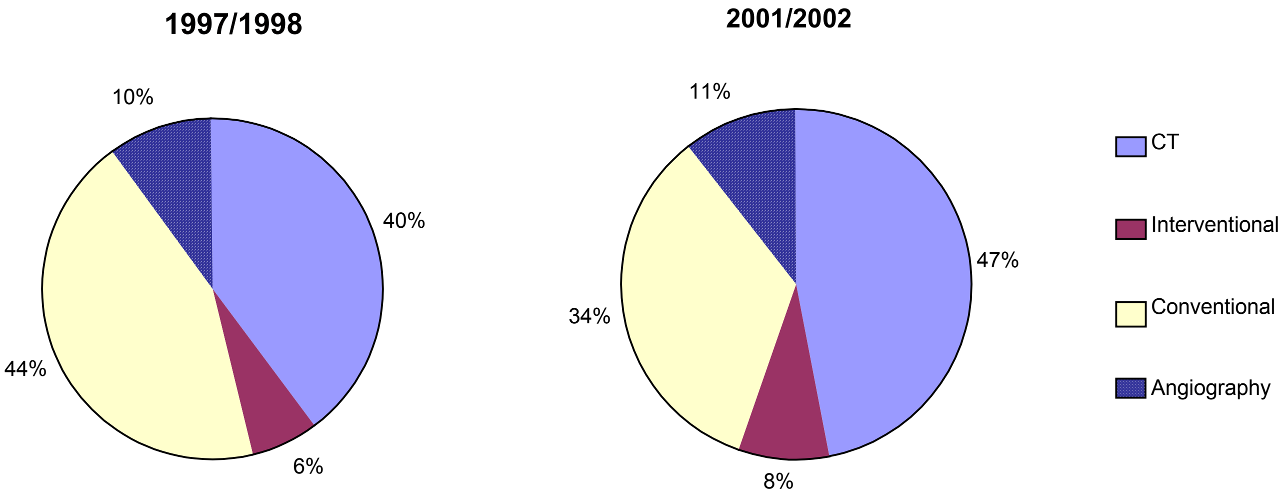


Figure 6 Contributions to the UK medical exposure collective dose from X-ray examinations for financial years 1997/1998 and 2001/2002

TABLE 10 Contributions to the UK collective dose from X-ray examinations for financial years 1997/1998 and 2001/2002*

Examination Type	1997/1998		2001/2002	
	man Sv	% of total dose	man Sv	% of total dose
CT	7662	39.7	10650	46.9
Interventional	1239	6.4	1920	8.5
Conventional	8473	43.9	7720	34.0
including:				
Barium enema	*2588*	*13.4*	*2379*	*10.5*
Abdomen	*852*	*4.4*	*749*	*3.3*
Lumbar spine	*825*	*4.3*	*692*	*3.0*
Pelvis	*644*	*3.3*	*559*	*2.5*
Mammography	*466*	*2.4*	*513*	*2.3*
Dental	*77*	*0.4*	*82*	*0.4*
Other	*3021*	*15.7*	*2746*	*12.1*
Angiography	1923	10.0	2423	10.7
Total	19298	100	22713	100

Note: * Data from Hart and Wall 2004

Figure 6 and Table 10 shows that the contribution from CT to the UK collective dose from X-ray examinations has risen over this period to 47%, while the contribution from conventional radiology has fallen to 34% and the contribution from interventional radiology has risen slightly to about 8%.

CT has now overtaken conventional radiology in terms of its contribution to the UK collective dose, despite the comparatively low frequency of CT (7% of all X-ray examinations in NHS hospitals). Next to CT, interventional radiology is an area associated with elevated patient doses. While interventional radiology has seen a large increase (55%) in frequency between 1997/1998 and 2001/2002, it still accounts for only 2% of the X-ray examinations in English NHS hospitals (Hart and Wall, 2004). However, the high exposures involved mean that it contributes 8% of the UK collective dose from all procedures.

Dental X-rays are the most frequent examination, making up 30% of all medical and dental X-ray examinations, though they contribute a very small amount (0.4%) to the collective dose (Hart and Wall, 2002; Hart and Wall, 2004).

There is a requirement to keep patient exposures as low as reasonably practicable, by minimising both the exposures from examinations and the number of unnecessary exposures. To provide guidance on unusually high levels of exposure, national reference doses have been developed and 'diagnostic reference levels' are now required to be established and used locally (IR(ME)R, 2000). National reference doses have been recommended for many common diagnostic X-ray procedures, which hospitals should demonstrate that they can keep below by making regular measurements on representative groups of patients. With this increasing awareness and with improved technology there is a trend towards reduced exposures, with almost all conventional examinations showing a decrease in the mean exposures between the periods 1983-1985, 1988-1995 and 1996-2000 (Hart et al, 2002). The development of reference levels has played a major part in this reduction, together with factors such as the increase in speed of the film-screen combinations used in conventional radiography and other technological improvements. With reduced exposure levels per examination, the average annual dose from X-ray examinations has not increased substantially, despite an increase in the number of examinations.

3.3 Nuclear medicine procedures

Besides X-ray examinations, a portion of the UK dose from medical procedures comes from nuclear medicine. In a survey of nuclear medicine workloads in the early 1990s (Elliott et al, 1996) the number of diagnostic nuclear medicine procedures performed annually in the UK was estimated at around 490,000 in 1993. The number of procedures has increased steadily since then. Table 11 shows Department of Health data for England (DH, 2000; DH, 2001), with a 7% increase in diagnostic radioisotope procedures between the financial years 1996/97 and 2000/01. Adjusting these data for the whole UK population implies around 640,000 diagnostic nuclear medicine procedures in the financial year 2000/2001. This is an increase of 33% compared with the estimated workload in 1993.

TABLE 11 Number of diagnostic nuclear medicine procedures performed annually in England (DH, 2000; DH, 2001)

Department Type	Financial year 1996/1997	Financial year 2000/2001
Imaging	466,982	515,222
Other	32,758	20,054
Total	499,740	535,276

A recent survey of nuclear medicine procedures in the UK has been carried out (Hart and Wall, to be published). The number of diagnostic nuclear medicine procedures in the UK in the financial year 2003/ 2004 had increased slightly to 656,000, and the estimated annual collective dose was 1,600 man Sv. This represents an average annual dose to the UK population of 0.027 mSv.

3.4 All medical procedures

The sum of the average annual dose from nuclear medicine procedures, and the average of 0.38 mSv from X-ray examinations, results in an average annual dose to the UK population of 0.41 mSv from all medical procedures.

In addition there will be some dose from radiotherapy and therapeutic use of nuclear medicine but no estimate is made here of the collective patient dose from these procedures. As noted in previous reviews, it is difficult to make meaningful estimates of these doses, and because therapeutic procedures intentionally deliver high cell-killing doses to specific tissues, these doses are not indicative of the risk for stochastic radiation effects. This makes them unsuitable for comparison with the lower diagnostic doses. While there are risks with the exposure levels arising from therapeutic doses, it is not felt appropriate to consider these exposures in this review.

4 OCCUPATIONAL EXPOSURE

During the period covered by this review the regulations controlling occupational exposure to ionising radiation were revised to implement the 1996 European Directive on Basic Safety Standards (EC, 1996). On January 1st, 2000, the Ionising Radiations Regulations 1985 (GB Parliament, 1985) were replaced by the Ionising Radiations Regulations 1999 (GB Parliament, 1999a). With this change in regulation the main annual dose limit came down from 50 mSv to 20 mSv, still with the requirement to keep doses as low as reasonably practicable. To ensure this, the employer is required to carry out an investigation in cases where a worker exceeds an annual dose of 15 mSv, or other, lower, limit set by the employer. The regulations also require that any person likely to receive a dose in excess of 6 mSv, or three-tenths of any dose limit, should be classified. Classified workers must have their doses assessed and recorded by an Approved Dosimetry Service (ADS).

Each ADS supplies personal monitoring information on classified workers to the Central Index of Dose Information (CIDI), which is maintained by HPA-RPD for the Health and Safety Executive. Annual analyses of recent data held by CIDI have been published (CIDI, 1998; CIDI, 1999; CIDI, 2000; CIDI, 2001; CIDI, 2002; CIDI, 2003). The information in these reports, together with data published in annual company reports and data obtained by direct enquiry are the sources of data on occupational exposure presented here.

The data are presented where possible as dose distributions, showing the numbers of workers in ranges of individual annual dose. The collective dose is also given, being the sum of the individual doses of the workers shown. The average annual dose is obtained by dividing the annual collective dose by the number of workers. The average dose is used because of its simplicity, in preference to other possible parameters such as the geometric mean or the median dose.

4.1 Nuclear industry

During the period covered by this review, British Nuclear Fuels plc (BNFL) has carried out a variety of operations, including nuclear power operation, fuel manufacture, enrichment, reprocessing and radioactive waste disposal. The advanced gas cooled reactor power stations (AGRs) and the Sizewell B pressurised water reactor station (PWR) have been operated by British Energy. In addition, the Magnox reactor power stations were operated by Magnox Electric plc, part of the BNFL Magnox Generation Business Group, but during the period covered by this review management of the Magnox reactor sites became the responsibility of the British Nuclear Group.

The tables of occupational exposure data for workers in the nuclear industry (Tables 12 to 19) include both employees and contractors when monitored by the organisation's ADS. Other groups of contractors may be monitored by other ADSs and are therefore not included in the tables, but these will be small groups and the omission of this data would not affect the overall pattern of the data discussed below. Data are usually for classified workers, with some unclassified workers included. Data for NNC Limited are included in nuclear power stations, Table 17. Data on occupational exposure in the nuclear industry were obtained from a number of sources, but the majority were obtained directly from each organisation.

4.1.1 Fuel enrichment

URENCO (Capenhurst) Limited (UCL) operates uranium enrichment facilities using the gas centrifuge process. UCL is located at the Capenhurst site, which is jointly shared with BNFL Capenhurst. Occupational exposure data for UCL staff (Lawrence, 2003; Lawrence, 2004) are given in Table 12. All workers receive less than 5 mSv annually, and though the collective dose, and therefore the average dose, is seen to vary slightly from year to year, the average annual dose is still low, and is comparable with doses quoted in the previous review (Hughes, 1999).

TABLE 12 Occupational exposure of workers at URENCO (Capenhurst) Limited

	Number of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	345	0	0	0	345	0.056	0.16
1999	311	0	0	0	311	0.053	0.17
2000	310	0	0	0	310	0.109	0.35
2001	309	0	0	0	309	0.068	0.22
2002	329	0	0	0	329	0.093	0.28
2003	292	0	0	0	292	0.065	0.22

TABLE 13 Occupational exposure of classified workers at BNFL Capenhurst

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	99	0	0	0	99	0.030	0.30
1999	105	0	0	0	105	0.028	0.27
2000	167	0	0	0	167	0.070	0.42
2001	12	0	0	0	12	0.028	2.33
2002	17	0	0	0	17	0.022	1.30
2003	93	0	0	0	93	0.036	0.39

BNFL continues to have workers at the Capenhurst site, having operated the enrichment works until 1993, and now being engaged in decommissioning work. Occupational doses for classified BNFL workers (Thomas, 2003; Thomas 2004; Caine, 2004) at Capenhurst are shown in Table 13. The average annual dose is higher than in the previous review (Hughes, 1999). This is largely because previous data for BNFL Capenhurst included both classified and unclassified workers, while the data in Table 13 is for classified workers only, who would be expected to receive higher doses than non-classified workers. As the number of classified workers decreases it would also be expected that the remaining classified workers are likely to receive higher doses than those who have become unclassified, therefore increasing the average annual dose. This is especially true in 2001 and 2002, where the number of workers is very low. However, while there were small increases in individual doses, all individual annual doses remained below 5 mSv and in most years the average annual dose was less than 0.5 mSv.

Although the average individual dose of 0.39 mSv in 2003 is slightly higher than the 0.3 mSv reported for 1997 (Hughes, 1999), because of the lower number of workers (93 compared with 238) the collective dose has dropped from 0.07 man Sv in 1997 to 0.036 man Sv in 2003.

4.1.2 Fuel fabrication

The manufacture of nuclear fuel involves the handling of uranium compounds, which can lead to external exposure from gamma rays and the intake of airborne radionuclides. Data for occupational exposure of workers at the BNFL Springfields factory (Thomas, 2003; Thomas, 2004; Caine, 2004) is given in Table 14. The number of workers over the period 1998-2003 shows a downward trend, continuing the decline in the number of workers noted in the previous review. Of these workers, less than 1% receive an annual dose higher than 5 mSv, with the average annual dose being less than 1 mSv. The collective and average doses over the period 1998-2003 are lower than the doses seen in the previous review, (Hughes, 1999) though they show minor fluctuations from year to year.

TABLE 14 Occupational exposure of classified workers at BNFL Springfields

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	2431	2	0	0	2433	1.80	0.74
1999	2322	0	0	0	2322	1.69	0.73
2000	2312	0	0	0	2312	1.75	0.76
2001	2285	0	0	1	2286	1.92	0.84
2002	2185	0	0	0	2185	1.63	0.75
2003	1919	0	0	0	1919	1.32	0.69

4.1.3 Nuclear power stations

Occupational exposures of workers in nuclear power stations in the UK are given in Tables 15 and 16 (Morris, 2003; McNamara, 2004; Varcoe, 2002; Varcoe, 2003). It should be noted that the data presented in Table 15 were obtained from doses received at individual sites. A number of workers move between British Energy sites, and may accumulate doses at different sites. A worker's dose from each site would combine to give an individual annual dose. As a result of this there are likely to be more workers whose individual annual doses fall in the higher dose ranges than shown. The following discussion is based solely on the reported doses and so does not consider the total individual doses to workers at BE sites. However it should be noted that British Energy has a Company Dose Restriction Level (CDRL) of 10 mSv, which applies to an individual's dose across all sites. In 2003 no staff exceeded the CDRL.

The number of workers is lower than in the previous review, and average doses continue to be low. The vast majority of workers at British Energy and Magnox sites received annual doses of less than 5 mSv between 1998 and 2003. Only 30 workers out of 12394 (0.2%) had a dose of more than 5 mSv in 2003 (Tables 15 and 16).

Occupational exposures for BNFL workers at the Calder Hall site are included in the data for BNFL Sellafield in Section 4.1.4. Data for nuclear power station workers are given in Table 17, including data for NNC Limited, a group of contractors who also work at other types of sites (Catterall, 2002; Hawkrigg, 2004), together with data for BNFL Chapelcross workers and data for workers at BE and Magnox sites. The average annual dose received by these workers was 0.18 mSv in 2003, compared with 0.3 mSv in 1997. The collective dose to this group of workers has also fallen from 7.8 man Sv in 1997 to 2.4 man Sv in 2003.

TABLE 15 Occupational exposure at British Energy power stations

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	9521	1	0	0	9522	1.20	0.13
1999	10627	42	0	0	10669	2.30	0.22
2000	9605	23	1	0	9629	1.73	0.18
2001	7681	1	0	0	7682	0.62	0.08
2002	9836	49	0	0	9885	1.54	0.16
2003	9565	30	0	0	9595	1.28	0.13

TABLE 16 Occupational exposure at Magnox sites (not including Chapelcross)

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	9526	28	0	0	9554	3.08	0.32
1999	8951	83	0	0	9034	2.71	0.30
2000	8526	10	0	0	8536	2.01	0.24
2001	8166	14	0	0	8180	1.41	0.17
2002	8229	6	0	0	8235	1.23	0.15
2003	2799	0	0	0	2799	0.47	0.17

TABLE 17 Occupational exposure at UK power stations, 2003

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Sites	0-5	5-10	10-15	>15			
BE Sites	9565	30	0	0	9595	1.28	0.13
Magnox Sites	2799	0	0	0	2799	0.47	0.17
BNFL Chapel-cross	418	4	0	0	422	0.58	1.37
NNC	322	0	0	0	322	0.0396	0.12
Total	13104	34	0	0	13138	2.37	0.18

4.1.4 Fuel reprocessing and other work

Nuclear fuel reprocessing is carried out at the BNFL Sellafield site along with decommissioning and waste disposal work. Data on the occupational exposure of workers at Sellafield (Thomas, 2003; Thomas, 2004; Caine, 2004), including workers at the Calder Hall nuclear power station, are given in Table 18. The data show continuation of a downward trend, though there is some variation in average annual dose from year to year. Although the number of workers has increased, the annual collective dose has remained at a comparable level over the period 1998 to 2003, resulting in a reduction in average annual dose from 1.26 to 0.78 mSv. No workers received an annual dose more than 15 mSv during this period, and there is a significant decrease in individual doses, with no worker receiving more than 10 mSv in 2003, compared with 64 workers (0.7%) in 1997 (Hughes, 1999).

Workers at BNFL headquarters, Risley, can receive occupational exposures while visiting other sites. Dose data for these workers (Thomas, 2003; Thomas, 2004; Caine, 2004) are shown in Table 19. Their doses are generally very low, with only one dose in excess of 5 mSv during the period 1998-2003. The number of workers and the collective and average annual doses are comparable with numbers reported previously, showing no trend, just minor fluctuations from year to year.

TABLE 18 Occupational exposure of classified workers at BNFL Sellafield

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	8744	665	53	0	9462	11.900	1.26
1999	8175	559	17	0	8751	10.820	1.24
2000	10721	312	1	0	11034	8.620	0.78
2001	11638	341	2	0	11981	11.110	0.93
2002	12288	250	3	0	12541	10.064	0.80
2003	12339	208	0	0	12547	9.752	0.78

TABLE 19 Occupational exposure of classified workers at BNFL Risley

	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
Year	0-5	5-10	10-15	>15			
1998	422	0	0	0	422	<0.200	<0.47
1999	618	0	0	0	618	0.120	0.19
2000	749	0	0	0	749	0.190	0.25
2001	810	0	0	0	810	0.332	0.41
2002	785	1	0	0	786	0.247	0.31
2003	541	0	0	0	541	0.176	0.33

4.2 Nuclear and technology services

Workers in the United Kingdom Atomic Energy Authority (UKAEA) receive exposures from a range of activities, including a significant fraction from decommissioning operations. Occupational exposure data (Crofts, 2002; NuSAC 2004; NuSAC 2005) are given in Table 20. Doses continue the downward trend reported in the previous review, with the average dose being 0.17 mSv in 2003, compared with 0.2 mSv in 1997. Individual doses have remained comparable with the low levels attained at the end of the period covered in the last review, with no workers receiving a dose in excess of 15 mSv during the period 1998-2003.

Occupational exposures for workers in AEA Technology (AEAT) (Ward, 2004) are shown in Table 21. Between 1998 and 2000, average doses are seen to fall. However in 2001 the company began to divest its nuclear activities, leading to the significant fall in the number of monitored workers. Groups who only occasionally undertook radioactive work and therefore only received low radiation doses were divested first, leading to an increase in the average dose for the remaining staff in 2002. Less significantly, the change from routine operations to decommissioning during this period resulted in changes to work and exposure patterns. These changes were managed to achieve a steady reduction in maximum dose (8.6 mSv in 1999, 4.95 mSv in 2002 and 1.22 mSv in 2003).

TABLE 20 Occupational exposure at UKAEA sites

Year	No of workers in range (mSv)			Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
	0-5	5-15	>15			
1998	4787	10	0	4797	0.877	0.18
1999	4805	7	0	4812	0.766	0.16
2000	4846	8	0	4854	0.658	0.14
2001	5237	0	0	5237	0.669	0.13
2002	5313	5	0	5318	0.85	0.16
2003	4978	13	0	4991	0.83	0.17

TABLE 21 Occupational exposure at AEAT sites

Year	No of workers in range (mSv)				Total number of workers	Collective Dose (man Sv)	Average Dose (mSv)
	0-5	5-10	10-15	>15			
1998	1139	15	0	0	1154	0.43	0.5
1999	1001	6	0	0	1007	0.41	0.4
2000	958	2	0	0	960	0.31	0.3
2001	385	0	0	0	385	0.25	0.6
2002	336	0	0	0	336	0.28	0.8
2003	172	0	0	0	172	0.06	0.3

4.3 Defence Workers

4.3.1 Ministry of Defence

Workers receive exposures from radiation sources and radioactive materials used by the Ministry of Defence (MoD) and its contractors, including submarine refitting and maintenance. Most of these workers are monitored by DERA Radiation Protection Services and occupational exposures (Phillips, 2002; Phillips, 2004) to these workers for the years 1998 to 2003 are given in Table 22. After a significant reduction in the annual collective dose in the period covered by the previous review, it has remained fairly steady for the period covered here. The numbers of staff monitored each year also remained fairly level, with the result that the average annual dose also shows little change over this period. The majority of staff received an annual dose less than 5 mSv, with only one worker in 1998 receiving more than 10 mSv.

TABLE 22 Occupational exposure in MoD (DERA monitored sites)

Year	Number of workers in dose range (mSv)					Total	Collective dose (man Sv)	Average dose (mSv)
	0-5	5-10	10-15	15-20	>20			
1998	9835	15	1	0	0	9,851	2.45	0.25
1999	9986	16	0	0	0	10,002	3.26	0.33
2000	9829	24	0	0	0	9,853	2.97	0.30
2001	9979	17	0	0	0	9,996	2.60	0.26
2002	9942	3	0	0	0	9,945	2.99	0.30
2003	9248	0	0	0	0	9,248	1.92	0.21

A separate dosimetry service monitors workers at Atomic Weapons Establishment (AWE) sites and occupational exposures (Phillips, 2002; Phillips, 2004) for the years 1998 to 2003 are given in Table 23. The number of workers (both MoD and non-MoD personnel) and the annual collective dose are both slightly lower than in the previous review, with the average annual dose indicating a slight reduction in doses, though they were already at a low level. Only one worker at AWE sites received an annual dose of more than 5 mSv over this period.

TABLE 23 Occupational exposure in MoD (AWE sites)

Year	Number of workers in dose range (mSv)					Total	Collective dose (man Sv)	Average dose (mSv)
	0-5	5-10	10-15	15-20	>20			
1998	3824	1	0	0	0	3,825	0.7	0.18
1999	3646	0	0	0	0	3,646	0.6	0.16
2000	3629	0	0	0	0	3,629	0.5	0.13
2001	3479	0	0	0	0	3,479	0.5	0.14
2002	3162	0	0	0	0	3,162	0.3	0.09
2003	2839	0	0	0	0	2,839	0.2	0.07

For all MoD and AWE workers in 2003 the annual collective dose was 2.1 man Sv and the average annual dose was 0.2 mSv, compared respectively with 4.1 man Sv and 0.3 mSv in 1997 (Hughes, 1999).

4.3.2 Defence Industry

Rolls-Royce (RR) has been involved in the UK naval nuclear programme since its inception in the 1950s. The company designs, supplies and supports the pressurised water reactor systems and equipment that power the Royal Navy's submarines. Data supplied from Rolls Royce Marine Power Operations Ltd (Hales, 2003; Cresswell, 2004), giving occupational exposures to employees involved in manufacturing for 1998-2003, are shown in Table 24. During this period both the annual collective dose and the average annual dose fell by a factor of 3 and no worker received an annual dose in excess of 5 mSv.

TABLE 24 Occupational exposure at RR

Year	Number of workers in dose range (mSv)				Total	Collective dose (man Sv)	Average dose (mSv)
	0-5	5-10	10-20	>20			
1998	437	0	0	0	437	0.13	0.3
1999	427	0	0	0	427	0.12	0.3
2000	440	0	0	0	440	0.06	0.1
2001	442	0	0	0	442	0.07	0.2
2002	429	0	0	0	429	0.06	0.1
2003	412	0	0	0	412	0.04	0.1

4.4 Medicine

Individual doses in medicine tend to be low and therefore there are very few classified workers in this field. There were less than 200 classified workers in the medical sector, with the number decreasing over the period covered by this review (CIDI 1998; CIDI 1999; CIDI 2000; CIDI 2001; CIDI 2002; CIDI, 2003). However, there is a tendency for a large number of workers to be issued with personal dosimeters to provide reassurance that doses continue to remain low, and to provide a means to monitor work procedures. As in the previous two reviews, a survey was carried out with the co-operation of some of the larger dosimetry services, which were contacted through the UK Personal Radiation Monitoring Group. Requests for data from the dosimetry services were made at an early stage in the collection of data for this review. Data were requested and supplied for 2001 (Pryor, 2002; Biggart, 2002; Green, 2002; Boreham, 2002; Thomas, 2002; Marland, 2002; Moore, 2002; Rajendram, 2002; Dhanse, 2002; Marsden, 2002; Gilvin 2003) and are shown in Tables 25-29. Some dosimetry services were able to supply dose information grouped by area of work: data from these are shown in Tables 25-27, and summarised in Table 28 under the heading "main sample". Other services were unable to distinguish between different occupational groups, and these data are under the heading "Further sample" in Table 28. Some dosimetry services were unable to supply data. The data presented in Tables 25-29 may include data for classified workers, if the dosimetry services providing the data monitored any of the small number of classified workers in the medical sector.

For this review, as well as collecting data on whole body doses, data was also collected for extremity doses. Extremity dosimeters are worn in a variety of body locations, the location being determined by the occupation or procedure. The most commonly monitored locations are the hands, forehead (or eye) and the tibia (lower leg). The extremity data (equivalent doses, rather than effective doses) for these most commonly monitored positions are summarised in Table 29.

4.4.1 Diagnostic radiology

Annual doses in diagnostic radiology departments for 2001 are shown in Table 25. In this survey, unlike previous reviews, there is differentiation between diagnostic and interventional radiologists (see Glossary). This is in recognition of the fact that interventional radiology is now more widely used, is becoming more advanced, and now often involves lengthy procedures. These data show that interventional radiologists have a noticeably higher average annual dose than the diagnostic radiologists. In fact, interventional radiologists have the highest average annual dose (0.35 mSv) of all the occupational groups in this field, closely followed by cardiologists (0.20 mSv). For both of these groups almost 95% of staff receive annual doses less than 1 mSv. Other occupational groups receive very low average annual doses, with 99% of all workers in this field receiving less than 1 mSv annually. Overall the average annual dose in diagnostic radiology is 0.08 mSv, the same as in the previous review (Hughes, 1999).

TABLE 25 Occupational exposures in diagnostic radiology departments in 2001*

Occupational Group	Number of workers in dose range (mSv)						Total	Collective dose (milli man Sv)	Average dose (mSv)
	0-1	>1-5	>5-10	>10-20	>20-30	>30			
Diagnostic radiologists	456	11	0	0	0	0	467	68.3	0.15
Interventional radiologists	63	4	0	0	0	0	67	23.1	0.35
Cardiologists	544	29	0	0	0	0	573	114.0	0.20
Other Clinicians	1178	19	0	0	0	0	1197	91.8	0.08
Radiographers	4581	30	1	0	0	0	4612	297.4	0.06
Nurses	2120	21	0	0	0	0	2141	159.0	0.07
Scientists and Technicians	590	2	0	0	0	0	592	20.6	0.03
Other Staff	804	5	0	0	0	0	809	65.5	0.08
Total	10336	121	1	0	0	0	10458	839.6	0.08

Notes: * Survey data supplied by a number of UK dosimetry services.

Extremity equivalent doses in diagnostic radiology are shown in Table 29. The most commonly monitored position was the eye/forehead, and the highest annual doses were recorded on the hand, fingers and leg. For most monitoring positions the majority of annual equivalent doses recorded were less than 1 mSv, with almost all (>95%) of the doses being less than 20 mSv. However for the left hand/finger measurements, there were a number of annual equivalent doses to the finger greater than 50 mSv, leaving only 89% of annual equivalent doses below 20 mSv. It must be noted that while these values appear high compared to the effective doses, the annual dose limits (IRR, 1999) are higher for the extremities (150 mSv for the eye, 500 mSv for the skin or for hands, forearms, feet and ankles).

4.4.2 Radiotherapy

Annual doses to workers in radiotherapy departments for 2001 are given in Table 26. Modern equipment for radiotherapy treatment tends to be very well shielded, and most treatments with implanted sources are now managed remotely, so reducing the need to work closely with sources or with patients implanted with sources. However this area of work can lead to elevated doses. The group of source technicians is very small and although they all receive an annual dose of less than 1 mSv, they have the highest average annual dose (0.34 mSv) of all the occupational groups in radiotherapy. Doses among other occupational groups are very low, with 99% of staff receiving less than 1 mSv annually and nobody received more than 5 mSv. Overall the average annual dose is 0.07 mSv, marginally, but not significantly, less than that found in the previous review.

TABLE 26 Occupational exposures in radiotherapy departments in 2001*

Occupational Group	Number of workers in dose range (mSv)						Total	Collective dose (milli man Sv)	Average dose (mSv)
	0-1	>1-5	>5-10	>10-20	>20-30	>30			
Beam Radiographers	763	1	0	0	0	0	764	60.5	0.08
Radiotherapists	340	2	0	0	0	0	342	23.0	0.07
Theatre Nurses	276	2	0	0	0	0	278	6.9	0.02
Other Nurses	490	2	0	0	0	0	492	37.5	0.08
Source Technicians	8	0	0	0	0	0	8	2.7	0.34
Scientists and Technicians	253	6	0	0	0	0	259	25.7	0.10
Other Staff	267	0	0	0	0	0	267	16.3	0.06
Total	2397	13	0	0	0	0	2410	172.6	0.07

Notes: * Survey data supplied by a number of UK dosimetry services.

Very little extremity monitoring occurs in radiotherapy departments. Extremity equivalent doses are shown in Table 29. Most monitors were worn on the right hand or finger, and were worn by scientists or technicians. The average annual equivalent dose for this position was 6 mSv, with 87% of doses being less than 10 mSv.

4.4.3 Nuclear Medicine

As in the previous review (Hughes, 1999) whole body doses in nuclear medicine departments are noticeably higher than in diagnostic radiology and radiotherapy departments. In 2001, the groups of nurses and radiographers/technicians show the highest average annual dose of 0.7 mSv, followed by pharmacists with an average dose of 0.4 mSv. The higher doses in nuclear medicine are largely due to the close contact with patients and radiopharmaceuticals (largely ^{99m}Tc). The doses recorded are also noticeably higher than in the previous review. In this survey the overall annual average dose of nuclear medicine workers was 0.40 mSv, compared with 0.33 mSv in the previous review. Only 85% of workers received less than 1 mSv, compared with 92% in the previous review. Some of this increase in doses could be due to the increasing workload in nuclear medicine, with some departments showing a 15% increase in the number of imaging procedures carried out between 1998 and 2001 (Keir, 2002).

TABLE 27 Occupational exposures in nuclear medicine departments in 2001*

Occupational Group	Number of workers in dose range (mSv)						Total	Collective dose (milli man Sv)	Average dose (mSv)
	0-1	>1-5	>5-10	>10-20	>20-30	>30			
Pharmacists	82	13	1	0	0	0	96	40.3	0.42
Radiographers & Nuclear Medicine Technicians	181	81	0	0	0	0	262	186.0	0.71
Scientists	83	5	0	0	0	0	88	22.4	0.25
Clinicians	62	6	0	0	0	0	68	19.2	0.28
Nurses	49	15	0	0	0	0	64	44.9	0.70
Other Staff	220	3	0	0	0	0	223	5.8	0.03
Total	677	123	1	0	0	0	801	318.6	0.40

Notes: * Survey data supplied by a number of UK dosimetry services.

Extremity equivalent doses in nuclear medicine are shown in Table 29. Technicians and radiographers are the most monitored group, followed by pharmacists, with pharmacists receiving the highest average annual extremity doses. Extremity monitoring in nuclear medicine is almost exclusively on the left and right hand/fingers. The average annual equivalent dose recorded in these positions was 10 mSv, with 73% of doses being less than this average value. Again these doses are noticeably higher than for diagnostic radiology or radiotherapy groups.

4.4.4 All medical workers

The dose data for the three main work areas, shown in Tables 25-27, are summarised as the main sample in Table 28. In addition to this, data were supplied for a further sample, which have been added to the main sample in Table 28, to give an overall sample of almost 26,000 workers in the medical sector. The average annual dose for these workers was 0.14 mSv, which is a little higher than the value found in the previous review.

TABLE 28 Occupational exposures in medicine in the UK in 2001*

Work category	Number of workers in dose range (mSv)							Total	Collective dose (milli man Sv)	Average dose (mSv)
	0-1	>1-5	>5-10	>10-20	>20-30	>30	NS#			
Main Sample:										
Diagnostic Radiology	10336	121	1	0	0	0	-	10458	839.6	0.08
Radiotherapy	2397	13	0	0	0	0	-	2410	172.6	0.07
Nuclear Medicine	677	123	1	0	0	0	-	801	318.6	0.40
Main Sample Total	13410	257	2	0	0	0	-	13669	1330.8	0.10
Further Sample	5671	120	2	0	0	0	6437	12230	2337.4	0.19
Survey Total	19081	377	4	0	0	0	6437	25899	3668.2	0.14
Survey Total as Percentage†	98.0	1.9	<0.1	0	0	0	-	100	-	-
Dental Practice	3427	4	0	0	0	0	8270	11701	982.2	0.08
(see section 4.5)										

Notes: * Survey data supplied by a number of UK dosimetry services.

NS = Sample for which dose range distribution not specified

† For data supplied with dose distribution

Table 29 shows the distribution of extremity doses in the three main work areas for the commonly monitored body positions, together with the total and average extremity doses. The breakdown of doses in each dose range is given in Figure 7, which also shows the total numbers of dosimeters at each body location. The right hand/finger is the most commonly monitored location. While there were a number of cases where individual doses for the left and right hand/finger were not specified, of those dosimeters where the dose range was reported it can be seen that the hand/fingers receive the highest annual equivalent doses.

TABLE 29 Occupational extremity exposures (equivalent doses) in medicine in the UK in 2001*

Work area and monitor position	Number of workers in dose range† (mSv)									Total	Collective equivalent dose (mSv)	Average equivalent dose (mSv)
	0-1	>1-5	>5-10	>10-20	>20-30	>30-40	>40-50	>50	NS#			
Diagnostic radiology												
Left Hand/Finger	60	45	29	18	5	4	0	15	-	176	1082.1	6.15
Right Hand/Finger	130	71	26	12	11	7	3	1	-	261	1225.6	4.70
Hand	62	32	2	1	2	0	0	1	-	100	250.2	2.50
Eye/Forehead	449	283	69	21	6	3	0	0	-	831	1794.5	2.16
Lower Leg	20	49	22	12	1	1	0	0	-	105	536.3	5.11
Radiotherapy												
Left Hand/Finger	5	2	0	1	1	0	0	0	-	9	38.9	4.32
Right Hand/Finger	30	13	10	1	4	2	0	1	-	61	364.5	5.98
Hand	0	0	0	0	0	0	0	0	-	0	0.0	0
Eye/Forehead	1	0	0	0	0	0	0	0	-	1	0.8	0.77
Nuclear Medicine												
Left Hand/finger	74	71	32	41	9	3	2	12	-	244	2460.3	10.08
Right Hand/Finger	108	82	36	40	15	8	2	15	-	306	3059.1	10.00
Hand	1	0	0	0	0	0	0	0	-	1	0.0	0
Eye/Forehead	3	1	1	0	0	0	0	0	-	5	10.2	2.04
Unspecified												
Left Hand/Finger	32	24	21	11	5	2	1	0	81	177	640.1	3.62
Right Hand/Finger	80	46	20	11	10	5	2	6	499	679	4839.5	7.13
Hand	65	28	6	9	5	5	3	11	-	132	1611.3	12.21
Eye/Forehead	160	82	19	13	5	0	0	0	-	279	691.3	2.48
Total dosimeters												
Left Hand/Finger	171	142	82	71	20	9	3	27	81	606	4221.4	6.97
Right Hand/Finger	348	212	92	64	40	22	7	23	499	1307	9488.7	7.26
Hand	128	60	8	10	7	5	3	12	0	233	1861.5	7.99
Eye/Forehead	613	366	89	34	11	3	0	0	0	1116	2496.8	2.24
Lower Leg	20	49	22	12	1	1	0	0	0	105	536.3	5.11

Notes: * Survey data supplied by a number of UK dosimetry services.

\# NS = Sample for which dose range distribution not specified

† These equivalent doses should be compared against the annual dose limits of

Eye: 150 mSv

Other location: 500 mSv

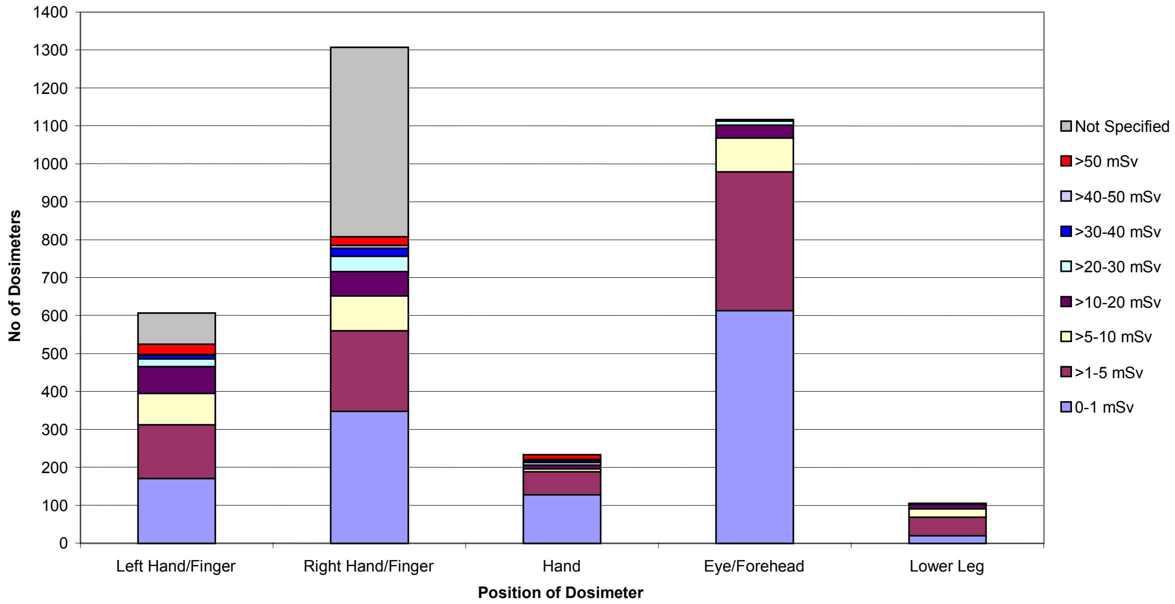


Figure 7 Annual occupational extremity doses in the UK medical sector

Data for almost 26,000 workers in the medical field were provided for this review. However, some dosimetry services were not able to provide data for this survey. It is therefore not possible to accurately estimate the total number of monitored workers in the medical sector in the UK, but it is unlikely to be significantly higher than the 40,000 estimated in the previous review. If the average annual dose of 0.14 mSv is applied to 40,000 workers, the annual collective dose received by workers in medicine is 5.6 man Sv. Dose distribution data was supplied for 19462 workers. The vast majority of these workers (98%) receive less than 1 mSv annually. The 150 or so classified medical workers registered with CIDI received an annual collective dose of 236 milli man Sv in 2001, giving an average annual dose of 1.6 mSv (CIDI, 2001).

4.5 Dentistry

Doses from dental examinations, if carried out correctly, should give only very low doses to dental staff. A few dentists with high workloads and using specialist equipment may receive a few millisieverts in a year. Only seven dentists were registered as classified workers in 2001 (CIDI, 2001) and they received an average annual dose of 2.3 mSv.

Occupational exposure data for dental workers were collected with the survey of medical workers described in Section 4.4. Data were supplied for nearly 12,000 workers, as shown in Table 28. Of these workers, 99% received an annual dose of less than 1 mSv. The average annual dose to dental workers in this survey was 0.08 mSv, which while low, is higher than the value of 0.01 mSv obtained in the previous review (Hughes, 1999). It is not known whether this represents a trend.

The General Dental Council (GDC, 2003) indicates that there were 32,500 dentists registered in the UK in 2003. Applying the average annual dose of 0.08 mSv found in this survey to this number of workers, gives a collective dose in dentistry of 2.6 man Sv. This value is noticeably higher than in the previous review (Hughes, 1999), partly due to the higher average annual dose and partly due to the greater number of workers.

4.6 Veterinary practice

A survey carried out by the Institute for Employment Studies for the Royal College of Veterinary Surgeons in 2000 (Robinson and Hooker, 2001) found that there were around 10,000 veterinary surgeons in the UK. Some of these will use X-ray equipment and other sources of radiation. Some will use radiation sources more than others and doses are expected to be low, but many wear dosimeters both as a precaution and to provide reassurance that doses do continue to be low.

A small number of veterinary staff are classified workers, with 122 classified workers receiving an average annual dose of 0.6 mSv in 2003 (CIDI, 2003). Analysis of doses received by around 1800 unclassified workers monitored by the NRPB and Cardiff monitoring services in 2001 (Gilvin, 2003; Thomas, 2002) indicates an average annual dose of 0.2 mSv. Assuming all 10,000 workers use radiology or radiation sources at some time, this implies an annual collective dose of around 2 man Sv. This is higher than that recorded in the previous survey. This is partly due to an increased number of workers, and partly due to the higher average annual dose. It is possible that the higher average annual dose is due to an increasing number of procedures involving X-rays or other sources of radiation being carried out on animals.

4.7 Research and tertiary education

University laboratories and research establishments use various sources of radioactive materials and sources of ionising radiation for experimental work. Many workers wear dosimeters for short periods while carrying out particular experiments but few are monitored continuously. Annual doses tend to be low and only a minority of workers are classified. In 2001 there were 545 classified workers in academic research and teaching and their average dose was 0.1 mSv (CIDI, 2001).

Information for this review was provided from data collected by the Association of University Radiation Protection Officers (AURPO), in 26 universities and research establishments (Moseley, 2002). Data were collected for recent years, giving the number of workers and average dose for each year. The results are given in Table 30. In 2001, a total of 4194 workers were included in this survey.

This number is lower than in recent years; in fact, numbers have been steadily declining since 1997. This is partly due to a decline in the use of radionuclides and partly due to restrictions on the numbers of people provided with dosimeters, with dosimeters tending to be provided only to those workers more likely to record a dose. This would account for the slight increase in average dose since 1997. Despite this slight increase over recent years, the average annual dose remains very low at below 0.1 mSv.

TABLE 30 Occupational exposure in academic research and teaching

Year	1997	1998	1999	2000	2001
No of workers	4900	4737	4553	4375	4194
Average Annual Dose (mSv)	0.043	0.046	0.046	0.048	0.065

Not all universities were able to supply data, so an accurate estimate of the total number of workers monitored in this field is not possible. However it was estimated that very approximately 40% of monitored university workers were included in this survey, and therefore it is estimated that there are around 10,000 monitored workers in this field. The annual collective dose in this field is therefore estimated as 0.6 man Sv.

4.8 General industry

There are many uses of ionising radiations in industry, including engineering, construction, production of oil and gas and maintenance of aircraft. For example, radioactive materials are used in research; X-rays and sealed gamma sources are used for industrial radiography, for the detection and evaluation of flaws in materials; sealed sources are used to measure the thickness of some materials during production. Many workers using ionising radiation will wear dosimeters, but may not be classified workers. Most workers use sources that are well shielded so receive very low doses, but some workers, such as industrial radiographers, use sources that are not, or are only partially, shielded, and therefore tend to receive higher doses.

Occupational data for classified workers are collated and published annually by CIDI, the Central Index of Dose Information (CIDI, 1998; CIDI, 1999; CIDI, 2000; CIDI, 2001; CIDI, 2002; CIDI, 2003). Data for classified workers in industry in 2003 are given in Table 31. Workers transporting radioactive materials continue to have the highest average annual dose (0.9 mSv), with the lowest doses occurring in the fields of onshore and offshore drilling, and industrial research.

The number of classified workers in general industry has fallen by 37% from 11376 in 1997 (Hughes, 1999) to 7181 in 2003. The collective dose has also fallen, so the average annual dose is unchanged at 0.4 mSv. Overall doses are low, and around 90% of these classified workers received a dose of no more than 1 mSv in 2003.

TABLE 31 Occupational exposures of classified workers in general industry in 2003

Type of work	Number of workers in dose range (mSv)								Total	Collective dose (milli man Sv)	Average dose (mSv)
	0	0 - 1	1 - 6	6 - 10	10 - 15	15 - 20	20 - 30	>30			
Industrial radiography	1240	1100	197	10	6	1	0	0	2554	917	0.4
Use and servicing of ionising radiation machinery	616	306	25	7	0	0	0	1	955	568	0.6
Application & manipulation of radioactive substances	457	572	189	4	0	0	0	0	1222	632	0.5
Transport work	21	28	20	1	0	0	0	0	70	65	0.9
Offshore work	404	358	13	0	0	0	0	0	775	120	0.2
Onshore drilling	13	11	1	0	0	0	0	0	25	7	0.3
Industrial research	354	511	56	0	0	0	0	0	921	234	0.3
Other industrial applications	425	204	22	8	0	0	0	0	659	159	0.2
Total	3530	3090	523	30	6	1	0	1	7181	2702	0.4

Some data for about 500 non-classified workers in general industry in 2001 (Thomas, 2002; Gilvin, 2003) were supplied. This represents a fraction of the non-classified workers but these data indicate that doses are very low. The average annual dose for that group was calculated to be less than 0.01 mSv, and 99% of these workers received less than 1 mSv.

Amersham plc (now GE Healthcare) manufactures and supplies radioactive materials from its main sites at Amersham and Cardiff. Occupational data (McHardy, 2002; NuSAC 2004; NuSAC 2005) for Amersham employees at all these sites are shown in Table 32. The number of workers has remained fairly stable, but the collective dose has fallen by more than a third between 1998 and 2003, leading to a fall in the average annual dose. This continues the downwards trend reported in the previous review (Hughes, 1999). While the majority (98%) of employees received a dose of less than 5 mSv in 2003, and the average dose was 0.7 mSv, a few employees do receive higher doses, though no employee received a dose greater than 10 mSv in 2003. Amersham plc also has large numbers of contract workers who tend to receive lower doses. The average annual dose for contractors at Amersham sites is around 0.2 mSv.

TABLE 32 Occupational exposure in radionuclide production

Year	Number of workers in dose range (mSv)				Total	Collective dose (milli man Sv)	Average dose (mSv)
	0-5	5-10	10-15	15-20			
1998	1077	72	0	0	1149	1259	1.1
1999	1116	46	0	0	1162	1078	0.9
1998	1127	32	0	0	1159	935	0.8
2001	1116	25	0	0	1141	795	0.7
2002	1067	25	0	0	1092	790	0.7
2003	1064	23	0	0	1087	720	0.7

Based on the data available it is estimated that around 10,000 workers in general industry receive an annual collective dose of around 3 man Sv. This implies an average annual dose of 0.3 mSv.

4.9 Radon in mines and caves

Radon concentrations in the air in underground workplaces tend to be elevated above those outdoors, due to the restricted ventilation. In large mines ventilation rates are generally good and this prevents radon concentrations becoming excessive. The average annual individual dose from radon in large coal mines has previously been assessed to be 0.6 mSv (Hindmarsh, 1992), and this is taken as the current estimate, as no more recent assessment is available. The current number of coal miners is estimated to be about 5,000 (HSE, 2004), and these workers therefore receive an annual collective dose of about 3 man Sv.

Industrial mineral mines, and small private coal mines, tend to have higher radon levels than large coal mines. The average annual dose for these mines, estimated from data in the previous review, was 2.6 mSv (Hughes, 1999). At the time of the previous review it was estimated that there were some 1,500 miners working in these mines. Since then some mines have closed and currently there are about 800 such miners (Fenton, 2004). One mine has about 500 underground workers, and in this mine the average annual dose is approximately 0.3 mSv (Gooding, 2004). In the absence of other new data, the average annual dose for the other 300 miners is assumed to be 2.6 mSv, as estimated above from data in the previous review. From these data, the annual collective dose for all 5,800 miners is estimated to be 3.9 man Sv, and the average annual dose is therefore 0.7 mSv. In 2003, 55 miners were classified workers, with an average dose of 5.2 mSv, and 28 of these received annual doses in the range 6 to 10 mSv (CIDI, 2003).

4.10 Radon in above-ground workplaces

In areas of the country where there are homes with generally elevated levels of indoor radon, such as the south west of England, workplaces are similarly affected. If the radon concentration, averaged over a 24 hour period, exceeds 400 Bq m^{-3}, the Ionising Radiations Regulations, 1999, (IRR) applies (GB Parliament, 1999a). Employers are required to identify all sources of risk to employees (GB Parliament, 1999c). In radon Affected Areas this must include assessments of occupational exposures to radon, which involves carrying out measurements of the radon air concentrations at the premises. Through these measurements, and other surveys being carried out by NRPB, such premises continue to be identified, but currently the number identified is small in relation to the predicted number. The results of the national survey (Wrixon et al, 1988) that was carried out in the early 1980s enable such a prediction to be made by statistical methods.

For the previous review it was estimated that there were some 5,000 premises that would be subject to statutory controls under the IRR, in which some 50,000 workers would be employed. There has been no change in the estimates of numbers of workers (Dixon, 2004), or their doses, since the previous review. The average annual dose received by these workers is estimated to be 5.3 mSv. From the distribution of radon concentrations it is further estimated that about 2,500 of these workers will receive annual doses in excess of 15 mSv. The annual collective dose to these 50,000 workers in premises that would be subject to statutory controls is approximately 270 man Sv.

4.11 Aircraft crew

Cosmic radiation is discussed in Section 2.1, with some doses quoted for a range of typical flights. While passengers may typically make just a few flights per year, aircrew will have a far greater number of hours in the air and may therefore receive significantly higher doses from cosmic radiation.

Since 1990 the exposure of aircrew to cosmic radiation has been recognised by ICRP as occupational exposure (ICRP, 1991). In 2000 legislation concerning exposure of aircrew came into force in the UK (GB Parliament, 2000a; GB Parliament, 2000b). Occupational exposure of aircrew consists of cosmic radiation and exposure from packages of radioactive material being transported by air, with the major portion coming from cosmic radiation.

Exposure from cosmic radiation will be dependent on the number of hours that aircrew spend airborne. A survey carried out by the NRPB (Warner Jones et al, 2003) showed that crew on long-haul flights might be airborne for up to about 900 hours per year, while crew on short haul flights might be airborne for up to 400 hours per year. With an average dose rate from cosmic radiation of 4 $\mu Sv\ h^{-1}$ (see Section 2.1) this implies annual doses up to 1.6 and 3.6 mSv for short and long haul staff respectively. Taking an average flight time of around 600 hours per year would imply an annual dose of 2.4 mSv.

The study quoted above was based on data received from many air operators. A study carried out for British Airways (Irvine and Flower, 2002) indicated average doses for the various fleets of between 0.99 and 2.61 mSv in 2001, with the average of all fleets being about 1.6 mSv. This was lower than normal, due to the grounding of Concorde from August 2000 until November 2001. Considering the two estimates of average dose given here, an overall average annual dose for all aircrew is estimated as 2 mSv. With approximately 40,000 flight deck and cabin crew (CAA, 2001) in the UK, this average annual dose implies an annual collective dose of 80 man Sv, which is higher than the value given in the previous review, due to the use of a more representative number of aircrew.

The NRPB survey (Warner Jones et al, 2003) indicated that doses to aircrew from the transport of radioactive material could vary from 0.27 to 64 μSv per year depending on the type of flight and whether the crew are cabin crew or flight deck crew. With an average annual dose of 19 μSv, to 40,000 workers, this gives an annual collective dose from transport of radioactive packages of around 0.8 man Sv.

4.12 All occupational exposure

Summaries of the occupational exposure data from the sections above are compiled in Table 33. The total number of workers for whom doses have been complied is about 245,000 compared with 236,000 workers in 1987 (Hughes, 1999), the increase being partly due to the increased number of aircrew. The overall collective dose, 385 man Sv, remains at about the same level and the overall average annual dose, 1.6 mSv, is the same as that reported in the previous review.

The ranking of average annual doses from the different types of work is very similar to that seen in the previous review (Hughes, 1999). The highest average occupational doses still arise from radon in workplaces and from radiation exposure of aircrew. Within the nuclear industry the average annual dose has fallen in all areas, but the areas of fuel reprocessing and fabrication still give the highest average doses. Doses from medicine, dentistry and research still give the lowest average annual doses over all work areas, though the average annual dose in medicine has risen slightly.

TABLE 33 Overall doses from occupational exposure

Type of work	Number of workers in dose range (mSv)				Total	Annual collective dose (man Sv)	Average annual dose (mSv)
	0-5	5-10	10-20	>20			
Nuclear industry:							
Fuel enrichment	385	0	0	0	385	0.1	0.3
Fuel fabrication	1,919	0	0	0	1,919	1.3	0.7
Power stations	13,104	34	0	0	13,138	2.4	0.2
Fuel reprocessing	12,880	208	0	0	13,088	9.9	0.8
Technology services	5,150	13	0	0	5,163	0.9	0.2
Defence	12,499	0	0	0	12,499	2.2	0.2
Medicine etc							
Medical*	40,000	<10	0	0	40,000	5.6	0.1
Dental*	32,500	0	0	0	32,500	2.6	0.1
Veterinary*	10,000	0	0	0	10,000	2.0	0.2
Research and teaching*	10,000	0	0	0	10,000	0.6	0.1
General industry*#	9,950	50	<10	<10	10,000	3.0	0.3
Natural radiation:							
Radon in mines & caves*	5,800	<100	0	0	5,800	3.9	0.7
Radon in other places*†	32,000	13,000	4,000	~1,000	50,000	270	5.3
Air crew*	39,900	<100	0	0	40,000	80	2.0
Totals (rounded)	226,100	13,400	4,000	~1,000	245,000	385	1.6

Notes:

* Dose distribution derived from sample data.

Derived from sample data in which some data was for the range 0-6 mSv.

† Exposures from increased radon concentrations in workplaces subject to regulatory control.

5 CONSUMER PRODUCTS AND MISCELLANEOUS ITEMS

A number of products, bought for everyday use, contain low levels of radioactivity. Some of these items contain low levels of naturally occurring radioactive materials but the majority of consumer products containing radioactive substances have the radioactive material deliberately added, to make use of their chemical and radioactive properties. For example in the case of radioluminous articles, beta-emitting isotopes are combined with a phosphor to produce luminescence. The recommended annual dose constraints from the use of a particular product should not exceed 30 μSv for safety items and 3 μSv for all other items, except those that are unacceptable in principle such as toys and jewellery (NRPB, 1992).

Table 34 summarises the doses from the various items discussed below.

TABLE 34 Doses from some consumer products and miscellaneous items

Product	Estimated individual annual dose* (μSv y^{-1})	Estimated average annual dose to UK population (μSv y^{-1})
Radioluminous items – wrist watch containing ^{147}Pm	0.3	N/A
Radioluminous items – wrist watch containing tritium	10	N/A
Radioluminous items - Gaseous tritium light source in a timepiece	0.9	N/A
Smoke alarms	0.07	0.06
Vaseline glass, collection displayed on shelves	50	N/A
Uranium glazed wall tiles	<1	N/A
Geological specimens	100	N/A
Photographic lenses	200-300	N/A

Note:

* Very conservative estimates of effective dose.

N/A Not applicable. Only small numbers of people receive doses from these items, so it is not appropriate to give an average dose to the UK population in these cases.

5.1 Radioluminous items

Historically the most significant radionuclide for use in radioluminous consumer products is radium-226 (^{226}Ra). However, production of items luminised with radium ceased a few decades ago with radium being replaced by tritium (^{3}H) and promethium-147 (^{147}Pm), as these radionuclides are less radiotoxic. Premises where luminous clocks and watches are serviced may be exempt from some provisions of the Radioactive Substances Act, 1993 (GB Parliament, 1993), under recent regulations in England and Wales (GB Parliament, 2001b), Northern Ireland (NI DoE, 2003) and Scotland (Scottish Executive, 2000).

Advice given by NRPB on the maximum activities and dose rates for radioluminous time-pieces states that the dose rate must not exceed 2 μSv h^{-1} at the front face of an item and 0.2 μSv h^{-1} on the back plate (NRPB, 1992). The equivalent dose to the skin of the wrist that would be received from a watch containing a radioluminous source is therefore 1.8 mSv per year assuming that the watch is worn at all times and the dose rate is the maximum permissible. This represents an effective dose of around 0.3 μSv y^{-1}. This dose would be the maximum that would be received if the radioactive source is retained within the timepiece (such as for ^{147}Pm). However, for timepieces containing a tritium compound, some leakage of the radioactive source may occur as tritium is very mobile. Once the tritium has left the timepiece intake into the body may take place by mechanisms such as inhalation and absorption through the skin. Tritium emits only very weak beta radiation that is unable to penetrate the skin so that it only contributes to the effective dose once the tritium has entered the body. Assessments of the dose a wearer of a timepiece containing tritium might receive over a year suggest doses in the order of a few microsieverts (NRPB, 1992). Therefore a nominal annual dose of about 10 μSv is assumed.

The number of such timepieces in circulation in the UK is uncertain. The number used in the previous review was 100,000 timepieces and it is again assumed here that this number is currently applicable. It is assumed that these are being used on a regular basis.

Gaseous tritium light sources (GTLs) consist of small sealed vessels of borosilicate glass internally coated with a phosphor and filled with tritium gas. They can be made small enough to be used as markers on watches and compass dials. NRPB has published (NRPB, 1992) standards for GTLs used in consumer products, including specifying a maximum activity of 7.4 GBq per timepiece and 10 GBq per compass. Also, the tritium leakage rate should not exceed 2 kBq per day. The dose equivalent rate at the surface of the timepiece from low energy bremsstrahlung should also not exceed 0.1 μSv h^{-1}. Assuming that a person wears such a device for an entire year the maximum equivalent dose to the skin is about 0.9 mSv. The annual effective dose if such a device leaks tritium at the maximum allowed rate has been calculated to be about 0.9 μSv (NRPB, 1992).

The number of GTLs timepieces in circulation in the UK is uncertain. The number used in the previous review, 50,000 timepieces, is again assumed to be the approximate number currently being used on a regular basis.

5.2 Smoke alarms

Ionisation chamber smoke detectors are used to give an early warning of fire. Modern smoke detectors contain a small foil of americium-241 (^{241}Am) with an activity not greater than 40 kBq. A report by the NRPB (NRPB, 1992) has reviewed the doses from ionisation chamber detectors. The dose rate at a distance of 2 m from a detector is about 2.4 10^{-5} μSv h^{-1}, assuming it contains the maximum amount of activity. In assessing the doses from a detector the most conservative assumption is that a smoke detector has been placed in the bedroom so that a person will spend 8 hours per day at a distance of approximately 2 m from a detector. This results in an estimated annual dose of 0.07 μSv y^{-1}. In reality most people place smoke detectors at the top of stairs or in hallways. In these cases little time is spent near to the smoke detectors as people only pass them when moving around the house. Thus the actual dose from smoke detectors in the house is much lower than that presented above.

Several recent surveys in the UK have found that about 80% of homes have a smoke detector fitted. Although not all of these may be ionisation chamber detectors it is assumed here that they are. If the smoke detectors are located in the bedroom and the above dose rates are used, an average effective dose to the UK population is about 0.06 μSv y^{-1}. This is expected to be an overestimate.

5.3 Vaseline glass

Uranium oxides have been commonly used as colourants in glassware and ceramics since the 19th century. The addition of uranium to glass produces a yellow or green colour. It was also found that the uranium exhibited fluorescence under ultraviolet light, causing the glass to glow with a bright green colour. This type of glass is often referred to as Vaseline glass. Depending on the exact mix of uranium salts and other elements used a range of colours can be produced, covering various shades of green, yellow, amber, pink, turquoise, blue and ivory.

Use of uranium in glass became increasingly popular in the late 1800s, and remained popular until the Second World War. After this time increasing concerns over its safety led to a fall in the use of uranium in glass. There is no production of Vaseline glass in the UK at present, though it is still produced in the USA and Czech Republic. There are many collectors of Vaseline glass in the UK, with collectors obtaining pieces from the UK antiques market and by importing pieces from abroad.

Measurements of the dose rates of several items were made by NRPB from items lent by collectors. The gamma dose rate close to the surface of the glass items is very low, and was measured as ≤0.1 μSv h^{-1} from all the items studied. Measurements of beta dose rate at the surface of the glass pieces studied ranged from 1.4 μSv h^{-1} to 107 μSv h^{-1}. The variation is mainly due to the different uranium content of the glass samples, and to a much lesser extent to the density of the glass. A typical surface dose rate from beta radiation was 15 μSv h^{-1}. The beta dose rate measured a few centimetres from the surface was negligible. For a typical beta dose rate at the surface, of 15 μSv h^{-1}, if a collector was to spend the equivalent of 7 h y^{-1} handling this glass, the annual equivalent dose to the hands would be about 100 μSv. This corresponds to an effective dose of much less than 1 μSv.

These measurements indicate that for a typical situation where a collector keeps glassware on shelves or in a display cabinet the external dose rate will be negligible. However, some pieces are known to give rise to higher dose rates than noted above. It is estimated that the individual dose from some collections of uranium glass could be up to 0.5 mSv y^{-1} (Skelcher, 2002). However, for a large collection with a range of uranium concentrations, a maximum annual dose an order of magnitude lower, 0.05 mSv y^{-1}, may be more representative.

5.4 Uranium glazed ceramics

Uranium salts have also been used in the glaze on ceramic products such as tableware and tiles. Measurements (Taylor, 2002) on a sample of ceramic tiles found that there was 0.6 g natural uranium per six inch square tile, giving a surface dose rate of between 0.2 and 1 μSv h^{-1} – though the majority of measurements were at the lower end of this range. If a person is in contact with such tiles for a few tens of hours a year, a maximum annual equivalent dose to skin of approximately 50 μSv would be received, representing an annual effective dose of much less than 1 μSv. The use of this type of tile tends to be historical but they may still be found in areas such as hospital corridors, where large numbers of the public may visit. However in areas such as this, individual occupancy is low, and dose rates away from the tile surface are very low. An Italian study (Cucchi and Amadesi, 1980) of a sample of uranium glazed tiles found that beta dose rates at 20 cm from the tile surface was in the range of 5 to 70 μSv h^{-1}, and gamma dose rates were negligible. Uranium salts have also been used as colourants in ceramic tableware produced in the 1930s and 1940s in the USA, which may now be found in collectors' markets. It has been found (Streets and Thompson, 1995) that handling such items may give rise to very low levels of contamination on the skin, and the use of this tableware for eating could lead to very low ingestion doses. It is unknown how many such items are in circulation in the UK, and therefore it is not possible to estimate an overall dose to the UK population from these items.

5.5 Geological specimens

Some members of the public have collections of fossils, rocks or minerals. In some parts of the UK, in particular Devon and Cornwall, the native rocks can contain significant concentrations of uranium and its decay products. Studies have been performed on rocks collected from Devon and Cornwall to determine the radionuclide content (Dixon, 1993). It was found that the uranium concentration generally ranged from 0.1 Bq g^{-1} to 1000 Bq g^{-1}, with a few specimens at around 3000 Bq g^{-1}. The mean concentration of these minerals was approximately 300 Bq g^{-1}. Measurements of beta/ gamma surface dose rate gave a typical value of about 100 μSv h^{-1}, of which some 20% was from gamma radiation. High quality specimens of uraninite, not necessarily from the UK, can have uranium concentrations in the range 5 to 10 kBq g^{-1}.

The estimated equivalent dose to the hands from someone who has a substantial collection of such rocks is about 300 μSv per year for a handling time of 1 hour per year, corresponding to an effective dose of less than 0.1 μSv. An annual effective dose of about 100 μSv may also be received assuming that the collector views the rocks at a distance of 0.5 m for a time of 100 hours. Exposure to radon emanating from the specimens would be a small fraction of the average UK exposure from radon gas (Dixon, 1993). The overall levels of exposure from such specimens under normal conditions of handling and display are therefore only a small fraction of the overall dose from natural radiation.

5.6 Photographic lenses

Thorium-232 (^{232}Th) used to be added to photographic lenses in order to increase the refractive index. The use of thoriated lenses dates approximately from the late 1930s to the late 1980s. One study (Taylor et al, 1983) estimated that a professional or keen amateur photographer, carrying a camera with such a lens around the neck for several hours a day on many days of the year, could receive an annual effective dose of a few hundred μSv. Another study (Waligorski et al, 1985) estimated that in the extreme situation of holding such a camera 1 cm from the eye for 10 hours per week could give an annual dose equivalent of 12.5 mSv to the lens of the eye.

6 RADIOACTIVE FALLOUT IN THE ENVIRONMENT

6.1 Atomic weapons fallout

In the decade before the implementation, by the major powers, of the Partial Nuclear Test Ban Treaty in 1964 there was large-scale testing of nuclear weapons in the atmosphere and these tests released radionuclides into the environment. In the period since then, tests have been carried out mostly underground which released either no radionuclides or low levels of radionuclides locally. Most recently, India and Pakistan reported carrying out underground tests in 1998. However, some countries that were non-signatories to the Treaty carried out a small number of tests in the atmosphere, the last being conducted by China in 1980.

Some of the radionuclides released from the testing of nuclear weapons in the atmosphere were deposited in areas around the test site and some were carried into the upper atmosphere, to be dispersed globally. Over many years this activity transferred downwards into the troposphere and was deposited on the ground, mainly in rainfall. In the period since the implementation of the Treaty the main radionuclides of radiological interest have been the longer-lived species: strontium-90 (^{90}Sr) and caesium-137 (^{137}Cs). These radionuclides are taken up from the soil by plants and can subsequently be incorporated into foodstuffs, resulting in radiation exposure from ingestion. Gamma radiation from deposited ^{137}Cs also contributes an external radiation exposure. The activation product carbon-14 (^{14}C) was dispersed globally mainly in the form of carbon dioxide and its principal radiological impact is made via its uptake by plants and subsequent entering into the human foodchain.

Since the 1950s national and international surveillance programmes have been established to monitor the environmental levels of radionuclides from weapons fallout in air, foodstuffs and other materials. Throughout most of this period, in the UK, the United Kingdom Atomic Energy Authority (UKAEA) conducted a measurement programme, including the determination of activity concentrations in air and rainwater. This programme was continued by AEA Technology plc

(AEAT) until 1998 when NNC Limited were awarded the contract to carry out this work on behalf of the Environment Agency and Department of the Environment, Transport and Regions (DETR). They have published their results of radioactivity in air and rainwater in the UK in a number of publications (Dale, 2000; Dale, 2001; Dale, 2002).

Measurements of fallout activity in foodstuffs have mainly been made on milk, due to its convenience for sampling. Intakes of radionuclides from milk also provide a good indication of intakes from total diet. A milk sampling programme was initially conducted by the former Agricultural Research Laboratory at Letcombe, and this was continued by NRPB up to 1997. The Food Standards Agency (FSA) and the Scottish Environment Protection Agency (SEPA) now arrange surveillance measurements on milk sampled from a number of locations throughout the UK. NRPB continue to carry out an independent milk and air sampling programme principally designed to provide data typical of the UK (Hammond, 2003).

The milk monitoring programme carried out at NRPB showed that for both ^{137}Cs and ^{90}Sr the activity concentrations were either close to or below detection limits (Hammond, 2003).

Recent environmental measurements in air and rainwater confirm the slow decline of levels of anthropogenic radioactivity in the environment (Dale, 2002). The 10 year running mean of ^{137}Cs in air and rainwater is given in Table 35a (Dale, 2002), for sites monitored in the UK. Values for ^{90}Sr are shown in Table 35b (Dale, 2002). The values currently being measured are at very low levels, and in some cases below the detection level.

TABLE 35a Measurements of caesium-137 in air and rainwater

Radionuclide	Environmental media	10 year (1991-2000) running mean range,
Caesium-137	Air	$4.1\ 10^{-7}$ – $7.0\ 10^{-7}$ Bq kg^{-1}
	Rainwater	$8.9\ 10^{-3}$ – $3.15\ 10^{-2}$ Bq kg^{-1}

TABLE 35b Measurements of strontium-90 in rainwater and from deposition

Radionuclide	Environmental media	Annual concentration (1999)
Strontium-90	Rain (Chilton, Oxfordshire)	$<3.50\ 10^{-3}$ Bq l^{-1}
	Deposition	<2.4 Bq m^{-2}

The very low measured levels preclude an accurate assessment of the average annual dose from weapons fallout in the UK. An assessment based on international data has been carried out by UNSCEAR (UN, 2000). The average annual total dose from fallout in the Northern Hemisphere for 1999 was assessed as 5.9 µSv (UN, 2000). The contribution from external radiation was 3.2 µSv, which was mainly from ^{137}Cs, while ^{90}Sr and ^{14}C were the main contributors to the ingestion dose of 2.7 μSv. The average annual dose in the UK is therefore taken to be approximately 6 μSv. This is slightly higher than the estimate given in the previous review, for which the contribution from external radiation was uncertain.

6.2 Fallout from Chernobyl

Cumbria, north Wales and southern Scotland were the parts of the UK most affected by the ^{137}Cs deposition from the Chernobyl reactor accident. This activity was taken up by grass and entered the human foodchain mainly via sheepmeat. In 1986 a restriction was placed on the movement and marketing of sheep from parts of these areas, and an EC action level on sheep of 10^3 Bq kg^{-1} was implemented (EA et al, 2004). In 2003, 377 farms were still restricted in England, Scotland and Wales, whereas in 1986, 8,900 farms were under restriction. Thus 96% of farms have been derestricted over the intervening period. In Northern Ireland, since 2000, there have been no farms under restriction since monitoring showed that all sheep are well below the action level (EA et al, 2004). As noted in previous reviews, a person consuming sheepmeat continuously contaminated with a ^{137}Cs concentration of 10^3 Bq kg^{-1}, at an average rate for consumers of 8 kg y^{-1} (Smith and Jones, 2003), would receive an additional annual dose of about 100 μSv.

7 DISPOSALS OF RADIOACTIVE WASTES

Discharges of radioactive wastes to air and sea, and disposals of solid wastes, are made under the provisions of the Radioactive Substances Act 1993 (GB Parliament, 1993), subject to authorisation and agreement by the Environment Agency (EA) in England and Wales, the Scottish Environmental Protection Agency (SEPA) in Scotland and the Northern Ireland Office in Northern Ireland. In 2001 there were approximately 850 non-nuclear premises authorised to discharge radioactive wastes in England and Wales with a further 34 sites licensed under the 1965 Nuclear Installations Act (EA, 2003). The non-nuclear sites include hospitals, universities, industries and research centres.

Following publication of the recommendations of ICRP (ICRP, 1991), NRPB recommended a maximum dose constraint of 0.3 mSv y^{-1} for a single controlled source (NRPB, 1993b). This was further reinforced by a government White Paper (CM 2919, 1995) on waste management policy that proposed a 'site constraint' of 0.5 mSv y^{-1}. The ICRP recommendations were also adopted by the EC directive on Basic Safety Standards (EC, 1996). The main requirement for public dose limitation is that the annual dose to the most exposed members of the public, excluding natural background radiation and medical procedures, must not exceed 1 mSv. This requirement was transposed into UK legislation by means of a Direction (DETR, 2000) extending to England and Wales, issued by the then

Secretary of State for Environment Transport and Regions in 2000. This Direction requires the EA to ensure, wherever possible, that:

a all public radiation exposures from radioactive waste disposal are kept as low as reasonably achievable (ALARA);
b the sum of such exposures does not exceed the dose limit of 1 mSv y^{-1};
c the dose received from any new source does not exceed 0.3 mSv y^{-1};
d the dose received from any single site does not exceed 0.5 mSv y^{-1}.

The Scottish Environment Protection Agency (SEPA) is subject to a similar Direction in Scotland.

The UK strategy for Radioactive Discharges 2001-2020 (Defra, 2002) sets out the UK plans for implementing the Oslo and Paris Commission (OSPAR) convention for radioactive substances. The OSPAR strategy with regard to Radioactive Substances states that the Commission will ensure that by 2020, discharges, emissions and losses of radioactive substances are reduced to levels where the additional concentrations in the marine environment above historic levels, resulting from such discharges, emissions and losses, are close to zero (OSPAR, 1998). The discharge reductions set out in the UK strategy are expected to result in an estimated average annual dose of no more than 0.02 mSv to a representative member of a local critical group of the general public, as a result of authorised radioactive liquid discharges made from 2020 onwards.

The UK regulatory bodies operate monitoring programmes to measure the levels of radionuclides in the environment as a result of authorised discharges. The results for the major sites are published annually. Radioactivity In Food and the Environment (RIFE) reports (FSA, 2001) (FSA, 2000) (FSA, 1999) are published by the Foods Standards Agency (FSA) and SEPA, and in 2003, and 2004, by the Environment Agency (EA), Environment & Heritage Service for Northern Ireland (E&HS), FSA and SEPA (EA et al, 2003; EA et al, 2004). They contain the results of foodstuff and external dose rate monitoring throughout the UK, the Channel Islands and the Isle of Man. The FSA was formed in April 2000 taking over the responsibilities previously held by the Ministry of Agriculture, Fisheries and Food (MAFF), Department of Health (DH) and the National Assembly for Wales in relation to food safety. The information in those reports is collected by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), on behalf of the interested parties. The EA has also produced annual reports on Radioactivity in the Environment (EA, 2003) summarising the results of the EA's monitoring programmes. This monitoring is carried out to assess the impact of authorised waste discharges on the environment. The monitoring results are used by EA to assess doses to critical groups, which are identified on the basis of location and habits. A critical group may be defined by above average consumption rates of certain foodstuffs, carrying out certain working practices or pastimes, or living in close proximity to a site. Other members of the public who live in the vicinity of a site but have more average habits receive doses at a lower level than the critical group. The rest of the population may also receive doses from that site's operations but usually at extremely low levels.

The doses to the critical groups assessed (EA et al, 2004) for the main routes of exposure for discharges made in 2003 are given in Table 36. More detailed information of these assessments is provided in the annual RIFE reports which are available to download from the FSA (www.fsa.gov.uk) and SEPA (www.sepa.org.uk) websites. A discussion of the main industries follows, which includes data from Table 36 and other referenced sources.

TABLE 36 Radiation doses to critical groups due to discharges of liquid and atmospheric radioactive waste in the UK, 2003 (EA et al, 2004)

Establishment		Exposure routes	Exposed group	Dose $\mu Sv\ y^{-1}$
BNFL	Sellafield	Seafood consumption and external	Local consumers	210
		Terrestrial food, external and inhalation (near Sellafield)	Local consumer (1 year old)	34
		Terrestrial food (Ravenglass)	Local consumer (1 year old)	19
		External (Ravenglass)	Local occupant	41
		External (Ribble estuary)	Houseboat occupants	79
		External (dose to skin)	Anglers	210*
		External (dose to skin)	Fisherman handling fishing gear	110*
	Springfields	Seafood consumption	Local consumers	19
		External gamma exposure	Houseboat occupants	79
		External (dose to skin)	Local fishing community	670*
		Terrestrial foods	Local consumers	<5#
	Capenhurst	Inadvertent ingestion of freshwater and sediments	Children (10 years old) playing near river	9
		Terrestrial foods	Local consumers (1 year old)	<5
	Chapelcross	Seafood consumption and external	Local consumers	37
		Terrestrial foods	Local consumers (1 year old)	20
	Drigg	Terrestrial foods	Local consumers (1 year old)	46
UKAEA/AEAT	Dounreay	Seafood consumption	Local consumers	<5
		External gamma exposure	Beach occupants	11
		Terrestrial foods	Local consumers	6
	Culham	River water and sediment ingestion	Local consumers	<5
	Harwell	Freshwater fish and external	Anglers	11
		Terrestrial foods	Local consumers (1 year old)	<5
	Winfrith	Seafood consumption and external	Local consumers	6
		Terrestrial foods	Local consumers (1 year old)	<5
Nuclear power stations	Berkeley and Oldbury	Seafood consumption and external	Local consumers	7
		Terrestrial foods	Local consumers (1 year old)	<5
	Bradwell	Seafood consumption and external	Local consumers	13
		Terrestrial foods	Local consumers (1 year old)	<5
	Dungeness	Seafood consumption and external	Local consumers	7
		Terrestrial foods, external and inhalation near site	Local consumers	110
	Hartlepool	Seafood consumption and external	Local consumers	<5
		Terrestrial foods	Local consumers (1 year old)	<5
	Heysham	Seafood consumption and external	Local consumers	75
		Terrestrial foods	Local consumers (1 year old)	6
	Hinkley Point	Seafood consumption and external	Local fishing community	13
		Terrestrial foods	Local consumers (1 year old)	<5
	Hunterston	Seafood consumption	Local consumers	<5
		External	Beach occupants	7
		Terrestrial foods	Local consumers (1 year old)	14
	Sizewell	Seafood consumption and external	Local consumers	<5
		Terrestrial foods, external and inhalation near site	Local consumers	57

TABLE 36 (Continued) Radiation doses to critical groups due to discharges of liquid and atmospheric radioactive waste in the UK, 2003 (EA et al, 2004)

Establishment		Exposure routes	Exposed group	Dose $\mu Sv\ y^{-1}$
Nuclear power stations	Torness	Seafood consumption and external	Local consumers	5
		Terrestrial foods, external and inhalation near site	Local consumers (1 year old)	19
	Trawsfynydd	Freshwater fish and external	Anglers	32
		Terrestrial foods	Local consumers (1 year old)	6
	Wylfa	Seafood consumption and external	Local consumers	12
		Terrestrial foods	Local consumers (1 year old)	<5
Defence establishments	Aldermaston	Freshwater fish and external	Anglers	<5
		Terrestrial foods	Local consumers (1 year old)	<5#
	Derby	River water	Local consumers	<5
	Devonport	Seafood consumption and external	Local consumers	<5
		Terrestrial foods	Local consumers	<5
	Faslane	Seafood consumption and external	Local consumers	<5
	Holy Loch	External	Anglers	9
	Rosyth	External	Boat users	<5
Amersham	Amersham	Freshwater fish and external	Anglers	5
		Terrestrial foods	Local consumers (1 year old)	<5
	Cardiff	Seafood consumption and external	Local consumers	24
		Inadvertent ingestion of sediment	Anglers	<5
		Consumption of wildfowl	Local consumers	<5
		Terrestrial foods, external and inhalation near site	Local consumers (1 year old)	16
Rhodia	Whitehaven	Seafood consumption†	Local consumers	410
		Seafood consumption¶	Local consumers	620

* Skin doses are subject to an annual limit of 50 mSv.
# Includes contribution from natural sources of radionuclides.
† Excluding radionuclides from Sellafield.
¶ Including radionuclides from Sellafield.

7.1 Uranium enrichment and fuel manufacture

Uranium for the production of nuclear fuel is enriched at the URENCO Capenhurst site, where very low quantities of radionuclides are discharged to the atmosphere from stacks, and via liquid effluent into a local brook. BNFL also operates from this site; it is mainly concerned with the decommissioning of plant that is no longer in operation. The radionuclides discharged by URENCO operations are predominantly uranium and its decay products, tritium (^{3}H), technetium-99 (^{99}Tc) and neptunium-237 (^{237}Np) (from recycled fuel). At this site a hypothetical critical group is specified, who are assumed to be children playing in and around the local brook. In 2003, members of this group would have received a dose of around 9 $\mu Sv\ y^{-1}$ (EA et al, 2004). Typical individuals in the vicinity of the site would receive lower doses.

Nuclear fuel is manufactured at the BNFL Springfields site, which results in low quantities of aerial and liquid radioactive discharges. The radionuclides discharged from this site mainly consist of uranium and thorium and their decay products. The liquid effluents are discharged into the River Ribble, which flows into the Ribble Estuary. Here fishermen and houseboat dwellers are the main critical groups. The sediments of the estuary have also adsorbed radionuclides discharged from Sellafield for many years, and this source still represents the major contribution to the radiation exposure from the aquatic environment. In 2003, it was assessed that houseboat dwellers would receive a dose of 79 μSv (EA et al, 2004) (mainly due to historic Sellafield discharges), which is similar to previous years.

7.2 Nuclear power stations

Discharges from nuclear power stations contain low levels of activation and fission products such as tritium (^{3}H), carbon-14 (^{14}C), sulphur-35 (^{35}S), cobalt-60 (^{60}Co) and caesium-137 (^{137}Cs). Each of the operators carries out environmental monitoring around the site, as do CEFAS and EA. The results of the monitoring programmes are produced in the operators' annual environmental reports as well as the RIFE and EA reports. The principal critical group doses assessed by CEFAS are listed for each station in Table 36 (EA et al, 2004). For stations around the Irish Sea, the critical group dose is mainly due to external exposure to americium-241 (^{241}Am) and ^{137}Cs in intertidal areas, and ingestion of seafood containing ^{137}Cs, mainly from Sellafield discharges. The highest critical group dose in 2003, 110 μSv, was received in the vicinity of Dungeness nuclear power station (EA et al, 2004). All other critical group doses from nuclear power station discharges in 2003 were assessed to be below 100 μSv. This was also the case in both 2001 and 2002 (FSA and SEPA, 2002; EA et al, 2003).

Members of the public who frequent or live in areas close to nuclear power stations, in particular some of the older Magnox stations, can receive external exposures from direct radiation from parts of the plant. In general, the critical group for this route of exposure is not the same as for other exposure pathways. The annual exposures of these small groups in 2002, which are typical of recent years and given in Table 37, were less than 100 μSv apart from Chapelcross, Bradwell and Dungeness A stations. The doses in 2002 to the critical groups at these stations were assessed as 110 μSv, 220 μSv and 560 μSv, respectively (BNFL, 2002). Direct radiation from British Energy stations tends to be much lower. Annual doses at the site fence are typically less than 10 μSv (British Energy, 2004).

TABLE 37. Doses from direct radiation from Magnox power stations and other sites in 2002

Sites	Annual dose from direct radiation*, μSv
Magnox sites	
Berkeley	23
Bradwell	220
Chapelcross	110
Dungeness A	560
Hinkley Point A	Bg#
Hunterston A	43
Oldbury	Bg#
Sizewell A	16-28†
Trawsfynydd	10
Wylfa	5.1
Other sites	
Sellafield	19
Drigg	84
Springfields	Bg#
Capenhurst	70

Notes:

* Measurements taken from TLDs on perimeter fence. Doses to members of the public at the critical location are calculated using these data, corrected for background radiation.

Bg = background

† Four critical groups were identified: habitation near site, 28 μSv; fishermen, 28 μSv; anglers, 17 μSv; and dog walkers, 16 μSv.

7.3 Fuel reprocessing

Although there have been decreases in discharges made by Sellafield in recent years, the environmental levels have not reduced substantially. This is mainly due to historical discharges of ^{137}Cs. Liquid wastes from Sellafield are discharged directly to the Irish Sea via a pipeline. The main routes of exposure are the consumption of seafood and external exposures to radionuclides adsorbed onto estuarine and harbour sediments, as well as through handling contaminated fishing gear. The local critical group of seafood consumers was assessed by CEFAS (EA et al, 2004) to have received 210 μSv in 2003, from Sellafield discharges (including a contribution from external exposure). This is slightly higher than the value of 190 μSv noted in the previous year's report, and was mainly due to an increase in the consumption of crustaceans by the critical group.

The doses received by the main critical groups around the Sellafield site in the years 1998 to 2003 (EA et al, 2004), (EA et al, 2003), (FSA and SEPA, 2002), (FSA and SEPA, 2001), (FSA and SEPA, 2000) and (MAFF and SEPA, 1999) are summarised in Table 38.

TABLE 38 Radiation doses to critical groups due to discharges of radioactive waste from Sellafield

Pathway	Critical Group	Annual Dose, mSv					
		1998	1999	2000	2001	2002	2003
Fish and Shellfish consumption	Local consumers	0.20	0.21	0.15	0.16	0.19*	0.21*
Terrestrial foods	Local consumers	0.04[c]	0.04	0.03	0.04	0.04[#,†]	0.03[#,†]
External (Skin)	Anglers	0.30	0.18	0.16	0.20	0.22	0.21
Handing Fishing Gear	Local fishing community	0.07	0.11	0.12	0.13	0.15	0.11
Seaweed fertilised crops	Local consumers	0.03	0.03	0.02	0.02	0.01	0.03

* Includes external dose from intertidal areas.

[#] Includes external and inhalation doses.

[†] Dose to 1 year old.

The main exposure pathways are the consumption of foodstuffs, external exposure from skin contamination and exposure through handling fishing gear. These exposures were received by three main critical groups: the local commercial fishing community, anglers and local consumers. In general these annual doses are low. In addition to the exposures received from radionuclides discharged from Sellafield in seafoods, the local critical group also receives an exposure from natural radionuclides discharged from an industrial plant in Whitehaven. In 2003, this additional dose was 410 µSv, which increases the overall dose to the critical group of seafood consumers to 620 µSv.

The critical group doses calculated for immersion in ^{41}Ar released from the Sellafield site in 2002, are significantly lower than in from previous years, due to the final shut-down of the Calder reactors. The total critical group doses assessed by BNFL for terrestrial pathways from all airborne discharges, were 24 µSv, 20 µSv and 25 µSv for adults, children and infants respectively (BNFL, 2003). For comparison, in 2001, the total doses to the terrestrial critical group were assessed by BNFL to be 58, 44 and 48 µSv (BNFL, 2002).

It has recently been calculated (Roberts, 2004) that the annual individual dose attributable to Sellafield, averaged over the population of Cumbria, is 10.7 µSv. This is dominated by the dose due to marine discharges (10.3 µSv) with the remainder (0.4 µSv) due to atmospheric discharges.

7.4 Defence establishments

Ministry of Defence (MoD) establishments are not subject to the same formal legal control as other nuclear sites; however, discharges are made with the formal agreement of the authorising bodies. Sites managed by contractors on behalf of the MoD must be regulated in the same way as civilian sites. CEFAS, EA, FSA, SEPA and MoD carry out monitoring surveys around each of the nine main defence-related sites to assess the radiological significance of the discharges. In 2003 doses were estimated as insignificant, or extremely low.

Exposures of less than 5 μSv (EA et al, 2004) were estimated to have been received by the critical groups around all defence sites except Holy Loch. At that location, a critical group member might have received 9 μSv from external exposure in intertidal areas (EA et al, 2004), arising from the presence of ^{60}Co in sediments as a result of past discharges from the US submarine support facility that closed in 1992.

A report produced by the Defence Science and Technology Laboratory, Radiological Protection Services (Corns and Aylward, 2004), reports the results of marine environmental radioactivity surveys carried out at nuclear submarine berths in 2002. The nuclide of major importance in naval discharges is ^{60}Co. Tritium (^{3}H) and ^{14}C are also discharged. These radionuclides were below the limit of detection at Plymouth, Loch Striven, Isle of Bute, Loch Goil, Loch Long and Gareloch.

At Rosyth Royal Dockyard, ^{60}Co was detected in 2 out of 36 samples (Corns and Aylward, 2004) and the annual effective dose received by the Rosyth critical group (occupancy of intertidal sediments) was calculated to be <1 μSv. Trace levels of ^{14}C were found in marine biota. The dose to a critical group of seafood consumers was calculated to be <1 μSv. At Barrow-in-Furness only very low levels of ^{60}Co were detected. Although other radionuclides, such as ^{137}Cs and ^{241}Am were detected in higher concentrations: it is understood that these are attributable to authorised discharges from Sellafield, weapons testing fallout and the Chernobyl accident. From the low levels of ^{60}Co detected, a critical group dose was calculated to be approximately 2 μSv. At Portsmouth and the Isle of Wight very low levels of ^{60}Co were detected. The annual dose to a critical group spending time on intertidal sediments in these areas was calculated to be 1 μSv. It was concluded that the naval contribution to either external or internal public doses was at negligible levels.

7.5 Nuclear and technology services

This subsection covers sites that were formerly operated wholly by UKAEA, namely Dounreay, Harwell and Winfrith. However, there have been administrative changes at each of these sites, and now many of the activities on these sites are carried out by other organisations as tenants. All three sites house research reactors that have been, or are in the process of being decommissioned.

7.5.1 Dounreay

The Dounreay site was opened in 1955, and since that time three research reactors have been built, operated and shut down. They are now undergoing decommissioning, as is the rest of the site. All discharges from Dounreay are now as a result of decommissioning works and are made to the sea via a pipeline.

There are four potential exposure pathways considered in the marine surveillance programme (EA et al, 2004). The first relates to external exposure to radioactivity adsorbed onto fine particulate matter that becomes entrained on fishing gear that is regularly handled. The critical group in this case is a group of fishermen who operate a fishery close to Dounreay. Measurements made in 2003 showed that this pathway was of no radiological significance. The second potential pathway relates to the ingestion of locally collected seafoods. The estimated dose from this pathway for the critical group was less than 5 μSv in 2003 (EA et al, 2004). The third potential pathway is a result of external exposure over local beaches. The estimated dose from this pathway for the critical group was 11 μSv in 2003 (EA et al, 2004). The fourth potential pathway relates to external exposure from the uptake of radioactivity by particulate material that has accumulated in rocky areas of the foreshore. Measurements have shown that the estimated dose from this pathway for the critical group was less than 5 μSv in 2003 (EA et al, 2004).

Fragments of irradiated nuclear fuel have been discovered on the Dounreay foreshore and nearby public beaches. The dose implications are currently being assessed by HPA Radiation Protection Division on behalf of SEPA. On the basis of current monitoring data the probability of a member of the public encountering a fragment is extremely low. Current knowledge on the behaviour of the fragments is described in the Dounreay Particles Advisory Group's second interim report, available on the SEPA website.

For the terrestrial environment, the critical group of food consumers were estimated to have received 6 μSv in 2003, which includes a contribution due to weapons test fallout (EA et al, 2004).

7.5.2 Harwell

Liquid wastes are discharged to the River Thames at Sutton Courtney and to the Lydebank Brook north of the site. Monitoring showed that there were some enhanced concentrations of radionuclides near to the River Thames outfall, but these were of small radiological significance. Anglers have been identified as the critical group for liquid discharges in the Harwell area. Although consumption of fish from the river was not found to occur, an assumed consumption rate of 1 kg y^{-1} was used in the dose assessment. This, excluding external exposure, was found to result in a dose of less than 11 μSv in 2003 (EA et al, 2004). The dose to the critical group of local consumers from gaseous discharges was estimated to be less than 5 μSv in 2003 (EA et al, 2004).

7.5.3 Winfrith

Liquid wastes are discharged into deep water in Weymouth Bay under authorisation. Technetium-99 (^{99}Tc) found in seaweed in the area could occur as a result of discharges from Sellafield, the Cap de la Hague reprocessing plant in France or from weapons testing. The critical group doses in 2003 were assessed to be 6 μSv from liquid discharges and less than 5 μSv from gaseous discharges (EA et al, 2004). These estimates are similar to those made in recent years.

7.6 Radionuclide production

Amersham Plc (now part of GE Healthcare) manufactures radioactive materials, including radioactively labelled materials for use in medicine, research and industry. The company operates from two main sites in the UK, located in Amersham, Buckinghamshire and Cardiff, South Glamorgan. Liquid discharges from the Amersham site are made into the local sewer system, which releases into the Grand Union Canal and the River Colne, which in turn flows into the River Thames. It was determined that anglers are the most exposed group affected by the liquid discharges. As in the Harwell area, there is no evidence of the anglers consuming their catches, but it has been assumed that a small quantity would be eaten annually. An angler's total annual dose from this discharge route was assessed to be less than 5 μSv in 2003 (EA et al, 2004). The dose to the critical group of terrestrial food consumers was assessed to be less than 5 μSv in 2003 (EA et al, 2004), which is similar to previous years.

The laboratory at Cardiff produces radiolabelled compounds containing ^{3}H and ^{14}C used in research and medical diagnostic kits. Liquid discharges are made into the Severn Estuary via the sewer system after passing through a new waste water treatment works. Aerial discharges of tritium and carbon-14 are also made from the site. The dose to the most exposed group of seafood consumers was 24 μSv in 2003 (EA et al, 2004) including a contribution due to external radiation. The dose to anglers on the River Taff was estimated to be much less than 5 μSv. In 2003 a habit survey identified the consumption of wildfowl as a pathway. Based on a high rate of consumption (5.6 kg y^{-1}) the dose was estimated to be less than 5 μSv. The critical group for terrestrial foodstuffs was infants, from ingestion of food produced on land conditioned by pelleted sludge produced at the new waste water treatment works. It was assessed that in 2003 the highest dose would have been less than 16 μSv, with doses from non-foodstuffs pathways being less than 1 μSv (EA et al, 2004).

7.7 Research laboratories

Three research laboratories are mentioned in the EA, E&HS, FSA and SEPA, 2004 report: Imperial College Reactor Centre, Ascot, Berkshire; Imperial Chemical Industrial plc, Billingham, Cleveland; Scottish Universities' Research Reactor Centre, South Lanarkshire. Monitoring carried out at all three sites in 2003 shows that, as in recent years, there was no detected impact on the environment from the operation of these sites.

7.8 Drigg

The authorisation for the Drigg landfill site allows aerial discharges from the site. These discharges are at very low levels, and consist of escaping gases. Also, migration of leachate from the site into groundwater can occur, with subsequent uptake into local foodstuffs. In 2001, there were enhanced levels of ^{3}H in foodstuffs found near to the Drigg site. All other radionuclides detected were at a similar level to or lower than those for the Sellafield site. The dose to the critical group who live close to the Drigg disposal facility, including a component due to Chernobyl and weapons testing fallout, was 46 μSv in 2003 (EA et al, 2004).

Another critical group identified at this site is campers or picnickers drinking from the Drigg stream. The dose to this critical group from the inhalation and ingestion of radionuclides was assessed to be less than 5 μSv in 2003 (EA et al, 2004).

7.9 Other landfill sites

Low levels of radioactive materials may be disposed of at some landfill sites. For example, iodine-125 (^{125}I) is detected in borehole water at some landfill sites, typically at very low levels of <0.1 Bq l^{-1} (EA et al, 2004). However, ^{125}I is not detected in seawater or seaweed in areas around nuclear power plants, as its main use is for medical diagnostic procedures.

It is estimated that a dose arising from inadvertent ingestion of water contaminated by leachate arising from a landfill accepting ^{125}I contaminated waste is 5 μSv y^{-1} (EA et al, 2004). Tritium is also detected near some landfill sites. At a site in the Thames region, a person drinking water from a nearby borehole, assuming the maximum tritium concentration observed in 2001 (958 Bq l^{-1}), would have received an annual dose of less than 12 μSv (EA, 2003; EA et al, 2003).

7.10 The NORM industries

There are several industries in the UK which use or process materials that contain Naturally Occurring Radioactive Materials (NORM). These industries include the steel industry, the oil and gas industries, and mineral sands industries. Coal fired power stations produce ash containing NORM, and both coal and gas fired power stations release NORM. Historically, other NORM related industries in the UK were a phosphates industry and a tin mining industry.

As a result of their processes, these industries produce NORM contaminated wastes that require disposal to, for example, landfill. In recent years the NRPB has carried out studies into the radiological impact on the UK population of the remaining NORM industries on behalf of the Environment Agency (Smith et al, 2001; Crockett et al, 2003; Warner Jones et al, to be published; Oatway et al, to be published). Table 39 summarises the results of these studies for the main discharge routes and pathways, showing the critical group dose, as well as the dose to the average member of the local population where appropriate. The data refer to typical discharge practices over the past decade. The reports describing the coal-fired power production and the steel industry also considered exposure from using waste that has low levels of natural radioactivity as building products, since ash can be used in cement in place of some of the normal constituents. However, in this case it was noted that the materials that these industry wastes replace often have a higher activity concentration of natural radionuclides than the waste materials. So although a dose is being received from these materials, this may represent a dose saving over using standard materials (Smith et al, 2001; Crockett et al, 2003).

TABLE 39 Radiation doses to critical groups and average individuals due to releases of Naturally Occurring Radioactive Materials (NORM) in industry, typical of recent years

Industry	Discharge Route	Pathway	Annual critical group dose, μSv	Average annual dose, μSv
Coal Fired Power Stations	Atmospheric releases via stack*	All	1.5	0.1
	Building materials made from power station ash	Inhalation of Radon	600†	
	Building materials made from power station ash	External	900†	
Oil and gas extraction	Authorised discharges to sea and NORM contaminated scales	Ingestion of seafood and external exposure to fishing gear	<30	
	Discharges to sea of NORM contaminated produced waters		10	
Gas Fired Power Stations	Atmospheric releases via stack*	All	0.75	0.032
Use of Natural Gas	Cooking with natural gas	Inhalation and External	<20 to 500#	<10#
Steel Production	Atmospheric Releases	All	<100	<2
	Building materials made from slag	Inhalation of Radon	550†	
	Building materials made from slag	External	800†	
Zircon Sands	Atmospheric releases	Inhalation	<1	<1
	Liquid disposal of floor washings	External	<1	<1

Notes:

* The critical group are individuals living in close proximity to the power station. Average individual doses are to members of the public living in the locality of a power station.

Critical group dose to workers in a commercial kitchen, average dose is the average dose to the population from cooking with natural gas.

† As this dose is not necessarily higher than from other building materials it is not strictly a critical group dose.

Annual doses to critical groups, due to releases from coal and gas fired power stations are very low, in the order of 1 μSv. The average annual dose from emissions from coal fired power stations is about 0.1 μSv. Indoor exposures from radon in natural gas are included in the estimates of exposures from all sources of indoor radon described in Section 2.4.4. Low doses may also be received from other industrial emissions and disposals of NORM into the marine environment by the oil and gas industries.

7.11 Small users

The Government's Radioactive Waste Management Advisory Committee (RWMAC) has coined the term 'Small Users' to describe hospitals, higher educational establishments and other research laboratories where radioactive materials are used (RWMAC, 1991). Doses to members of the public from disposal of liquid radioactive waste have been estimated using a published methodology. The relevant pathways considered in that methodology for exposure of the public from liquid disposals are: drinking water obtained downstream of a sewage works outfall, freshwater or marine fish consumption, inhalation of re-suspended river or marine sediments, and external exposure from radionuclides that may be adsorbed onto river or marine sediments (McDonnell, 2004).

A study was carried out by NRPB and the Centre for Ecology and Hydrology for the EA to estimate potential doses from radionuclide discharges reaching rivers (Hilton et al, 2003). The study concentrated on the River Thames and its tributaries since this river is the most significant regarding sources of discharges and potentially exposed population. In 2002, a total of 103 discharges were authorised into the River Thames above Teddington lock, through sewage treatment facilities. Estimated potential doses upstream of Teddington Lock ranged from 0.019 $\mu Sv\ y^{-1}$ to 13 $\mu Sv\ y^{-1}$. The highest estimated annual dose was 170 μSv on the River Colne, which receives discharges from a large industrial site. It is postulated in the assessment report that this is due to the use of authorised discharges as opposed to actual discharges (which are generally very much lower). The choice of a generic representative radionuclide and high fish consumption from this river also contribute to the conservatism of this estimate.

7.12 Collective and per-caput doses from marine discharges

An EC study on the radiation exposure of the European Community from radionuclides in North European marine waters has recently been carried out (Simmonds et al, 2002).

The EC study also included assessments of the collective and per-caput doses to each of the European populations from all discharges made in the EU. The study included discharges from the nuclear industry and discharges of natural radionuclides into the sea by the oil and gas industries. The results for the UK population are presented in Table 40 for doses received in the years 1998 to 2001[†]. The annual collective dose has fallen by 58% between 1998 and 2001 to 39.8 man Sv. This results in a per-caput (or average individual) dose to the UK population from all EC marine discharges of 0.68 μSv in 2001. About 10% of this is from the nuclear industry. This represents an increase compared to that reported in the previous review due to the inclusion of discharges of naturally occurring radioactive materials by the oil and gas industries. In previous reviews the annual collective dose from marine discharges was mainly derived from measurements of radiocaesium in seafood.

TABLE 40 Dose to the UK population from liquid discharges made in the EC*

Year	Annual collective dose, man Sv	Annual per-caput dose, μSv
1998	68.4	1.17
1999	68.3	1.16
2000	52.6	0.895
2001[#]	39.8	0.678

Note:

* Dose to the UK population from all EC liquid discharges.

[#] Assuming discharges were made at the same rate as in 2000

7.13 Collective and per-caput doses from atmospheric discharges

Collective doses to the UK population due to atmospheric discharges from nuclear power stations integrated to one year were calculated using PC CREAM (Simmonds et al, 1995). The calculation was made for discharges reported in 2002 (EA, 2003). The methodology was based on an assessment of the radiological impact of routine atmospheric and liquid discharges from UK civil nuclear sites (Bexon, 2000).

The collective doses to the population of the UK for each site are presented in Table 41, the total for all sites being 6.3 man Sv. This is similar to that found in previous reviews. Figure 8 shows the contribution from each site to each of the pathways considered in PC CREAM. The major contribution to the overall collective dose is mainly due to airborne discharge of ^{14}C, from Oldbury nuclear power station. The main pathways are consumption of grain products and milk.

[†] The study used actual discharge data up to 2000. It was assumed that discharges made in 2001 were made at the same rates as in 2000. Historic discharges were also taken into account for all other years.

Table 41 also gives the UK collective doses due to global circulation of atmospheric discharges of four radionuclides from each site, and Figure 9 depicts the contribution made by the four radionuclides. The major contributors to the global circulation collective dose are from the atmospheric discharge of ^{85}Kr and ^{129}I from Sellafield. These contributions are at least two orders of magnitude lower than those from the direct emissions.

In 2000 the population of the UK was reported to be 58.8 million (Laverty, 2003). The annual collective dose from UK civil nuclear sites in 2002 was 6.3 man Sv, giving an annual per caput dose of 0.11 μSv.

TABLE 41 Total and global circulation collective doses to the UK population following discharges from UK civil nuclear sites in 2002

Nuclear Power Station	Total, man Sv	Global circulation, man Sv
Bradwell	$7.30\ 10^{-2}$	$4.51\ 10^{-5}$
Chapelcross	$7.40\ 10^{-1}$	$5.08\ 10^{-4}$
Dounreay	$3.80\ 10^{-4}$	$2.67\ 10^{-5}$
Dungeness A	$6.00\ 10^{-2}$	$1.84\ 10^{-4}$
Dungeness B	$3.70\ 10^{-1}$	$9.90\ 10^{-4}$
Hartlepool	$2.30\ 10^{-1}$	$5.04\ 10^{-4}$
Heysham 1	$1.80\ 10^{-1}$	$3.75\ 10^{-4}$
Heysham 2	$1.80\ 10^{-1}$	$3.63\ 10^{-4}$
Hinkley Point A	$6.00\ 10^{-4}$	$7.47\ 10^{-7}$
Hinkley Point B	$3.20\ 10^{-1}$	$3.06\ 10^{-4}$
Hunterston B	$3.50\ 10^{-1}$	$6.35\ 10^{-4}$
Oldbury	$1.90\ 10^{0}$	$1.27\ 10^{-3}$
Sellafield	$1.30\ 10^{0}$	$1.62\ 10^{-2}$
Sizewell A	$3.50\ 10^{-1}$	$3.33\ 10^{-4}$
Sizewell B	$3.30\ 10^{-2}$	$5.54\ 10^{-5}$
Torness	$3.70\ 10^{-2}$	$1.47\ 10^{-4}$
Wylfa	$2.10\ 10^{-1}$	$4.38\ 10^{-4}$
Total	$6.33\ 10^{0}$	$2.24\ 10^{-2}$

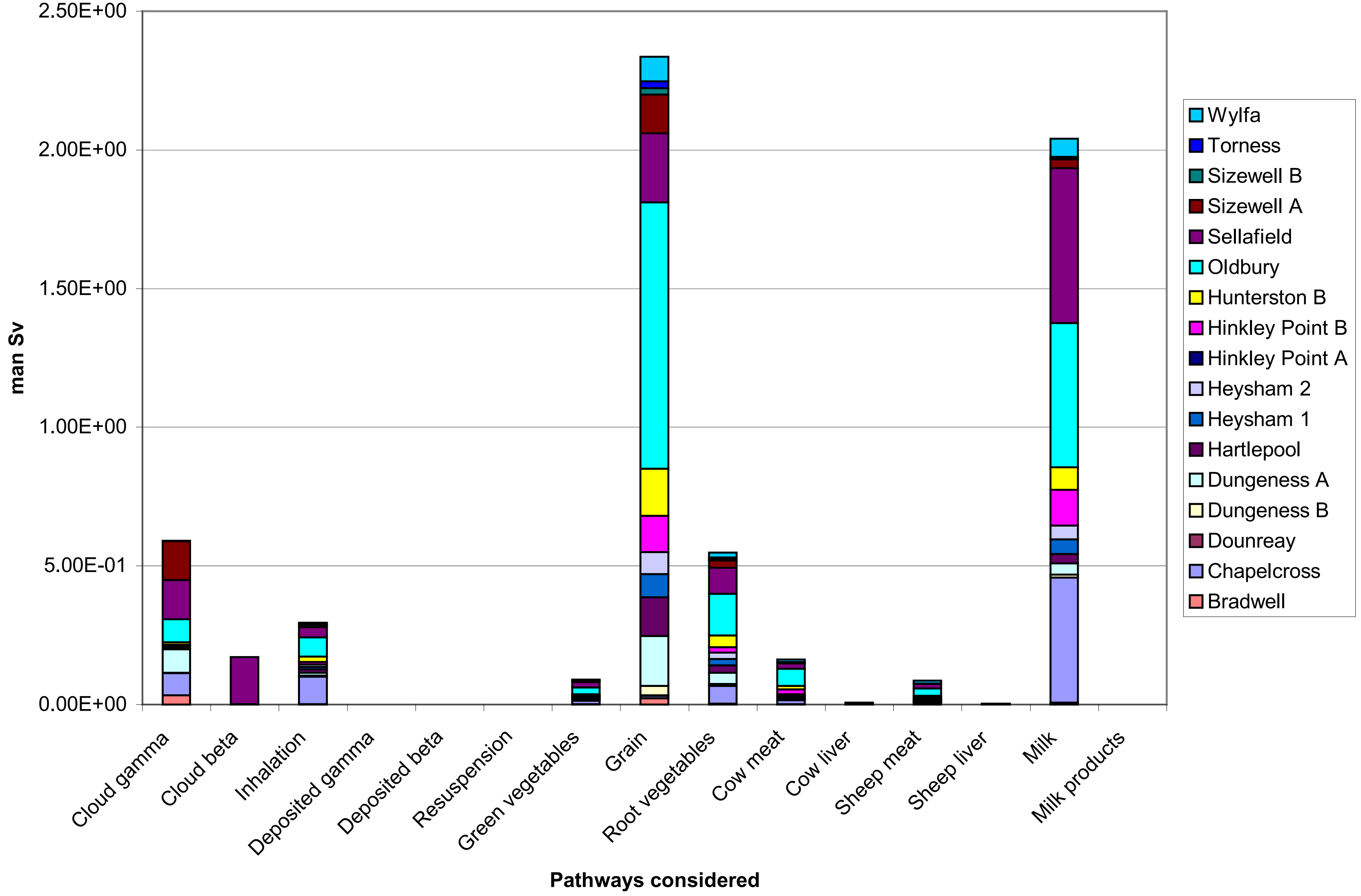


Figure 8 Collective dose integrated to 1 year, to the UK population, from atmospheric discharges in 2002

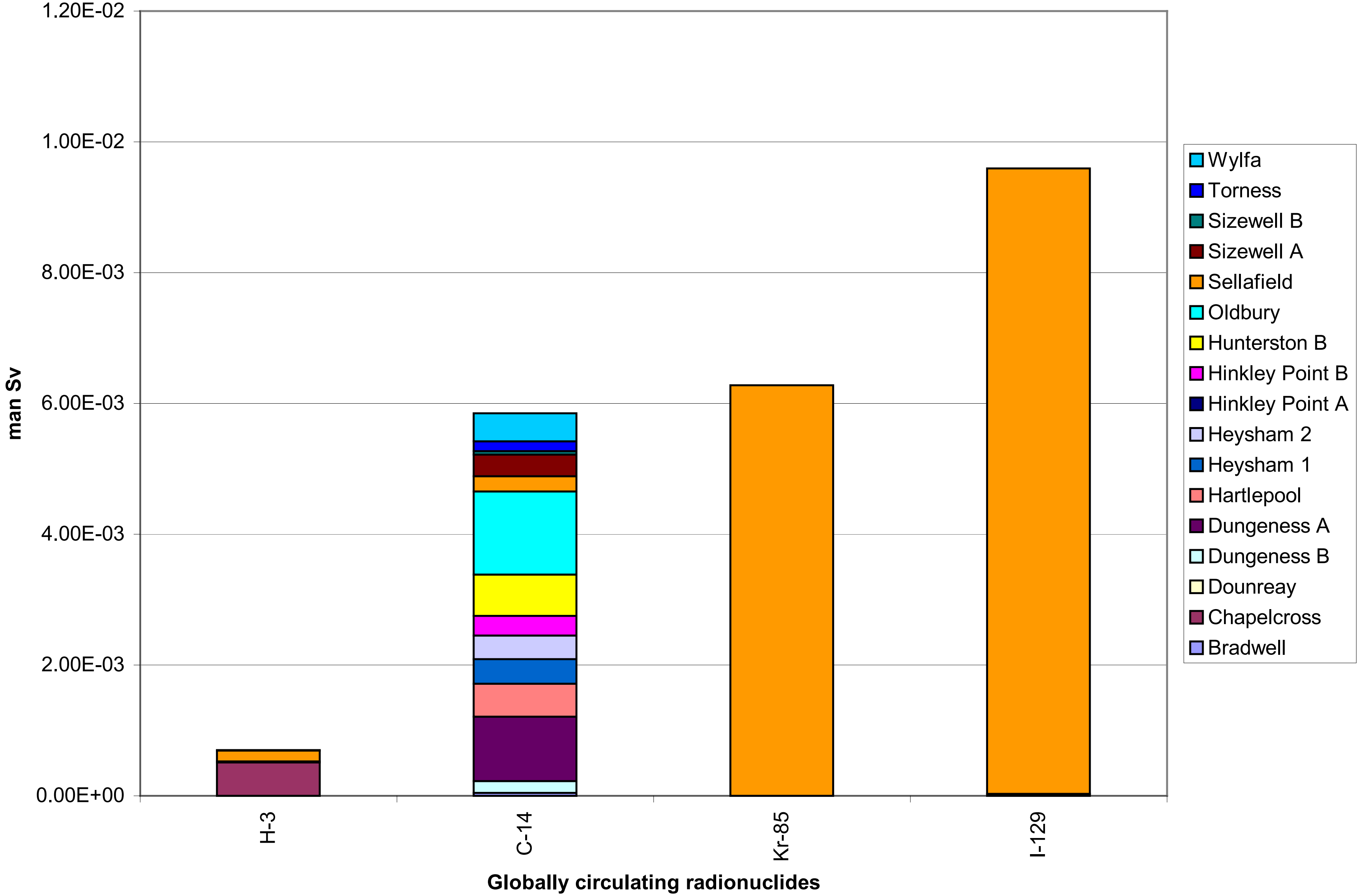


Figure 9 Collective dose from global circulation, integrated to 1 year, to the UK population from atmospheric discharges

8 DISCUSSION

8.1 Radiation exposures from all sources

The annual collective doses and average annual doses from all the sources considered in this review are summarised in Table 42. The overall average annual dose is 2.7 mSv. This represents a slight increase on that found in the previous review, due to an increased contribution from medical irradiation. About half of the average annual dose is from radon isotopes (^{222}Rn and ^{220}Rn). The relative contributions to the overall exposure are shown in Figure 10, and the main findings for each of the sources are described in the following sections. It should be noted that the average annual doses listed in Table 42 are averages over the whole UK population. For some sources however, such as air travel, medical or occupational exposures, only a part of the population receives those exposures.

TABLE 42 Annual exposure of the UK population from all sources of ionising radiation

Source	Annual collective dose, man Sv	Average annual dose, μSv
Natural:		
Cosmic	19,400	330*
Gamma	20,600	350
Internal	14,700	250
Radon	76,400	1,300
Artificial:		
Medical	24,300	410
Occupational	385	6
Fallout	350	6
Disposals	50	0.9
Consumer products	4	0.1
Total (rounded)	157,000	2,700

* Includes 30 μSv from air travel

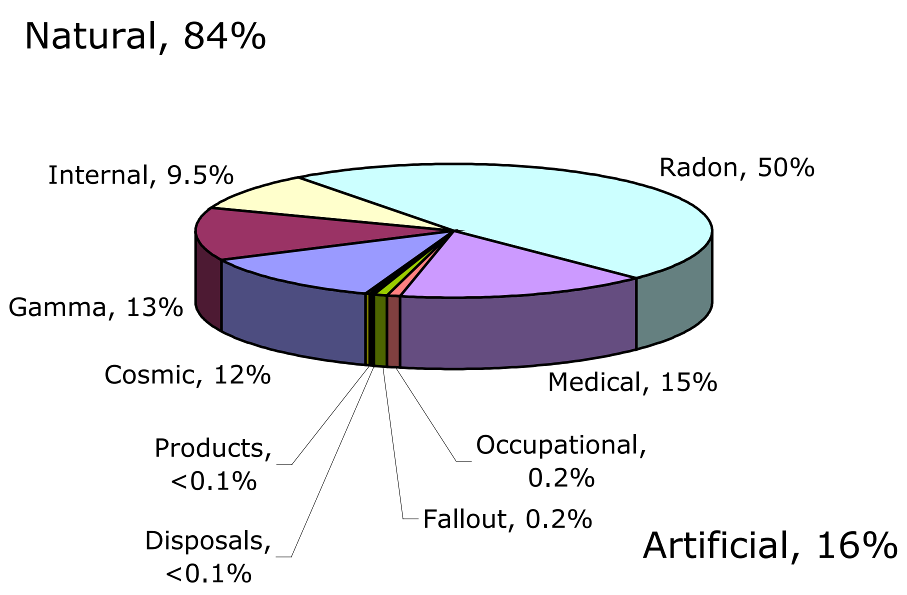


Figure 10 Average annual dose to the UK population from all sources, 2.7 mSv

8.1.1 Natural radiation

The average annual dose from cosmic radiation at ground level is the same as that estimated previously, at 300 μSv. Individual annual exposures vary from 200 to 400 μSv. The average annual dose from airtravel has however increased slightly to 30 μSv, so increasing the overall average annual dose from cosmic radiation to 330 μSv.

The average annual dose from terrestrial gamma radiation, from the ground and buildings, is 350 μSv and is unchanged from the previous review. Individual doses range from about 100 μSv to about 1,000 μSv.

The radiation exposure from internal radionuclides was assessed from intakes of radionuclides in foodstuffs, and measured values of ^{40}K content of the body. The average annual dose was calculated for three age groups. For 1 y and 10 y olds the average annual dose was estimated as 320 μSv, and for adults 250 μSv. The value for adults is slightly less than assessed in the previous review. Individual annual doses range from about 100 μSv to 1,000 μSv, depending mainly on the radionuclide concentration of foods, and consumption rates.

The estimate of average indoor concentration of radon gas in the UK is unchanged from the previous review. The average annual dose from radon, currently estimated to be 1300 μSv, is almost half the overall average annual dose. Radon also gives rise to the largest exposures from natural radiation, and some individual annual doses are in the order of 100,000 μSv.

Natural radiation comprises some 84% of the average annual dose in the UK from all sources.

8.1.2 Medical uses of radiation

Medical irradiation, comprising radiology and nuclear medicine, has continued to increase during the period since the previous review. The average annual dose to the UK population has increased by about 10% to 410 μSv, and now accounts for some 15% of the overall average annual dose in the UK. This is largely due to the increased use of computed tomography, which gives superior diagnostic information, but which also leads to higher patient doses. There has also been an increase in the number of nuclear medicine procedures performed, and the estimate of the average annual dose from these procedures, 27 μSv, has increased by about a third since the previous review. Individual annual doses from diagnostic procedures can range from zero, if none are undertaken, to several tens of millisieverts.

8.1.3 Occupational exposure

The number of workers monitored in the nuclear industry has reduced since the previous review, and the average annual dose has decreased to 0.4 mSv. Less than 1% of these workers receive an annual dose more than 5 mSv, and in 2003 there were no annual doses over 10 mSv.

Annual doses continue to be very low in medicine and research, the average being 0.1 mSv for both areas. However, in nuclear medicine departments the average annual dose, 0.40 mSv was higher than that found in the previous review, 0.33 mSv. This appears to be the result of an increased workload in these departments. Occupational exposures in general industry tend to be very low, the annual average being 0.3 mSv. However, as has been found in previous reviews, some individual industrial radiographers can receive annual doses up to around the annual dose limit. Among groups of classified workers in general industry, the highest average annual dose, 0.9 mSv, was received by transport workers. These exposures are mainly from handling packages containing ^{99m}Tc for nuclear medicine procedures.

That radon can give rise to appreciable occupational exposures in mines has been recognised for many decades. However, the numbers of workers exposed underground has decreased in the UK. The main area for assessing and controlling doses from radon is now in above ground workplaces in radon-prone areas. There are some 50,000 workers in workplaces with radon concentrations high enough to require statutory controls. Their average annual dose is about 5.3 mSv, which is unchanged since the previous review. The other main source of occupational exposure from natural radiation is cosmic radiation. Aircrew receive an average annual dose of 2 mSv. The overall average annual dose to occupationally exposed workers is 1.6 mSv, the same as that found in the previous review. The annual collective dose from all occupational exposure is

385 man Sv, which can be expressed as an average annual dose to the UK population of about 0.006 mSv.

8.1.4 Consumer products

In this review, individual radiation exposures were assessed to members of the public from a number of items containing radioactive materials, and these were found to be low. Maximum annual doses are likely to be much less than 1 mSv. The most common item in this category used by members of the public is the smoke alarm. These contain a very low activity source, and the average annual dose to the population from these was assessed to be less than 0.1 μSv.

8.1.5 Fallout

Nuclear weapons testing in the atmosphere has resulted in low levels of environmental contamination of fission and activation products. However, the environmental levels of these radionuclides are slowly declining, and the main radionuclides are now below the limits of detection. The current estimate of the average annual dose from intakes of these radionuclides, 6 μSv, is from an international assessment. This value is slightly higher than reported previously, but is considered to be a better estimate, being from a comprehensive world-wide assessment.

8.1.6 Disposals of radioactive wastes

Discharges of liquid radioactive wastes into the sea from the nuclear industry have greatly decreased over the past three decades. However, other industries, such as the phosphate, oil and gas industries also make discharges of naturally occurring radioactive materials (NORM) into the marine environment. Since the previous review a major assessment has been carried out of the exposure of the UK (and EU) population resulting from marine discharges from all sources in the EU, taking into account all radionuclides discharged. This results in an increase in the assessed exposure of the UK population from these discharges. This results in an average annual dose from liquid discharges, of about 0.7 μSv, which is higher than reported in the previous review. About 10% of this is from the nuclear industry. This increase is due to the inclusion of exposures from disposals of NORM in the marine environment. The exposure of the population from airborne discharges from nuclear sites is similar to that assessed previously, and results in an average annual dose of about 0.1 μSv. A similar average annual dose arises from emissions from coal fired power stations. Therefore the average annual dose is about 0.9 μSv for all discharges. The highest doses are received by the critical group of seafood consumers near Sellafield, for which the dose in 2003 was 0.62 mSv, and 66% of this was from past discharges of natural radionuclides from an industrial plant.

8.2 Exposure to widespread natural background and environmental radiation

The average annual doses presented in Table 42 and Figure 10 are averages over the UK population. However, in any one year not all of the population is exposed to some of the sources, for example occupational or medical exposure. Everyone is exposed to natural radiation at ground level to some degree, and also to sources that are widespread in the environment at low levels. The latter consists mainly of radionuclides in the environment from weapons fallout and discharges. The average annual doses from these widespread and persistent sources are presented in Table 43. The doses represent those that an average member of the UK population may receive in a year. The overall average annual dose from widespread and persistent sources is 2.20 mSv. Examples of the variation in natural sources are given in Section 8.3, and examples of additional doses from various sources are given in Section 8.4.

TABLE 43 UK average annual doses from widespread natural and environmental sources

Source	Annual dose, μSv	% of total
Cosmic at ground level	300	14
Terrestrial gamma	350	16
Internal	250	11
Radon	1,300	59
Fallout	6	0.3
Discharges	0.9	0.04
Total (rounded)	2,200	100

Considering only these widespread and persistent sources that everyone is exposed to, some 59% of the dose is from indoor radon. This contribution can vary considerably depending on the location, and this is discussed in Section 8.3. The contributions given in Table 43 are shown in Figure 11 for illustration.

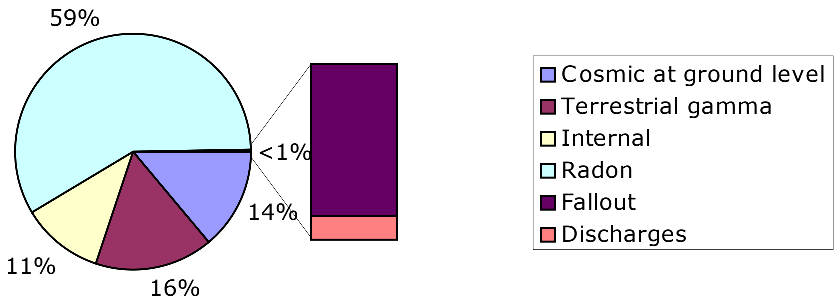
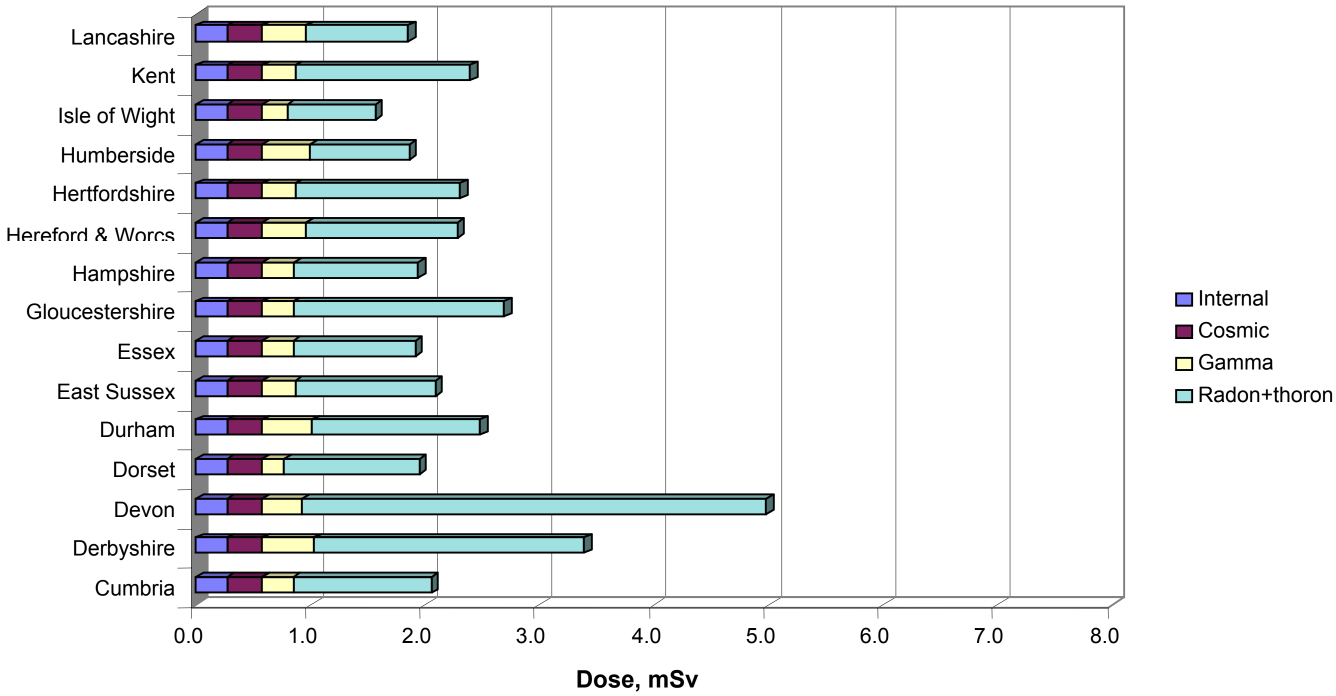


Figure 11 Contributions from widespread natural and environmental radiation: UK average

8.3 Variation in county average annual doses from natural radiation

Figure 12 shows the average annual doses from natural background radiation to the population across the UK by county. All the graphs are on the same scale allowing an easy comparison between them to be made. From these graphs it is evident that the dose from sources other than radon is fairly constant across the UK, with an annual dose of just under 1 mSv. However, a large variation is found with the dose from radon. Cornwall has the highest average annual dose from radon, at around 6 mSv, and most other counties have average annual doses of between 1 and 2 mSv.



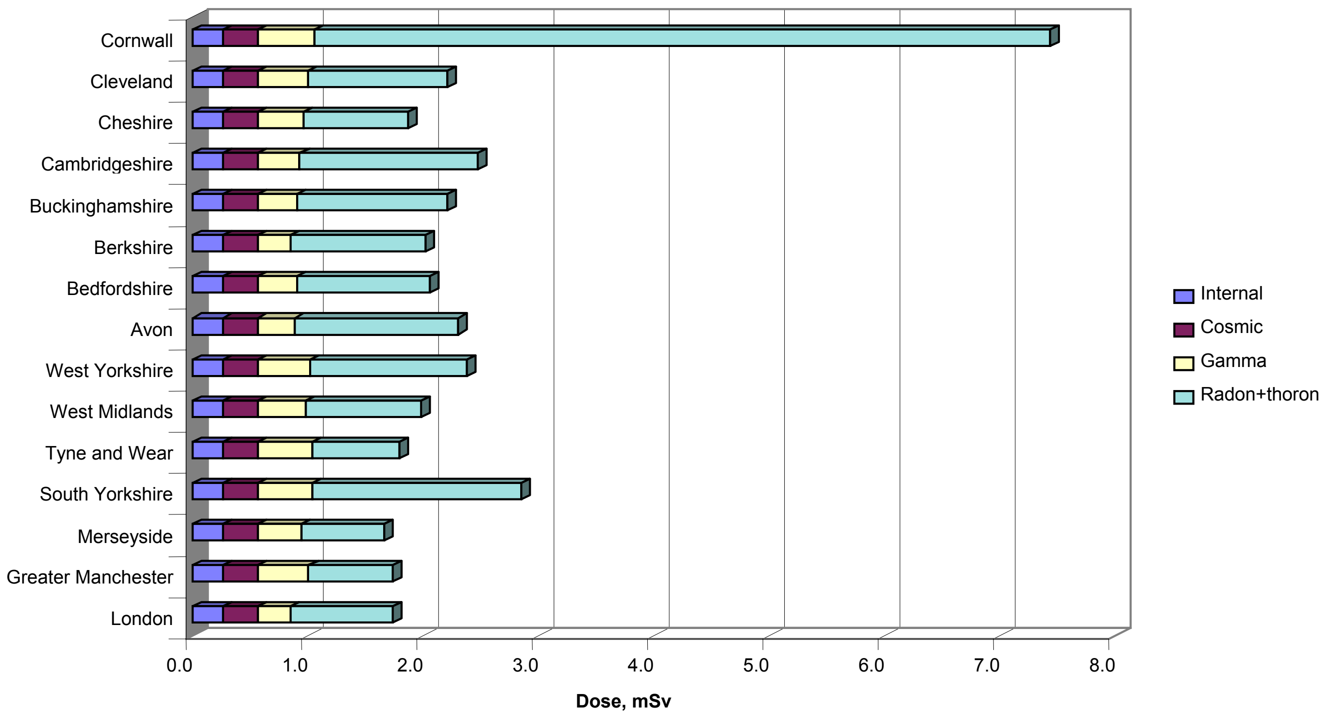
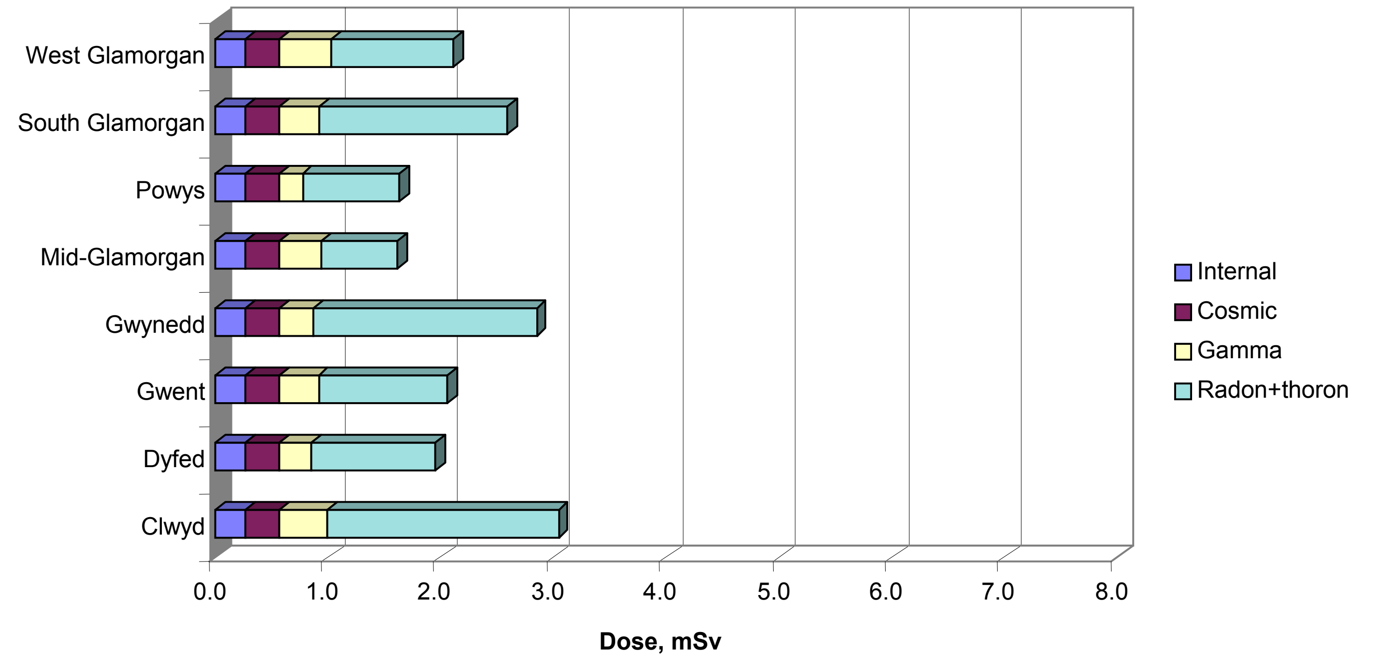


Figure 12 Variation of exposure to natural background radiation by region



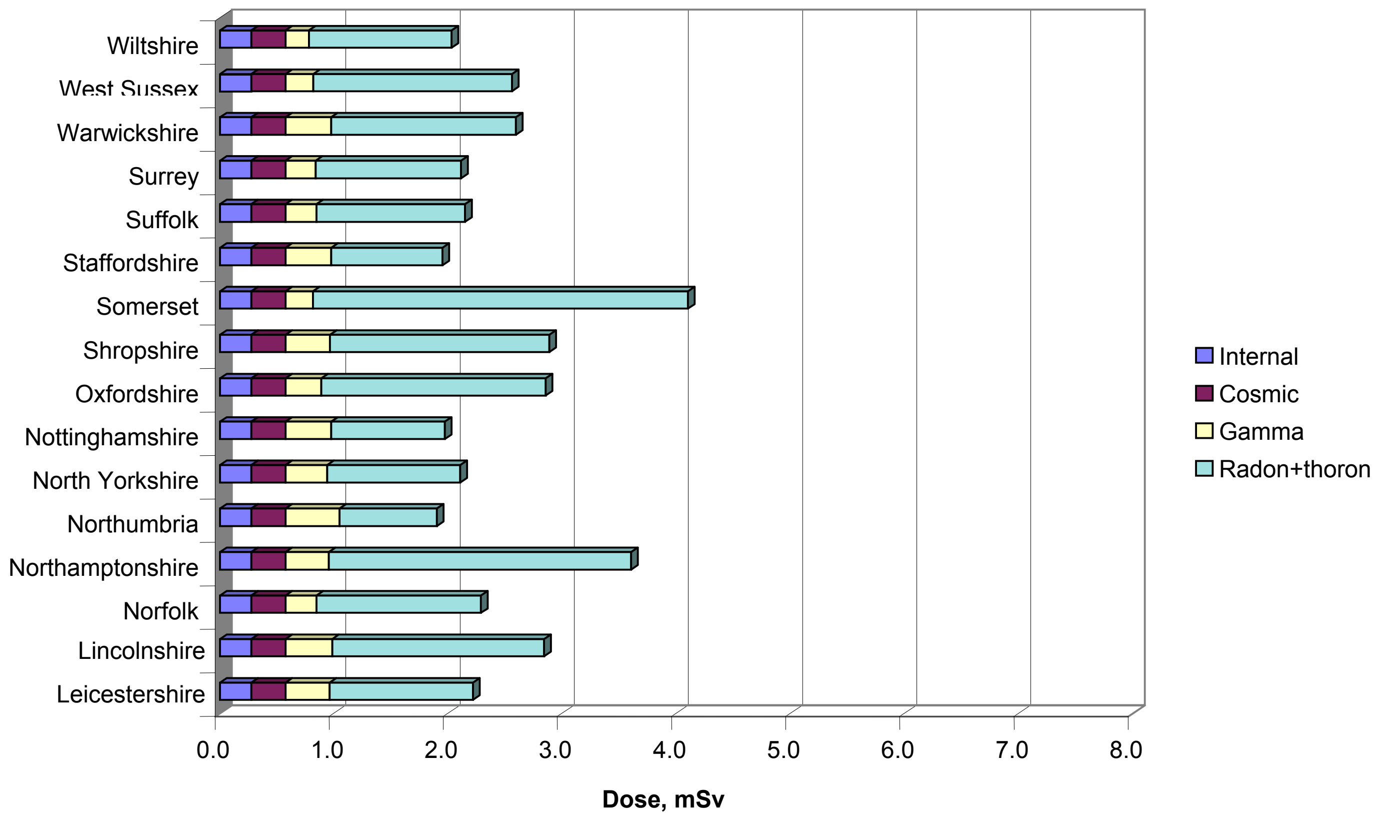


Figure 12 (continued) Variation of exposure to natural background radiation by region

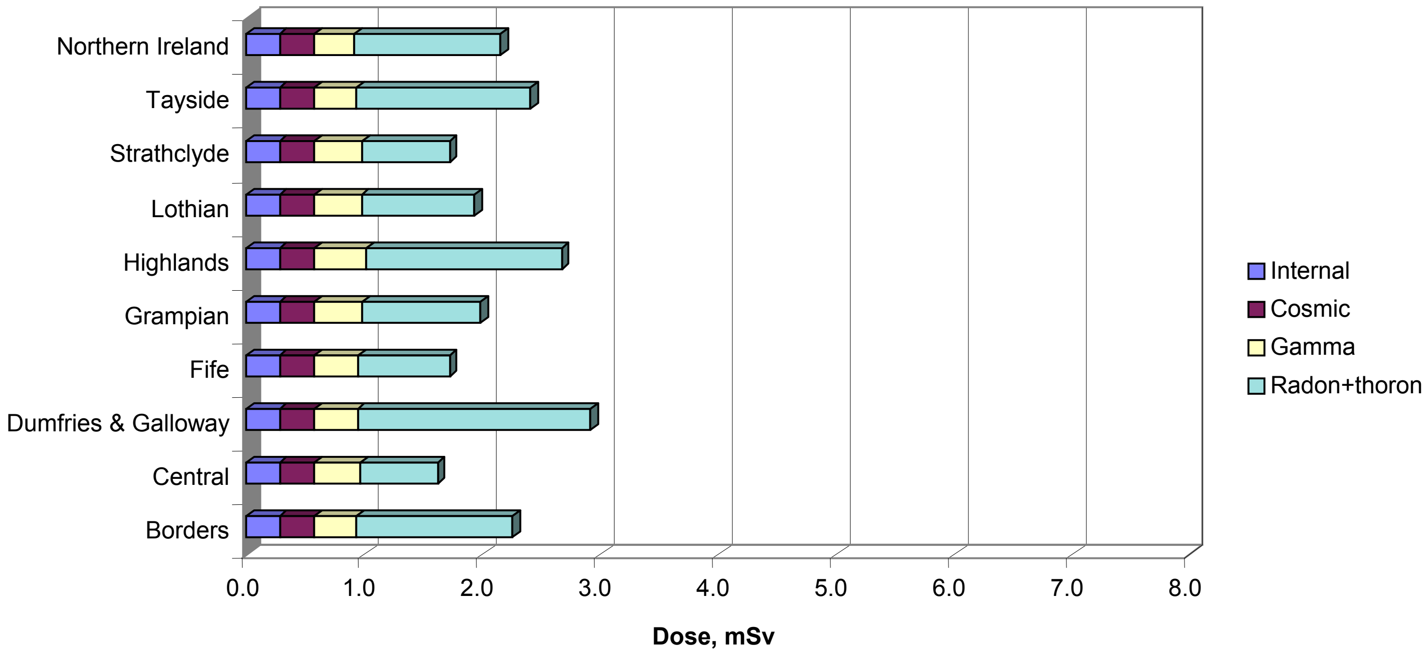


Figure 12 (continued) Variation of exposure to natural background radiation by region

8.4 Individual variations in exposures from other sources

Figures 13 to 16 illustrate typical doses from other common sources: medical procedures, flights, occupational exposure and consumption of certain food products. Not everyone will be exposed to these sources in every year, and even when someone is exposed the dose received can be vary depending on the circumstances of the exposure. For example, the length of a journey by aircraft or the part of the body being X-rayed, influence the dose received. These graphs enable a comparison to be made with the average annual dose from widespread natural background and persistent sources, as described in Section 8.2. From Figures 13 to 16 it can be seen that most of these additional exposures are small when compared to the average annual dose. However, some exposures from medical diagnostic radiology (Figure 13) can result in a considerable dose that may more than double the individual's overall exposure over a year.

The cosmic radiation dose from a single return flight ranges up to over 0.2 mSv (Figure 14), while aircrew receive an average annual dose of about 2 mSv (Figure 15). Regular consumption of some foods, such as mussels or brazil nuts could lead to an annual dose of around 0.2 mSv (Figure 16).

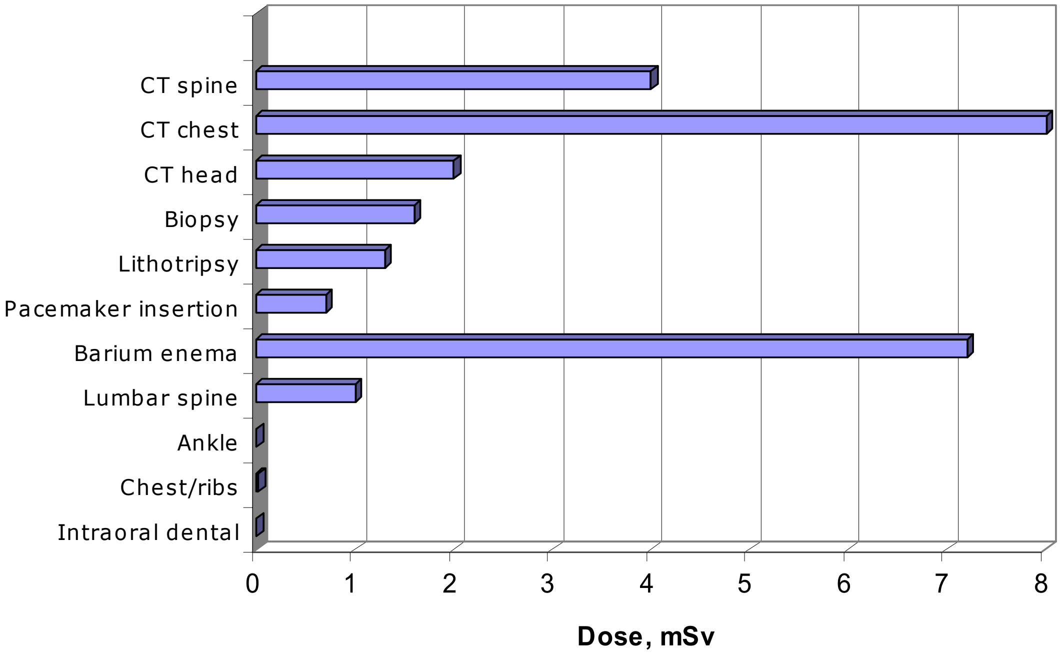


Figure 13 Summary of the potential doses from some common medical procedures

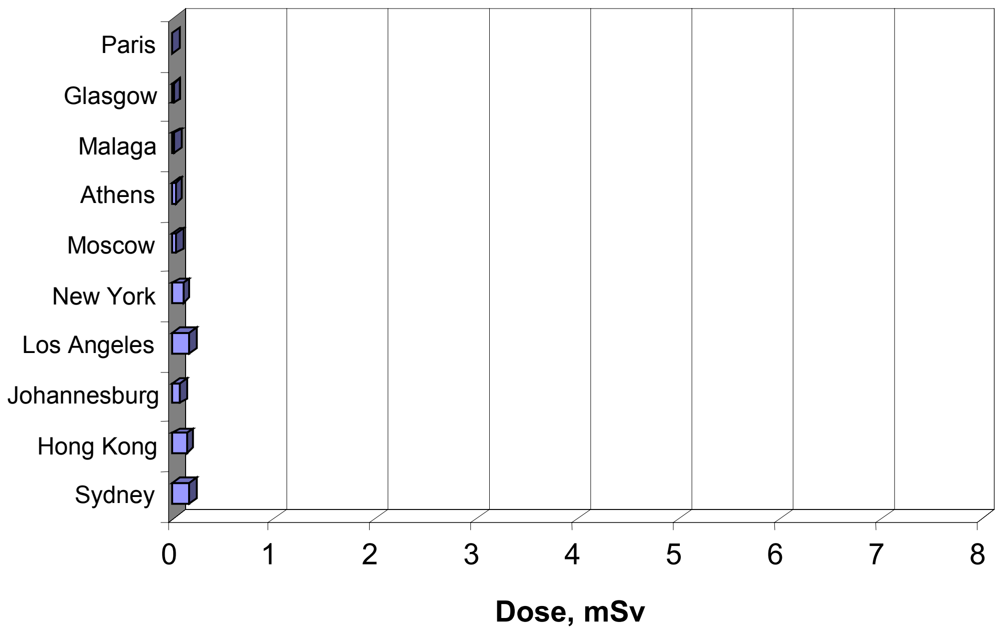


Figure 14 Average doses from return flights from London to various destinations

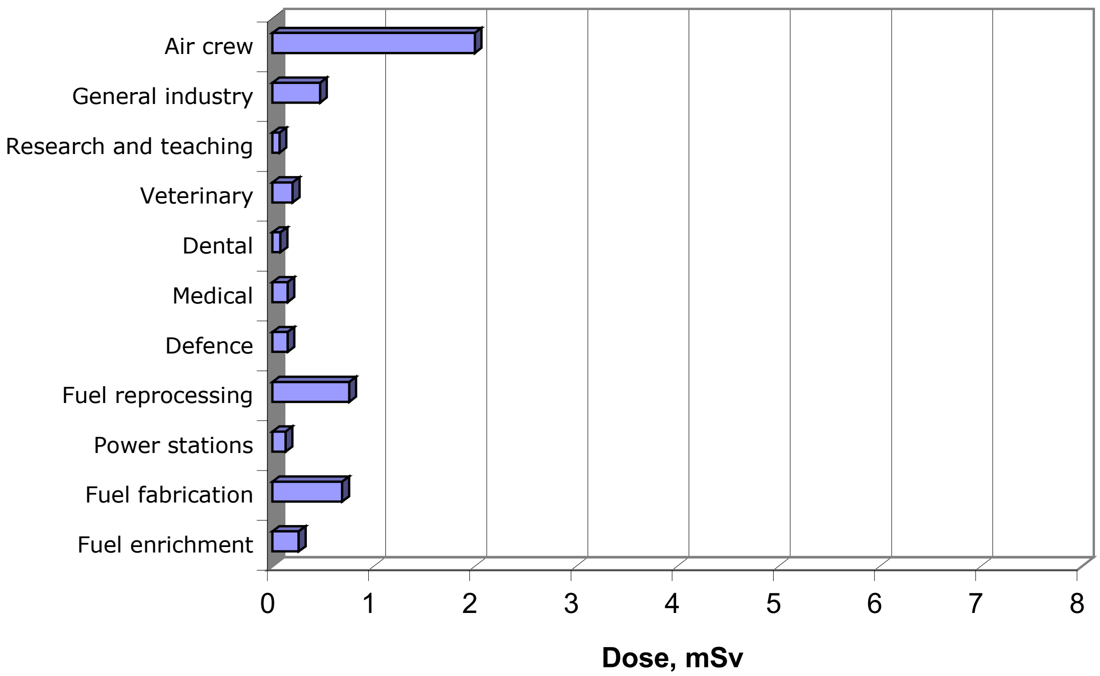


Figure 15 Average doses from various occupations

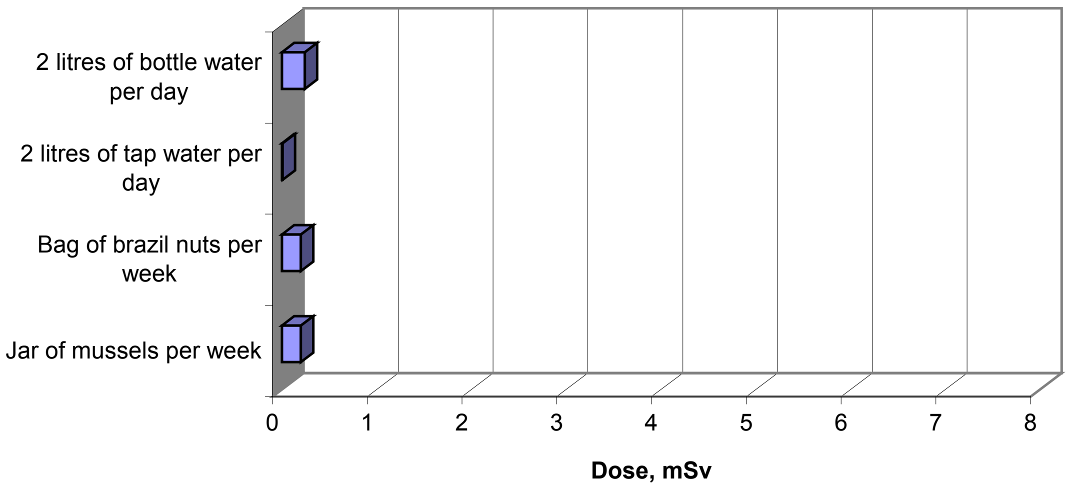


Figure 16 Average doses from consumption of various products

9 CONCLUSIONS

The main conclusions of this review of the radiation exposure of the UK population are summarised in Table 42 and Figure 10, which show the contributions from each source. It was found that the average annual dose is 2.7 mSv, which is a slight increase on that assessed in the previous review, due mainly to the increased contribution from medical exposure. The main findings were as follows:

a) while the estimate of average annual dose from cosmic radiation at ground level has remained the same as that in the previous review, there has been a slight increase in the dose to the population from cosmic radiation exposure during air travel, due to the increased number of flights made by UK residents;

b) the estimate of average annual dose from natural terrestrial gamma radiation has remained the same as assessed in previous reviews;

c) a reassessment of the intakes of natural radionuclides in foodstuffs has resulted in a slightly lower estimate of the average annual dose from internal radiation;

d) the estimate of average annual dose from radon is unchanged from the previous review;

e) medical irradiation has been found to be the largest artificial source of radiation exposure, and recent surveys of the frequency and type of medical diagnostic procedures have resulted in an estimate of the average annual dose which is some 10% greater than that found in the previous review;

f) occupational exposures in the nuclear industry have decreased significantly, while radon exposure at work continues to account for the largest contribution to all occupational exposure and the highest individual annual doses;

g) the annual exposure from consumer products remains at a very low level;

h) residual environmental contamination from past nuclear weapons tests is declining and annual exposures remain very low; and

i) the average annual dose from discharges and disposals of radioactive wastes remains very low.

10 ACKNOWLEDGEMENTS

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Also, a number of colleagues from NRPB provided comments on drafts of the report. The authors are grateful for these contributions which have added to the comprehensiveness of the review.

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APPENDIX A DATA USED TO CALCULATE DOSES FROM NATURAL RADIONUCLIDES IN FOODSTUFFS

Consumption rates of the main food categories (Smith and Jones, 2003) are listed in the second, third and fourth columns of Table A1. Per caput consumption rates were used, as the average annual dose to the UK population was required, from intakes of the natural radionuclides shown. Concentrations of natural radionuclides in the foods shown were obtained from the following references: Bradley, E J, 1993; Dale A A, 2000; Dale A A, 2001; Dale A A, 2002; FSA and SEPA, 2002; Ham G J, et al, 1998; Hughes J S, 1999; UNSCEAR, 2000; Young et al, 2002. Annual average inhalation rates (Smith and Jones, 2003) were used and dose coefficients for inhalation and ingestion were taken from a publication of ICRP (ICRP, 1996).

TABLE A1 Data used to calculate doses to infants, children and adults from intakes of foodstuffs containing natural radioactivity

Foodstuffs	Food intake rates, kg y^{-1}			Average activity concentrations of naturally occurring radionuclides in foodstuffs, Bq kg^{-1}											
	Infant (1y)	Child (10y)	Adult	^{7}Be	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{14}C
Fruit (domestic and imported)	17	25	40		$9.80\ 10^{-3}$	$7.00\ 10^{-3}$	$5.00\ 10^{-4}$	$9.00\ 10^{-3}$	$1.80\ 10^{-2}$	$4.00\ 10^{-2}$	$5.00\ 10^{-4}$	$2.00\ 10^{-2}$	$5.00\ 10^{-4}$	$1.00\ 10^{-4}$	$1.00\ 10^{1}$
Nuts	0	0.4	0.8		$6.20\ 10^{-3}$	$7.00\ 10^{-3}$	$1.00\ 10^{-2}$	$9.40\ 10^{-2}$	$1.10\ 10^{-1}$	$2.90\ 10^{-2}$	$3.00\ 10^{-3}$	$9.40\ 10^{-2}$	$3.00\ 10^{-3}$	$1.00\ 10^{-3}$	$1.48\ 10^{2}$
Potatoes	10	45	50		$4.80\ 10^{-3}$	$5.00\ 10^{-3}$	$6.00\ 10^{-3}$	$2.30\ 10^{-2}$	$1.60\ 10^{-2}$	$9.00\ 10^{-3}$	$3.00\ 10^{-3}$	$2.00\ 10^{-2}$	$5.00\ 10^{-4}$	$1.00\ 10^{-4}$	$2.30\ 10^{1}$
Root vegetables	4.5	5.5	10		$1.20\ 10^{-2}$	$7.00\ 10^{-3}$	$9.70\ 10^{-3}$	$6.00\ 10^{-2}$	$3.00\ 10^{-2}$	$2.10\ 10^{-2}$	$7.00\ 10^{-3}$	$2.00\ 10^{-2}$	$5.00\ 10^{-4}$	$1.00\ 10^{-4}$	$8.00\ 10^{0}$
Green vegetables	2	4.5	15		$9.80\ 10^{-3}$	$4.90\ 10^{-3}$	$6.00\ 10^{-3}$	$9.60\ 10^{-3}$	$3.10\ 10^{-2}$	$9.00\ 10^{-2}$	$4.00\ 10^{-3}$	$4.00\ 10^{-2}$	$1.50\ 10^{-2}$	$1.00\ 10^{-3}$	$8.00\ 10^{0}$
Other domestic and imported vegetables	4.5	13	25		$4.70\ 10^{-3}$	$4.90\ 10^{-3}$	$6.00\ 10^{-3}$	$6.10\ 10^{-2}$	$2.80\ 10^{-1}$	$9.00\ 10^{-2}$	$4.00\ 10^{-3}$	$4.00\ 10^{-2}$	$1.50\ 10^{-2}$	$1.00\ 10^{-3}$	$2.00\ 10^{1}$
Mushrooms	0	0.3	1		$9.80\ 10^{-3}$	$4.90\ 10^{-3}$	$6.00\ 10^{-3}$	$9.60\ 10^{-3}$	$3.10\ 10^{-2}$	$9.00\ 10^{-2}$	$4.00\ 10^{-3}$	$4.00\ 10^{-2}$	$1.50\ 10^{-2}$	$1.00\ 10^{-3}$	$5.00\ 10^{0}$
Sugar	3	20	15		$2.50\ 10^{-3}$	$7.00\ 10^{-3}$	$9.70\ 10^{-3}$	$2.40\ 10^{-2}$	$4.10\ 10^{-2}$	1.8010^{-2}	$7.00\ 10^{-3}$	$2.00\ 10^{-2}$	$5.00\ 10^{-4}$	$1.00\ 10^{-4}$	$7.90\ 10^{1}$
Honey	0.2	0.1	0.2		$2.50\ 10^{-3}$	$7.00\ 10^{-3}$	$9.70\ 10^{-3}$	$2.40\ 10^{-2}$	$4.10\ 10^{-2}$	$1.80\ 10^{-2}$	$7.00\ 10^{-3}$	$2.00\ 10^{-2}$	$5.00\ 10^{-4}$	$1.00\ 10^{-4}$	$7.90\ 10^{1}$
Pig meat	1	8	15		$4.90\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$1.20\ 10^{-2}$	$7.20\ 10^{-2}$	$7.20\ 10^{-2}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$1.00\ 10^{-3}$	$5.00\ 10^{-5}$	$5.40\ 10^{1}$
Cattle meat	3	10	15		$4.90\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$1.20\ 10^{-2}$	$7.20\ 10^{-2}$	$1.10\ 10^{-1}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$1.00\ 10^{-3}$	$5.00\ 10^{-5}$	$4.40\ 10^{1}$
Sheep meat	0.6	1.5	3		$4.90\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$1.20\ 10^{-2}$	$7.20\ 10^{-2}$	$1.10\ 10^{-1}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$1.00\ 10^{-3}$	$5.00\ 10^{-5}$	$5.40\ 10^{1}$
Offal	0.4	1	2		$1.70\ 10^{-2}$	$1.30\ 10^{-2}$	$2.00\ 10^{-3}$	$2.20\ 10^{-2}$	$5.20\ 10^{-1}$	$4.90\ 10^{-1}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$9.30\ 10^{-2}$	$5.00\ 10^{-5}$	$3.10\ 10^{1}$
Poultry	1	3.5	7.5		$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$1.00\ 10^{-2}$	$4.30\ 10^{-2}$	$7.20\ 10^{-2}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$1.00\ 10^{-3}$	$5.00\ 10^{-5}$	$7.20\ 10^{1}$
Oil (non-dairy)	2	10	10		$2.50\ 10^{-2}$	$7.00\ 10^{-3}$	$1.00\ 10^{-2}$	$8.50\ 10^{-3}$	$1.10\ 10^{-1}$	$2.90\ 10^{-2}$	$3.00\ 10^{-3}$	$6.00\ 10^{-2}$	$3.00\ 10^{-3}$	$1.00\ 10^{-3}$	$1.05\ 10^{2}$

Foodstuffs	Food intake rates, kg y^{-1}			Average activity concentrations of naturally occurring radionuclides in foodstuffs, Bq kg^{-1}											
	Infant (1y)	Child (10y)	Adult	^{7}Be	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{14}C
Milk	120	110	95		$1.20\ 10^{-4}$	$1.00\ 10^{-3}$	$5.00\ 10^{-4}$	$3.00\ 10^{-3}$	$3.50\ 10^{-2}$	$1.50\ 10^{-2}$	$3.00\ 10^{-4}$	$5.00\ 10^{-3}$	$3.00\ 10^{-4}$	$5.00\ 10^{-5}$	$1.80\ 10^{1}$
Cheese and butter	1.3	4.5	10		$4.90\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$5.60\ 10^{-2}$	$7.20\ 10^{-2}$	$1.10\ 10^{-1}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$5.60\ 10^{-2}$	$5.00\ 10^{-5}$	$4.40\ 10^{1}$
Other milk products	10	10	9.5		$1.00\ 10^{-3}$	$1.00\ 10^{-3}$	$5.00\ 10^{-4}$	$3.00\ 10^{-3}$	$3.50\ 10^{-2}$	$1.50\ 10^{-2}$	$3.00\ 10^{-4}$	$5.00\ 10^{-3}$	$3.00\ 10^{-4}$	$5.00\ 10^{-5}$	$1.80\ 10^{1}$
Eggs	4.5	6.5	8		$4.90\ 10^{-3}$	$2.00\ 10^{-3}$	$2.00\ 10^{-3}$	$5.20\ 10^{-2}$	$8.80\ 10^{-2}$	$1.10\ 10^{-1}$	$1.00\ 10^{-3}$	$1.00\ 10^{-2}$	$1.00\ 10^{-3}$	$5.00\ 10^{-5}$	$3.80\ 10^{1}$
Fish	2	4	9.5		$3.90\ 10^{-3}$	$4.50\ 10^{-3}$	$8.10\ 10^{-4}$	$4.00\ 10^{-2}$	$5.00\ 10^{-2}$	$1.00\ 10^{0}$	$9.70\ 10^{-4}$	–	$5.40\ 10^{-3}$	–	$2.60\ 10^{1}$
Crustaceans	0	0.1	0.6		$3.50\ 10^{-2}$	$4.00\ 10^{-2}$	$2.60\ 10^{-3}$	$3.00\ 10^{-2}$	$2.00\ 10^{-1}$	$8.80\ 10^{0}$	$1.40\ 10^{-3}$	–	$9.60\ 10^{-3}$	–	$2.70\ 10^{1}$
Cereals	15	45	50		$6.20\ 10^{-3}$	$7.00\ 10^{-3}$	$1.00\ 10^{-2}$	$5.20\ 10^{-2}$	$9.30\ 10^{-2}$	$2.90\ 10^{-2}$	$3.00\ 10^{-3}$	$6.00\ 10^{-2}$	$3.00\ 10^{-3}$	$1.00\ 10^{-3}$	$1.05\ 10^{2}$
Water	260	350	600		$1.00\ 10^{-3}$	$1.00\ 10^{-3}$	$1.00\ 10^{-4}$	$5.00\ 10^{-4}$	$1.00\ 10^{-2}$	$5.00\ 10^{-3}$	$5.00\ 10^{-5}$	$5.00\ 10^{-4}$	$5.00\ 10^{-5}$	$4.00\ 10^{-5}$	–
Air				$2.00\ 10^{-3}$	$1.00\ 10^{-6}$	$1.00\ 10^{-6}$	$5.00\ 10^{-7}$	$1.00\ 10^{-6}$	$1.55\ 10^{-4}$	$9.33\ 10^{-6}$	$5.00\ 10^{-7}$	$1.00\ 10^{-6}$	$1.00\ 10^{-6}$	$5.00\ 10^{-8}$	–
Inhalation rates, $m^3\ y^{-1}$	$1.9\ 10^{3}$	$5.6\ 10^{3}$	$8.1\ 10^{3}$												
Ingestion dose coefficients – Adult				–	$4.50\ 10^{-8}$	$4.90\ 10^{-8}$	$2.10\ 10^{-7}$	$2.80\ 10^{-7}$	$6.90\ 10^{-7}$	$1.20\ 10^{-6}$	$2.30\ 10^{-7}$	$6.90\ 10^{-7}$	$7.20\ 10^{-8}$	$4.70\ 10^{-8}$	$5.80\ 10^{-10}$
Inhalation dose coefficients – Adult				$5.00\ 10^{-11}$	$2.90\ 10^{-6}$	$3.50\ 10^{-6}$	$1.40\ 10^{-5}$	$3.50\ 10^{-6}$	$1.10\ 10^{-6}$	$3.30\ 10^{-6}$	$2.50\ 10^{-5}$	$2.60\ 10^{-6}$	$4.00\ 10^{-5}$	$8.50\ 10^{-6}$	$2.00\ 10^{-9}$
Ingestion dose coefficients – Children				–	$6.80\ 10^{-8}$	$7.40\ 10^{-8}$	$2.40\ 10^{-7}$	$8.00\ 10^{-7}$	$1.90\ 10^{-6}$	$2.60\ 10^{-6}$	$2.90\ 10^{-7}$	$3.90\ 10^{-6}$	$1.40\ 10^{-7}$	$7.10\ 10^{-8}$	$8.00\ 10^{-10}$
Inhalation dose coefficients – Children				$8.30\ 10^{-11}$	$4.00\ 10^{-6}$	$4.80\ 10^{-6}$	$1.60\ 10^{-5}$	$4.90\ 10^{-6}$	$1.50\ 10^{-6}$	$4.60\ 10^{-6}$	$2.60\ 10^{-5}$	$4.60\ 10^{-6}$	$5.50\ 10^{-5}$	$1.10\ 10^{-5}$	$2.80\ 10^{-9}$

Foodstuffs	Food intake rates, kg y^{-1}			Average activity concentrations of naturally occurring radionuclides in foodstuffs, Bq kg^{-1}											
	Infant (1y)	Child (10y)	Adult	^{7}Be	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{14}C
Ingestion dose coefficients – Infants				–	1.20 10^{-7}	1.30 10^{-7}	4.10 10^{-7}	9.60 10^{-7}	3.60 10^{-6}	8.80 10^{-6}	4.50 10^{-7}	5.70 10^{-6}	3.70 10^{-7}	1.30 10^{-7}	1.60 10^{-9}
Inhalation dose coefficients - Infants				2.10 10^{-10}	9.40 10^{-6}	1.10 10^{-5}	3.50 10^{-5}	1.10 10^{-5}	3.70 10^{-6}	1.10 10^{-5}	5.00 10^{-5}	1.00 10^{-5}	1.30 10^{-4}	2.60 10^{-5}	6.60 10^{-9}

TABLE A2 Annual average doses to adults in the UK from consumption of foodstuffs containing natural radionuclides

	Annual doses, μSv										
Foodstuffs	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{14}C
Fruit (domestic and imported)	1.76 10^{-2}	1.37 10^{-2}	4.20 10^{-3}	1.01 10^{-1}	4.97 10^{-1}	1.92 10^{0}	4.60 10^{-3}	5.52 10^{-1}	1.44 10^{-3}	1.88 10^{-4}	2.32 10^{-1}
Nuts	2.23 10^{-4}	2.74 10^{-4}	1.68 10^{-3}	2.11 10^{-2}	6.07 10^{-2}	2.78 10^{-2}	5.52 10^{-4}	5.19 10^{-2}	1.73 10^{-4}	3.76 10^{-5}	6.87 10^{-2}
Potatoes	1.08 10^{-2}	1.23 10^{-2}	6.30 10^{-2}	3.22 10^{-1}	5.52 10^{-1}	5.40 10^{-1}	3.45 10^{-2}	6.90 10^{-1}	1.80 10^{-3}	2.35 10^{-4}	6.67 10^{-1}
Root vegetables	5.40 10^{-3}	3.43 10^{-3}	2.04 10^{-2}	1.68 10^{-1}	2.07 10^{-1}	2.52 10^{-1}	1.61 10^{-2}	1.38 10^{-1}	3.60 10^{-4}	4.70 10^{-5}	4.64 10^{-2}
Green vegetables	6.62 10^{-3}	3.60 10^{-3}	1.89 10^{-2}	4.03 10^{-2}	3.21 10^{-1}	1.62 10^{0}	1.38 10^{-2}	4.14 10^{-1}	1.62 10^{-2}	7.05 10^{-4}	6.96 10^{-2}
Other domestic and imported vegetables	5.29 10^{-3}	6.00 10^{-3}	3.15 10^{-2}	4.27 10^{-1}	4.83 10^{0}	2.70 10^{0}	2.30 10^{-2}	6.90 10^{-1}	2.70 10^{-2}	1.18 10^{-3}	2.90 10^{-1}
Mushrooms	4.41 10^{-4}	2.40 10^{-4}	1.26 10^{-3}	2.69 10^{-3}	2.14 10^{-2}	1.08 10^{-1}	9.20 10^{-4}	2.76 10^{-2}	1.08 10^{-3}	4.70 10^{-5}	2.90 10^{-3}
Sugar	1.69 10^{-3}	5.15 10^{-3}	3.06 10^{-2}	1.01 10^{-1}	4.24 10^{-1}	3.24 10^{-1}	2.42 10^{-2}	2.07 10^{-1}	5.40 10^{-4}	7.05 10^{-5}	6.87 10^{-1}
Honey	2.25 10^{-5}	6.86 10^{-5}	4.07 10^{-4}	1.34 10^{-3}	5.66 10^{-3}	4.32 10^{-3}	3.22 10^{-4}	2.76 10^{-3}	7.20 10^{-6}	9.40 10^{-7}	9.16 10^{-3}
Pig meat	3.31 10^{-3}	1.47 10^{-3}	6.30 10^{-3}	5.04 10^{-2}	7.45 10^{-1}	1.30 10^{0}	3.45 10^{-3}	1.04 10^{-1}	1.08 10^{-3}	3.53 10^{-5}	4.70 10^{-1}
Cattle meat	3.31 10^{-3}	1.47 10^{-3}	6.30 10^{-3}	5.04 10^{-2}	7.45 10^{-1}	1.98 10^{0}	3.45 10^{-3}	1.04 10^{-1}	1.08 10^{-3}	3.53 10^{-5}	3.83 10^{-1}
Sheep meat	6.62 10^{-4}	2.94 10^{-4}	1.26 10^{-3}	1.01 10^{-2}	1.49 10^{-1}	3.96 10^{-1}	6.90 10^{-4}	2.07 10^{-2}	2.16 10^{-4}	7.05 10^{-6}	9.40 10^{-2}
Offal	1.53 10^{-3}	1.27 10^{-3}	8.40 10^{-4}	1.23 10^{-2}	7.18 10^{-1}	1.18 10^{0}	4.60 10^{-4}	1.38 10^{-2}	1.34 10^{-2}	4.70 10^{-6}	3.60 10^{-2}
Poultry	6.75 10^{-4}	7.35 10^{-4}	3.15 10^{-3}	2.10 10^{-2}	2.23 10^{-1}	6.48 10^{-1}	1.73 10^{-3}	5.18 10^{-2}	5.40 10^{-4}	1.76 10^{-5}	3.13 10^{-1}
Oil (non-dairy)	1.13 10^{-2}	3.43 10^{-3}	2.10 10^{-2}	2.38 10^{-2}	7.59 10^{-1}	3.48 10^{-1}	6.90 10^{-3}	4.14 10^{-1}	2.16 10^{-3}	4.70 10^{-4}	6.09 10^{-1}
Milk	5.13 10^{-4}	4.66 10^{-3}	9.98 10^{-3}	7.98 10^{-2}	2.29 10^{0}	1.71 10^{0}	6.56 10^{-3}	3.28 10^{-1}	2.05 10^{-3}	2.23 10^{-4}	9.92 10^{-1}
Cheese and butter	2.21 10^{-3}	9.80 10^{-4}	4.20 10^{-3}	1.57 10^{-1}	4.97 10^{-1}	1.32 10^{0}	2.30 10^{-3}	6.90 10^{-2}	4.03 10^{-2}	2.35 10^{-5}	2.55 10^{-1}
Other milk products	4.28 10^{-4}	4.66 10^{-4}	9.98 10^{-4}	7.98 10^{-3}	2.29 10^{-1}	1.71 10^{-1}	6.56 10^{-4}	3.28 10^{-2}	2.05 10^{-4}	2.23 10^{-5}	9.92 10^{-2}
Eggs	1.76 10^{-3}	7.84 10^{-4}	3.36 10^{-3}	1.16 10^{-1}	4.86 10^{-1}	1.06 10^{0}	1.84 10^{-3}	5.52 10^{-2}	5.76 10^{-4}	1.88 10^{-5}	1.76 10^{-1}
Fish	1.67 10^{-3}	2.09 10^{-3}	1.62 10^{-3}	1.06 10^{-1}	3.28 10^{-1}	1.14 10^{1}	2.12 10^{-3}	0.00 10^{0}	3.69 10^{-3}	0.00 10^{0}	1.43 10^{-1}
Crustaceans	9.45 10^{-4}	1.18 10^{-3}	3.28 10^{-4}	5.04 10^{-3}	8.28 10^{-2}	6.34 10^{0}	1.93 10^{-4}	0.00 10^{0}	4.15 10^{-4}	0.00 10^{0}	9.40 10^{-3}
Cereals	1.40 10^{-2}	1.72 10^{-2}	1.05 10^{-1}	7.28 10^{-1}	3.21 10^{0}	1.74 10^{0}	3.45 10^{-2}	2.07 10^{0}	1.08 10^{-2}	2.35 10^{-3}	3.05 10^{0}
Water	2.70 10^{-2}	2.94 10^{-2}	1.26 10^{-2}	8.40 10^{-2}	4.14 10^{0}	3.60 10^{0}	6.90 10^{-3}	2.07 10^{-1}	2.16 10^{-3}	1.13 10^{-3}	0.00 10^{0}
Total	1.18$10^{-1}$	1.10 10^{-1}	3.49 10^{-1}	2.71 10^{0}	2.22 10^{1}	4.17 10^{1}	1.90 10^{-1}	6.24 10^{0}	1.27 10^{-1}	6.84 10^{-3}	8.84 10^{0}

TABLE A3 Annual average doses to children in the UK from consumption of foodstuffs containing natural radionuclides

	Annual doses, μSv										
Foodstuffs	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{14}C
Fruit (domestic and imported)	1.67$10^{-2}$	1.30 10^{-2}	3.00 10^{-3}	1.80 10^{-1}	8.55 10^{-1}	2.60 10^{0}	3.63 10^{-3}	1.95 10^{0}	1.75 10^{-3}	1.78 10^{-4}	2.00 10^{-1}
Nuts	1.69 10^{-4}	2.07 10^{-4}	9.60 10^{-4}	3.01 10^{-2}	8.36 10^{-2}	3.02 10^{-2}	3.48 10^{-4}	1.47 10^{-1}	1.68 10^{-4}	2.84 10^{-5}	4.74 10^{-2}
Potatoes	1.47 10^{-2}	1.67 10^{-2}	6.48 10^{-2}	8.28 10^{-1}	1.37 10^{0}	1.05 10^{0}	3.92 10^{-2}	3.51 10^{0}	3.15 10^{-3}	3.20 10^{-4}	8.28 10^{-1}
Root vegetables	4.49 10^{-3}	2.85 10^{-3}	1.28 10^{-2}	2.64 10^{-1}	3.14 10^{-1}	3.00 10^{-1}	1.12 10^{-2}	4.29 10^{-1}	3.85 10^{-4}	3.91 10^{-5}	3.52 10^{-2}
Green vegetables	3.00 10^{-3}	1.63 10^{-3}	6.48 10^{-3}	3.46 10^{-2}	2.65 10^{-1}	1.05 10^{0}	5.22 10^{-3}	7.02 10^{-1}	9.45 10^{-3}	3.20 10^{-4}	2.88 10^{-2}
Other domestic and imported vegetables	4.15 10^{-3}	4.71 10^{-3}	1.87 10^{-2}	6.34 10^{-1}	6.92 10^{0}	3.04 10^{0}	1.51 10^{-2}	2.03 10^{0}	2.73 10^{-2}	9.23 10^{-4}	2.08 10^{-1}
Mushrooms	2.00 10^{-4}	1.09 10^{-4}	4.32 10^{-4}	2.30 10^{-3}	1.77 10^{-2}	7.02 10^{-2}	3.48 10^{-4}	4.68 10^{-2}	6.30 10^{-4}	2.13 10^{-5}	1.20 10^{-3}
Sugar	3.40 10^{-3}	1.04 10^{-2}	4.66 10^{-2}	3.84 10^{-1}	1.56 10^{0}	9.36 10^{-1}	4.06 10^{-2}	1.56 10^{0}	1.40 10^{-3}	1.42 10^{-4}	1.26 10^{0}
Honey	1.70 10^{-5}	5.18 10^{-5}	2.33 10^{-4}	1.92 10^{-3}	7.79 10^{-3}	4.68 10^{-3}	2.03 10^{-4}	7.80 10^{-3}	7.00 10^{-6}	7.10 10^{-7}	6.32 10^{-3}
Pig meat	2.67 10^{-3}	1.18 10^{-3}	3.84 10^{-3}	7.68 10^{-2}	1.09 10^{0}	1.50 10^{0}	2.32 10^{-3}	3.12 10^{-1}	1.12 10^{-3}	2.84 10^{-5}	3.46 10^{-1}
Cattle meat	3.33 10^{-3}	1.48 10^{-3}	4.80 10^{-3}	9.60 10^{-2}	1.37 10^{0}	2.86 10^{0}	2.90 10^{-3}	3.90 10^{-1}	1.40 10^{-3}	3.55 10^{-5}	3.52 10^{-1}
Sheep meat	5.00 10^{-4}	2.22 10^{-4}	7.20 10^{-4}	1.44 10^{-2}	2.05 10^{-1}	4.29 10^{-1}	4.35 10^{-4}	5.85 10^{-2}	2.10 10^{-4}	5.33 10^{-6}	6.48 10^{-2}
Offal	1.16 10^{-3}	9.62 10^{-4}	4.80 10^{-4}	1.76 10^{-2}	9.88 10^{-1}	1.27 10^{0}	2.90 10^{-4}	3.90 10^{-2}	1.30 10^{-2}	3.55 10^{-6}	2.48 10^{-2}
Poultry	4.76 10^{-4}	5.18 10^{-4}	1.68 10^{-3}	2.80 10^{-2}	2.86 10^{-1}	6.55 10^{-1}	1.02 10^{-3}	1.37 10^{-1}	4.90 10^{-4}	1.24 10^{-5}	2.02 10^{-1}
Oil (non-dairy)	1.70 10^{-2}	5.18 10^{-3}	2.40 10^{-2}	6.80 10^{-2}	2.09 10^{0}	7.54 10^{-1}	8.70 10^{-3}	2.34 10^{0}	4.20 10^{-3}	7.10 10^{-4}	8.40 10^{-1}
Milk	8.98 10^{-4}	8.14 10^{-3}	1.32 10^{-2}	2.64 10^{-1}	7.32 10^{0}	4.29 10^{0}	9.57 10^{-3}	2.15 10^{0}	4.62 10^{-3}	3.91 10^{-4}	1.58 10^{0}
Cheese and butter	1.5010^{-3}	6.66 10^{-4}	2.16 10^{-3}	2.02 10^{-1}	6.16 10^{-1}	1.29 10^{0}	1.31 10^{-3}	1.76 10^{-1}	3.53 10^{-2}	1.60 10^{-5}	1.58 10^{-1}
Other milk products	6.80 10^{-4}	7.40 10^{-4}	1.20 10^{-3}	2.40 10^{-2}	6.65 10^{-1}	3.90 10^{-1}	8.70 10^{-4}	1.95 10^{-1}	4.20 10^{-4}	3.55 10^{-5}	1.44 10^{-1}
Eggs	2.17 10^{-3}	9.62 10^{-4}	3.12 10^{-3}	2.70 10^{-1}	1.09 10^{0}	1.86 10^{0}	1.89 10^{-3}	2.54 10^{-1}	9.10 10^{-4}	2.31 10^{-5}	1.98 10^{-1}
Fish	1.06 10^{-3}	1.33 10^{-3}	7.78 10^{-4}	1.28 10^{-1}	3.80 10^{-1}	1.04 10^{1}	1.13 10^{-3}	0.00 10^{0}	3.02 10^{-3}	0.00 10^{0}	8.32 10^{-2}
Crustaceans	2.38 10^{-4}	2.96 10^{-4}	6.24 10^{-5}	2.40 10^{-3}	3.80 10^{-2}	2.29 10^{0}	4.06 10^{-5}	0.00 10^{0}	1.34 10^{-4}	0.00 10^{0}	2.16 10^{-3}
Cereals	1.90 10^{-2}	2.33 10^{-2}	1.08 10^{-1}	1.87 10^{0}	7.95 10^{0}	3.39 10^{0}	3.92 10^{-2}	1.05 10^{1}	1.89 10^{-2}	3.20 10^{-3}	3.78 10^{0}
Water	2.38 10^{-2}	2.59 10^{-2}	8.40 10^{-3}	1.40 10^{-1}	6.65 10^{0}	4.55 10^{0}	5.08 10^{-3}	6.83 10^{-1}	2.45 10^{-3}	9.94 10^{-4}	0.00 10^{0}
Total	1.22 10^{-1}	1.20 10^{-1}	3.26 10^{-1}	5.73 10^{0}	4.35 10^{1}	4.66 10^{1}	1.90 10^{-1}	2.76 10^{1}	1.30 10^{-1}	7.42 10^{-3}	1.05 10^{1}

TABLE A4 Annual average doses to infants in the UK from consumption of foodstuffs containing natural radionuclides

	Annual doses, μSv										
Foodstuffs	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	^{14}C
Fruit (domestic and imported)	$2.00\ 10^{-2}$	$1.55\ 10^{-2}$	$3.49\ 10^{-3}$	$1.47\ 10^{-1}$	$1.10\ 10^{0}$	$5.98\ 10^{0}$	$3.83\ 10^{-3}$	$1.94\ 10^{0}$	$3.15\ 10^{-3}$	$2.21\ 10^{-4}$	$2.72\ 10^{-1}$
Potatoes	$5.76\ 10^{-3}$	$6.50\ 10^{-3}$	$2.46\ 10^{-2}$	$2.21\ 10^{-1}$	$5.76\ 10^{-1}$	$7.92\ 10^{-1}$	$1.35\ 10^{-2}$	$1.14\ 10^{0}$	$1.85\ 10^{-3}$	$1.30\ 10^{-4}$	$3.68\ 10^{-1}$
Root vegetables	$6.48\ 10^{-3}$	$4.10\ 10^{-3}$	$1.79\ 10^{-2}$	$2.59\ 10^{-1}$	$4.86\ 10^{-1}$	$8.32\ 10^{-1}$	$1.42\ 10^{-2}$	$5.13\ 10^{-1}$	$8.33\ 10^{-4}$	$5.85\ 10^{-5}$	$5.76\ 10^{-2}$
Green vegetables	$2.35\ 10^{-3}$	$1.27\ 10^{-3}$	$4.92\ 10^{-3}$	$1.84\ 10^{-2}$	$2.23\ 10^{-1}$	$1.58\ 10^{0}$	$3.60\ 10^{-3}$	$4.56\ 10^{-1}$	$1.11\ 10^{-2}$	$2.60\ 10^{-4}$	$2.56\ 10^{-2}$
Other domestic and imported vegetables	$2.54\ 10^{-3}$	$2.87\ 10^{-3}$	$1.11\ 10^{-2}$	$2.64\ 10^{-1}$	$4.54\ 10^{0}$	$3.56\ 10^{0}$	$8.10\ 10^{-3}$	$1.03\ 10^{0}$	$2.50\ 10^{-2}$	$5.85\ 10^{-4}$	$1.44\ 10^{-1}$
Sugar	$9.00\ 10^{-4}$	$2.73\ 10^{-3}$	$1.19\ 10^{-2}$	$6.91\ 10^{-2}$	$4.43\ 10^{-1}$	$4.75\ 10^{-1}$	$9.45\ 10^{-3}$	$3.42\ 10^{-1}$	$5.55\ 10^{-4}$	$3.90\ 10^{-5}$	$3.79\ 10^{-1}$
Honey	$6.00\ 10^{-5}$	$1.82\ 10^{-4}$	$7.95\ 10^{-4}$	$4.61\ 10^{-3}$	$2.95\ 10^{-2}$	$3.17\ 10^{-2}$	$6.30\ 10^{-4}$	$2.28\ 10^{-2}$	$3.70\ 10^{-5}$	$2.60\ 10^{-6}$	$2.53\ 10^{-2}$
Pig meat	$5.88\ 10^{-4}$	$2.60\ 10^{-4}$	$8.20\ 10^{-4}$	$1.15\ 10^{-2}$	$2.59\ 10^{-1}$	$6.34\ 10^{-1}$	$4.50\ 10^{-4}$	$5.70\ 10^{-2}$	$3.70\ 10^{-4}$	$6.50\ 10^{-6}$	$8.64\ 10^{-2}$
Cattle meat	$1.76\ 10^{-3}$	$7.80\ 10^{-4}$	$2.46\ 10^{-3}$	$3.46\ 10^{-2}$	$7.78\ 10^{-1}$	$2.90\ 10^{0}$	$1.35\ 10^{-3}$	$1.71\ 10^{-1}$	$1.11\ 10^{-3}$	$1.95\ 10^{-5}$	$2.11\ 10^{-1}$
Sheep meat	$3.53\ 10^{-4}$	$1.56\ 10^{-4}$	$4.92\ 10^{-4}$	$6.91\ 10^{-3}$	$1.56\ 10^{-1}$	$5.81\ 10^{-1}$	$2.70\ 10^{-4}$	$3.42\ 10^{-2}$	$2.22\ 10^{-4}$	$3.90\ 10^{-6}$	$5.18\ 10^{-2}$
Offal	$8.16\ 10^{-4}$	$6.76\ 10^{-4}$	$3.28\ 10^{-4}$	$8.45\ 10^{-3}$	$7.49\ 10^{-1}$	$1.72\ 10^{0}$	$1.80\ 10^{-4}$	$2.28\ 10^{-2}$	$1.38\ 10^{-2}$	$2.60\ 10^{-6}$	$1.98\ 10^{-2}$
Poultry	$2.40\ 10^{-4}$	$2.60\ 10^{-4}$	$8.20\ 10^{-4}$	$9.60\ 10^{-3}$	$1.55\ 10^{-1}$	$6.34\ 10^{-1}$	$4.50\ 10^{-4}$	$5.70\ 10^{-2}$	$3.70\ 10^{-4}$	$6.50\ 10^{-6}$	$1.15\ 10^{-1}$
Oil (non-dairy)	$6.00\ 10^{-3}$	$1.82\ 10^{-3}$	$8.20\ 10^{-3}$	$1.63\ 10^{-2}$	$7.92\ 10^{-1}$	$5.10\ 10^{-1}$	$2.70\ 10^{-3}$	$6.84\ 10^{-1}$	$2.22\ 10^{-3}$	$2.60\ 10^{-4}$	$3.36\ 10^{-1}$
Milk	$1.73\ 10^{-3}$	$1.56\ 10^{-2}$	$2.46\ 10^{-2}$	$3.46\ 10^{-1}$	$1.51\ 10^{1}$	$1.58\ 10^{1}$	$1.62\ 10^{-2}$	$3.42\ 10^{0}$	$1.33\ 10^{-2}$	$7.80\ 10^{-4}$	$3.46\ 10^{0}$
Cheese and butter	$7.64\ 10^{-4}$	$3.38\ 10^{-4}$	$1.07\ 10^{-3}$	$6.99\ 10^{-2}$	$3.37\ 10^{-1}$	$1.26\ 10^{0}$	$5.85\ 10^{-4}$	$7.41\ 10^{-2}$	$2.69\ 10^{-2}$	$8.45\ 10^{-6}$	$9.15\ 10^{-2}$
Other milk products	$1.20\ 10^{-3}$	$1.30\ 10^{-3}$	$2.05\ 10^{-3}$	$2.88\ 10^{-2}$	$1.26\ 10^{0}$	$1.32\ 10^{0}$	$1.35\ 10^{-3}$	$2.85\ 10^{-1}$	$1.11\ 10^{-3}$	$6.50\ 10^{-5}$	$2.88\ 10^{-1}$
Eggs	$2.65\ 10^{-3}$	$1.17\ 10^{-3}$	$3.69\ 10^{-3}$	$2.25\ 10^{-1}$	$1.43\ 10^{0}$	$4.36\ 10^{0}$	$2.03\ 10^{-3}$	$2.57\ 10^{-1}$	$1.67\ 10^{-3}$	$2.93\ 10^{-5}$	$2.74\ 10^{-1}$
Fish	$9.36\ 10^{-4}$	$1.17\ 10^{-3}$	$6.64\ 10^{-4}$	$7.68\ 10^{-2}$	$3.60\ 10^{-1}$	$1.76\ 10^{1}$	$8.73\ 10^{-4}$	$0.00\ 10^{0}$	$4.00\ 10^{-3}$	$0.00\ 10^{0}$	$8.32\ 10^{-2}$
Cereals	$1.12\ 10^{-2}$	$1.37\ 10^{-2}$	$6.15\ 10^{-2}$	$7.49\ 10^{-1}$	$5.02\ 10^{0}$	$3.83\ 10^{0}$	$2.03\ 10^{-2}$	$5.13\ 10^{0}$	$1.67\ 10^{-2}$	$1.95\ 10^{-3}$	$2.52\ 10^{0}$
Water	$3.12\ 10^{-2}$	$3.38\ 10^{-2}$	$1.07\ 10^{-2}$	$1.25\ 10^{-1}$	$9.36\ 10^{0}$	$1.14\ 10^{1}$	$5.85\ 10^{-3}$	$7.41\ 10^{-1}$	$4.81\ 10^{-3}$	$1.35\ 10^{-3}$	$0.00\ 10^{0}$
Total	$9.93\ 10^{-2}$	$1.04\ 10^{-1}$	$1.92\ 10^{-1}$	$2.89\ 10^{0}$	$4.58\ 10^{1}$	$8.13\ 10^{1}$	$1.06\ 10^{-1}$	$1.64\ 10^{1}$	$1.29\ 10^{-1}$	$5.78\ 10^{-3}$	$8.87\ 10^{0}$

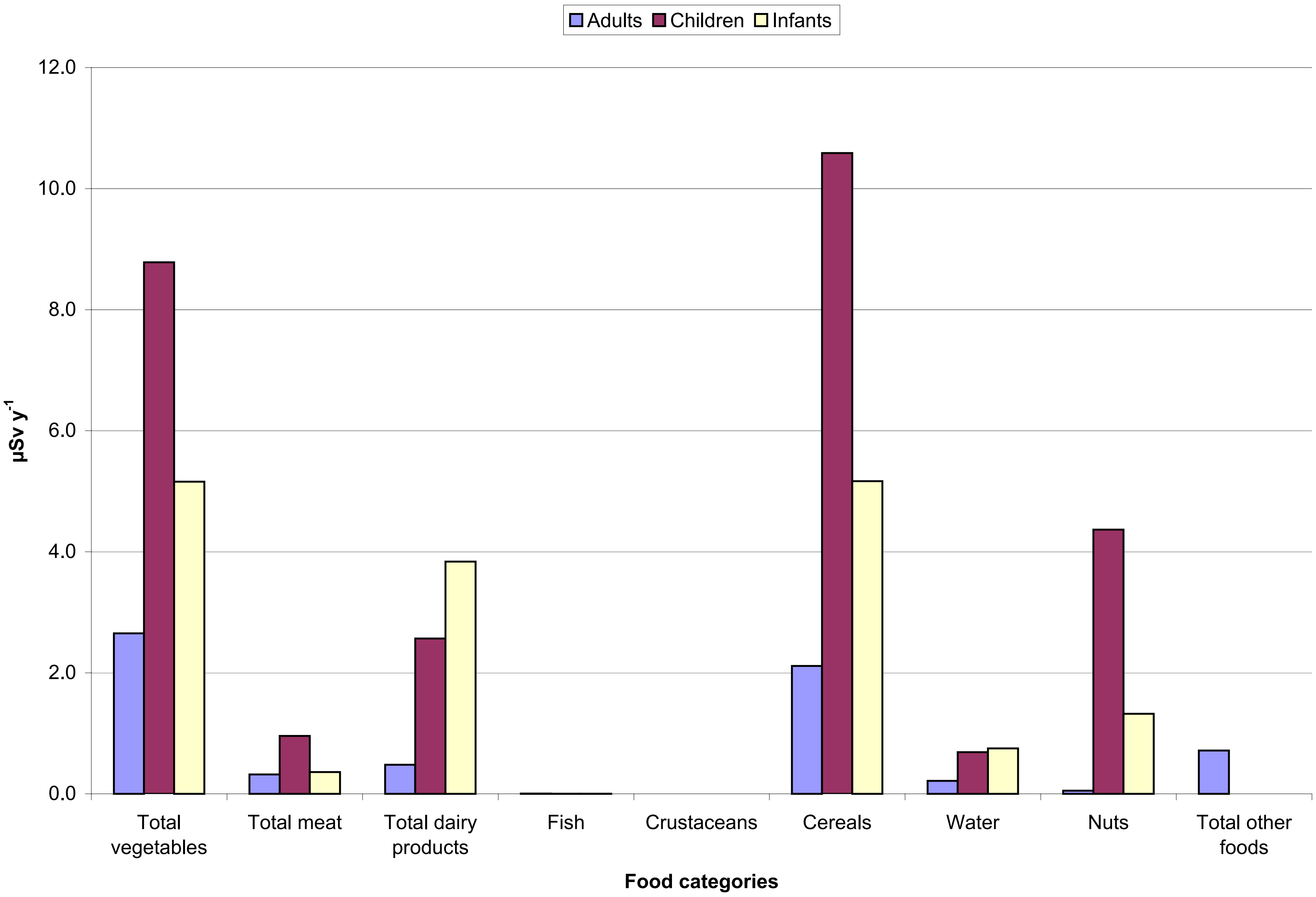

Figure A1 Dose to each age group from natural radionuclides in foodstuffs in the ^{232}Th series

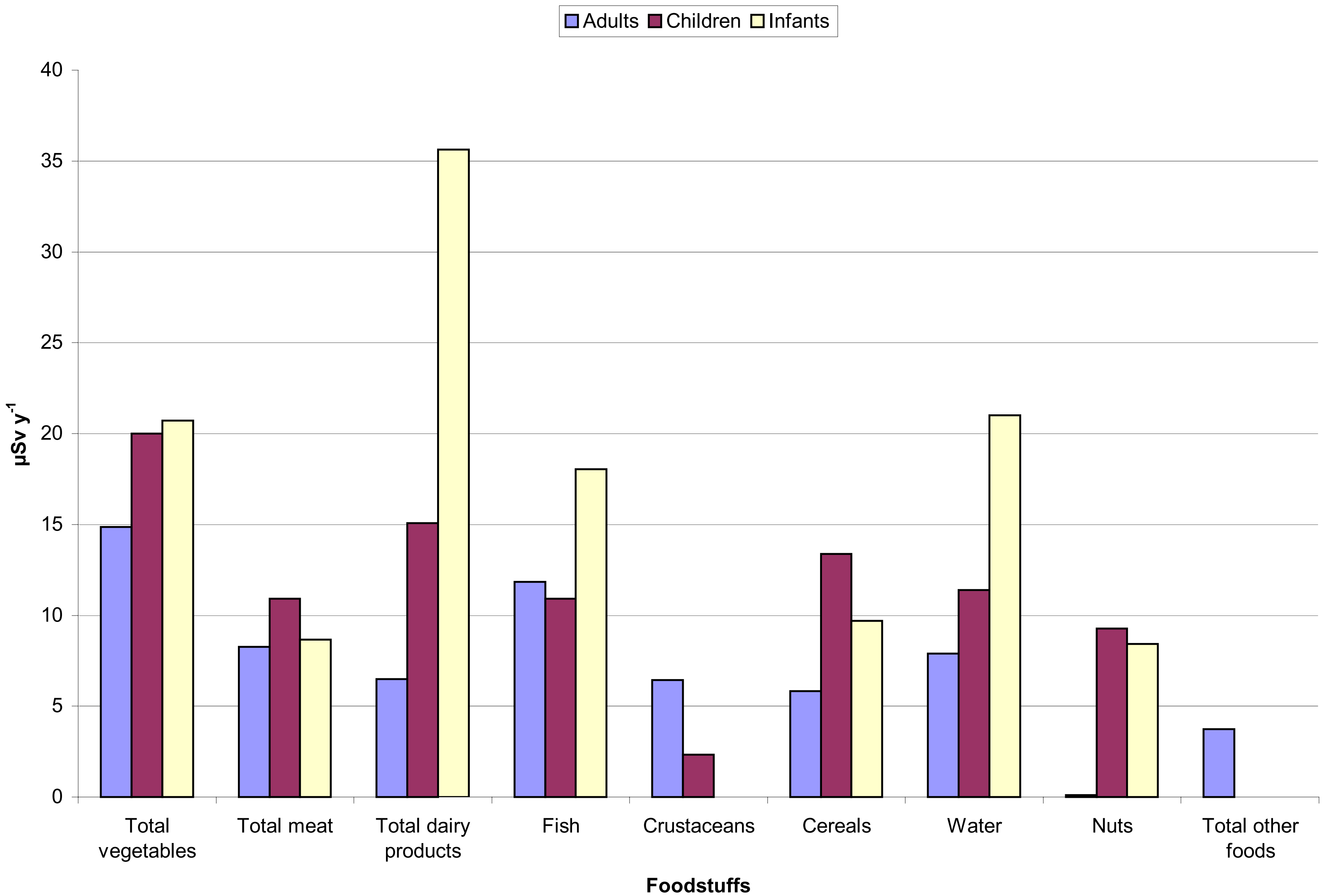

Figure A2 Dose to each age group from natural radionuclides in foodstuffs in the ^{238}U series

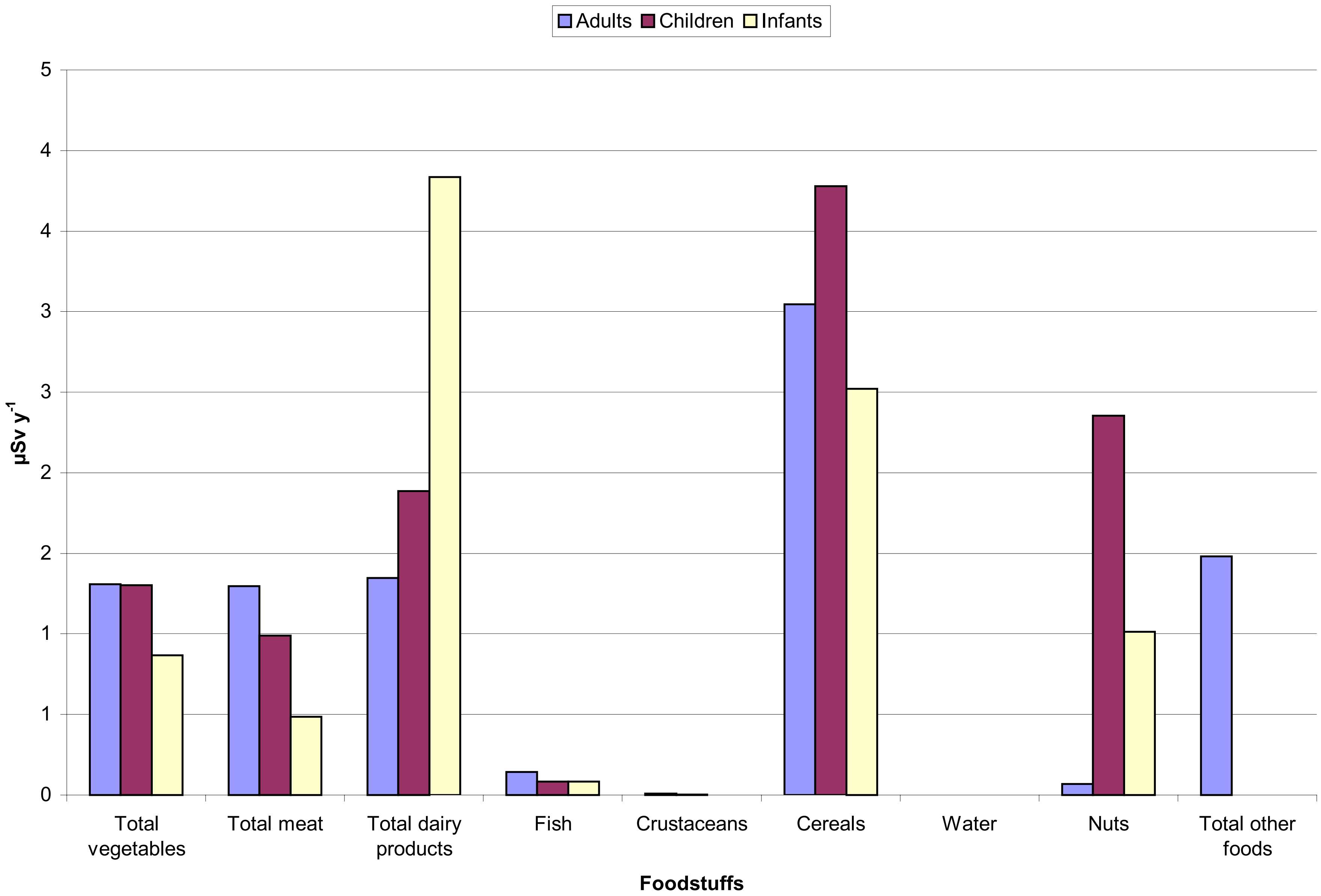

Figure A3 Dose to each age group from ^{14}C in foodstuffs

APPENDIX B GLOSSARY

absorbed dose

The quantity of energy imparted by **ionising radiation** to a unit mass of matter such as tissue. Absorbed dose has the unit joules per kilogram ($J\ kg^{-1}$) which has the special name **Gray** (Gy).

activation products

Activation products are created when a stable radionuclide is converted into an unstable radionuclide by interaction with radiation.

alpha activity

The alpha activity is the number of alpha particles emitted per unit time. An alpha particle is identical to the nucleus of a helium atom, consisting of two protons plus two neutrons. An alpha particle has low penetrating power but high **linear energy transfer** (LET). The unit of activity is the **Becquerel** (Bq).

atoms

The simplest unit into which a substance can be broken down whilst retaining its unique identity and properties. They consist of a central nucleus with a net positive electrical charge, orbiting around which are small lightweight negatively charged particles called **electrons**.

authorised discharges

Discharges of radioactive wastes are made from various establishments. The disposals are authorised by the environment agencies in the UK under the Radioactive Substances Act 1993.

background radiation

The radiation level to which the general population is exposed. It consists of radiation from outer space, and radiation from radionuclides in rocks, soil, air, food and from within the human body.

Becquerel (Bq)

The international (SI) unit for the number of nuclear disintegrations occurring per unit time, in a quantity of radioactive material. 1 Bq = 1 radioactive disintegration per second. This is an extremely small unit and levels are of often prefixed with mega (10^6 Bq – MBq), giga (10^9 Bq – GBq) and tera (10^{12} Bq – TBq) particularly in the context of discharges of activity into the environment. Conversely, under normal circumstances, activity concentrations in environmental materials are generally low and so prefixes such as milli (10^{-3} Bq – mBq) and micro (10^{-6} Bq - μBq) are used.

beta radiation/beta particle

Beta radiation is a form of radioactivity in which beta particles are emitted from an atom. It has greater penetrative power than an alpha particle, but has a low **linear energy transfer** (LET). A beta particle has a mass and charge identical to that of an electron. Beta particles can be either positively (called a positron) or negatively charged (called an electron).

collective effective dose

The quantity obtained by multiplying the average **effective dose** by the number of people exposed to a given source of **ionising radiation**. Unit man sievert (man Sv). Frequently abbreviated to collective dose.

computed tomography – see **X-ray procedures**.

conventional X-rays – see **X-ray procedures**.

cosmogenic radionuclides

Cosmogenic refers to radioactive isotopes created when cosmic radiation interacts with an atomic nucleus. These isotopes are produced on Earth, in Earth's atmosphere, and in extraterrestrial items such as meteorites.

critical group

Members of the population who because of their habits or sources of foodstuff are likely to have the highest exposure to radiation from a particular source.

decay

The process of spontaneous transformation of a **radionuclide**. The decrease in the activity of a radioactive substance.

decay product

A nuclide or **radionuclide** produced by **decay**.

discharges - see **radioactive discharges**.

dose

General term for quantity of **ionising radiation**. See **absorbed dose**, **effective dose**, **equivalent dose** and **collective effective dose**. Frequently used for effective dose.

dose coefficient

Dose coefficients are values recommended by the International Committee on Radiological Protection that allow the activity taken into the body, either by inhalation or ingestion, to be converted into an **effective dose**. These values have been calculated by modelling the movement of a radionuclide within the body and determining the resulting tissue doses.

effective dose

The effective dose is the sum of the weighted **equivalent doses** in all the tissues and organs of the body. It takes account of the susceptibility of organs and tissues to radiation damage. Unit **Sievert** (Sv).

electron

An elementary particle with a low mass, of $5\ 10^{-4}$ that of a **proton**, and unit negative electric charge. Positive charged electrons, called positrons, also exist (see **beta particle**).

equivalent dose

The quantity obtained by multiplying the **absorbed dose** by a factor to allow for the different effectiveness of the various **ionising radiations** in causing harm to tissue. Unit **sievert**, symbol Sv. Usually the factor for **gamma rays**, **X-rays** and **beta** particles is 1 but for **alpha** particles it is 20.

fission (products)

The spontaneous or induced disintegration of a heavy atomic nucleus into two or more lighter fragments (nuclei). The energy released in the process is referred to as nuclear energy.

fluoroscopy – see **X-ray procedures**

gamma rays

High energy photons, without mass or charge, emitted from the nucleus of a **radionuclide** following radioactive **decay**, as an electromagnetic wave. They are very penetrating but have a low **linear energy transfer** (LET).

Gray (Gy)

The international (SI) unit of **absorbed dose**. 1 Gy is equivalent to 1 joule of energy absorbed per kilogram of matter such as body tissue. Can also be used with prefixes such as nano to make units such as nanogray (nGy - 10^{-9} Gy).

half-life

The time taken for the activity of a **radionuclide** to lose half its value by **decay**. During each subsequent half-life its activity is halved again so its activity decays exponentially.

igneous rocks

Igneous rocks are formed when molten rock (magma) cools and solidifies either below the surface or on the surface of the Earth. This magma can be derived from either the Earth's mantle or pre-existing rocks made molten by extreme temperature and pressure changes. Over 700 types of igneous rocks have been described, most of them formed beneath the surface of the Earth's crust.

interventional X-rays or **interventional radiology** – see X-ray procedures

ionising radiation

Radiation which is sufficiently energetic to remove electrons from atoms in its path. In human or animal exposures, ionising radiation can result in the formation of highly reactive particles in the body which can cause damage to individual components of living cells and tissues. The term includes radiation at least as energetic as **X-ray**; **gamma rays** and charged particles such as **alpha** and **beta particles** are also forms of ionising radiation.

isotope

Nuclides containing the same number of **protons** (ie, same atomic number) but a different number of **neutrons**.

linear energy transfer (LET)

This property of radiation relates to how much energy is lost by the radiation when travelling a given distance. High LET radiation loses a lot of energy quickly and in a short distance. For example an alpha particle may not travel far but it may cause a lot of damage to a cell it is travelling through compared to a radiation that loses energy over a larger distance (for example, a **beta particle**).

luminescence

Luminescence is the emission of light by a material.

man sievert – see **collective effective dose.**

microsievert – see **Sievert.**

millisievert – see **Sievert.**

nanogray – see **Gray.**

muon

An elementary particle with a mass about one-tenth of a **proton** or about 200 times heavier than an **electron**.

neutron

The uncharged particle in an atomic nucleus; its mass is similar to the mass of a hydrogen atom.

nuclear medicine

Diagnostic nuclear medicine is used to obtain information on internal organs of the body. It involves administering a radioisotope to a patient, usually by injection. The radioisotope is taken up into specific body tissues. Some procedures take pictures of the body with a special camera to see where the radioisotope has gone within the body. Other procedures (known as non-imaging procedures) measure the level of radioactivity remaining in body fluids, such as blood, after a known length of time. Some nuclear medicine procedures are for therapy purposes, giving a high dose of activity in order to kill cells within a specific organ.

photon

The basic unit of light or other electromagnetic energy.

proton

The positively charged particle in an atomic nucleus; its mass is similar to the mass of a hydrogen atom.

radioactive discharges

Some establishments produce radioactive waste as by-products and this is disposed of, usually to the environment, as a radioactive discharge under authorisation.

radioluminosity

The emission of light from the interaction of radiation with some materials.

radionuclide

A type of atomic nucleus which is unstable and which may undergo spontaneous **decay** to another atom by emission of **ionising radiation** (usually **alpha**, **beta** or **gamma** radiation).

radiotherapy

High-energy X-rays can be used to treat tumours by directing the X-rays at the tumour and so destroying the tumour cells.

Sievert (Sv)

The international (SI) unit of effective and equivalent dose. Because the Sievert is a large unit, effective dose is commonly expressed in milliSieverts (10^{-3} Sv, or mSv) and microSieverts (10^{-6} Sv, or μSv).

stable isotopes

Non-radioactive **isotopes**.

troposphere

The troposphere is the lowermost portion of Earth's atmosphere and the one in which clouds and most other weather phenomena occur. This layer extends to an altitude range of 8 – 15 km. Generally, jets fly near the top of this layer.

uraninite

Uraninite is a uranium-rich mineral with a composition that is largely UO_2 (uranium oxide), but which also contains UO_3 and oxides of lead, thorium, and rare earths. All uraninites and pitchblende contain a small amount of radium a radioactive decay product of uranium. Uraninite is a major ore of uranium.

uranium oxide – see uraninite

X-radiation

X-radiation is also a form of electromagnetic radiation and differs from gamma-rays only in its mechanism of production. X-rays are generally produced artificially by an X-ray set. They are produced when high-speed electrons strike a solid target. The energy is dependent on the voltage applied across the electrodes of the X-ray tube.

X-ray procedures

X-rays are frequently used in medicine. They are used to diagnose problems and to help with treatment.

Conventional X-rays make static images on film or increasingly, store digital images on computer.

Interventional X-rays guide treatments, such as opening blood vessels. They involve a combination of fluoroscopy, where moving or static images may be viewed in real-time on a display screen.

Fluoroscopy can be described as a "moving X-ray". Like an X-ray machine it provides images of the interior of the body, but the image may be projected continuously onto a fluorescent screen, thus producing a moving image.

Computed Tomography (CT) uses X-ray equipment that rotates around the body so that detectors receive X-rays that have passed through the body. The output of the detectors is analysed to provide cross-sectional images of the body, and three-dimensional images of tissues.