Department of the Environment, Transport and the Regions
Commissioned research for Radioactive Substances Division

Report Title

Natural Radioactivity in Private Water Supplies in Devon

DETR Report No: DETR/RAS/00.010

Contract Title: Assessment of hazard from radon from private water supplies

DETR Reference: RW5/2/299 (EPG1/4/51) **Sector: B and C**

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Abstract (100-200 words as desired):

This report details a study of the occurrence of natural radioactivity in private water supplies in West Devon. Supplies sourced from wells, springs boreholes and a small number surface supplies were sampled. The findings of a laboratory simulation of the radon content in drinks such as tea, coffee and squash are also presented.

Of supplies sampled in phase one of the work approximately 8% of tap water and 9% of samples directly from the supply contained radon at concentrations exceeding the draft European Union Commission Recommendation action level of 1000Bq/l for individual and public water supplies. In a small number of supplies ^{238}U is present at levels exceeding 2µg/l, the World Health Organisation (WHO) provisional guideline value for uranium in drinking water.

The final aspect of the study looked at seasonal variation in the radon content of selected supplies. This showed considerable variability in radon concentration over the course of a week and between studies carried out several months apart.

Keywords (5 Maximum): Radon, drinking water, ground water, uranium, Devon

BRITISH GEOLOGICAL SURVEY

Natural radioactivity in Private Water Supplies in Devon.

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CONTENTS

1) INTRODUCTION

Between 1986 and 1996 the Department of Environment (DOE) commissioned annual radiological assessments on various private water supplies to households in England and Wales. Each study examined samples from approximately 100 different households in a selected area for a range of natural and artificial radionuclides and, out of the samples studied, about 20% were also analysed for ^{222}Rn. In each study, committed effective dose equivalents (CEDEs) were calculated for the observed radionuclides for hypothetical critical groups of householders based on the consumption of a year's supply of drinking water. Three groups of consumers were studied - infants (< 1 year old), children (1-10 year old) and adults. The most recent dose conversion factors (ie. Dose per unit uptake factors) were used. Some of the results obtained for areas studied in 1990 (e.g. Kerrier and Restormel districts in Cornwall), exceed the World Health Organisation's (WHO's) guideline activity concentration value for radioactivity in drinking water. The WHO recommend a reference level of committed effective dose of 0.1mSv (for adults) for one year's consumption of drinking water (based on the consumption of two litres of drinking water per day). Although the WHO guideline does not differentiate between natural and man-made radionuclides, the CEDEs calculated for the areas in Cornwall were predominantly due to the naturally occurring radionuclide ^{222}Rn and, to a lesser extent, ^{210}Po. The WHO recognise the difficulty in applying its guideline to ^{222}Rn

An area of West Devon around Tavistock was selected by the Department of the Environment, Transport and the Regions (DETR) for further, more focused, research. The aim of the research, as identified in the project specification, is to define:

- the concentration of ^{222}Rn in 100 private water supplies from West Devon;
- temporal and spatial variations (within the household supply and distribution system) of ^{222}Rn and ^{210}Po content in the three water supplies selected from the detailed study;
- the dose received by members of the household taking into account their actual drinking water consumption patterns rather than by assuming the 2 litres per day estimate given by WHO.

The DETR awarded the British Geological Survey (BGS) a contract, reference number RW 5/2/299, EPG 1/4/51, to carry out this work. As the first phase of the project the BGS arranged for 128 private supplies in West Devon to be sampled and analysed for ^{222}Rn, ^{226}Ra, ^{238}U and ^{232}Th. Three supplies with very high radon concentrations have also been sampled for ^{210}Po. Although the original work programme envisaged sampling only springs, wells and boreholes, discussions with West Devon Borough Council (WDBC) revealed a number of other private water supply types in the district. With the agreement of the DETR, a small number of these supplies, including river/stream extractions, mine drainage from adits and open, artificial waterways (known in the area as leats) were included in the sampling programme. Under sub-contract to BGS WDBC staff liaised with local householders to obtain the samples.

2) SAMPLING PROCEDURES

2.1 Sampling for ^{222}Rn and ^{226}Ra.

Although radon analysis by liquid scintillation counting (LSC) only requires 10ml of sample experience has shown that such small samples can be difficult to take in the field. Better results are obtained by taking 200 ml samples into glass bottles in the field and then sub-sampling 10ml aliquots in the laboratory. The 200ml sample size allows for duplicates and aliquots to be taken for the subsequent analysis of ^{226}Ra. Each 200 ml sample bottle was carefully pre-rinsed with the sample, filled and capped. Excessive disturbance and agitation of the sample was avoided during sampling to prevent the loss of ^{222}Rn.

After analysis of ^{222}Rn the vials containing the mixed water samples and LSC cocktails are stored for a period of time sufficiently long to allow the ^{222}Rn unsupported by an equivalent activity of its parent isotope, ^{226}Ra, to decay to levels below the detection limit. ^{226}Ra in the vials can then be determined by analysing the residual concentration of ^{222}Rn, since the activity of the two radionuclides will now be in equilibrium.

2.2) Sampling for ^{210}Po.

Previous work has shown glass bottles to be unsuitable for the storage of samples awaiting analysis for ^{210}Po (Flynn, 1968). An approximate 2 litre sample was, therefore, collected from each specified location into fresh 2 litre polyethylene terphalate (PET) sample bottles. Each sample was acidified with 5mls of concentrated Analar grade hydrochloric acid to prevent sorption of the ^{210}Po onto the sample bottle. On receipt in the radiochemical laboratories each sample was split and spiked with ^{209}Po to monitor recovery of ^{210}Po during the subsequent pre-concentration and plating process..

2.3) Sampling Uranium and Thorium.

One 30ml sample of water was collected at each sampling location in a fresh, pre-rinsed, 30ml Nalgene(TM) bottle. Experience has demonstrated that the typical blank obtained from such sample vessels is less than 0.05 µg/l U and Th. On return to BGS, and prior to analysis, each sample was acidified by the addition of 3 ml of concentrated Aristar nitric acid, recapped, agitated and left to stand for one week prior to analysis to allow for the re-solution of any sorbed Uranium or Thorium.

3) ANALYTICAL PROCEDURES

3.1) ^{222}Rn and ^{226}Ra.

The concentration of radon in water was determined using alpha particle liquid scintillation counting (LSC) (Talbot, 1994). A 10ml aliquot of water is placed in a low background glass LSC vial which already contains 10ml of a toluene-based LSC cocktail. Immediately prior to analysis the vial is shaken to extract the radon into the organic layer. The sample is counted on an LBK Wallac Rackbeta liquid scintillation counter using pulse shape analysis to differentiate alpha and beta scintillation events. Duplicates, standards, and blank samples are included in each batch. At an activity of 1 Bq/l analytical error (2σ) is typically of the order of 5 – 10 %, for a 1 hour count time, though this will vary slightly depending on physical characteristics of the sample such as salinity and discolouration.

A ^{226}Ra standard is used since its long half life (1602 years) means it provides a stable source of ^{222}Rn within the time frame of this project. This solution has been compared to a certified standard solution at Central Mining Institute, Poland and to a certified standard solution in the Water Authority of Jordan (Certificate No. 425-56-3, Isotope Products Laboratory, Burbank, California, USA). Once the samples from the initial screening survey had been analysed a standard ^{226}Ra solution of an activity reflecting that found in the screening programme was ordered from AEA Technology QSA. Work has also been undertaken outside this project to verify the uncertified standard and provide more direct traceability to an internationally recognised standard.

3.2) ^{210} Po

The likelihood of any interfering ions in a potable water supply are low, as compared to a biological or mineralogical sample, therefore a simple pre-concentration by evaporation was used. This evaporation step both cuts down on solvent use and generation of solvent vapour waste streams as used in traditional methods (Shannon and Orren, 1970), and on expense in use of state of the art resins (Vadja et al., 1995), for a small loss in recovery.

After acidifying the approximately 2 litres of collected sample, the sample was split. A spike of 0.16Bq ^{209}Po was added to each 800ml water split. Each sample was slowly evaporated down to about 30ml. In sequence, 2ml of Analar grade hydrochloric acid, 5ml of 2M hydroxylamine hydrochloride (w/v) and 2ml of 25% sodium citrate, were added. The pH was adjusted to 2 with ammonia and the whole diluted to 50ml. ^{210}Po and the ^{209}Po spike were then chemically plated out onto a silver disc, as described by Flyn (1968). Samples were counted by alpha spectroscopy which allowed the quantitative determination of both the

^{210}Po and ^{209}Po (spike). Within each batch of ten samples, two were determined in duplicate and two blanks were measured.

Typical background measurements made using the BGS alpha spectroscopy system yielded count rates of less than 1 count per day. This gave a theoretical detection limit of <0.0001 Bq/l (2σ). Extraction and plating efficiencies obtained during ^{210}Po analysis by this method were typically > 85%, about 7% less than the other methods outlined above. Counting efficiencies when monitored against a range of standard alpha emitters (Amersham, NBS/NAMAS certified mixed alpha source, 0020RN) were 20-22%. With such a low background, precision was directly dependent upon counting time, for an activity of 0.01 Bq/l a precision of 6% (2σ) was achieved by counting for 4 days.

3.3) Uranium and Thorium.

Uranium and Thorium can be quantitatively determined at concentrations between 1000 and 0.01 μg/l by ICP-MS using a VG Plasma quad PQ2 plus. In terms of radioactivity 1μg/l corresponds to approximately 0.01Bq/l. This technique does not provide isotopic information on the Uranium and Thorium analysed. The accuracy of Uranium and Thorium determinations was validated through the analysis of an international standard basalt (BCR1) as U and Th do not constitute part of the Aquacheck scheme to which BGS subscribes. Standardisation of the ICP-MS was achieved through certified commercially available multi-element solutions (Spex Industries). During analysis, each batch of 50 samples contained 5 blanks, 5 duplicates and 5 internal QC solutions.

4) FIELD STUDY

4.1 Radon and Radium Screening Study

Arrangements were made for staff of the Environmental Health Department of WDBC to sample private water supplies at 128 properties in the Borough. It proved impossible to sample a number of sealed sources directly and a few samples were delayed or damaged in transit. This resulted in a final total of 105 samples from the sources and 116 tap water samples being analysed for radon. In addition the 114 samples of tap water were analysed for uranium and thorium as two samples were damaged in transit.

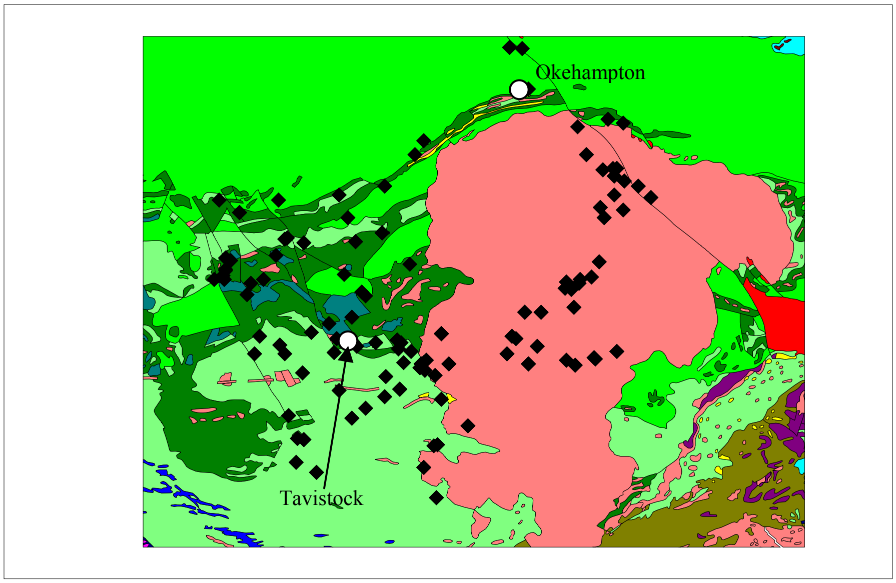
Details of the number and age of occupants of the house and of the supply system were also recorded. Although the normal situation in this area is for a private supply to provide water for single properties, four of the sources sampled supply water to several homes. Full details are provided in Appendix 1.

Care was taken to avoid sampling waters that were obviously highly turbid as these would not normally be consumed by the householder. Where there were obvious large particulates (such as orange iron precipitates) the sample was carefully decanted into the sampling vessel to avoid the transference of such material, which again would not normally be consumed by the householder.

The distribution of sample sites and their relationship to geology is illustrated in Figure 1. For clarity only those geological formations which contain samples are included in the key. A variety of types of groundwater source are in use in the study area. In addition to the more common source types of wells springs and boreholes a number of leats, river extractions and mine adits were sampled.

The full analysis results are given in Appendix 2. Statistical summaries, analysed by source type and underlying geology, are given in Tables 1 to 4. Geology based on the BGS 1:250 000 scale mapping has been assigned to sample points using a GIS. Although only 105 properties have both source and tap analysis, all available results are included in the tables, giving 105 analyses from the source and 116 analyses of tap water. Where duplicate analyses are available for a sample the mean of the two determinations has been used in the production of the statistical summaries.

Figure 1. Simplified geological map showing sample locations. Based on BGS 1:250000 digital cartography. Black diamonds represent sampling sites.



Simplified 1:250 000 Scale Geology
of West Devon

🟩 CRACKINGTON FORMATION

🟩 LOWER CARBONIFEROUS ROCKS [argillaceous rocks and chert]

🟩 UPPER DEVONIAN AND LOWER CARBONIFEROUS ROCKS [UNDIFFERENTIATED]

🟦 SILURIAN IGNEOUS ROCKS

🟫 BASIC INTRUSIVE IGNEOUS ROCKS

🟥 DARTMOOR GRANITE

Table 1. Radon in tap water (Bq/l) by source type.

Source Type	Samples	Mean	Min	Max
Adit	2	22.8	11.3	38.6
Borehole	39	435	<1	5340
Combined spring and river extraction	1	34.3	34.3	34.3
Leat	2	2.7	<1	5.4
River / Stream	2	2.1	<1	2.1
Spring	46	298	<1	2780
Well	24	260	<1	974
All tap water samples	116	341	<1	5340

Table 2. Radon in tap water (Bq/l) by geology

Geology at source	Samples	Mean	Minimum	Maximum
Basic Igneous Intrusion	1	179	179	179
Crackington Formation	13	80.2	<1	353
Dartmoor Granite	42	706	<1	5340
Lower Carboniferous argillaceous rocks and chert	17	117	1.5	1180
Silurian igneous rocks	7	42.7	6.4	80.4
Upper Devonian & Lower Carboniferous rocks (undifferentiated)	36	109	<1	1100

Table 3. Radon at source (Bq/l) by source type

Source type	Samples	Mean	Minimum	Maximum
Adit	2	13.3	6.9	19.6
Borehole	34	455	<1	2780
Combined spring and river extraction	1	32.3	32.3	32.3
Leat	2	6.7	<1	6.7
Spring	43	356	<1	2500
Stream	1	4.1	4.1	4.1
Well	22	301	<1	1210
All source water samples	105	356	<1	2780

Table 4. Radon at source (Bq/l) by geology

Geology at source	Samples	Mean	Minimum	Maximum
Basic Igneous Intrusion	1	657	657	657
Crackington Formation	11	102	1.9	296
Dartmoor Granite	38	775	<1	2780
Lower Carboniferous argillaceous rocks and chert	15	61.2	0.8	184
Silurian igneous rocks	6	69.2	16.1	118
Upper Devonian & Lower Carboniferous rocks (undifferentiated)	34	144	<1	1360

^{222}Rn was found to be above the draft European Union Commission Recommendation action level of 1000Bq/l for individual and public water supplies in 8% of the tap water samples and 9% of the source water samples analysed. In terms of the geology at the source only the Upper Devonian etc and Granite rocks yielded tap waters over 1000 Bq/l. Dartmoor Granite produced the highest average radon levels of over 700 Bq/l with the single highest value in the whole screening study resulting from a borehole source in this formation and the other highest values found in springs and wells also coming from these rocks. The few examples of surface water supplies sampled during the study, such as those drawn from streams and leats, all show low radon concentrations (<35 Bq/l).

For water from groundwater sources, mean values (by source type) at the tap are consistently lower than those at the source. This is consistent with loss of radon due to degassing as a result of water turbulence within the supply system and natural radioactive decay while the water is resident in the household supply system. Appendix 2 shows that in the majority of individual cases ^{222}Rn concentrations in tap water for a particular supply are lower than, or similar to that at the source. In a number of individual instances water from the tap contains higher levels of ^{222}Rn than the source. This may indicate that there is considerable short term variability in ^{222}Rn concentrations in the supply or may relate to degassing, and so loss of radon, occurring while sampling the source. There are also reported instances of radium building up in pipe scale, which could then release radon into the water flowing through them (Field et al, 1995). Further work would be necessary to determine if this is a factor in the case of these supplies.

The samples collected during the screening study were also analysed for ^{226}Ra. In all cases no ^{226}Ra was detected above the detection limit of approximately 0.1 Bq/l

4.2 Seasonal Variations in Radon

Three sites were selected for a more detailed study, designed to allow the short term and seasonal variation in radon at the source to be assessed. One of these sites had a borehole supply, one a well and one a spring. The borehole site gave the highest radon concentration found in the screening study. The spring site had a radon concentration close to the mean value for all sites studied. The occupants of well site included an infant less than 1 year old, it was also the only property with an infant occupant where radon in tap water exceeded 200 Bq/l. Figures 2 - 5 show the variability in radon at the sites of the detailed study.

During the summer study samples were taken morning and afternoon at the source, tap and in the case of the spring supply from the storage tank on the system. For the winter study a single sample was collected from the source in the morning and evening.

Figure 2, Well summer study

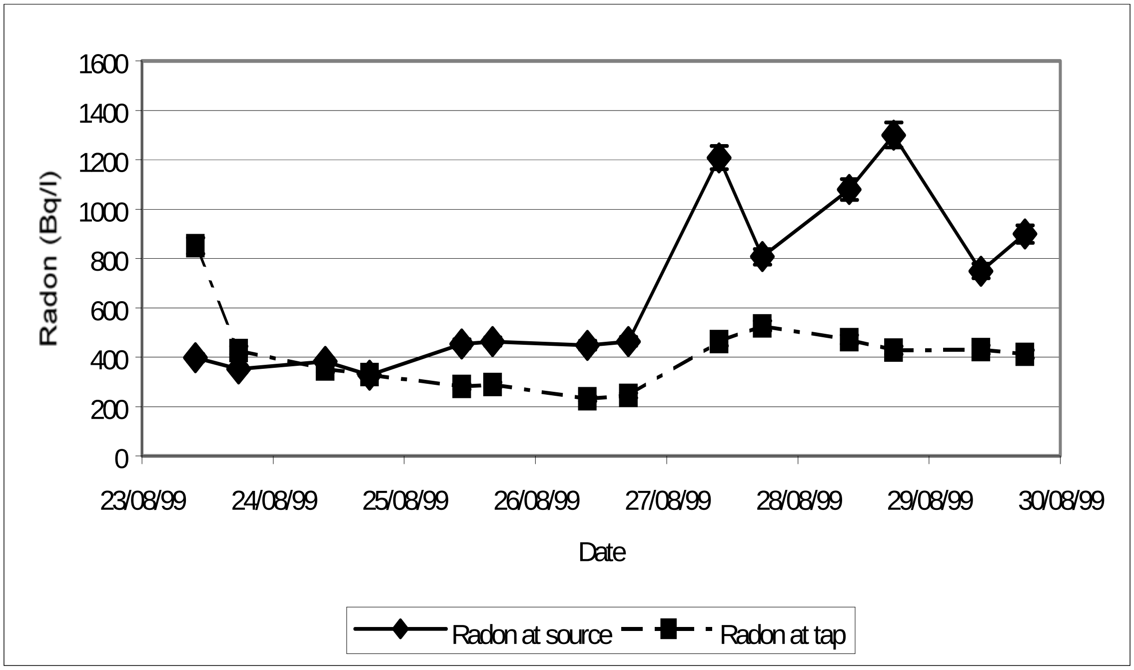


Figure 3, Spring summer study.

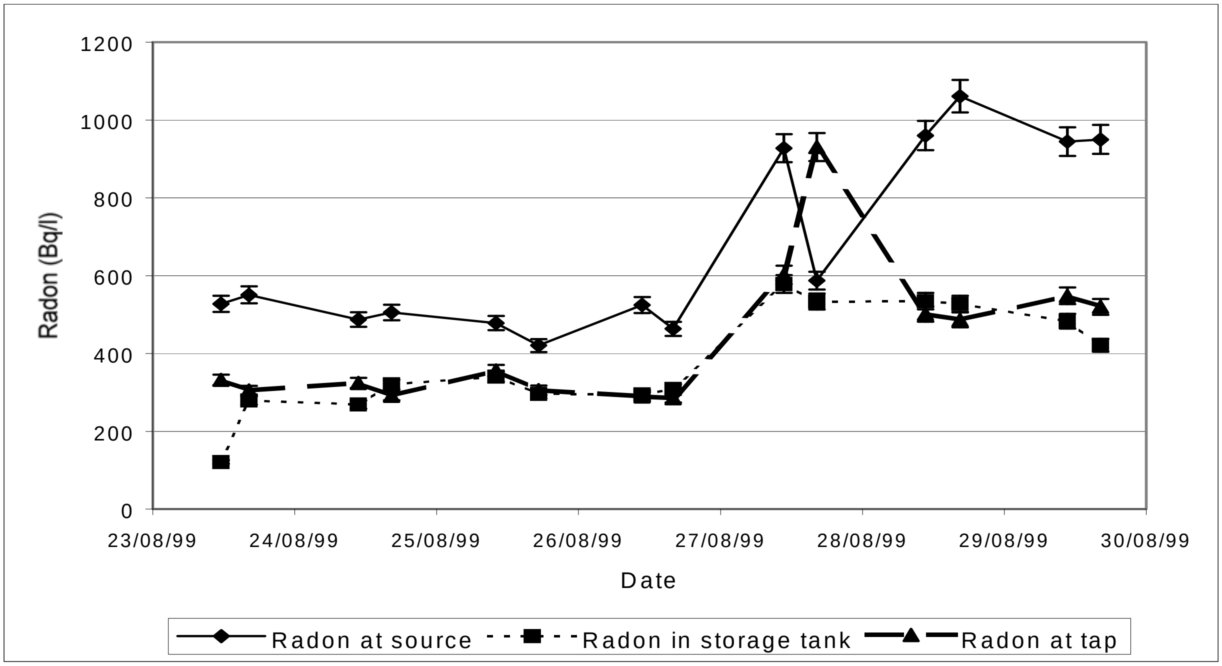


Figure 4, Borehole summer study

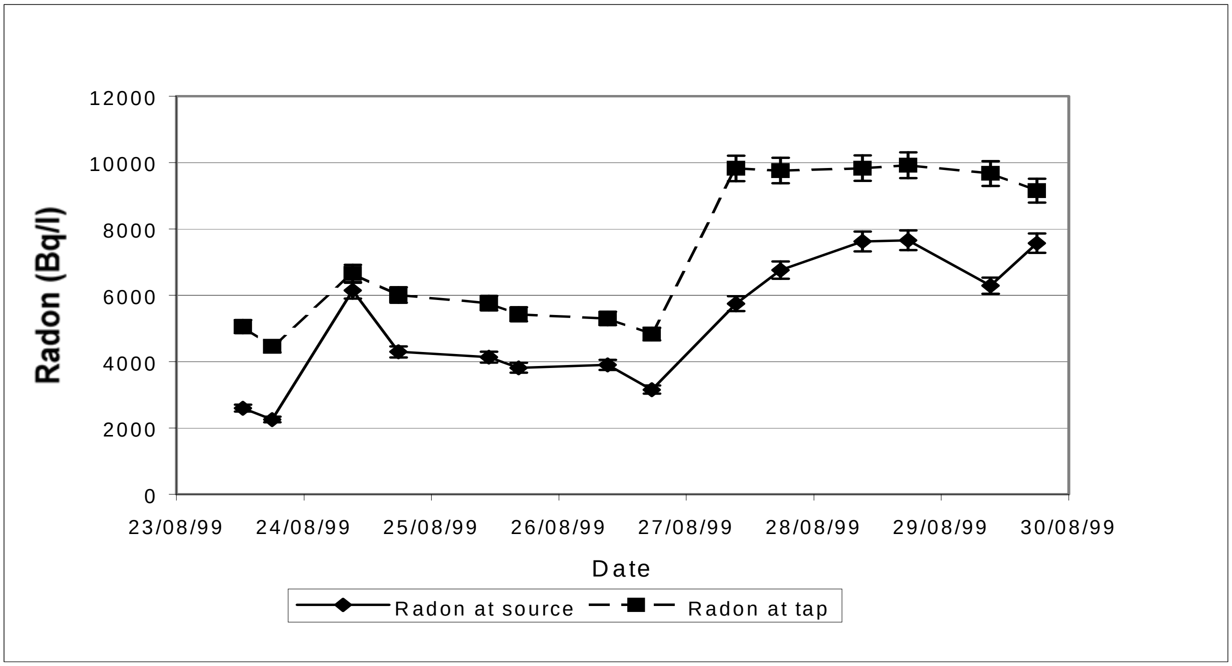
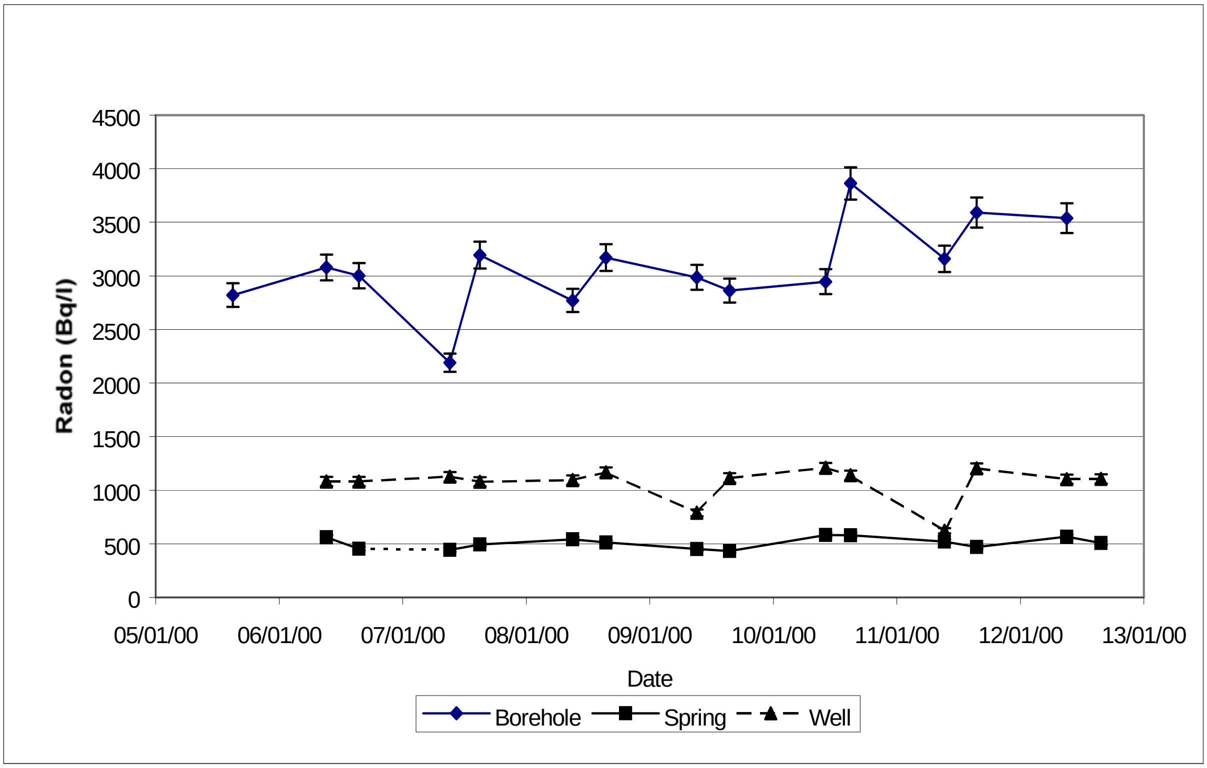


Figure 5, Winter Study (source sampling)



Figures 2 – 5 show there to be no constant change in radon between morning and evening or evening to following morning, error bars indicate the mean sampling errors determined in the screening study. The borehole site consistently has higher radon at the tap than at the source. This observation, coupled with the short distribution system at this property indicates that radon is lost due to degassing at the borehole sampling point, or gained from radium bearing pipe scale, rather than indicating a large, fast variation in radon in the water An increase in radon is apparent at all three sites in the summer study (Figs2-4) around the 27th of August, this coincides with a change in weather from showers, prevalent during the first part of the sampling period, to dry weather for the second part of the week.

It appears that the tap and source samples from spring site on the afternoon of 27th August have been mislabelled by the sampling subcontractor, all checks on the samples and sample cards show the situation to be as shown in Figure 3, however the results are consistent with a switch between the samples.

Table 5. Summary of summer and winter radon measurements at source (Bq/l)

	Summer			**Winter**		
Source type	**Samples**	**Mean**	**RSD (%)**	**Samples**	**Mean**	**RSD (%)**
Borehole	14	5520	35.8	14	3080	13.2
Spring	14	661	34.9	14	509	10.3
Well	14	644	52.4	14	1070	15.2

All the sources sampled showed large variability in radon concentration over the summer sampling period. Less pronounced variability was observed during the winter sampling. Maximum values were observed during the summer sampling and winter values were generally within the range of those found during the summer. Although no clear trends are visible in this data a more intensive and longer term sampling programme would be needed to reveal any systematic variability.

4.3 Uranium and Thorium

The full analysis results for uranium and thorium analyses are given in Appendix 2. Statistical summaries, analysed by source type and underlying geology, are given in Tables 6 to 9. Where duplicate analyses are available for a sample the mean of the two determinations has been used in the production of the statistical summaries.

Table 6. Uranium in tap water (µg/l) by source type.

Source Type	Samples	Mean	Min	Max
Adit	2	0.025	0.023	0.027
Borehole	40	1.09	<0.007	11.6
Combined spring and river extraction	1	0.362	0.362	0.362
Leat	2	0.331	0.211	0.452
River / Stream	2	0.157	0.149	0.164
Spring	43	0.455	<0.007	5.82
Well	24	0.301	<0.007	2.57
All tap water samples	114	0.625	<0.007	11.6

Table 7. Uranium in tap water (µg /l) by geology.

Geology at source	Samples	Mean	Minimum	Maximum
Basic Igneous Intrusion	1	<0.007	<0.007	<0.007
Crackington Formation	13	0.064	<0.007	0.317
Dartmoor Granite	44	1.48	0.023	11.6
Lower Carboniferous argillaceous rocks and	15	0.034	<0.007	0.163
Silurian igneous rocks	7	0.042	<0.007	0.173
Upper Devonian & Lower Carboniferous rocks	34	0.127	<0.007	0.865

Table 8. Thorium in tap water (µg /l) by source type.

Source Type	Samples	Mean	Min	Max
Adit	2	0.026	<0.03	0.036
Borehole	40	0.020	<0.03	0.066
Combined spring and river extraction	1	<0.03	<0.03	<0.03
Leat	2	0.028	<0.03	0.041
River / Stream	2	<0.03	<0.03	<0.03
Spring	43	0.017	<0.03	0.069
Well	24	0.016	<0.03	0.031
All tap water samples	114	0.018	<0.03	0.069

Table 9. Thorium in tap water (µg /l) by geology.

Geology at source	Samples	Mean	Minimum	Maximum
Basic Igneous Intrusion	1	<0.03	<0.03	<0.03
Crackington Formation	13	0.021	<0.03	0.059
Dartmoor Granite	44	0.020	<0.03	0.069
Lower Carboniferous argillaceous rocks and chert	15	0.016	<0.03	0.036
Silurian igneous rocks	7	<0.03	<0.03	<0.03
Upper Devonian & Lower Carboniferous rocks	34	0.016	<0.03	0.041

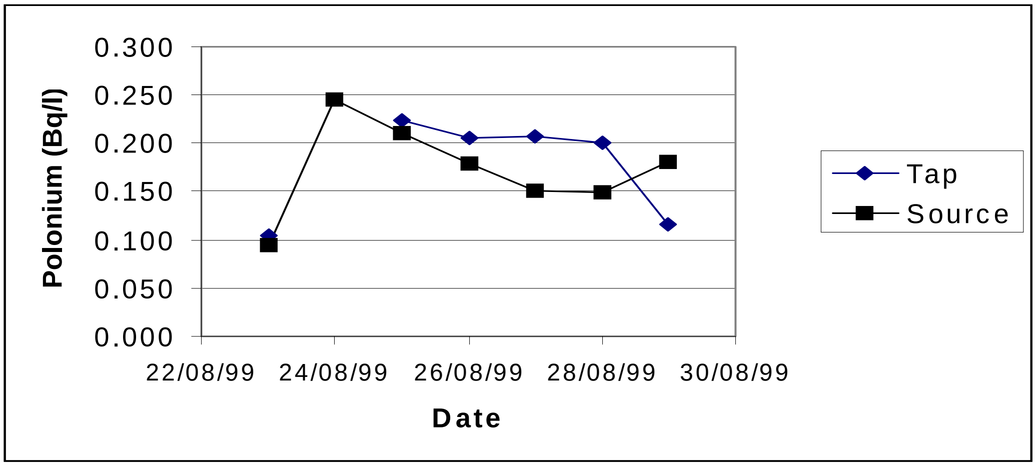
4.4 Polonium Analysis

Single samples for polonium analysis were collected during the summer detailed study from the well and spring sites found to have the highest radon concentrations in the screening study. A series of samples were taken from the borehole site, at the tap and the source during the summer and at the source during the winter. Analysis results are shown in Figure 6. The analysis method has a lower limit of detection of 0.01 Bq/l.

Table 10. ^{210}Po. **(Bq/l)**

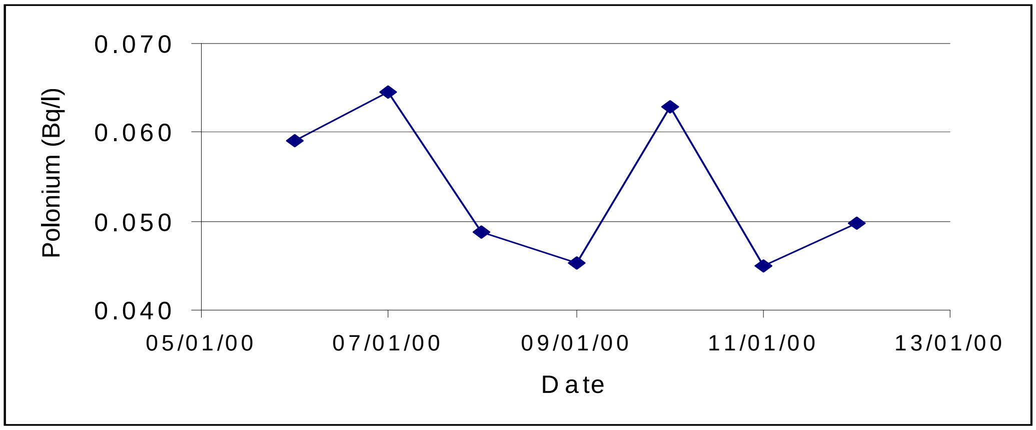
Site Name	Summer			Winter		
	Samples	**Mean**	**StdDev**	**Samples**	**Mean**	**StdDev**
Borehole	14	0.175	0.048	7	0.054	0.009
Well with max. radon	1	0.047				
Spring with max. radon	1	0.054				

Figure 6. Summer polonium analysis, Borehole site



Polonium concentrations were found to be markedly lower during the winter study than the summer study for reasons which are not apparent in this study.

Figure 7. Winter polonium analysis, Borehole site

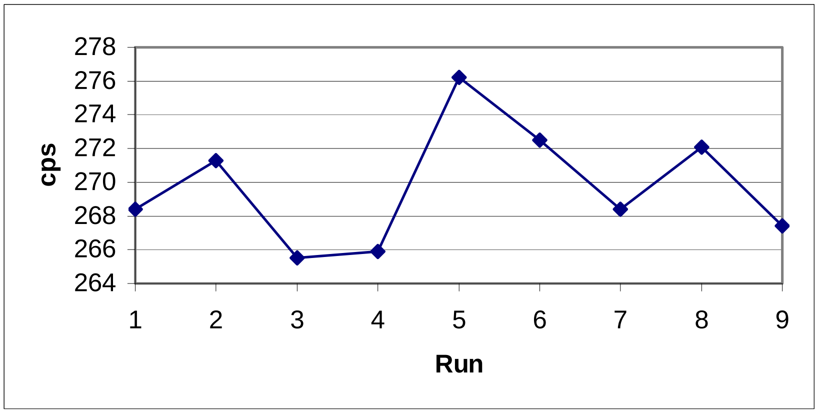


5) CALIBRATION AND ERROR ANALYSES.

5.1) Activity calibration

Throughout the 9 radon analysis runs undertaken for this stage of the project, standard radium solutions with a nominal activity of 200 Bq/l were counted. The mean decay corrected count rate is shown in Figure 8. The overall mean standard count rate was 269.7cps corresponding to an activity calibration of 1.35cps per Bq/l. Long term monitoring of the standard has yielded an overall mean count rate of 270.1 +/- 6.3 counts per second.

Figure 8. Analysis of standards



Analysis of the BGS standard against a traceable international standard has shown its value to be correct to within analytical errors.

5.2) Duplicate samples

Throughout the screening programme duplicate samples were collected at approximately 15% of sites. Duplicate analyses for ^{222}Rn show a sampling variability between samples ranging from 0.5 to 11%, with all but four of the pairs displaying a difference of less than 4.4% (Table 11). Analytical errors for the individual samples range from 1.1% to 5.6%. Analysis for ^{238}U of nine sets of duplicate samples shows a sampling error between 2.4% and 11% (Table12). For ^{232}Th, all of the duplicate samples have activities lower than the detection level.

Figure 9 shows a comparison between duplicate analyses results and the theoretical 1:1 match assuming no sampling or analytical errors for radon. Error bars on the individual data points represent the 3σ analytical error. Figure 10 shows the comparison between duplicates for uranium.

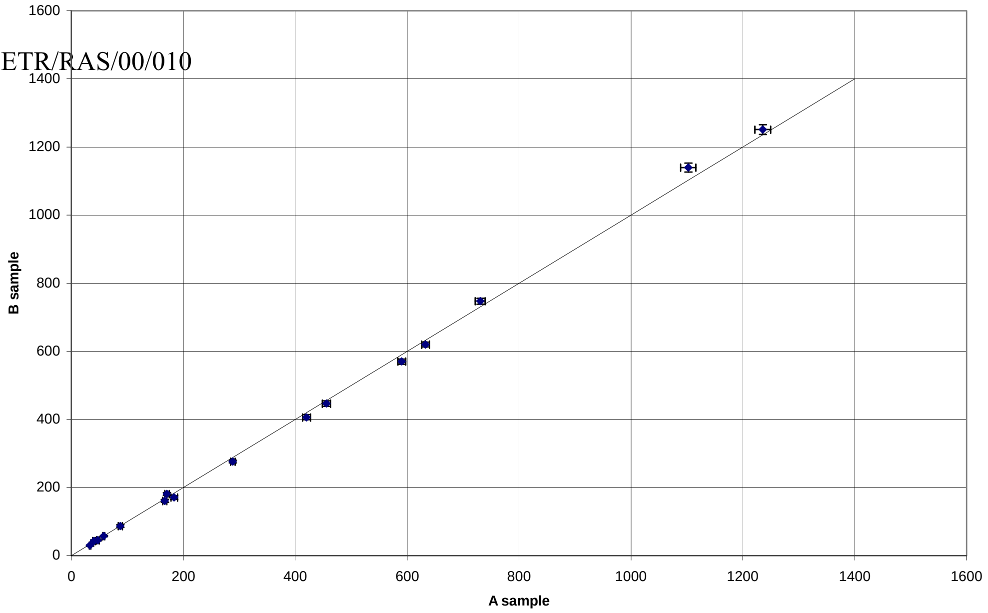


Figure 9. Duplicate analysis (^{222}Rn, Bq/l).

Table 11. Percentage errors in duplicate analysis of radon samples

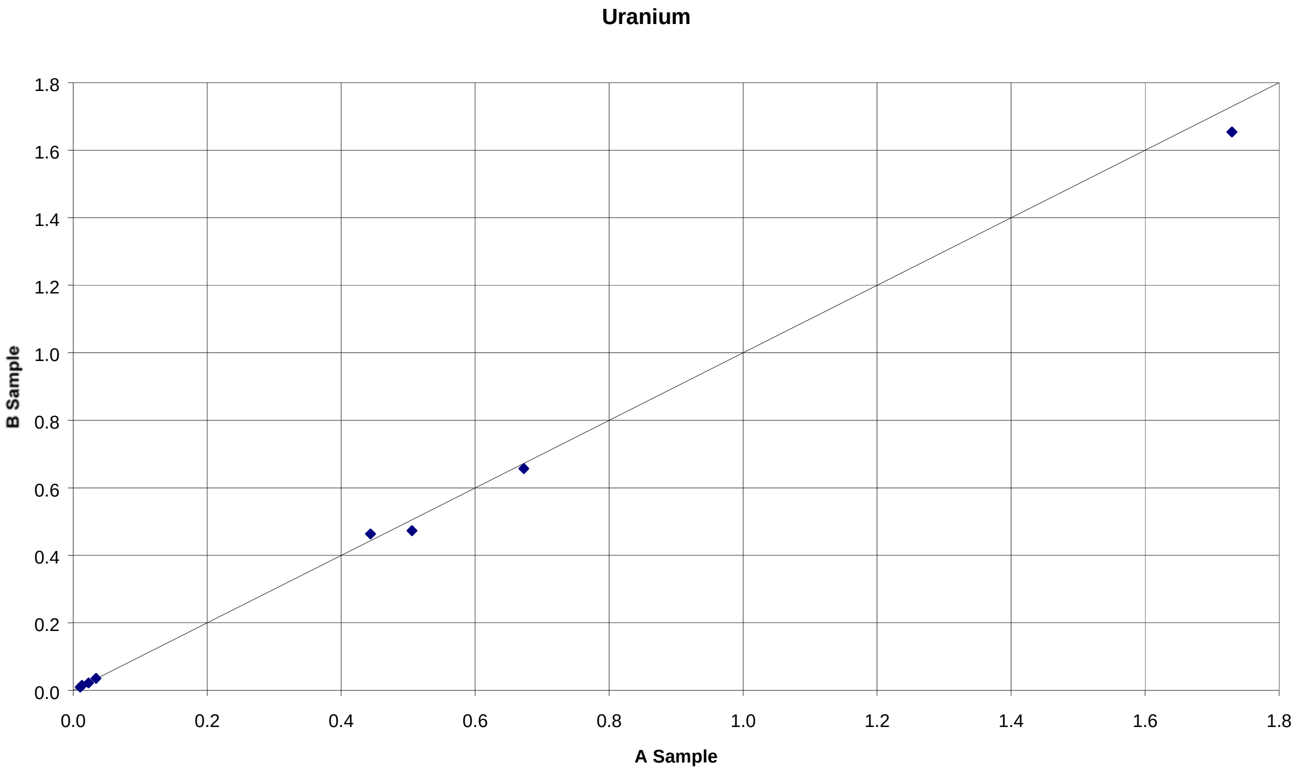
Duplicate	% Error		
	Between A and B	Analytical A	Analytical B
1	10.7	4.0	5.0
2	8.0	5.5	5.4
3	2.9	5.4	5.6
4	0.5	3.1	3.4
5	0.8	4.3	4.8
6	3.7	2.2	2.3
7	6.1	2.3	2.1
8	7.1	3.2	3.5
9	4.3	1.4	1.5
10	3.3	1.7	1.9
11	2.1	1.6	1.8
12	3.4	1.2	1.3
13	2.1	1.1	1.1
14	2.2	1.2	1.2
15	3.4	1.2	1.1
16	1.3	1.1	1.1

Table 12. Percentage errors in duplicate analysis of uranium and thorium sample.

Duplicate	% ERROR BETWEEN DUPLICATES	
	Uranium	Thorium
1	*	*
2	5.7	*
3	3.8	*
4	9.5	*
5	4.6	*
6	6.8	*
7	4.1	*
8	2.4	*
9	10.7	*

***** Measurements of one or both duplicate samples are below detection levels.

Figure 10. Duplicate analysis (^{238}U, μg/l)



6) Reduction due to drink preparation study.

6.1 Rationale to study

Studies on the inhalation of radon are well documented given that inhalation accounts for 89% of 'risk' arising from radon while ingestion accounts for only 11% (USEPA, 1999). The aim of this part of the project was to further refine the understanding of radionuclide uptake with a brief study to determine the quantity of ^{222}Rn lost during the preparation of various beverages and storage of water within household containers.

The proportion of the original concentration of radon released from water is dependent on (Becker and Lachajcyk, 1984):

- Surface Area
- Duration of air : water contact
- Agitation
- Temperature

A radium standard was purchased to use in creating a synthetic radon containing water. The solution was diluted, maintaining acidity, to a level were the radon generated from the radium would be at a concentration similar to the levels found in the preliminary sampling exercise. A bulk sample of radon-bearing groundwater unsupported by radium was also used. This was needed since a radium-supported standard cannot be used for any experiments which involved storage of the 'drink' as any radon lost due to process will rapidly be replaced from radium. The radon-bearing groundwater came from a source, of negligible radium content, sampled for previous work at the BGS, and a repeat analysis of the sample collected for this work confirmed radium concentration to be below the lower limit of detection.

The study consists of sub-sampling of water, spiked with ^{222}Rn, and calculating simple loss as a result of combinations of filling a kettle, boiling a kettle, pouring, stirring and storage associated with the making of both hot and cold drinks. Whilst most previous research on the risks of radon have centred mostly on inhalation problems and degassing during showering, studies relevant to the current one have concluded;

- Filling a kettle from a tapped source results in 0-50% loss, with USEPA 1991 stating 20% as a good average;
- Normal exchange to air very low (~0.15% per minute from a still sample), this rate increased by up to 20 times that if the sample was agitated, (Gesell and Pritchard 1980);
- Ratio of air to water exchange has been found to double from 10°C to 30°C, and double again from 30°C to 40°C over long term (Hess, 1987). This study was performed using a water bath and sampling under a layer of mineral oil to minimise Radon loss during sampling;

- In well experiments Tedesco et al (1996) found an order of magnitude difference in radon levels, using etched track detectors, in well bores at a temperature of 44-60°C c.f. well bores with a temperature range of 20-27°C.

The experimental outline is described in Appendix 3.

6.2 Results

The data from the experiments was used to calculate the 'removal factors', ρ , used in dose calculations, as described in section 7 of this report. The experimental results can be summarised as follows:

- Over the series of experiments loss on pouring ranged from 4% to 25%. The mean was 10.6% and the standard deviation 7.6%. These numbers are similar to those reported in previous studies (USEPA 1991)
- Over the series of experiments loss on reaching boiling for a few moments (as occurs in modern automatic electric kettles) from the ^{222}Rn left after pouring ranged from 63-83%. The mean was 73.4% with a standard deviation of 9.7%. Most literature values predict total, or near total, loss on boiling.
- 8 hour storage of an unsealed water sample resulted in a 60% loss of radon whether refrigerated or not.
- 24-hour storage of an unsealed sample resulted in total loss from the non-refrigerated samples and 95% loss in the refrigerated samples. The rate of loss is similar to that reported by Gessel and Pritchard (1980).
- Samples which were boiled, and then sealed and allowed to cool before storing, were used to simulate the content of bottles used for bottle fed infants. After boiling only 25% of the remaining ^{222}Rn is lost during this cooled and sealed storage.
- After boiling no significant losses occurred on pouring and stirring.

7) Estimation of adjusted Committed Effective Dose Equivalents

The IAEA Rasanet web-site (Radiation and Waste Safety Division, 1998) outlines the rationale for the use of CEDE. A measure of the total risk of specified somatic and hereditary effects to an average individual and progeny from an intake of a radioactive material, including the risk from irradiation in the subsequent 50 years resulting from the intake is given by the committed effective dose equivalent (CEDE), H_{50}. Values are calculated taking into account a number of factors such as gut and blood transfer parameters and chemical form of the ingested radionuclide.

7.1 Calculation and Rationale of dose parameters

The values for CEDE in this study were obtained by multiplying the dose equivalents resulting from ingestion only, by appropriate weighting factors and summing. When calculated for a unit intake of radioactivity i.e. 1 Bq, the result is a dose conversion factor **(DCF)**f in Sv/Bq.

The values used for (DCF)f [in this study are taken from the IAEA Rasanet web-site (Radiation and Waste Safety Division, 1998) http://www.iaea.org/ns/rasanet/information/doselim.htm. The parameters for Committed Effective Dose per Unit Intake via Ingestion in (Sv/Bq) for members of the public were used as recommended by the NRPB 1999. Many literature values exist for Radon (DCF)f by ingestion and some of these are shown in Table 14, with the value used in the study of 1x 10^{-8} being a good approximation.

Table 13. Dose Conversion Factors used in the current study.

Radionuclide	Target	$(DCF)_{f,}$ Sv/Bq
Rn-222	Adult	1x10-8
	Infant	1x10-8
Ra-226	Adult	2.8x10-7
	Infant	4.7x10-6
U-238	Adult	4.5x10-8
	Infant	3.4x10-7
Th-232	Adult	4.5x10-8
	Infant	3.4x10-7
Po-210	Adult	1.2x10-6
	Infant	2.6x10-5

A transfer parameter, termed $P(i)_{09}$, relating the dose to humans from intake of drinking water is calculated as:

$$P(i)_{09} = \rho\, k''_W\, I_W\, (DCF)_f$$

where $(DCF)_f$ = dose conversion factor for intake by ingestion (Sv/Bq),

I_W = intake of drinking water (l/a),

k''_W = fraction of the intake of drinking water arising from the contaminated source,

ρ = removal factor to account for a process, such as sedimentation and removal of radio-nuclides by water treatment processes.

The default value for k''_W is 1.

The value of ρ is site specific and in this case will be assumed to be unity.

The value of I_W intake of water is taken from the survey.

A number of assumptions are made in calculating CEDEs:

-The same dose conversion factor for infant and child groups was used

-In the absence of a definitive literature value, the same dose conversion factor is used for all age groups with regard to ^{222}Rn, though the effective dose is expected to be higher per unit intake for infants and young children (Crowford-Brown, 1987). Recent literature values for dose from ingested ^{222}Rn include:

Table 14. Some published values for ^{222}Rn dose conversions $(DCF)_f$ based on a ^{222}Rn content of 1 Bq/l.

Source	μSv/Bq/l	$(DCF)_f$
Jordan, 1994	3.7	1.00E-08
Khursheed, 2000	30.0	8.22E-08
Amrani, 1999	5.2	1.42E-08
UNSCEAR, 1988	4.0	1.10E-08
Kendall, 1988	3.7	1.00E-08

The newly released NRPB (2000) booklet on Health Risks on Radon also contains a brief appendices on non-lung cancers, gives some dose equivalent details, and stresses the substantial uncertainties in all the estimations of dose.

The drinks survey undertaken by BGS included collection of data on consumption rates. Most literature CEDE values work on an assumption that an adult drinks 0.5l/day, with some values as high as 1l. The survey shows this value can be higher and varies by season. All members of the households involved in the detailed study were asked to complete a questionnaire detailing their water consumption during the study periods. It is worth noting that the water consumption reported for Infant 1 is exceptionally high. This data can then be used to calculate the CEDE arising due to water consumption Table 15 summarises these surveys. Although one aspect of the lab. experiments simulated the storage of water before making drinks all those completing the questionnaire reported that water was always drawn fresh from the tap prior to preparing a drink.

Table 15. Observed water consumption patterns (l/day), based on householders completion of a questionnaire

	Summer			Winter		
	Boiled	Tap	Total	Boiled	Tap	Total
Child 1	0.5	0.25	0.75	0.25	0	0.25
Child 2	0	0.3	0.30	0	0.3	0.3
Infant 1	0.564	0.564	1.13	0.564	0.564	1.128
Infant 2	0.5	0	0.50	0.4	0	0.4
Adult 1	0.75	1	1.75	0.75	0.75	1.50
Adult 2	0.75	1.41	2.16	0.75	0.94	1.70
Adult3	1.25	0.25	1.50	1.50	0.00	1.50
Adult4	1.43	0.25	1.68	1.43	0.00	1.43
Adult5	2.33	0.53	2.86	2.13	0.28	2.41
Adult6	0.25	1.25	1.50	0.25	1.11	1.36

7.2 Doses derived from field study data.

The calculation of potential internal ionising radiation doses received has been calculated for each sample, and these are shown in Appendix 4. The average value for the whole study area was 1.10 mSv. The average contribution of each study radionuclide is shown in Table 16 as well as its maximum and minimum contribution. Radionuclide contributions in this table are based on analytical data from the screening samples

Table 16. Average contribution to annual dose by individual radionuclide.

Radioisotope From field study	Mean % contribution to CEDE	Minimum % contribution to CEDE	Maximum % contribution to CEDE
Rn-222	71.9	0.05	99.6
Ra-226	0.4	0.01	1.5
U-238	<0.02	0.00	<0.01
Th-232	<0.01	0.00	0.00
Po-210	27.6	0.35	98.5

The vast majority of dose from consumption of water comes from ^{222}Rn, with significant contribution from ^{210}Po. The higher the overall potential CEDE, the greater the contribution of total dose is from radon.

7.3 Incorporation of reductive factors derived from drink making study

Table 17 gives the average water consumption patterns of those surveyed in the detailed study. The adults involved in this study consumed noticeably more tap water than the 1.138 l/day suggested to be the national average by the Environment Agency (1998),

Table 17. Average water consumption from the survey.

Season	Category	Litres/day Tap	Litres/day Boiled	Litres/day Boiled, Sealed, Stored	Total Consumption (litres/day)
Summer	Adult	0.78	1.13	0	1.91
	Child	0.26	0.30	0	0.52
	Bottle-fed infant	0.56	0	0.56	1.13
	Breast-fed infant	0	0.5	0	0.50
Winter	Adult	0.51	1.14	0	1.65
	Child	0.15	0.13	0	0.28
	Bottle-fed infant	0.56	0	0.56	1.13
	Breast-fed infant	0	0.40	0	0.40

No person detailed in the consumption survey drank water that had been stored in cold storage without pre-boiling and only the bottle fed infant consumed water other than freshly drawn from the tap.

The loss due to process and consumption data was then combined with analytical results to attain an estimate of actual dose which would be received based on average water consumption at each of the properties in the detailed study and this is given in Table 19. A worst case taking into account the losses predicted from the drink making study, using the highest values of water consumption (summer consumption by adult 5), and the highest analytical results would give a CEDE potential of 22.5 mSv for an adult. In comparison 2.6mSv is the average dose received from background sources in the UK. The significance of the high dosage from ^{222}Rn observed in this study is evidenced by the fact that ingested radon normally only contributes about 10% of all risk from indoor radon, and radon itself only contributes 50% of background dose. On 'average' a householder would therefore get a CEDE from ingestion of water of only about 0.1mSv, the WHO recommended guideline from ingestion of radionuclides in groundwater.

The average potential CEDE from householders in this study is 1.1 mSv (calculated before any losses due to process).

Table 18. Dose based on observed average consumption, mSv per annum.

	Borehole site	Spring site	Well site
Adult	13.56	1.80	2.49
Child	3.93	0.51	0.67
Bottle-fed infant	9.43	1.28	1.87
Breast-fed infant	1.60	0.21	0.30

Table 19. Dose based on individual consumption patterns, mSv per annum.

	Borehole site	Spring site	Well site
Adult1	16.73	2.27	3.32
Adult2	22.53	3.06	4.47
Adult3	7.83	1.06	1.56
Adult4	8.45	1.15	1.68
Adult5	15.51	2.11	3.08
Adult6	18.53	2.52	3.68
Child1	5.25	0.71	1.04
Child2	3.53	0.48	0.70
Bottle-fed infant	9.43	1.28	1.87
Breast-fed infant	7.07	0.96	1.40

Tables 18 and 19 assume, based on the findings of the drink making experiments.

- 10% of radon is lost on pouring
- No significant further loss occurs prior to cold drink consumption (*90% of original radon content is consumed*).
- 73% of what remains is lost on boiling (total loss of 76% from original)
- 10% is lost on pouring (total loss of 78% from original)
- No significant further loss occurs prior to hot drink consumption (*22% of original radon content is consumed*).
- After sealing and cooled storage 25% is lost prior to consumption by a bottle fed infant (*16% of original radon content is consumed*).

The dose values calculated for the study only account for radionuclides physically ingested. The values may be raised significantly by inhalation of radon degassing from water supplies by processes in the household such as during drinks making, filling of baths, water storage tanks and showering. Radon has a greater dose conversion factor for inhalation than ingestion (Cross et al. 1985). There have been a number of studies on degassing effects of radon in the household (Hess et al., 1987, Fitzgerald et al. 1997). These studies derive transfer parameters from water-air during water processing. Using the data from the current project it may be possible to scale up from smaller scale water processes to larger scale (e.g. from kettle to bath). The overall 'dose burden' for a dwelling can than be calculated by including gas levels from ground intrusion.

8) CONCLUSIONS

^{222}Rn was found to be above the draft Commission Recommendation action level of 1000 Bq/l in 8% of the tap water samples analysed.

In terms of the geology at the source Dartmoor Granite and Undifferentiated Upper Devonian & Lower Carboniferous rocks yielded tap water with radon concentrations over 1000 Bq/l, while some water with a source on the Lower Carboniferous argillaceous rocks and chert had a radon concentration of over 1000 Bq/l at the source. Dartmoor Granite produced the highest average radon levels with the single highest value resulting from a borehole source in this formation and the highest values found in springs and wells coming from these rocks. The high degree of variability observed during the detailed study make it impossible to estimate the proportion of supplies which exceed the advisory level for what proportion of the time. The few examples of surface water supplies such as those drawn from streams and leats all show low radon concentrations (<35 Bq/l).

As a baseline all private water supplies would need to be sampled. More detailed sampling over a longer time period may clarify the relationship between ^{222}Rn and weather conditions indicated by the summer sampling so enabling a detailed picture of radon levels throughout the year to be built up.

For water from groundwater sources, mean values (by source type) at the tap are consistently lower than those values at the source. This is consistent with loss of radon due to degassing, as a result of water turbulence within the supply system and natural radioactive decay while the water is resident in the supply system.

Appendix 2 shows that in the majority of cases ^{222}Rn concentrations in tap water for a particular supply are lower than, or similar to, that at the source. However in a number of cases ^{222}Rn is significantly higher in the tap water sample than in the source sample. This may indicate very large short-term variability of ^{222}Rn levels in the supply. However at the particular borehole site, radon was consistently higher at the tap than the source during both of the detailed sampling exercises indicating the discrepancy is due to the loss of radon from the water while sampling the source, or an increase in radon while the water is in the supply pipe work, possibly due to the presence of radium bearing pipe scale.

The potential internal ionising radiation doses received has been calculated for each site involved in the screening study based on water consumption patterns found in the detailed study. In these cases the majority of dose from consumption of water arises from ^{222}Rn, with a small contribution from ^{210}Po, and insignificant dose from other uranium series elements. In all cases where there is a potential CEDE of above 1mSv at least 95% of the dosage will be from ^{222}Rn.

In the locations with the highest radon values experiments have shown the dosage was well in excess of the WHO recommendation of 0.1mSv even after reduction due to the drink making process are taken into account. In the most extreme case it is over 13mSv per annum. Were a person to receive a dose at a place of employment(eg. in a hotel) of greater than 6mSv they would need to be a classified radiation worker (IRR 1999), which would then ensure work was conducted under a regime of monitoring, medical checks, personal protective equipment.

To fully understand the exposure received by individuals it would also be necessary to incorporate dose due to inhalation of ^{222}Rn. Workers in areas having greater than 400Bq/m3 are also covered by the procedures of IRR 1999.

Although ^{222}Rn is the principal isotope contributing to radiological dose it is worth noting that ^{238}U is present in a number of supplies at levels exceeding 2µg/l, the World Health Organisation (WHO) provisional guideline value for uranium in drinking water (WHO, 1998).

9) REFERENCES

Amrani, D., and Cherouati, D.E., 1999. Health effects from radon-222 in drinking water in Algiers. *Journal of Radiological Protection.* **19**, *3*, 375-279.

Becker A.P., and Lachajcyk T.M., 1984. Evaluation of waterborne radon impact on indoor air quality and assessment of control options. U.S. Environmental Protection Agency. EPA-600/7-84-093.

Cross, F. T., Harley, N. H. and Hofmann, W. (1985). Health effects and risks from 222-Rn in drinking water. Health Phys., **48**, 649-.

Crowford-Brown, D.J.,1987. Age dependent lung doses from ingested 222Rn in drinking water. *Journal of Health Physics*, **52**, 149-152.

Environment Agency website 1998, http://www.environment-agency.gov.uk/modules/MOD31.250.html

Field, RW, Fisher, EL, Valentine, RL and Kross, BC, 1995. Radium-beraing pipe scale deposits – implications for national waterborne radon sampling methods. *American Journal of Public Health,* **85**, 4, 567-570.

Flyn, 1968. The determination of ^{210}Po in environmental materials. *Anal Chim Acta* **43**, 221-227.

Fitzgerald, B., Hopke, P.K., Datye, V., Raunemaa, T., and Kuuspalo, K., 1997. Experimental assessment of the short- and long-term effects of ^{222}Rn from domestic shower water on the dose burden incurred in normally occupied homes. Journal of Environmental Science and Technology, **31**, 1822-1829.

Gessel, T.F., and Pritchard H.M., 1980 . The contribution of radon in tap water to indoor radon concentrations. *Natural Radiation Environment III.* . US Department of Energy, Technical Information Centre. CONF-780422 (vol.2). 1347-1363

Hess, C.T, 1987. Development of a method for integrated measurement of radon in water. *Terradex Corporation Newsletter*, (March 1987).

Hess, C.T., Vietti, M.A., and Mage, D.T., 1987. Radon from drinking water- evaluation of water-borne transfer into a house. Journal of Environmental Geochemistry and Health, **9**, *3-4*, 68-73.

IAEA 1989. The application of the principles for limiting releases of radioactive effluents in the case of the mining and milling of radioactive ores. *Safety Series No.90*, IAEA, Vienna.

IAEA Rasanet web-site (Radiation and Waste Safety Division , 1998)
http://www.iaea.org/ns/rasanet/information/doselim.htm

Ionising Radiation Regulations, 1999*. Statutory Instrument No. 3232*. HMSO.

Jordan, D.A., 1994. Implications and extent of contamination of drinking water supplies by natural series radionuclides: A case study. University of Birmingham. (Unpublished MSc Thesis).

Kendall, G.M., Fell, T.P. and Phipps, A.W., 1988. A model to evaluate doses from radon in drinking water. *Radiation Protection Bulletin*, **97**, 7-8.

Khursheed A. 2000, In Press. Doses to systemic tissues from radon gas. *Journal of Radiation Protection Dosimetry.*

NRPB 2000. Guide to dose coefficients . UK National Radiation Protection Board . *Non-specialist publication series*, 22..

NRPB 2000. Health Risks from Radon . UK National Radiation Protection Board . *Non-specialist publication series*, 28-31.

Talbot. 1994. A new, laboratory based, analytical method for the assessment of levels of radon contamination in the built environment. Unpublished MSc. thesis. Loughborough University of Technology.

Tedesco D., Pece R., and Avino R., 1996. Radon, pH and temperature monitoring in water wells at Campi Flegrei Caldera (southern Italy). *Geochemical journal*, **30**, 131-138,

UNSCEAR, 1988. Sources effects and risks of ionising radiation, report to the general assembly. (New York: United Nations), 24-79.

USEPA, 1991. EPA's estimations of risk for indoor radon exposure. *Radiation Advisory Subcommittee of the Science Advisory Board*. U.S. Environmental Protection Agency

USEPA, 1999. Radon in drinking water: health risk reduction and cost analysis. *Federal register*. **64**,*.38.* 9562 26/2/99/Notices.

WHO, 1998, Guidelines for Drinking-water Quality, Second edition, Addendum to Volume 1: Recommendations.

Vajda, N., LaRosa, J., Zeisler, R..,Danesi, P., Kis-Benedek, G. 1997. "A Novel Technique for the Simultaneous Determination of ^{210}Pb and ^{210}Po using a Crown Ether " *Journal of Environmental Radioactivity*, **30**, *3*, 355-372.

Draft Commission Recommendation on the protection of the public against exposure to radon in domestic water supplies, 2000.

Appendix 1. Sample site details.

Sample No	Source Type	Location	Location notes	Infants	Children	Adults	Notes
URW7501	Borehole	Source	Tap in bottling room, first access to water after borehole, no storage after borehole	0	1	4	Children aged 10,12,14
URW7502	Borehole	Tap	No other sampling location within house	0	1	4	Children aged 10,12,15
URW7503	Well	Souce	Storage tank present near source	0	1	4	
URW7504	Well	Tap	No other sampling location within house	0	1	4	
URW7505	Spring	Source	Sample from collection chamber, storage tank present near chamber	0	0	3	
URW7506	Spring	Tap	No other sampling location within house	0	0	3	
URW7507	Spring	Source	Sample from collection chamber, no other sampling on supply	0	0	3	
URW7508	Spring	Tap	No other sampling location within house	0	0	3	
URW7509	Borehole	Source	Pumped through sealed system to house taps	1	1	2	Borehole difficult to sample
URW7510	Borehole	Tap	Pumped through sealed system to house taps	1	1	2	
URW7511	Borehole	Source	Sampled from storage tank as borehole sealed	0	0	5	Occupancy refers to permanent residents
URW7512	Borehole	Tap	No other sampling location within house	0	0	5	Occupancy refers to permanent residents
URW7513	Borehole	Source	Sampled from storage tank as borehole sealed				Charity Holiday Home
URW7514	Borehole	Tap	No other sampling location within house				Charity Holiday Home
URW7515	Borehole	Source	Sampled from borehole outlet pipe	1	0	4	
URW7516	Borehole	Tap	No other sampling location within house	1	0	4	
URW7517	Well	Source	Sampled direct from well	0	0	4	
URW7518	Well	Tap	No other sampling location within house	0	0	4	
URW7519	Spring	Source	Sample taken from collection Chamber, storage tank present	0	0	6	
URW7520	Spring	Tap	No other sampling location within house	0	0	6	
URW7521	Borehole	Source	Sample taken from inlet to loft tank, first sampling point on system	0	0	4	
URW7522	Borehole	Tap	Storage in loft	0	0	4	
URW7523	Well	Source	Sample taken direct from well	1	0	2	
URW7524	Well	Tap	No other sampling location within house	1	0	2	
URW7525	Spring	Source	Sample taken at inlet to storage tank	0	0	4	
URW7526	Spring	Tap	No other sampling location within house	0	0	4	
URW7527	Borehole	Source	Sample from outlet from borehole				No permanent residents
URW7528	Borehole	Tap	No other sampling location within house				No permanent residents
URW7529	River	Source	Sample from collection chamber				No permanent residents
URW7530	River	Tap	Storage tank in buildings				No permanent residents
URW7531	Spring	Source	Sample taken from collection Chamber, storage tank present	0	0	2	
URW7532	Spring	Tap	No other sampling location within house	0	0	2	
URW7533	Borehole	Source	Sampled from tap on borehole outlet	0	0	8	Residential home for 5 mentally impaired adults
URW7534	Borehole	Tap	No other sampling location within house	0	0	8	Residential home for 5 mentally impaired adults
URW7535	Borehole	Source	Direct from BH, no storage tank	0	1	5	
URW7536	Borehole	Tap	No other sampling location within house	0	1	5	
URW7537	Spring	Source	Storage tank in field	0	0	2	
URW7538	Spring	Tap	No other sampling location within house	0	0	2	
URW7539	Borehole	Source	Sample from filter on BH outlet, no other sampling point before house	0	0	2	
URW7540	Borehole	Tap	Storage in loft	0	0	2	
URW7541	Borehole	Source	No other sampling on distribution system	0	0	2	
URW7542	Borehole	Tap	No other sampling on distribution system	0	0	2	
URW7543	Well	Source	No other sampling on distribution system	0	0	2	
URW7544	Well	Tap	No other sampling on distribution system	0	0	2	
URW7545	Spring	Tap	Source not accessible, household tap only available sampling point	0	0	2	
URW7546	Spring	Source	Storage tank in farmyard	0	0	6	
URW7547	Spring	Tap	Sealed storage tank in loft	0	0	6	
URW7548	Spring	Source	Sample from collection chamber, accessable storage tank present near chamber	0	3	2	
URW7549	Spring	Tap	Sealed storage tank in loft	0	3	2	
URW7550	Borehole	Source	No other sampling point on distribution system	0	3	2	
URW7551	Borehole	Tap	No other sampling point on distribution system	0	3	2	
URW7552	Borehole	Tap	No other sampling point on distribution system				Holiday cottage
URW7553	Borehole	Source	Sample taken from storage tank next to BH	0	0	3	
URW7554	Borehole	Tap	No other sample point in house	0	0	3	
URW7555	Borehole	Tap	No other sampling point on distribution system	0	0	1	
URW7556	Borehole	Source	No storage before house	0	0	2	
URW7557	Borehole	Tap	No other sampling point in house	0	0	2	
URW7558	Spring	Source	No storage on supply	0	0	2	
URW7559	Spring	Tap	Sealed storage tank in roof	0	0	2	
URW7560	Well	Source	Two sealed storage tanks, no other sampling points	0	3	2	
URW7561	Well	Tap	Two sealed storage tanks, no other sampling points	0	3	2	

Sample No	Source Type	Location	Location notes	Infants	Children	Adults	Notes
URW7562	Well	Source	Two sealed storage tanks, no other sampling points	0	3	2	Duplicate
URW7563	Well	Tap	Two sealed storage tanks, no other sampling points	0	3	2	Duplicate
URW7564	Borehole	Source	Sample taken from tap between BH and House, no other sampling point available	0	0	2	
URW7565	Borehole	Tap	Sealed storage tank in loft	0	0	2	
URW7566	Well	Source	No storage before house	0	0	2	
URW7567	Well	Tap	Sealed storage tank in loft	0	0	2	
URW7568	Spring	Source	Sample from storage tank in field, source inaccessible	0	0	3	
URW7569	Spring	Tap	No storage in house	0	0	3	
URW7570	Spring	Source	Sample from storage tank in field, source inaccessible	0	0	5	
URW7571	Spring	Tap	Sealed storage tank in loft	0	0	5	
URW7572	Well	Source	No storage before house	0	2	2	
URW7573	Well	Tap	Sealed storage tank in loft	0	2	2	
URW7574	Spring	Source	Sample taken from inlet to collector chamber, only assessable source	0	0	2	
URW7575	Spring	Tap	Sealed storage tank in loft	0	0	2	
URW7576	Spring	Source	Sample taken from inlet to storage tank	0	0	2	Hotel houses max. 17 people
URW7577	Spring	Tap	Storage present in building	0	0	2	
URW7578	Spring	Source	No storage before house	0	0	2	
URW7579	Spring	Tap	Sealed storage tank in loft	0	0	2	
URW7580	Spring	Source	No storage before house	0	0	2	
URW7581	Spring	Tap	Sealed storage tank in loft	0	0	2	
URW7582	Adit	Source	Sampled from tap on reservoir, storage between source & house	0	0	4	
URW7583	Adit	Tap	Sealed storage in house	0	0	4	
URW7584	Well	Source	No storage before house	0	0	3	
URW7585	Well	Tap	Sealed storage in house	0	0	3	
URW7586	Spring	Source	Sampled from reservoir overflow, storage tank present	0	0	7	
URW7587	Spring	Tap	Sealed storage in house	0	0	7	
URW7588	Well	Source	Well in conservatory, only used as D/W in autumn and winter	0	0	2	
URW7589	Borehole	Source	No storage on supply	0	0	4	
URW7590	Borehole	Tap	No storage on supply	0	0	4	
URW7591	Borehole	Source	Sample taken from inlet to storage tank	0	0	4	
URW7592	Borehole	Tap	No storage in house	0	0	4	
URW7593	Well	Source	Sample direct from well under kitchen floor	0	0	2	
URW7594	Well	Tap	Sealed storage in house	0	0	2	
URW7595	Borehole	Source	No storage before house	0	0	4	
URW7596	Borehole	Tap	Storage tank in loft	0	0	4	
URW7597	Borehole	Source	Storage in field	0	0	5	
URW7598	Borehole	Tap	No other storage in house	0	0	5	
URW7599	Well	Tap	Source inaccessible, loft storage tank possibly open	0	0	4	
URW7600	Borehole	Source	Sample taken from inlet to storage tank	0	0	7	Occupancy no refers to permanent residents
URW7601	Borehole	Tap	No other storage in house	0	0	7	Occupancy no refers to permanent residents
URW7602	Borehole	Source	Sample taken from inlet to storage tank	0	0	7	
URW7603	Borehole	Tap	No other storage in house	0	0	7	
URW7604	Spring	Source	Sample taken from collector chamber, no other storage before house	0	3	2	
URW7605	Spring	Tap	Sealed storage tank in loft	0	3	2	
URW7606	Borehole	Source	No other storage before house	0	0	12	Residential home
URW7607	Borehole	Tap	No other storage in house	0	0	12	Residential home
URW7608	Spring	Source	Sealed storage tank in farmyard	0	0	1	
URW7609	Spring	Tap	No storage in house	0	0	1	
URW7610	Borehole	Source	No storage before tap	0	0	4	
URW7611	Borehole	Tap	No storage before tap	0	0	4	
URW7612	Spring	Source	Storage in field, sample taken from collection chamber	0	0	2	Single source supplies 11 homes
URW7613	Spring	Tap	No other sampling point in house	0	0	2	Single source supplies 11 homes
URW7614	Well	Source	Storage in field	0	0	4	
URW7615	Well	Tap	No other sampling point in house	0	0	4	
URW7616	Borehole	Source	No storage on system	0	0	2	
URW7617	Borehole	Tap	No other sampling point on system	0	0	2	U sample lost in transit
URW7618	Leat	Source	Storage on moor	0	0	1	Leat fed from river Walkham Nr Mistor
URW7619	Leat	Tap	No other sample point in house	0	0	1	
URW7620	Spring	Source	Storage in yard, sample taken from collection chamber on moor.	0	0	4	
URW7621	Spring	Tap	Sealed storage tank in loft	0	0	4	
URW7622	Spring	Source	Storage in field	0	0	1	

Sample No	Source Type	Location	Location notes	Infants	Children	Adults	Notes
URW7623	Spring	Tap	No other storage in house	0	0	1	
URW7624	Spring	Source	Storage in field	0	0	1	
URW7625	Spring	Tap	No other storage in house	0	0	1	
URW7626	Spring	Source	Storage on moor, sample from reservoir inlet	0	0	2	
URW7627	Spring	Tap	No other storage in house	0	0	2	
URW7628	Spring	Source	Sample from after storage tank, first sampling location on supply	0	0	2	
URW7629	Spring	Tap	No other storage in house	0	0	2	
URW7630	Spring	Source	Sample from collection chamber, storage in field.	0	0	2	Supply shared with 9 other properties
URW7631	Spring	Tap	No other storage in house	0	0	2	Supply shared with 9 other properties
URW7632	Spring	Source	Storage in field	0	0	2	Supply shared with 23 other properties
URW7633	Spring	Tap	No other storage in house	0	0	2	Supply shared with 23 other properties
URW7634	Borehole	Source	No storage before house	0	0	2	
URW7635	Borehole	Tap	Sealed storage in loft	0	0	2	
URW7636	Borehole	Source	No other storage on system	0	0	4	
URW7637	Borehole	Tap	No other storage on system	0	0	4	
URW7638	Well	Source	No storage before house	0	0	2	
URW7639	Well	Tap	Sealed storage tank on roof	0	0	2	
URW7640	Spring	Source	Storage in field	0	0	6	
URW7641	Spring	Tap	Sealed storage on roof	0	0	6	
URW7642	Borehole	Source	No storage before house	0	0	3	
URW7643	Borehole	Tap	Sealed storage on roof	0	0	3	
URW7644	Borehole	Source	No storage before house	0	0	3	
URW7645	Borehole	Tap	Sealed storage on roof	0	0	3	
URW7646	Stream	Source	Sealed storage in wood	0	0	1	1 permanent resident, up to 50 scouts
URW7647	Stream	Tap	Storage in roof	0	0	1	1 permanent resident, up to 50 scouts
URW7648	Spring	Source	Storage in field	0	0	5	
URW7649	Spring	Tap	Sealed storage in roof	0	0	5	
URW7650	Well	Source	No storage before house				Holiday let, no permanent occupants
URW7651	Well	Tap	Sealed storage in roof				Holiday let, no permanent occupants
URW7652	Borehole	Source	Storage in field	0	0	2	
URW7653	Borehole	Tap	Sealed storage in roof	0	0	2	
URW7654	Spring	Source	Storage in field	0	0	2	
URW7655	Spring	Tap	No other storage in house	0	0	2	
URW7656	Borehole	Source	Sample direct from BH, no other storage before house	0	0	2	
URW7657	Borehole	Tap	Sealed storage in roof	0	0	2	
URW7658	Borehole	Source	No storage in system	0	0	2	
URW7659	Borehole	Tap	No storage in system	0	0	2	
URW7660	Well	Source	No storage before house	0	0	2	
URW7661	Well	Tap	Sealed storage in roof	0	0	2	
URW7662	Well	Source	No storage before house. Sample from tap by well, well head sealed	0	0	1	
URW7663	Well	Tap	Storage in bathroom	0	0	1	
URW7664	Well	Source	No storage before house. Sample from tap by well, well head sealed	0	0	1	
URW7665	Well	Tap	Storage in bathroom	0	0	1	
URW7666	Borehole	Source	No storage on system	1	0	4	
URW7667	Borehole	Tap	No storage on system	1	0	4	
URW7668	Spring	Source	Storage in field	0	1	4	
URW7669	Spring	Tap	Sealed storage in roof	0	1	4	
URW7670	Spring	Source	Storage in field	0	0	2	
URW7671	Spring	Tap	No storage in house	0	0	2	
URW7672	Well	Source	No storage on system	1	0	4	
URW7673	Well	Tap	No storage on system	1	0	4	
URW7674	Spring	Source	Storage tank in field, difficult to sample but possible	0	0	2	
URW7675	Spring	Tap	Sealed storage in roof	0	0	2	
URW7676	Mine addit	Source	Storage in stable block	0	0	5	Hotel accommodates up to 28 guests
URW7677	Mine addit	Tap	No storage within hotel	0	0	5	Hotel accommodates up to 28 guests
URW7678	Leat	Source	No storage before hostel				Activity center, no permanent residents
URW7679	Leat	Tap	Storage in roof				Activity center, no permanent residents
URW7680	Leat	Source	No storage before house				Activity center, no permanent residents
URW7683	Spring	Tap	No storage in house	0	0	4	Hotel accommodates up to 15 guests
URW7684	Borehole	Source	No storage on system, BH supplies 5 other properties	0	0	2	
URW7685	Borehole	Tap	No storage on system, BH supplies 5 other properties	0	0	2	

Sample No	Source Type	Location	Location notes	Infants	Children	Adults	Notes
URW7686	Borehole	Tap	Kitchen tap is first sampling point on a pressurized system	0	0	2	
URW7687	Spring	Source	Storage tank on moor	0	1	2	
URW7688	Spring	Tap	No storage in house	0	1	2	
URW7691	Well	Source	No storage before house	0	1	3	
URW7692	Well	Tap	Sealed storage in roof	0	1	3	
URW7693	Well	Source	No storage before house	0	0	4	
URW7695	Spring	Source	Buried, sealed storage tank	0	0	1	Youth hostel sleeps up to 36
URW7696	Spring	Tap	No storage in house	0	0	1	Youth hostel sleeps up to 36
URW7697	Well	Source	No storage before house	0	0	2	
URW7698	Well	Tap	Sealed storage in roof	0	0	2	
URW7699	Borehole	Tap	Pressurized system, tap only sampling point.	0	0	4	
URW7700	Well	Source	No storage before house	0	2	4	
URW7701	Well	Tap	Sealed storage in roof	0	2	4	
URW7703	Well	Tap	Sealed storage in roof	0	0	2	
URW7704	Well	Source	No storage before house	0	0	1	
URW7705	Well	Tap	Sealed storage in roof	0	0	1	
URW7706	Spring & river	Source	Sample from mixing chamber, storage on system	0	0	6	
URW7707	Spring & river	Tap	No storage in house	0	0	6	
URW7708	Spring	Source	No storage before house, sample from tap on spring	0	1	2	
URW7709	Spring	Tap	Sealed storage in roof	0	1	2	
URW7710	Spring	Tap	Tap only sample point on sealed system	0	0	4	
URW7711	Borehole	Source	No storage on system	0	0	4	
URW7712	Borehole	Tap	No storage on system	0	0	4	
URW7713	Spring	Source	No storage on system, sample from collection chamber	0	1	3	
URW7714	Spring	Tap	No storage on system	0	1	3	
URW7715	Spring	Source	Storage on moor	0	0	2	
URW7716	Spring	Tap	No storage in house	0	0	2	
URW7717	Spring	Source	Storage on moor	0	0	2	
URW7718	Spring	Tap	No storage in house	0	0	2	
URW7719	Well	Source	No storage on system	0	0	2	
URW7720	Well	Tap	No storage on system	0	0	2	
URW7721	Spring	Source	Storage on moor	0	0	5	Village supply, serves about 12 properties
URW7722	Spring	Tap	No storage in house	0	0	5	Village supply, serves about 12 properties
URW7723	Borehole	Source	No storage before house	0	2	2	
URW7724	Borehole	Tap	Sealed storage in roof	0	2	2	
URW7725	Well	Tap	Sealed system, tap only sampling point	0	0	4	
URW7726	Borehole	Source	Storage in shed	0	0	4	
URW7727	Borehole	Tap	No storage in house	0	0	4	
URW7728	Spring	Source	Sample taken from storage tank, spring collection chamber sealed	0	0	4	
URW7729	Spring	Tap	No storage in house	0	0	4	
URW7730	Spring	Source	Sample taken from storage tank, spring collection chamber sealed	0	0	4	
URW7731	Spring	Tap	No storage in house	0	0	4	
URW7732	Spring	Source	Storage in field				
URW7733	Spring	Tap	No storage in house				
URW7734	Borehole	Source	No storage on system	0	0	4	Boarding school for 40 11-16 year old boys
URW7735	Borehole	Tap	No storage on system	0	0	4	Boarding school for 40 11-16 year old boys
URW7736	Well	Source	No storage before house	0	0	2	
URW7737	Well	Tap	Sealed storage in roof	0	0	2	
URW7738	Borehole	Source	Storage tank in orchard	0	0	2	
URW7739	Borehole	Tap	No storage in house	0	0	2	
URW7740	Spring	Tap	No other sampling point on system	0	1	4	
URW7741	Borehole	Source	Storage tank in roof	0	2	2	
URW7742	Borehole	Tap	Storage tank in roof	0	2	2	
URW7743	Spring	Source	No storage on system	0	1	4	
URW7744	Spring	Tap	No storage on system	0	1	4	
URW7745	Spring	Source	No storage on system	0	1	4	
URW7746	Spring	Tap	No storage on system	0	1	4	
URW7747	Borehole	Tap	No other samplining point on system	0	1	2	
URW7748	Spring	Source	No storage on system	0	0	2	
URW7749	Spring	Tap	No storage on system	0	0	2	

Appendix 2. Screening study analysis results.

Sample No.	Source Type	Sample Location	Radon Bq/l	Error 3 sigma	Uranium ug/l	Thorium ug/l
URW7501	Borehole	Source	118	4.11		
URW7502	Borehole	Tap	42.7	2.61	0.013	<0.03
URW7503	Well	Souce	37	2.46		
URW7504	Well	Tap	13.5	1.74	0.008	<0.03
URW7505	Spring	Source	1140	14.96		
URW7506	Spring	Tap	541	9.33	0.223	<0.03
URW7507	Spring	Source	2500	26.43		
URW7508	Spring	Tap	2780	28.71	5.82	<0.03
URW7509	Borehole	Source	47.2	2.71	0.015	<0.03
URW7510	Borehole	Tap	60.2	3.01	0.016	<0.03
URW7511	Borehole	Source	150	4.63		
URW7512	Borehole	Tap	18.8	1.92	0.114	<0.03
URW7513	Borehole	Source	5.97	0.79		
URW7514	Borehole	Tap	3.21	0.68	0.150	<0.03
URW7515	Borehole	Source	120	2.82		
URW7516	Borehole	Tap	113	2.74	0.007	<0.03
URW7517	Well	Source	72.2	2.17		
URW7518	Well	Tap	104	2.62	0.025	<0.03
URW7519	Spring	Source	98.1	2.54		
URW7520	Spring	Tap	75.6	2.22	<0.007	<0.03
URW7521	Borehole	Source	163	3.35		
URW7522	Borehole	Tap	99.6	2.56	0.028	<0.03
URW7523	Well	Source	67.9	2.03		
URW7524	Well	Tap	222	3.88	0.475	<0.03
URW7525	Spring	Source	604	7.41		
URW7526	Spring	Tap	181	3.45	0.241	<0.03
URW7527	Borehole	Source	1040	11.01		
URW7528	Borehole	Tap	672	7.99	2.51	<0.03
URW7529	River	Source	<1			
URW7530	River	Tap	<1		0.149	<0.03
URW7531	Spring	Source	761	8.84		
URW7532	Spring	Tap	320	4.94	0.995	<0.03
URW7533	Borehole	Source	551	7.05		
URW7534	Borehole	Tap	788	9.07	1.07	<0.03
URW7535	Borehole	Source	2770	25.03		
URW7536	Borehole	Tap	2610	23.75	6.97	0.04
URW7537	Spring	Source	78	41.63		
URW7538	Spring	Tap	78	41.63	<0.007	<0.03
URW7539	Borehole	Source	940	72.86		
URW7540	Borehole	Tap	767	67.7		
URW7541	Borehole	Source	213	47.86		
URW7542	Borehole	Tap	453	60.95	0.129	0.06
URW7543	Well	Source	120	43.41	0.140	0.08
URW7544	Well	Tap	135	44.37	<0.007	<0.03
URW7545	Spring	Tap	1180	94.13		
URW7546	Spring	Source	109	3.02	<0.007	<0.03
URW7547	Spring	Tap	77.3	2.52	<0.007	<0.03
URW7548	Spring	Source	1480	15.5		
URW7549	Spring	Tap	1040	11.81	0.499	<0.03
URW7550	Borehole	Source	262	4.72		
URW7551	Borehole	Tap	274	4.85	0.519	<0.03
URW7552	Borehole	Tap	118	3.02	4.85	<0.03
URW7553	Borehole	Source	1530	15.93		
URW7554	Borehole	Tap	717	9.05	1.49	<0.03
URW7555	Borehole	Tap	79	2.45	0.009	<0.03
URW7556	Borehole	Source	95.9	4.39		
URW7557	Borehole	Tap	80.4	4.05	0.087	<0.03
URW7558	Spring	Source	16.1	2.11		
URW7559	Spring	Tap	6.43	1.65	<0.007	<0.03
URW7560	Well	Source	184	6.04		
URW7561	Well	Tap	87.7	4.21	<0.007	<0.03
URW7562	Well	Source	171	5.92		

Sample No.	Source Type	Sample Location	Radon Bq/l	Error 3 sigma	Uranium ug/l	Thorium ug/l
URW7563	Well	Tap	87	3.79	<0.007	<0.03
URW7564	Borehole	Source	54.8	3.47		
URW7565	Borehole	Tap	115	4.87	0.056	<0.03
URW7566	Well	Source	77.4	4.05		
URW7567	Well	Tap	62.2	3.67	0.109	<0.03
URW7568	Spring	Source	25	2.64		
URW7569	Spring	Tap	30.7	2.86	0.163	<0.03
URW7570	Spring	Source	26.8	2.81		
URW7571	Spring	Tap	43.5	3.37	0.173	<0.03
URW7572	Well	Source	97.8	4.7		
URW7573	Well	Tap	55.7	3.64	<0.007	<0.03
URW7574	Spring	Source	94.3	3.55		
URW7575	Spring	Tap	35.9	2.26	<0.007	<0.03
URW7576	Spring	Source	82.1	3.31		
URW7577	Spring	Tap	63.7	2.93	0.008	<0.03
URW7578	Spring	Source	40.7	2.39		
URW7579	Spring	Tap	47.3	2.56	0.023	<0.03
URW7580	Spring	Source	43.9	2.24		
URW7581	Spring	Tap	46	2.56	0.022	<0.03
URW7582	Adit	Source	6.94	1.28		
URW7583	Adit	Tap	11.3	1.47	0.023	0.04
URW7584	Well	Source	262	4.96		
URW7585	Well	Tap	174	3.94	<0.007	<0.03
URW7586	Spring	Source	296	5.33		
URW7587	Spring	Tap	353	5.93	0.037	<0.03
URW7588	Well	Source	395	6.41	0.893	<0.03
URW7589	Borehole	Source	113	3.16		
URW7590	Borehole	Tap	142	3.56	0.082	0.03
URW7591	Borehole	Source	1.93	0.67		
URW7592	Borehole	Tap	3.28	0.74	0.317	<0.03
URW7593	Well	Source	5.39	0.88		
URW7594	Well	Tap	3.02	0.76	0.025	<0.03
URW7595	Borehole	Source	64.9	2.42		
URW7596	Borehole	Tap	95.3	2.94	1.66	<0.03
URW7597	Borehole	Source	53.8	2.21		
URW7598	Borehole	Tap	34.9	1.8	0.023	<0.03
URW7599	Well	Tap	61.9	2.25	0.008	<0.03
URW7600	Borehole	Source	171	3.83		
URW7601	Borehole	Tap	167	3.78	0.010	<0.03
URW7602	Borehole	Source	181	3.96		
URW7603	Borehole	Tap	161	3.61	0.009	<0.03
URW7604	Spring	Source	1360	14.78		
URW7605	Spring	Tap	1100	12.59	0.865	<0.03
URW7606	Borehole	Source	79.7	2.61		
URW7607	Borehole	Tap	78.3	2.58	<0.007	<0.03
URW7608	Spring	Source	67.9	2.4		
URW7609	Spring	Tap	82.7	2.72	0.016	<0.03
URW7610	Borehole	Source	94.3	2.89		
URW7611	Borehole	Tap	33.7	1.79	0.019	<0.03
URW7612	Spring	Source	153	3.76		
URW7613	Spring	Tap	38.6	1.93	0.011	<0.03
URW7614	Well	Source	92.8	2.91		
URW7615	Well	Tap	51.1	2.81	0.021	0.03
URW7616	Borehole	Source	45.5	2.08		
URW7617	Borehole	Tap	149	3.71		
URW7618	Leat	Source	<1			
URW7619	Leat	Tap	<1		0.211	0.04
URW7620	Spring	Source	924	12.1		
URW7621	Spring	Tap	488	8	0.305	<0.03
URW7622	Spring	Source	456	8		
URW7623	Spring	Tap	421	7.68	0.506	<0.03
URW7624	Spring	Source	447	7.48		

Sample No.	Source Type	Sample Location	Radon Bq/l	Error 3 sigma	Uranium ug/l	Thorium ug/l
URW7625	Spring	Tap	407	7.16	0.473	<0.03
URW7626	Spring	Source	455	7.78		
URW7627	Spring	Tap	140	4.05	1.08	<0.03
URW7628	Spring	Source	112	3.62		
URW7629	Spring	Tap	115	3.67	0.983	0.04
URW7630	Spring	Source	41.3	2.29		
URW7631	Spring	Tap	6.44	1.28	<0.007	<0.03
URW7632	Spring	Source	42.1	2.3		
URW7633	Spring	Tap	52.3	2.54	<0.007	<0.03
URW7634	Borehole	Source	1.37	0.81		
URW7635	Borehole	Tap	<1		0.008	<0.03
URW7636	Borehole	Source	2050	20.63		
URW7637	Borehole	Tap	5340	47.41	11.6	0.05
URW7638	Well	Source	768	9.84		
URW7639	Well	Tap	599	8.32	0.081	<0.03
URW7640	Spring	Source	1030	12.31		
URW7641	Spring	Tap	768	9.97	0.263	<0.03
URW7642	Borehole	Source	1240	14.03		
URW7643	Borehole	Tap	1100	12.89	0.673	<0.03
URW7644	Borehole	Source	1250	14.21		
URW7645	Borehole	Tap	1140	13.38	0.657	0.05
URW7646	Stream	Source	4.1	0.61		
URW7647	Stream	Tap	2.07	0.53	0.164	<0.03
URW7648	Spring	Source	115	2.49		
URW7649	Spring	Tap	110	2.42	0.603	<0.03
URW7650	Well	Source	162	3.02		
URW7651	Well	Tap	162	3.02	0.539	<0.03
URW7652	Borehole	Source	28.5	1.26		
URW7653	Borehole	Tap	29.6	1.28	0.371	<0.03
URW7654	Spring	Source	<1			
URW7655	Spring	Tap	<1		0.149	0.07
URW7656	Borehole	Source	468	6		
URW7657	Borehole	Tap	143	2.85	0.054	<0.03
URW7658	Borehole	Source	89.7	3.4		
URW7659	Borehole	Tap	<1		0.016	<0.03
URW7660	Well	Source	657	7.71		
URW7661	Well	Tap	179	3.3	<0.007	<0.03
URW7662	Well	Source	58	1.95		
URW7663	Well	Tap	33.5	1.5	0.034	<0.03
URW7664	Well	Source	57.8	1.82		
URW7665	Well	Tap	29.9	1.33	0.036	<0.03
URW7666	Borehole	Source	22.3	1.26		
URW7667	Borehole	Tap	21.7	1.24	0.046	0.03
URW7668	Spring	Source	5.82	0.81		
URW7669	Spring	Tap	3.79	0.64	<0.007	<0.03
URW7670	Spring	Source	63	2.05		
URW7671	Spring	Tap	75.1	2.24	0.068	<0.03
URW7672	Well	Source	12	1.01		
URW7673	Well	Tap	8.56	0.91	0.026	<0.03
URW7674	Spring	Source	21.1	1.27		
URW7675	Spring	Tap	42.9	1.73	0.013	<0.03
URW7676	Mine addit	Source	19.6	1.24		
URW7677	Mine addit	Tap	38.6	1.65	0.027	<0.03
URW7678	Leat	Source	6.71	0.79		
URW7679	Leat	Tap	5.38	0.74	0.452	<0.03
URW7680	Leat	Source	5.96	0.76		
URW7683	Spring	Tap	266	4.35	1.82	<0.03
URW7684	Borehole	Source	1470	14.02		
URW7685	Borehole	Tap	1540	15.34	3.00	<0.03
URW7686	Borehole	Tap	1.92	0.6	3.58	0.07
URW7687	Spring	Source	333	5		
URW7688	Spring	Tap	1160	12.15	0.415	<0.03

Sample No.	**Source Type**	**Sample Location**	**Radon Bq/l**	**Error 3 sigma**	**Uranium ug/l**	**Thorium ug/l**
URW7691	Well	Source	626	7.74		
URW7692	Well	Tap	818	9.4	0.819	<0.03
URW7693	Well	Source	786	9.12		
URW7695	Spring	Source	370	5.43		
URW7696	Spring	Tap	416	5.85	0.658	<0.03
URW7697	Well	Source	693	8.33		
URW7698	Well	Tap	739	8.51	2.57	<0.03
URW7699	Borehole	Tap	344	7.4	1.84	<0.03
URW7700	Well	Source	1210	12.47		
URW7701	Well	Tap	610	7.4	0.312	<0.03
URW7703	Well	Tap	206	3.64	0.107	<0.03
URW7704	Well	Source	256	4.15		
URW7705	Well	Tap	238	3.97	1.24	<0.03
URW7706	Spring & river	Source	32.3	1.39		
URW7707	Spring & river	Tap	34.3	1.43	0.362	<0.03
URW7708	Spring	Source	8.44	0.76		
URW7709	Spring	Tap	33.1	1.32	<0.007	<0.03
URW7710	Spring	Tap	223	3.66	0.010	<0.03
URW7711	Borehole	Source	113	2.46		
URW7712	Borehole	Tap	42.6	1.49	0.064	<0.03
URW7713	Spring	Source	60.7	1.77		
URW7714	Spring	Tap	56.7	1.71	<0.007	<0.03
URW7715	Spring	Source	633	7.1		
URW7716	Spring	Tap	289	4.08	1.73	<0.03
URW7717	Spring	Source	620	6.99		
URW7718	Spring	Tap	276	3.97	1.65	<0.03
URW7719	Well	Source	692	7.59		
URW7720	Well	Tap	974	9.94	0.453	<0.03
URW7721	Spring	Source	760	8.17		
URW7722	Spring	Tap	702	7.75	0.966	<0.03
URW7723	Borehole	Source	814	8.68		
URW7724	Borehole	Tap	605	6.92	1.42	<0.03
URW7725	Well	Tap	928	9.63	0.299	<0.03
URW7726	Borehole	Source	340	4.6		
URW7727	Borehole	Tap	123	2.46	0.534	<0.03
URW7728	Spring	Source	<1			
URW7729	Spring	Tap	<1		0.013	<0.03
URW7730	Spring	Source	<1			
URW7731	Spring	Tap	<1		0.015	<0.03
URW7732	Spring	Source	0.82	0.53		
URW7733	Spring	Tap	1.5	0.36	0.008	<0.03
URW7734	Borehole	Source	84.2	2.5		
URW7735	Borehole	Tap	36.6	1.69	0.014	<0.03
URW7736	Well	Source	64.2	2.19		
URW7737	Well	Tap	68.3	2.26	0.067	<0.03
URW7738	Borehole	Source	21.2	1.49		
URW7739	Borehole	Tap	51	2	0.053	<0.03
URW7740	Spring	Tap	19.7	1.33	0.044	<0.03
URW7741	Borehole	Source	8.31	0.99		
URW7742	Borehole	Tap	7.38	0.96	0.031	<0.03
URW7743	Spring	Source	731	8.81		
URW7744	Spring	Tap	591	7.58	0.444	<0.03
URW7745	Spring	Source	747	8.95		
URW7746	Spring	Tap	570	7.21	0.463	<0.03
URW7747	Borehole	Tap	6.41	0.85	0.064	<0.03
URW7748	Spring	Source	145	3.2		
URW7749	Spring	Tap	27.3	1.45	<0.007	<0.03

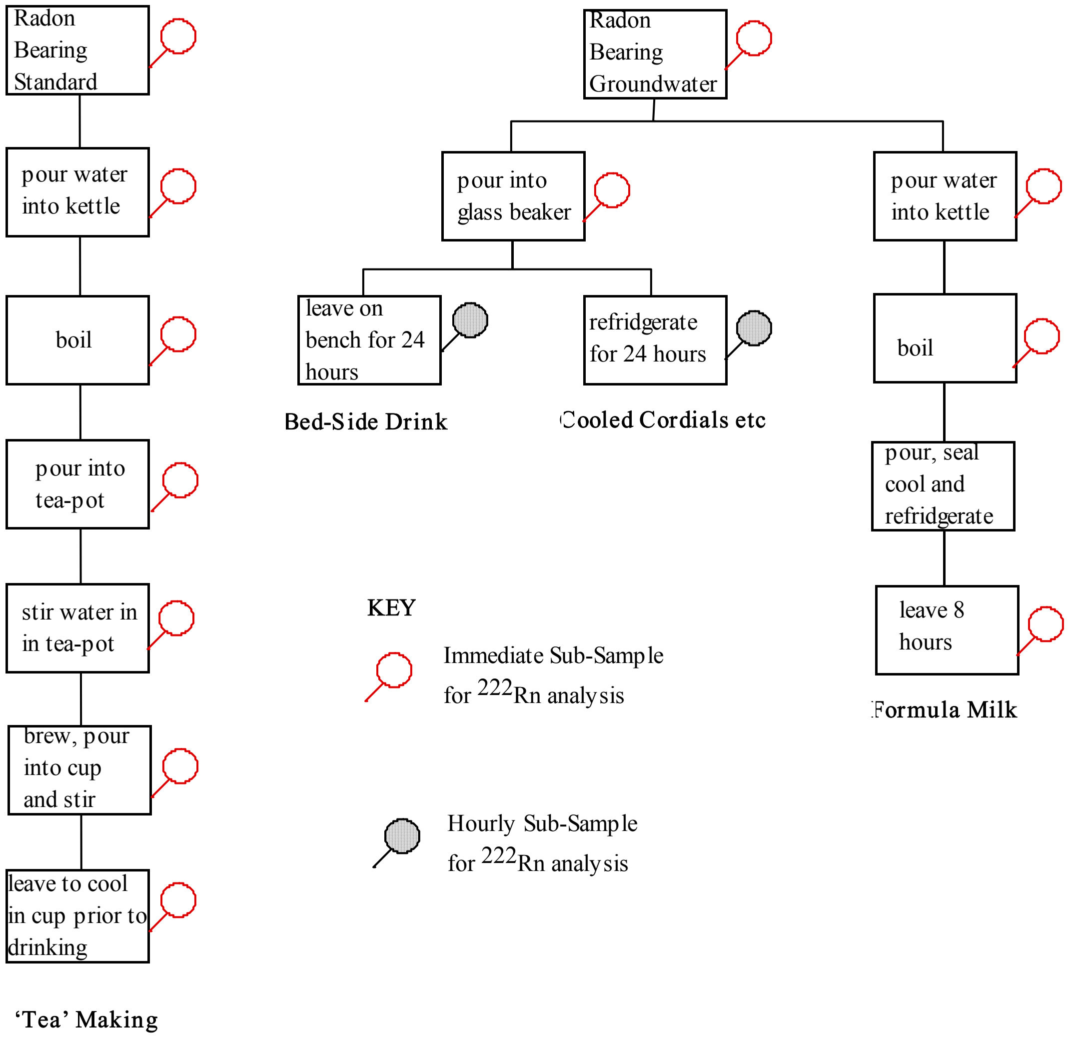
Appendix 3.

Methods used for study of loss due to drink making process.

Purchase a standard radium supported, radon-bearing solution and have a radon-bearing groundwater unsupported by radium. The two differing solutions are needed, as a radium-supported standard cannot be used for any long-term experiments as any radon lost due to process will rapidly be replaced from radium. The radon-bearing groundwater came from a source of negligible radium content

The protocol below was used. Sub-sampling involved using a pipette to gently remove 10ml of sample and, without degassing effects, transfer the sample under the solvent scintillation fluid, see 3.1

Flow-Chart Showing Experimental Protocol for Reduction due to Drink-Making Study



Appendix 4

Complete list of adjusted CEDE's

The dose rates presented in this table are based on the average adult water consumption pattern observed in the study

Sample No.	Source Type	Adult Dose
URW7502	Borehole	0.254
URW7504	Well	0.165
URW7506	Spring	1.76
URW7508	Spring	8.55
URW7510	Borehole	0.307
URW7512	Borehole	0.182
URW7514	Borehole	0.134
URW7516	Borehole	0.466
URW7518	Well	0.439
URW7520	Spring	0.353
URW7522	Borehole	0.426
URW7524	Well	0.796
URW7526	Spring	0.673
URW7528	Borehole	2.16
URW7530	River	0.128
URW7532	Spring	1.09
URW7534	Borehole	2.51
URW7536	Borehole	8.03
URW7538	Spring	0.361
URW7540	Borehole	2.45
URW7542	Borehole	1.49
URW7544	Well	0.534
URW7545	Spring	3.69
URW7547	Spring	0.358
URW7549	Spring	3.27
URW7551	Borehole	0.954
URW7552	Borehole	0.482
URW7554	Borehole	2.30
URW7555	Borehole	0.364
URW7557	Borehole	0.368
URW7559	Spring	0.144
URW7561	Well	0.390
URW7563	Well	0.388
URW7565	Borehole	0.472
URW7567	Well	0.313
URW7569	Spring	0.218
URW7571	Spring	0.256
URW7573	Well	0.293
URW7575	Spring	0.233
URW7577	Spring	0.317
URW7579	Spring	0.268

URW7581	Spring	0.264
URW7583	Adit	0.159
URW7585	Well	0.652
URW7587	Spring	1.19
URW7590	Borehole	0.554
URW7592	Borehole	0.135
URW7594	Well	0.134
URW7596	Borehole	0.414
URW7598	Borehole	0.230
URW7599	Well	0.312
URW7601	Borehole	0.630
URW7603	Borehole	0.612
URW7605	Spring	3.45
URW7607	Borehole	0.362
URW7609	Spring	0.375
URW7611	Borehole	0.227
URW7613	Spring	0.241
URW7615	Well	0.279
URW7617	Borehole	0.576
URW7619	Leat	0.125
URW7621	Spring	1.60
URW7623	Spring	1.40
URW7625	Spring	1.36
URW7627	Spring	0.548
URW7629	Spring	0.474
URW7631	Spring	0.144
URW7633	Spring	0.283
URW7635	Borehole	0.125
URW7637	Borehole	16.3
URW7639	Well	1.94
URW7641	Spring	2.45
URW7643	Borehole	3.46
URW7645	Borehole	3.57
URW7647	Stream	0.131
URW7649	Spring	0.456
URW7651	Well	0.614
URW7653	Borehole	0.214
URW7655	Spring	0.125
URW7657	Borehole	0.558
URW7659	Borehole	0.125
URW7661	Well	0.668
URW7663	Well	0.226
URW7665	Well	0.215
URW7667	Borehole	0.191
URW7669	Spring	0.136
URW7671	Spring	0.352
URW7673	Well	0.151
URW7675	Spring	0.254
URW7677	Adit	0.242

URW7679	Leat	0.141
URW7683	Spring	0.931
URW7685	Borehole	4.79
URW7686	Borehole	0.13
URW7688	Spring	3.62
URW7692	Well	2.60
URW7696	Spring	1.38
URW7698	Well	2.36
URW7699	Borehole	1.17
URW7701	Well	1.97
URW7703	Well	0.747
URW7705	Well	0.845
URW7707	Spring and river	0.229
URW7709	Spring	0.225
URW7710	Spring	0.800
URW7712	Borehole	0.254
URW7714	Spring	0.296
URW7716	Spring	1.00
URW7718	Spring	0.962
URW7720	Well	3.07
URW7722	Spring	2.25
URW7724	Borehole	1.96
URW7725	Well	2.93
URW7727	Borehole	0.497
URW7729	Spring	0.125
URW7731	Spring	0.125
URW7733	Spring	0.129
URW7735	Borehole	0.236
URW7737	Well	0.331
URW7739	Borehole	0.279
URW7740	Spring	0.184
URW7742	Borehole	0.147
URW7744	Spring	1.91
URW7746	Spring	1.85
URW7747	Borehole	0.144
URW7749	Spring	0.207