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Radon in Drinking Water in Co. Wicklow – a Pilot Study

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Summary

Attention has been focused on the issue of radon in drinking water by a European Commission recommendation proposing that surveys should be undertaken in Member States to determine the scale and nature of exposures caused by radon in domestic drinking water supplies. The Commission recommends 1000 Bq/l as the radon activity concentration in private drinking water supplies above which remedial action to reduce the concentration should be taken. The logic behind the proposed action level is that it would broadly correspond to the risk posed to an individual from exposure to radon in the home at the current Reference Level of 200 Bq/m^3 in air.

A pilot study to assess the distribution and concentrations of radon in private ground water supplies was recently completed in Co. Wicklow. County Wicklow was selected for the study primarily on the basis that the underlying geology is predominantly granite with elevated uranium content. Furthermore, there is an estimated 1200 to 5000 private ground water supplies in use in the county and high radon activity concentrations in air in a significant number of dwellings have previously been predicted. As part of the pilot study, a number of scientific issues were addressed in order to underpin the results obtained and these are also discussed in the report.

Radon activity concentrations were measured in the private ground water supplies of 166 houses in Co. Wicklow. In all cases the ground water was the principal source of drinking water for the house occupants. Four supplies had activity concentrations in excess of the Recommended EC action level of 1000 Bq/l, fifteen had activity concentrations between 500 and 1000 Bq/l, 51 were between 100 and 500 Bq/l and 96 had activity concentrations below 100 Bq/l.

The doses estimated for the ingestion of radon bearing water vary significantly with the quantity of drinking water consumed and the degree to which the water has been processed prior to consumption. However dose estimates based on measurements made in this study demonstrate that radon in drinking water may pose a significant additional health risk, in the longer term, to some consumers who depend on private ground water supplies as their primary source of drinking water.

1. INTRODUCTION

Radon-222 is a naturally occurring radioactive gas that is part of the uranium decay series. Its presence in the environment is associated mainly with trace amounts of uranium and its immediate parent, radium-226, in rocks and soil. Because of its gaseous nature, radon can move freely through porous media such as soil or fragmented rock. Where pores in rock and soil under the water table are saturated with water, radon is dissolved into the water and is transported with it. Surface waters are generally least affected by radon [EC, 2001]. Radon in indoor air, identified as the principal contributor to radiation dose in Ireland, has been comprehensively studied and reported [Fennell *et al.,* 2002]. To date, little or no data have been collected on radon in drinking water.

Radon in domestic water supplies can cause human exposure to a radiation dose both through inhalation and ingestion. Radon is easily released from water into the atmosphere by agitation or heating. Many domestic uses of water result in such a release and can contribute to the total indoor air radon concentration. It has been estimated that 1000 Bq/l of radon in water will, on average, increase the radon concentration in indoor air by 100 Bq/m^3 [EC, 2001]. Prolonged exposure to high concentrations of radon in indoor air increases the risk of lung cancer. The organ at greatest risk from the ingestion of water containing radon and radon decay products is considered to be the stomach [Khursheed, 2000].

Attention has been focused on the issue of radon in drinking water by a European Commission recommendation [EC, 2001] proposing that surveys should be undertaken in Member States to determine the scale and nature of exposures caused by radon in domestic drinking water supplies. The Commission recommends 1000 Bq/l as the radon activity concentration in private drinking water above which remedial action to reduce the concentration should be taken. The logic behind the proposed action level is that it would broadly correspond to the risk posed to an individual from exposure to radon in the home at the current Reference Level of 200 Bq/m^3. This Reference Level applies in Ireland and several other EU Member States.

It is further recommended that remedial action should be taken when public supplies are found in excess of 100 Bq/l. According to the Environmental Protection Agency [EPA, 2000], surface waters account for 75% of all water supplies in the Republic while 25% of water supplies, both public and private, are derived from ground waters. It is estimated by the Department of the Environment and Local Government that there may be as many as 150,000 boreholes supplying drinking water in use throughout the country.

A pilot study of radon in drinking water was recently completed in Co. Wicklow. County Wicklow was selected for the study on the basis of the following:

- the underlying geology is predominantly granite with elevated uranium content. This represents a potential source for the production of radon and its accumulation in drinking water;
- high indoor radon levels in homes have already been identified throughout the county; and
- where high radon levels are present in drinking water, these are often associated with supplies derived either partially or totally from ground water. There are an estimated

1200 to 5000 private ground water supplies in use in the county and each of these could potentially contain elevated concentrations of radon.

2. PILOT STUDY OBJECTIVES

The principal objective of the study was to assess the distribution of radon levels in private drinking water supplies in an area of Ireland where some high levels would be expected on the basis of underlying geology and existing information on indoor radon levels in homes. As part of the study a number of scientific issues were addressed in order to underpin the results obtained. These were:

- to devise an appropriate sampling and analysis methodology for radon in drinking water;
- to analyse a subset of samples for radon decay products (polonium-210) and elemental uranium;
- to determine the temporal behaviour of radon in drinking water at a sub-set of locations; and
- to determine the radon concentration in air in a selection of houses.

The study was designed and implemented in close co-operation with Wicklow County Council and involved the measurement of radon in drinking water collected from 166 individual homes. Council staff carried out the majority of sampling following training in sampling procedures by RPII personnel. Samples were collected as part of the Council's routine sampling scheme for other contaminants. A commercial courier service was used to transport samples from Wicklow County Council to the RPII.

3. SAMPLING AND ANALYSIS

3.1 Radon in Drinking Water Sampling Protocol

The drinking water sampling protocol devised for this study is detailed in Annex A. A copy of the sampling form is provided in Annex B. When sampling water for radon, it is important that the sample is stored in an airtight container that is completely filled to avoid diffusion of radon from the water into an air pocket. It is also desirable that the sample is analysed for radon as soon as possible after collection to avoid uncertainties that may be introduced by radioactive decay and losses from the sample container.

In this study, samples were collected in duplicate from the cold water kitchen tap in each house. This was considered to be the water most likely to be consumed directly by the householders. Samples were dispatched to the RPII for analysis typically within 24 hours of collection. In the interim period, samples were stored in a refrigerator with care taken to ensure that the samples did not freeze. All measurements were decay corrected to the time of sampling. Plotting the results of measurements of duplicate samples showed that there was very good agreement between pairs of samples (R^2 = 0.99). This correlation can be clearly seen in Figure 1 and provides confidence in the reproducibility achievable with the sampling protocol.

However some losses do occur from the sample container between sampling and analysis. The magnitude of these losses for the sampling procedure employed in this study was estimated to be about 6% after twenty-four hours. This is typically within the uncertainty of the measurement. This percentage loss was estimated by preparing samples on location for measurement, measuring them within five hours of sampling and comparing them with measurements made on duplicates 24 hours later (Figure 2).

Where the duplicate water samples were found to have radon activity concentrations in excess of 1000 Bq/l, water from these houses was re-sampled with samples taken from different taps inside and outside the house. Measurements of indoor radon were also made in these houses over a three month period.

One house in Co. Wicklow was sampled on a twice-monthly basis for five months in order to establish temporal trends. More comprehensive details of the sampling and analysis methodologies may be found in Sequeira *et al.* (in press).

Figure 1

Linear Regression Analyses of Duplicate Water Samples from 166 Houses in Co Wicklow

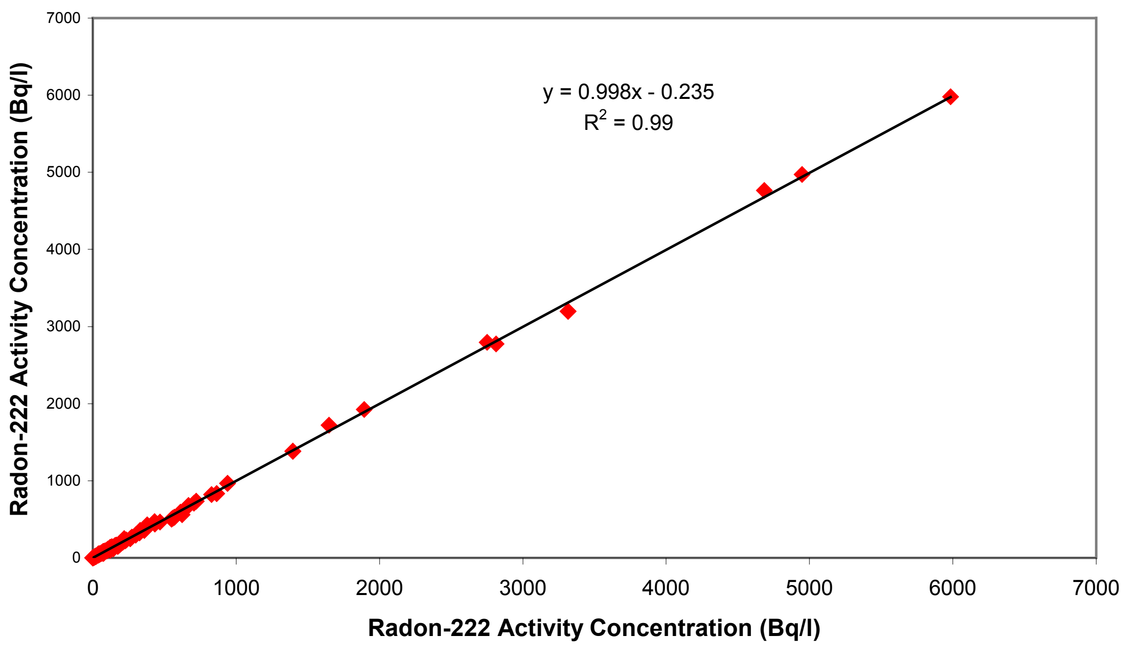
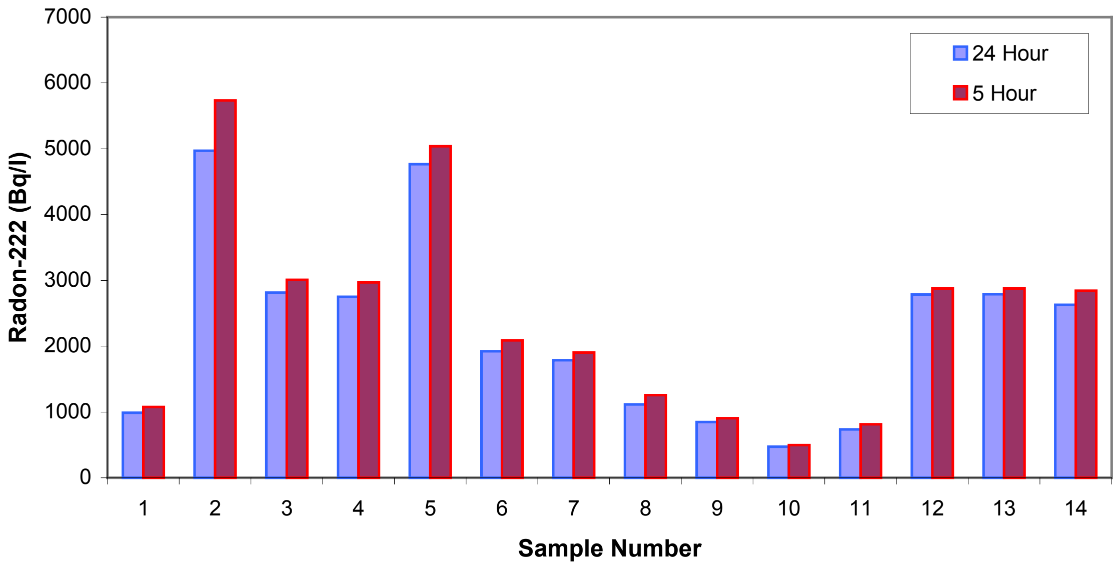


Figure 2

Radon-222 Measurements in Drinking Water - 5 and 24 hours after Sampling



3.2 Radon in Drinking Water Analysis

Radon in water was measured by low level liquid scintillation counting using a non-water miscible organic scintillant and a detector configuration which facilitates the separation of alpha (α) and beta (β) particles.

When samples arrived at the laboratory they were stored in a cool (greater than 4^{o} C), dark place for thirty minutes. This minimises the loss of radon when the sample container is opened. A known quantity of the water sample was gently added to 11 ml of the proprietary liquid scintillant *Ultima Gold™ F* in a 20 ml glass scintillation vial. The vial was capped tightly and mixed by continuous inversion for 30 seconds.

A blank sample for quality control was prepared for each batch in the same way but using cooled, purified water. The vials were placed in the liquid scintillation counter (Packard 2270) and allowed to equilibrate for 4 hours. The expanded uncertainty (k=2) on each measurement was typically 10%. The counting conditions and characteristics are summarised in Table 1.

Table 1

Liquid Scintillation Counting Conditions

Parameter	Value
Instrument	Packard 2270
Scintillant	Ultima Gold™ F
Count time	30 Minutes
No. of cycles	2
Mode	Low level
α/β discriminator setting	175
Counting window	300 to 1000 keV
Rn-222 counting efficiency	260%
Typical blank count rate	1.5 cpm
Minimum detectable activity (30 mins)	0.5 Bq/l

3.3 Analysis of Other Radionuclides

Additional analyses were carried out on a sub-set of samples in the study. These analyses included total alpha, polonium-210 and radium-226 measurements using radiochemical techniques. Uranium and thorium mass concentrations were measured on behalf of RPII by the Analytical and Regional Geochemistry Group of the British Geological Survey in Nottingham, England using inductively coupled plasma mass spectrometry (ICP-MS).

4. RESULTS AND DISCUSSION

4.1 Radon in Drinking Water

Drinking water from 166 houses in Co. Wicklow that use private boreholes as their primary supply was sampled and analysed in duplicate for radon. Of the supplies sampled, four had radon activity concentrations which exceeded 1000 Bq/l, (representing 2.4% of the total). These activity concentrations were 1396 Bq/l, 1720 Bq/l, 3316 Bq/l and 5736 Bq/l. Fifteen houses had activity concentrations between 500 and 1000 Bq/l (9.0%), 51 had activity concentrations between 100 and 500 Bq/l (30.7%) and 96 had activity concentrations less than 100 Bq/l (57.8%). The full data set is presented in Annex C and is summarised in Figure 3.

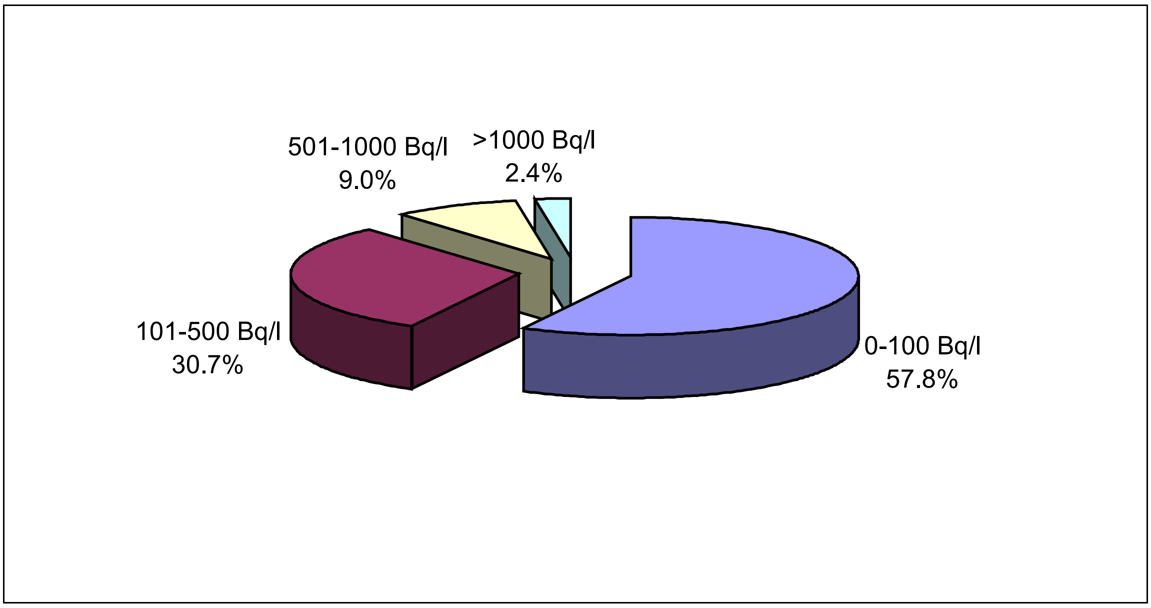
By comparison, a similar study carried out recently in a known High Radon Area in Devon in the UK, found that 8% of the 100 water supplies examined had radon activity concentrations above 1000 Bq/l [Talbot *et al*., 2000]. The highest concentration found was 5340 Bq/l. A study carried out in Sweden estimated that nationally, 5% of drilled wells have radon activity concentrations in excess of 1000 Bq/l. Activity concentrations in excess of 50,000 Bq/l have been observed in ground water in Sweden [Akerblom *et al*., 1988].

It should be noted that radon activity concentrations in surface waters are low, usually below 1 Bq/l [EC, 2001] and a small number of measurements made in Ireland show similar values.

In the absence of comprehensive information regarding the national distribution of boreholes and their underlying geology, it is very difficult to estimate the number of supplies providing drinking water containing radon concentrations above 1000 Bq/l. The Geological Survey of Ireland estimates that there may be as many as 150,000 boreholes in use throughout the country, although not all of these necessarily provide drinking water. Using the assumption that the data for county Wicklow are replicated nationally, then approximately 3000 to 4000 boreholes in Ireland might provide drinking water with radon concentrations above the 1000 Bq/l level. This is likely to be an overestimate since the underlying granitic geology of much of county Wicklow favours the accumulation of radon in groundwater supplies.

Figure 3

Radon in Drinking Water, Co. Wicklow



4.2 Detailed Investigations

Each of the four houses with radon activity concentrations in excess of 1000 Bq/l identified in the study was revisited so that a more detailed study of each could be carried out. Water samples were taken from the taps inside and outside the house for comparison with the original measurement made on water from the kitchen tap. These were all analysed for radon. A subset of samples was analysed for gross alpha activity, thorium-232, polonium-210, radium-226 and uranium. Cr-39 track-etch detectors, to measure the indoor air radon activity concentration, were placed in a number of rooms in each of the four houses for a three-month period. The results of these analyses are presented in Tables 2, 3 and 4.

Table 2

Radon Activity Concentrations (Bq/l) in a Variety of Taps from the Four Selected Houses

House	Kitchen (Original)	Outside	Kitchen (Cold)	Kitchen (Hot)	Bathroom (Cold)	Bathroom (Hot)
1	5985	5040	5736	2089	3006	nm
2	3316	2877	2887	nm	2845	1016
3	1396	905	813	nm	498	411
4	1720	1901	1870	nm	1258	970

Note: nm = not measured

Table 3

Indoor Air Radon Activity Concentrations in the Four Selected Houses

House	Indoor air radon activity concentrations (Bq/m^3)				
	House average	Kitchen	Bedroom	Bathroom	Living Room
1	130	nm	97	110 (es: 197)	158
2	339	291	390	515	314
3	55	66	18	105	73
4	139	77	139	103 (es: 439)	65

Notes: es = *en suite*
nm = not measured

Table 4

Additional Radionuclide Measurements in Water from the Four Selected Houses

House	Thorium (µg/l)	Uranium (µg/l)	Gross alpha (Bq/l)	Ra-226 (Bq/l)	Po-210 (Bq/l)
1	<0.02	4.61	0.391	< 0.5	0.194
2	<0.02	2.16	0.404	<0.5	0.020
3	<0.01	27.1	0.768	< 0.5	0.208
4	<0.02	1.14	0.049	< 0.5	0.009

4.2.1 Radon in drinking water
Repeat measurements of radon in drinking water in samples taken between two and three months after the original measurement, confirmed that radon activity concentrations in 3 of the 4 selected houses remained above 1000 Bq/l. One house, which originally had a concentration of 1396 Bq/l, was found to have a concentration of 813 Bq/l at the second analysis (Table 2).

4.2.2 Radon reduction
Water from each selected house was brought to boiling point in a beaker on a hot plate in the laboratory and reanalysed after cooling. In each case the radon concentration was reduced to below 0.5 Bq/l by the boiling action. These samples were stored and re-measured after thirty days. The activity concentration was found to remain below 0.5 Bq/l. This confirmed that in all four selected houses the radon was unsupported by parent radionuclides.

4.2.3 Radon in air
The seasonally adjusted mean indoor radon air concentration in three of the houses were found to be significantly below 200 Bq/m^3, the national Reference Level at which remedial action to reduce radon concentrations is always advised for private dwellings (Table 3). One house had an indoor air radon concentration of 339 Bq/m^3. In all four cases, either the main bathroom or the *ensuite* to the master bedroom had the highest concentration of radon in indoor air.

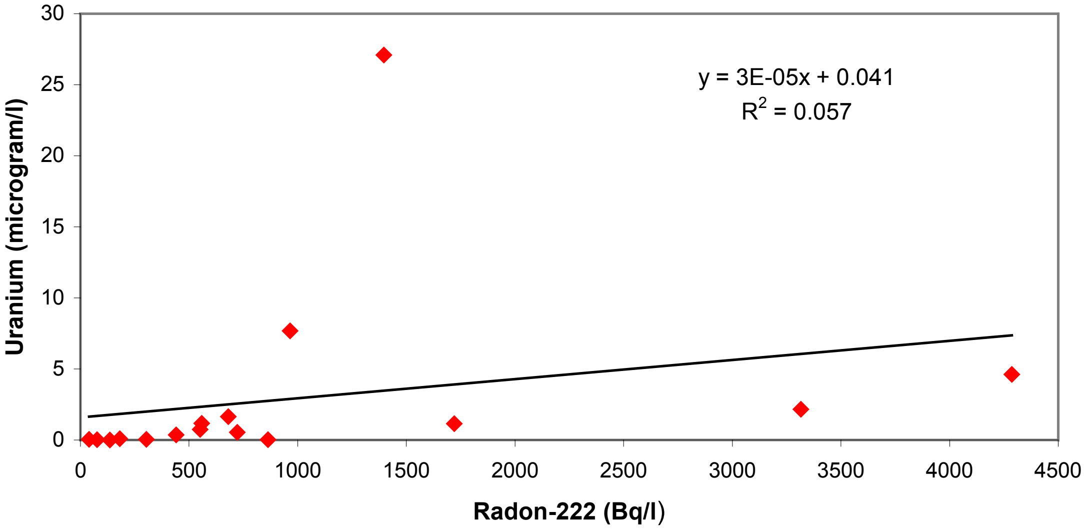
4.2.4 Analysis of other radionuclides
Kitchen tap water samples from the four selected houses were analysed for gross alpha activity, radium-226 and polonium-210 as well as mass concentrations of thorium and uranium isotopes. Three of the four houses had gross alpha activities above the screening level of 0.1 Bq/l recommended by the World Health Organisation (WHO). Following determination of individual radionuclide activity concentrations, two of these were found to have polonium-210 activity concentrations of 0.194 Bq/l and 0.208 Bq/l respectively. Based on a daily consumption rate of 2 litres, these concentrations give rise to a radiation dose greater than 0.1 mSv per annum. In the case of the third house, the polonium-210 activity concentration of 0.02 Bq/l gives rise to an annual radiation dose of approximately 0.02 mSv.

The "total indicative dose" of 0.1 mSv per annum set out in Statutory Instrument 439 of 2000 [Stationery Office, 2000] applies to all public water supplies, to private water supplies serving greater than 50 people and to any supplies that form part of a commercial activity. In the case of non-commercial private water supplies serving less than 50 people, there is no limit set for doses from radionuclides contained in the water. S.I. 439 implements the European Council Directive on the quality of water intended for human consumption [EC, 1998].

Thorium was not detected in any of the water samples from the four selected houses. Uranium concentrations in the waters ranged between 1.14 µg/l to 27 µg/l (Table 4). The WHO currently recommends that uranium concentrations in drinking water should be below 2 µg/l, predominantly because of its chemical toxicity [WHO, 1993]. The equivalent recommendation in the USA is 20 µg/l [USEPA, 2000]. Uranium concentrations were measured in the drinking water of a further 12 houses during the study in Wicklow with a range of radon activity concentrations. Using all sixteen data points, a poor correlation (R^2=0.06) was observed between uranium concentration in drinking water and radon in drinking water (Figure 4). However this correlation is greatly improved (R^2=0.83) with the elimination of the two highest uranium concentrations.

Figure 4

Linear Regression Analysis of Radon and Uranium Concentrations in Drinking Water



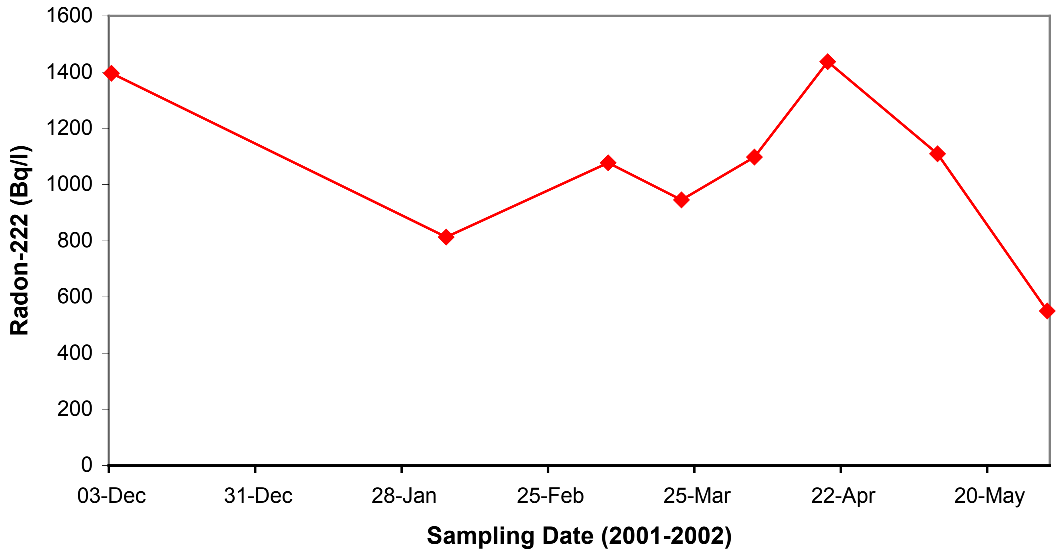
More data would be valuable in determining whether or not a relationship exists between uranium and radon concentrations in drinking water.

4.3 Temporal Trends in Radon Activity Concentrations

One house with radon in drinking water activity concentrations greater than 1000 Bq/l was sampled at regular intervals (mainly fortnightly) between December 2001 and May 2002 to study temporal trends and the results of these analyses are presented in Figure 5. While only one house was used in the study and the study period was relatively short, a significant variation in the radon activity concentration was found. In this case the radon concentration was found to vary from 550 Bq/l (May 2002) to a high of 1437 Bq/l (April 2002). Other studies have also found large variations in activity concentrations over time which may have a seasonal component [Talbot *et al*., 2000]. The fact that such variability exists means that the results for any individual supply should be interpreted with caution. However, because of the large number of supplies measured as part of the survey, random or seasonal variability is unlikely to significantly affect the overall distribution of observed radon concentrations.

Figure 5

Variations in Radon Activity Concentration in Water with Time at a Location in Co. Wicklow



5. DOSES FROM WATER CONSUMPTION DUE TO RADON

Assuming the validity of the linear no threshold dose model, the committed effective dose received from the ingestion of water containing radon may be estimated using the following equation:

Dose(Sv) = [radon activity concentration (Bq/l) x annual consumption (l) x dose conversion factor (Sv/Bq)]

For a given activity concentration of radon, the estimated dose can vary significantly depending on the water consumption rates and the dose conversion factors used. The United Nations Scientific Committee on the Effects of Atomic Radiation [UNSCEAR, 1993] estimated that the committed effective dose from the ingestion of radon in water is 10^{-8} Sv/Bq for an adult, 2 x 10^{-8} Sv/Bq for a child and 7 x 10^{-8} Sv/Bq for an infant. The US National Research Council (1999) suggests a lower conversion factor of 0.35 x 10^{-8} Sv/Bq without any distinction between age groups. It should be noted that an additional dose contribution will be received by the consumer from radon decay products in the water such as polonium-210. This contribution is generally considered to be minor in comparison to the contribution from radon [Talbot *et al*., 2000].

The annual consumption of water by individuals can vary significantly. As radon is generally removed efficiently from water on agitation or boiling, the dose also depends on that fraction of water that has been consumed from the tap without processing. Water consumption habits were not addressed in this study. However in a recent study in the UK [Talbot *et al*., 2000] the average unprocessed tap water consumption by adults in summer and winter was found to be 0.78 litres/day and 0.51 litres/day respectively. The consumption of processed water was higher at 1.13 litres/day and 1.14 litres/day respectively.

A range of potential annual doses to adults from the consumption of water over a range of radon activity concentrations and water consumption rates has been estimated and is presented in Table 5. The dose calculations are based on the assumption that all of the water consumed at the rates indicated is directly from the tap without further processing such as boiling. The dose conversion factor used is 1 x 10^{-8} Sv/Bq for adults [UNSCEAR, 1993]. According to UNSCEAR (2000), doses to children and infants for similar consumption rates could be a factor of 2 and 7 higher, respectively. Similarly, a range of possible annual doses to adults from the consumption of water from the four selected houses found in this study has been estimated and is presented in Table 6.

Table 5

Potential Annual Doses (mSv) to Adults due to the Consumption of Water over a Range of Radon Activity Concentrations and Consumption Rates

Activity Concentration (Bq/l)	Daily water consumption rates				
	0.1 l/d	0.5 l/d	1.0 l/d	1.5 l/d	2 l/d
	Doses to adults due to the consumption of water at above rates (mSv[1])				
100	0.04	0.18	0.37	0.55	0.73
500	0.18	0.91	1.83	2.74	3.65
1000	0.37	1.83	3.65	5.48	7.30
5000	1.83	9.13	18.25	27.38	36.50

Note: (1) The dose conversion factor used was 1 x 10^{-8} Sv/Bq. It is assumed that all of the water consumed is unprocessed and directly from the tap without loss of radon.

Table 6

Potential Annual Doses (mSv) to Adults in the Selected Houses due to the Consumption of Water using a Range of Consumption Rates

House	Activity Concentration (Bq/l)	Daily water consumption rates				
		0.1 l/d	0.5 l/d	1.0 l/d	1.5 l/d	2 l/d
		Doses to adults due to the consumption of water at above rates (mSv)[1]				
1	5985	2.18	10.9	21.8	32.8	43.7
2	3316	1.60	6.0	12.1	18.2	24.2
3	1396	0.50	2.5	5.0	7.5	10.0
4	1720	0.62	3.1	6.2	9.3	12.4

Note: (1) The dose conversion factor used was $1x10^{-8}$ Sv/Bq. It is assumed that all of the water consumed is unprocessed and directly from the tap without loss of radon.

The results indicate that even at seemingly modest water consumption rates, relatively high doses can be received. For example a consumption of 1 litre of water per day containing 1000 Bq/l of radon activity would result in a dose to an adult consumer of 3.65 mSv annually. This dose estimate may be significantly higher for children and infants [UNSCEAR, 1993]. It may be compared to the annual average dose of 3.62 mSv to a person in Ireland from all sources of radioactivity.

It should be noted that on the basis of current knowledge of the effects of exposure to radiation, a dose of 1 mSv per annum carries a lifetime risk of one in 20,000 of contracting a fatal cancer. The stomach wall has been identified as the organ most at risk following the ingestion of drinking water containing radon. In Ireland, stomach cancer accounts for approximately 2.2% of all cancers with 476 cases in 1997 [National Cancer Registry Board, 2000]. In the absence of more detailed information on the national distribution of radon in drinking water, it is not possible to evaluate the extent to which radon might be implicated in the development of these cancers.

It should be further noted that it has been estimated [EC, 2001] that 1000 Bq/l of radon in water from a tap will, on average, increase the indoor air radon concentration by 100 Bq/m^3. The limited data on radon in indoor air collected as part of this study do not support a relationship between these data and the measured concentration of radon in the water supply. This may possibly be explained by differences in ventilation rates or other house-specific factors.

6. RADON REMEDIATION AND DRINKING WATER

The issue of remediation of drinking water containing high radon levels has been substantially addressed by the TENAWA project (Treatment Techniques for Removing Natural Radionuclides from Drinking Water) which was commissioned by the European Commission [Turtiainen *et al*., 2000]. The project concluded that radon could be removed efficiently (>95%) from domestic water supplies by both granular activated carbon (GAC) filtration and by aeration. The significant drawback of GAC filtration is the elevated gamma dose rates (up to 120 μSv/h) that can occur near the filter and the build up of radioactivity on the filter which can give rise to problems with disposal. This is not a problem with aeration, which appears to be the preferred option for domestic supplies. However, defects in technical reliability or radon removal efficiency were observed in a small number of commercial aerators available in some European countries.

The project concluded that aeration was also a suitable method for removing radon at waterworks. The removal efficiencies at waterworks where the aeration process was designed to remove radon or carbon dioxide were 67–99%. If the aeration process was properly designed, removal efficiencies higher than 95% could be attained. At the time of writing the authors are unaware of devices commercially available in Ireland for the purposes of radon removal.

In general high radon activity concentrations indicate the potential presence of other radionuclides of the uranium decay series in the water. When remedial action is taken to reduce the radon concentration, the presence of other natural radionuclides should be considered so that a suitable technique can be chosen to remove all radiologically significant natural radionuclides from the water at the same time.

7. CONCLUSIONS

- A sampling and analysis methodology for the determination of radon in drinking water based on liquid scintillation spectrometry was tested and successfully implemented by the RPII. This has allowed a high degree of confidence to be placed in the results outlined in this report.

- Radon activity concentrations were measured in the private drinking water supplies of 166 houses in Co. Wicklow. Four houses had activity concentrations in excess of the EC action level of 1000 Bq/l. Fifteen houses had activity concentrations between 500 and 1000 Bq/l, 51 between 100 and 500 Bq/l and 96 had activity concentrations below 100 Bq/l. These results confirm that radon concentrations in excess of those recommended for application within the European Union exist in some Irish domestic water supplies.

- The estimated doses due to the consumption of drinking water containing radon vary significantly with the quantity of drinking water consumed and the degree to which the water has been processed prior to consumption. However dose estimates based on measurements made in this study demonstrate that radon in drinking water may pose a significant additional health risk, in the longer term, to certain consumers who depend on drinking water supplies derived from groundwater as their primary source of drinking water.

- Additional analyses identified the presence of both polonium-210 and uranium in a subset of water samples taken from the supplies with the highest radon concentrations. In the case of two of these supplies, the "total indicative dose" of 0.1 millisievert was exceeded. This is based on an assumed daily consumption rate of 2 litres of water.

- No correlation could be established between the uranium and radon concentrations measured in individual water supplies. However, as the number of data points was small (n=16), more data would be valuable in determining if any relationship exists.

- It should be noted that while significant doses have been estimated for radon ingestion in drinking water, it is likely that the number of people affected is small in comparison with the greater number of people likely to be affected as a consequence of exposure to radon in indoor air.

- While proven radon in drinking water remediation products are available and in use in other countries, the authors are unaware of any similar commercial products currently available on the Irish market. It was established in the course of the study that where there was immediate concern, boiling the water in a well-ventilated area prior to consumption could reduce the level of radon in water supplies to negligible concentrations. However, this should only be considered as an interim measure as it does not deal with radon emanation from taps, showers and toilets.

8. RECOMMENDATIONS

- Four houses have been identified in which the recommended EC value of 1000 Bq/l for radon in drinking water is exceeded. Remedial action needs to be taken to reduce these concentrations. At the same time, the presence of other natural radionuclides, including isotopes of uranium, should be taken into account so that a suitable technique can be chosen to remove all radiologically significant natural radionuclides from the water at the same time.

- All homes which use private ground water supplies as their primary source of water should be advised to have their supply tested for radon and other radionuclides. If necessary, priority areas could be identified using bedrock data together with information on ground waters, uranium concentrations and indoor air radon concentrations.

- While the EC recommends that, for private water supplies, remedial action should be taken when levels are found to be above 1000 Bq/l, this should not be interpreted to imply that activity concentrations below this level are completely safe. Particularly in situations where householders are exposed to radiation through a number of pathways, individuals should be encouraged to take reasonable steps to reduce their exposure.

- All houses in areas with elevated natural background radiation, including those with elevated radon levels in water, should have their indoor air measured for radon.

- All public drinking water supplies sourced from ground water should be tested for their radon activity concentrations and where they exceed 100 Bq/l, action should be considered to reduce these levels.

- The sampling of water for radon analysis should be carried out in accordance with a well-defined protocol that is designed to minimise radon losses from the sample prior to measurement.

9. ACKNOWLEDGEMENTS

The co-operation and support of the staff of Wicklow County Council during this pilot study is gratefully acknowledged.

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11. GLOSSARY OF TERMS

Absorbed Dose
Quantity of energy imparted by the ionising radiation to unit mass of matter such as tissue. It is measured in grays (Gy). One Gy produces different biological effects on tissue depending on the type of radiation i.e. alpha, beta or gamma.

Activity
Activity is a measure of the rate at which nuclear disintegration occurs. The unit of activity is the becquerel (Bq). One Bq is equivalent to one disintegration per second.

Collective Effective Dose
Total dose over a population group exposed to a given source. It is represented by the product of the average effective dose equivalent to the individuals in the group by the number of persons comprising the group. It is measured in man sieverts (manSv).

Committed Effective Dose
Total dose gradually delivered to an individual over a given period of time by the decay of a radionuclide following its intake into the body. The integration time is usually taken as 50 years for adults and 70 years for children.

Effective Dose
Weighted sum of the *equivalent doses* to the various organs and tissues. The weighting factor for each organ or tissue takes account of the fractional contribution of the risk of death or serious genetic defect from irradiation of that organ or tissue to the total risk from uniform irradiation of the whole body. The unit of effective dose is the sievert (Sv).

Equivalent Dose
The quantity obtained by multiplying the *absorbed dose* by a factor representing the different effectiveness of the various types of radiation in causing harm to tissues. It is measured in sieverts (Sv). One Sv produces the same biological effect irrespective of the type of the radiation.

Half-life
The time taken for the activity of a radionuclide to lose half its value by decay.

Radionuclide
An unstable nuclide that emits ionising radiation. The emissions may be either alpha, beta or gamma radiation.

Radiotoxicity
A measure of the dose per becquerel resulting from the ingestion of a particular radionuclide.

12. RADIATION QUANTITIES AND UNITS

Activity and Dose Units

Quantity	***Unit and Symbol***
Activity	Becquerel (Bq)
Activity Concentration	Becquerel per unit mass or volume (Bq/kg or Bq/l)
Absorbed Dose	Gray (Gy)
Effective Dose	Sievert (Sv)
Committed Effective Dose	Sievert (Sv)
Equivalent Dose	Sievert (Sv)
Collective Effective Dose	Man sievert (manSv)

Commonly Used Activity and Dose Unit Multiples and Sub-multiples

Activity	**Dose**
1 millibecquerel (1 mBq) $=1 \times 10^{-3}$ Bq	1 microsievert (1 µSv) $=1 \times 10^{-6}$ Sv
1 kilobecquerel (1 kBq) $=1 \times 10^{3}$ Bq	1 millisievert (1 mSv) $=1 \times 10^{-3}$ Sv
1 megabecquerel (1 MBq) $=1 \times 10^{6}$ Bq	1 nanogray (1 nGy) $=1 \times 10^{-9}$ Gy
1 terabecquerel (1 TBq) $=1 \times 10^{12}$ Bq	1 microgray (1 µGy) $=1 \times 10^{-6}$ Gy

Annex A

Drinking Water Sampling Protocol

Step	Procedure	Note
1	Locate kitchen tap	All samples should be taken from the kitchen tap. Any deviation should be noted on the sampling form
2	Turn the tap on gently and allow the water to run at a slow rate for at least five minutes.	Try to minimise the occurrence of air bubbles in the water stream as much as possible by adjusting the flow rate
3	Slowly fill the 40ml glass vial to the brim	A positive meniscus should appear above the brim
4	Cap the vial immediately and tightly with the Teflon-rubber disc cap, ensuring that there is no trapped air in the vial	
5	Repeat steps 3 and 4 for the second vial	
6	Complete the *Radon in Drinking Water Sampling Form*	
7	Stick one of the numbered labels provided on each of the sample vials and on the associated *Radon in Drinking Water Sampling Form*	
8	Place both vials together in one of the plastic bags provided	
9	Insert the *Radon in Drinking Water Sampling Form* in a second plastic bag together with the plastic bag containing the samples	
10	Secure the plastic bag with an elastic band and dispatch to the RPII within 48 hours in the containers provided	If the samples are retained overnight, then they should be stored in a cool, dark place. Do not freeze

Annex B

Drinking Water Sampling Form

Attach Label →

County:	
Sampling: Date: Time	
House: Name: Address	
Coordinates: Longitude Latitude	
Pre-treatment:	*(✔ Tick as appropriate)*
Aeration	❑
Holding Tank	❑
Filtration	❑
Other	❑ Specify:
None	❑
Borehole Depth	
Comments (including how long the borehole has been in use for domestic purposes)	
Sampler:	

Annex C

Radon in Drinking Water – Results of the Pilot Study in County Wicklow.

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Annamoe	WW0033A WW0033B	RD0101503 RD0101504	03/09/01	52 51
Annamoe	WW0067A WW0067B	RD0102078 RD0102079	26/11/01	14 13
Annamoe	WW0069A WW0069B	RD0102080 RD0102081	26/11/01	6 6
Arklow	WW0006A WW0006B	RD0101388 RD0101389	20/08/01	76 79
Arklow	WW0052A WW0052B	RD0101497 RD0101498	03/09/01	12 10
Arklow	WW0024A WW0024B	RD0101585 RD0101586	17/09/01	32 35
Arklow	WW0053A WW0053B	RD0101644 RD0101645	24/09/01	17 22
Arklow	WW0091A WW0091B	RD0101696 RD0101697	01/10/01	74 75
Arklow	WW0100A WW0100B	RD0101700 RD0101701	08/10/01	60 65
Arklow	WW0056A WW0056B	RD0102019 RD0102020	12/11/01	33 36
Arklow	WW0156A WW0156B	RD0102160 RD0102161	12/12/01	1 0
Arklow	WW0195A WW0195B	RD0200078 RD0200079	07/01/02	0 0
Arklow	WW0196A WW0196B	RD0200080 RD0200081	07/01/02	29 30

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Arklow	WW0197A WW0197B	RD0200082 RD0200083	07/01/02	66 71
Arklow	WW0199A WW0199B	RD0200086 RD0200087	07/01/02	84 87
Ashford	WW0151A WW0151B	RD0101570 RD0101571	10/09/01	63 62
Ashford	WW0054A WW0054B	RD0101982 RD0101983	05/11/01	76 63
Ashford	WW0083A WW0083B	RD0101986 RD0101987	05/11/01	135 129
Ashford	WW0201A WW0201B	RD0200090 RD0200091	07/01/02	128 125
Ashford	WW0192A WW0192B	RD0200138 RD0200139	14/01/02	10 9
Ashford	WW0193A WW0193B	RD0200140 RD0200141	14/01/02	44 44
Ashford	WW0216A WW0216B	RD0200336 RD0200337	04/02/02	69 63
Ashford	WW0217A WW0217B	RD0200338 RD0200339	04/02/02	47 45
Aughrim	WW0005A WW0005B	RD0101386 RD0101387	20/08/01	300 296
Aughrim	WW0093A WW0093B	RD0101698 RD0101699	01/10/01	99 99
Aughrim	WW0141A WW0141B	RD0101702 RD0101703	01/10/01	51 53
Aughrim	WW0144A WW0144B	RD0101704 RD0101705	01/10/01	161 162

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Aughrim	WW0084A WW0084B	RD0101988 RD0101989	05/11/01	38 37
Aughrim	WW0086A WW0086B	RD0102023 RD0102024	12/11/01	163 161
Aughrim	WW0158A WW0158B	RD0102029 RD0102030	12/11/01	105 114
Aughrim	WW0214A WW0214B	RD0200262 RD0200263	28/01/02	179 181
Avoca	WW0153A WW0153B	RD0101591 RD0101592	17/09/01	1 1
Avoca	WW0110A WW0110B	RD0101862 RD0101863	22/10/01	74 58
Avoca	WW0163A WW0163B	RD0102098 RD0102099	26/11/01	74 85
Avoca	WW0185A WW0185B	RD0102164 RD0102165	12/12/01	470 465
Avoca	WW0175A WW0175B	RD0200253 RD0200254	28/01/02	37 37
Ballinaeleen	WW0107A WW0107B	RD0101858 RD0101859	22/10/01	43 44
Ballyconnell	WW0165A WW0165B	RD0102033 RD0102034	12/11/01	430 467
Baltinglass	WW0071A WW0071B	RD0101562 RD0101563	10/09/01	66 68
Baltinglass	WW0164A WW0164B	RD0102031 RD0102032	12/11/01	100 98
Blessington	WW0097A WW0097B	RD0102125 RD0102126	03/12/01	1396 1382

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Brittas	WW0132A WW0132B	RD0200163 RD0200164	21/01/02	235 232
Brittas Bay	WW0200A WW0200B	RD0200088 RD0200089	07/01/02	56 57
Brittas Bay	WW0122A WW0122B	RD0200159 RD0200160	21/01/02	108 103
Carceen	WW0051A WW0051B	RD0101515 RD0101516	03/09/01	121 136
Carnew	WW0025A WW0025B	RD0101587 RD0101588	17/09/01	155 156
Carnew	WW0198A WW0198B	RD0200084 RD0200085	07/01/02	129 138
Carnew	WW0129A WW0129B	RD0200128 RD0200129	14/01/02	194 202
Carnew	WW0206A WW0206B	RD0200331 RD0200332	04/02/02	81 73
Clonegal	WW0060A WW0060B	RD0101560 RD0101561	10/09/01	165 165
Clonegal	WW0078A WW0078B	RD0101566 RD0101567	10/09/01	73 79
Clonegal	WW0026A WW0026B	RD0101589 RD0101590	17/09/01	77 80
Coolkenno	WW0008A WW0008B	RD0101392 RD0101393	20/08/01	611 595
Delgany	WW0133A WW0133B	RD0200244	28/01/02	25 [2]
Donard	WW0125A WW0125B	RD0200124 RD0200125	14/01/02	77 76

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Donard	WW0182A WW0182B	RD0200321 RD0200322	04/02/02	55 45
Dunganstown	WW0039A WW0039B	RD0101433 RD0101434	27/08/01	331 357
Dunlavin	WW0036A WW0036B	RD0101558 RD0101559	10/09/01	132 128
Enniskerry	WW0027A WW0027B	RD0101394 RD0101395	20/08/01	705 711
Enniskerry	WW0029A WW0029B	RD0101398 RD0101399	20/08/01	130 129
Enniskerry	WW0020A WW0020B	RD0101495 RD0101496	03/09/01	272 270
Enniskerry	WW0161A WW0161B	RD0101574 RD0101575	10/09/01	211 219
Enniskerry	WW0149A WW0149B	RD0101652 RD0101653	24/09/01	218 249
Enniskerry	WW0106A WW0106B	RD0102084 RD0102085	26/11/01	197 188
Enniskerry	WW0142A WW0142B	RD0200132 RD0200133	14/01/02	301 304
Enniskerry	WW0194	RD0200259	28/01/02	27 [2]
Glencree	WW0028A WW0028B	RD0101396 RD0101397	20/08/01	5985 5981
Glenealy	WW0128A WW0128B	RD0200126 RD0200127	14/01/02	15 18
Glenealy	WW0215A WW0215B	RD0200334 RD0200335	04/02/02	51 49

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Glenealy	WW0222A WW0222B	RD0200342 RD0200343	04/02/02	25 22
Grange Con	WW0012A WW0012B	RD0101428 RD0101429	27/08/01	157 157
Hacketstown	WW0187A WW0187B	RD0102193 RD0102194	17/12/01	360 356
Hollywood	WW0154A WW0154B	RD0101706 RD0101707	01/10/01	1648 1720
Kilbride	WW0143A WW0143B	RD0101648 RD0101649	24/09/01	0 0
Kilbride	WW0118A WW0118B	RD0101702 RD0101703	08/10/01	180 178
Kilbride	WW0096A WW0096B	RD0102123 RD0102124	03/12/01	261 248
Kilbride	WW0070A WW0070B	RD0102119 RD0102120	03/12/01	327 323
Kilbride	WW0134A WW0134B	RD0200245 RD0200246	28/01/02	31 31
Kilbride	WW0136A WW0136B	RD0200247 RD0200248	28/01/02	35 32
Kilmacanogue	WW0031A WW0031B	RD0101499 RD0101500	03/09/01	97 98
Kilmacanogue	WW0138A WW0138B	RD0101776 RD0101777	08/10/01	45 47
Kilmacanogue	WW0082A WW0082B	RD0101764 RD0101765	08/10/01	18 16
Kiltegan	WW0147A WW0147B	RD0102090 RD0102091	26/11/01	549 500

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Kiltegan	WW0130A WW0130B	RD0200130 RD0200131	14/01/02	667 681
Mullinaveigue	WW0030A WW0030B	RD0101400 RD0101401	20/08/01	3 3
Newtownmountkennedy	WW0042A WW0042B	RD0101439 RD0101440	27/08/01	70 80
Newtownmountkennedy	WW0095A WW0095B	RD0102121 RD0102122	03/12/01	72 71
Newtownmountkennedy	WW0123A WW0123B	RD0200242 RD0200243	28/01/02	49 50
Newtownmountkennedy	WW0218A WW218B	RD0200340 RD0200341	04/02/02	18 14
Rathdangan	WW0159A WW0159B	RD0102094 RD0102095	26/11/01	380 427
Rathdrum	WW0040A WW0040B	RD0101435 RD0101436	27/08/01	43 41
Rathdrum	WW0041A WW0041B	RD0101437 RD0101438	27/08/01	33 38
Rathdrum	WW0072A WW0072B	RD0101564 RD0101565	10/09/01	209 205
Rathdrum	WW0075A WW0075B	RD0101694 RD0101695	01/10/01	77 75
Rathdrum	WW0137A WW0137B	RD0101704 RD0101705	08/10/01	40 38
Rathdrum	WW0114A WW0114B	RD0101868 RD0101869	22/10/01	8 9
Rathdrum	WW0117A WW0117B	RD0101870 RD101871	22/10/01	19 16

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Rathdrum	WW0087A WW0087B	RD0102025 RD0102026	12/11/01	5 4
Rathdrum	WW0066A WW0066B	RD0102076 RD0102077	26/11/01	156 153
Rathdrum	WW0115A WW0115B	RD0102086 RD0102087	26/11/01	25 24
Rathdrum	WW0166A WW0166B	RD0102100 RD0102111	26/11/01	88 88
Rathdrum	WW0057A WW0057B	RD0200076 RD0200077	07/01/02	60 65
Rathdrum	WW0124A WW0124B	RD0200122 RD0200123	14/01/02	131 147
Rathdrum	WW0167A WW0167B	RD0200249 RD0200250	28/01/02	42 43
Rathdrum	WW0168A WW0168B	RD0200251 RD0200252	28/01/02	22 22
Redcross	WW0152A WW0152B	RD0101572 RD0101573	10/09/01	863 832
Redcross	WW0089A WW0089B	RD0102027 RD0102028	12/11/01	16 17
Redcross	WW0191A WW0191B	RD0200136 RD0200137	14/01/02	284 300
Roundwood	WW0017A WW0017B	RD0101489 RD0101490	03/09/01	111 110
Roundwood	WW0018A WW0018B	RD0101491 RD0101492	03/09/01	67 72
Roundwood	WW0019A WW0019B	RD0101493 RD0101494	03/09/01	21 21

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Roundwood	WW0032A WW0032B	RD0101501 RD0101502	03/09/01	140 143
Roundwood	WW0034A WW0034B	RD0101505 RD0101506	03/09/01	48 45
Roundwood	WW0035A WW0035B	RD0101507 RD0101508	03/09/01	17 18
Roundwood	WW0162A WW0162B	RD0101576 RD0101577	10/09/01	83 89
Roundwood	WW0073A WW0073B	RD0101646 RD0101647	24/09/01	2 4
Roundwood	WW0148A WW0148B	RD0101650 RD0101651	24/09/01	45 55
Roundwood	WW0099A WW0099B	RD0101700 RD0101701	01/10/01	68 65
Roundwood	WW0088A WW0088B	RD0101766 RD0101767	08/10/01	53 54
Roundwood	WW0080A WW0080B	RD0101850 RD0101851	22/10/01	26 24
Roundwood	WW0081A WW0081B	RD0101852 RD0101853	22/10/01	2 3
Roundwood	WW0065A WW0065B	RD0102074 RD0102075	26/11/01	6 7
Roundwood	WW0090A WW0090B	RD0102082 RD0102083	26/11/01	134 124
Roundwood	WW0116A WW0116B	RD0102088 RD0102089	26/11/01	88 86
Roundwood	WW0190A WW0190B	RD0200134 RD0200135	14/01/02	106 112

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Roundwood	WW0202A WW0202B	RD0200142 RD0200143	14/01/02	118 118
Roundwood	WW0121A WW0121B	RD0200157 RD0200158	21/01/02	90 89
Roundwood	WW0131A WW0131B	RD0200161 RD0200162	21/01/02	5 5
Roundwood	WW0178A WW0178B	RD0200255 RD0200256	28/01/02	41 42
Roundwood	WW0211A WW0211B	RD0200260 RD0200261	28/01/02	38 40
Roundwood	WW0184A WW0184B	RD0200323 RD0200324	04/02/02	11 9
Roundwood	WW0203A WW0203B	RD0200325 RD0200326	04/02/02	54 49
Roundwood	WW0204A WW0204B	RD0200327 RD0200328	04/02/02	85 72
Roundwood	WW0205A WW0205B	RD0200329 RD0200330	04/02/02	132 128
Shillelagh	WW0009A WW0009B	RD0101422 RD0101423	27/08/01	123 101
Shillelagh	WW0010A	RD0101424	27/08/01	111 [2]
Shillelagh	WW0011A WW0011B	RD0101426 RD0101427	27/08/01	226 221
Shillelagh	WW0050A WW0050B	RD0101513 RD0101514	03/09/01	7 7
Shillelagh	WW0108A WW0108B	RD0101860 RD0101861	22/10/01	40 43

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Stratford-on-Slaney	WW0014A WW0014B	RD0101430 RD0101431	27/08/01	24 23
Three Mile Water	WW0037A	RD0101432	27/08/01	393 [2]
Tinahely	WW0004A WW0004B	RD0101384 RD0101385	20/08/01	204 206
Tinahely	WW0049A WW0049B	RD0101511 RD0101512	03/09/01	93 97
Tinahely	WW0094A WW0094B	RD0101768 RD0101769	08/10/01	144 117
Tinahely	WW0111A WW0111B	RD0101864 RD0101865	22/10/01	185 167
Tinahely	WW0150A WW0150B	RD0102092 RD0102093	26/11/01	64 62
Tinahely	WW0160A WW0160B	RD0102096 RD0102097	26/11/01	39 50
Tinahely	WW0180A WW0180B	RD0102166 RD0102167	12/12/01	103 95
Tinahely	WW0181A WW0181B	RD0102168 RD0102169	12/12/01	622 559
Tinahely	WW0186A WW0186B	RD0102191 RD0102192	17/12/01	21 21
Tinahely	WW0188A WW0188B	RD0102195 RD0102196	17/12/01	940 965
Tinahely	WW0210A WW0210B	RD0200257 RD0200258	28/01/02	554 551
Tullow	WW0007A WW0007B	RD0101390 RD0101391	20/08/01	662 664

General Sampling Location	Sample Number	RPII Reference	Sampling Date	Radon in Drinking Water (Bq/l)[1]
Tullow	WW0103A WW0103B	RD0101568 RD0101569	10/09/01	434 441
Tullow	WW0016A WW0016B	RD0101583 RD0101584	17/09/01	722 734
Tullow	WW0079A WW0079B	RD0101984 RD0101985	05/11/01	570 527
Tullow	WW0092A WW0092B	RD0101990 RD0101991	05/11/01	3316 3196
Tullow	WW0109A WW0109B	RD0101992 RD0101993	05/11/01	559 516
Tullow	WW0183A WW0183B	RD0102162 RD0102163	12/12/01	200 195
Valleymount	WW0038A WW0038B	RD0101509 RD0101510	03/09/01	828 822
Valleymount	WW0104A WW0104B	RD0101854 RD0101855	22/10/01	174 150
Valleymount	WW0105A WW0105B	RD0101856 RD0101857	22/10/01	12 12
Valleymount	WW0237A WW0237B	RD0200344 RD0200345	04/02/02	787 827
Wicklow	WW0155A WW0155B	RD0101654 RD0101655	24/09/01	31 33
Wicklow	WW0085A WW0085B	RD0102021 RD0102022	12/11/01	133 124
Woodenbridge	WW0112A WW0112B	RD0101866 RD0101867	22/10/01	96 90

Note: (1) Measurements were made in duplicate.
(2) Duplicate sample unsuitable for analysis.