NRPB-R263

Radiation Exposure of the UK Population – 1993 Review

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NRPB

National Radiological Protection Board

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Units

As from 1 April 1978 NRPB adopted the International System of Units (SI). The relationships between the SI units and those previously used are shown in the table below.

Quantity	Unit	In other SI units	Old unit	Conversion factor
Exposure	-	$C\ kg^{-1}$	röntgen (R)	$1\ C\ kg^{-1} \sim 3876\ R$
Absorbed dose	gray (Gy)	$J\ kg^{-1}$	rad (rad)	1 Gy = 100 rad
Dose equivalent	sievert (Sv)	$J\ kg^{-1}$	rem (rem)	1 Sv = 100 rem
Activity	becquerel (Bq)	s^{-1}	curie (Ci)	$1\ Bq \sim 2.7\ 10^{-11}\ Ci$

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Abstract

This is the latest comprehensive review of radiation doses in the UK compiled by NRPB. It deals with exposure of the entire population from all sources of ionising radiation, natural and artificial. The annual collective dose is 150,000 man Sv and the average dose about 2.6 mSv, with a range from 1 mSv to 100 mSv or so. Radon is the dominant average source of human exposure in the home and at work. Exposure of patients to X-rays is next in magnitude. Doses to workers in the nuclear industry are in decline because of improvements in plant and procedures: the average dose of 1 mSv a year is about half of that from natural background radiation. Doses from nuclear discharges to the environment are trivial for the general population and well within the annual dose limit of 1 mSv a year for particularly exposed groups of people. Fuller application of recent, more stringent recommendations is set to improve further the state of radiation protection in the UK.

Dedicated to Geoffrey Webb who initiated the reviews

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Approval date: July 1993
Publication date: September 1993

HMSO, £10.00
ISBN 0 85951 364 5

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1 Introduction

This review is the fifth in a series that the National Radiological Protection Board has published in the last two decades[1-4]. As noted in the Government response[5] to the report of the Royal Commission on Environmental Pollution[6], it is the intention of NRPB to report periodically on the overall radiation exposure of the UK population. The reviews are submitted to the Commission of the European Communities in compliance with the UK obligation to provide such data under the terms of the European Directive on Basic Safety Standards[7].

NRPB reviews provide a summary of the recent contributions from various radiation sources to the total exposure of the UK population as a whole and to groups of particular interest within the population. In this issue, temporal trends are shown where appropriate. Some of the sources of radiation, in particular natural radiation, show no significant trend with time: changes in estimates of exposure are generally due to better data. For some sources of man-made radiation, significant trends in exposure can be seen and the causes are discussed here.

Attention is focused on the year 1991, the latest year for which relatively complete data are available. The last review referred mainly to the year 1987, so some data are presented here for the intervening years. During this period, the population increased[8] from 56.9 million to 57.6 million. Further data have become available in the medical field, for example, which enable improved estimates to be made of exposure. Some uncertainties still exist in the estimates, and work continues to reduce them.

The latest ICRP recommendations[9] have introduced, among other things, new dose quantities. NRPB has now published a formal statement on the recommendations[10], following extensive consultation[11], in which it advocates the adoption of the new quantities, including effective dose, for the future. However, because of the historical nature of this review, the established quantity effective dose equivalent[12] is utilised for determining human exposure: it is abbreviated throughout to dose unless the full term is required for clarity. Nevertheless, the implications of the change to effective dose are alluded to in Section 8.

2 Natural radiation

2.1 Cosmic radiation

The cosmic rays detected at the surface of the earth are produced in the upper atmosphere from the interaction of high energy protons from outer space with the atoms of the atmosphere. The fluence of these high energy protons is fairly constant, although there is some variation with the solar cycle. The sun is also a source of high energy protons: however, these are not as energetic as the galactic protons and are only of significance at high altitude.

At sea level, the average dose rate from the ionising component of cosmic radiation is about 0.03 μSv h^{-1} and gives rise to an annual dose[13] outdoors of 280 μSv. Since the average indoor occupancy is 92% and buildings provide some shielding, the dose is reduced to 230 μSv a year[4]. Dose rates increase with altitude – by a factor of two at 2 km compared with sea level. In the UK, this has little significance because most of the population is in low lying areas. Dose rate also increases with latitude so that the average annual dose in northern Scotland is slightly greater than that in southern England by just a few microsieverts.

There is a small contribution from neutrons in the cosmic rays at sea level, the annual absorbed dose[13] being about 3.5 μGy. With a quality factor[13] of six, this was converted to an annual dose of 20 μSv in the previous review[4]. The average annual dose from cosmic radiation is therefore about 250 μSv and the range is not large – from 200 μSv to 300 μSv. Doses to individuals depend somewhat on indoor occupancy and the shielding afforded by particular buildings.

Exposure to cosmic rays is greatly increased during air travel. The flying altitude of an aircraft depends on such factors as the route taken and overall distance flown: a recent review[14] finds some evidence of increasing altitudes to improve fuel economy and reduce airway congestion. For long-haul flights, an altitude of about 12 km is typical[15] and for short-haul flights about 10 km. At these altitudes, dose rates are about 5 μSv h^{-1} and 3 μSv h^{-1}, respectively; consequently, a dose rate of 4 μSv h^{-1} is used here as an overall average for passengers on flights in mid-latitudes. For transpolar flights, a dose rate of about 10 μSv h^{-1} is typical[15]. At altitudes between 9 km and 20 km, almost half of the dose rate is from neutron radiation[16].

Frequent fliers – those who spend perhaps 100 h in flight during the year – would receive a dose of 400 μSv. A dose approaching 1 mSv could be received if the flights were on transpolar routes as, for example, on five flights from the UK to Japan. It is most unlikely therefore that an ordinary business traveller would receive a substantial dose, but international couriers, who can accumulate flying times of 1200 h in a year[17], could receive 5 mSv.

The total number of passenger-kilometres flown on UK airlines in the latest year for which complete information is available[8] is 1.2 10^{11}. The average cruising speed of modern planes is about 900 km h^{-1} with 75% of the flight at cruising altitude, which implies that the annual passenger-hours flown at cruising altitude is 10^8. This gives rise to a collective dose of 400 man Sv to the UK population. However, this value is quite approximate: not all the passengers are UK citizens but some UK passengers would also have used non-UK airlines. A rounded value of 10 μSv is perhaps a good estimate of the average annual dose. The overall dose from cosmic radiation, including air travel, is therefore 260 μSv a year on average.

2.2 Gamma radiation

Some of the naturally occurring radionuclides in rocks, soils and building materials emit gamma rays. To determine the population dose from gamma rays, dose rate measurements were made throughout the UK both indoors[18] and outdoors[19]. In the previous review, the results of these studies were used to estimate an average annual dose in the UK of 350 μSv. Since then, no further studies have been made that would indicate the need for a change. Individual annual doses range from about 100 μSv to 1000 μSv.

2.3 Internal activity

Natural radionuclides are taken into the body in food and drink. In the previous review, the average annual dose from these radionuclides was estimated to be 300 μSv as indicated in Table 1. Individual values range from about 100 μSv to 1000 μSv depending on the type and quantity of food consumed. The contributions from ^{210}Pb and ^{210}Po were estimated from measurements of activity concentrations in foodstuffs and standard consumption rates[20]. Values are lower than international estimates[21], but measurements of ^{210}Pb in tissues suggest that they are more appropriate for the UK[22]. Intakes of ^{210}Pb and ^{210}Po from diet give rise to an average annual dose of 54 μSv. Inhalation of ^{210}Pb and ^{210}Po results in annual intakes[21] of 4 Bq and 0.3 Bq, respectively, implying an annual dose of 14 μSv when appropriate conversion coefficients[23] are used. The total annual dose from these radionuclides is therefore 68 μSv.

Some shellfish[24] contain elevated levels of ^{210}Po. Shellfish are a minor component of the UK diet, but the concentration of this radionuclide in them exceeds that in fish by an order of magnitude[25]; determined consumers of shellfish can therefore receive appreciable annual doses[4]. Activity concentration varies markedly from sample to sample, and estimates of the annual dose to heavy consumers[25] range up to 500 µSv. Measurements of ^{210}Po in shellfish at numerous locations around the coast show that it generally derives from natural sources. However, at one location, the natural level appears to have been elevated by discharges from a phosphoric acid plant[25]: this is considered further in Sections 6.1.4 and 6.1.8. Natural radionuclides in seafood give rise to an average annual dose of about 9 µSv, almost all from ^{210}Po and representing about 3% of the average dose from all internal exposure[25].

2.4 Radon and progeny

Exposure to ^{222}Rn and progeny in dwellings and other buildings makes the largest contribution to the overall population dose[4]. Indoor concentrations vary widely, and doses considerably above the average are incurred. The UK and other countries have introduced measurement programmes and systems of control. Following some initial assessments of exposure in the UK[26], NRPB undertook a national survey in which measurements were made in a stratified sample of homes. Average radon gas concentrations in homes throughout the UK are shown in Figure 1. The population-weighted annual average for the UK is 20 Bq m^{-3}, low compared to that in most other European countries[27]. Much higher indoor concentrations were found in some places, however, especially in southwest England and parts of the Pennines.

Exposure in homes at the average concentration leads to an annual dose of 1 mSv; a further 0.2 mSv arises from the occupancy of other buildings[4]. There is also a slight contribution of about 0.1 mSv from thoron, the common name for ^{220}Rn. The average annual dose from both radon isotopes is therefore 1.3 mSv. The contribution from outdoor radon is insignificant: concentrations are low and average outdoor occupancy is only 8%.

2.4.1 High radon levels

In 1990, NRPB revised its advice to Government on the action to be taken to limit exposure to high levels of radon in homes[28]: an Action Level of 200 Bq m^{-3} was recommended. It also advised that future homes be designed so that radon would be as low as reasonably practicable. Moreover, the concept of 'Affected Area' was introduced and defined as an area with 1% probability or more of present or future homes being above the Action Level. Government accepted the advice[29] and also responded positively[30] to a report of the Select Committee on the Environment[31] that dealt with radon and other indoor pollutants.

From an extrapolation of the UK frequency distribution of radon concentrations, some 100,000 homes are estimated to be over 200 Bq m^{-3} with Cornwall and Devon[28] accounting for 60,000. The occurrence of homes with radon concentrations above the Action Level is shown in Figure 2. They can occur virtually anywhere in the country, but there is a preponderance in Cornwall, Devon, Somerset, Northamptonshire and Derbyshire.

Figure 2 is based on data collected before 1990: many more measurements have been made subsequently[32,33]. The occurrence of homes above the Action Level in the five counties is shown in Figures 3–6 where the concentration contours reflect a degree of statistical smoothing of the underlying data.

NRPB is conducting extensive surveys throughout the UK for government departments. Recent measurements in Scotland[34], England[35] and Wales[36] complement earlier measurements in Northern Ireland[37]. The results for 92,000 dwellings in England up to the end of 1991 revealed 12,000 above the Action Level. The average radon concentration in England is 21 Bq m^{-3}, close to the UK average: the highest concentration approaches 10,000 Bq m^{-3}. In Scotland, the average concentration is 16 Bq m^{-3} with 2000 homes above the Action Level. Measurement results for Wales suggest that at least 3000 homes exceed the Action Level and that the average is 20 Bq m^{-3}. As for Northern Ireland, the average is about 19 Bq m^{-3} and 1000 homes are estimated to exceed the Action Level. Guidance has been issued by Government on action against radon in homes[38].

2.5 All natural sources

The average annual dose in the UK from all natural sources is 2210 µSv, virtually the same as that in the previous review: the contributors to this total are given in Table 2 as are the approximate ranges. Annual doses can reach a few hundred millisieverts in some homes because of radon. Averages for administrative areas of the UK are shown in Figures 7 and 8: values markedly above the national average are due to radon. The average annual dose of 2210 µSv implies an annual collective dose of about 127,000 man Sv.

3 Medical exposure

3.1 Diagnostic radiology

The diagnostic use of X-rays in medicine involves a wide variety of techniques ranging from single radiographs of limbs to complex fluoroscopic investigations of the abdomen. An NRPB survey of examination frequencies[39] and doses[40] about a decade ago yielded an estimate[41] of about 35 million X-ray examinations a year with an annual collective dose of about 16,000 man Sv from conventional diagnostic radiology, both medical and dental. Since then, there have been changes in practice, some of which have led to an increase in collective dose and others to a reduction. For example, computed tomography is now more widely used and entails relatively high doses to patients: conversely, some X-ray procedures have been giving way to other diagnostic techniques that do not involve ionising radiation, such as ultrasound, endoscopy, and magnetic resonance imaging. There has also been increasing attention to patient dose reduction as exemplified by the joint report of the Royal College of Radiologists and NRPB[42]. It is judged therefore that the collective dose from conventional techniques remains unchanged at 16,000 man Sv approximately, although recommendations in the joint report could bring about substantial reductions.

The estimate of collective dose given above does not include a contribution from computed tomography (CT). In view of the growing use of the technique and the higher doses involved, NRPB conducted a national survey of the practice, as it was in 1989[43-45], with the Institute of Physical Sciences in Medicine, and subsequently published recommendations on patient protection[46]. Some 200 CT scanners were in use with 850,000 examinations being conducted each year. Measured absorbed doses were converted into effective dose equivalent for each type of CT examination using computational models[45]. Table 3 gives the doses for common examinations with CT and conventional radiography: the doses from CT are several times larger. In 1989, the collective dose from CT in the UK was about 4500 man Sv.

The overall collective dose from diagnostic radiology is the sum of those from conventional and CT examinations. It must be emphasised that there is considerable uncertainty in the conventional estimate and that the CT contribution is rising: nevertheless, a rounded value of 20,000 man Sv would seem to be appropriate for 1991, the year of primary interest for this review. The relative contributions from various types of examination are given in Table 4. Some low frequency examinations make a disproportionate impact: over 80% of the collective dose is from 15% of the procedures.

Averaged over the whole population, the annual dose from diagnostic radiology is therefore about 350 μSv, but this does not reflect the fact that part of the population has no X-ray examinations in a particular year. In order to estimate the distribution of individual doses from diagnostic radiology, a study of hospital X-ray records was undertaken by NRPB[47], and typical doses were assigned to the various procedures. The outcome is shown in Table 5, which demonstrates that a large fraction of the population receives a small fraction of the collective dose and vice versa. It is also possible to conclude that well over half the population has no X-ray examination during the year.

Low dose examinations, as of arms and legs, tend to involve younger people, whereas more complex, high dose examinations are predominantly of older people; most of the collective dose is therefore received in the later years of life. This is illustrated in Figure 9 by the age distribution of the UK population[8] and the collective dose[43,44,48]. Since the adverse effects of radiation exposure may be delayed for a number of years, many older people may not live long enough for potential cancers to be expressed; consequently, the risk of cancer is considerably reduced compared with that for younger people. Table 6 has a more elaborate presentation of the data on age distribution of doses from diagnostic radiology: they relate to the nominal collective dose of 20,000 man Sv in a year.

3.2 Nuclear medicine

A national survey[49] of nuclear medicine procedures was carried out in 1982, when the annual collective dose was estimated to be 950 man Sv. Nuclear medicine techniques were increasingly used: there had been an average growth of 14% each year from 1974[50]. To gauge the rate of more recent changes, a further survey[51] was conducted in 1990, which showed an increase of 14% from 1982 or 1.6% a year on average; the upward trend was therefore continuing but at a lower rate. Imaging procedures accounted for 89% of the work, 8% were for non-imaging diagnostic procedures, and 3% for therapeutic procedures. Between 1982 and 1990, the number of imaging procedures had risen by 22%, but this was offset by a reduction of 30% in non-imaging procedures. The total number of patients in the UK to whom radionuclides were administered in 1990 was estimated to be 430,000 and the average number of procedures per 1000 head of population was 7.6 compared with 6.8 in 1982. It was found, however, that other diagnostic techniques had increasingly been used: the greater availability of CT scanners and ultrasound had resulted in less frequent use of radionuclides for brain and liver investigations. The changes in the frequencies of investigations are given in Tables 7 and 8: for brain and liver scans the reductions are clear. With non-imaging procedures, there had been a reduction in the overall number with a marked decrease in haematological investigations set against an increase in renal work.

Average activities administered in the most frequent diagnostic procedures are given in Table 9. Effective dose equivalents in each procedure[52,53] are used to calculate the annual collective dose: the value is about 1200 man Sv, and the inclusion of other procedures is estimated to bring the total to 1400 man Sv a year. The average annual dose in the UK from nuclear medicine is therefore about 24 µSv. Procedures involving ^{99m}Tc account for three-quarters of the dose, of which bone scans with ^{99m}Tc account for half.

3.3 Radiotherapy

Cancer accounts for approximately 20% of deaths in the UK[8], and about 140,000 patients receive radiotherapy annually[54], mainly in the older age groups. The absorbed dose in the target tissue is large – many gray in most cases. Some healthy tissues are inevitably irradiated, and there may therefore be a small risk of inducing cancer in them. By the nature and circumstance of the exposure, there are great uncertainties in the estimation of effective dose equivalent and in the utility of doing so; it is not attempted here.

3.4 All medical exposure

In round terms, 35 million medical X-ray examinations are probably still undertaken each year giving rise to a collective dose of 20,000 man Sv. CT examinations account for one-fifth of this dose although they represent only one-fiftieth of the total number of examinations. Nuclear medicine accounts for a further 1400 man Sv, and so the UK population receives an annual collective dose of about 21,400 man Sv from all medical exposures excluding radiotherapy; the average annual dose is therefore 370 µSv compared with 300 µSv estimated in the previous review. For the reasons given earlier, these estimates are attended by some uncertainty.

4 Consumer products

Some consumer goods contain low activity materials and may cause radiation exposure of the public. An EC Directive[7] on radiological protection requires member states to establish a system of prior authorisation for the inclusion of radioactive materials in toys, cosmetics and other household goods – apart from the use of radioluminescent paint in clocks, watches, and compasses. Government is to introduce regulations requiring prior approval by NRPB of items being brought to sale. In expectation of this, NRPB developed criteria[55] for the approval of such items. Since that time, the risks of radiation have been revised[9] and the Nuclear Energy Agency has published guidance[56] on consumer products containing radioactive material. NRPB has therefore revised its original criteria and made clear[57] its intention to introduce a scheme of approval consonant with the basic principles of radiological protection.

Before approval, consumer products will be subjected to rigorous physical testing to assess their integrity and to estimate the doses that might be incurred under conditions of normal use, misuse, and accidental damage. The numerical criterion[57] for approval is that no individual person should receive an annual dose above 3 µSv. It is recognised, however, that some items, such as smoke alarms, have a safety function: for these, a dose constraint of 30 µSv a year is the criterion of acceptability.

4.1 Smoke alarms

Ionisation chamber smoke detectors give early warning of fires: more and more are being installed in homes. Each detector contains an ^{241}Am source with an activity no greater than 40 kBq incorporated in metal foil[57]. The dose rate at the surface of such a detector is about 1 µSv h^{-1}; at

2 m, it is about 2.4 10^{-5} μSv h^{-1}. Most are installed on staircases or in hallways, but if it is assumed that a detector is installed in a bedroom and a person sleeps for 8 h daily at a distance of 2 m, the annual dose would be 0.07 μSv. If it is further assumed that a person handles the device for about 3 h a year during maintenance, an extra 0.001 μSv could be received. The final assumption is that 10 million homes in the UK, with 25 million occupants, each have one detector. The annual collective dose would thus be about 2 man Sv, giving an average dose of 0.03 μSv.

4.2 Radioluminous timepieces

The luminising of clocks and watches has been carried out commercially since the 1920s, first with ^{226}Ra and later with ^{147}Pm or preferably ^{3}H. The EC Directive[7] does not require a system of prior authorisation for clocks and watches with radioluminous paint since they have long been subject to international standards[58,59]: nevertheless, the NRPB scheme brings them into the same system of control for the UK.

NRPB specifies maximum activities for clocks, watches and special timepieces: the dose rate must not exceed 2 μSv h^{-1} at the front face and 0.2 μSv h^{-1} at the back surface. When a wristwatch meeting these requirements is worn continuously, the annual dose to the wrist is about 1.8 mSv, but the average dose to the rest of the body is as little as 0.001 μSv.

Very small amounts of ^{3}H could be released from luminous paint and be inhaled. Cautious assumptions of release rates, room size and room occupancy[57] imply that a child could receive an annual dose of 1 μSv and an adult about half as much. For a pocket watch luminised with ^{147}Pm and kept in a hip pocket for 16 h a day, the annual dose to the skin would be about 350 μSv and to the whole body less than 1 μSv.

To judge from these examples, an average annual dose of 1 μSv to the wearers of such timepieces is a cautious estimate. If there are 500,000 of them in the UK[57], the annual collective dose is at most 0.5 man Sv, with a population average dose of no more than 0.01 μSv.

4.3 Tritium light sources

Gaseous tritium light sources may be installed in a watch, clock or compass to illuminate the dial in the dark: they consist of a small glass tube internally coated with a phosphor and filled with ^{3}H. NRPB recommends[57] a limit on activity of 7.4 GBq for clocks and watches and 10 GBq for compasses – considerably more stringent than the international standard[60]; it has also set a limit of 0.1 μSv h^{-1} for the surface dose rate. The maximum annual dose to the skin from a wristwatch would therefore be 900 μSv and the dose to the rest of the body virtually zero[57].

The other mode of exposure during routine use is intake of some of the ^{3}H that leaches through the glass envelope: a limit of 2000 Bq a day is set on this. The annual dose to a child exposed under such circumstances would be about 0.9 μSv: adult doses would be about half. If there are 50,000 such watches in the UK, the annual collective dose is at most 0.05 man Sv, corresponding to an average annual dose of 0.001 μSv.

4.4 Thoriated gas mantles

Gas mantles have been used for almost a century to provide illumination from a gas flame: they consist of a mesh impregnated with thorium and cerium compounds for incandescence. Mantles are mainly bought for camping and caravanning and are used only for a short period of the year. The radioactive decay products of thorium are released from the mantle as it is burned and may be inhaled. A limit of 1 kBq of thorium per mantle has been recommended by NRPB[57]. If a mantle is burned in a closed caravan for 4 h on five occasions, an annual dose of 100 μSv and 50 μSv would be received by children and adults, respectively: greater doses would be received by more frequent campers. It is not possible to calculate accurately the collective dose from thoriated gas mantles because the circumstances of their use are not well known. About 200,000 mantles are sold each year, and if the assumption is made that a typical camping group of four people uses five mantles a year, a collective dose of about 20 man Sv might be received in the UK, implying an average dose of 0.4 μSv.

4.5 All consumer products

The estimates of doses to the public from the consumer products of interest are summarised in Table 10. In previous reviews, a dose estimate was included for other products that are less significant in radiological terms. The overall collective dose is about 20 man Sv a year, or an average dose of 0.4 μSv, mostly from thoriated gas mantles. Although these values are low, the estimates are quite uncertain and there might be some merit in refining them.

5 Fallout

The testing of nuclear weapons in the atmosphere, which commenced in the late 1940s, largely ceased in the early 1960s following the Partial Nuclear Test Ban Treaty. Some non-signatories to the treaty continued testing, however, with the last test being conducted by China in 1980. Concern over the build-up of fission and activation products in the environment led to the establishment of measurement programmes in the early 1950s to monitor the fallout[4,61,62].

Deposition of radionuclides increased to a maximum in the early 1960s and thereafter declined. In the UK[4], the average annual dose from fallout reached a peak of about 140 μSv in 1963 and had decreased to 5 μSv by 1985. The important radionuclides are the long-lived species ^{90}Sr, ^{137}Cs and ^{14}C. The reactor accident at Chernobyl in May 1986 led to an increase in environmental levels of fission products, notably radiocaesium, a mixture of ^{137}Cs and ^{134}Cs. Deposition was low in the south where the weather conditions were dry and high in the north where the weather conditions were wet. North Wales, Cumbria and southern Scotland were the worst affected with somewhat lower levels in other parts of Scotland and northern England. Many measurements were made of the concentration of radionuclides in environmental materials and foodstuffs – especially milk – and of radiocaesium in people so as to assess the radiological impact of the event[63-69].

Measurements of radiocaesium with a whole-body monitor give a direct means of estimating doses from intakes of radionuclides. Soon after the Chernobyl fallout, the body activity of people in dry areas was about half of those in wet areas[64]. Whole-body monitoring results also showed that milk accounted for about 80% of the radiocaesium intake in 1986 and about 50% thereafter[65]. In 1991, the body activity of people in dry areas had fallen below pre-Chernobyl levels[66].

Measurements of radioactivity in the environment have been made by NRPB since 1979[70]: the results have been used to determine the dose to the population from weapons and Chernobyl fallout. Estimates are based mainly on milk samples from dairies throughout the UK. Radiocaesium in milk gave an average dose[71] of 0.1 μSv in 1991. A similar contribution was made by radiocaesium in other foodstuffs[65].

The average dose from ^{90}Sr in milk was 0.2 μSv in 1991 and about twice as great in wet areas. Concentrations of ^{90}Sr in milk have generally fallen since the 1960s and are now close to the limit of detection: levels reported in recent years have seemed quite variable[72-74] owing to statistical uncertainties. Intakes of ^{90}Sr from the total diet are generally a factor of two or so greater than that from milk alone[72-74].

An important radionuclide produced by the weapons tests was the activation product ^{14}C: by the early 1960s, weapons tests had doubled the amount in the troposphere[75]. This is now diminishing in a predictable fashion, and measurements[76] made in the UK during the 1980s indicate that 14% of the ^{14}C in the atmosphere during 1991 was due to the tests. The presence of this radionuclide in diet gave rise to an average dose of 2.2 μSv in 1991.

External irradiation from the deposition of weapons fallout can be estimated from the decreasing trend[77] before 1986: a dose of about 1.5 μSv is appropriate for 1991. The contribution from the Chernobyl radiocaesium, 0.7 μSv in 1991, is estimated from an assessment of the radiological consequences of the accident[63] and calculations of dose rates from radiocaesium in the environment[78].

The overall average dose from fallout was approximately 5 μSv in 1991, about 40% being due to ^{14}C and less than 20% due to the Chernobyl accident. Average doses in the wet areas of the UK were about three times greater than the UK average, the main component being external radiation[71]. The contributions of the major components of fallout for the years since the Chernobyl accident are given in Table 11: the downward trend is clear. The historical trend in the annual dose from fallout, established for the previous review and now extended to 1991, is shown in Figure 10.

In some wet upland regions, the effects of the Chernobyl fallout could linger for some more years. Radiocaesium is expected to be persistent owing to the nature of the soil in these areas[79], which include parts of north Wales, Cumbria and southern Scotland. Restrictions were placed on the marketing of sheep to ensure that meat with a radiocaesium content above 1000 Bq kg^{-1} did not enter the foodchain. The restricted areas, holding about 4.2 million sheep, were defined in June 1986. Restrictions have gradually been lifted, but at the end of 1991 there were still some 600 farms and 0.5 million sheep subject to restrictions[80-82]. Levels of radiocaesium quickly decrease when sheep are transferred to lowland pasture, and the contribution made by sheep meat to the overall dose from Chernobyl fallout in the UK is small. A person who consumes sheep meat with 1000 Bq kg^{-1} of radiocaesium at an average rate of 7 kg y^{-1} would receive an annual dose[23,83] of about 90 μSv.

6 Discharges to the environment

Under certain conditions, authorisation may be granted for radioactive effluents to be discharged to the environment and disposal of solid radioactive wastes to suitable facilities. The conditions imposed on such operations arise from the radiological protection objectives set by Government[84] for the management of radioactive wastes, these objectives including elements of justification, optimisation and dose limitation. Of particular significance is the requirement that the effective dose equivalent from all sources, excluding natural background radiation and medical procedures, should not exceed 1 mSv in a year to representative members of a critical group. Government has also accepted[84] the advice of the Radioactive Waste Management Advisory Committee[85,86] that for individual authorisations the committed effective dose equivalent to the critical group should be no more than 500 μSv in a year. NRPB also had previously recommended that critical group doses from effluent discharges should be so controlled as not to exceed an effective dose equivalent of 500 μSv in a year for a single site[87]. In response to the latest recommendations of ICRP[9], NRPB has further recommended[10,88] that the overall annual effective dose to an average member of the critical group should not exceed a maximum dose constraint of 300 μSv from a proposed new facility.

To ensure that the objectives are met, rigorous controls are required on the keeping, use and disposal of radioactive substances under the terms of the Radioactive Substances Act[89,90]. There are currently about 7000 premises registered to keep and use radioactive substances[91] and about 1000 of these are authorised to discharge limited quantities of radioactive waste to the environment: most of the premises are hospitals, universities and research establishments. However, the largest discharges are made from nuclear sites. Authorisations for disposals from nuclear sites are the responsibility of the Department of the Environment, the Ministry of Agriculture, Fisheries and Food, and the territorial Departments. What follows is based mainly on environmental monitoring programmes in support of these responsibilities[92-99]. The operators of nuclear sites also carry out monitoring programmes specified by the Authorising Departments: some data from these programmes[100-103] are also used.

6.1 Liquid and aerial effluents

Apart from uranium mining, operations at nuclear sites in the UK cover the full range of work associated with the production of nuclear electricity – fuel enrichment, fuel manufacture, power generation, fuel reprocessing, and waste disposal. These operations can entail the release of liquid and aerial radioactive effluents to the environment. The locations of the main nuclear sites are shown in Figure 11; the operations at each site are summarised in Table 12.

Assessments of the exposure of the critical group are made at each site. For liquid discharges, the consumption of seafoods and external exposure from sediments are generally the most important exposure pathways. For aerial discharges, an important mechanism of human exposure is deposition on grazing land and subsequent consumption in milk. Doses are assessed from activity concentrations in foodstuffs and consumption rates and from measurements of external dose rates, except that external irradiation from discharged noble gases is determined by calculation. Available estimates of critical group doses from the main mechanisms of exposure are summarised in Tables 13 and 14 by site.

6.1.1 Fuel fabrication

Liquid discharges of radioactivity from BNFL Springfields are made into the River Ribble and consist mainly of isotopes of uranium and thorium and their decay products. The critical group is identified as houseboat dwellers exposed to external radiation from mud. In 1991, an annual dose of 150 μSv was estimated for the group, almost all due to discharges from Sellafield and only about 10 μSv from Springfields[99]. The maximum dose received by wildfowlers and anglers in the area was 20 μSv and the maximum skin dose about 1500 μSv or 3% of the dose limit for this tissue[99]. Aerial discharges of natural uranium are very low: the dose to the critical group in 1991 was about 4 μSv from inhalation[103].

6.1.2 Fuel enrichment

Liquid discharges from BNFL Capenhurst contain very low levels of uranium and ^{99}Tc. The dose to the critical group of seafood consumers was about 40 μSv in 1991, mainly due to discharges from Sellafield[99]. Aerial discharges of low activities of uranium gave rise to a critical group dose[103] of no more than 1 µSv.

6.1.3 Nuclear power stations

The liquid wastes discharged from nuclear power stations contain a range of fission and activation products consisting mainly of ^{134}Cs, ^{137}Cs, ^{35}S, ^{60}Co and ^{3}H: discharges of alpha emitters are extremely low. The total activity discharged by all nuclear power stations is a small fraction of that from BNFL Sellafield; consequently, the activity in seafoods near power stations is in many cases mainly due to Sellafield. In 1991, the highest critical group dose was at Heysham, where 110 µSv from the consumption of seafoods was mainly caused by Sellafield[99]. The highest critical group dose not influenced by Sellafield discharges was due to Trawsfynydd from the consumption of fish caught in the lake near the station[99]: it was about 110 µSv.

Aerial discharges of radioactive wastes mainly contain ^{14}C, ^{3}H, ^{41}Ar and ^{35}S. Critical group doses are assessed at each power station either from samples of local milk or by calculation from known rates of discharge[92,93,100-103]. At each site, many milk samples contain activity below the limit of detection. Doses in Table 14 are calculated on the assumption that samples are at least at the limit of detection and are therefore upper estimates: annual doses are greatest for 1 year old infants and are in general a few microsieverts.

In the Magnox stations with steel pressure vessels, natural argon in the air used for cooling is converted to ^{41}Ar which is then discharged. Doses from gamma rays emitted by ^{41}Ar are calculated for each station. In 1991, the highest dose received[102] by a member of the public was 80 µSv at Dungeness A: at stations with concrete pressure vessels, the maximum dose was less than 5 µSv.

Some nuclear power stations emit direct radiation so that the few local people who spend significant time in the vicinity could be exposed. The annual dose incurred by such people is calculated from measurements around the site and assumed occupancy times. The highest doses in 1991 were at Dungeness and Bradwell[102] where some people could have received 670 µSv and 630 µSv, respectively. These doses contain a contribution from ^{41}Ar discharges and are comparable to doses estimated in recent years. The dose at Dungeness has an appreciable neutron component[102].

6.1.4 Fuel reprocessing

The main fuel reprocessing plant in the UK is at BNFL Sellafield. Discharges of liquid radioactive wastes from Sellafield have been markedly reduced in the past decade. Previous reviews have shown that the national collective dose has been mainly due to ^{137}Cs from Sellafield. New plant installed during the last decade has been effective in removing activity that would previously have been released: the annual discharge of ^{137}Cs has been reduced from 4000 TBq in the mid-1970s to 16 TBq in 1991[103]. There have also been significant decreases in discharges of other beta-emitting radionuclides.

Discharges of alpha-emitting radionuclides have been reduced by almost two orders of magnitude since the 1970s, and this development has had a major impact on the dose from transuranic radionuclides to consumers of seafood, as noted in the previous review[4]. The annual dose to the critical group had decreased[99] to 150 µSv in 1991, of which 80% was due to isotopes of americium and plutonium. Two other factors have contributed to this decrease, namely revised consumption rates and the revised gut uptake factors discussed below. The recent trend[95-99] in the annual dose to this group of high rate consumers is shown in Table 15 which also has data for typical consumers of fish along the coast of Cumbria and Lancashire. Further reductions in the discharges of transuranic radionuclides will be made by the Enhanced Actinide Removal Plant expected to be commissioned in 1993.

Studies have been carried out by MAFF on the uptake of plutonium and americium from the consumption of shellfish by volunteers[104-106]. They led to a revision, endorsed by NRPB[107], of the gut transfer factors used in the calculation of committed effective dose equivalent from $5\ 10^{-4}$ down to $2\ 10^{-4}$. The lower factor is used here for the years in Table 15 after 1987 and accounts for the decrease in the dose received by seafood consumers from 1987 to 1988.

The 1991 doses to seafood consumers are from existing environmental radioactivity which is mainly from past discharges. Current levels of discharge contribute[99] about 30 µSv to the effective dose of 110 µSv received by the high rate consumers as assessed on the basis of the new ICRP recommendations[9]. Seafoods consumed by this group also contain natural radionuclides, notably ^{210}Po and ^{210}Pb, which were increased above normal levels by discharges from a phosphoric acid plant at Whitehaven north of Sellafield. An estimate of the annual dose in 1991 from these radionuclides[99] was 210 µSv – somewhat greater than was estimated for discharges from Sellafield (but see Section 6.1.8).

Measurements of external dose rates in coastal areas near Sellafield and further afield are also made by MAFF with occupancy times obtained from local habit surveys. The group receiving the highest external dose from the liquid discharges is composed of the houseboat dwellers mentioned in Section 6.1.1 who received[99] 150 µSv in 1991. As Table 13 also shows, men who handle fishing gear on the coast near Sellafield received about 180 µSv to the skin in 1991.

Aerial releases from the Sellafield site contain ^{41}Ar in the cooling air for the Calder Hall reactors. The maximum dose from ^{41}Ar was calculated[103] to be 16 µSv in 1991. Direct gamma radiation from the reactors gave an annual dose[103] up to 80 µSv to adults at a nearby dwelling. Under cautious assumptions, adults at the same place would have received a further dose, not exceeding 90 µSv, from airborne activity and the consumption of locally grown food. Estimates of the dose to 1 year old infants have been made by MAFF from samples of local milk[92]: in 1991, the maximum value was 28 µSv.

As noted in the previous review[4], the highest activity discharged to atmosphere is of ^{85}Kr. In 1991, $4.4\ 10^{4}$ TBq were discharged[92], which are estimated to have given rise to a dose to the critical group[108] of 0.1 µSv.

The maximum dose from the inhalation of particulate airborne activity near the Sellafield site perimeter is estimated[103] to be no more than 9 µSv for 1991: this includes direct discharges as well as activity originally discharged to sea and then transferred back to land in spray. Such resuspended material can be detected up to a few kilometres inland, but concentrations are greatest on the coast. In a study of this phenomenon, temporal trends in exposures were estimated[109]. A person with high occupancy of beaches in the area would currently receive an annual dose through inhalation of about 10 µSv, mainly from ^{241}Am and $^{239/240}$Pu. In 1991, the annual dose to a typical person in Seascale would be 2 µSv from inhalation with a further 0.5 µSv from ingestion of local foodstuffs contaminated by seaspray. The annual dose to a hypothetical critical group in Seascale with elevated intakes by ingestion and inhalation would be 18 µSv. Estimates of annual doses to hypothetical critical groups from radionuclides in seaspray have also been made for the coastal areas of southern Scotland, north Wales and Northern Ireland. In 1991 these were 1.5 µSv, 0.6 µSv and 0.06 µSv, respectively[110-112].

6.1.5 AEA Technology

During 1990, two materials testing reactors were closed on the Harwell site, but a wide range of radioactive materials continues to be used for research and development work. Liquid discharges of low levels of radioactivity are made to the River Thames. MAFF carries out analyses of environmental materials and fish from which estimates of critical group doses are made[99]: in 1991, a keen angler would not have received a dose greater than 4 µSv. Aerial discharges from the site have also decreased owing to the closures. In 1991, milk samples from farms around Harwell did not indicate any elevation in activity above that expected from nuclear weapons fallout[101].

The main source of liquid radioactive waste discharged into the sea at Winfrith was the Steam Generating Heavy Water Reactor (SGHWR) which closed in 1990. A range of radionuclides was discharged, the most significant being ^{60}Co and ^{65}Zn. The maximum dose to high rate consumers of seafood[99] in 1991 was 9 µSv. Aerial discharges were also mainly from this reactor: in 1991, milk samples from farms around Winfrith indicated no elevation in activity above that expected from nuclear weapons fallout[101].

Discharges of liquid radioactive wastes have been made from the Dounreay site as a result of the operation of the Prototype Fast Reactor, its associated fuel processing plant, and a naval test reactor. A range of radionuclides is discharged to the sea; there are a number of exposure pathways. People who collect and consume molluscs from the coastal area around the site are also exposed to slightly increased levels of external gamma radiation: during 1991, their overall dose[99] was 10 µSv due partly to discharges from Sellafield. Local fishermen handling nets received a low skin dose from activity in seawater, about 10 µSv in 1991. Local seafood consumers received less than 5 µSv. There are also low level aerial discharges of a range of radionuclides, mainly ^{137}Cs and ^{90}Sr. The critical group dose was less than 20 µSv in 1990: there are no longer any milk producers near the site[101].

6.1.6 Ministry of Defence

Low activities of a range of radionuclides are discharged from AWE Aldermaston into the River Thames. Water and sediment samples are periodically analysed by HMIP, and fish near the discharge point are analysed by MAFF. The dose to a critical group of anglers[99] was less than 5 µSv in 1991. Aerial releases of ^{3}H are routinely made from the site, the annual activity varying from 20 TBq to 200 TBq throughout the past decade with 72 TBq discharged in 1991, which gave rise to an annual dose[92] below 0.1 µSv.

Defence operations at naval dockyards and submarine bases have resulted in discharges of low levels of radionuclides, of which ^{60}Co is the most prominent. External dose rates in shoreline areas and radioactivity in seafoods are monitored by MAFF. The maximum dose in 1991 was 10 µSv to anglers at Faslane from a combination of external irradiation and consumption of seafoods, again mainly due to Sellafield discharges[99]. The highest critical group dose not influenced by Sellafield discharges was at Chatham, which has been closed for several years: some houseboat dwellers received 7 µSv in 1991 owing to external radiation from past discharges[99].

6.1.7 Amersham International

A range of radionuclides is discharged into the River Colne, a tributary of the Thames, from the company premises at Amersham. HMIP monitors the water and sediments of the rivers in the area: in 1990, the only radionuclide in river water above the detection level was ^{125}I, which caused annual doses[94] well below 5 µSv. In 1991, measurements by MAFF indicated that a dose of less than 5 μSv was received[99] by the critical group of anglers in the locality from external radiation and fish consumption. Aerial discharges of radionuclides are also made at Amersham, but measurements of local milk generally indicate levels below the limits of detection[92]: the maximum dose to a 1 year old infant during 1991 was about 6 μSv.

Liquid radioactive wastes from the Cardiff site, which contain mainly ^{3}H, ^{14}C and ^{35}S, are made through the sewer system into the Bristol Channel. Low levels of activity are detected near the outfall, with the annual dose[99] to the critical group of fish and shellfish consumers in 1991 being about 20 μSv.

6.1.8 Non-nuclear sites

Discharges of low levels of liquid radioactive wastes are made by hospitals, universities and some industries through the municipal sewer systems. Exposure of the public from this practice is negligible, but sewer workers need consideration. The maximum annual dose to a maintenance worker in a sewer serving a hospital has been estimated at 20 μSv with men at the sewage works unlikely to receive[113] more than 30 μSv. Low levels of ^{125}I discharged from hospitals have been detected in the thyroids of ordinary members of the public, especially where drinking water is drawn from the Thames. The maximum annual thyroid dose found in a recent study[114] was 7.2 μSv, corresponding to an annual effective dose equivalent of less than 1 μSv.

Until recently, a factory in Cumbria manufacturing phosphoric acid from imported phosphate ore discharged liquid wastes into the Irish Sea to the north of Sellafield. These discharges, authorised by HMIP, contained uranium, thorium and decay products including ^{210}Po, which is known to concentrate in some seafoods[25]. The activities of natural radionuclides in fish and shellfish near the factory were such that 500 μSv was received by high rate consumers in 1991, mainly from ^{210}Po in winkles[99]. An additional dose of 30 μSv was incurred from artificial radionuclides discharged from Sellafield[99]. After 1991, the discharges from the phosphate factory were substantially lower owing to changes in the manufacturing and waste treatment processes.

Two companies that manufacture devices with ^{3}H, such as light sources, make aerial discharges. Environmental materials in the immediate localities are monitored by HMIP. In 1990, levels of ^{3}H in local waters were not elevated above that expected from nuclear weapons fallout[94]. Low level solid radioactive wastes that exceed the set activity limits for disposal with ordinary refuse are buried under controlled conditions at designated landfill sites. Leachate from these sites is routinely monitored by HMIP, which generally finds activity concentrations at the level expected from weapons fallout. The sole exception was a site in Cheshire where borehole water had an elevated level of ^{3}H: contamination of drinking water could give rise to an annual dose of 1 μSv, but there was no evidence of elevation beyond the site[94].

In the previous review[4], the discharge of fly ash from coal-fired power stations was crudely estimated to give rise to an annual collective dose of 5 man Sv in the UK, mainly from inhalation of natural radionuclides. There have been no changes in the intervening years that would significantly alter this value: it is therefore taken to represent the current circumstance.

6.2 Disposal of solid wastes

A site operated by BNFL at Drigg near Sellafield has been used for many years for the disposal of low level solid radioactive wastes. Wastes used to be buried in trenches, but the disposal facilities were developed considerably from the late 1980s onwards. A large concrete-lined vault has been constructed and wastes, sealed in containers, are stacked in the vault. Older trenches have been improved by the addition of a low permeability cap. Drainage from the site has been re-routed: with the new scheme, which came into operation early in 1991, leachate waters are diverted into holding tanks and emptied under authorisation through a marine pipeline when tidal conditions favour maximum dispersal. Previously, the leachate ran into a stream where measurements during 1990 by HMIP indicated the presence of a range of radionuclides but principally ^{3}H. The stream water was not used routinely for drinking, but it could possibly have been used for a short time by campers or picnickers: it was estimated that such people would need to consume 700 litres of stream water to incur a dose[94] of 500 µSv.

Some low level radioactive waste from the BNFL Springfields and Capenhurst sites is taken for disposal at Clifton Marsh, a general landfill site operated by Lancashire County Council. Monitoring results at the site indicate that there are no exposures of any significance[103].

Until 1982, low level solid radioactive wastes from various countries were sent for disposal at a designated location in the northeast Atlantic Ocean. The suitability of the site is kept under review by the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development. The latest review[115] indicated that critical group doses from the consumption of seafoods would not exceed 1 µSv even under the most cautious assumptions.

6.3 All discharges to the environment

Discharges of liquid radioactive wastes flow either directly or indirectly into the coastal waters around the UK. Samples of seafood are collected and monitored for a range of radionuclides by MAFF. Fish catch statistics are used to calculate the intake of activity with seafoods consumed by the population. The estimate for the annual collective dose[99] in 1991 from consumption is 7 man Sv, mostly due to discharges from Sellafield. The critical groups with the highest doses in 1991 were houseboat dwellers on the River Ribble who received 150 µSv from external radiation and high rate seafood consumers in Cumbria who also received 150 µSv.

Aerial discharges of radioactive gases and particles from nuclear sites during 1991 were typical of recent years[92,116], with the collective dose to the UK population being about 10 man Sv and unchanged from that in the previous review[4]. At Sellafield, the dose received by people living close to the site from aerial discharges is cautiously estimated to be 90 µSv.

Critical group doses for both liquid and aerial discharges were well within the annual dose target for discharges of radioactive wastes for single sites, namely 500 µSv. The maximum annual dose to members of the public from direct radiation at Bradwell and Dungeness was above 500 µSv in 1991 but within the annual dose limit of 1 mSv.

For the nuclear industry as a whole, the collective dose from both liquid and aerial discharges of radioactive wastes was approximately 17 man Sv in 1991, implying an average dose of 0.3 µSv throughout the whole population. Inclusion of coal-fired power stations brought the totals to 22 man Sv and 0.4 µSv, respectively.

7 Occupational exposure

Exposure to ionising radiation at work is controlled by the Ionising Radiation Regulations 1985, which specify certain dose limits and an overall requirement to keep doses as low as reasonably practicable[117]. The Regulations also require that if the annual dose to a worker exceeds three-tenths of the whole-body dose limit, an investigation is to be carried out to determine whether doses are indeed as low as reasonably practicable. This annual dose limit is 50 mSv and the investigation level is 15 mSv. The Health and Safety Commission has also introduced further guidance[118] requiring an investigation if the cumulative dose to a worker over any 5 year period reaches 75 mSv.

Under the present law, a person who works in areas where three-tenths of the dose limit might be exceeded should be classified and have his dose assessed by an Approved Dosimetry Service (ADS). There are currently about 40 such services with each providing information for the Central Index of Dose Information (CIDI) maintained for the Health and Safety Executive by NRPB. Summaries of the data held[119-121] by CIDI for 1986–88 and annual reports from the nuclear industry are the main sources of the data on occupational exposure presented here. Other data were obtained by direct inquiry.

7.1 Nuclear industry

During the period of this review, the nuclear power stations formerly operated by the Central Electricity Generating Board came under the control of Nuclear Electric plc (NE) and those in the South of Scotland Electricity Board came under Scottish Nuclear Limited (SNL). The United Kingdom Atomic Energy Authority now trades under the name of AEA Technology (AEA). British Nuclear Fuels plc (BNFL) carries out a variety of operations including nuclear power station operation, fuel manufacture, enrichment and reprocessing, and waste disposal. Data on occupational exposure in the nuclear industry are from several sources[122-136].

7.1.1 Fuel fabrication

The manufacture of nuclear fuel involves the handling of uranium compounds, which can lead to external exposure from gamma rays and intake of airborne activity. Data for workers at the BNFL Springfields factory in Table 16 include external and internal doses to employees and contractors. There was a slight reduction in the number monitored from 1988 to 1990 with a slight increase in the average dose because of increased workload[132], but the downward trend in dose was then resumed. The number of workers in the higher dose bands has also been decreasing: in 1990 and 1991, no worker received more than 15 mSv. In 1991, about 97% of the collective dose of 5.9 man Sv was received by employees and the remainder by contractors who comprise 17% of all those monitored. Some 30% of the collective dose in 1990 was due to internal exposure – this apportionment is typical of recent years.

7.1.2 Fuel enrichment

Radiation doses received by the workforce at the BNFL Capenhurst enrichment factory are given in Table 17. External irradiation from uranium hexafluoride is the main cause of exposure. Doses are low: the average dose of 0.2 mSv and collective dose of 0.2 man Sv in 1991 are typical of recent years, and no worker has received an annual dose above 5 mSv for several years.

7.1.3 Nuclear power stations

Most of the nuclear power stations are operated by NE, with SNL having stations at Hunterston and Torness. BNFL also operates stations at Chapelcross and Calder Hall, but occupational exposures at Calder Hall are included with those for the whole Sellafield site in

Section 7.1.4. Reactors at all these sites are gas cooled, either Magnox or AGR, although other types of reactors have been operated in the UK (see Section 7.1.5).

Occupational exposures at NE stations are summarised in Table 18. The slight fall in the annual collective dose from 1988 to 1989 was largely due to the closure of Berkeley. The number of workers in the higher dose bands has been decreasing for some years: no worker has received more than 15 mSv recently and only four exceeded 10 mSv in 1991. There was a further decrease of the collective dose[133] to 8.9 man Sv in 1991.

Hunterston A was shut in 1990, which largely accounts for the decrease in collective dose to SNL workers shown in Table 19. In 1990 and 1991, no worker received more than 15 mSv a year. In 1991, the collective and average doses were 2.6 man Sv and 0.7 mSv, respectively.

BNFL Chapelcross is a Magnox station of early design. Occupational exposures have consistently been higher there than at later stations, but steady reductions in collective and average doses have been achieved in recent years by modifying the plant and procedures. As Table 20 shows, no worker exceeded 15 mSv in 1990 or 1991 and only 19 received more than 10 mSv in 1991. The collective and average doses in 1991 were 2.4 man Sv and 3.2 mSv, respectively.

A summary of occupational exposures during 1991 at nuclear power stations is given in Table 21 with the exclusion of Calder Hall but including peripatetic employees of National Nuclear Corporation who work at different nuclear sites[135]. Almost 25,000 monitored workers received about 15 man Sv resulting in an average annual dose of 0.6 mSv. No worker exceeded 15 mSv during 1991 and only 50 or so received a dose greater than 10 mSv.

7.1.4 Fuel reprocessing

Nuclear fuel reprocessing is the main enterprise at BNFL Sellafield, but exposures also arise from the Calder Hall reactors and waste disposal work. Doses are due mainly to external irradiation: only one-tenth of the collective dose is from intakes[124]. Temporal trends in occupational exposure at the site, shown in Table 22, are generally downwards – towards lower collective dose, lower average dose, and fewer workers in the higher dose bands. No worker exceeded 30 mSv in 1991, one exceeded 20 mSv, and seven exceeded 15 mSv. Contractors at the site are included in the table: they make up one-quarter of those monitored in 1991 and received one-fifth of the collective dose of 18.5 man Sv. The average dose to all workers on the Sellafield site in 1991 was 2.1 mSv.

Annual doses at Sellafield have been coming down for more than a decade, the trend coinciding with a period of major refurbishment and plant construction. Design features that minimise operator doses have been incorporated into the new plant[137].

Some of the BNFL engineering design teams are based at the headquarters in Risley. They and other headquarters staff receive doses while visiting nuclear sites – mainly Sellafield. Annual doses are low, as shown in Table 23, the average for 1991 being 0.1 mSv.

7.1.5 Nuclear technology services

The AEA workforce receives radiation doses from a range of nuclear technology services including waste disposal, decommissioning, and the operation of prototype reactors. Recent trends in annual doses at all AEA sites for employees and contractors are shown in Table 24. The collective dose has been continually reduced during recent years with a corresponding decrease in the average dose. The collective and average doses in 1991 were 5.6 man Sv and 1.0 mSv, respectively. No one exceeded a dose of 15 mSv in 1991.

Most of the workers receiving annual doses above 15 mSv before 1991 were engaged in maintenance work on the Steam Generating Heavy Water Reactor (SGHWR) at Winfrith, although decreases had been brought about by a number of dose reduction techniques[138]. The reactor ceased operation in 1990, which almost entirely accounts for the elimination of entries in the high dose band. During 1990, two materials testing reactors at Harwell were also closed. Decommissioning work commenced on these and on the SGHWR in 1991 and will continue for some years[129].

7.2 Ministry of Defence

Some 8500 MOD service personnel and contractors including submarine maintenance workers at naval dockyards are monitored by the Defence Radiological Protection Service (DRPS). The average dose received by monitored workers in 1991 was 1.0 mSv: the distribution of annual doses[139] in recent years is given in Table 25. Collective and average doses have decreased during the period of this review as has the number of workers receiving annual doses greater than 15 mSv. Occupational exposures[140] at the Atomic Weapons Establishment (AWE) Aldermaston are given in Table 26. The annual dose in 1991 was 0.3 mSv, which is typical of recent years, with no one in the higher dose bands. For all MOD personnel, the collective and average doses were 9.8 man Sv and 0.8 mSv, respectively.

7.3 Medicine

As noted in previous reviews, occupational exposures in medicine are generally low. Most dosemeters record doses below the reporting level: in recent years, annual doses have been less than 1 mSv on average[141,142]. Some Approved Dosimetry Services have published summaries of dose statistics, but no nationwide survey has been made since the previous review[4]. A fresh survey was therefore undertaken with the cooperation of the larger NHS dosimetry services that together make up the Personal Radiation Monitoring Group. Data[143-153] are presented in Tables 27–30 for diagnostic radiology, radiotherapy, and nuclear medicine, the latter including research with radiopharmaceuticals. Some dosimetry services maintain differential records of occupational groupings: these make up the dose distributions in the tables under the heading ‘Main sample’. Some services do not do so: their data are combined under ‘Further sample’. Yet other services make dose distributions available but not the collective doses: these are collated under ‘Additional sample’ in these tables.

7.3.1 Diagnostic radiology

Table 27 has the dose data for diagnostic radiology departments in 1991. It can be misleading to compare the calculated averages for groups because of the large number of low doses, but some comments may be made. Radiographers receive less than 0.1 mSv whereas radiologists receive a few times more. Cardiologists tend to be the most exposed: their average dose was 0.4 mSv, an appreciable proportion received more than 1 mSv, and one recorded more than 15 mSv. Generally, however, the average annual dose in diagnostic radiology is less than that in the previous review.

7.3.2 Radiotherapy

Doses to members of staff in radiotherapy departments are given in Table 28. During teletherapy, beam radiographers are in well-shielded positions and average doses are less than

0.1 mSv. Radiotherapists, scientific staff, and other support staff also receive low doses with few exceeding 1 mSv in a year. With brachytherapy procedures, some theatre nurses receive over 5 mSv as do some ward nurses. Efforts have clearly been made to reduce exposures in radiotherapy, since the doses to most groups are lower by a factor of a few than those in the previous review.

7.3.3 Nuclear medicine

Diagnostic tests with radiopharmaceuticals generally involve low activities; consequently, external irradiation levels are generally low. However, ^{99m}Tc can cause appreciable exposure and is the source of most dose in nuclear medicine departments: its use for organ imaging leads to average annual doses of about 0.5 mSv among radiographers, pharmacists, physicists and technicians. As Table 29 shows, however, there are no annual doses greater than 5 mSv and 90% or more of those working in diagnostic imaging receive less than 1 mSv a year.

7.3.4 All medical workers

All the medical data are combined in Table 30. About 99% of all medical workers receive annual doses below 1 mSv and only 0.1% receive more than 5 mSv. The overall average for 1991 is 0.1 mSv. The total number of medical staff monitored by the dosimetry services is about 35,000. Allowance for a further few thousand monitored by other services brings the total monitored in medicine to around 40,000 as in the previous review[4]. Most workers receive little or no occupational exposure and do not really need monitoring, but personal dosimetry is a useful check on working procedures and provides reassurance for members of staff. The final row in Table 30 scales the results up to the overall total of 40,000 and yields an annual collective dose of 5.0 man Sv.

7.4 Dentistry

There are estimated to be about 20,000 dentists and dental assistants engaged in diagnostic radiography or working close to X-ray sets. If correct procedures are used, they are exposed only to low levels of X-rays scattered from the main beam. Many nevertheless wear dosemeters, and the data from NHS dosimetry services for about 2200 people give an average dose of 0.02 mSv a year, with 99.7% below 1 mSv. A small number of dentists monitored by NRPB had an average annual dose[154] of 0.06 mSv in 1991. Annual collective and average doses of 2 man Sv and 0.1 mSv, respectively, are therefore upper estimates.

7.5 Veterinary work

Diagnostic radiography in veterinary practices can give rise to low doses mainly from scattered radiation. It is estimated that there are about 4000 people involved in this type of work. A small sample of veterinarians and assistants monitored by NRPB had an average annual dose[154] in 1991 of 0.07 mSv. Annual collective and average doses are estimated to be approximately 0.4 man Sv and 0.1 mSv, respectively.

7.6 Research and tertiary education

Research workers in universities and polytechnics use radioactive sources, X-ray equipment, and unsealed radioactive materials. Information from the NRPB dosimetry service[155], supplemented by other data, suggests that about 10,000 are monitored annually. Many wear dosemeters for short periods while carrying out particular experiments but are not monitored continually. Annual doses are generally low – of about 0.1 mSv – but some people are classified workers. About 1300 such people engaged in academic research and teaching registered on CIDI in 1988 received an average dose[121] of 0.3 mSv with only 3 being above 15 mSv. It can safely be assumed that all non-classified workers in this field receive annual doses of less than 5 mSv.

7.7 General industry

There are many industrial applications of ionising radiation particularly for quality control in manufacture: gauges are used for the measurement of density, position and thickness; X-ray fluoroscopy and crystallography are used to determine composition and structure; radioactive sources are used for well-logging in the oil and gas business. Industrial radiography with sealed radioactive sources or X-ray sets is important in construction, engineering, oil and gas production, the maintenance of aircraft, and so on. Equipment is almost always well shielded so that operators receive virtually no dose, but some exposure can occur during servicing and source replacement. Sometimes it is necessary to carry out radiography on site where the radiographer is likely to be more exposed.

Of the 7500 industrial radiographers in the UK, monitoring records for 3525 were held by NRPB[154] in 1991: 97% did not exceed 5 mSv, but almost 1% had annual doses over 15 mSv. There are usually a few industrial radiographers every year, however, who exceed 50 mSv because of accidental exposure to sources. An emphasis on adequate training has reduced these incidents in recent years. Data for the radiographers on record are scaled to the national total in Table 31 to give a collective dose of 6.3 man Sv and an average dose of 0.8 mSv.

Apart from industrial radiographers, there are another 16,000 radiation workers in general industry[155]. Dose data for 7500 of these on record at NRPB were analysed and scaled to the total in Table 31. Collective and average doses in 1991 are 2.2 man Sv and 0.1 mSv, respectively. The table also has data for some workers engaged in the manufacture of tritium light sources and the like whose average annual dose[156] in 1991 was 2.7 mSv.

Radioactive products widely used in industry, medicine and research are manufactured in the UK by Amersham International. Occupational exposures can occur at each stage of the manufacture, packaging and transport of radioactive materials. The distribution of annual doses in 1991 is also given in Table 31: the average value was 1.9 mSv, a slight improvement on previous years[157].

In round terms, therefore, 25,000 workers in general industry accumulated 11 man Sv in 1991, implying an average dose of around 0.4 mSv.

7.8 Radon

7.8.1 Mines and caves

Restricted ventilation in underground mines and caves can lead to a build-up of radon concentrations. The radon derives from trace quantities of uranium in the surrounding rocks and from mine water.

A fairly comprehensive survey of non-coal mines and private-sector coal mines was conducted[158] from 1990 to 1991. Dose distributions for non-coal miners are given in Table 32:

the average annual dose is 4.5 mSv – about three times less than that in the previous review[4] because of improvements in ventilation, the sealing of old workings, and the closure of some mines that had become uneconomic.

Deep coal mines of necessity have good ventilation so radon levels are low. In 1991, there were 47,790 underground workers employed by British Coal[159]. Radon exposure was estimated by extensive monitoring and assessment. The average dose was 0.6 mSv, as indicated in Table 33, and no miner received more than 5 mSv. Private coal mines have smaller and shallower workings and are therefore less well ventilated. The average dose in 1991 was 1.8 mSv with about 1% of the men receiving over 15 mSv. The average dose to all 50,000 miners in 1991 was 0.7 mSv, and the collective dose was approximately 35 man Sv.

Guides in showcaves can spend considerable time underground during the tourist season – perhaps as much as 500 h. Measurements in several caves around the country[160] yielded estimates of annual dose of 40 mSv on average.

7.8.2 Other workplaces

In some parts of the UK, radon concentrations in buildings such as offices, schools and libraries are much higher than the national average. If the level is above 400 Bq m^{-3}, corresponding to an annual dose of 5 mSv, the Ionising Radiations Regulations 1985 are deemed to apply[117] and radiological surveillance is required. In order to avoid this circumstance, employers are generally inclined to take measures that will reduce the concentrations.

NRPB has made many measurements of such workplaces, especially in Affected Areas. In 3100 surveyed[161] to 1991, an appreciable fraction was subject to the Regulations. Analysis indicated that there are likely to be some 5000 premises with 50,000 workers in this position: their collective and average doses are 270 man Sv and 5.3 mSv in a year, respectively, with 2500 or so exceeding 15 mSv in a year[162]. These projections are rather uncertain, but there is no doubt that this area of occupational exposure requires more attention.

7.9 Aircrew

Cosmic ray dose rates at various altitudes and latitudes are discussed in Section 2.1. Aircrew on long-haul operations may be airborne for 600 h a year[15] and so could receive an annual dose of 3 mSv. In the unlikely case of continual transpolar work, as much as 6 mSv could be received. To take account of short-haul as well as long-haul work, an annual average of 500 h aloft was used in the previous review[4] and is used again here. Since the average dose rate is 4 μSv h^{-1}, the average annual dose for all aircrew is about 2 mSv. With 24,300 UK aircrew[163], the annual collective dose is approximately 50 man Sv.

Radiation monitors are installed in supersonic Concorde aircraft, and the results are used to compute crew doses. Annual doses are between 2 mSv and 3 mSv but could be double this if the maximum hours were flown. In collective dose terms, the contribution of Concorde is negligible.

7.10 All occupational exposure

All of the data for occupational exposure in the UK are brought together in Table 34 aggregated and rounded as circumstances require. It is worth repeating that there are some uncertainties in the compilation, especially since some of the estimates are based on extrapolation.

The table is headed by the nuclear industry in which almost 45,000 workers receive a collective dose of 45 man Sv a year or 1 mSv on average with few exceeding 15 mSv. These low values are the outcome of a drive for dose reduction during the past several years, the course of which is clear[164] from Figure 12. As noted elsewhere, dose reductions have also been brought about in other sectors such as defence.

More attention is being focused on occupational exposure to natural radiation, where collective doses are substantial and most of the doses above 15 mSv a year arise. Radon is the most significant source of exposure both above and below ground: as indicated earlier, doses are incurred from the inhalation of the progeny. With a collective dose around 300 man Sv for radon and about 5 man Sv from the intake of radionuclides in the nuclear industry and other occupations, internal exposure accounts for 70% or more of the occupational dose in the UK.

The 280,000 workers in Table 34 with a collective dose of 430 man Sv make a contribution of about 7 µSv a year to the average dose throughout the whole population of the UK.

8 Discussion

Annual doses from all sources of radiation are summarised in Table 35 and Figure 13. In precise terms, the quantities are the effective dose equivalent and the collective effective dose equivalent, both for the year 1991. The overall average is 2600 µSv a year, slightly higher than the 2500 µSv in the previous review[4]: about half the collective dose is due to radon. Some changes and developments, especially for artificial sources, are highlighted here. Some attention is also paid to the potential impact of the new ICRP dose quantities[9].

8.1 Natural sources

The estimate of cosmic ray dose rates at sea level and at altitude are unchanged since the previous review, but the addition of public exposure during air travel to the general population value increases the annual total from 250 µSv to 260 µSv. Use of the new ICRP weighting factor for neutrons would give an effective dose of about 4% more. At sea level, annual doses range roughly from 200 µSv to 300 µSv.

In the previous review the average annual dose from terrestrial gamma rays was given as 350 µSv. No new data have been obtained so there are no grounds for changing the estimate. Individual doses range between 100 µSv and 1000 µSv a year. It is unlikely that the change to effective dose will cause much numerical difference.

The average annual dose from natural radionuclides taken in with food and drink is again estimated to be 300 µSv, which includes a small contribution from inhalation. New dose per unit intake data for some radionuclides[165] would give an effective dose of about 10% less. Individual annual doses range between 100 µSv and 1000 µSv.

Although many more measurements of indoor radon are available compared with the previous review, there are no grounds for changing the previous estimate of the average concentration in homes. Moreover, there is no reason to expect significant numerical differences between effective dose equivalent and effective dose for the same radon exposure, although the position will need to be monitored. The average annual dose from ^{222}Rn therefore remains at 1200 µSv with a further 100 µSv from ^{220}Rn, making a total of 1300 µSv a year from the progeny of the radon isotopes. Individual doses range from 100 µSv to 100,000 µSv a year with scattered higher values.

8.2 Medical exposure

There have been changes in medical exposures during recent years not least the increasing contribution of computed tomography to the collective dose from diagnostic radiology – about 20% of 20,000 man Sv. Nuclear medicine procedures have also increased moderately so that the annual collective dose now totals 21,400 man Sv, implying an average dose of 370 μSv, up 20% or so since the last review. Diagnostic X-ray procedures can give rise to substantial annual doses, but a majority of the population undergoes no form of X-ray examination in the year. Changing from effective dose equivalent to effective dose would increase the collective quantity for conventional radiography by 5% and decrease it by 25% for CT procedures[166]. However, since CT gives about 20% of the total dose, the changes cancel each other. Changes in the limited contribution of nuclear medicine to collective dose can be discounted.

8.3 Consumer products

The collective dose from consumer products containing radioactive substances – 20 man Sv a year – is about 0.01% of the overall total and comes mainly from gas mantles. Individual doses as high as 100 μSv a year might be incurred by some people. The change to the new ICRP dose quantities will not cause much numerical difference.

8.4 Fallout

Annual doses from fallout are now back to pre-Chernobyl levels and declining. The incremental dose from the accident is likely to be around 50 μSv when averaged over the entire population with nearly all the dose having been received in the few years following the accident. In 1991, the national average was about 5 μSv with a collective dose of 290 man Sv mainly from external irradiation and radiocarbon. The numerical values of the new ICRP quantities are similar.

8.5 Occupational exposure

There are about the same number of workers in the nuclear industry as in 1987, but the annual collective dose has been halved mainly by dose management programmes that applied the principles of optimisation and in expectation of more restrictive dose limits. Some of the reduction was due, however, to the closure of reactors, which accounts in particular for the virtual elimination of annual doses over 15 mSv.

The numbers of occupationally exposed workers in other sectors are similar to those reported in 1987 apart from coal miners whose numbers are declining steeply. However, the inclusion, for the first time in this series, of workers exposed to radon in some buildings throughout Affected Areas has more than compensated: it has also maintained the number of workers above 15 mSv at an appreciable level.

Since 80% or more of occupational exposure is from penetrating radiation and radon, the adoption of effective dose will not alter numbers appreciably. Aircrew are, however, exposed to neutrons as well as the directly ionising component of cosmic rays; the increased radiation weighting factors for neutrons would make the overall effective dose about 20% greater than the effective dose equivalent. In 1991, however, some 280,000 people were exposed to radiation at work for whom the collective dose was 430 man Sv and the average dose 1.5 mSv.

8.6 Discharges to the environment

In previous reports, doses from discharges were dominated by liquid releases of ^{137}Cs from Sellafield with some contribution from transuranics, but aerial discharges from the nuclear industry are now of about equal significance. Conversion to effective dose will reduce the collective value for liquid discharges by 15% or so[99], and the individual values for high rate seafood consumers by 25%, but the values for aerial discharges will remain more or less the same. At all sites apart from Dungeness and Bradwell, critical group doses were also within the maximum annual effective dose constraint[88] of 0.3 mSv that NRPB has recommended for proposed new facilities: at these two sites, the critical group exposures were dominated by direct external irradiation.

With the inclusion of the contribution from coal-fired power stations here, the collective effective dose equivalent in 1991 comes to a round 20 man Sv and the average effective dose equivalent for the population to 0.4 μSv.

9 Conclusions

The main conclusions of this report may be inferred from Table 35 and Figure 13: they show that the annual dose to citizens of the UK from all sources of ionising radiation is 2600 μSv on average and that the collective dose is about 150,000 man Sv. More precisely, these quantities are the effective dose equivalent and the collective effective dose equivalent, respectively. (The numerical values of the new quantities effective dose and collective effective dose would be similar.) These estimates are virtually identical with those of the previous review[4]. Such general stability is due to the predominance of natural radiation, exposure to which does not alter much over the years, but there have been particular developments and fresh insights.

(a) Exposure to cosmic radiation of the public now includes the doses incurred during air travel, and the exposure of aircrew is properly regarded as an occupational matter: these changes have led to a slight increase in the estimates of dose under both headings.

(b) All information collected during the past few years reinforces the view that exposure to radon in some places of work other than mines is a matter of concern in certain parts of the country: it contributes well over half the dose from all occupational practices.

(c) The growth of medical exposure is reflected in a significant increase in dose, but there has been a concomitant increase in professional awareness of the need to monitor the trend without compromising clinical utility.

(d) Fallout for nuclear tests in the atmosphere is still detectable, but the doses are now quite low. The Chernobyl increment has virtually disappeared.

(e) Occupational doses in the nuclear industry continue to decline steadily and are now about half of the level at the last review. The decline is more the result of improved practices than workforce contraction.

(f) Doses from nuclear discharges are trivial in general and, for the most highly exposed groups, well within the annual dose limit and below the dose constraint recommended by NRPB.

(g) Doses from radioactive consumer products are equally trivial.

10 Acknowledgements

Draft sections of this review were circulated to many organisations and individuals: valuable comments were received and taken into account. Occupational data in medicine were obtained from many Approved Dosimetry Services and particularly from the Personal Radiation Monitoring Group. Several colleagues at NRPB commented on the review. The authors are most grateful for all the information and comments received.

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TABLE 1 Average annual internal doses from long-lived natural radionuclides

Radionuclides	Average annual dose (μSv)
Cosmogenic radionuclides	
^{7}Be	3
^{14}C	12
Primordial radionuclides	
^{40}K	180
^{87}Rb	6
^{238}U series	
$^{238}U \rightarrow {}^{234}U$	5
^{230}Th	7
^{226}Ra	3
$^{210}Pb \rightarrow {}^{210}Po$	68
^{232}Th series	
^{232}Th	3
$^{228}Ra \rightarrow {}^{224}Ra$	13
Total (rounded)	300

TABLE 2 Summary of doses to the UK population from natural sources

	Average annual dose (μSv)		
Source	Previous estimate	Present estimate	Broad range
Cosmic radiation	250	260	200–300
External irradiation from terrestrial sources	350	350	100–1,000
Internal irradiation from terrestrial sources	300	300	100–1,000
Exposure to radon and progeny	1,200	1,200	300–100,000
Exposure to thoron and progeny	100	100	50–500
Total	2,200	2,210	1,000–100,000

TABLE 3 Typical patient doses from CT and conventional X-ray examinations

Examination	Effective dose equivalent (mSv) Computed tomography	Conventional examination
Head	3.5	0.2
Cervical spine	1.9	–
Thoracic spine	7.8	0.9
Chest	9.1	0.05
Abdomen	8.8	1.4
Lumbar spine	6.0	2.2
Pelvis	9.4	1.2
Intravenous urography	–	4.4
Barium meal	–	3.8
Barium enema	–	7.7

TABLE 4 Contributions to the annual collective dose from medical X-ray examinations in the UK

Examination	% frequency	% collective dose
Computed tomography	2.4	22
Lumbar spine	3.3	15
Barium enema	0.9	14
Barium meal	1.6	12
Intravenous urography	1.3	11
Abdomen	2.9	8
Pelvis	2.9	6
Chest	24	2
Limbs and joints	25	1.5
Skull	5.6	1.5
Thoracic spine	0.9	1
Dental	25	1
Others	4.2	5
Total	100	100
Annual collective dose from all procedures		20,000 man Sv

TABLE 5 Distribution of annual doses from diagnostic radiology

Dose range (mSv)	Population (%)	Collective dose (%)
0–1	93	18
1–2	4	26
2–3	2	21
>3	1	35

TABLE 6 Age distribution of doses from diagnostic radiology

Age group (years)	Percentage of collective dose*	Number in age group (x 10^6)	Average annual dose (μSv)
0–4	2.7	3.9	140
5–9	1.7	3.7	100
10–14	2.3	3.5	130
15–19	3.9	3.7	210
20–24	5.3	4.5	240
25–29	4.7	4.7	200
30–34	5.3	4.2	250
35–39	7.1	3.8	380
40–44	6.9	4.1	340
45–49	6.6	3.5	370
50–54	7.4	3.1	480
55–59	7.3	2.9	500
60–64	8.5	2.8	600
65–69	8.1	2.8	590
70–74	8.5	2.3	750
75–79	6.6	1.9	710
80–84	4.1	1.3	650
>84	3.0	0.9	660
Total	100	57.6	350

*The percentages relate to the rounded annual value of 20,000 man Sv. This table should only be regarded as indicative.

TABLE 7 Trends in the percentage of imaging investigations in nuclear medicine

Investigation	1982	1990
Bone	28.6	36.7
Lung	15.0	24.0
Renal	7.6	12.7
Cardiac	3.1	8.0
Thyroid/parathyroid	7.0	6.5
Brain	15.7	5.6
Liver/spleen	16.4	2.7
Tumours/abscesses	1.0	1.9
Stomach/intestine	0.7	1.1
Vascular	0.6	0.6
Other	4.3	0.2
Total	100	100

TABLE 8 Trends in the percentage of non-imaging investigations in nuclear medicine

Investigation	1982	1990
Renal	17.2	42.3
Haematology	55.0	32.8
Thyroid	15.2	13.9
Metabolic	1.9	3.2
Cardiac	3.9	2.1
Water/electrolyte	2.5	1.0
Other	4.3	4.7
Total	100	100

TABLE 9 Characteristics of the most frequently performed nuclear medicine diagnostic procedures in 1990

Procedure	Radionuclide	Radiopharmaceutical	Number of procedures ($x10^3$)	Mean activity used (MBq)	Dose per intake ($mSv\ MBq^{-1}$)	Procedure dose (mSv)	Collective dose (man Sv)
Bone scan	^{99m}Tc	Phosphate	$1.4\ 10^2$	$5.5\ 10^2$	$8.0\ 10^{-3}$	4.4	$6.2\ 10^2$
Lung perfusion scan	^{99m}Tc	MAA	$5.1\ 10^1$	$8.4\ 10^1$	$1.2\ 10^{-2}$	1.0	$5.1\ 10^1$
Kidney scan	^{99m}Tc	DTPA	$1.9\ 10^1$	$2.0\ 10^2$	$6.3\ 10^{-3}$	1.2	$2.4\ 10^1$
Thyroid scan	^{99m}Tc	Pertechnetate	$1.9\ 10^1$	$8.5\ 10^1$	$1.3\ 10^{-2}$	1.1	$2.1\ 10^1$
Lung ventilation scan	^{81m}Kr	Gas	$1.6\ 10^1$	$5.0\ 10^3$	–	$1.3\ 10^{-1}$	2.1
Kidney scan	^{99m}Tc	DMSA	$1.5\ 10^1$	$8.0\ 10^1$	$1.6\ 10^{-2}$	1.3	$1.9\ 10^1$
Lung ventilation scan	^{99m}Tc	Aerosol	$1.3\ 10^1$	$5.2\ 10^1$	$7.0\ 10^{-3}$	$3.6\ 10^{-1}$	4.7
Dynamic cardiac scan	^{99m}Tc	Labelled red cells	$1.2\ 10^1$	$7.2\ 10^2$	$8.5\ 10^{-3}$	6.1	$7.4\ 10^1$
GFR measurement	^{51}Cr	EDTA	$1.2\ 10^1$	2.7	$3.4\ 10^{-2}$	$9.2\ 10^{-2}$	1.1
Lung ventilation scan	^{133}Xe	Gas	$1.1\ 10^1$	$4.0\ 10^2$	–	$3.0\ 10^{-1}$	3.3
Myoc. perfusion scan (planar)	^{201}Tl	Thallous ion	9.2	$7.4\ 10^1$	$2.3\ 10^{-1}$	$1.7\ 10^1$	$1.6\ 10^2$
Kidney scan	^{99m}Tc	MAG3	8.5	$8.7\ 10^1$	$1.6\ 10^{-2}$	1.4	$1.2\ 10^1$
Brain scan	^{99m}Tc	Pertechnetate	7.6	$5.3\ 10^2$	$1.3\ 10^{-2}$	6.9	$5.2\ 10^1$
Liver scan	^{99m}Tc	Colloid	6.5	$8.7\ 10^1$	$1.4\ 10^{-2}$	1.2	7.9
Brain scan	^{99m}Tc	Gluconate	5.3	$5.2\ 10^2$	$9.0\ 10^{-3}$	4.7	$2.5\ 10^1$
Vitamin B12 absorption	^{57}Co	Cyanocobalamin	4.7	$3.0\ 10^{-2}$	5.8	$1.7\ 10^{-1}$	$8.2\ 10^{-1}$
Brain scan (tomo.)	^{99m}Tc	HMPAO	3.5	$5.6\ 10^2$	$1.3\ 10^{-2}$	7.3	$2.5\ 10^1$
Thyroid uptake	^{131}I	Iodide	3.3	1.0	$1.3\ 10^1$	$1.3\ 10^1$	$4.0\ 10^1$
Myoc. perfusion scan (tomo.)	^{201}Tl	Thallous ion	3.1	$7.8\ 10^1$	$2.3\ 10^{-1}$	$1.8\ 10^1$	$5.6\ 10^1$
Total (rounded)			$3.6\ 10^2$				$1.2\ 10^3$

TABLE 10 Doses from consumer products

Product	Cautious dose estimate ($\mu Sv\ y^{-1}$)	Annual collective dose (man Sv)	Average annual dose (μSv)
Smoke alarms	0.07	2.0	0.03
Radioluminous timepieces	1.0	0.5	0.01
Tritium light sources	0.9	0.05	0.001
Thoriated gas mantles	100	20	0.4
Total (rounded)*		20	0.4

*The total is made up almost entirely of the contribution from thoriated gas mantles for which the collective dose is quite uncertain.

TABLE 11 Trend in annual doses from fallout

Source	Average annual dose in the UK (μSv)					
	1986	1987	1988	1989	1990	1991
External irradiation						
Weapons	1.8	1.8	1.7	1.6	1.5	1.5
Chernobyl	5.7	1.7	1.3	1.0	0.8	0.7
Internal irradiation						
Inhalation	2	0.02	0.02	0.02	0.02	0.02
Ingestion						
^{131}I in milk	3	–	–	–	–	–
^{134}Cs and ^{137}Cs						
Milk	8	5	0.7	0.4	0.2	0.1
Other diet	2	5	0.7	0.4	0.2	0.1
^{14}C	2.6	2.4	2.3	2.3	2.3	2.2
^{90}Sr	0.8	0.8	0.5	0.7	0.6	0.4
Total	25.9	16.7	7.2	6.4	5.6	5.0

TABLE 14 Exposure of infants from the consumption of milk containing radionuclides discharged to atmosphere in 1991[a]

Site	Main radionuclides[b]	Maximum annual dose (μSv)
British Nuclear Fuels plc		
Springfields	Total U	0.4[c]
Capenhurst	Total U, ^{99}Tc	0.6[d]
Chapelcross	^{3}H, ^{35}S	5
Sellafield	^{3}H, ^{35}S, ^{90}Sr, ^{99}Tc, ^{129}I, ^{131}I,	28
AEA Technology		
Harwell	^{3}H, ^{90}Sr, Total Cs	2.4
Winfrith	^{3}H, ^{90}Sr, Total Cs	3.3
Dounreay	^{90}Sr, ^{137}Cs	16[e]
Nuclear Electric		
Bradwell	^{35}S	0.8
Dungeness	^{35}S	1.3
Hartlepool	^{35}S	1.0
Heysham	^{3}H, ^{35}S	1.1
Hinkley Point	^{3}H, ^{35}S	1.3
Oldbury/Berkeley	^{35}S	1.7
Sizewell	^{35}S	1.1
Trawsfynydd	^{35}S, ^{137}Cs	2.6
Wylfa	^{35}S	0.8
Scottish Nuclear		
Hunterston	^{35}S	1.7
Torness	^{35}S	1.3
Ministry of Defence		
Aldermaston	^{3}H	<0.1
Amersham International		
Amersham	^{3}H, ^{35}S, ^{125}I, ^{131}I	5.9
Cardiff	^{3}H, ^{125}I	1.5

Notes

(a) The doses are calculated under the cautious assumption that concentrations are never lower than the limit of detection. The annual milk consumption rate is assumed[92] to be 350 litres.

(b) ^{14}C is discharged from most of the sites listed. It was measured in samples from Heysham, Hinkley and AI Cardiff and Sellafield, where the annual doses from discharges of ^{14}C were assessed as 6.9 μSv, 5.6 μSv, 3.4 μSv and 10 μSv, respectively.

(c) Critical group inhalation dose at this site is 4 μSv.

(d) Critical group inhalation dose at this site is 1 μSv.

(e) From measurements in 1990: there are no longer any milk producers near the site.

TABLE 15 Committed doses from artificial radionuclides to consumers of fish and shellfish from the Irish Sea

		Consumption rates (g d^{-1})			Committed doses from intakes (μSv)										
Exposed group	Year	Fish	Crustaceans	Molluscs	$^{14}C^{a}$	^{90}Sr	^{106}Ru	^{134}Cs	^{137}Cs	$^{237}Np^{a}$	^{238}Pu	$^{239/240}Pu$	^{241}Pu	^{241}Am	Total[b]
High rate consumers in local fishing community near Sellafield	1987	100	16	23		4	7	1	22		18	83	34	150	330
	1988	100	16	23		3	7		15		7	36	13	64	150
	1989	100	16	23		4	10		15		9	45	17	84	190
	1990	100	16	23		4	5		15		7	34	12	75	160
	1991	100	16	23	2	3	7		14	2	6	32	11	70	150
Typical member of the public consuming fish landed at Whitehaven and Fleetwood	1987	40							5						6
	1988	40							4						5
	1989	40							3						4
	1990	40							3						4
	1991	40							3						3

Notes

(a) Reported for the first time in 1991.

(b) The sum of the individual doses, including those below 1 μSv not shown in the table, may differ slightly from the total shown because of numerical rounding.

TABLE 16 Occupational exposure at BNFL Springfields

Year	Number of workers in annual dose range (mSv)							Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–5	5–10	10–15	15–20	20–30	30–40	>40			
1988	2,751	315	52	9	1	0	0	3,128	7.2	2.3
1989	2,570	361	56	2	1	0	0	2,990	7.1	2.4
1990	2,362	406	90	0	0	0	0	2,858	7.8	2.7
1991	2,942	209	24	0	0	0	0	3,175	5.9	1.9

TABLE 17 Occupational exposure at BNFL Capenhurst

Year	Number of workers in annual dose range (mSv)							Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–5	5–10	10–15	15–20	20–30	30–40	>40			
1988	898	0	0	0	0	0	0	898	0.2	0.2
1989	900	0	0	0	0	0	0	900	0.1	0.1
1990	899	0	0	0	0	0	0	899	0.3	0.3
1991	888	0	0	0	0	0	0	888	0.2	0.2

TABLE 18 Occupational exposure at NE nuclear power stations

Year	Number of workers in annual dose range* (mSv)				Total number of workers*	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–5	5–10	10–15	>15			
1988	22,752	261	30	0	23,043	10.9	0.5
1989	24,366	214	18	0	24,598	10.5	0.4
1990	23,583	204	4	0	23,791	10.5	0.4
1991	21,975	164	4	0	22,143	8.9	0.4

*Some workers receive doses at more than one site. The aggregation of data for each site may slightly overestimate the total number of workers

TABLE 19 Occupational exposure at SNL nuclear power stations

Year	Number of workers in annual dose range (mSv)						Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–1.2	1.3–2.5	2.6–5.0	5.1–10.0	10.1–15.0	>15			
1988*	–	–	–	–	–	–	3,200	3.8	1.2
1989*	–	–	–	–	–	–	3,500	3.5	1.0
1990	3,230	150	134	32	1	0	3,547	1.6	0.5
1991	3,236	117	109	163	27	0	3,652	2.6	0.7

*Detailed dose distributions for 1988 and 1989 are not available.

TABLE 20 Occupational exposure at BNFL Chapelcross nuclear power station

	Number of workers in annual dose range (mSv)							Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Year	0–5	5–10	10–15	15–20	20–30	30–40	>40			
1988	401	159	88	25	3	0	0	676	3.4	5.1
1989	387	173	68	17	1	0	0	646	3.1	4.8
1990	394	208	55	0	0	0	0	657	2.9	4.4
1991	541	193	19	0	0	0	0	753	2.4	3.2

TABLE 21 Occupational exposure at UK nuclear power stations in 1991[a]

	Number of workers in dose range (mSv)				Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Sites	0–5	5–10	10–15	>15			
All NE stations[b]	19,235	174	8	0	19,417	9.7	0.5
BNFL Chapelcross	541	193	19	0	753	2.4	3.2
All SNL stations	3,462	163	27	0	3,652	2.6	0.7
NNC[c]	903	1	0	0	904	0.2	0.2
Total	24,141	531	54	0	24,726	14.9	0.6

Notes

(a) Excluding Calder Hall which is subsumed in Table 22.

(b) Includes workers at BNL and some workers of non-licensed sites. The total does not match Table 18 because the latter includes workers who receive doses at more than one site.

(c) NNC workers receive doses at many different sites (see text).

TABLE 22 Occupational exposure at BNFL Sellafield

	Number of workers in annual dose range (mSv)							Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Year	0–5	5–10	10–15	15–20	20–30	30–40	40–50			
1988	5,756	1,392	655	289	127	2	0	8,221	34.7	4.2
1989	6,394	1,162	490	198	81	2	0	8,327	27.0	3.2
1990	6,603	1,185	601	123	2	0	1	8,515	27.0	3.2
1991	7,817	939	256	6	1	0	0	9,019	18.5	2.1

TABLE 23 Occupational exposure at BNFL Risley

	Number of workers in annual dose range (mSv)							Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Year	0–5	5–10	10–15	15–20	20–30	30–40	>40			
1988	809	2	0	0	0	0	0	811	0.1	0.2
1989	776	0	0	0	0	0	0	776	0.2	0.3
1990	735	0	0	0	0	0	0	735	0.2	0.3
1991	804	0	0	0	0	0	0	804	0.1	0.1

TABLE 24 Occupational exposure at AEA sites

Year	Number of workers in annual dose range[a] (mSv)					Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–5	5–10	10–15	15–50	>50			
1988[b]	7,876			208	0	8,084	18.4	2.3
1989[b]	7,173			281	0	7,454	18.2	2.4
1990[b]	6,124	547		126	0	6,797	12.4	1.8
1991	5,460	153	12	0	0	5,625	5.6	1.0

Notes
(a) A number followed by a dotted line applies to all the dose ranges so indicated.
(b) Detailed distribution available only for 1991.

TABLE 25 Occupational exposure in MOD (DRPS)

Year	Numbers of workers in annual dose range[a] (mSv)								Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–5	5–10	10–15	15–20	20–30	30–40	40–50	>50			
1988[b]	7,699			21	10	0	0	0	7,730	9.0	1.2
1989	7,788	403	114	46	46	5	1	0	8,403	11.6	1.4
1990	7,902	409	128	41	35	1	0	0	8,516	11.1	1.3
1991	8,195	333	84	7	4	1	0	0	8,534	8.6	1.0

Notes
(a) A number followed by a dotted line applies to all the dose ranges so indicated.
(b) Data for employees only.

TABLE 26 Occupational exposure in MOD (AWE)

Year	Numbers of workers in annual dose range[a] (mSv)								Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
	0–5	5–10	10–15	15–20	20–30	30–40	40–50	>50			
1988[b]	4,094			0	0	0	0	0	4,094	2.1	0.5
1989	3,739	30	0	0	0	0	0	0	3,769	1.0	0.3
1990	3,893	37	5	0	0	0	0	0	3,935	1.7	0.4
1991	3,998	29	4	0	0	0	0	0	4,031	1.2	0.3

Notes
(a) A number followed by a dotted line applies to all the dose ranges so indicated.
(b) Data for employees only.

TABLE 27 Occupational exposure in some diagnostic radiology departments during 1991

Occupational group	Numbers of workers in dose range (mSv) 0–1	1–5	5–10	10–15	15–20	>20	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Main sample									
Radiographers	5,663	55	1	0	0	0	5,719	0.282	0.05
Radiologists	729	38	0	0	0	0	767	0.136	0.18
Cardiologists	171	22	2	0	1	0	196	0.089	0.44
Other clinicians	465	9	0	0	0	0	474	0.044	0.09
Departmental nurses	1,522	38	0	1	0	0	1,561	0.130	0.08
Scientific/technical staff	1,070	27	1	0	0	0	1,098	0.090	0.08
Other staff	937	5	2	0	0	0	944	0.053	0.06
Further sample									
All diagnostic	2,939	37	0	0	0	0	2,976	0.600	0.20
Total	13,496	231	6	1	1	0	13,735	1.420	0.10
Additional sample									
Cardiologists	24	9	0	0	0	0	33	–	–
Scientific/technical staff	29	0	0	0	0	0	29	–	–
Other staff	2,348	4	0	0	0	0	2,352	–	–

TABLE 28 Occupational exposure in some radiotherapy departments during 1991

Occupational group	Numbers of workers in dose range (mSv) 0–1	1–5	5–10	>10	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Main sample							
Beam radiographers	541	15	0	0	556	0.038	0.07
Radiotherapists	192	6	0	0	198	0.019	0.09
Sealed sources technicians	8	1	0	0	9	0.001	0.12
Radiotherapy theatre nurses	9	1	0	0	10	0.003	0.28
Brachytherapy ward nurses	548	5	3	0	556	0.053	0.10
Other nurses	203	9	1	0	213	0.051	0.24
Scientific/technical staff	130	1	0	0	131	0.008	0.06
Other staff	354	6	0	0	360	0.028	0.08
Further sample							
All radiotherapy	597	46	4	0	647	0.200	0.30
Total	2,582	90	8	0	2,680	0.400	0.15
Additional sample							
Sealed sources technicians	2	2	0	0	4	–	–
Radiotherapy theatre nurses	15	0	4	0	19	–	–
Brachytherapy ward nurses	264	5	0	0	269	–	–
Scientific/technical staff	17	0	0	0	17	–	–
Other staff	181	2	2	0	185	–	–

TABLE 29 Occupational exposure in some nuclear medicine departments during 1991

Occupational group	Number of workers in dose range (mSv) 0–1	1–5	>5	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Main sample						
Pharmacists	51	15	0	66	0.041	0.62
Radiographers/technicians	157	49	0	206	0.105	0.51
Physicists	60	16	0	76	0.036	0.48
Clinicians	67	5	0	72	0.016	0.23
Other staff	649	14	0	663	0.029	0.04
Research workers	221	4	0	225	0.024	0.11
Further sample						
All nuclear medicine	85	1	0	86	0.020	0.20
Total	1,290	104	0	1,394	0.270	0.19
Additional sample						
Physicists	6	1	0	7	–	–
Other staff	170	13	0	183	–	–
Research workers	810	1	0	811	–	–

TABLE 30 Estimate of occupational exposure of all medical workers

Work category	Number of workers in dose range (mSv) 0–1	1–5	5–10	10–15	15–20	>20	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Diagnostic	13,496	231	6	1	1	0	13,735	1.42	0.10
Radiotherapy	2,582	90	8	0	0	0	2,680	0.40	0.15
Nuclear medicine	1,290	104	0	0	0	0	1,394	0.27	0.19
Totals reported	17,368	425	14	1	1	0	17,809	2.1	0.12
Totals scaled to 40,000	39,000	950	50	<10	<10	<10	40,000	5.0	0.12

TABLE 31 Occupational exposure of workers in general industry in 1991

Type of work	Numbers of workers in dose range[a] (mSv) 0–5	5–10	10–15	15–50	>50	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Industrial radiography[b]	7,250	150	50	50	<10	7,500	6.3	0.8
Other industrial[b]	15,970	15	10	5	<10	16,000	2.2	0.1
Tritium devices	31	4	1	0	0	36	0.1	2.7
Radioisotope manufacture	1,062	159		1	0	1,222	2.4	1.9
Totals (rounded)	24,550	400		50	<10	25,000	11	0.4

Notes
(a) A number followed by a dotted line applies to all the dose ranges so indicated.
(b) Numbers of workers in each range were obtained from sample groups.

TABLE 32 Occupational exposure of non-coal miners in 1991

Mineral	Number of miners in dose range (mSv) 0–5	5–15	15–50	>50	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Barytes	10	0	0	0	10	0.04	3.6
Clay	22	12	0	0	34	0.10	3.0
Fluorspar	75	10	55	0	140	1.67	12.0
Gypsum	181	0	57	0	238	1.14	4.8
Limestone	7	21	11	0	39	0.32	8.3
Metalliferous	2	45	110	3	160	2.51	15.7
Sandstone	7	0	0	0	7	0.01	0.7
Slate	57	0	0	0	57	0.10	1.7
Others	658	0	4	0	662	0.19	0.3
Total	1,019	88	237	3	1,347	6.09	4.5

TABLE 33 Occupational exposure of coal and other miners in 1991

Mine type	Number of miners in dose range (mSv) 0–5	5–15	15–50	>50	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Deep coal	47,790	0	0	0	47,790	27.0	0.6
Private-sector coal	810	59	10	0	879	1.58	1.8
Non-coal	1,019	88	237	3	1,347	6.09	4.5
Total	49,619	147	247	3	50,016	34.7	0.7

TABLE 34 Overall doses from occupational exposure in 1991

Type of work	Number of workers in dose range[a] (mSv) 0–5	5–10	10–15	15–20	20–30	30–50	>50	Total number of workers	Annual collective dose (man Sv)	Average annual dose (mSv)
Nuclear										
Fuel fabrication	2,942	209	24	0	0	0	0	3,175	5.9	1.9
Fuel enrichment	888	0	0	0	0	0	0	888	0.2	0.2
Power stations	24,141	531	54	0	0	0	0	24,726	14.9	0.6
Fuel reprocessing	8,621	939	256	6	1	0	0	9,823	18.6	1.9
Technology services	5,460	153	12	0	0	0	0	5,625	5.6	1.0
All nuclear industry	42,052	1,832	346	6	1	0	0	44,237	45.2	1.0
Defence	12,103	362	88	7	4	1	0	12,565	9.8	0.8
General industry	24,550	400		50			<10	25,000	11.0	0.4
Research, education[b]	10,000	0		0			0	10,000	1.0	0.1
Medicine										
Medical[b]	39,950	50		0			0	40,000	5.0	0.1
Dental[b]	20,000	0		0			0	20,000	2.0	0.1
Veterinary[b]	4,000	0		0			0	4,000	0.4	0.1
Natural										
Coal mines	48,600	59		10			0	48,669	28.6	0.6
Non-coal mines	1,019	88		237			<10	1,347	6.1	4.5
Other workplaces[b,c]	32,000	13,000 . . .	3,000	1,000	1,000	500	<100	50,000	270	5.3
Aircrew[b]	24,000	0		0			0	24,000	50.0	2.0
Total (rounded)	258,000	20,000		2,500			<100	280,000	430	1.5

Notes

(a) A number followed by a dotted line applies to all the dose ranges so indicated.

(b) Dose distribution estimated from sample data. Where a zero is indicated a few workers might receive annual doses in the relevant range.

(c) Exposures from increased radon concentration in premises subject to regulatory control.

TABLE 35 Annual exposure of the UK population from all sources of radiation

Source	Annual collective dose (man Sv)	Average annual dose (μSv)
Natural		
Cosmic	15,000	260
Gamma	20,200	350
Internal	17,300	300
Radon	74,900	1,300
Artificial		
Medical	21,400	370
Occupational[a]	430	7
Fallout	290	5
Discharges[b]	20	0.4
Products	20	0.4
Total (rounded)	150,000	2,600

Notes
(a) Some 80% from natural sources.
(b) Some 20% from natural activity.

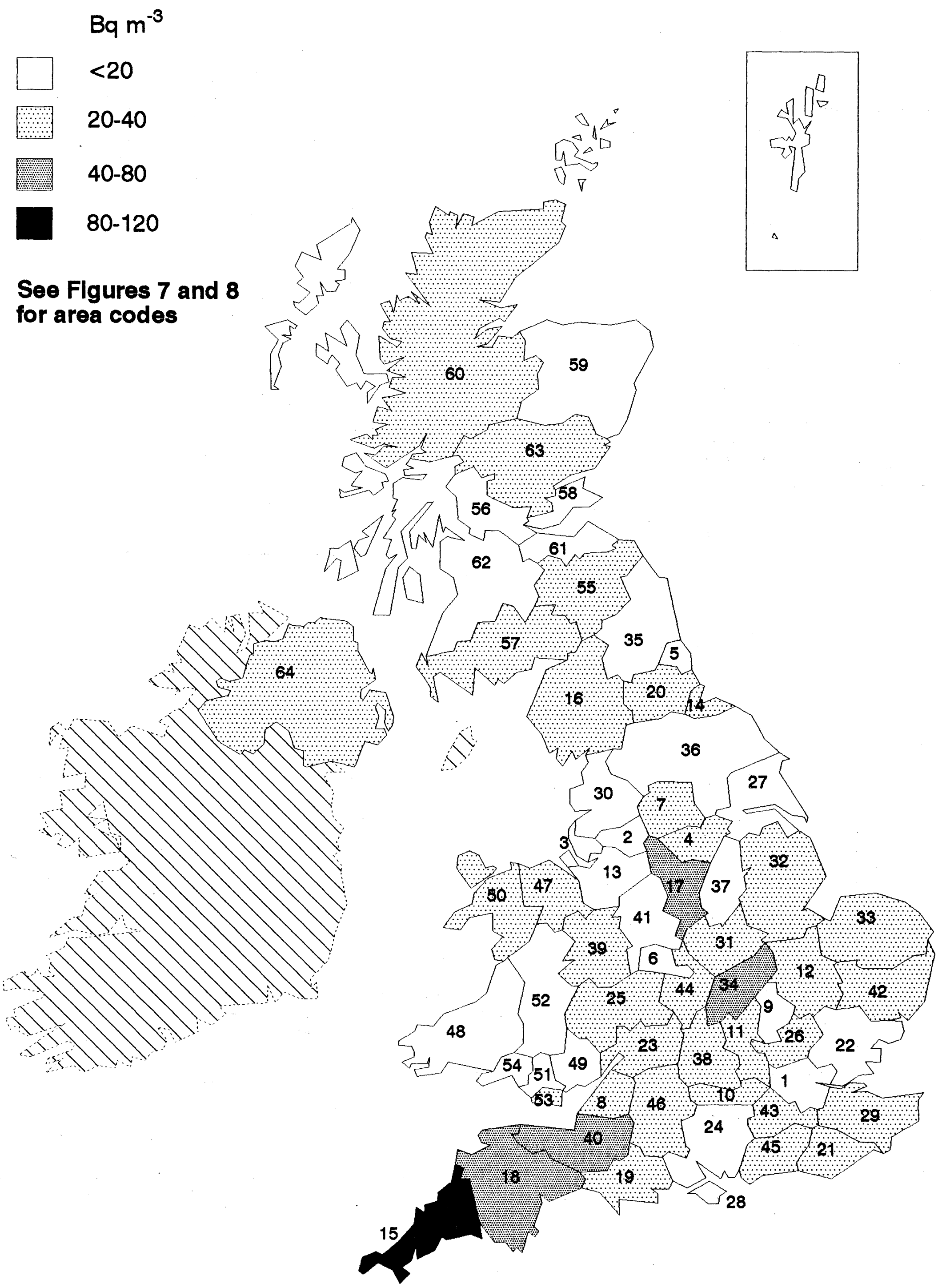

FIGURE 1 Average indoor radon levels in the UK by administrative area

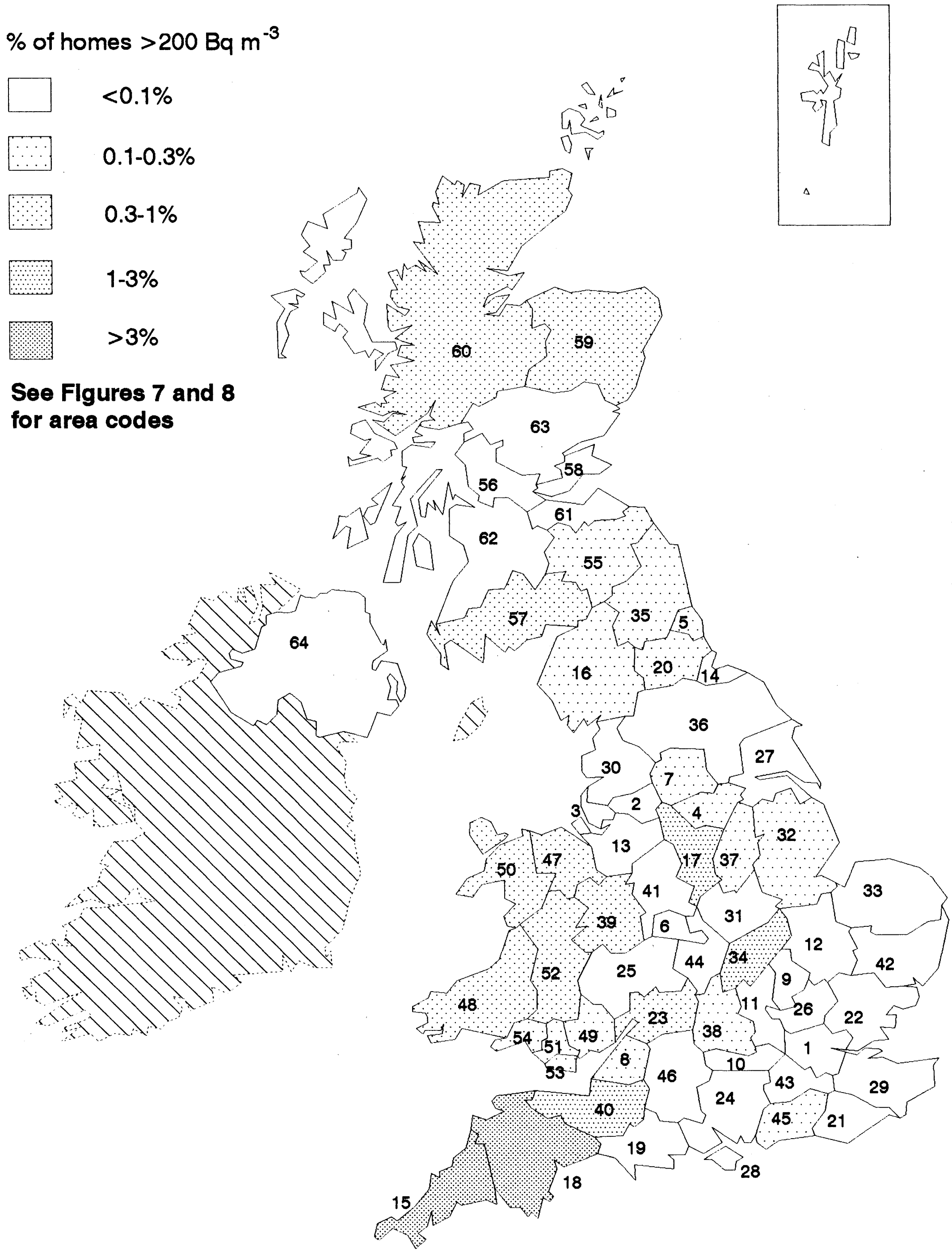

FIGURE 2 Estimated proportion of homes in the UK exceeding the radon Action Level by administrative area

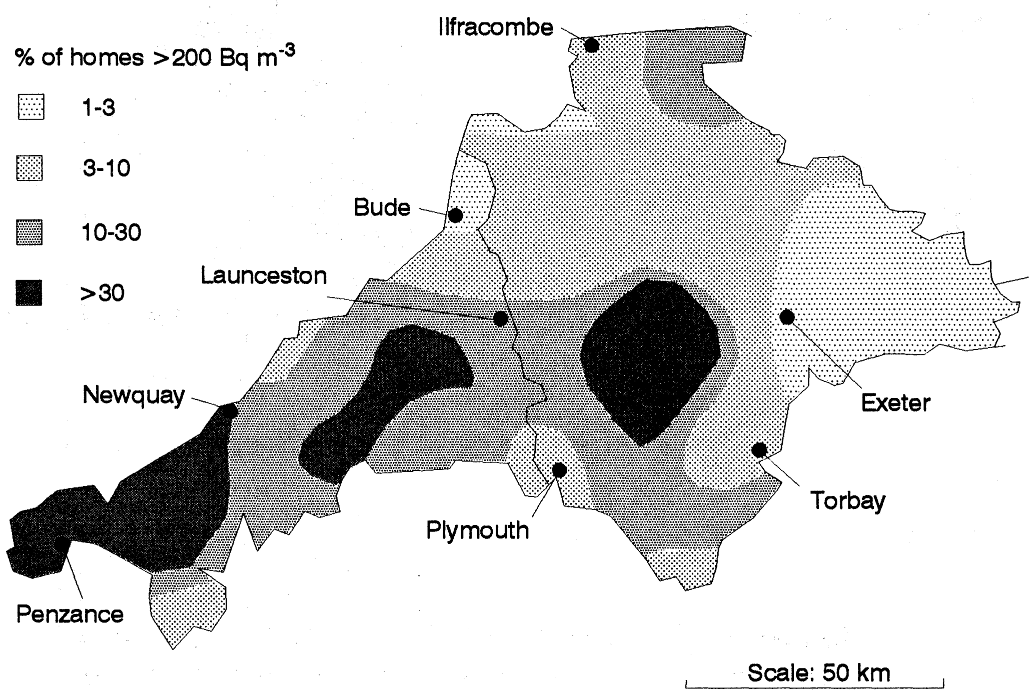

FIGURE 3 Estimated proportion of homes exceeding the radon Action Level in areas of Cornwall and Devon

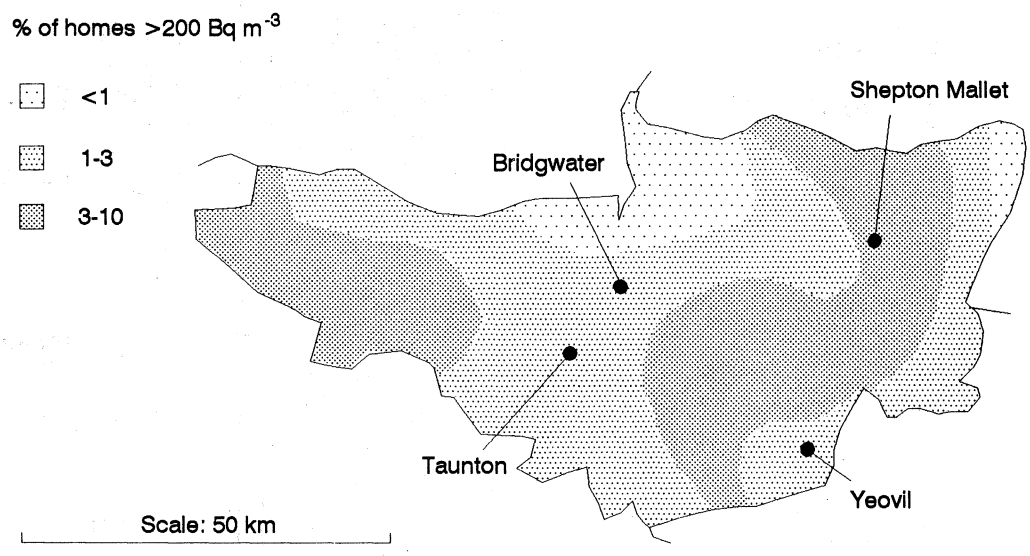

FIGURE 4 Estimated proportion of homes exceeding the radon Action Level in areas of Somerset

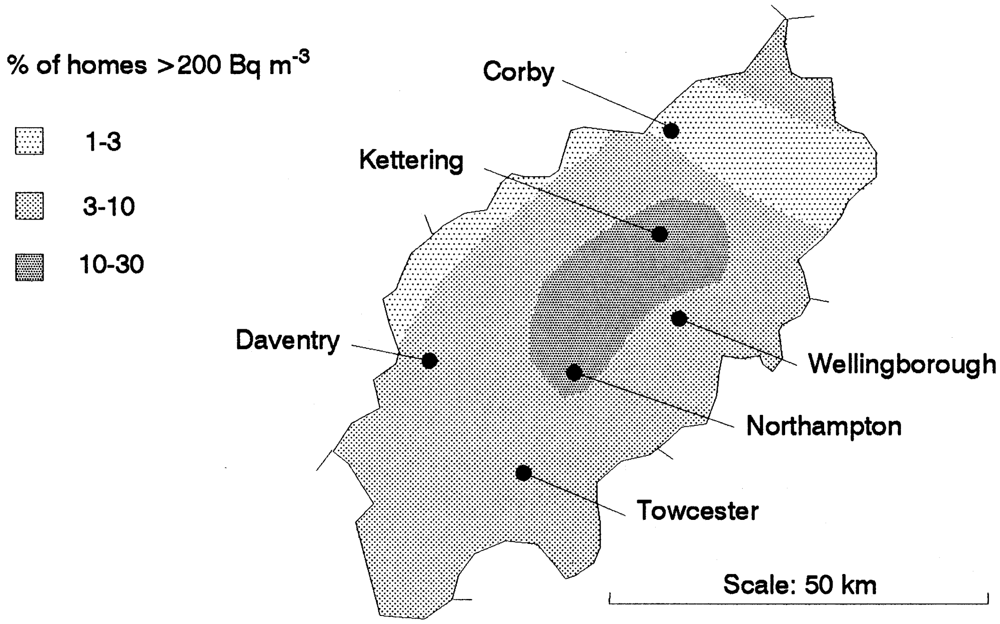

FIGURE 5 Estimated proportion of homes exceeding the radon Action Level in areas of Northamptonshire

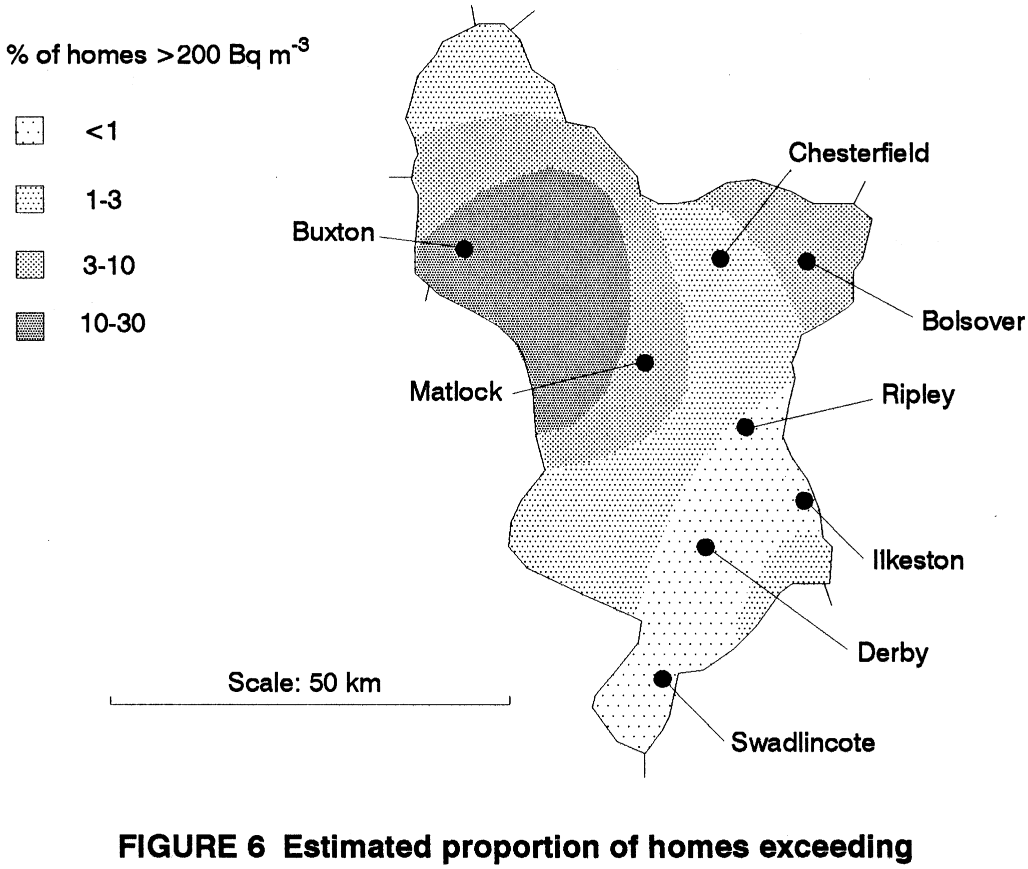

FIGURE 6 Estimated proportion of homes exceeding the radon Action Level in areas of Derbyshire

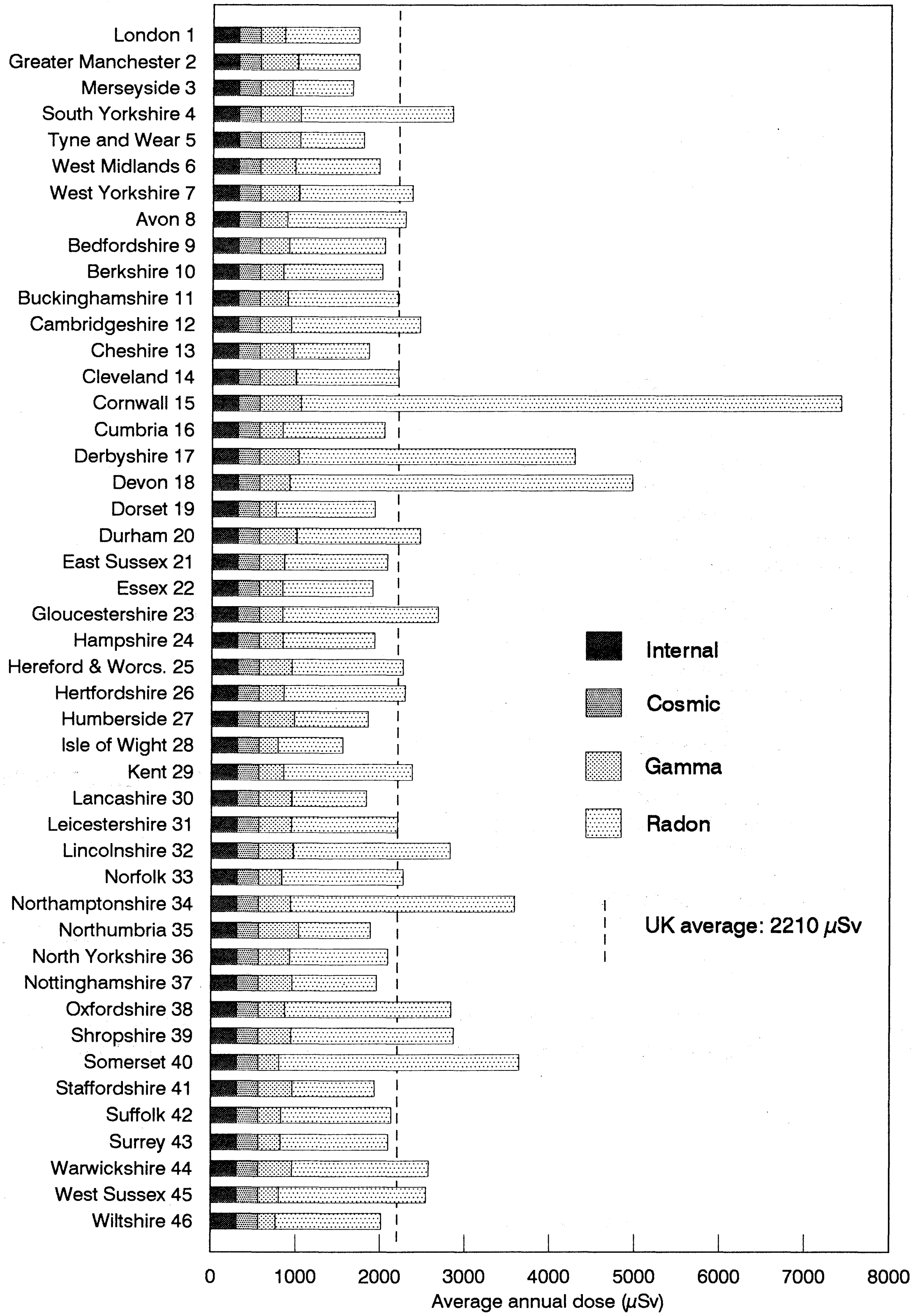

FIGURE 7 Average annual doses from natural radiation in England by administrative area

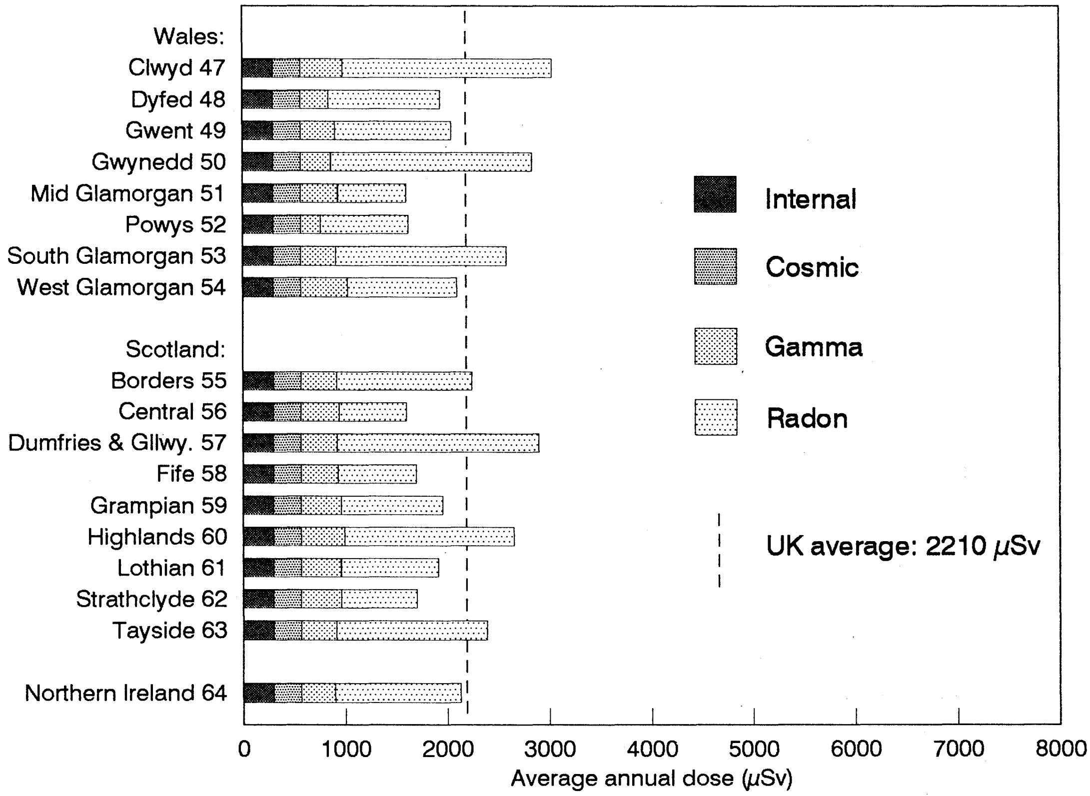

FIGURE 8 Average annual doses from natural radiation in Wales, Scotland and Northern Ireland by administrative area

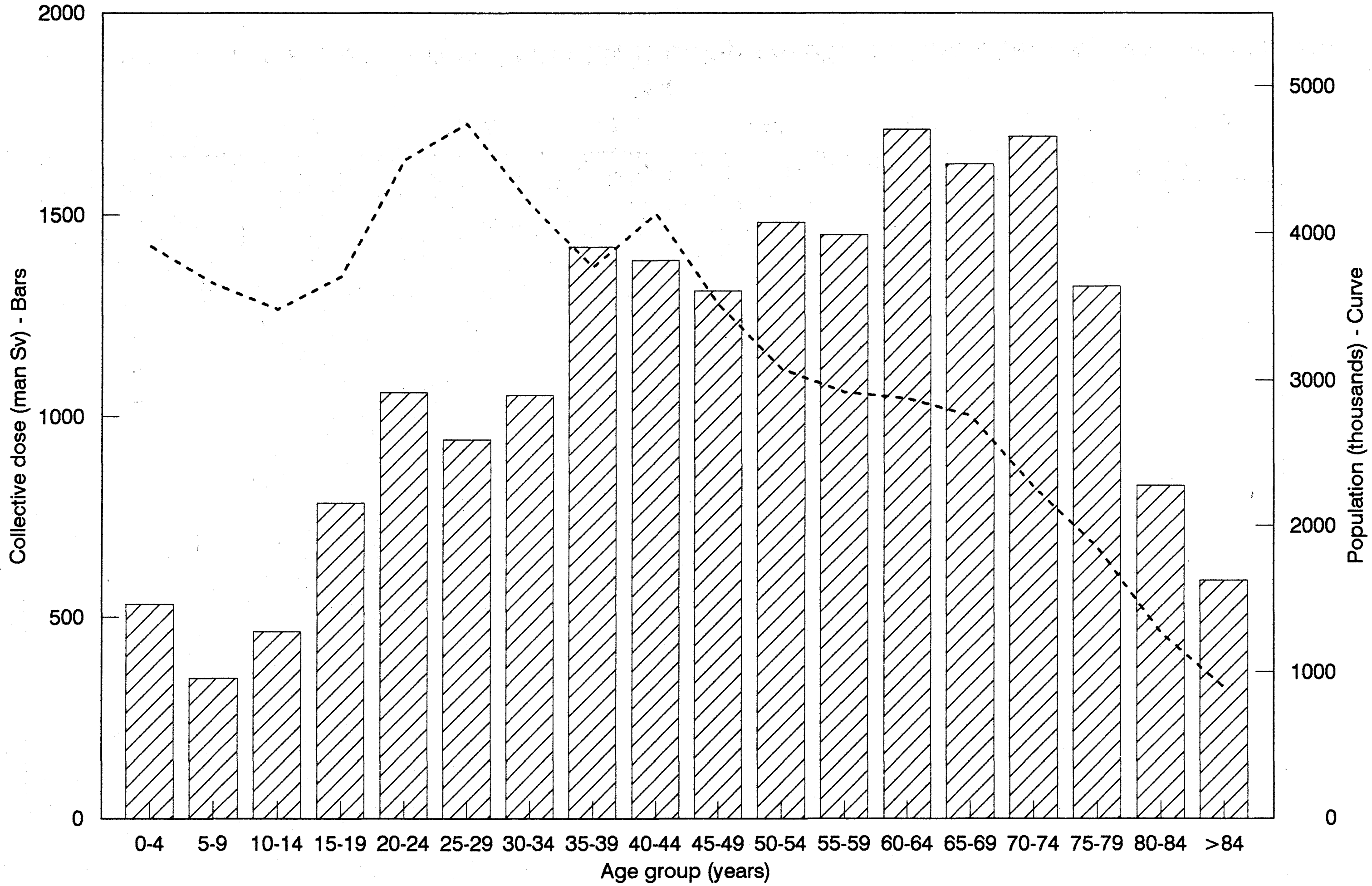

FIGURE 9 Age distribution of the population and of the collective dose from diagnostic radiology

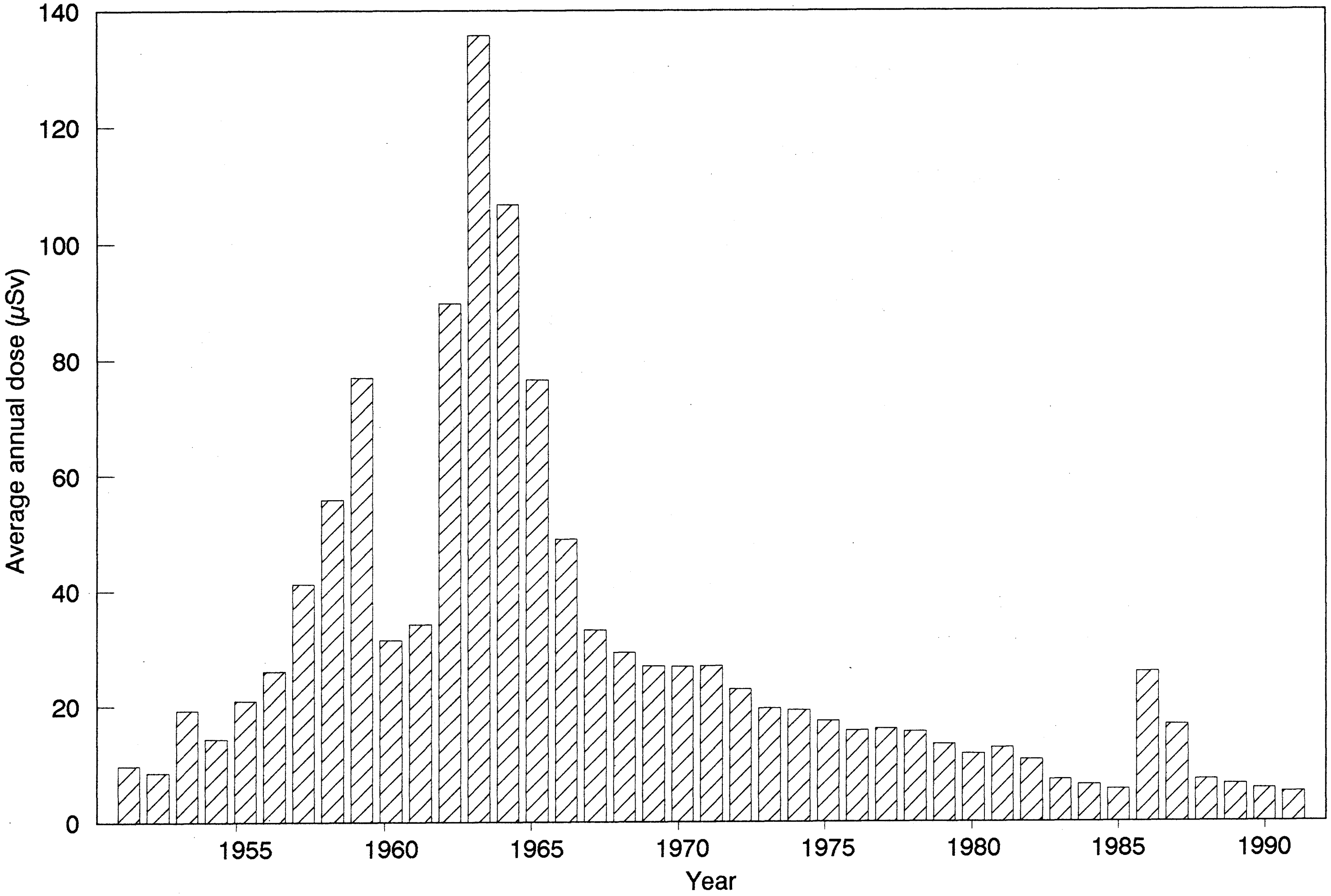

FIGURE 10 Average annual dose from fallout in the UK showing the effect of the Chernobyl accident in 1986

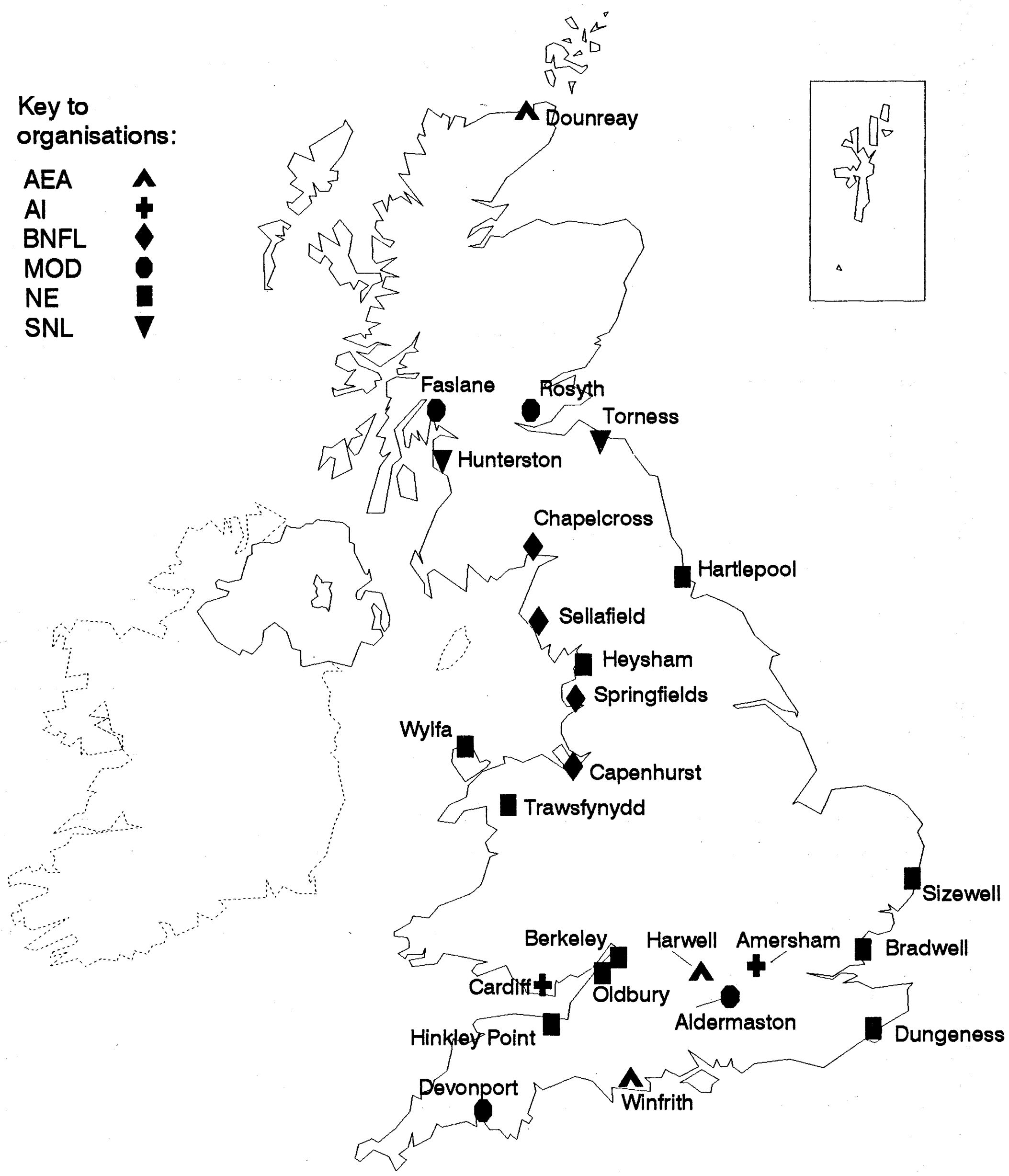

FIGURE 11 Locations of the main nuclear sites that give rise to liquid or aerial radioactive wastes

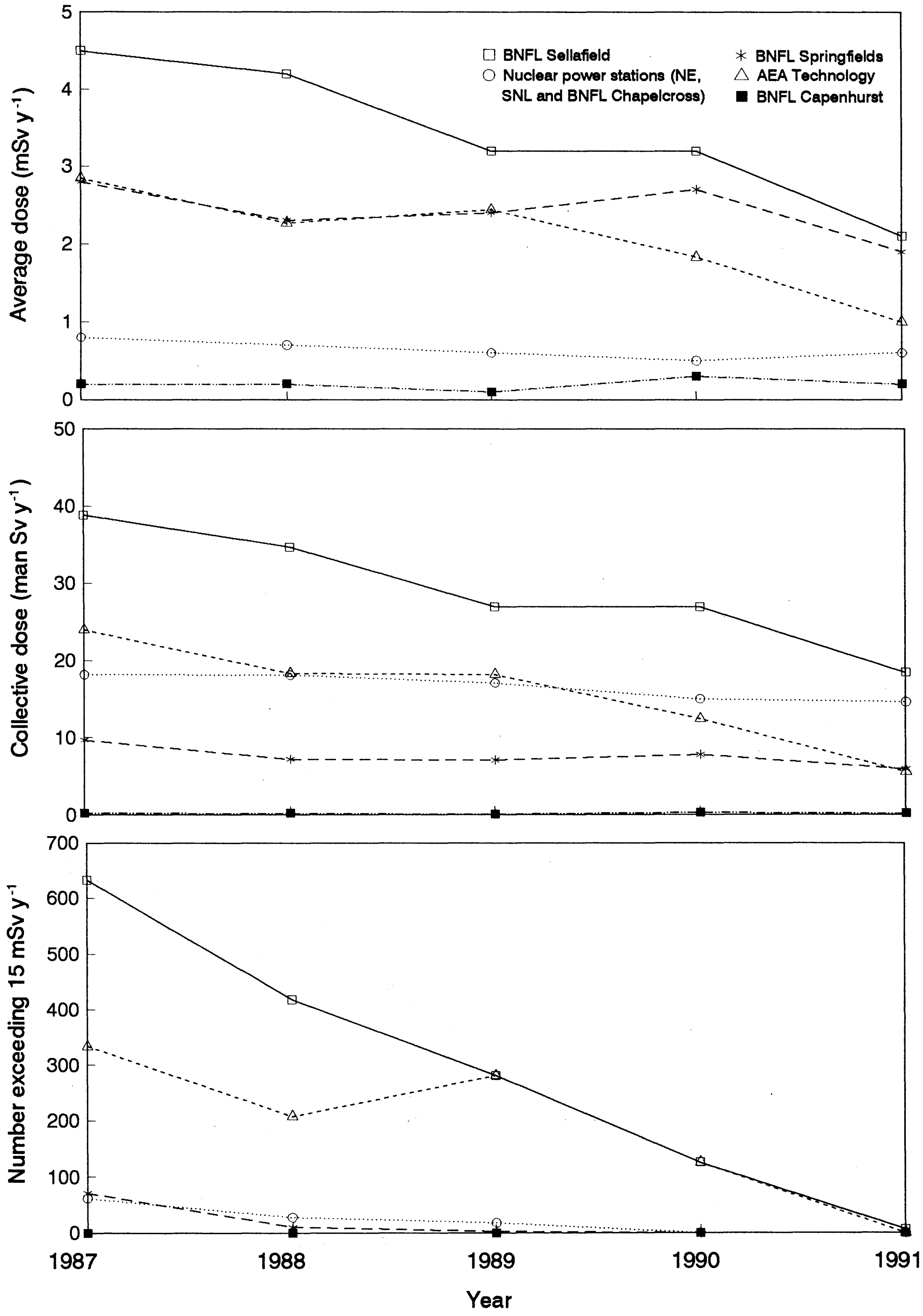

FIGURE 12 Temporal trends in occupational exposure at nuclear sites in the UK

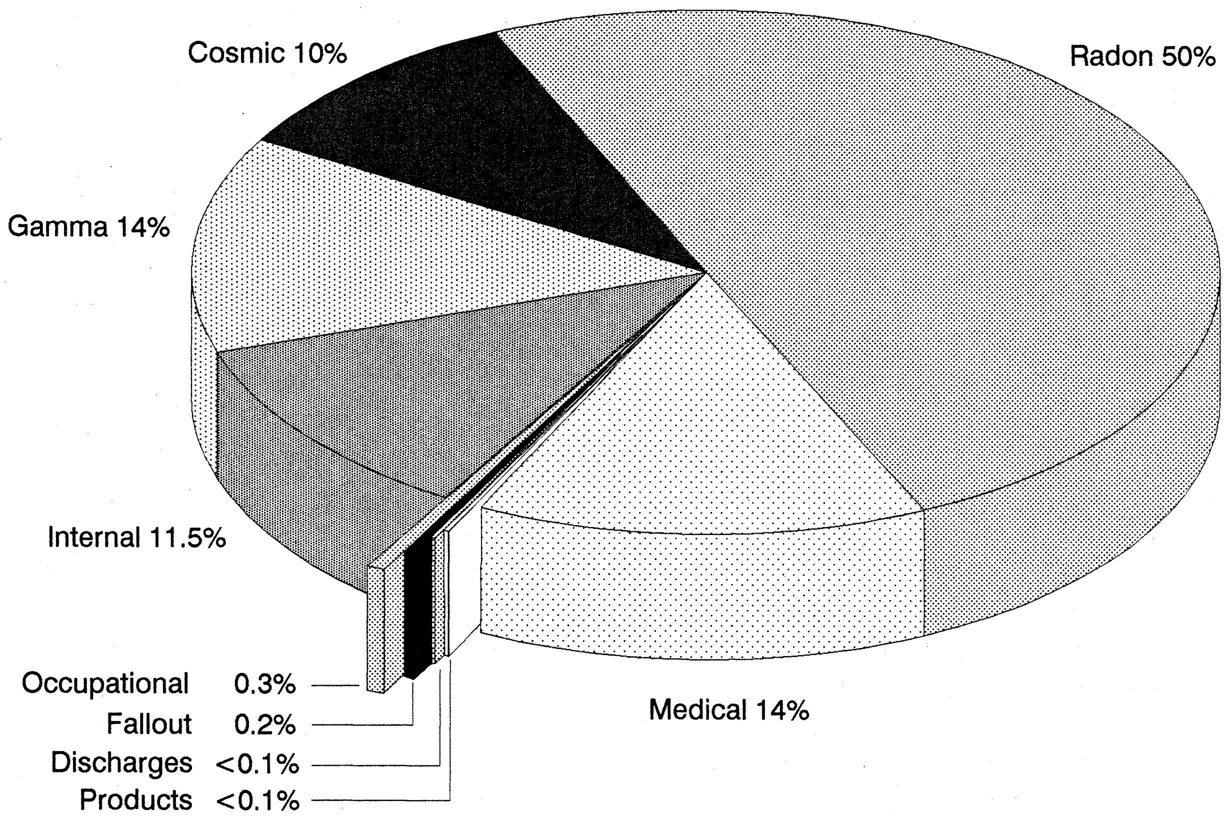

FIGURE 13 Average annual dose to the UK population - 2.6 mSv overall