Appendix 8

CALCULATION OF RADIATION DOSE

METHOD 1

This Appendix details the processes and assumptions used to calculate the lifetime average annual radiation dose resulting from the drinking water pathway.

The lifetime average annual dose associated with a sampling site was calculated from the expression:

$$D = \sum_i A_i F_i$$

where: D is the lifetime average annual dose (mSv/a)

A_i is the annual average activity concentration of radionuclide i (Bq/ℓ)

F_i is a proportionality constant for radionuclide i with units of (mSv/a) per (Bq/ℓ).

The determination of the parameters A_i and F_i is described in Sections A8.1 and A8.2 below.

A8.1 Determination of Activity Concentration, A_i

The determination of annual average radionuclide activity concentrations at the various sites was complicated by the following factors:

- not all the radionuclide activity concentrations were measured;
- of those that were measured, not all were measured at all sampling sites;
- fewer radionuclides were measured in the first phase of the study than in the second phase; and
- some new sampling sites were added and some removed during the course of the study.

Details of the sampling data set are given in Table A8.1. The methods of dealing with the complications mentioned above are described in sections A8.1.1 to A8.1.3 below.

Table A8.1 Details of individual radionuclide measurements

1: measured only in phase 1
2: measured only in phase 2
1+2: measured in phases 1 and 2
Shaded areas indicate months during which measurements were made.

Site	Phase 1						Phase 2						Radionuclide												
	J	F	M	A	M	J	J	A	S	O	N	D	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{235}U	^{231}Pa	^{227}Ac	^{227}Th	^{223}Ra	^{232}Th	^{228}Ra	^{224}Ra
1													1			1			1				1	1		1
2													1			1			1				1	1		1
3													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
4													1			1			1				1	1		1
5													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
6													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
6a													1			1			1				1	1		1
7													1+2	2	2	1+2	2	2	1+2	2	2	2	1+2	1+2	2	1+2
7a													1+2	2	2	1+2	2	2	1+2	2	2	2	1+2	1+2	2	1+2
8													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
9													1+2	2	2	1+2	2	2	1+2	2	2	2	1+2	1+2	2	1+2
10													1			1			1				1	1		1
11													1			1			1				1	1		1
12													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
13													1			1			1				1	1		1
14													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
15													1			1			1				1	1		1
16													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
17													1			1			1				1	1		1
18													1			1			1				1	1		1
19													1			1			1				1	1		1
20													1			1			1				1	1		1
21													1			1			1				1	1		1
22													1			1			1				1	1		1
23													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
24													1			1			1				1	1		1
25													1			1			1				1	1		1
26													1			1			1				1	1		1
27													1	2	2	1	2	2	1			2	1	1	2	1
28													1			1			1				1	1		1
29													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
30													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
31													1			1			1				1	1		1
32													1			1			1				1	1		1
33													1			1			1				1	1		1
34													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
35													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
36													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
37													1+2	2	2	1+2	2	2	1+2			2	1+2	1+2	2	1+2
38													1			1			1				1	1		1
39													1			1			1				1	1		1

Complications also arose from the analysis techniques:

- some radiochemical analyses involving very low activities gave negative values due to the statistical nature of the measurement technique; these negative values were included in the calculation of the annual mean values, but any annual mean values less than zero were set to zero.
- some IPC-MS analyses involving very low activities gave values below the detection limit; these were set to half the detection limit.

A8.1.1 Estimating the activities of radionuclides not measured at some sites

The following radionuclides:

^{227}Ac, ^{231}Pa, ^{210}Pb, ^{210}Po, ^{228}Ra and ^{230}Th

were not measured at some sampling sites (see Table A8.1). It was found that, at the sites where these radionuclides were measured, the activity values were all very low and varied in a random fashion. The activity of each radionuclide at the sites where measurements were not made was therefore taken to be the mean value for that radionuclide calculated from all the samples at all other sites. The additional doses at the sites where these radionuclides were not measured, resulting from the use of these global mean values, are shown in Table A8.2. The doses are so small that even very large errors will be inconsequential.

Table A8.2 Dose contributions resulting from the use of global mean activity values

Radionuclide	Dose (Msv/a)
Actinium-227	0,0026
Protactinium-231	0,00008
Lead-210	0,0068
Polonium-210	0,0005
Radium-228	0,0088
Thorium-230	0.0005

A8.1.2 Estimating the activities of radionuclides never measured

The following radionuclides:

^{228}Ac, ^{210}Bi, ^{212}Bi, ^{214}Bi, ^{211}Pb, ^{214}Pb, ^{228}Th, ^{231}Th, and ^{234}Th

having very low dose conversion factors, were never measured. The activity concentration of these radionuclides was simply taken to be equal to the mean activity of all measured radionuclides over all sites (0.00672 Bq/ℓ). On the basis of this assumption, the never-measured radionuclides contributed only 0.0005 mSv/a to the dose associated with each sampling site. This was deemed to be sufficiently small a contribution that no further sophistication was justified. For example, even if the activity concentration were to be underestimated by a factor of 3, the dose would be underestimated by only 0.001 mSv/a, a trivial amount.

In practice, the interquartile range (± 0.019 Bq/ℓ) of the mean values of all the measured radionuclides would be a fair first-order estimate of the range of uncertainty of the activity of the never-measured radionuclides. Thus, the uncertainty in the dose contributed by the never-measured radionuclides is 0.0028 mSv/a.

A8.1.3 Extrapolations for radionuclides not measured in phase 1

The following radionuclides:

^{227}Ac, ^{231}Pa, ^{210}Pb, ^{228}Ra, ^{227}Th, ^{230}Th and ^{234}U

were measured only in phase 2 of the study. In an attempt to extrapolate the activities of these radionuclides into the phase 1 period, multilinear regressions were sought against chemical and radiation variables measured during Phase I.

The following procedure was used:

1. To decrease the noise influence of values near the detection limit, all values at or below the detection limit or within one standard deviation of 0, were discarded.

2. Those Phase I variables with relatively few values remaining were discarded.

   It was also found that some of the stations, for example Station1, had exceedingly high (two orders of magnitude) values of certain variables, for example aluminum. Unfortunately, some stations, including Station 1, were dropped from sampling in the second half of the year. Thus including aluminum in the regression variables would result in extrapolating to aluminum values 100 times higher than were calibrated and tested on.

To ensure that this problem did not occur in other variables, the chosen predictors were inspected to ensure that the calibrating stations covered the full range for the variables.

Stations 10 and 2 had exceptionally high values of phosphate and calcium respectively. Phosphate at Station 10 was 5.7 standard deviations above the mean of the other stations. Calcium at Station 2 was 3 standard deviations above the mean of the other stations. Thus Ca and PO4-P were also excluded from the set of possible predictors.

Those variables left were:
Cl, EC, F, gross alpha, gross beta, K, Mg, Na, NH4-N, NO3+NO2-N, pH, Ra-223, Ra-226, Si, SO4, Sr-diss, TAL as CaCO3, TDS, U-235,
U-238.

3. All subsets shorter than 5 of these variables were tested.

4. For each Phase II variable and for each subset of Phase I variables the data was extracted.

5. If there were too few samples to get a good test of the significance of the fit, that subset was rejected.

6. The samples were divided into a calibration set and a test set.

7. The Phase II variable was fitted to the subset of the Phase I variables using the calibration set.

8. The goodness of fit parameter was calculated, using the regression calculated in the previous step, on the both the calibration and the test data sets. The worst value was reported and used in the next step.

9. The subset with the best-reported goodness of fit was selected.

   The goodness of fit parameter was the sum of the squared residuals divided by the number of degrees of freedom, divided by the standard deviation of the variable being fitted i.e. Fitting a subset of length 0, would simply be the mean value of the variable being fitted. The goodness of fit parameter would then simply be 1.

   Thus the goodness of fit tells you how much sharper (if < 1) your prediction is than simply taking the mean value as your predictor. It is never worth selecting a subset for which the goodness of fit parameter, is greater than or equal to 1.

   It was possible, for only two of the Phase II nuclides (Th-227 and U-234), to find a subset of Phase I nuclides which improved our predictive ability. The per station doses are presented in Table 8.3.

Table 8.3 The per station doses.

Site No.	Place	Dose (mSv/year)
29	Turffontein	0,0184
30	Gerhardminnebron	0,0187
14	Gerhardminnebron-Rysmierbult road bridge upstream of Boskop dam	0,0191
35	Potchefstroom purification works-western abstraction point	0,0194
27	Welverdiend municipal water supply 2km south of Welverdiend	0,0206
34	Bovenste Eye	0,0226
6	Wonderfontein Eye-canal from Wonderfontein eye	0,0239
31	Wonderfontein Eye 110 is between piggery buildings	0,0261
26	Plot Welverdiend	0,0268
20	Kraalkop-old Johannesburg/Potchefstroom road bridge	0,0273
25	Plot no 9 Carltonville	0,0286
28	Blaaubank 100m east of house	0,0296
32	Plot 84 De Pan	0,0297
19	Elandsfontein-Johannesburg/Potchefstroom road bridge	0,0299
33	Plot Kraalkop	0,0305
22	Klipdrift dam-outflow into concrete irrigation canal	0,0306
18	Buffelsdoorn-Johannesburg/Potchefstroom road bridge	0,0314
24	Plot 40 Luipaardsvlei - 35m south east of farm house	0,0317
21	Weltevreden-Losberg/bank road bridge	0,0318
6a	West Driefontein (down stream north shaft purification works)	0,0328
36	Potchefstroom purification works-eastern abstraction point	0,0335
38	Varkenslaagte	0,0341
16	Buffelsdoorn-Elandsrand gold mine	0,037
13	Turffontein-gravel road bridge to Muiskraal	0,0423
3	Luipaardsvlei (Doornkop Randfontein (R559) road bridge)	0,0536
10	Blyvooruitzicht gm-discharge to Doornfontn canal east of purification works	0,0563
4	No 7 at Gemsbokfontein	0,0568
2	Rietvlei (Randfontein Azaadville bridge)	0,0591
39	Doornfontein	0,0594
5	Wonderfontein-end of 1m pipe from Venterspost gold mine	0,0653
23	Gempost-Venterspost gold mine no 5 shaft	0,0761
37	Harry's dam	0,0786
8	Wonderfontein-low water bridge to Abe Bailey nature reserve	0,0805
17	Deelkraal-gold mine recreational dam overflow	0,0832
9	Blaauwbank	0,108
11	Doornfontein gold mine-gold plant discharge in canal upstream of Doornfontein excess	0,135
7	Rooipoort	0,155
15	Western Deep levels-farm bridge down stream of no 7 shaft slimes dam	0,178
1	Luipaardsvlei (at rail bridge from Turk shaft to 1st West gold mine	0,24
7a	Carltonville West Driefontein gold mine –Carltonville cemetary road bridge	0,271
12	Doornfontein gold mine-number 3 shaft discharge	0,525

A8.1.4 The Uranium - Dose relationship

Plotting U-238 concentration against yearly dose and performing a least squares linear fit gives us the following relationship...

Dose = 0,0012895 * U + 0,0212758

Correlation coefficient r = 0,99063,

A8.2 Determination of Proportionality Constant F_i

The proportionality constant F_i for radionuclide *i* was determined from the following relationship:

$$F_i = \sum_x C_x (DCF)_{ix} W_x$$

where: C_x is the annual water consumption for age group *x* (ℓ/a)

$(DCF)_{ix}$ is the dose conversion factor for radionuclide *i* and age group *x* (mSv/Bq)

W_x is the weighting factor for age group *x*

The annual water consumption values for the various age groups were taken from CNS Licensing Guide LG-1032[1], and are given in Table A8.3.

Table A8.3 Annual Water Consumption Values

Age Group	Water Consumption (ℓ/a)
0 - 1 years	200
1 - 2 years	260
2 - 7 years	300
7 – 12 years	350
12 - 17 years	600
> 17 years	730

The dose conversion factors for the various radionuclides and age groups were taken from the IAEA Basic Safety Standards[2].

The weighting factor for each age group was determined by dividing the number of years in the age group by the average life expectancy, taken to be 70 years. For example, the weighting factor for the 7 - 12 years age group was:

$$W_{7-12} = \frac{12-7}{70} = 0.0714$$

and for the > 17 years age group:

$$W_{>17} = \frac{70-17}{70} = 0.757$$

The resulting proportionality factors for each radionuclide are listed in Appendix 2 as the 'annual dose per unit activity concentration in water'.

References:

[1] International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, International Atomic Energy Agency, Vienna (1996).

[1] Licensing Guide LG-1032, Guideline on the Assessment of Radiation Hazards to Members of the Public from Mining and Mineral Processing Facilities, Rev. 0, Council for Nuclear Safety, Centurion (18 April 1997)

[2] International Basic Safety Standards for the Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, International Atomic Energy Agency, Vienna (1996)

[2] Licencing Guide LG-1032, Guideline on the Assessment of Radiation Hazards to Members of the Public from Mining and Mineral Processing Facilities, Rev 0, Council for Nuclear Safety, Centurion (1997/04/18).

[3] Detection Limit Concepts: Foundations, Myths, and Utilization, D. A. Chambless et al, Health Physics, volume 63, Number 3, September 1992.