Radiological Protection Institute of Ireland
An Institiúid Éireannach um Chosaint Raideolaíoch

Radiation Doses Received by the Irish Population

2014

Radiation Units

Radioactivity is measured in units called becquerels (Bq). One becquerel corresponds to one radioactive disintegration per second.

When measuring radioactive discharges to the environment or referring to the content of radioactive sources used in medicine, industry and education, it is more usual to talk in terms of kilobecquerels (kBq), megabecquerels (MBq), gigabecquerels (GBq) or terabecquerels (TBq)

1 kBq = 1000 Bq

1 MBq = 1,000,000 Bq

1 GBq = 1,000,000,000 Bq

1 TBq = 1,000,000,000,000 Bq

Much lower concentrations of radioactivity are normally found in the environment and so the measurement is often reported in units of millibecquerels (mBq). There are one thousand millibecquerels in a becquerel.

1 Bq = 1000 mBq

Radiation Dose When radiation interacts with body tissues and organs, the radiation dose received is a function of factors such as the type of radiation, the part of the body affected, the exposure pathway, etc. This means that one becquerel of radioactivity will not always deliver the same radiation dose. A unit called 'effective dose' has been developed to take account of the differences between different types of radiation so that their biological impact can be compared directly. Effective dose is measured in units called sieverts (Sv).

The sievert is a large unit, and in practice it is more usual to measure radiation doses received by individuals in terms of fractions of a sievert.

1 sievert = 1000 millisievert (mSv)
= 1,000,000 microsievert (μSv)
= 1,000,000,000 nanosievert (nSv)

In RPII reports the term 'effective dose' is often referred to as 'radiation dose' or simply 'dose'.

Collective dose is the sum of the radiation doses received by each individual in the population. This allows comparison of the total radiation dose received from different sources. Collective dose is reported in units of man sieverts (man Sv) or man millisieverts (man mSv).

Average Annual Dose is the collective dose divided by the total population. Average Annual Dose is reported in units of sieverts, or fractions of a sievert.

Radiological Protection Institute of Ireland
An Institiúid Éireannach um Chosaint Raideolaíoch

RPII 14/02

Radiation Doses Received by the Irish Population

2014

by
C. O'Connor
L. Currivan
N. Cunningham
K. Kelleher
M. Lewis
S. Long
P. McGinnity
V. Smith
C. McMahon

June 2014

Contents

Executive Summary

People are constantly exposed to a variety of sources of both natural and artificial radioactivity. The radiation dose received by the population from such sources is periodically estimated by the Radiological Protection Institute of Ireland (RPII). This report is an update of a population dose assessment undertaken in 2008 and includes the most recent data available on the principal radiation exposure pathways.

The average annual dose to a person in Ireland from all sources of radiation is now estimated as 4037 microsievert (μSv) which is consistent with the value, 3950 μSv, estimated in 2008. Natural sources of radioactivity account for 86% of all radiation exposures in Ireland. Artificial sources contribute approximately 14% and are dominated by the beneficial use of radiation in medicine. Doses from other artificial sources such as Sellafield, Chernobyl, occupational exposure, etc., account for less than 1%.

Radon is the principal source of radiation exposure in Ireland, representing just over 55% of the average radiation dose. Most of this dose is received in people's homes although radon exposure at work accounts for the largest contribution to occupational exposure. For the individual, exposure to radon is extremely variable with a measured range of exposure in Irish homes of between 250 μSv and 1,225,000 μSv per annum.

This assessment includes data on pathways of exposure for which few Irish data were available in 2008, including: the results of a new study of radioactivity in the Irish diet; new data on thoron in Irish homes; and a detailed evaluation of medical exposures which was undertaken by the Health Service Executive (HSE). Wherever possible, the collective dose (i.e. the sum of the radiation doses received by the entire population) and the resulting average annual dose to an individual living in Ireland, based on the most recently published figure for the population of Ireland, have been calculated for each of the pathways of exposure.

Sources of radioactivity

Natural sources include external radiation coming from outer space (cosmic radiation); external radiation produced by naturally occurring radioactive elements contained in the earth's crust (terrestrial radiation); the radioactive gases radon and thoron which can accumulate in buildings; and radioactivity transferred to food and water which are consumed.

Artificial sources of radioactivity include nuclear weapons testing, nuclear accidents such as those at Chernobyl and Fukushima and authorised releases from nuclear facilities abroad. Irish hospitals and research facilities also release small amounts of radioactivity into the Irish marine environment.

Ionising radiation is used in medicine, industry and education and can result in radiation doses being received by some workers. In the medical field, patients undergoing certain procedures will also receive measurable radiation doses.

Cosmic Radiation

The earth is continuously bombarded by high energy particles of extra-terrestrial origin. Collectively these particles are referred to as cosmic radiation. Cosmic radiation is absorbed by the earth's atmosphere and its intensity decreases strongly with decreasing altitude, but some of it still reaches the earth's surface. People receive a radiation dose from cosmic radiation both on the ground and while flying. The radiation dose estimated for cosmic radiation (343 μSv) is consistent with the value found in the 2008 study.

Natural and Artificial Radioactivity in Soils

Naturally occurring radioactive elements have been present in rocks and soils since the formation of the earth. External exposure due to gamma radiation from natural radionuclides in the ground varies with location and is mainly due to differences in the local geology and/or soil type. There is an additional small contribution from artificial radioactivity present as a result of deposition following nuclear weapons testing in the 1950s and 1960s and the Chernobyl accident in 1986. Gamma radiation is normally higher indoors than outdoors due to radioactivity in building materials. The estimate of radiation dose from gamma radiation in the environment (301 μSv) is consistent with that from the 2008 study.

Indoor Radon in Homes and Workplaces

Radon is a naturally occurring radioactive gas constantly formed in the soil by the radioactive decay of radium-226, a component of the uranium-238 decay series. Outdoors, radon quickly dilutes to harmless levels, but when it enters a house or other building, it can sometimes accumulate to unacceptably high levels.

The degree to which radon seeps indoors from these rocks and soil depends on a number of factors, including the type of underlying rocks and soil, the porosity of the soil, the composition and condition of the foundation materials, and the ventilation rate of the building.

The public are exposed to radon at home and at work. Radon in the home is the largest component of the public's exposure because of the time spent at home compared to the workplace. The total average annual dose from radon is 2224 μSv, taking into account exposure at home and in work. However, for the individual, exposure to radon is extremely variable depending on the concentration of radon to which they are exposed.

Thoron in Homes

Thoron is a naturally occurring radioactive gas that is produced by the radioactive decay of radium-224, a component of the thorium-232 decay series. Where thoron differs from radon is that thoron has a very short half-life of 56 seconds and can only migrate a short distance before it decays. For this reason, building materials rather than the soil beneath the house are usually the principal source of thoron in indoor air.

The population dose assessment undertaken in 2008 estimated the average annual dose from thoron based on a pilot study of 40 Irish homes. Since then, a more comprehensive study of thoron and its decay products has been completed in 205 Irish homes. In addition, new estimates for dose coefficients for thoron and its decay products have been calculated. The current estimate of the average annual dose from thoron is 350 μSv, which is an increase from 280 μSv in 2008. This increase is due to the updated dose conversion coefficients rather than from increased thoron levels.

Radioactivity in food and drinking water

Radioactivity is present in all plants, animals and water from both natural and artificial sources. The radiation dose received from the consumption of food and drinking water is dependent on the concentration of radionuclides in the food and water and on consumption rates. In order to provide a representative figure for the average level of key radionuclides in the Irish diet, analysis of these levels of key radionuclides in complete meals was conducted. The naturally occurring radionuclides included in the assessment were potassium-40, carbon-14, radium-228, radium-226, polonium-210, lead-210 and rubidium-87. In addition, radionuclides present in seafood as a result of discharges from the Sellafield reprocessing plant are analysed on an ongoing basis. The current estimate of the average annual dose from radioactivity in food and water is 267 μSv which is marginally higher than the figure estimated in 2008 which was mainly based on data from UK studies. Naturally occurring radioactivity in food accounts for 98% of the radiation dose with 2% as a result of artificial radioactivity.

Occupational Exposure

In addition to radon in all indoor workplaces, other groups of workers that are exposed to radiation include air crew who are occupationally exposed to cosmic radiation, workers in mines and show caves who are exposed to enhanced levels of radon and staff working with radioactive sources and X-rays in medicine, industry and education/research. Data from radon measurement companies, airlines, previous RPII studies of certain classes of workplaces and the measurement of doses to staff who wear personal dosimeters were used to estimate the collective occupational exposure to radiation, and hence the annual average to the whole population.

More than 99.9% of the radiation dose due to occupational exposure is attributable to exposure to natural radiation – mainly from radon in above-ground workplaces but with a small contribution from the cosmic ray exposure of aircrew. Occupational exposure to artificial radiation accounts for just 0.01% of the average dose estimate of 235 μSv.

Medical Exposure of Patients

Medical exposures are typically the largest component of the average dose from artificial sources of radiation. Estimating these exposures requires information on the typical dose per investigation and the frequency of each investigation. Since the 2008 population dose report was published, the HSE has carried out national surveys of a number of different diagnostic imaging modalities, including computed tomography (CT) and dental radiography in 2010, general X-ray imaging and nuclear medicine in 2011 and PET-CT in 2013. A pilot survey for interventional radiology (including cardiology) was also carried out in 2013.

When the results from these surveys are combined, the resulting average annual dose is 546 μSv. The largest contributor is CT which accounts for only 6% of examinations but contributes 55% of the dose due to medical exposures of patients. There is also a significant contribution of 20% to this dose from interventional cardiology, which accounts for only 0.7% of the examinations.

Distribution of Doses

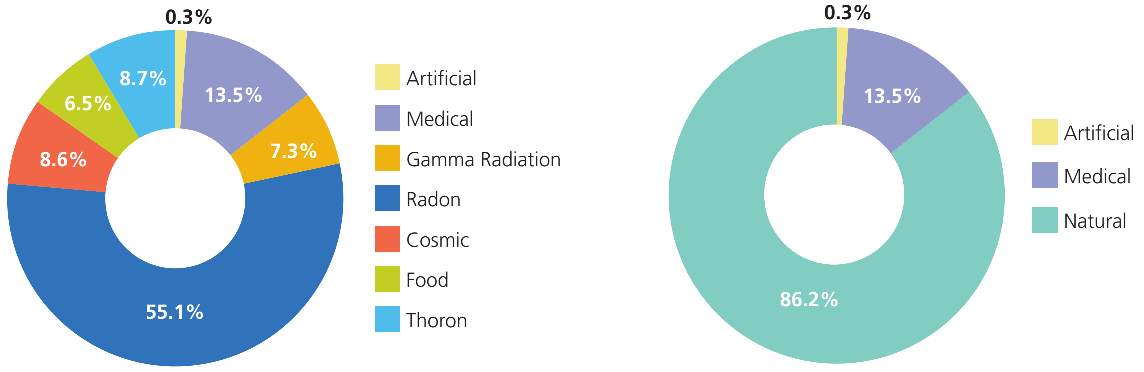
The table and pie-charts below show the estimated doses for the different exposure pathways considered in this report

Average annual radiation doses in Ireland

Exposure pathway	Dose due to natural sources of radiation (μSv)	Dose due to artificial sources of radiation (μSv)
Cosmic radiation	**343**	
At sea level	302	
Airline travel	41	
Gamma radiation in the environment	**295**	**6.01**
Radon in homes	**1,995**	
Thoron in homes	**350**	
Radioactivity in food and water[†]	**262**	**5**
Carbon-14	6	2
Potassium-40	170	
Rubidium-87	2	
Radium-228 (from thorium-232)	7	
Radium-226	4	
Polonium-210 (from uranium-238)	47	
Lead-210 (from uranium-238)	26	
Discharges from Sellafield		0.07
Radioactivity in milk		0.5
Caesium-137 in mixed diet		2.7
Occupational exposures	**235**	**0.02**
Aircrew cosmic radiation	6	
Radon in schools	3.3	
Radon in above ground workplaces	226	
Radon in below ground workplaces	<0.02	
NORM industries	<0.1	
Artificial radioactivity		0.02
Medical exposures		**546**
CT		298
Dental		1.3
General x-ray		56.4
Nuclear medicine (excluding PET-CT)		24.4
PET-CT		28.3
Interventional radiology and cardiology		137.3
TOTAL (4,037)	**3,480 (86%)**	**557 (14%)**

[†] *Drinking water accounts for an average annual dose of <100 μSv*

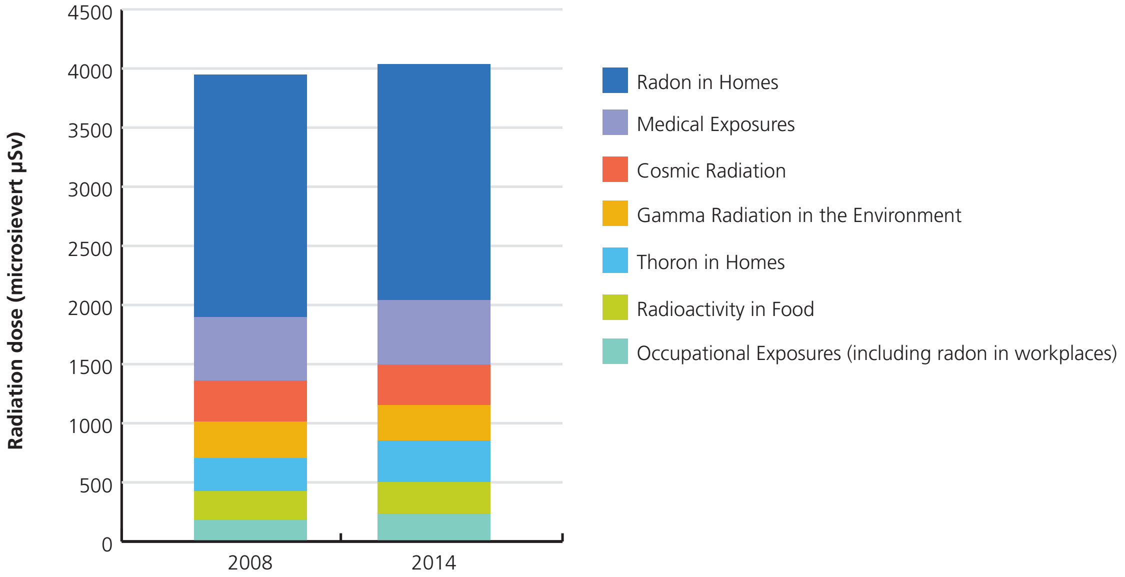
Distribution of average radiation dose in Ireland



Comparison between 2008 and 2014 assessments

The average annual doses (μSv) estimated for each exposure pathway in this study and as reported in 2008 are summarised in the table and graph below.

Exposure pathway	**2008**	**2014**
Cosmic radiation	345	343
Gamma radiation in the environment	310	301
Radon in homes	2,050	1,995
Thoron in homes	280	350
Radioactivity in food	240	267
Occupational exposures (including radon in workplaces)	185	235
Medical exposures	540	546
TOTAL	**3,950**	**4,037**



Main findings

The main findings were as follows:

- Radon continues to be the principal source of radiation exposure in Ireland, representing just over 55% of the radiation dose received by the Irish population. Radon is also the most variable source of radiation exposure with radon concentrations in Irish homes ranging from 10 Bq/m^3 up to 49,000 Bq/m^3, corresponding to annual doses of 250 µSv to 1,225,000 µSv.
- Medical exposure of patients remains by far the largest man-made contributor to the collective dose.
- No significant increase has been observed in the collective and average annual doses from medical exposure since 2008, however, the HSE surveys that were conducted between 2010 and 2013 now provide a comprehensive set of national baseline data against which future surveys may be compared to track changes to the population's radiation doses from medical exposure.
- Other sources such as fallout from nuclear accidents and weapons tests or discharges of nuclear or radioactive waste to the environment remain at very low levels

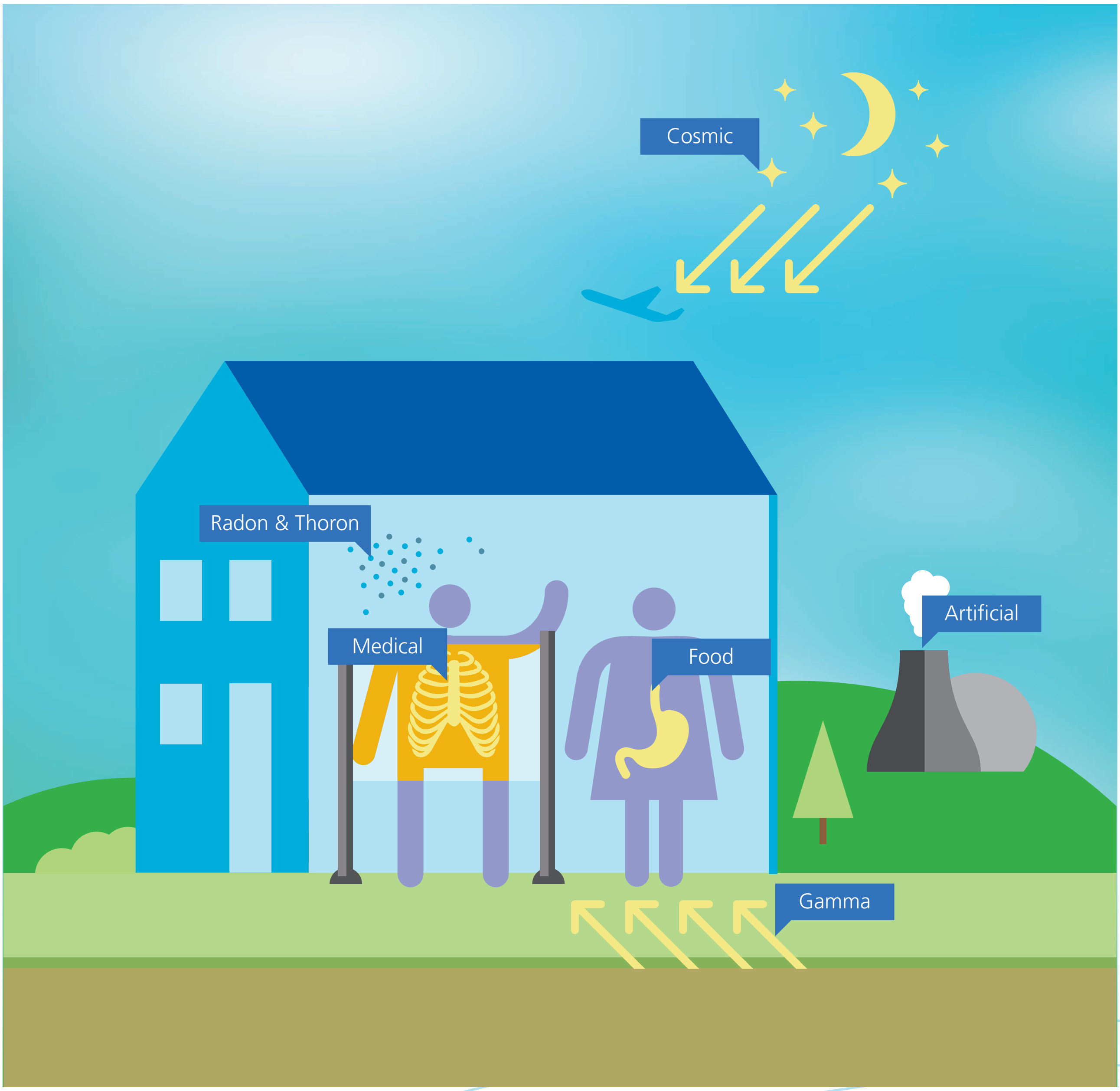
1 Introduction

People are constantly exposed to radiation from a variety of sources, natural and artificial.

Natural sources include external radiation coming from outer space (cosmic radiation); external radiation produced by naturally occurring radioactive elements contained in the earth's crust (terrestrial radiation); the radioactive gases radon and thoron, which can accumulate in buildings; and radioactivity transferred to food and water that are then consumed by humans.

Artificial (or man-made) sources of radioactivity include nuclear weapons testing, nuclear accidents such as those at Chernobyl and Fukushima, and authorised releases from nuclear facilities abroad. All these have resulted in radioactivity reaching Ireland. Irish hospitals and research facilities located along the coastline also release small amounts of radioactivity into the Irish marine environment. As with sources of natural radioactivity, artificial radioactivity can give an external radiation dose and can also be transferred through the food chain to give an internal radiation dose.

Radioactivity and radiation sources are used in medicine, industry and education. This can result in radiation doses being received by some workers in all these sectors. In the medical field, patients undergoing certain procedures will also receive measurable radiation doses.



Under Statutory Instrument No. 125 of 2000 (Stationery Office, 2000) the Radiological Protection Institute of Ireland is obliged to make periodic assessments of the radiation dose received by the population. This report is an update of the 2008 population dose assessment (Colgan et al., 2008) and includes the most recent available data on all of the principal radiation pathways. This report also includes data on pathways for which few Irish data was available in 2008. Where possible, the collective dose (i.e. the sum of the radiation doses received by the entire population) is calculated for the pathway, which allows comparison of the total radiation dose received from each pathway. The average annual dose to an individual person living in Ireland is also estimated based on the most recently published figure for the total population of 4.59 million (Central Statistics Office, 2012b). The collective and average annual doses are compared to those in the 2008 population dose assessment to determine if there has been any significant change since the previous evaluation was done.

Some radiation sources involve exposure to radiation both out-of-doors and inside buildings. Estimates of radiation doses in the home have traditionally been based on an occupancy rate of 80% recommended by international organisations (ICRP, 1993) (UNSCEAR, 2000). For the sake of consistency, this 80% value is applied throughout this report.

The report also presents some additional information to explain how doses to the population are assessed; these include, for example, a radon prediction map and methodologies for screening drinking water. The report deals only with ionising radiation. Exposure to other types of radiation such as that from microwaves, mobile telephones and overhead power lines is not considered.

2 Radiation exposure pathways

2.1 Cosmic radiation

Cosmic radiation refers both to energetic, charged particles of extra-terrestrial origin that strike the earth's atmosphere (primary particles) and particles generated by the interaction of these with stable nuclides in the atmosphere (secondary particles) (UNSCEAR, 2000).

2.1.1 Cosmic radiation at sea level

As the primary particles from cosmic radiation (mainly protons) are quickly attenuated by the earth's atmosphere, at sea level the cosmic rays that irradiate humans are mainly secondary particles, such as muons, electrons and neutrons (Bouville & Lowder, 1988).

Cosmic radiation is generally categorised into a neutron component and a directly ionising component. The intensity of the directly ionising component decreases strongly with decreasing altitude: the mass of air available for attenuation of incident particles decreases with height above sea level. The intensity is also affected, to a lesser extent, by the (geomagnetic) latitude, with the intensity of the lower-energy primary cosmic ray charged particles highest at the poles and lowest at the equator. The intensity of the neutron component on the other hand does not vary significantly with altitude or latitude.

Ireland is centred at a latitude of approximately 54°N. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000), at sea level between the latitudes of 50° and 60° the directly ionising component of cosmic radiation delivers a dose rate of 32 nSv/h while that due to neutrons is 9 nSv/h. This gives a total of 41 nSv/h.

The directly ionising component of cosmic radiation can be calculated (see the insert **Cosmic radiation and altitude** on page 13) or measured. A small number of such measurements have been made in Ireland, with the values obtained ranging from 27 to 49 nSv/h, with a mean value of 35 nSv/h (Colgan, 1980). Thus, the results obtained are consistent with the values quoted in international reviews, such as UNSCEAR (2000).

Based on the recommended UNSCEAR value of 41 nSv/h, the individual annual dose outdoors arising from cosmic radiation is 360 μSv. This figure must be adjusted to take account of the shielding effect of building materials, which absorb cosmic radiation with the consequence that exposures are lower indoors compared with outdoors. UNSCEAR (2000) recommends the use of an average building shielding factor of 0.8 along with an indoor occupancy factor of 0.8. Applying these correction factors, the individual annual dose caused by to exposure to cosmic radiation at sea level in Ireland is typically 302 μSv.

2.1.2 Cosmic radiation due to air travel

As cosmic radiation increases with altitude, those who travel by air have an additional radiation dose. This section considers the dose to air passengers caused by cosmic radiation. Air crew doses are discussed in Section 2.6.1 on occupational exposures.

The Central Statistics Office publishes detailed information on the frequency of air trips abroad each year by Irish residents to the most popular destinations. This information has been used to calculate the collective dose on each route for 2012 (Central Statistics Office, 2013a and Central Statistics Office, 2013b) and the average annual individual dose has been calculated from that. As a first step, a 'typical' routing was chosen for each country or region – this was normally the capital city or, if this was considered unrepresentative, either a large city close to the centre of the country or region, or a well-known holiday destination. In the case of Spain, calculations were made both for Madrid, as a location typical of the mainland, and for Tenerife, because of the large number of holiday flights from Ireland to the Canary Islands. Dublin has been used as the departure point for all the calculations. In the case of routes that are not served by a direct flight, doses were calculated for travel via London, with the exception of Sydney (via Abu Dhabi) and Los Angeles (via New York).

A number of computer programs have been developed to estimate the doses from cosmic radiation received by air crew. The same programs can be used to calculate the doses received by passengers. For this study, all calculations have been made using EPCARD (European Package for the Calculation of Aviation Route Doses), a model approved and tested by the European Commission for use in estimating occupational radiation exposure of air crew (European Commission, 2004) (European Commission, 2012). EPCARD can be found online at http://www.helmholtz-muenchen.de/en/epcard-portal/.

The distribution of collective doses as a result of passenger airline travel by Irish residents is summarised in Table 1, and worldwide and European collective dose distributions are shown in Figure 1. While trips to Europe account for approximately 88% of all the trips taken in 2012, they account for only 58% of the collective dose. In contrast, trips to the United States account for only 6% of all flights but for 22% of the collective dose.

Flights from Ireland to Spain, including the Canary Islands, account for 38% of the collective dose on European routes. This is followed by the United Kingdom (15%) and the popular holiday destinations of Italy (9%), Portugal (8%) and France (7%). The distribution is broadly similar to that observed in the 2008 population dose assessment (Colgan et al., 2008) though with a considerable increase in the collective dose from trips to the UK and Portugal (UK routes increased by 53%, from 10.4 man Sv to 15.9 man Sv; and Portugal routes by 67% from 5.2 man Sv to 8.7 man Sv). The increase in the collective dose from flights to the UK and Portugal is due to a significant increase in the total number of journeys to each of these countries.

The overall collective dose for flights to North America was found to be 36% lower than that calculated for the 2008 assessment – this was due to a large drop in the number of return trips made by Irish residents to the US since the previous study. A similar trend was evident in the number of return trips to Africa which have also decreased resulting in a collective dose that is 25% lower than in the 2008 assessment (Colgan et al., 2008). In contrast, there has been a significant increase in the number of return trips to Asia and the Middle East as well as to Central, South and Other Americas, resulting in the collective dose increasing by 80% and 67%, respectively for flights to those regions.

Differences between the return trip doses calculated for this assessment and that of 2008 may be attributable to variations in the intensity of the cosmic ray flux for the years being assessed and, in some cases, to changes in the airline routings being operated within Europe.

The total collective dose from airline travel undertaken by Irish residents in 2012 is estimated to be approximately 187 man Sv which is very similar to that estimated for the 2008 assessment (189 man Sv). The contribution that airline travel makes to the average annual dose is arrived at by dividing the total collective dose from airline travel (187 man Sv) by the total population of 4.59 million (Central Statistics Office, 2012b), giving 41 μSv.

While the average annual dose for the whole population is 41 μSv, those people who never fly will receive no dose while those who fly regularly may receive a higher dose from cosmic radiation. The Radiation Dose Calculator application on the RPII website allows the calculation of individual doses that are caused by air travel.

Table 1. International air travel by Irish residents in 2012: collective doses by destination

Country/region	Representative destination	Number of return trips	Return trip dose (μSv)	Collective dose (man Sv)
Austria	Vienna	58,000	30	1.7
Belgium/Lux/Netherlands	Amsterdam	181,000	15	2.8
Denmark/Finland/Sweden	Stockholm	53,000	32	1.7
France	Paris	601,888	13	7.9
Germany	Berlin	164,000	26	4.2
Italy	Rome	345,000	30	10.2
Other EU[†]	Warsaw	229,000	32	7.4
Portugal	Faro	358,000	24	8.7
Spain	Madrid	703,500	22	15.6
Spain	Tenerife	703,500	36	25.2
United Kingdom[‡]	London	1,992,625	8	15.9
Other Europe	Dubrovnik	202,000	33	6.6
All Europe		5,591,513		107.8
North America Northeast[¶]	New York	266,000	102	27.2
North America Southeast[¶]	Atlanta	44,000	135	5.9
North America Midwest[¶]	Chicago	41,000	125	5.1
North America West[¶]	Los Angeles	19,000	174	3.3
All North America		370,000		41.6
Central, South and Other Americas*	Buenos Aires	69,000	89.7	6.2
Asia & Middle East	Bangkok	165,000	113.2	18.7
Africa	Nairobi	58,000	58.0	3.4
Australia, New Zealand & Oceania	Sydney	64,000	150.9	9.7
All Other		356,000		37.9
TOTAL		**6,317,513**		**187**

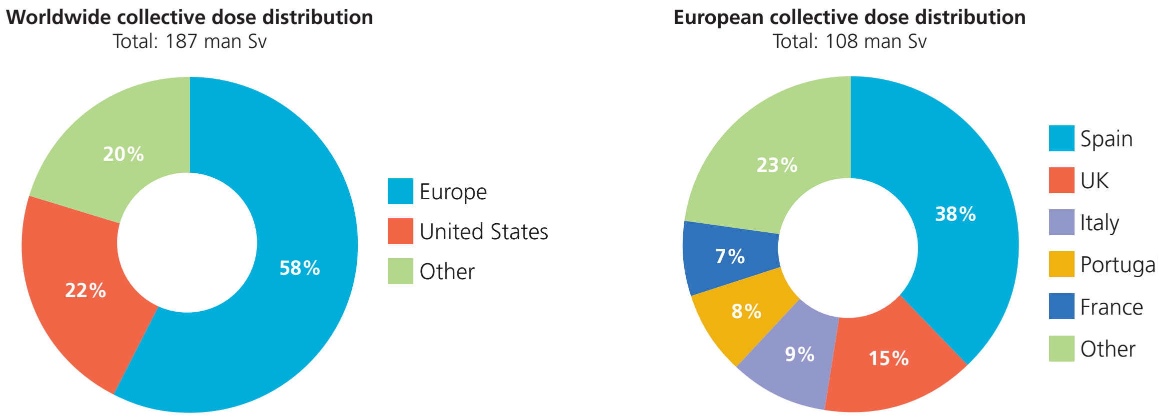
[†] *Other EU includes Bulgaria, Cyprus, Czech Republic, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia and Slovenia.*

[‡] *Flights between Ireland and Northern Ireland have not been included*

[¶] *For consistency with the 2008 report it was assumed that 72% of flights to North America were to the Northeast, 12% were to the Southeast, 11% were to the Midwest and 5% were to the West.*

* *Also includes the Caribbean region and Greenland.*

Figure 1. Distribution of collective doses received by Irish residents from airline travel (2012)



Worldwide collective dose distribution
Total: 187 man Sv

European collective dose distribution
Total: 108 man Sv

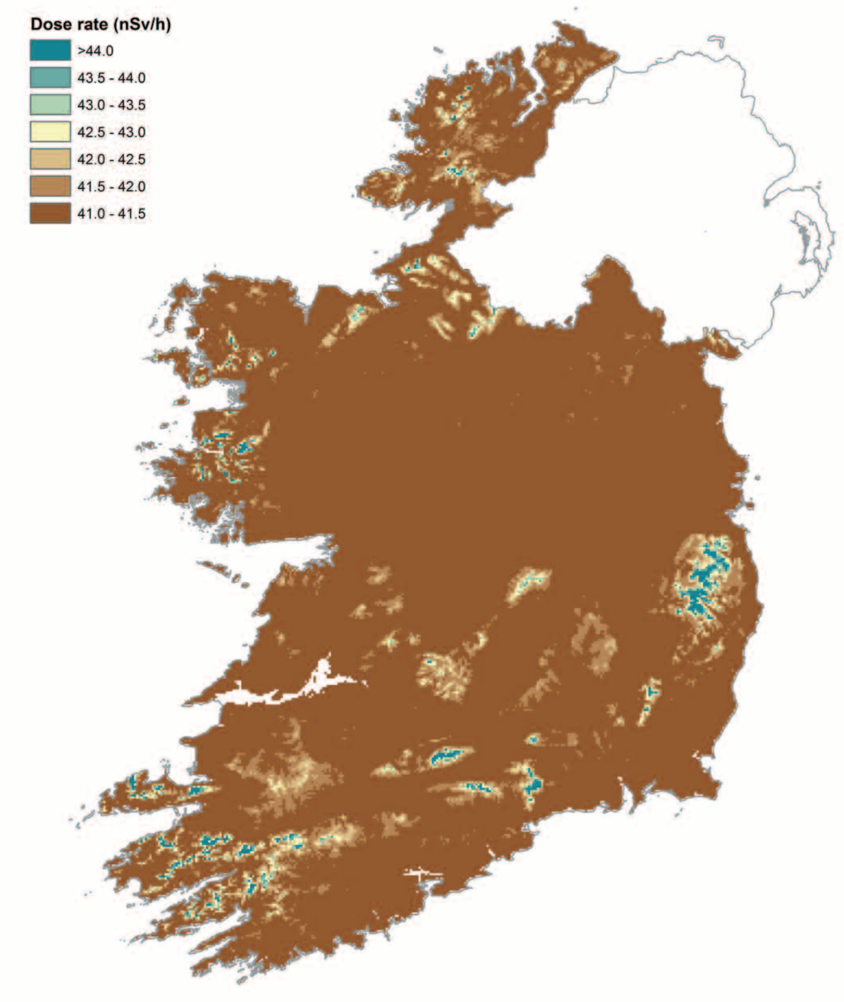
Cosmic radiation and altitude

Bouville & Lowder (1988) have derived an equation allowing the increase in cosmic radiation with altitude to be calculated as follows:

$$E_z = E_0\,[0.21\ \mathrm{exp}(-1.649\ z) + 0.79\ \mathrm{exp}(0.4528\ z)]$$

Where: E_z is the dose rate at height z above sea level;
E_0 is the dose rate at sea level; and
z is the height above sea level (in km).

This equation can be applied to a map of height above sea level – a Digital Elevation Model (DEM) – in order to calculate the variation in cosmic radiation with location. A DEM for over 80% of the Earth's land surface, including Ireland, has been acquired by the Shuttle Radar Topography Mission (NASA, 2009) (USGS, 2011). The results of applying this formula to the DEM for Ireland using map algebra in a Geographic Information System are shown in the map below.



Map of Ireland showing variation in dose rate from cosmic radiation at ground level

This map demonstrates the extremely low variation in the dose rate from cosmic radiation at ground level across Ireland. The highest town in Ireland is Rathdrum in County Wicklow (270 metres above sea level). Applying the equation above, the value for E_z is 1.03 E_0 i.e. the dose due to cosmic radiation in Rathdrum is 3% higher than along the Irish coastline. At the top of Carrauntoohill, the highest mountain in Ireland (1039 metres), the dose from cosmic radiation is higher by 30% than that at sea level.

2.2 Radioactivity in the environment

2.2.1 Natural radioactivity in the ground

Naturally occurring radioactive elements have been present in rocks and soils since the formation of the earth. The amount of external exposure from natural radionuclides in the ground varies with location and is mainly due to differences in the local geology and/or soil type.

Outdoor gamma radiation levels in Ireland have been surveyed by a number of researchers. The contributions from cosmic radiation and from instrument electronic noise were eliminated from the results of each survey in order to provide extensive datasets of radiation levels due solely to radioactivity in the ground, both of natural and artificial origin. Further details on the surveys that were carried out can be found in Appendix 1.

As in the 2008 population dose report, the best estimate for an average external gamma dose rate used here is found by weighting the two national surveys by Colgan (1980) and by Marsh (1991) in accordance with the number of measurements in each. This results in an average external gamma dose rate of 0.037 µGy/h. Following UNSCEAR's recommendation that a factor of 0.7 be used to convert absorbed gamma dose rate in air (in µGy/h) to units of radiation dose (in µSv/h) (UNSCEAR, 2000), we arrive at an average radiation dose of 0.026 µSv/h.

Account has to be taken of the fact that gamma radiation is normally higher indoors than outdoors. This is because while the materials from which buildings are made tend to absorb the ambient terrestrial gamma radiation (and so reduce the dose received indoors), this is counterbalanced by the additional contribution from the radioactivity contained in the building materials themselves.

The concentrations of radium-226 (Ra-226), thorium-232 (Th-232) and potassium-40 (K-40) in a range of building materials commonly used in Ireland have been previously evaluated (Lee et al., 2004). The final results of the study were published in 2006 (Doorly, 2006) and have been summarised in the 2008 population dose report (Colgan et al., 2008). The authors concluded that the normal use of these materials would not result in radiation doses in excess of 1000 µSv per year, and that in the majority of cases the doses would be less than 300 µSv per year to occupants.

McAulay and Colgan assessed the effect of building materials on gamma dose rate by performing measurements inside and outside 119 Irish houses of different ages and construction materials (McAulay & Colgan, 1984). Measurements were made in the open air outside each house and in three inside rooms. Surveys were carried out in two separate regions – one of known low background gamma radiation and the other with relatively high natural background radioactivity. After the elimination of the cosmic radiation component, the average gamma dose rates measured were 0.055 µGy/h indoors and 0.040 µGy/h outdoors. Therefore, in Ireland on the basis of this study, terrestrial gamma dose rates arising from radioactivity in the soil are on average higher indoors than outdoors by a factor of 1.38. By comparison, the worldwide average terrestrial gamma dose rate indoors is 1.4 times higher than outdoors, with regional values ranging from 0.8 to 2.0 (UNSCEAR, 1993).

Using an indoor occupancy factor of 0.8 (and therefore an outdoor occupancy factor of 0.2) and assuming a 38% higher dose rate indoors compared with outdoors, the average annual individual dose, D, in Ireland due to terrestrial gamma radiation is:

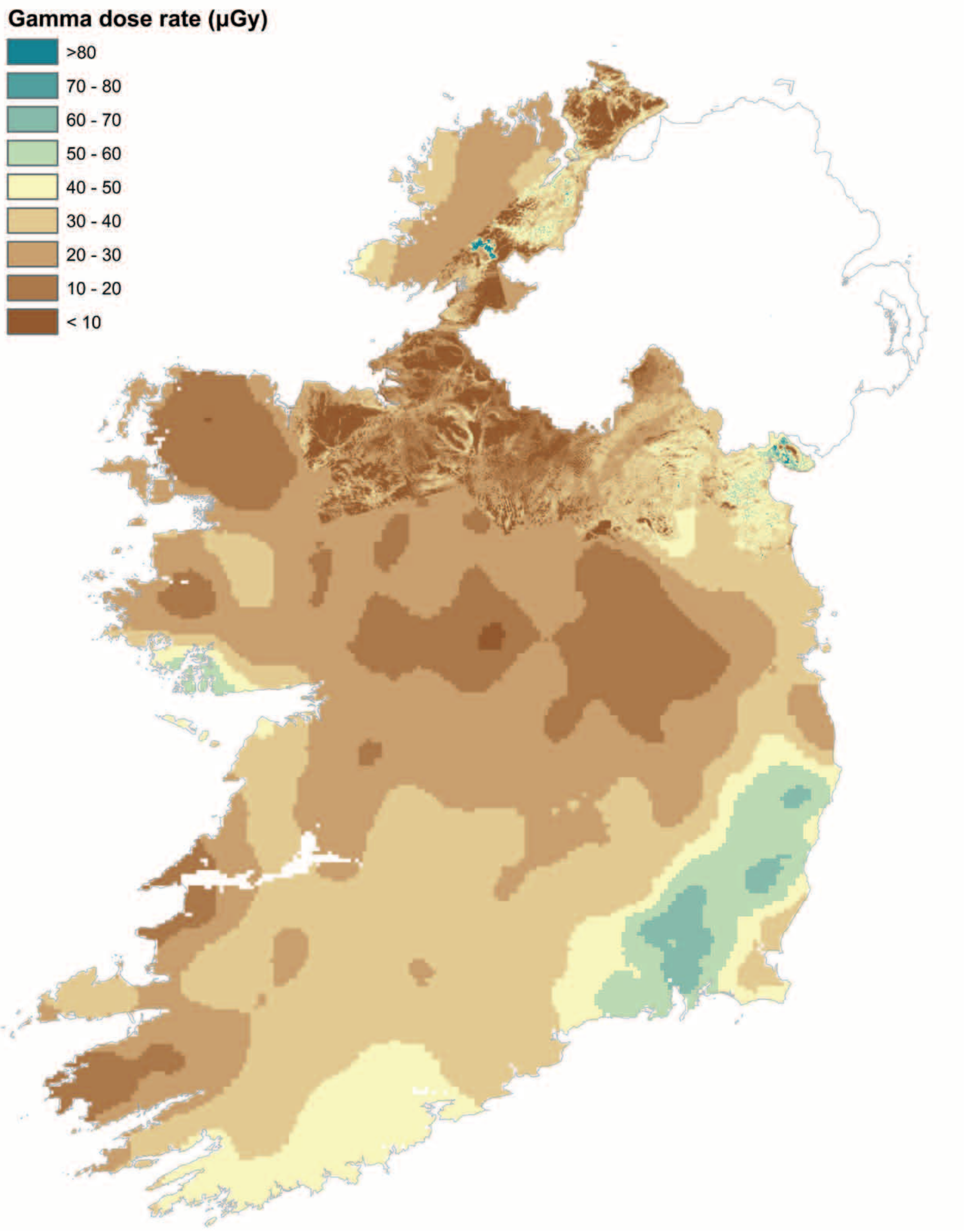
$D = 0.026\ \mu Sv/hr \times 24\ hrs \times 365\ days \times [(0.8 \times 1.38) + 0.2]$

This gives a value of 297 µSv.

The work reported by Colgan and by McAulay & Colgan was carried out before the 1986 Chernobyl accident. For that reason, the figures quoted above do not take into account the radioactivity deposited in Ireland following that accident. On the other hand, artificial radioactivity deposited as a result of the atmospheric nuclear weapons tests carried out between 1954 and 1963 does contribute to the measured gamma dose rates. This contribution is estimated to be 2 µSv annually (see Section 2.2.2). Therefore the representative annual dose due to natural radioactivity present in the ground (terrestrial gamma radiation) has been taken as 295 µSv, with a typical range of 50 to 1200 µSv.

In order to examine the spatial variation, the measurements of gamma radiation from the ground from these studies[1] were mapped – see Appendix 1. Point measurements (and values interpolated from these) were integrated into one comprehensive dataset. The high resolution results from the TELLUS Border geophysics survey[2] (TELLUS Border, 2013) were then overlaid on this dataset. The resulting map is shown in Figure 2. The highest values are associated with the underlying granite geology found in small areas of Donegal and Galway, in parts of counties Wicklow, Wexford, Carlow, Kilkenny and Waterford, and in the Cooley Peninsula in Louth.

Figure 2. Spatial variation in gamma radiation from the ground in Ireland



---

[1] With the exception of the first national survey by Colgan, which did not include latitude and longitude co-ordinates

[2] TELLUS Border is a regional mapping project in which geo-environmental data on soils, water and rocks has been collected across six counties – Donegal, Sligo, Leitrim, Cavan, Monaghan and Louth – in the border region between the Republic of Ireland and Northern Ireland, as part of a cross-border initiative between the Geological Survey of Northern Ireland (GSNI), the Geological Survey of Ireland (GSI), Queen's University Belfast and Dundalk Institute of Technology. This project (mid 2011 – end 2012) is a follow-up from the first TELLUS survey which was completed in Northern Ireland in 2007. The TELLUS Border project included an airborne geophysical survey to study the physical properties of the soils and rocks, including electromagnetic radiation and gamma radiation from the radionuclides contained in the ground. The data resulting from the project can be downloaded from http://www.tellusborder.eu/.

2.2.2 Artificial radioactivity in soils

In addition to the dose from natural radioactivity, there is an additional contribution from artificial radioactivity present in Irish soils. Artificial radionuclides are present mainly as a result of deposition following the Chernobyl accident and to a lesser extent from nuclear weapons testing in the 1950s and 1960s. The most significant artificial radionuclide from the point of view of radiation dose is caesium-137 (Cs-137) – this is due to its relatively long half-life (approximately 30 years).

The distribution of artificial radioactivity in Irish soils has been studied by Ryan (1991); the Cs-137 deposition data from both nuclear weapons testing and from the Chernobyl accident are summarised in Table 2 below.

Table 2. Caesium-137 deposition in Irish soils

Source	**Mean deposition (Bq/m²)**	**Range (Bq/m²)**
Nuclear weapons testing	3717 ± 1191	1509–6592
Chernobyl	4126 ± 2354	949–9212

Because rainfall is the most important mechanism by which airborne radioactivity is deposited on the ground, there is a strong relationship between mean annual rainfall and deposition from nuclear weapons testing.

For converting Cs-137 deposition to dose, UNSCEAR recommends values of 1.0 nSv per Bq/m^2 for periods of 21–50 years and 0.4 nSv per Bq/m^2 for periods of 51–100 years after initial deposition (UNSCEAR, 2000). The reason the conversion value reduces with time is that the Cs-137 migrates down the soil profile, thereby resulting in a lower radiation dose caused by the shielding effect of the soil. The amount of Cs-137 in the soil will also be reduced every year owing to its natural radioactive decay.

Applying the UNSCEAR conversion factor of 0.4 nSv per Bq/m^2 to the deposition data relating to nuclear weapons testing, the current average annual external dose in Ireland is 2 μSv. For the Cs-137 deposited following the Chernobyl accident, the conversion factor of 1.0 nSv per Bq/m^2 gives an estimated current annual average external dose in Ireland of 4 μSv. Shielding by building materials will result in a slightly lower dose indoors than outdoors but this may be offset by the presence in the building materials themselves of artificial radioactivity, such as Cs-137 from nuclear weapons testing. Thus the total annual dose due to artificial radioactivity in Irish soils is 6 μSv.

2.2.3 Artificial radioactivity in air

The RPII routinely monitors airborne radioactivity through its network of online and offline air samplers. Apart from the trace amounts of radioactivity consistent with the Fukushima nuclear accident, which were detected between March and May 2011, no activity above normal levels was detected in outdoor air in recent years (McGinnity et al., 2012a).

For 2012, the average annual dose from inhalation of Cs-137 was estimated at 2.0×10^{-4} μSv. Krypton-85 concentrations in air were also monitored in the past by RPII, in order to assess the impact of discharges to air from nuclear fuel reprocessing abroad, and the average annual dose was estimated at 0.01 μSv (Ryan et al., 2007). Thus the total average annual dose from artificial radioactivity in air is approximately 0.01 μSv.

2.3 Radon in air

Radon-222, commonly referred to as radon, is a naturally occurring radioactive gas constantly formed in the soil by the radioactive decay of radium-226 (Ra-226), a component of the uranium-238 decay series. You cannot smell it, see it or taste it and it can only be measured with special equipment. Outdoors, radon quickly dilutes to harmless levels, but when it enters a house or other building, it can sometimes accumulate to unacceptably high levels. The degree to which radon seeps indoors from these rocks and soil depends on a number of factors, including the type of underlying rocks and soil, the porosity of the soil, the composition and condition of the foundation materials, and the ventilation rate in the rooms. Small cracks in the floors or foundation of a building or gaps around pipes or cables may allow high levels of radon to enter a building.

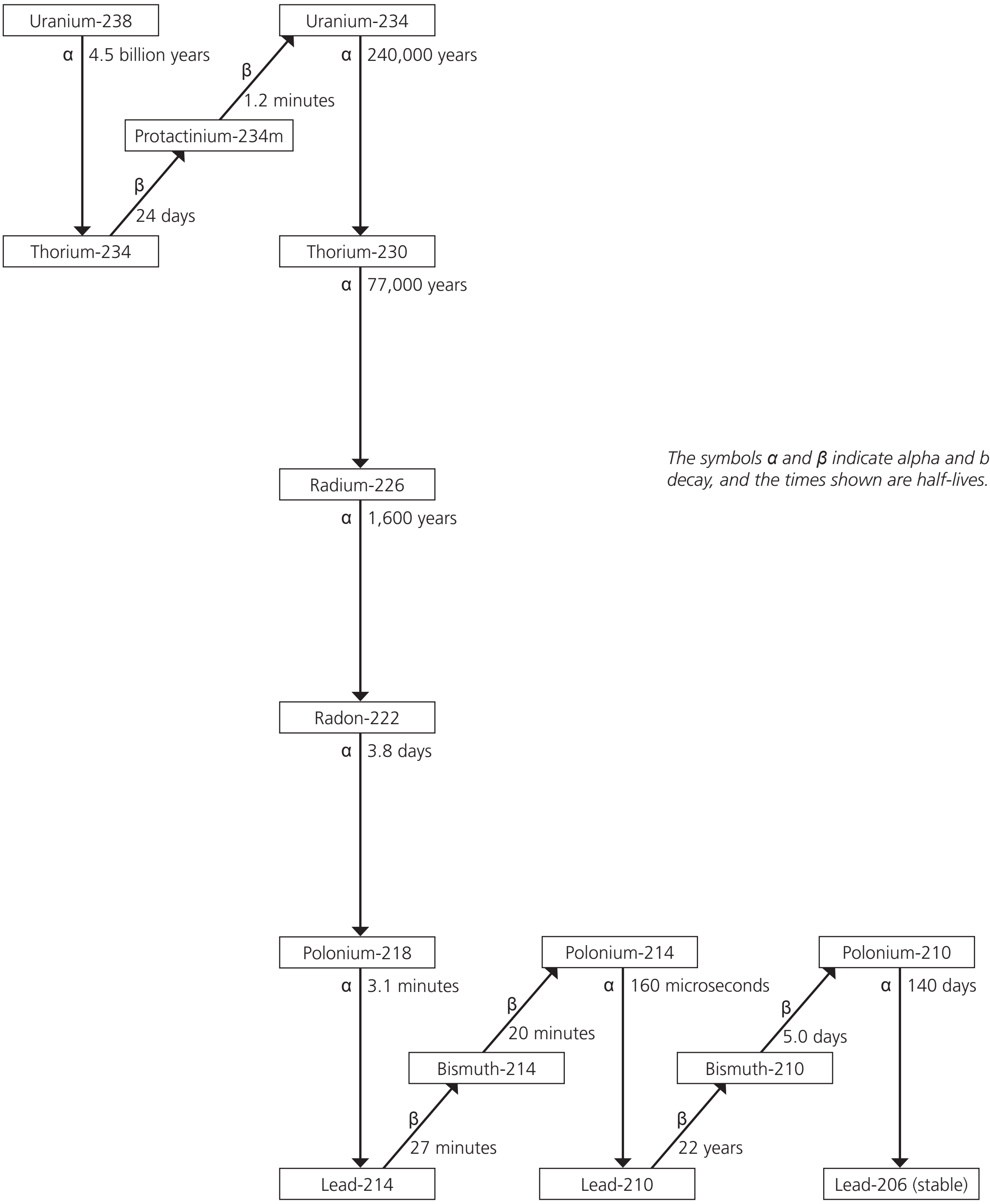
A research project carried out by RPII and Trinity College Dublin during 2011–2012 measured the concentration of radon in outdoor air at a number of locations throughout Ireland. The average concentration measured was 5.6 Bq/m^3 (Gunning et al., [in press]), which tallies closely with the previous estimate of 6 Bq/m^3 which was based on the extrapolation of data analysed during the National Radon Survey (Fennell et al., 2002), rather than on direct measurements.

The concentration of radon in indoor air is normally higher and more variable than that found outdoors and depends on several factors such as the concentration present in the underlying soil, the existence of entry routes in the foundations and the substructure of the building, and on the prevailing weather conditions. In addition, the pressure differential between outdoors and indoors leads to a pressure-driven flow of radon into buildings. Considering the shorter time that people spend outdoors and the low concentrations of radon, the radiation dose received from radon outdoors is considered to be negligible relative to that received indoors.

As mentioned in Section 2.2.1, Ra-226 is also present in most building materials. This is an additional source of radon in indoor air. However, in situations where high indoor radon concentrations are present, it is normally the soil rather than the building materials that is the primary source (ICRP, 1993). There can also be a small additional contribution to the radon concentration in air from domestic water supplies. Relatively high radon concentrations have previously been identified in a small number of private Irish groundwater supplies (Ryan et al., 2003). However, a recent study of radon in groundwater has shown that none of the samples measured exceeded the recommended maximum (500 Bq/l) for public drinking water supplies (Dowdall et al., 2013). Surface water supplies normally contain little or no radon because agitation of the water releases any radon present into the air. Overall, radon dissolved in drinking water generally makes a small contribution to the indoor radon concentrations relative to that derived from the soil beneath the building.

What is referred to as ‘radon’ is in fact a mixture of radon gas and associated decay products (see Figure 3). When inhaled, radon gas may decay within the body, thereby giving rise directly to a radiation dose. However, of much more significance from the point of view of dose are the radon decay products, in particular those that emit alpha radiation. These daughter products can attach themselves to microscopic particles in the air and, when inhaled, can be deposited in the lungs and deliver high radiation doses to a small volume of lung tissue. It has been estimated that only 2% of the dose from radon is actually due to radon gas, with the remainder attributable to the inhalation of its decay products (Peterman & Perkins, 1988).

Figure 3. Uranium-238 decay series



The symbols α and β indicate alpha and beta decay, and the times shown are half-lives.

2.3.1 The National Radon Survey

Between 1992 and 1999 the RPII carried out the National Radon Survey (NRS), a comprehensive survey of radon concentrations in Irish houses (Fennell et al., 2002). The NRS measured radon in houses on a geographical basis using the Irish 10 km x 10 km national grid as the basic geographical unit. The principal objective of the survey was to quantify the scale of the radon problem in Ireland and to identify areas where there was a higher risk of finding high indoor radon concentrations.

Radon measurements were completed in 11,319 houses, representing a sampling frequency of 1 in 116 of the national housing stock at the time. All measurements were made for a continuous 12-month period in two rooms of each house surveyed, normally the main living area and a bedroom. The two measurement results from each house were averaged. The data generated by the NRS is summarised on a county basis in Table 3.

Table 3. Results of the national survey of radon in Irish houses

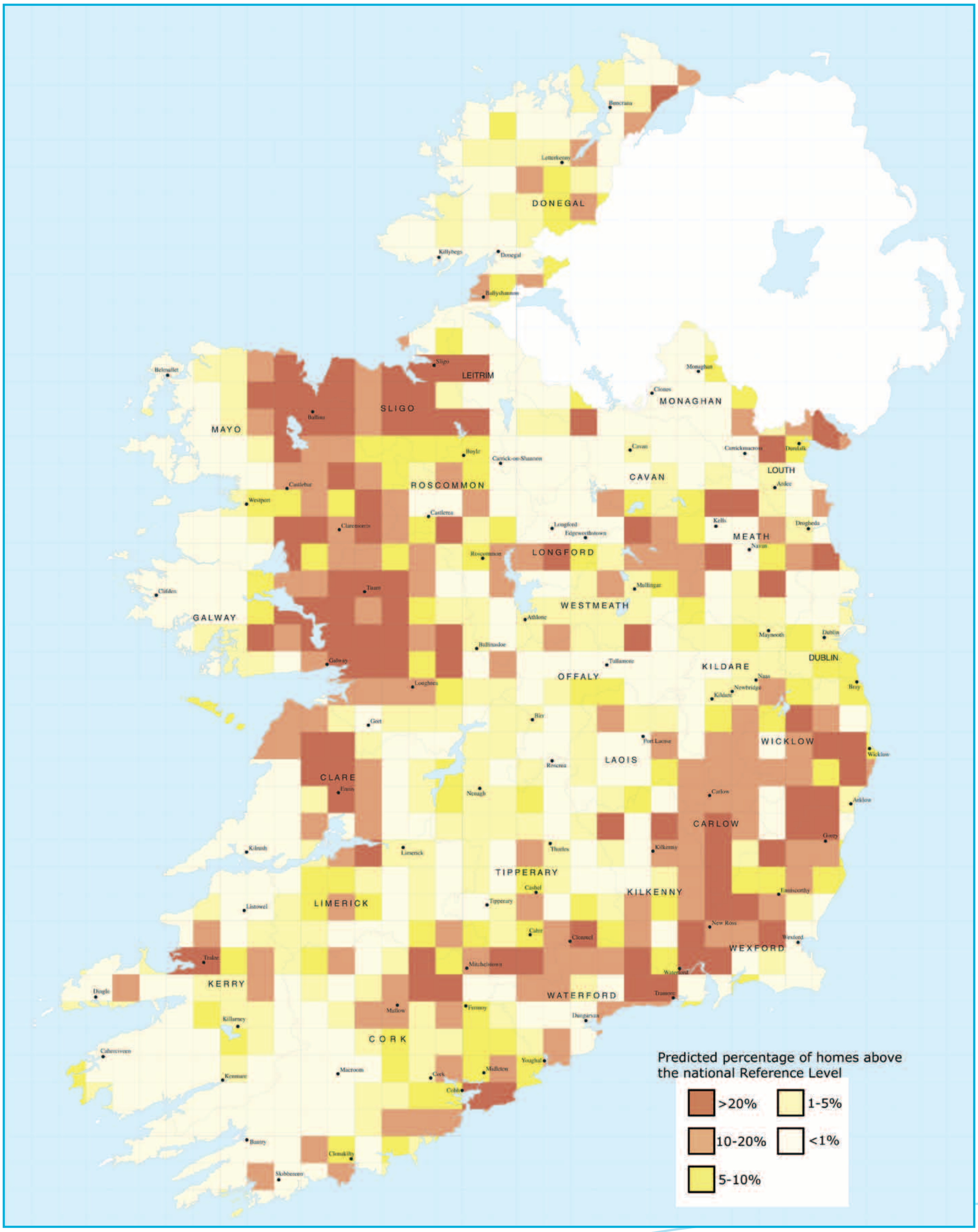
County measured	Number of houses	Number of houses > 200 Bq/m^3	Radon concentration (Bq/m^3)	
			Average	Maximum
Carlow	194	30 (15%)	123	1,562
Cavan	180	5 (3%)	67	780
Clare	742	66 (9%)	88	1,489
Cork	1,211	71 (6%)	76	1,502
Donegal	487	18 (4%)	69	512
Dublin	155	6 (4%)	73	260
Galway	1,213	181 (15%)	112	1,881
Kerry	932	52 (6%)	70	1,924
Kildare	480	29 (6%)	90	1,114
Kilkenny	181	16 (9%)	100	717
Laois	334	17 (5%)	83	565
Leitrim	145	6 (5%)	60	433
Limerick	524	41 (8%)	77	1,102
Longford	132	8 (6%)	75	450
Louth	124	14 (11%)	112	751
Mayo	1,184	152 (13%)	100	1,214
Meath	233	18 (8%)	102	671
Monaghan	120	4 (3%)	68	365
Offaly	286	7 (2%)	68	495
Roscommon	235	17 (7%)	91	1,387
Sligo	270	54 (20%)	145	969
Tipperary	852	63 (7%)	79	1,318
Waterford	162	20 (12%)	119	1,359
Westmeath	289	20 (7%)	91	699
Wexford	469	54 (12%)	99	1,124
Wicklow	185	24 (13%)	131	1,032

Radon concentrations in the measured houses ranged from 10 to 1,924 Bq/m^3. The average indoor radon concentration was 89 Bq/m^3, with a population-weighted average of 91 Bq/m^3. Using the current population figure of 4.59 million and an indoor occupancy factor of 0.8, this corresponds to a collective dose of 10,210 man Sv. This does not take account of the time that people spend in their work buildings. The collective dose from radon in workplaces is estimated to be 1,052 man Sv. The collective dose in homes is therefore approximately 9,158 (10,210 – 1,052) man Sv. The corresponding average annual dose is obtained by dividing by the total population, giving a value of 1,995 μSv. For more details, see **Radon in workplaces** on page 34.

The results of the NRS were used to produce a map which predicts high radon areas across the country. National grid squares classified as high radon areas (squares where 10% or more of the houses are predicted to have an annual average radon concentration above the national reference level of 200 Bq/m^3) have been identified in every county as displayed in Figure 4.

An interactive version of the map in Figure 4 is available on the RPII website at www.rpii.ie/radon-map.aspx. Users can input their address and see the predicted level of radon risk in their area.

Figure 4. Map of Ireland showing predicted high radon areas.



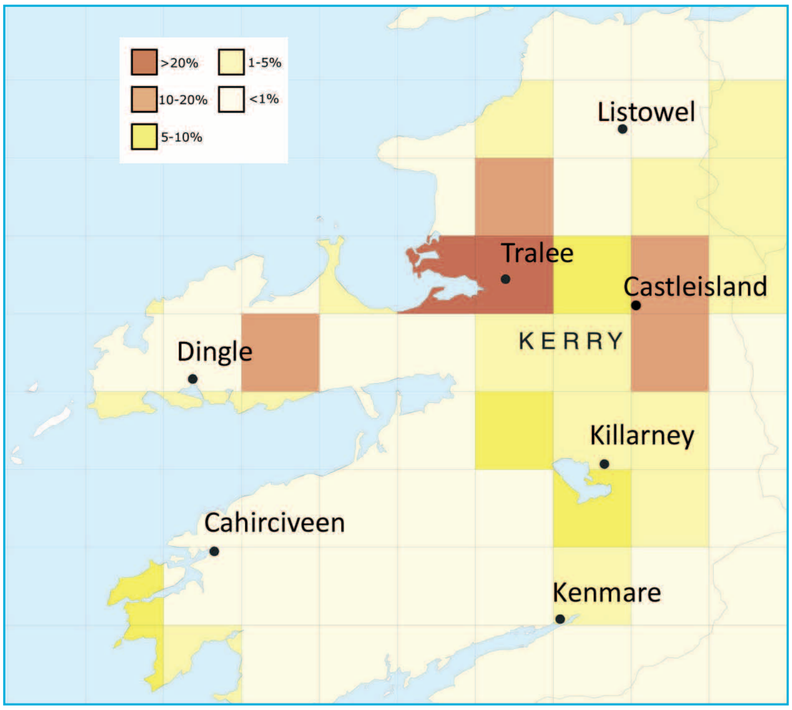
Apart from the measurements made for the NRS, the RPII has also completed measurements in over 44,000 additional houses. Many of these measurements were for a period of three months and cannot be compared directly with NRS measurements which were made for a continuous period of one year. In addition, for the majority of these measurements there is no information on the exact location of the house. For all these reasons, these additional measurements have not been included in the calculation of the average radon concentration in Irish homes. They are, however, included in the summary of all the radon measurements available to the RPII up to 31 December 2013 in Appendix 2 (Table A.1). Table A.2 of the Appendix also shows that, of the 50 homes with the highest indoor radon concentrations, 20 were in Castleisland or Tralee in County Kerry.

2.3.2 Study of variation in radon concentrations in North Kerry

The National Radon Survey identified parts of County Kerry as high radon areas (Figure 5). In July 2003, the RPII found a house in the Castleisland area with an estimated average radon concentration of 49,000 Bq/m^3 (Organo et al., 2004). This corresponds to an annual radiation dose to the occupants of 1.2 Sv (or 1,200,000 μSv) and to a daily dose of about 3,400 μSv. Subsequent radon measurements in and around the town of Castleisland identified other homes with high radon concentrations. In 2011, a second house in Castleisland (about 4 km from the first house) was found to have an average radon concentration of 37,000 Bq/m^3.

To date, radon measurements have been carried out in 1,947 homes with postal addresses in Castleisland or Tralee. The results of these measurements are summarised in Table 4. In many cases, the postal address encompasses an area that extends well beyond the immediate town or village. This is particularly the case for Tralee, where the postal district covers well over 1,000 km^2. This area contains a mix of high radon areas and low radon areas.

Figure 5. Map of Kerry showing predicted High Radon Areas.



An analysis of the data for these 1,947 homes gives an average radon concentration of 196 Bq/m^3, more than twice the national average of 89 Bq/m^3. This is likely to be related to the high density of karst features in the limestone geology. It is also likely that there are other areas of the country with similar geology where homes may have exceptionally high radon concentrations. The RPII is involved in ongoing work with the Geological Survey of Ireland to identify such areas.

Table 4. Summary of RPII radon measurements carried out in houses in Castleisland and Tralee

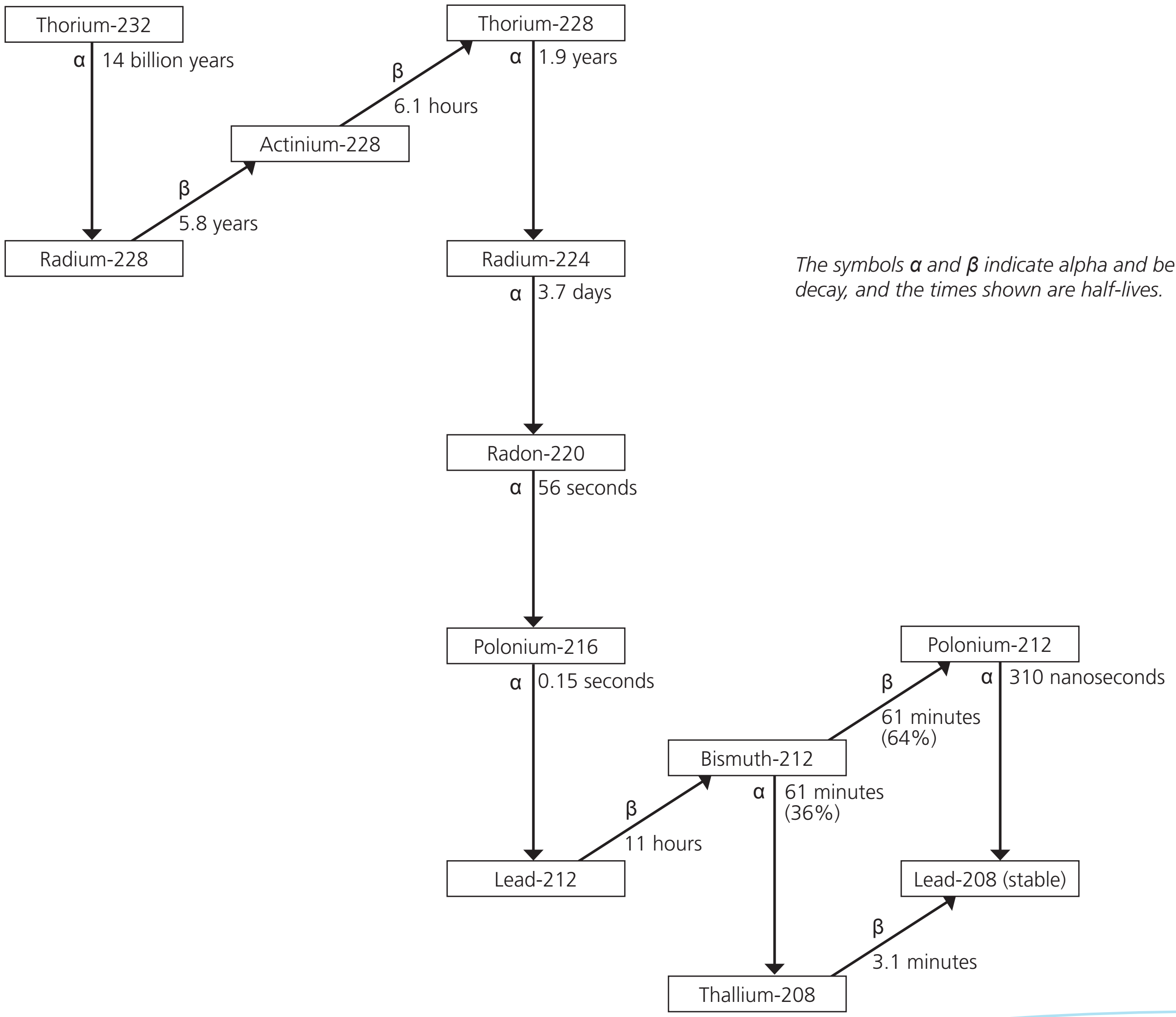
	Number of results	Average (Bq/m^3)	No. above 200 Bq/m^3	No. above 1,000 Bq/m^3	Highest (Bq/m^3)
Castleisland	593	193	80 (13%)	12 (2.0%)	4,310
Tralee	1,353	197	366 (27%)	76 (5.6%)	18,850
Total	**1,946**	**196**	**446 (23%)**	**88 (4.5%)**	

Note: The data in this table does not include the two homes that had extremely high measurements – 49,000 Bq/m^3 in one case and 37,000 Bq/m^3 in the other.

2.4 Thoron in indoor air

Thoron (radon-220) is a naturally occurring radioactive gas that is produced by the radioactive decay of radium-224 (Ra-224), a component of the thorium decay series – see Figure 6. Thoron has a half-life of 56 seconds and can only migrate a short distance before it decays. For this reason, building materials rather than the soil beneath the house are usually the principal source of thoron in indoor air. The concentration of thoron gas indoors varies significantly with the distance from walls and floors while thoron decay products are uniformly distributed within the room.

Figure 6 Thorium-232 decay series



The symbols α and β indicate alpha and beta decay, and the times shown are half-lives.

As with radon, it is the thoron decay products rather than the gas itself that constitute the main source of radiation dose. Thoron decay products can also be inhaled and deposited in the respiratory tract where they give rise to a radiation dose. No direct studies have been carried out on the health effects of human exposure to thoron.

Except in extreme circumstances, the concentrations of thoron in indoor air are much lower than those of radon. Examples of extreme circumstances are the use of building materials with high concentrations of thorium or, as is the case in some countries, living in houses where the floors and/or walls are made of earth.

Thoron may decay almost completely in indoor air while significant concentrations of its decay products remain. Unlike the situation with radon, direct measurements of thoron gas are not a reliable indicator of the presence of its decay products, and therefore do not provide an estimate of the dose. Thoron daughters are difficult to measure and Ireland is one of very few countries to have carried out surveys to assess the radiation dose from thoron and its decay products.

2.4.1 Thoron in Ireland

The naturally occurring radioactive gas thoron and its decay products were first measured in Irish homes in a pilot study of 40 houses in 2005 (Ní Choncubhair, 2007). The average concentration of thoron decay products reported in units of equilibrium equivalent thoron concentrations (EETC) was 1 Bq/m^3. This value was used in the 2008 population dose report along with a dose conversion factor of 40 nSv per (Bq/m^3.h) (UNSCEAR, 2000) to estimate an average annual dose of 280 µSv (Colgan et al., 2008).

A more recent study measured thoron and its decay products in 205 homes in Ireland between 2007 and 2009 in a collaborative project between RPII, University College Dublin (UCD) and the National Institute of Radiological Sciences (NIRS) in Japan (McLaughlin et al., 2011). This study found the average concentration of thoron decay products to be 0.47 Bq/m^3, which is approximately half the average value reported in the pilot study.

In addition, new estimates for dose coefficients for thoron and its decay products have been calculated in recent years (Kendall & Phipps, 2007) (Ishikawa et al., 2007) using ICRP models such as the Human Respiratory Tract Model for Radiological Protection (ICRP, 1994). Assuming a typical breathing rate of 0.78 m^3/h and an indoor occupancy factor of 0.8, the estimated average annual doses to an adult breathing air containing thoron decay products at a concentration of 1 Bq/m^3 (EETC) calculated using the Kendall & Phipps and the Ishikawa et al. models are close at approximately 700 µSv and 800 µSv, respectively. Therefore, it is estimated that exposure to air containing thoron decay products at a concentration of 1 Bq/m^3 (EETC) gives rise to an average annual dose of approximately 750 µSv.

Taking the average concentration of thoron decay products of 0.47 Bq/m^3 (McLaughlin et al., 2011) we can assume an average annual dose of 350 µSv, which is higher than the 280 µSv reported in the 2008 dose assessment report (Colgan et al., 2008).

2.5 Radioactivity in food and drinking water

As already discussed radioactivity has been around since the earth was formed and it exists naturally in the atmosphere, soil, seas and rivers. It is also created by human activity during energy production and military operations and is dispersed in the environment. Inevitably some of this gets into the food and water we ingest.

The level of ingestion of radioactivity is dependent on the concentration of radionuclides in the food and water being ingested and on consumption rates.

Concentrations of naturally occurring radionuclides in foods vary because of the differing levels of naturally occurring radioactivity in the environment, climate and agricultural conditions that exist in any given area (UNSCEAR 2000). Plants and animals routinely take in radioactivity because of the similar chemical properties of radionuclides and essential nutrients. The amount of radioactivity taken up by plants and animals is dependent upon the radioactivity of the source media – for example, the soil or water, the nutrients present, and other conditions at the location of the plants or animals. The ingestion by humans of plant and animal products that contain radionuclides contributes to their overall dose.

Similarly, the levels of man-made radioactivity in foodstuffs arise from the levels of this radioactivity in any given environment. The levels of man-made radioactivity in the environment are dependent on discharges from nuclear facilities, on nuclear accidents and nuclear weapons tests.

Naturally occurring radioactivity in drinking water arises from radionuclides in the natural decay series, uranium-238 and thorium-232. When a source of drinking water comes in contact with rocks bearing these naturally occurring radionuclides, radioactivity may accumulate in the water and enter the water cycle (Dowdall et al., 2013).

Monitoring programmes for radionuclides in food and water are carried out annually by RPII and results are published in its monitoring reports – see, for example, McGinnity et al., (2012a). In addition RPII has carried out a study of natural radioactivity in food, the results of which are presented below.

2.5.1 Natural radioactivity in food

Carbon-14

Cosmic radiation (see Section 2.1) produces neutrons that interact with nitrogen in the upper atmosphere to produce carbon-14 at a fairly constant rate (Lehto & Hou, 2011). This carbon-14 is distributed throughout the environment worldwide and, because carbon is a key component of all living material, carbon-14 is present in plants and animals and also throughout the food chain.

Foods high in fatty acids normally contain a large amount of carbon, and therefore also carbon-14 (C-14). Examples of such foods are milk and milk products, oils, almonds, walnuts, avocados and fish such as mackerel, trout and salmon.

In order to provide a representative figure for the average level of C-14 and other key radionuclides in the Irish diet, RPII conducted an analysis of complete meals sourced over a five-day period from a large university restaurant in Dublin, and found that they contained an average C-14 concentration of 31 Bq/kg. The typical Irish diet consists of 440 kg of foodstuffs and 560 kg of water annually (IUNA, 2011). A dose conversion factor of 5.8 x 10^{-10} Sv/Bq (ICRP, 1995) was applied to the food component of the diet (drinking water was assumed to have a zero carbon-14 content), yielding an average annual dose due to carbon-14 in the Irish diet of 8 μSv, which is consistent with the range 8–12 μSv estimated by Colgan (2008).

Alongside its naturally produced component, C-14 is also present in the environment as a result of the atmospheric nuclear weapons tests that took place in the 1950s and 1960s. UNSCEAR has estimated that the worldwide average annual dose from carbon-14 in the diet from nuclear weapons testing is 1.7 μSv (UNSCEAR, 2000). Artificial C-14 is also produced by various nuclear fuel cycle activities, including the routine operation of nuclear power plants, fuel reprocessing activities and the decommissioning of old or disused nuclear facilities. UNSCEAR quotes the worldwide annual collective dose from C-14 released as part of nuclear fuel cycle activities as being of the order of 200 man Sv (UNSCEAR, 2000). Assuming a worldwide population of 7 x 10^9 persons (Worldometers, 2013), the average annual dose from ingestion of C-14 from this pathway is approximately 0.03 μSv, which added to the 1.7 μSv from weapons testing, gives a rounded total average annual dose from ingestion of artificial C-14 of 2 μSv.

As the total average annual dose due to C-14 in the Irish diet is 8 μSv, and the average annual dose from ingestion of artificial C-14 is 2 μSv, it can therefore be concluded that approximately 6 μSv (75% of the carbon-14 in the Irish diet) is of natural origin.

Potassium-40

Potassium is a key element involved in regulating body functions such as digestion, heart rate and the water content of cells. For that reason, the potassium content of the body is held constant by metabolic processes, although some variability between men and women as well as with age has been observed. Natural potassium is made of 0.012% by weight of potassium- 40 (K-40) which is naturally radioactive. The K-40 content of the body is therefore also constant. UNSCEAR (2000) quotes an average annual dose of 170 μSv from this exposure pathway.

Potassium-40 in food

Typical concentrations of potassium-40 in food

Foodstuff	Typical concentration (Bq/kg)
Lettuce	20–40
Milk (low fat)	40–60
Yoghurt	40–60
Tomatoes (fresh)	60–80
Orange juice	60–80
Melon (fresh)	60–90
Bananas (fresh)	80–100
Chicken	80–100
Sardines	100–150
Spinach (cooked)	100–150
Muesli	100–150
Potatoes (raw)	140–180
Gammon	140–180
Cod	140–170
Beef	150–200
Raisins	200–250
Wheatgerm	300–350
Seaweed (dried)	1,000–1,500

Potassium levels in the body are controlled by metabolic processes. This means that, regardless of the amount of potassium consumed with the diet, the dose to an individual from potassium-40 will be relatively constant. There will also be little variability between individuals in terms of the dose received.

Rubidium-87

Rubidium is the 16th most abundant element in the earth's crust and is made of two isotopes: rubidium-85 (Rb-85) and rubidium-87 (Rb-87). Only rubidium-87 is radioactive. It represents just under 30% of the total abundance of the element.

Meats, dairy products and certain nuts tend to have the highest natural content of rubidium. The typical human dietary intake of rubidium is 4 to 5 milligrams per day while humans contain approximately 300 mg of rubidium in total, distributed between various tissues.

There are no data currently available on the rubidium content of the typical Irish diet. Watson (2005) quotes an average annual dose from ingestion of Rb-87 in the UK of 2 µSv. In the absence of national data on rubidium exposure in Ireland, the UK value was used as it is likely to approximate to the dose in Ireland.

Radium-228 (from thorium-232)

Thorium-232 (Th-232) is found in the earth's crust and is, on average, three times more abundant than uranium and as abundant as lead. The highest thorium concentrations are usually found in igneous rocks such as granites, while the lowest concentrations are found in carbonate rocks such as limestones. The Th-232 decay chain ends with stable lead-208. Most of the dose attributed to Th-232 is produced by one of its decay products, radium-228 (Ra-228).

There is currently no data available on the thorium content of the Irish diet. Watson (2005) quotes an average annual dose from the ingestion of thorium in the United Kingdom of 7 µSv. In the absence of Irish national data, the UK value has been used in this report and assumed to be representative of the dose received by the Irish population.

Radium-226 (from uranium-238)

People may ingest radium that is naturally contained in food and/or water, and may also inhale it in dust particles suspended in the air. Radium can also be produced in the body from its parent radionuclide (uranium) that has been inhaled or swallowed, but this is not normally a significant source.

Calculating doses from the consumption of foodstuffs

Three pieces of information are required to assess the doses received from the consumption of foodstuffs: the radioactivity content (or concentration) in the food consumed, the amount of food consumed, and the dose received per unit intake of the radionuclides present in the food.

Different radionuclides are found in varying amounts in different foods. This is due to several factors, one of which is the chemical properties of the radionuclide in question. For example, strontium-90 (Sr-90) concentrates in milk because of its chemical similarity to calcium, one of the main constituent elements found in milk. Several radionuclides may be present in any given food and specialised analytical techniques are necessary to isolate each of them.

Identifying the type and amount of food consumed by the general population or by a specific group of individuals (consumption habits) is normally evaluated by carrying out a habit survey which often involves directly interviewing individuals and asking them to identify the types of food and quantities of it they consume.

The dose received following ingestion of radioactivity will depend on the characteristics of the radionuclide ingested – for example, its biological behaviour, its half-life, and the type of radiation it emits. There can often be considerable variability in the dose received by different age groups for the same intake, and this is another factor that must be taken into account when undertaking a dose assessment.

Dose conversion factors allow the dose received per unit intake of a given radionuclide to be calculated. These factors are derived from a combination of theoretical calculations and experimental observations. They are published by the International Commission on Radiological Protection (ICRP) who update them regularly as more information becomes available.

Once all three input parameters are known, the dose D (Sv) received by an individual in any given year is calculated from the following equation:

$D = \Sigma (A \times B \times C)$

where A is the activity of a given radionuclide in the foodstuff in question (Bq/kg)
B is the amount of food consumed (kg)
C is the dose conversion factor for the individual or population group being assessed (Sv/Bq).
Σ indicates that the calculation has to be carried out and summed for every radionuclide and for every food being considered.

Example: A mixed diet sample has been analysed and the average concentrations of C-14, Po-210 and Pb-210 are 31 Bq/kg, 0.089 Bq/kg and 0.086 Bq/kg (fresh weight), respectively.

The corresponding dose conversion factors as published by the ICRP (1995) are 5.8×10^{-10}, 1.2×10^{-6} and 6.9×10^{-7} Sv/Bq.

The Irish Universities Nutrition Alliance Survey (IUNA, 2011) indicates that the annual average consumption by the adult population is 440 kg of food.

The annual dose per adult is therefore:

$D = 31 \times 440 \times 5.8 \times 10^{-10} = 8$ μSv from C-14
$D = 0.089 \times 440 \times 1.2 \times 10^{-6} = 47$ μSv from Po-210
$D = 0.086 \times 440 \times 6.9 \times 10^{-7} = 26$ μSv from Pb-210.

Hence the total annual dose for an adult from the consumption of this mixed diet sample from C-14, Po-210 and Pb-210 is 81 μSv.

The recent study carried out by RPII on analysis of complete meals yielded an average annual dose from ingestion of radium-226 of 4 µSv.

Polonium-210 and Lead-210

Uranium-238 is also found in the earth's crust in concentrations that vary from a few to several thousand ppm. Uranium-238 decays through a series of steps to produce stable lead-206. The radioactive decay of uranium-238 produces radon gas (Rn-222) which, in turn, produces Pb-210 and Po-210. Pb-210 and Po-210 are relatively long-lived radionuclides with half-lives of 22 years and 140 days respectively, and both occur widely in nature. The main pathway for exposure to Pb-210 and Po-210 is through ingestion. Indeed, most of the ingestion dose from the U-238 series is due to the presence of Po-210 in foodstuffs (UNSCEAR, 2000). Pb-210 also contributes significantly to the total radiation dose received by the population because of its long residence time in the human body, particularly in the skeleton (Swift, 1998).

Polonium-210

Analysis of complete meals (as described previously) led to the determination of an average Po-210 activity concentration of 0.089 Bq/kg. Based on an annual food consumption of 440 kg, the annual intake of Po-210 in the Irish diet is 39 Bq, which is within the range of reported values (28–55 Bq) for other European countries (UNSCEAR, 2000).

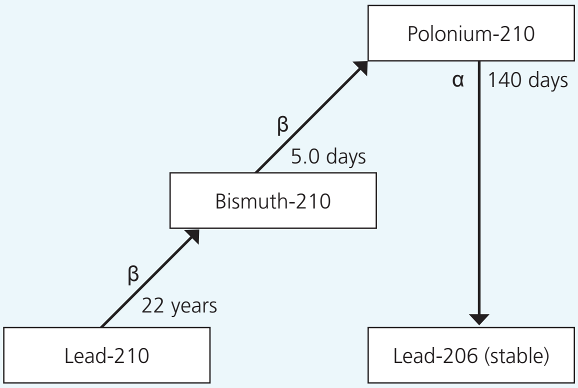
Applying a dose conversion factor of 1.2 x 10^{-6} Sv/Bq (ICRP, 1995) to the above annual intake, we arrive at an average annual ingestion dose of 47 µSv, which is similar to the value of 45 µSv estimated in 2008 (Colgan et al., 2008) and that of 42 µSv calculated for the UK population (Watson et al., 2005).

Lead-210

Analysis of typical Irish meals led to the determination of an average Pb-210 activity concentration of 0.086 Bq/kg. Based on an average annual consumption of 440 kg (IUNA, 2011), the calculated annual intake of Pb-210 in the Irish diet is 38 Bq. Applying a dose conversion factor of 6.9 x 10^{-7} Sv/Bq (ICRP, 1995), the corresponding average annual ingestion dose is typically 26 µSv. This value is comparable to those found in other European and worldwide studies that ranged between 22 and 32 µSv (Watson et al., 2005) (UNSCEAR, 2000) (Ham et al., 1998).

Lead-210 and Polonium-210

Lead-210 (Pb-210) has a half-life of 22.3 years and is part of the uranium-238 (U-238) natural decay chain. Radon gas (Rn-222) exhalation from the ground is the main source of Pb-210 in the environment. Pb-210 decays (via beta and gamma decay) to bismuth-210 (Bi-210), which is the immediate parent of polonium-210 (Po-210).



The dose arising from the ingestion of Pb-210 is mainly due to the high-energy alpha radiation emitted from its daughter product polonium-210 (Po-210). The beta rays arising from the disintegration of Pb-210 and Bi-210 contribute to only about 10% of the total radiation dose (Yamamoto et al., 2009).

While Po-210 occurs naturally, it can also be produced artificially in a nuclear reactor when bismuth-209 is bombarded with neutrons.

Concentrations of Pb-210 and Po-210 are usually low in meat and milk products and relatively high in marine organisms. Intermediate concentrations are found in cereals and vegetables. Typical concentrations of Po-210 and Pb-210 worldwide are shown in the table below.

Foodstuff	**Pb-210**	**Po-210**
	Bq/kg	
Milk Products	0.015	0.015
Meat Products	0.08	0.06
Grain Products	0.05	0.06
Leafy Vegetables	0.08	0.10
Root Vegetables and Fruits	0.03	0.04
Fish Products	0.20	2
Drinking Water	0.01	0.005

Po-210 accumulates in tobacco leaves and smokers will receive a higher radiation dose than non-smokers. For smokers, much of Po-210 will concentrate in the lungs rather than in other parts of the body and will then contribute to an increased risk of lung cancer.

2.5.2 Artificial radioactivity in food

Nuclear discharges into the Irish Sea

During the routine operation of nuclear installations such as nuclear power plants and reprocessing plants, radioactive material is released into the environment. For Ireland's environment, the most significant source of artificial radioactivity is the discharge of low-level radioactive waste into the Irish Sea from the Sellafield reprocessing plant.

Sellafield is located approximately 180 km east of Ireland on the west coast of England. Reprocessing activities at the site have resulted in the discharge of radioactive material into the Irish Sea since the 1950s. These discharges peaked in the 1970s and early 1980s. Subsequently, modern abatement techniques have been introduced that significantly reduced the discharges of most radionuclides, in some cases by factors in excess of 100.

The RPII assesses the radiation doses to the Irish population from the Sellafield discharges as part of its annual marine monitoring programme. Because the main dose pathway is the consumption of seafood, samples of a wide range of fish and shellfish species are collected from commercial landings at major Irish fishing ports and aquaculture areas and the activity concentrations of the key radionuclides are determined.

The 2008 population dose report (Colgan et al., 2008) considered two types of consumers: a 'heavy' consumer who eats 73 kg of fish and 7.3 kg of shellfish annually, and a 'typical' consumer, who eats 15 kg of fish and 1.8 kg of shellfish annually. Since then, a habits survey carried out in 2008 along the north-east coast of Ireland (Cefas, 2008) identified two groups of 'most exposed' people: commercial fishermen (Group A) who consume large amounts of fish (26 kg) and crustaceans (10 kg), and commercial oyster and mussel farmers working along the north-east coast (Group B) who consume large amounts of molluscs (25kg). The annual average doses for members of Group A and Group B have been calculated respectively at 0.17 µSv and 0.21 µSv in 2010, and 0.12 µSv and 0.56 µSv in 2011. These doses include contributions from the artificial radionuclides technetium-99 (Tc-99), caesium-137 (Cs-137), plutonium-238,239,240 (Pu-238,239,240) and americium-241 (Am-241). The annual average dose to Group B was found to have increased in 2011 compared to 2010. This increase can be attributed to changes in the sampling protocol introduced to the 2011 monitoring programme, particularly the inclusion of winkles, as molluscs are known to concentrate actinides such as plutonium and americium.

The annual average dose to the typical seafood consumer for the period 1982 to 2010 is shown in Figure 7. A steady decrease can be seen, reflecting the overall reduction in the Sellafield discharges since the 1980s.

Figure 7. Annual average dose to the typical seafood consumer, 1982–2011

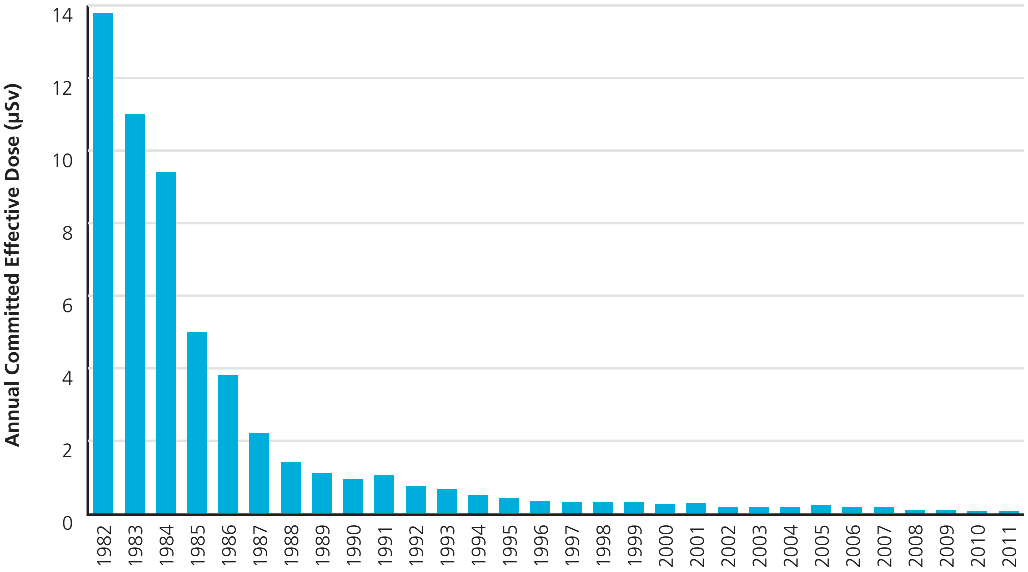


Figure 7 shows that the doses incurred by the Irish public in recent years as a result of artificial radioactivity in the marine environment are small. In general, the levels of radioactivity in the Irish marine environment have remained constant in recent years (McGinnity et al., 2012a).

Radioactivity in milk

The European Commission recommends that member states carry out routine measurements of radioactivity in milk, particularly levels of Cs-137 and Sr-90. This is because these radionuclides tend to concentrate in this particular food product in the event of an accidental release of radioactivity to the atmosphere (European Commission, 2000). Milk is of particular importance as a foodstuff for infants and children. The RPII regularly collects milk samples from Irish dairies and analyses them in line with the Commission's recommendations.

Estimates for 2011 (McGinnity et al., 2012a) show that Cs-137, Sr-90 and its daughter radionuclide yttrium-90 (Y-90) in milk jointly result in an average annual dose of 1.76 µSv to infants and 0.47 µSv to adults. The higher dose received by infants is due to the greater percentage of their total diet that comes from milk and milk products as well as a threefold higher dose per unit intake.

Artificial radioactivity in complete meals

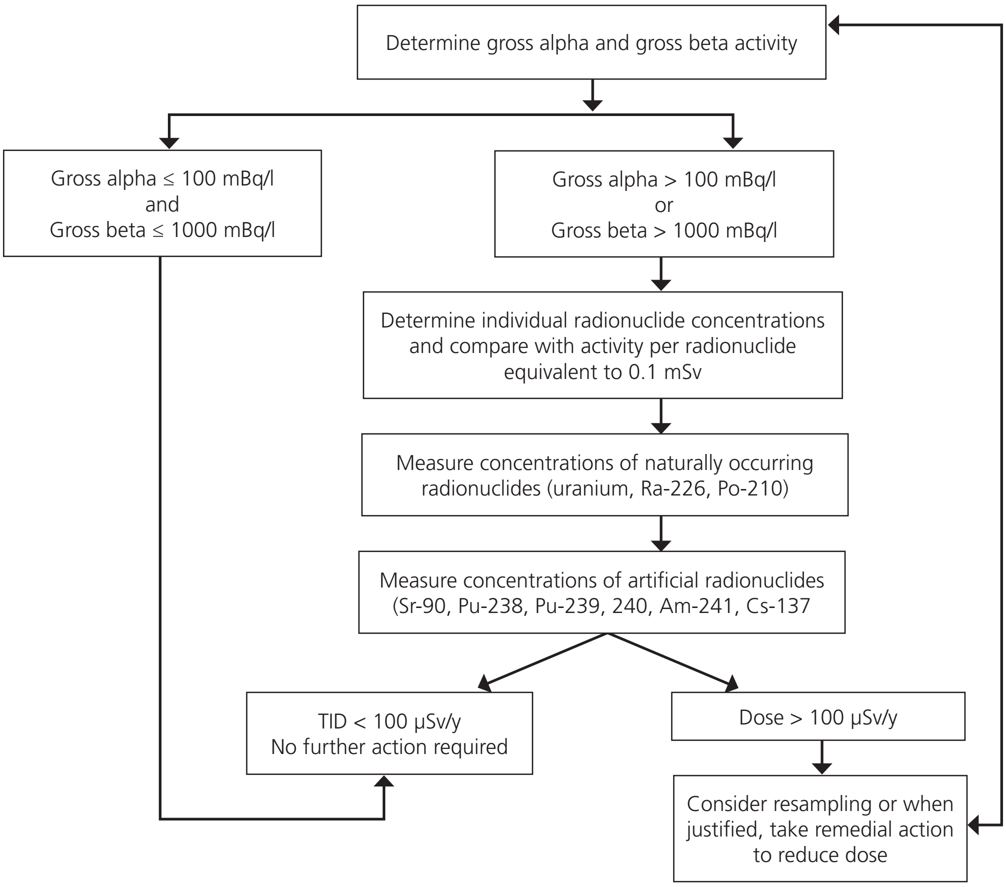
As part of RPII's routine monitoring programme, complete meals (mixed diet) from a restaurant in Dublin are sampled and analysed for gamma-emitting radionuclides on an approximately monthly basis. In 2011, all radionuclides, except Cs-137, were found to be below the limit of detection. The maximum Cs-137 concentration measured was 0.21 Bq/kg (McGinnity et al., 2012a). Assuming average annual consumption of foodstuffs and water of 1,000 kg (IUNA, 2011) and applying a dose conversion factor of 1.3×10^{-8} Sv/Bq, the average annual dose from Cs-137 in food is 2.7 µSv, which is consistent with that reported in 2008 (2.6 µSv) (Colgan et al., 2008).

Drinking water

The RPII monitors radioactivity in surface drinking water supplies (McGinnity et al., 2012a) for compliance with parameters set out in the European Communities Drinking Water Directive (European Commission, 2013a). Between 2007 and 2011, in collaboration with the Environmental Protection Agency (EPA), the RPII undertook a national survey of radioactivity in groundwater supplies. Over 200 samples were screened for radioactivity (Dowdall et al., 2013). In 2012 the RPII undertook a study of radioactivity levels in bottled water produced in Ireland – this involved analysis of 21 samples collected by Environmental Health Officers to assess compliance with the Drinking Water Directive (Currivan et al., 2013).

Due to the type of screening analysis performed (as shown in Figure 8), it is not possible to quantify the average radiation dose received as a result of consumption of drinking water. The results of these surveys do show, however, that all drinking sources tested complied with the Drinking Water Directives parametric guideline of less than 100 µSv per annum.

Figure 8. Procedure for screening for radionuclides in drinking water



2.5.3 Summary of radiation doses due to ingestion

A summary of the contribution of various nuclides to doses from the consumption of food and drinking water is shown in Table 5.

Table 5. Average annual radiation doses from consumption of foodstuffs in Ireland.

Exposure pathway	**Natural dose (µSv)**	**Artificial dose (µSv)**
Carbon-14	6	2
Potassium-40	170	
Rubidium-87	2	
Radium-228 (from thorium-232)	7	
Radium-226 (from uranium-238)	4	
Polonium-210	47	
Lead-210	26	
Nuclear discharges		0.07
Radioactivity in milk		0.5
Cs-137 in mixed diet		2.7
TOTAL	**262**	**5.3**

Note: Drinking water accounts for an average annual dose of <100 µSv

Chernobyl and Fukushima – Impact of Nuclear Accidents abroad on Ireland

Chernobyl

The accident at the Chernobyl nuclear power station in Ukraine occurred on 26 April 1986. Over a number of days radioactivity was dispersed in the atmosphere throughout Europe and first reached Ireland on 2 May. Heavy rainfall over Ireland at the time resulted in radioactivity being deposited on the ground. While many different radioactive isotopes were detected, the most important of these was Cs-137 because of its immediate and long-term impact on the food chain.

Cs-137 is important for a number of reasons:

- it is produced in relatively large amounts in nuclear reactors;
- it can travel over large distances if released into the atmosphere;
- it has a half-life of 30 years and persists in the environment for a few hundred years; and
- it is readily absorbed into living material and transfers very efficiently into the food chain.

Another radioactive isotope that has an impact on the food chain is iodine-131 (I-131), also called radioiodine, which can be transferred to the food chain through cows grazing on contaminated grass. Once ingested by the cows, the iodine is very effectively transferred into the milk and/or into the meat. Following ingestion of contaminated milk or meat by humans, I-131 tends to concentrate in the thyroid gland to which it delivers a high radiation dose. Infants and young children are particularly at risk from exposure to radioiodine because they usually drink large quantities of milk and their thyroid glands are still under development and hence more vulnerable to radiation. In the area around Chernobyl, consumption of foods contaminated with I-131 was responsible for over 90% of the total radiation dose received by the local population in the first six to eight weeks after the accident.

Measurable concentrations of both I-131 and Cs-137 were found in foodstuffs produced in Ireland from May 1986 onwards, including in milk and milk products, lamb, beef and leafy vegetables. Root vegetables, on the other hand, showed very low levels of contamination.

Cunningham et. al. (1987) estimated that, in the first six months after the accident, the ingestion doses from the consumption of contaminated foodstuffs were 99 μSv for adults, 105 μSv for 10-year-old children and 158 μSv for infants.

Overall, the long-term impact of the Chernobyl accident in Ireland has been low, and an increase in cancers caused by the additional radiation exposure above the normal background incidence of cancers in Ireland has not been detected.

Fukushima

The Great East Japan earthquake and associated tsunami(s) which occurred on 11 March 2011 resulted in the development of severe accident conditions at the Fukushima Dai-ichi nuclear power plant and, subsequently, in large releases of radioactivity into the environment.

Trace amounts of radioactivity originating from the Fukushima accident were detected in Ireland during the period March to May 2011, but the levels were so low that they were of no radiological significance and no protective measures were required.

An upper bound on the radiation dose received by an adult in Ireland from the additional radioactivity resulting from the Fukushima accident was estimated at 0.26 μSv, which is of no significance from a public health or food safety point of view (McGinnity et al., 2012b).

2.6 Occupational exposure

This section considers the doses incurred by individuals as a result of their work. These include, for example: air crew who are exposed to higher levels of cosmic radiation than the general population; indoor workers who are exposed to higher levels of radon in their workplaces than those whose work is predominantly outdoors; and miners and show cave workers who may also be exposed to higher levels of radon as their workplaces are underground. In addition, there are people who may potentially be exposed to artificial sources of radiation in the fields of medicine, industry and education/research.

Data on individual and average doses, along with statistical information on employee numbers for various sectors are used to estimate the collective dose for the entire relevant workforce. This collective dose is then averaged over the entire population to estimate the average annual occupational dose.

2.6.1 Occupational exposure to natural radiation

Cosmic radiation

Since 2000, Statutory Instrument No. 125 of 2000 (Stationery Office, 2000) requires all airlines holding an Air Operator's Certificate issued by the Irish Aviation Authority to evaluate the extent of exposure of their air crew to cosmic radiation. These regulations apply only in situations where air crew are likely to receive doses greater than 1 mSv in any 12-month period. Air crew who fly exclusively below altitudes of 8,000m are unlikely to receive such doses (Bartlett et al., 1997), and for that reason do not fall within the scope of the regulations.

Occupational exposure of air crew to cosmic radiation, based on data reported annually by the airlines to the RPII, is summarised in Table 6.

Table 6. Distribution of air crew doses (2006–2012)

Year	Number of airlines	Number of aircrew†	1000–2000 μSv	2000–4000 μSv	4000–6000 μSv
2006	7	5,692	2,794 (49.1%)	2,592 (45.5%)	306 (5.4%)
2007	8	8,199	4,077 (49.7%)	3,939 (48.0%)	183 (2.2%)
2008	7	9,726	3,695 (40.0%)	5,779 (59.4%)	252 (2.6%)
2009	7	9,666	2,917 (30.2%)	6,035 (62.4%)	714 (7.4%)
2010	7	11,077	4,415 (39.9%)	6,549 (59.1%)	113 (1.0%)
2011	7	11,362	4,175 (36.7%)	7,001 (61.6%)	186 (1.6%)
2012	5	12,036	5,315 (44.2%)	6,601 (54.8%)	120 (1.0%)

† *Those receiving doses less than 1 mSv are excluded.*

The average dose received per aircrew worker in 2012 was 2326 μSv. This compares with 2000 μSv in 2008 (Colgan et al., 2008). By analysis of the data we arrive at a collective dose of 28 man Sv for 2012, which is a significant increase on the dose calculated for 2008 (12 man Sv). The contribution this makes to the average annual dose for the whole population is 6 μSv.

The increase in the collective dose is directly related to the increase in the number of aircrew employed by Irish airlines, which has more than doubled since the 2008 report was published. Passenger numbers and air traffic have grown each year from 2006 to 2012 as airlines continue to open new bases and routes. It should be noted that the data reported annually by the airlines to the RPII includes all staff employed by Irish airlines regardless of whether or not they are resident in Ireland, so the collective dose figure is likely to be an overestimation.

Radon in workplaces

Radon in schools

While primary and secondary schools are most often thought of as centres of education for the 875,500 children who attend them (DES, 2012), they are also workplaces for teachers and other staff. For that reason, schools come under the regulations set out in Statutory Instrument No. 125 of 2000 (Stationery Office, 2000), and the radon concentrations in the ambient air of schools must be measured. If the results of the measurements, which are carried out over a continuous minimum period of three months, exceed the reference level of 400 Bq/m^3, then the employer is required to take steps to reduce the exposure of employees to radon.

Between September 1998 and June 2004 the RPII carried out a national survey of radon concentrations in schools (Synnott et al., 2004) (Synnott et al., 2006). Based on over 41,000 measurements in more than 3,000 schools, the average radon concentration observed was 93 Bq/m^3.

The results are assumed to be representative of the radon concentrations present during school hours. Based on a total number of 57,746 teachers (DES, 2012), as representing the largest group of schools' staff, exposed to an annual average radon concentration of 93 Bq/m^3 for 1,000 h every year, and on a dose-exposure coefficient of 1 mSv per 130 Bq/m^3 over 2000 hours, the annual collective dose is 20.6 man Sv.

This data is summarised in Table 7, which also includes the observed reduction factors that are due to an extensive remediation programme undertaken in Irish schools by Synnott et al. (2007). The final collective dose is 15.1 man Sv and the average dose received by a teacher in 2012 was 262 μSv. The contribution this makes to the average annual dose for the whole population is 3.3 μSv.

Table 7. Summary of collective dose to schoolteachers from radon in schools

Initial radon concentration (Bq/m^3)	**<200**	**200–400**	**400–1000**	**>1000**	**Total**
Number of measurements	37,698	2,461	791	146	**41,096**
Percentage of measurements	91.7%	6.0%	1.9%	0.4%	**100%**
Average radon concentration (Bq/m^3)	65	274	573	1,606	**93**
Exposed workforce[†]	52,944	3,464	1,097	231	**57,736**
Collective dose (man Sv)[‡]	13.2	3.6	2.4	1.4	**20.6**
Reduction factor	-	2.1	12	23	**-**
Final collective dose (man Sv)	13.2	1.7	0.2	0.06	**15.1**

[†] *The workforce distribution is matched with the distribution of radon concentrations*

[‡] *Using a dose exposure coefficient of 1 mSv per 130 Bq/m^3 over 2000 h (ICRP, 1993) (Stationery Office, 2000)*

Radon in other above-ground workplaces

Since 1999, the RPII has undertaken just over 18,000 measurements in 2,626 individual above-ground workplaces other than schools. Measurements have also been carried out by other radon measurement companies based in Ireland. When radon measurement data is analysed, the possibility of introducing biases is always a concern. For example, in highlighting the legal responsibilities of employers to have radon measurements carried out in their workplace(s), the RPII has always underlined that this was particularly important for those workplaces located in high radon areas. As a result, workplaces in high radon areas are possibly over-represented in RPII measurements.

When compiling the available data, seven specific national datasets were identified (Table 8). Apart from the RPII dataset, the remaining six were provided by other radon measurement services. The two datasets described in Table 8 as 'Specific Workplaces' contain results from national surveys conducted by employers throughout the country.

Table 8. Available data on radon concentrations in Irish above-ground workplaces (excluding schools)

Description of dataset	Source of the dataset	Number of measurements	Average radon concentration (Bq/m^3)
General workplaces	RPII	18,240 (74%)	85
General workplaces	Private[†]	1,049 (4%)	63
General workplaces	Private[†]	963 (4%)	51
General workplaces	Private	1435 (6%)	96
General workplaces	Private	1334 (5%)	93
Specific workplaces	Private[†]	968 (4%)	104
Specific workplaces	Private[†]	830 (3%)	62
Total		**24,819**	

[†] *This data was collated for the 2008 report. No further data was available from these sources when the data was updated in 2013.*

To make the best estimates of the average radon concentration in Irish above-ground workplaces and of the corresponding occupational dose, the seven datasets have been merged into one to give a weighted average radon concentration of 84 Bq/m^3. Using a typical working year of 2,000 hours, this equates to an average individual dose of 646 μSv, compared to 620 μSv calculated in the 2008 population dose assessment (Colgan et al., 2008).

The working population in indoor above-ground workplaces has been calculated by excluding, from the Central Statistics Office employment statistics for 2012 (CSO, 2012a), those involved in construction, agriculture, fishing and forestry. Teachers have also been omitted, as radon exposure in schools is considered separately. This leaves an estimated workforce in indoor, above-ground workplaces of 1.6 million. The collective dose from radon exposure in above-ground workplaces was found to be 1037 man Sv (see Table 9), and the contribution this makes to the average annual dose for the whole population is 226 μSv.

Table 9. Collective dose to Irish workers from radon in indoor above-ground workplaces.

Initial radon concentration (Bq/m^3)	<200	200–400	400–1000	>1000	Total
Number of measurements	22,779	1,300	618	122	**24,819**
Percentage of measurements	91.8%	5.2%	2.5%	0.5%	**100%**
Average radon concentration (Bq/m^3)	51	273	586	1,729	**84**
Exposed workforce[†]	1.47×10^6	8.32×10^4	4×10^4	8×10^3	**1.6×10^6**
Collective dose (man Sv)[‡]	576	175	180	106	**1037**

[†] *Dividing the total workforce of 1.6×10^6 in accordance with the distribution of radon concentrations*

[‡] *Using a dose-exposure coefficient of 1 mSv per 130 Bq/m^3 exposure over 2000 h (ICRP, 1993) (Stationery Office, 2000)*

Radon in mines and show caves

The radiation dose that individuals who work in underground workplaces receive from exposure to radon was assessed using passive alpha track detectors identical to those used to measure radon exposure in above ground premises. This type of detector measures the average radon concentration over the duration of the measurement (usually 3 months). This is then converted into a radon exposure and into dose using specific occupancy rates for each exposed worker.

Table 10 summarises the available data on the doses received by workers in show caves in Ireland for the years 2006 to 2012. In show caves, the number of exposed staff varies from year to year and many only work a limited number of hours because of the seasonal nature of the business.

Table 10. Doses (µSv) received by show cave guides in Ireland from radon exposure (2006 - 2012)

	2006	2007	2008	2009	2010	2011	2012
Number of show caves monitored	3	3	2	2	1	1	1
Number of exposed workers	33	40	32	10	5	3	4
Mean (µSv)	1600	2500	2000	2600	2400	3000	700
Range (µSv)	200–3,900	100–5,200	200–4,100	700–2,400	2,200–2,800	1,000–6,800	200–1,000
Collective dose (man Sv)	0.053	0.101	0.063	0.026	0.012	0.009	0.003

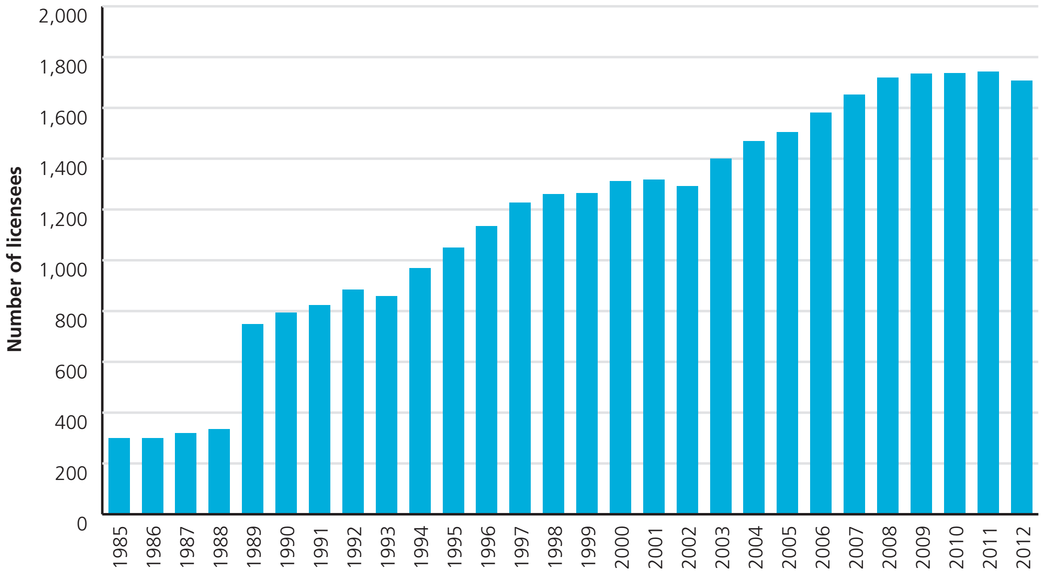
The total collective dose for exposed workers in show caves between 2006 and 2012 is 0.267 man Sv. This corresponds to an average collective dose of 0.038 man Sv per annum in that period. The average dose received by an exposed worker is approximately 2,000 µSv. The contribution this makes to the average annual dose for the whole population is less than 0.01 µSv.

There is no new data available on doses received by workers in mines since the 2008 population dose assessment which reported a collective dose of 0.020 man Sv (Colgan et al., 2008) along with a corresponding individual dose to an exposed worker of 700 µSv. The contribution this makes to the average annual dose for the whole population is less than 0.01 µSv.

2.6.2 Occupational exposure to artificial radiation

Radioactive sources are used in medicine, industry and education/research. Currently in Ireland, there are approximately 1,700 active licences, of which 55% are in the dental sector and 16% are in the industrial and the veterinary sectors (RPII, 2013). There was a significant increase in active licences in 1989 when the dental sector was brought within the licensing system and since then there has been a steady increase in the total number of new licensees, although the total number has levelled off in recent years as shown in Figure 9.

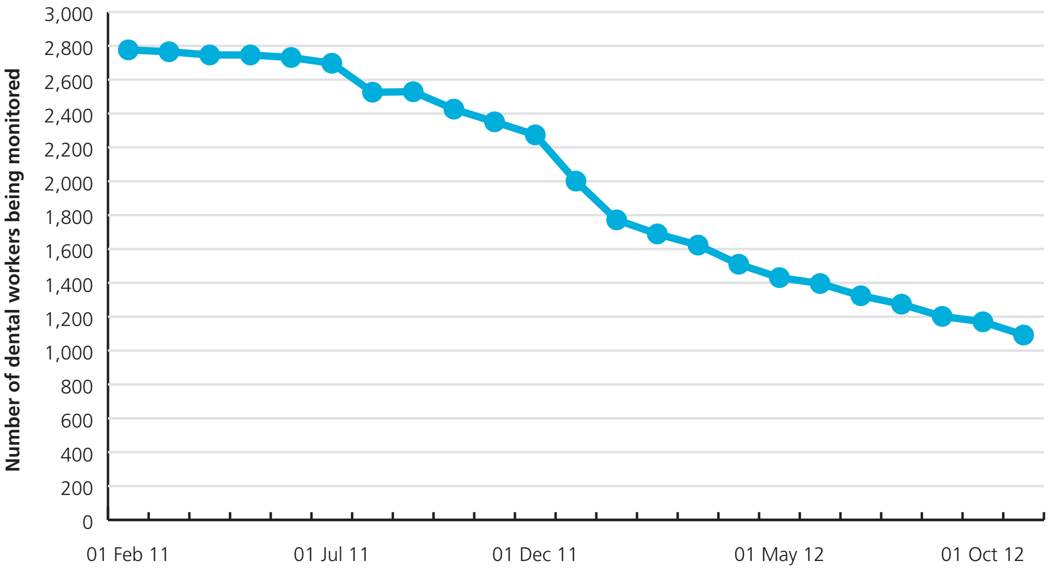
Figure 9. Numbers of RPII licensees between 1985 and 2012



In situations where radiation is being used, workers such as hospital radiographers, doctors, site radiographers, maintenance staff and research staff can potentially be exposed. To monitor these situations, workers who are deemed liable to receive a dose above 1 mSv (1000 µSv) per year from their occupational activity must be provided with personal dosimeters that assess their radiation dose while they work.

Between 2005 and 2008 the RPII Dosimetry Service provided personal dosimeters to approximately 9,000 Irish workers annually. This number decreased to approximately 8,000 workers in 2009 owing to the increased presence of other dosimetry services in the Irish market. In 2012, the number of workers provided with personal dosimeters by the RPII Dosimetry Service fell by approximately 17% from 8,151 workers in 2011 to 6,747 in 2012, mainly because of a fall-off in the number of workers being monitored in the dental sector. In June 2011 the licensing requirements for users of dental X-ray equipment changed. From that date personal dosimetry was no longer a mandatory requirement where a risk assessment carried out by a Radiation Protection Adviser (RPA) indicated that operators of X-ray equipment, or other relevant staff, were unlikely to be exposed to a dose exceeding 1 mSv (1000 μSv) in any 12-month period. The effect of this change on the number of dental workers being monitored can clearly be seen in Figure 10.

Figure 10. Number of workers in the dental sector monitored by the RPII Dosimetry Service during 2011 and 2012



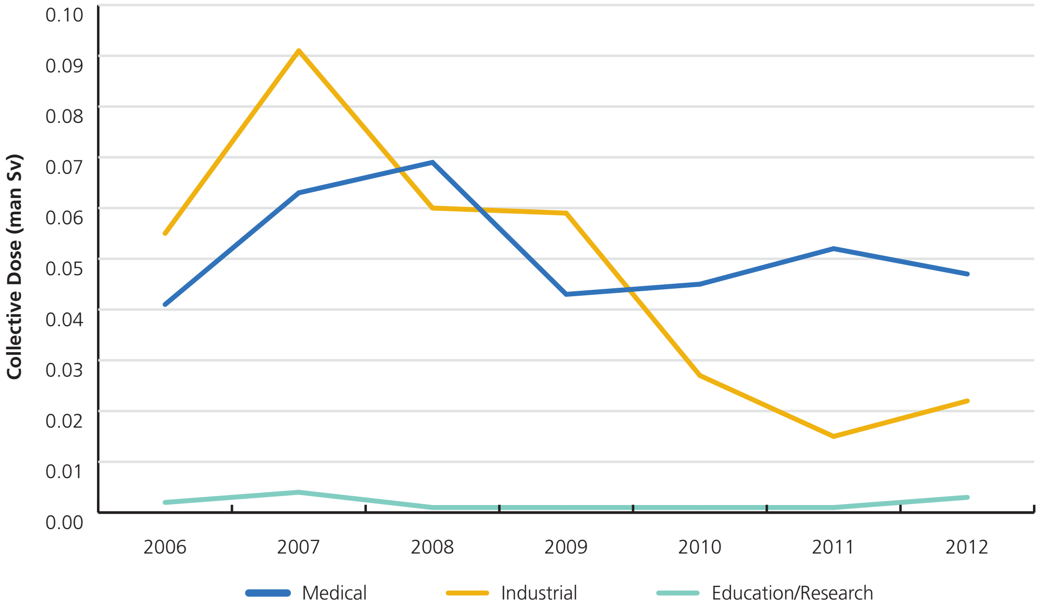
The number of workers receiving measurable doses (above 100 μSv) between 2006 and 2012 is presented in Table 11 and it shows a clear decline in all sectors, particularly since 2007. In the industrial sector the number of workers receiving doses above 100 μSv reduced by approximately 50%, mainly because of the decline in activity in this sector as a result of the economic downturn after 2007.

Table 11. Number of exposed workers in Ireland receiving a measurable radiation dose from artificial sources of radiation (2006–2012).

Sector	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Medical	114	216	162	95	71	85	74
Industrial	85	119	84	79	51	34	42
Education/research	7	10	6	7	5	2	10
TOTAL	**206**	**345**	**252**	**181**	**127**	**121**	**126**

The collective dose from occupational exposure in the medical, industrial and education/ research sectors is presented in Figure 11. The collective dose in the medical and education/ research sectors has remained relatively constant over this period. In the industrial sector, the collective dose displays a downward trend from 2007, in line with the reduction in the number of workers receiving measurable doses in this sector.

Figure 11. Collective dose (man Sv) from artificial sources of radiation per sector (2006–2012)



The average annual collective doses for the medical, industrial and education sectors over the period 2006-2012 were 0.051, 0.047 and 0.002 man Sv respectively. This corresponds to a total average annual collective dose of 0.1 man Sv, and the contribution this makes to the average annual dose for the whole population is 0.02 µSv.

2.6.3 Occupational exposure to naturally occurring radioactive material (NORM)

Natural radioactivity can sometimes be found in certain types of rocks and soils in enhanced concentrations. Natural radioactivity can also accumulate as part of some industrial processes, and to such an extent that it may pose a risk to both humans and to the environment if it is not controlled. Such naturally occurring radioactive materials are usually referred to by the acronym NORM and the industries dealing with such materials are known as NORM industries.

In 2001, the RPII initiated a programme to identify industries active in Ireland which, on the basis of the available literature, were involved in work activities which could result in exposure to diffuse NORM sources, and to quantify the associated radiation doses. The following Irish industries were assessed: the extraction of natural gas, the combustion of peat and coal in power plants for electricity production, and the processing of bauxite for the production of alumina.

The overall conclusion from this work was that no worker is likely to receive a dose in excess of 1 mSv and that doses likely to be received by members of the public are considerably lower and well within limits set in national legislation. The annual collective dose to workers from the four NORM industries considered was estimated to be approximately 0.35 man Sv (Organo et al., 2007) (Organo & Fenton, 2008), and the contribution this makes to the average annual dose for the whole population is less than 0.1 µSv.

2.6.4 Summary of occupational doses

The data on occupational exposure described in previous sections is summarised in Table 12 and Figure 12. More than 99.9% of the collective dose is attributable to exposure to natural radiation, mainly from radon in above-ground workplaces but with a small contribution from the cosmic ray exposure of aircrew. Occupational exposure to artificial radiation accounts for just 0.01% of the collective dose. This is consistent with the distribution observed in the 2008 population dose assessment (Colgan et al., 2008). The average annual dose received per worker in each of the exposed population groups ranges from 226 µSv to 2326 µSv.

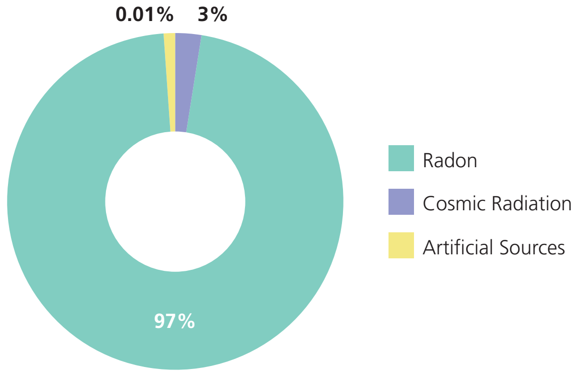
Table 12. Estimated annual dose from occupational radiation exposure in Ireland

Pathway	Number of workers receiving doses†	Dose per worker (μSv)	Year(s) of observation	Collective dose (man Sv)	Contribution to average annual dose (μSv)
Natural Sources					
Air crew	12,000	2326	2012	28	6
Radon – schools	57,000	262	2012	15.1	3.3
Radon – general	1,600,000	646	2012	1037	226
Show cave guides	18	2000	2006–2012	0.038	0.008
Underground miners	27	700	2002–2005‡	0.020	0.004
NORM industries	1560	224	2001–2006	0.35	0.08
Artificial Sources					
Medical	117	435	2006–2012	0.051	0.01
Industrial	71	662	2006–2012	0.047	0.01
Education/Research	7	286	2006–2012	0.002	0.0004
All Pathways				**1080**	**235**

† *Approximate numbers (variable year to year)*

‡ *No data for 2003.*

Figure 12. Distribution of radiation doses in workplaces in Ireland



2.7 Medical exposure of patients

Estimating the collective and average annual doses from medical examinations involving exposure to ionising radiation requires information on the typical dose per investigation and the frequency of each investigation. The collective dose is the sum for all modalities (types of examinations e.g. general X-ray, computed tomography, nuclear medicine) of the average effective dose per examination multiplied by the frequency of the examination. The average annual dose is the collective dose distributed across the entire population.

Hospitals using X-ray equipment and/or radioactive substances are required to hold a licence issued by the RPII. For this reason, there is a comprehensive database of all diagnostic medical radiological equipment and nuclear medicine sources in use in Ireland. In addition, the Health Services Executive (HSE) has a legal obligation, under Article 12 of the European Commission Medical Exposures directive (EU Council, 1997) and Article 22.6 of Statutory Instrument No. 478 (Stationery Office, 2002), to collect and publish statistics on population dose levels from the use of medical ionising radiation.

Since the 2008 population dose report was published, the Population Dose Sub-Committee of the HSE's National Radiation Safety Committee has carried out national surveys of a number of different diagnostic imaging modalities, including computed tomography (CT) and dental radiography in 2010, general X-ray imaging and nuclear medicine in 2011 and PET-CT in 2013. A pilot survey for interventional radiology (including cardiology) was also carried out in 2013.

All CT, X-ray, dental and PET-CT holders, both public and private, on the HSE register of ionising radiation installations with those modalities were surveyed. Nuclear medicine holders known to the HSE were also surveyed. Due to the complex nature of interventional radiology, a subset of hospitals was selected to participate in the pilot survey and the results of this are included in this report.

For each modality a subset of examinations was selected for the survey, in line with recommendations from the European Commission (European Commission, 2008), and with the 2008 UK Population dose survey (Hart et al., 2010). In addition, some examinations known to have a high frequency or to deliver higher doses were also included. While conducting the surveys it became clear that, in some cases, the data on the frequency of examination was challenging to collect, as many examinations include multiple body parts, multiple scan phases, and also because the methodology for coding and collating statistics varies from centre to centre.

As in the 2008 population dose report (Colgan et al., 2008), doses from radiotherapy procedures were not considered. This is because radiotherapy involves the intentional delivery to specific organs and tissues of high doses of radiation designed to kill targeted cells. It is not, therefore, considered appropriate to include these doses in surveys designed to indicate the distribution of radiation exposure across the population and the risks from generally much lower doses.

2.7.1 Surveys and dose calculations

Computed tomography

The HSE's survey on population dose from CT scanning (HSE, 2011a) gathered data on patient and examination frequency, CT dose index (CTDIvol) and dose length product (DLP) for six scan types in the 12-month period from January to December 2009. A 100% response rate was achieved. Effective dose was determined by applying published conversion factors to the DLP data submitted. Data on the frequency of examinations, rounded to the nearest 10, and on the average effective dose per examination is tabulated in Table 13.

Table 13. Results from Computed Tomography Survey (2009)

	Frequency of examinations per year	Average effective dose per examination (μSv)
Adult CT examinations		
Brain	79,030	1,700
C spine	3,210	1,900
High resolution thorax	7,710	3,800
Thorax	28,660	7,300
Abdomen/pelvis	50,310	8,400
Thorax/abdomen/pelvis	42,800	12,900
Paediatric CT examinations		
Brain	3,130	3,100
Abdomen/pelvis	400	10,300

The collective effective dose to the population from CT scans was found to be 1,368 man Sv, of which less than 1% is attributed to people under 15 years of age. This collective dose is higher than the value reported for the same type of dose in the 2008 population dose assessment (1,165 man Sv). Although it is in keeping with international evidence of increasing use of CT and the trend for increasing collective effective dose from CT over time (Borretzen et al., 2007) (Brenner & Hall, 2007) (Berrington et al., 2009), the increase in the collective dose from CT scans in Ireland since 2008 may also be due in part to the difference in scan types included in the surveys.

Dental radiology

The HSE's survey on population dose from dental radiology (HSE, 2011b) combined the results of the 2010 HSE Survey of Dental Compliance with SI 478 (Stationery Office, 2002), which calculated the estimated annual frequency of dental X-ray examinations, with published data on the dose from dental examinations, and together these give an estimate of the collective dose from dental radiology. Data on the frequency of examinations (rounded to the nearest 10), and an estimate of the effective dose per examination are tabulated in Table 14.

Table 14. Dental radiology data (2010)

Type of dental examination	Frequency of examinations per year	Estimated effective dose per examination (µSv)
Intraoral	737,780	5
Occlusal	14,960	7
Panoramic	97,670	19
CBCT	1,190	126
Lateral cephalometry	10,790	6

The collective effective dose to the population from dental radiology was found to be 6 man Sv Dental radiology was not included in the scope of the 2008 population dose report (Colgan et al., 2008). The data outlined above is similar to that in other European surveys on population dose (European Commission, 2008) that have included dental radiology, which indicate that dental radiology contributes less than 1% to the total collective dose from diagnostic medical exposures.

General X-ray

The HSE's survey on population dose from General Radiology and Nuclear Medicine (HSE, 2013) gathered data on examination frequency and average dose area product (DAP) (with the exception of mammography where the mean glandular dose (MGD) was returned) for 23 general X-ray examination types. The response rate amongst holders of general X-ray installations was 64%. Fourteen percent of those that responded provided only partial information, citing resource issues for their incomplete response.

Effective dose was determined from the DAP or MGD data submitted by applying the published conversion factors based on ICRP-103 (ICRP, 2007). Data on frequency of examinations, rounded to the nearest 10, and estimated effective dose per examination are tabulated in Table 15.

Table 15. General radiology data

Type of examination	Frequency of examinations per year	Average effective dose per examination (µSv)
Chest PA	637,590	20
Chest AP	154,734	40
Cervical spine AP	51,670	40
Cervical spine lat.	37,970	30
Thoracic Spine AP	22,810	220
Thoracic spine lat.	16,990	170
Lumbar spine AP	78,870	350
Lumbar spine lat.	57,370	220
Lumbar sacral junction	12,530	190
Full Spine (T+L)	1,320	1,220
Full Spine (C+T+L)	770	920
Skeletal survey	1,460	800
Abdominal AP	108,630	400
Pelvic AP	127,380	290
Single hip AP	42,800	180
Both hips	23,090	270
Femur AP	12,570	30
Femur lat.	8,420	2.2
Mammography screening	17,430	570
Mammography symptomatic	50,580	540
Feet/Ankles/Wrist/Hand	390,920	0.2
Knees AP/Lateral	138,590	0.58

The total number of general X-ray examinations was extrapolated from the data returned, using the relative frequency of the examinations surveyed supplemented by data on the total number of X-ray examinations carried out in each centre in 2010, giving an estimated total number of 2,575,180 X-rays.

The collective dose from general X-ray was found to be 259 man Sv, a decrease from that reported in the 2008 population dose report (Colgan et al., 2008). This decrease may be a reflection of the increased use of both direct and indirect digital radiography (as the values for average effective dose per examination are lower than those reported in the 2008 study), and also the more comprehensive list of examinations included in the 2010 survey.

Nuclear medicine

The HSE's survey on population dose from General Radiology and Nuclear Medicine (HSE, 2013) also gathered data on the frequency of examination and the average administered activity (MBq) for 14 nuclear medicine examination types. The survey response rate from nuclear medicine centres was 100%. The effective dose was determined from the submitted administered activities and based on the methodology of the ICRP (ICRP, 2000), with conversion factors taken from the Administration of Radioactive Substances Advisory Committee (ARSAC) Guidance notes (HPA, 2006). Data on frequency, rounded to the nearest 10, and estimated effective dose are tabulated in Table 16.

Table 16. Nuclear medicine data

Examination	Frequency of examinations per year	Average effective dose per examination (μSv)
Tc-99m bone scan	14,980	3,540
Tc-99m thyroid scan	1,140	1,320
I-131 thyroid uptake	110	47,200
I-131 thyroid metastases	330	7,370
Tc-99m V/Q lung perfusion scan	940	1,420
Tc-99m Aerosol V/Q lung ventilation scan	220	1,780
Tc-99m Technegas V/Q lung ventilation scan	350	1,880
Tc-99m DTPA renogram scan	570	1,260
Tc-99m MAG3 renogram scan	530	730
I-123 DaTSCAN	430	3,720
I-123 MIBG scan	80	2,890
In-111 octreoscan	120	9,030
Tc-99m myocardial scan	670	7,020
Tc-99m cerebral blood flow	40	6,650

The total number of nuclear medicine examinations was calculated using the relative frequency of the 14 examinations surveyed, supplemented by data on the total number of nuclear examinations carried out in each centre in 2010. A total number of 29,993 nuclear medicine examinations were estimated to have been performed in 2010.

The total collective dose from nuclear medicine scans was found to be 112 man Sv.

Positron Emission Tomography (PET) – Computed Tomography (CT)

In 2013, a survey of all PET-CT installations, both public and private, was instigated by the HSE. The survey response rate amongst licence holders was 88%.

The effective dose for the PET component of each examination was determined from the submitted administered activities while the effective dose for the CT component was determined using the methodology previously reported (HSE, 2011a). The total frequency has been extrapolated from submitted data, supplemented by knowledge of the number of patient doses delivered nationally.

By analysis of the responses to the 2013 survey of PET-CT installations, estimates of the collective dose are found to be of the order of 130 man Sv (MERU, Personal communication, 5 September 2013). Whole-body PET-CT constituted 95% of the examinations with 40% of those utilising a full diagnostic CT examination. PET-CT was not included in the 2008 population dose report (Colgan et al., 2008) as it was an emerging technology at the time of the survey.

Interventional radiology and cardiology

In 2013 a pilot survey of selected installations, both public and private, was instigated by the HSE for interventional radiology and cardiology. A subset of examinations, based on frequent examinations identified in the European Union Dose Datamed Project (European Commission, 2013), were selected for this survey and are listed in Table 17.

Due to the complex nature of the examinations and the varying levels of interventional radiology and cardiology between installations, hospitals were grouped according to the level of fluoroscopy or cardiology equipment on the HSE register of ionising radiation installations.

A subset of hospitals in each group provided data, from which an estimate of the frequency of examinations nationwide was extrapolated. The average effective dose from the surveyed installations in each group was then applied to all hospitals within the group.

Table 17. Fluoroscopy and interventional radiology procedures

	Procedure	Sub-procedure
Fluoroscopy	GI tract	Oesophageal & stomach & small intestine
		Colon
	Biliary tract	Biliary tract
Theatre	Orthopaedics	All orthopaedics
	Other (abdomen, spine, etc.)	Other (abdomen, spine, etc.)
Interventional	Radiology /cardiology	Cerebral procedures, high dose studies, e.g., embolisation
		Cerebral procedures, all other
		Cardiac procedures including electrophysiology (EP) studies
		All thoracic procedures
		All abdominal procedures
		All pelvic procedures
		All peripheral procedures
		Percutaneous transluminal coronary angioplasty (PTCA)
		Pacemaker
		All IV lines, e.g. Hickman
		Transjugular intrahepatic portosystemic shunt (TIPS)

Analysis of the responses to the 2013 survey gives a collective dose of around 630 man Sv, including those fluoroscopy studies surveyed as part of the general X-ray and nuclear medicine survey (MERU, Personal communication, 5 September 2013). Interventional cardiology accounts for 80% of this dose.

2.7.2 Total population dose from diagnostic medical imaging

The collective doses for each modality have been summarised in Table 18. Collective doses per diagnostic imaging modality. The total collective dose from diagnostic medical imaging is 2505 man Sv. The resulting average annual dose is 546 μSv which is consistent with the value obtained in 2008 (540 μSv) (Colgan et al., 2008). The distribution of collective dose from the various modalities is illustrated in Figure 13 while the distribution of examination frequency from the various modalities is illustrated in Figure 14.

Table 18. Collective doses per diagnostic imaging modality

Modality	Collective dose (man Sv)	Average annual dose (μSv)
CT	1,368	298
Dental	6	1.3
General X-ray	259	56.4
Nuclear medicine (excl. PET-CT)	112	24.4
PET-CT	130	28.3
Interventional radiology and cardiology	630	137.3
Total	**2,505**	**546**

Figure 13. Distribution of collective dose from diagnostic medical imaging 2009–2012

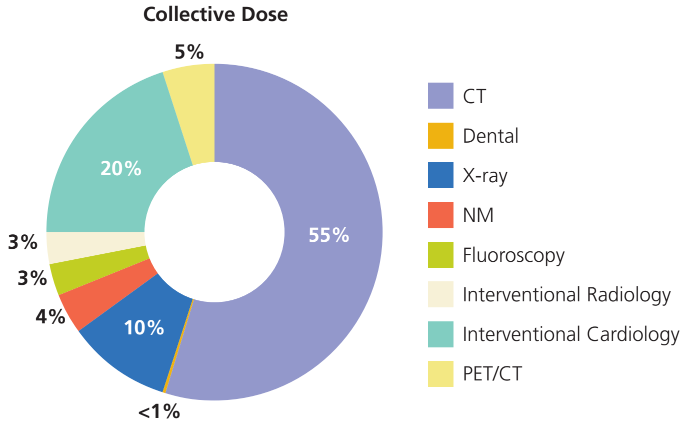
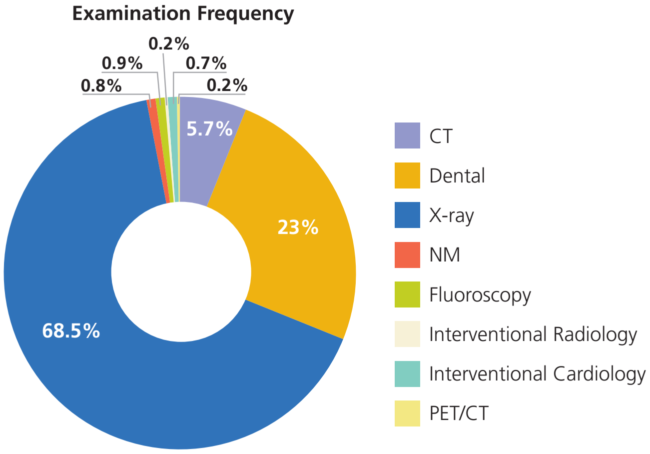


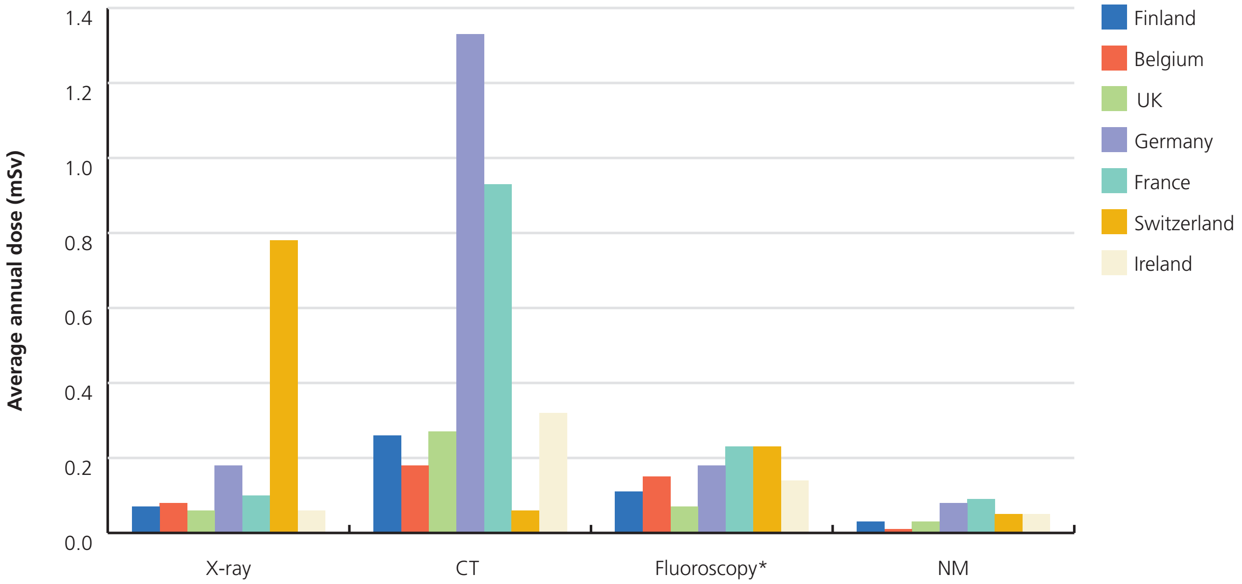
Figure 14. Distribution of examination frequency of diagnostic medical imaging 2009–2012



The largest contributor is CT which accounts for only 6% of examinations but contributes 55% of the collective dose. There is also a significant contribution of 20% to the overall collective dose from interventional cardiology, which accounts for only 0.7% of the examinations.

The average annual dose across the modalities from other EU countries published in the Draft Report of the EU Dose Datamed Project (European Commission, 2013b) is illustrated in Figure 15. The respective contributions from the various modalities in Ireland are similar to or lower than those in the other European countries shown.

Figure 15. Comparison of average annual dose (mSv) per modality across EU countries



**Including interventional radiology and cardiology*

The overall average annual dose of 546 μSv from all diagnostic medical procedures in Ireland is higher than the value reported in the UK (419 μSv (Hart et al., 2010), but lower than in other countries such as France (660–830 μSv (Scanff et al., 2008)) or Norway (1090 μSv (Borretzen et al., 2007)).

3 Summary of doses

In previous sections, each exposure pathway has been described and the associated dose calculated and compared, where possible, to the results published in 2008 (Colgan et al.) A number of pathways have been included in this report for which results were not available in 2008. A more complete analysis of radioactivity in the diet has also been completed, including measurements of the radioisotopes lead-210 and radium-226 in food, and new data is included on thoron in Irish homes. In addition, a more detailed evaluation of medical exposures has also been completed based on comprehensive HSE surveys which included a wider range of procedures in modalities such as CT, interventional radiology, general X-ray and nuclear medicine along with additional modalities such as PET-CT and dental radiology.

3.1 Collated results of this study

The estimated doses for the different exposure pathways are collated in Table 19. The percentage contributions that the different pathways make to the total dose are presented in Figure 16. In total, natural radiation pathways account for 86% of all radiation exposures in Ireland and the bulk of the remainder is due to diagnostic medical exposure of patients. Artificial sources make a very small contribution to both the collective and average annual doses.

It is important to remember that the data presented here represents average values for the Irish population. For many pathways, there can be large variability in the doses received by individuals. For example, radon concentrations in Irish homes range from 10 Bq/m^3 up to 49,000 Bq/m^3; these correspond to annual doses of 250 µSv to 1,225,000 µSv. The average annual dose from radon in homes is based on a population-weighted average radon concentration of 91 Bq/m^3.

Figure 17 shows the percentage contribution of each component of natural radioactivity to the total dose of 3,480 µSv from natural sources of radiation. Radon continues to be the dominant contributor to the dose, with radon in homes contributing a higher radiation dose than radon exposure in workplaces. This is due to the greater amount of time spent indoors in the home, to the higher average radon concentrations in homes compared to workplaces and to the fact that the working population is only about one third of the total population. Similar contributions of around 250–350 µSv each are received from cosmic radiation, thoron, natural radioactivity in soils and natural radioactivity in foodstuffs.

Table 19. Average annual radiation doses in Ireland

Exposure pathway	Dose due to natural sources of radiation (µSv)	Dose due to artificial sources of radiation (µSv)
Cosmic radiation	**343**	
At sea level	302	
Airline travel	41	
Gamma radiation in the environment	**295**	**6.01**
Radon in homes	**1995**	
Thoron in homes	**350**	
Radioactivity in food and water†	**262**	**5**
Carbon-14	6	2
Potassium-40	170	
Rubidium-87	2	
Radium-228 (from thorium-232)	7	
Radium-226	4	
Polonium-210 (from uranium-238)	47	
Lead-210 (from uranium-238)	26	
Discharges from Sellafield		0.07
Radioactivity in milk		0.5
Caesium-137 in mixed diet		2.7
Occupational exposures	**235**	**0.02**
Aircrew cosmic radiation	6	
Radon in schools	3.3	
Radon in above ground workplaces	226	
Radon in below ground workplaces	<0.02	
NORM industries	<0.1	
Artificial radioactivity		0.02
Medical exposures		**546**
CT		298
Dental		1.3
General X-ray		56.4
Nuclear medicine (excluding PET-CT)		24.4
PET-CT		28.3
Interventional radiology and cardiology		137.3
TOTAL (4037)	**3480 (86%)**	**557 (14%)**

† *Drinking water accounts for an average annual dose of <100 µSv*

Figure 16. Contributions of different pathways to average annual radiation doses in Ireland

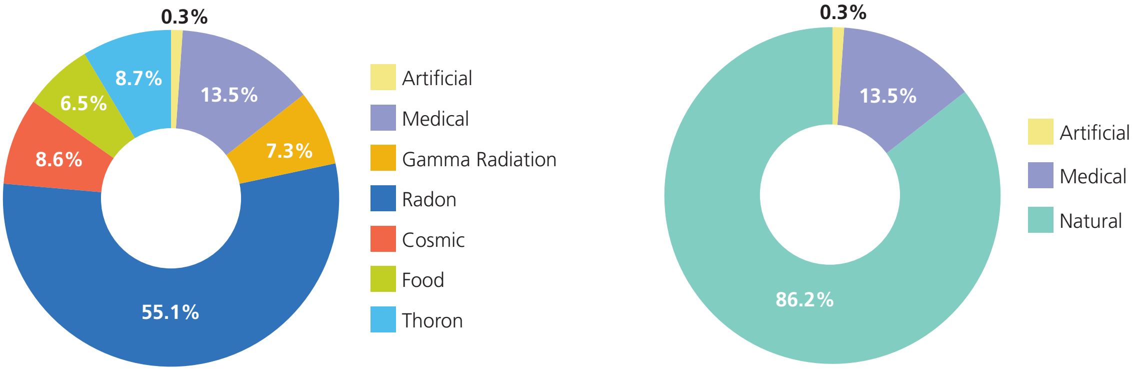
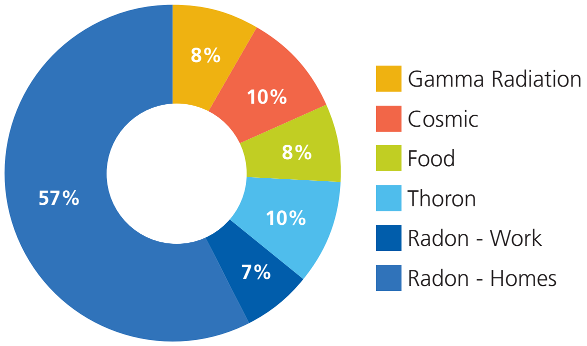


Figure 17. Contribution of different pathways to radiation doses from natural sources in Ireland



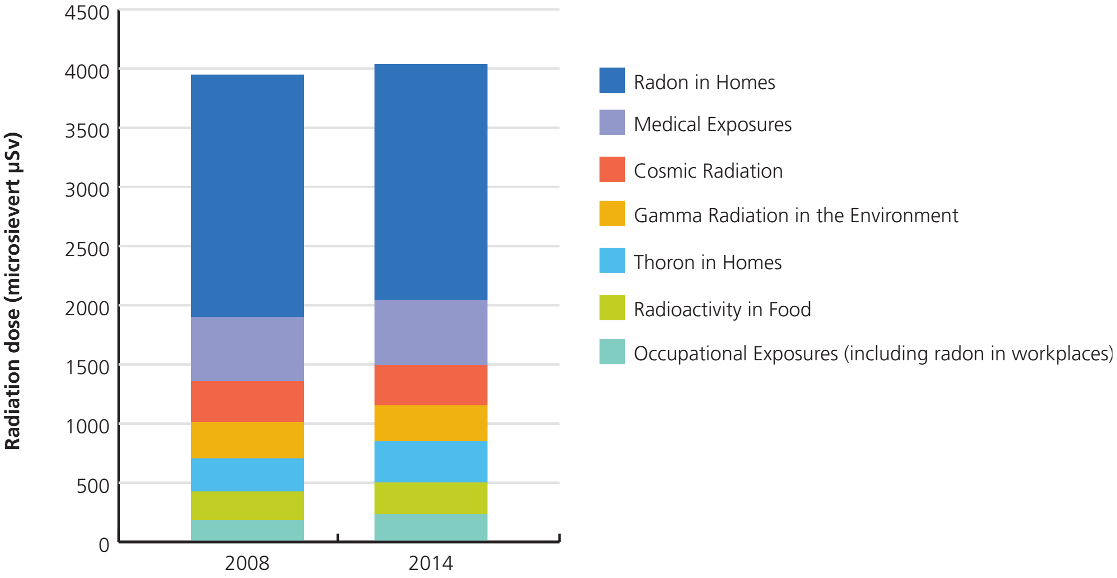
3.2 Comparison to 2008 population dose report

The average annual doses estimated for each exposure pathway in this study and as reported in 2008 (Colgan et al., 2008) are summarised in Table 20 and illustrated in Figure 18.

Table 20. Estimated average annual doses in Ireland (μSv)

Exposure pathway	2008	2014
Cosmic radiation	345	343
Gamma radiation in the environment	310	301
Radon in homes	2,050	1,995
Thoron in homes	280	350
Radioactivity in food	240	267
Occupational exposures (including radon in workplaces)	185	235
Medical exposures	540	546
TOTAL	**3,950**	**4,037**

Figure 18. Estimated average annual doses in Ireland (μSv) by exposure pathway



The slight increase in the total average annual dose observed (2%) is mainly due to the increase in the estimate of the average annual dose from thoron (increase from 280 μSv in 2008 to the current value of 350 μSv), which itself is due to the use of more recent and updated dose conversion coefficients, rather than from increased thoron levels. The estimated doses from exposure to radioactivity contained in food and from radon in above-ground workplaces also increased slightly. These increases are primarily due to the availability of additional or more comprehensive data than in 2008. The overall collective and average annual doses arising from medical exposures have not increased significantly since 2008 even though data from more examination types (e.g. PET-CT and interventional procedures) has been included.

4 Conclusions

The estimated average annual dose in Ireland from all sources of radiation of 4,037 µSv is consistent with the value of 3,950 µSv which was estimated in the 2008 assessment (Colgan et al., 2008).

Radon continues to be the principal source of radiation exposure in Ireland, representing just over 55% of the radiation dose received by the Irish population. Most of this dose is received in people's homes although radon exposure at work continues to account for the largest contribution to all occupational exposure. Radon is also the most variable source of radiation exposure with radon concentrations in Irish homes ranging from 10 Bq/m^3 up to 49,000 Bq/m^3, corresponding to annual doses of 250 µSv to 1,225,000 µSv. It is hoped that there will be a significant reduction in radiation exposure from radon over the coming years – this can be achieved by raising awareness of the radon problem and promoting prevention and remediation through the recently published National Radon Control Strategy.

Medical exposure of patients remains by far the largest man-made contributor to the collective dose. However, the collective and average annual doses from medical exposure have not increased significantly since 2008 despite the fact that we now have data from a wider range of modalities. Because of the significant differences in the range of data available to this assessment and that of 2008, it is difficult to be definitive about the existence of any trend in radiation doses attributable to medical procedures. The HSE surveys that were conducted between 2010 and 2013 now provide a comprehensive set of national baseline data against which future surveys may be compared to track changes to the population's radiation doses from medical exposure.

The remaining contributions to the total radiation exposure in Ireland come primarily from natural sources such as cosmic radiation, thoron and radioactivity in the ground and in food. While the contributions from cosmic radiation and radioactivity in the ground remain the same as in the 2008 assessment, the contributions from thoron and radioactivity in food have increased, predominantly as a result of the availability of additional data for this assessment. These sources make a relatively small contribution to the collective dose or are not amenable to control. Other sources such as fallout from nuclear accidents and weapons tests or discharges of nuclear or radioactive waste to the environment remain at very low levels.

5 Acknowledgements

The RPII wishes to express its appreciation to the following for their assistance in various ways towards the preparation of this report.

- Radon Measurement Services
- The First Restaurant, University College Dublin
- Dr Janette Walton of the Irish Universities Nutrition Alliance
- Health Service Executive

The report was prepared under the direction of Dr Ciara McMahon, Director, Environmental Surveillance and Assessment Division. The project was managed by Ms Lorraine Currivan and the principal author was Ms Collette O'Connor, Environmental Surveillance and Assessment Division.

Special thanks are due to the following RPII and HSE staff that provided material for the report and commented on specific aspects:

- Dr Kevin Kelleher, RPII
- Dr Paul McGinnity, RPII
- Ms Veronica Smith, RPII
- Ms Stephanie Long, RPII
- Ms Noeleen Cunningham, RPII
- Ms Mandy Lewis, HSE

Advice and comment on the report were also received from, Dr Ann McGarry, Chief Executive Officer, RPII, Dr Catherine Organo, RPII, and Prof. Ian Mc Aulay, TCD.

Production of the report was managed by the Communications section of the RPII, in particular, Mr David Dawson and Ms Linda Coyne.

Finally, many thanks to other RPII staff who provided invaluable technical support and assistance in the preparation of this report.

6 References

Bartlett, D. et al., 1997. Dosimetry for occupational exposure to cosmic radiation. *Radiation Protection Dosimetry*, Volume 70, pp. 394–404.

Berrington et al., 2009. Projected Cancer Risks from Computed Tomography Scans Performed in the United States in 2007. *Archives of Internal Medicine*, 169(22), pp. 2071–2077.

Borretzen, I., Lysdahl, K. & Olerud, H., 2007. Diagnostic radiology in Norway - trends in examination frequency and collective effective dose. Radiation Protection Dosimetry, 124(4), pp. 337–347.

Bouville, A. & Lowder, W., 1988. Human population exposure to cosmic radiation. *Radiation Protection Dosimetry*, Volume 24, pp. 293–298.

Brenner, D. & Hall, E., 2007. Computed Tomography - An Increasing Source of Radiation Exposure. *New England Journal of Medicine,* Volume 357, pp. 2277–2284.

Cefas, 2008. *An assessment of aquatic radiation pathways in Ireland*, 2008. Lowestoft: Environment Report RL 16/08, Cefas contract C3030.

Central Statistics Office, 2012a. *Principal statistics: employment and unemployment*. [Online]
Available at: http://www.cso.ie/en/statistics/labourmarket/principalstatistics/
[Accessed 03 02 2014].

Central Statistics Office, 2012b. *Statistical Yearbook of Ireland 2012 Edition*. [Online]
Available at: http://www.cso.ie/en/releasesandpublications/statisticalyearbookofireland/statisticalyearbookofireland2012edition/
[Accessed 06 03 2014].

Central Statistics Office, 2013a. *Household Travel Survey 2012*. [Online]
Available at: http://www.cso.ie/en/media/csoie/releasespublications/documents/tourismtravel/2012/hotra2012.pdf
[Accessed 5 March 2014].

Central Statistics Office, 2013b. *Tourism and Travel 2012*. [Online]
Available at: http://www.cso.ie/en/media/csoie/releasespublications/documents/tourismtravel/2012/tata_2012.pdf
[Accessed 6 March 2014].

Colgan, P., 1980. *Environmental radiation in Ireland and its possible health implications*. PhD Thesis. Dublin: Trinity College.

Colgan, P., Organo, C., Hone, C. & Fenton, D., 2008. *Radiation Doses Received by the Irish Population*. Dublin: Radiological Protection Institute of Ireland.

Cunningham, J., MacNeill, G. & Pollard, D., 1987. *Chernobyl: Its effect on Ireland*. Dublin: Nuclear Energy Board.

Currivan, L., Kelleher, K., Solodovnik, E. & McMahon, C., 2013. *Radioactivity in bottled water produced in Ireland*. RPII 13/05. Dublin: Radiological Protection Institute of Ireland.

DECLG, 2014. *National Radon Control Strategy*. Dublin:Department of Environment, Community and Local Government.

DES, 2012. *Key Statistics 2011/2012*. [Online]
Available at: http://www.education.ie/en/Publications/Statistics/Key-Statistics-2012.pdf
[Accessed 15 10 2013].

Doorly, E., 2006. *Radioactivity from building materials in the Republic of Ireland*. Ph.D. Thesis. Dublin: Trinity College Dublin.

Dowdall, A. et al., 2013. *Radioactivity levels in groundwater sources in Ireland*. Dublin: Radiological Protection Institute of Ireland.

EPA, 2010a. *Water Quality in Ireland 2007 – 2009*. Wexford: Environmental Protection Agency.

EPA, 2010b. *The Provision and Quality of Drinking Water in Ireland. A Report for the Years 2008–2009*. Wexford: Environmental Protection Agency.

EU Council, 1997. *Directive 97/43/Euratom of 30 June 1997 On the health protection of individuals against the dangers of ionising radiation in relation to medical exposure and repealing Directive 84/466/Euratom*. Luxembourg: Council of the European Union.

European Commission, 2000. Commission Recommendation 2000/473/EURATOM on the application of Article 36 of the Euratom Treaty concerning the monitoring of the levels of radioactivity in the environment for the purpose of assessing the exposure of the population as a whole. *Official Journal of the European Communities*, L191, 277.7.2000, pp.37–51.

European Commission, 2004. *Radiation Protection 140*. Cosmic Radiation Exposure of Aircraft Crew. Luxembourg: European Commission.

European Commission, 2008. *Radiation Protection No. 154. European Guidance on estimating population doses from medical X-rays*. Luxembourg: European Commission.

European Commission, 2012. *Radiation Protection No.173. Comparison of Codes Assessing Radiation Exposure of Aircraft Crew due to Galactic Cosmic Radiation*. Luxembourg: European Commission.

European Commission, 2013a. *Council Directive 2013/15/EURATOM of 22 October 2013 laying down requirements for the protection of the health of the general public with regard to radioactive substances in water intended for human consumption*. Luxembourg: European Commission.

European Commission, 2013b. *Draft Report: Study on European Population Doses from Medical Exposure (Dose Datamed II).* Luxembourg: European Commission.

European Communities, 1998. Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption. *Official Journal of the European Communities*, L330, 05/12/1998, pp. 32–54.

Fennell, S. et al., 2002. *Radon in dwellings. The Irish national radon survey*. Dublin: Radiological Protection Institute of Ireland.

Gunning, G.A.; Pollard, D.; Finch, E.C., In press. An outdoor radon survey and minimizing the uncertainties in low level measurements using CR-39 detectors. *Journal of Radiological Protection*.

Ham, G., Ewers, L. & Wilkins, B., 1998. *Variations in concentrations of naturally occurring radionuclides in foodstuffs*. Chilton: National Radiological Protection Board.

Hart, D., Wall, B., Hillier, M. & Shrimpton, P., 2010. *Frequency and Collective Dose for Medical and Dental X-ray Examinations in the UK*. Chilton: Health Protection Agency.

Hayes, A., *An Investigation of the Relationship between Soil Composition and External Radiation Dose Rates in Selected Parts of Ireland*. M.Sc. Thesis. Dublin: National University of Ireland.

HPA, 2006. *Notes for Guidance on the Clinical Administration of Radiopharmaceuticals and Use of Sealed Radioactive Sources*. Chilton: Health Protection Agency.

HSE, 2008. *National Radiation Safety Committee Annual Report*. Dublin: Health Services Executive.

HSE, 2011a. Population Dose from CT Scanning: 2009. Dublin: Health Services Executive.

HSE, 2011b. *Population Dose from Dental Radiology: 2010*. Dublin: Health Services Executive.

HSE, 2013. *Population Dose from General Radiology and Nuclear Medicine: 2011*. Dublin: Health Services Executive.

ICRP, 1993. *Protection against Radon-222 at Home and at Work*. International Commission on Radiological Protection. Publication 65. Oxford: Pergamon Press.

ICRP, 1994. *Human Respiratory Tract Model for Radiological Protection*. International Commission on Radiological Protection. Publication 66. Oxford: Pergamon Press.

ICRP, 1995. *Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5: Compilation of Ingestion and Inhalation Dose Coefficients*. International Commission on Radiological Protection. Publication 72. Oxford: Pergamon Press.

ICRP, 2000. *Radiation dose to patients from radiopharmaceuticals*. International Commission on Radiological Protection. Publication 80. Oxford: Pergamon Press.

ICRP, 2007. *The 2007 recommendations of the International Commission on Radiation Protection. International Commission on Radiological Protection*. Publication 103. Oxford: Pergamon Press.

Ishikawa, T., Tokonami, S. & Nemeth, C., 2007. Calculation of dose conversion factors for thoron decay products. *Journal of Radiological Protection*, 27(4), pp. 447–456.

IUNA, 2011. *National Adult Nutrition Survey Summary Report*. Cork: Irish Universities Nutrition Alliance.

Kendall, G. & Phipps, A., 2007. Effective and organ doses from thoron decay products at different ages. *Journal of Radiological Protection*, 27(4), pp. 427–35.

Lee, E., Menezes, G. & Finch, E., 2004. Natural radioactivity in building materials in the Republic of Ireland. *Health Physics*, Volume 86, pp. 378–383.

Lehto, J. & Hou, X., 2011. *Chemistry and Analysis of Radionuclides*. Germany: Wiley-VCH.

Madden, J. et al., 1994. *Radon in Selected Areas in Ireland*. Report RPII 94/3. Dublin: Radiological Protection Institute of Ireland.

Marsh, D., 1991. *Radiation mapping and soil radioactivity in the Republic of Ireland*. M.Sc. Thesis. Dublin: Trinity College.

McAulay, I. & Colgan, P., 1984. Gamma radiation levels in dwellings in the Republic of Ireland. *Radiation Protection Dosimetry*, Volume 7, pp. 309–311.

McGinnity, P. et al., 2012a. *Radioactivity Monitoring of the Irish Environment 2010–2011*. Report RPII 12/02. Dublin: Radiological Protection Institute of Ireland.

McGinnity, P. et al., 2012b. *Assessment of the Impact on Ireland of the 2011 Fukushima Nuclear Accident*. Report RPII 12/01. Dublin: Radiological Protection Institute of Ireland.

McLaughlin, J. et al., 2011. Long-term Measurements of Thoron, its Airborne Progeny and Radon in 205 Dwellings in Ireland. *Radiation Protection Dosimetry*, 145(2–3), pp. 189–193.

NASA, 2009. *Shuttle Radar Topography Mission - The Mission to Map the World*. [Online]
Available at: http://www2.jpl.nasa.gov/srtm
[Accessed 18 September 2013].

Ní Choncubhair, O., 2007. *Passive detection of environmental thoron gas and its progeny*. M.Sc. Thesis. Dublin: National University of Ireland.

Organo, C. et al., 2007. *Occupational exposure to natural sources of radiation in Ireland*. Presented at: 8th International Conference on the Natural Radiation Environment, Buzios, Brazil, 7–12 October 2007.

Organo, C. et al., 2004. High radon concentrations in a house near Castleisland, county Kerry (Ireland) - identification, remediation and post-remediation. *Journal of Radiological Protection*, Volume 24, pp. 107–120.

Organo, C. & Fenton, D., 2008. *Radiological assessment of NORM Industries in Ireland – Radiation doses to workers and members of the public*. Dublin: Radiological Protection Institute of Ireland.

Peterman, B. & Perkins, C., 1988. Dynamics of radioactive chemically inert gases in the human body. *Radiation Protection Dosimetry*, Volume 22, pp. 5–12.

RPII, 2013. *RPII Inspection and Licensing Activities and Annual Inspection Programme for 2013*. Dublin: Radiological Protection Institute of Ireland.

Ryan, R. et al., 2007. *Radioactivity Monitoring of the Irish Environment 2003–2005*. Report RPII-07/1. Dublin: Radiological Protection Institute of Ireland.

Ryan, T., 1991. *Nuclear fallout in the Irish terrestrial environment*. Ph.D. Thesis. Dublin: National University of Ireland.

Ryan, T., Sequeira, S., McKittrick, L. & Colgan, P., 2003. *Radon in Drinking Water in Co. Wicklow - A Pilot Study*. Report RPII-03/1. Dublin: Radiological Protection Institute of Ireland.

Scanff et al., 2008. Population exposure to ionizing radiation from medical examinations in France. *British Journal of Radiology*, Volume 81, pp. 204–213.

Stationery Office, 2000. *Radiological Protection Act, 1991 (Ionising Radiation) Order, 2000 (Statutory Instrument No. 125 of 2000).* Dublin: Stationery Office.

Stationery Office, 2002. *European Communities (Medical Ionising Radiation Protection) Regulations 2002 (Statutory Instrument No. 478 of 2000).* Dublin: Stationery Office.

Swift, B., 1998. Dating human skeletal remains: Investigating the viability of measuring the equilibrium between Po-210 and 210Pb as a means of estimating the post-mortem interval. *Forensic Science International*, 98(1–2), pp. 119–126.

Synnott., H., Colgan, P., Hanley, O. & Denton, D., 2007. The effectiveness of radon remediation in Irish schools. *Health Physics*, Volume 92, pp. 50–57.

Synnott, H. et al., 2004. *Radon in Irish Primary and post-Primary schools. The Results of a National Survey*. Report RPII-04/02. Dublin: Radiological Protection Institute of Ireland.

Synnott, H., Hanley, O., Fenton, D. & Colgan, P., 2006. *Radon in Irish Schools: the results of a national survey. Journal of Radiological Protection*, Volume 26, pp. 85-96.

TELLUS Border, 2013. *TELLUS Border*. [Online]
Available at: http://www.tellusborder.eu/
[Accessed 17 September 2013].

UNSCEAR, 1993. *Sources and Effects of Ionising Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation. New York: United Nations.

UNSCEAR, 2000. *Sources and Effects of Ionising Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation. New York: United Nations.

USGS, 2011. Shuttle Radar Topography Mission (SRTM). [Online]
Available at http://srtm.usgs.gov/index.php
[Accessed 14 March 2014]

Watson, S., Jones, A., Oatway, W. & Hughes, J., 2005. *Ionising Radiation Exposure of the UK Population:2005 review*. HPA-RPD-001. Chilton: Health Protection Agency.

WHO, 1993. *Guidelines for Drinking Water Quality, 2nd edition*. Geneva: World Health Organization.

Worldometers, 2013. *Worldometers - real time world statistics*. [Online]
Available at: http://www.worldometers.info/world-population/
[Accessed 02 October 2013].

Yamamoto, M. et al., 2009. Measurements of ^{210}Po and ^{210}Pb in total diet samples: Estimate of dietary intakes of ^{210}Po and ^{210}Pb for Japanese. *Journal of Radioanalytical and Nuclear Chemistry*, 279(1), pp. 93–103.

Appendix 1

Summary of surveys of outdoor gamma radiation levels in Ireland

Marsh carried out a survey of outdoor gamma dose rate levels based on the 10 x 10 km^2 Irish national grid (Marsh, 1991). In total, 650 measurements were made throughout the country, one close to the centre of each accessible grid square. The results indicated an average outdoor absorbed dose rate in air for the whole country of 31 nGy/h.

Hayes followed up the study by Marsh and measured gamma dose rate levels at 64 locations distributed along 5 different transects (Hayes, 1995). Four transects were located in regions previously known to contain high levels of the natural radionuclide Ra-226 while the fifth transect was located in a contrasting region that had previously shown low activities of Ra-226. An average value of 34 nGy/h was calculated based on this supplementary dataset.

An earlier study by Colgan considered two gamma dose rate datasets (Colgan, 1980). The first comprised measurements taken at 264 locations throughout Ireland and yielded an average value of 51 nGy/h. While the measurement points were not randomly selected and the sample size was considerably smaller than Marsh's, the data was relatively uniformly distributed across the country.

The second survey reported by Colgan was a more detailed assessment of eight eastern counties. The average of at least three individual gamma dose rate measurements were reported for each District Electoral Division (DED) in Carlow, Kildare, Kilkenny, Meath, Waterford, Westmeath, Wexford, Wicklow, leading to some 2,756 measurements in total and 622 aggregated results.

More recently, gamma radiation from the ground has been derived from airborne gamma spectrometry measurements carried out with a spatial resolution of 50m conducted as part of TELLUS Border geophysics survey discussed in Section 2.2.1 (TELLUS Border, 2013). Based on this survey, the average value for gamma radiation across six border counties between the Republic of Ireland and Northern Ireland - Donegal, Sligo, Leitrim, Cavan, Monaghan and Louth – was found to be 35 nGy/h.

Appendix 2

Radon measurements

Table A.1 Distribution of radon measurement results by county (based on measurements completed up to 31 December 2013)

County	Number of houses measured	% homes > 200 Bq/m³	Number of houses in categories of radon concentration			Highest measured concentration (Bq/m³)
			0–199 Bq/m³	200–799 Bq/m³	>800 Bq/m³	
Carlow	1,218	19%	982	224	12	2,300
Cavan	461	3%	447	14	0	800
Clare	4,216	12%	3,694	433	89	3,500
Cork	5,770	12%	5,057	661	52	4,500
Donegal	1,504	5%	1,423	79	2	3,400
Dublin	3,778	6%	3,554	222	2	1,400
Galway	7,919	21%	6,255	1,456	208	4,200
Kerry	4,196	16%	3,507	555	134	49,000
Kildare	1,404	4%	1,345	56	3	1,100
Kilkenny	1,398	14%	1,199	184	15	2,400
Laois	582	4%	558	24	0	600
Leitrim	411	7%	383	27	1	1,600
Limerick	1,428	8%	1,315	109	4	1,900
Longford	334	11%	296	37	1	900
Louth	1,172	10%	1,050	120	2	900
Mayo	4,283	18%	3,532	687	64	6,200
Meath	1,066	8%	985	79	2	900
Monaghan	309	6%	290	19	0	800
Offaly	795	2%	777	18	0	800
Roscommon	750	11%	667	79	4	1,400
Sligo	2,439	25%	1,828	511	100	5,600
Tipperary	2,634	12%	2,310	297	27	3,400
Waterford	2,551	20%	2,045	440	66	9,700
Westmeath	767	9%	698	68	1	1,100
Wexford	2,345	16%	1,969	345	31	2,900
Wicklow	2,214	17%	1,837	348	29	16,400
Total	**55,944**	**14%**	**48,003**	**7,092**	**849**	

Notes:

- The RPII database consists of 11,319 measurements undertaken as part of the National Radon Survey (NRS) and over 44,000 other measurements
- NRS measurements were made for a continuous 12-month period. All other measurements were made for a minimum period of three months and were seasonally adjusted.
- All measurements have been made in accordance with the RPII measurement protocol.
- Where there are duplicate measurements for any home, only the first measurement was used.
- All post-remediation measurements have been disregarded.
- Measurements made by other radon measurement services are not included.
- The maximum measurement for each county has been rounded to the nearest 100.

Table A.2 Highest indoor radon concentrations identified by the RPII (based on measurements completed up to 31 December 2013)

	County	Location	Radon concentration (Bq/m^3)
1	Kerry	Castleisland	49,000
2	Kerry	Castleisland	37,000
3	Kerry	Tralee	18,850
4	Wicklow	Aughrim	16,438
5	Waterford	Butlerstown	9,714
6	Kerry	Tralee	8,490
7	Kerry	Tralee	8,056
8	Mayo	Crossmolina	6,203
9	Kerry	Tralee	6,184
10	Sligo	Ballisodare	5,619
11	Sligo	Knocknarea	5,508
12	Kerry	Tralee	5,185
13	Kerry	Tralee	5,142
14	Kerry	Ardfert	4,913
15	Kerry	Tralee	4,772
16	Kerry	Tralee	4,759
17	Cork	Mallow	4,516
18	Cork	Carrigaline	4,444
19	Kerry	Castleisland	4,310
20	Galway	Castlerea	4,189
21	Kerry	Tralee	4,156
22	Carlow	Borris	4,050
23	Kerry	Tralee	3,986
24	Galway	Galway City	3,750
25	Sligo	Ballymote	3,733
26	Cork	Mallow	3,726
27	Galway	Castlegar	3,708
28	Kerry	Castleisland	3,677
29	Kerry	Tralee	3,667
30	Kerry	Tralee	3,593
31	Clare	Lisdoonvarna	3,541
32	Sligo	Sligo Town	3,515
33	Kerry	Tralee	3,452
34	Galway	Rahoon	3,434
35	Mayo	Ballinrobe	3,416
36	Donegal	Lifford	3,402
37	Tipperary	Clonmel	3,364
38	Galway	Castlerea	3,357
39	Mayo	Claremorris	3,261
40	Cork	Mallow	3,227
41	Mayo	Claremorris	3,216
42	Sligo	Boyle	3,191
43	Waterford	Fenor	3,140
44	Sligo	Castlebaldwin	3,102
45	Kerry	Castleisland	3,075
46	Kerry	Tralee	3,038
47	Kerry	Tralee	3,036
48	Waterford	Cappagh	3,023
49	Sligo	Hazelwood	3,009
50	Sligo	Knocknarea	3,004

Radiological Protection Institute of Ireland
An Institiúid Éireannach um Chosaint Raideolaíoch

Contact Us

Radiological Protection Institute of Ireland
3 Clonskeagh Square
Dublin 14
Ireland

Tel: 01 2697766
Fax: 01 2697437
Website: www.rpii.ie
Email: rpii@rpii.ie

Opening hours: 9:00am to 5:00pm