APPENDIX A

PARAMETERS FROM LITERATURE

Appendix A contains various constants and parameters referred to in the text which are used in calculations.

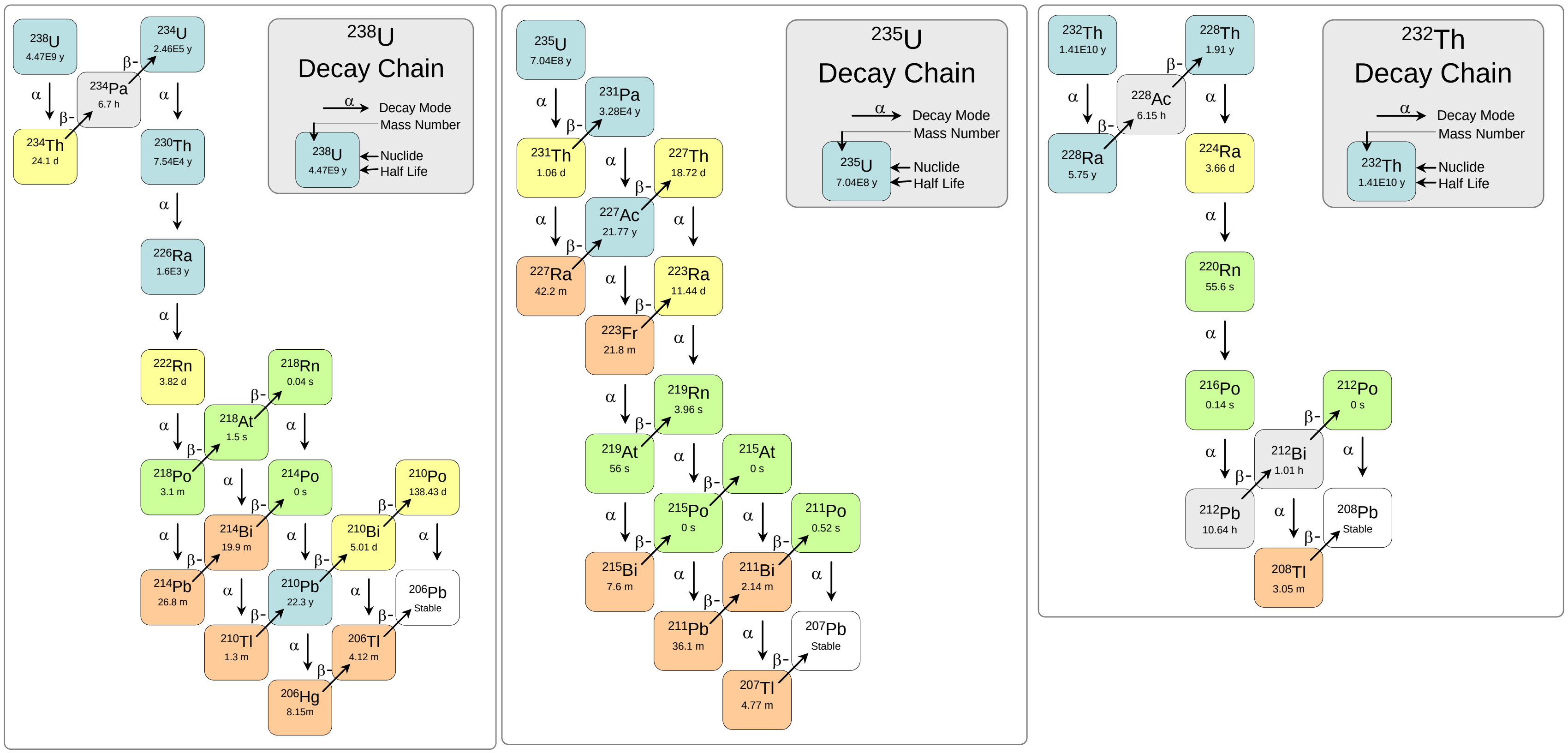

Figure A-1: Schematic illustration of the U-238, U-235, and Th-232 decay chains

Table A-1: Radiological properties for the natural decay chains (NUDAT, 2017)

Element	Radionuclide	Decay	Half Life	Units	Atomic Mass	Specific Activity ($Bq.kg^{-1}$)
Uranium-238 series						
Uranium	U-238	α	4.468E+09	Y	238.05	1.244E+07
Thorium	Th-234	β	2.410E+01	D	234.04	8.567E+17
Protactinium	Pa-234m	β	1.160E+00	m	234.04	2.541E+22
Uranium	U-234	α	2.455E+05	Y	234.04	2.312E+11
Thorium	Th-230	α	7.538E+04	Y	230.03	7.469E+11
Radium	Ra-226	α	1.600E+03	Y	226.02	3.658E+13
Radon	Rn-222	α	3.824E+00	D	222.02	5.692E+18
Polonium	Po-218	α	3.098E+00	m	218.01	1.046E+22
Lead	Pb-214	β	2.680E+01	m	214.00	1.213E+21
Bismuth	Bi-214	β	1.990E+01	m	214.00	1.633E+21
Polonium	Po-214	α	1.643E+02	µs	214.00	1.187E+28
Lead	Pb-210	β	2.220E+01	Y	209.98	2.825E+15
Bismuth	Bi-210	β	5.012E+00	D	209.98	4.591E+18
Polonium	Po-210	α	1.384E+02	D	209.98	1.663E+17
Uranium-235 series						
Uranium	U-235	α	7.038E+08	Y	235.04	7.997E+07
Thorium	Th-231	β	2.552E+01	H	231.04	1.967E+19
Protactinium	Pa-231	α	3.276E+04	Y	231.04	1.748E+12
Actinium	Ac-227	β	2.177E+01	Y	227.03	2.676E+15
Thorium	Th-227	α	1.868E+01	D	227.03	1.137E+18
Radium	Ra-223	α	1.143E+01	D	223.02	1.895E+18
Radon	Rn-219	α	3.960E+00	S	219.01	4.814E+23
Polonium	Po-215	α	1.781E-03	S	215.00	1.091E+27
Lead	Pb-211	β	3.610E+01	m	210.99	9.135E+20
Bismuth	Bi-211	α	2.140E+00	m	210.99	1.541E+22
Thallium	Tl-207	β	4.770E+00	m	206.98	7.048E+21
Thorium-232 series						
Thorium	Th-232	α	1.405E+10	Y	232.04	4.058E+06
Radium	Ra-228	β	5.750E+00	Y	228.03	1.009E+16
Actinium	Ac-228	α	6.150E+00	H	228.03	8.296E+19
Thorium	Th-228	α	1.912E+09	Y	228.03	3.034E+16
Radium	Ra-224	α	3.660E+00	D	224.02	5.893E+18
Radon	Rn-220	α	5.560E+01	S	220.01	3.413E+22
Polonium	Po-216	α	1.500E-01	S	216.00	1.288E+25
Lead	Pb-212	β	1.064E+01	H	211.99	5.141E+19
Bismuth	Bi-212	β	6.055E+01	m	211.99	5.421E+20
Thallium	Tl-208	β	3.053E+00	M	207.89	1.095E+22
Polonium	Po-212	α	3.050E-01	µs	211.99	6.457E+30

Table A-2: Main gamma emissions (keV) of α- and β-emitting natural radionuclides (NUDAT, 2017)

U-238 decay series			U-235 decay series			Th-232 decay series		
Nuclide	**Energy**	**Intensity**	**Nuclide**	**Energy**	**Intensity**	**Nuclide**	**Energy**	**Intensity**
U-238	49.55	0.064	U-235	143.76	10.96	Th-232	63.81	0.263
	113.5	0.010		163.36	5.08			
				185.72	**57.5**			
				205.32	5.02			
Th-234	63.29	3.7	Th-231	25.64	14.1	Ra-228	13.52	1.60
	92.38	2.13		84.21	6.6			
	92.80	2.10						
U-234	53.20	0.12	Pa-231	27.36	10.5	Ac-228	338.32	11.27
				300.06	2.41		463.00	4.4
				302.67	2.3		794.95	4.25
							911.20	**25.8**
							964.77	4.99
							969.97	15.8
							1588.2	3.22
Th-230	67.67	0.38	Th-227	50.13	8.4	Th-228	84.37	1.19
				235.96	12.9			
				256.23	7.0			
				329.85	2.9			
Ra-226	186.21	3.64	Ra-223	144.23	3.27	Ra-224	240.99	4.10
				154.21	5.70			
				269.46	13.9			
				323.87	3.99			
				338.28	2.84			
Pb-214	53.22	1.08	Rn-219	271.23	10.8	Pb-212	238.63	**43.6**
	241.99	7.3		401.81	6.6		300.09	3.3
	295.22	18.4						
	351.93	**35.6**						
Bi-214	609.36	**45.5**	Pb-211	404.85	3.78	Bi-212	727.33	6.67
	768.36	4.9		832.01	3.52			
	934.0	3.1						
	1120.3	14.9						
	1238.1	5.83						
	1377.7	3.99						
	1764.5	15.3						
	2204.0	4.9						
Pb-210	46.54	4.25	Bi-211	351.22	13.0	Tl-208	277.37	6.6
							510.77	22.6
							583.19	**84.5**
							860.56	12.5
							2614	99.0

Table A-3: Main intensity energies (MeV) for alpha emitters of interest (NUDAT, 2017)

U-238 decay series			**U-235 decay series**			**Th-232 decay series**		
Nuclide	**Energy**	**Intensity**	**Nuclide**	**Energy**	**Intensity**	**Nuclide**	**Energy**	**Intensity**
U-238	4.151	21	U-235	4.364	18.9	Th-232	3.947	21.7
	4.198	79		**4.395**	57.7		**4.012**	78.2
				4.415	3.09			
				4.597	4.77			
U-234	4.722	28.4	Pa-231	4.736	8.4	Th-228	5.340	26.0
	4.775	71.4		4.951	22.8		**5.423**	73.4
				5.014	25.4			
				5.028	20			
				5.058	11			
Th-230	4.621	23.4	Th-227	5.708	8.3	Ra-224	**5.685**	94.9
	4.687	76.3		5.757	20.4			
				5.977	23.5			
				6.038	24.2			
Ra-226	4.601	6.2	Ra-223	5.539	9.0	Rn-220	**6.288**	100
	4.784	93.8		5.607	25.2			
				5.716	51.6			
				5.747	9.0			
						Po-216	**6.778**	100
Rn-222	5.490	99.9	Rn-219	6.553	12.9	Bi-212	**6.051**	25.1
				6.819	79.4		6.090	9.75
Po-218	6.002	99.9	Po-215	7.386	**100**	Po-212	8.784	**100**
Po-214	7.687	99.9	Bi-211	6.278	**16.2**			
				6.623	**83.5**			
Po-210	5.304	**100**						
Tracers								
Th-229	4.815	9.3						
	4.845	**56.2**						
	4.901	10.2						
	4.967	5.97						
	5.054	6.60						
Po-209	5.115	**100**						
U-232	5.263	**31.6**						
	5.320	**68.1**						

Table A-4: Detection limits for radiometric methods obtained from literature

Nuclide	LOD		Reference	Exp Conditions
Alpha Spectrometry				
Alphas	0.0001	Bq	Smit, 1999b	-
	0.0001	$Bq.L^{-1}$	Vasile *et al.*, 2016	1.5 L, 3 days
^{210}Po	0.002-0.003	$Bq.L^{-1}$	Kim *et al.*, 2009	-
	0.00002	$Bq.L^{-1}$	Rozmaric *et al.*, 2012	1 L, 8 days
	0.0001	$Bq.L^{-1}$	Vesterbacka *et al.*, 2005	-
^{226}Ra	0.0001	$Bq.L^{-1}$	Jia & Jia, 2012	1 L, 10 days
	0.020	$Bq.L^{-1}$	Lawrie *et al.*, 2000	0.1 L
	0.00003	$Bq.L^{-1}$	Rozmaric *et al.*, 2012	1 L, 8 days
U/Th	0.00002	$Bq.L^{-1}$	Rozmaric *et al.*, 2012	1 L, 8 days
	0.0009-0.0011	$Bq.L^{-1}$	Tsai *et al.*, 2008	.5 L, 20 h
	0.5	$Bq.kg^{-1}$	Maxwell *et al.*, 2015	16 g, 16 h
Liquid Scintillation Counting				
Alphas	0.5	$Bq.L^{-1}$	Floeckher,1992	0.01 L, 100 min
	0.01	$Bq.L^{-1}$	Forte *et al.*, 2015	0.1 L, 16 hours
Betas	0.07	$Bq.L^{-1}$	Forte *et al.*, 2015	0.1 L, 16 hours
^{210}Po	0. 1	$Bq.L^{-1}$	Surbeck, 2000	-
^{210}Pb	0.010	$Bq.L^{-1}$	Vasile *et al.*, 2016	1.5 L, 300 min
^{226}Ra	0.05-0.2	$Bq.L^{-1}$	Jia & Jia, 2012	-
^{238}U	0.038	$Bq.L^{-1}$	Passo & Cook, 1994	-
	0.1	$Bq.L^{-1}$	Surbeck, 2000	-
Gas Flow Proportional Counting				
Alphas	2.1	$Bq.L^{-1}$	Floeckher,1992	0.01 L, 100 min
	0.04	$Bq.L^{-1}$		0.1 L, 200 min
^{210}Po	0.003-0.03	Bq	Kulzer *et al.*, 1996	via Bi-210
Gamma Spectrometry				
Gammas	0.05	Bq	Hou & Roos, 2008	-
^{210}Pb	0.4	Bq	Clayton & Bradley,1995	-
	0.662	Bq	Kulzer *et al.*, 1996	-
	0.030	$Bq.L^{-1}$	Surbeck, 2000	-
^{226}Ra	0.002-0.040	$Bq.L^{-1}$	Jia & Jia, 2012	5 L
	2-3	$Bq.kg^{-1}$	Medley *et al.*, 2015	15 g, 1 day
	0.1	$Bq.L^{-1}$	Surbeck, 2000	-
^{228}Th	0.01	$Bq.L^{-1}$	Surbeck, 2000	-
Neutron Activation Analysis				
U	50	ng	Jia *et al.*, 2008	U-235
Kinetic Phosphoresence Analysis				
U	5	ng	Jia *et al.*, 2008	U-238

Table A-5: Dose conversion factors ($Sv.Bq^{-1}$) to calculate human ingestion dose (NNR, 2013)

Age Group	^{238}U	^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{235}U	^{231}Pa	^{227}Ac	^{232}Th	^{228}Ra	^{228}Th	^{224}Ra
newborn	3.4E-07	3.7E-07	4.1E-06	4.7E-06	8.4E-06	2.6E-05	3.5E-07	1.3E-05	3.3E-05	4.6E-06	3.0E-05	3.7E-06	2.7E-06
1 year old	1.2E-07	1.3E-07	4.1E-07	9.6E-07	3.6E-06	8.8E-06	1.3E-07	1.3E-06	3.1E-06	4.5E-07	5.7E-06	3.7E-07	6.6E-07
5 year old	8.0E-08	8.8E-08	3.1E-07	6.2E-07	2.2E-06	4.4E-06	8.5E-08	1.1E-06	2.2E-06	3.5E-07	3.4E-06	2.2E-07	3.5E-07
10 year old	6.8E-08	7.4E-08	2.4E-07	8.0E-07	1.9E-06	2.6E-06	7.1E-08	9.2E-07	1.5E-06	2.9E-07	3.9E-06	1.5E-07	2.6E-07
15 year old	6.7E-08	7.4E-08	2.2E-07	1.5E-06	1.9E-06	1.6E-06	7.0E-08	8.0E-07	1.2E-06	2.5E-07	5.3E-06	9.4E-08	2.0E-07
Adults	4.5E-08	4.9E-08	2.1E-07	2.8E-07	6.9E-07	1.2E-06	4.7E-08	7.1E-07	1.1E-06	2.3E-07	6.9E-07	7.2E-08	6.5E-08

Values in Table A-5 from RG-002 (NNR, 2013) based on values published in ICRP publication 72 (ICRP, 1992). These values have been adopted in the International BSS (IAEA, 2014b). Value for ^{228}Ra is incorrect in RG-002. Discrepancies were observed with summarized values for infants in ICRP publication 119- indicated in red.

Table A-6: External dose coefficients for large quantities of material (IAEA, 2006)

Material	Dose coefficient ($\mu Sv.h^{-1}$ per $Bq.g^{-1}$)					Dominant Nuclide	Effective dose per unit activity ($mSv.a^{-1}$ per $Bq.g^{-1}$)
	$^{226}Ra \rightarrow {}^{214}Po$	$^{228}Ra \rightarrow {}^{228}Ac$	$^{228}Th \rightarrow {}^{208}Tl$	^{40}K	Overall		
Phosphate rock	0.39	0.21	0.37		0.51	^{238}U	0.204
Phosphogypsum	0.39	0.21	0.38		0.42	^{226}Ra	0.168
Zircon sand	0.37	0.20	0.35		0.43	^{238}U	0.172
Monazite sand	0.26	0.14	0.24		0.39	^{232}Th	0.156
Ilmenite	0.39	0.21	0.37		0.78	^{232}Th	0.312
Superphosphate fertilizer	0.41	0.22	0.39		0.31	^{238}U	0.124
K fertilizer	0.39	0.21	0.37	0.037	0.04	^{40}K	0.016

Table A-7: Partition coefficients, K_d, of radionuclides in soil and sediment ($L.kg^{-1}$)

Element					
U	**Th**	**Ra**	**Pb**	**Po**	**Reference**
SAND/MINERAL (sand fraction > 65%; clay fraction <15%					
35 (0.03-2200)	3200 (207-150000)	500 (57-21000)	150 (19-1405)	150 (9-7020)	EPA, 2004a
33	3000	490	270(0.027-27000)	150 (6-3600)	IAEA, 2010a
-	-	3100	-	-	IAEA, 2014a,
180	2600	1900	2200	1900	**NNR, 2013**
110 (0.7-66667)	700 (35-100000)	3100 (49-40000)	220 (25-1349)	100 (17-7020)	Vandenhove *et al.*, 2009a
CLAY (clay fraction > 35%)					
1500	5400	9000	540	2700	IAEA, 2010a
-	-	38000	-	-	IAEA, 2014a,
-	-	38000	**-**	**-**	**NNR, 2013**
28 (3-480)	4500 (800-24000)	13000 (696-1000000)	-	732	Vandenhove *et al.*, 2009a
ORGANIC (organic matter > 20%)					
400	89000	2400	22000	6600	IAEA, 2010a
1200	730	1300	13000	6600	**NNR, 2013**
1200 (33-7600)	730 (19-80000)	-	2500 (880-10266)	-	Vandenhove *et al.*, 2009a
ALL SOILS					
287	19660000	14000	17800	17800	ERICA, 2016
-	-	2500	-	-	IAEA, 2014a,
200	1900	2500	2000	210	**NNR, 2013**
SEDIMENT					
0.05	10	6	-	20	Brown *et al.*, 2004
	2.8	**21**			**UNSCEAR, 2008**
0.05	**180±21**	**7.4±3.1**	**10**	**40**	**UNSCEAR, 2016**

Table A-8: Annual Consumption – humans $L.a^{-1}$ or $kg.a^{-1}$; animal $L.d^{-1}$ or $kg.d^{-1}$

Pathway	RG-002 (NNR, 2013) Ingestion Dose for Different Age Groups					NNR, 1997	WHO, 1988	UNSCEAR, 2000, 2016, 2016 Africa	Summary from literature	
	1 year	5 year	10 year	15 year	Adult					
% of Adult consumption	40	50	60	85	100	-	-	-		
Water Ingestion	240	300	360	510	600	730	500	500		
Milk Ingestion	48	60	72	102	120	250	105	105,65,31	19-230	(10)
Grain/Cereal	100	125	150	212.5	250	150	140	140,130,130	11-192	(15)
Other Vegetables	-	-	-	-	-	75	-	230,230,220	1.9-75	(19)
Fruit ingestion	-	-	-	-	-				3-80	(22)
Leafy Vegetables	-	-	-	-	-	55	60		0.63-55	(17)
Root Vegetables	-	-	-	-	-	170	170		10-144	(31)
Beef Ingestion	12	15	18	25.5	30	100	50	50,44,17	6-16	(7)
Mutton Ingestion	10	12.5	15	21.25	25				3.7	(1)
Pork Ingestion	8	10	12	17	20				1.3-51	(7)
Poultry Ingestion	20	25	30	42.5	50	75	-	-	3.7-51	(9)
Eggs Ingestion	6	7.5	9	12.75	15	30	-	-	5-21	(6)
Fish Ingestion	10	12.5	15	21.2	25	25	15	15,*5.7,*2.7	1.7-43	(18)
Beef or cow daily consumption values										
Water ingestion ($L.d^{-1}$)					75					
Dry feed ingestion ($kg.d^{-1}$)					10	25				
Soil ingestion ($kg.d^{-1}$)					1.25					

REFERENCES: Arogunjo *et al.*, 2009; Carvalho, 1995; Choi *et al.*, 2008; Cunha *et al.*, 2001; Fisenne *et al.*, 1987; Ghiassa *et al.*, 2003; Ham *et al.*, 2001; Izak-Biran *et al.*, 1989; Kannan *et al.*, 2001; Lauria *et al.*, 2012; Lee *et al.*, 2009; Misdaq & Elamyn, 2006; Pietrzak-Flik *et al.*, 1997; Santos *et al.* 2002; Skwarzec *et al.*, 2001; Sugiyama *et al.*, 2009; Turtiainen *et al.*, 2011; Yamamoto *et al.*, 1994; Yu & Mao, 1999;

Summary of literature values (Number of publications in parenthesis)
Cereals - wheat, rye, oats, maize; Leafy - spinach, cabbage, lettuce; Root - carrot, beetroot, radish, onion, potato; Other - pumpkin, tomatoes, legumes; Fruit - apple, cherry, banana, orange; Fish - mostly marine and seafood; but UNSCEAR values are specified for freshwater fish*

Table A-9: Production quantity and per capita consumption of main agricultural products in South Africa (DAFF, 2016)

Agricultural products	Quantity produced ('000 tons)	Per capita consumption (kg.a^{-1})	
		DAFF, 2016	Ronquest *et al.* (2015)
Potatoes	2423	38.32	29.5
Carrots	201	-	-
Sweet potatoes	63	-	1.1
Pumpkin	256	-	-
Cabbage	146	-	-
Pumpkin	230	-	-
Green beans	25	-	2.9
Tomatoes	539	-	10.4
Green peas	9	-	0.4
Green mealies	373	-	-
Onions	675	-	7.9
Cauliflower	13	-	-
Beetroot	78	-	-
Other vegetables	446	-	24.6
TOTAL vegetables	**5247**	***46.68***	***42.9***
Fruit, deciduous	-	25.79	-
Fruit, citrus	-	13.23	34.8
Dry beans	81	2.45	-
Maize	9955	75.07	104
Wheat	1457	48.64	60.9
Grain/sorghum	139	1.72	1.5
Barley	302	4.44	0.1
Oats	33	0.80	1.1
Fish and seafood	-	-	7.5
Beef and veal	-	19	15.4
Pork	-	4.7	6.8
Sheep	-	3.6	3.8
Poultry	-	39.60	32
Eggs	-	8.76	6.7
Butter	-	0.3	-
Cheese	-	0.8	3.2
Milk	-	38.6	42.9

Table A-10: Dry-to-wet weight conversion factors for food products, plants and organisms

Plant /Food/Organism	Dry/wet ratio (dry weight fraction)			
	NNR,2013	Experimental	Literature	
Leafy vegetables	-	-	0.20	Staven *et al*., 2003
Cabbage	0.12	0.10	0.07	Ghiassi-Nejad *et al*., 2003
Lettuce	0.08	0.08	-	
Spinach	0.08	0.12	0.10	Ghiassi-Nejad *et al*., 2003
Other vegetables	-	-	0.25	Staven *et al*., 2003
Tomato	0.06	0.05	0.06	Ghiassi-Nejad *et al*., 2003

Plant /Food/Organism	Dry/wet ratio (dry weight fraction) NNR,2013	Experimental	Literature	
Root vegetables	-	-	0.25	Staven *et al.*, 2003
Beetroot	0.16	0.12	-	
Carrot	0.14	0.11	0.10	Ghiassi-Nejad *et al.*, 2003
Green vegetables	-	-	0.13	Staven *et al.*, 2003
Onion	0.11	0.18	0.09	Staven *et al.*, 2003
			0.12	Ghiassi-Nejad *et al.*, 2003
**Fruit*	-	0.15	0.18	Staven *et al.*, 2003
Apple	15.6 (0.09)	-	0.14	Yu & Mao, 1999
Pear	16.8 (0.06)	-		
Peach	10.9 (0.07)	-		
Grain: (Cereal)	-	0.87	0.91	Staven *et al.*, 2003
Maize	0.85	-		
Wheat	0.88			
Sorghum	0.87			
Oats/Barley	0.87	0.29		
Grass/Pasture/Forage	0.20 (0.10)	0.54	0.22	Staven *et al.*, 2003
Meat	-	0.25	0.25	Staven *et al.*, 2003
Beef		0.26	0.20	Yu & Mao, 1999
Intestines		0.32		
Chicken		0.30	0.34	Yu & Mao, 1999
Fish	-	0.27	0.21-0.28	Kim *et al.*, 2017
Seafood (mussel)	-	0.20	0.24	Kim *et al.*, 2017

Remarks NNR RG-002:

- The table heading in RG-002 indicate the values as wet/dry ratio, but the listed information is actually the dry/wet ratio (expected to be <1).
- For fruit the indicated value in RG-002 is the wet/dry ratio (expected to be >1). Dry-wet ratio is shown in green in parentheses in Table A-6
- No ratios indicated for fish, meat and animal products

Table A-11: Dosimetry parameters terrestrial ecosystem: Dose Conversion Factors (DCF) in (μGy.h^{-1} per Bq.kg^{-1}) (Brown *et al.*, 2016)

Nuclide	DCF Internal				DCF External	
	Grasses	Bird	Reptile	Mammal	Reptile	Mammal
^{238}U	2.40E-03	2.40E-03	2.40E-03	2.40E-03	4.60E-08	1.00E-08
^{234}U				2.80E-03	6.60E-08	1.70E-08
^{230}Th				2.70E-03	6.70E-08	2.50E-08
^{226}Ra	1.36E-02	1.43E-02	1.38E-02	1.34E-02	3.30E-04	1.80E-04
^{210}Pb	2.16E-04	2.45E-04	2.45E-04	2.45E-04	7.20E-06	7.70E-08
^{210}Po	3.10E-03	3.10E-03	3.10E-03	3.10E-03	1.60E-09	8.60E-10
^{232}Th	2.30E-03	2.30E-03	2.30E-03	2.30E-03	4.10E-08	1.30E-08
^{228}Ra				6.04E-04	1.80E-04	9.70E-05
^{228}Th				1.88E-02	2.80E-04	1.60E-04
Habitat Occupancy factor = 1 in soil						

Note: (i) Internal DCF is for alpha exposure for all nuclides, but for beta exposure for ^{210}Pb. (ii) External DCFs is insignificant compared to the internal DCF for all nuclides (iii) Radioactive daughter nuclides are included in the dose conversion coefficients of their parents, if their half-lives are shorter than 10 days

Table A-12: Radioecology parameters terrestrial ecosystem: Concentration Factor in (Bq.kg^{-1} fresh weight per Bq.kg^{-1} soil) (ERICA, 2016)

Nuclide	Grasses	Bird	Reptile	Mammal
^{210}Pb	1.2E-01	6.1E-01	3.9E-02	3.7E-02
^{210}Po	2.8E-01	1.0E-03	1.3E-01	8.9E-02
^{226}Ra	1.8E-01	3.6E-02	4.4E-02	4.4E-02
^{232}Th	1.6E-01	3.9E-04	2.2E-03	1.4E-04
^{238}U	1.3E-01	1.3E-03	5.2E-03	5.5E-03

Table A-13: Transfer coefficients (x10^{-4}), F_m for cow milk (d.L^{-1}), F_f (d.kg^{-1}) for beef or chicken (refer to dry mass) [feed – animal product]

Element					Reference
U	**Th**	**Ra**	**Pb**	**Po**	
COW MILK F_m					
290-440	-	1850-3700	-	-	Bain *et al.*, 1994
6	-	4	3	3	Ewers *et al.*, 2003
5-61	-	0.9-14	0.073-12	0.89-3	IAEA, 2010a
6.1	0.05	13	3	30	NNR, 1997
18	0.05	3.8	1.9	2.1	**NNR, 2013**
4	0.05	13	2.6	3.4	Staven *et al.*, 2003
32	31	8.6	2.6	2.3	Strok & Smodis, 2012
BEEF F_f					
-	-	5	10	-	Ewers *et al.*, 2003
2.5-6.3	0.4-9.6	-	2-16	-	Howard *et al.*, 2009
-	-	-	4	50	IAEA, 2010a
300	50	50	9.1	50	NNR, 1997
3.9	2.3	17	7	50	**NNR, 2013**
3	0.4	9	4	50	Staven *et al.*, 2003
BEEF LIVER					
2	10	5	20	800	Ewers *et al.*, 2003
SHEEP LIVER/KIDNEY					
20	100	-	200	6000	Ewers *et al.*, 2003
SHEEP					
20	10	50	100	500	Ewers *et al.*, 2003
300	50	50	71	50	**NNR, 2013**
CHICKEN/POULTRY					
12000	40	9.9	20	40	NNR, 1997
7500	40	9.9	20	24000	**NNR, 2013**
10000	60	300	8000	23000	Staven *et al.*, 2003

Table A-14: Radioecology parameters freshwater ecosystem: Concentration Factor in $L.kg^{-1}$ fresh weight

Element					Reference
U	**Th**	**Ra**	**Pb**	**Po**	
FRESHWATER FISH					
72	713	181	359	2030	ERICA, 2016
-	110±110	80±120	-	240±200	Hosseini *et al.*, 2008
-	-	-	300 (100-300)	50 (10-200)	IAEA, 2010a
50	1000	200	2000	500	NNR,1997
2.4	190	210	370	-	NNR, 2013 (whole body)
0.96	6	4	25	-	**NNR, 2013 (muscle)**
10	100	50	300	50	Staven *et al.*, 2003
0.96	6	4	25	36	UNSCEAR, 2016
0.3-50	**6-1000**	**4-210**	**10-2000**	**10-500**	**Range**
CRUSTACEAN					
200	600	2700	8200	8300	ERICA, 2016
-	-	1500±1300	-	9900±1400	Hosseini *et al.*, 2008
100	100	1000	500	20000	Staven *et al*, 2003
MOLLUSCS					
560	10000	24000	5800	120000	ERICA, 2016
-	-	1500±1600	-	38000±49000	Hosseini *et al.*, 2008
30	1000	100	1000	10000	Staven *et al.*, 2003
MAMMAL					
120	3200	0.21	440	2000	ERICA, 2016
REPTILE					
120	1000	770	440	4600	ERICA, 2016

Table A-15: Transfer factors; $Bq.kg^{-1}$ ($x10^{-4}$) in plant (dry mass) per $Bq.kg^{-1}$ soil (dry mass)

Element					Reference
U	**Th**	**Ra**	**Pb**	**Po**	
GRASS (PASTURE) and FORAGE (Fv: Soil – Hay)					
25-720		1.1-2500			Bain *et al.*, 1994
40	30	300	400	230	Ewers *et al.*, 2003
-	420	-	-	220-10000	IAEA, 2010a
137*	112 *	512*	-	-	Linsalata *et al.*, 1989
47	38				Washed, *unwashed
2000	1000	4000	5000	1000	NNR, 1997
170-460	420-990	710-3100	92-3100	1200	**NNR, 2013**
34	55	119	1990	412	Strok&Smodis, 2012
174	416	1260	919	1150	VandenHove *et al.*, 2009b
-	400-9000*	-	-	-	Wang *et al.*, 2015
	30-1800**				*gamma, **alpha
WHEAT/GRAIN/CEREAL (wheat, barley, rye, maize)					
20-640	-	-	280-2260	340-2000	Al-Masri *et al.*, 2010
10	3	80	80	300	Ewers *et al.*, 2003
-	21	300	-	-	IAEA, 2010a
13	10	100	500	20	NNR, 1997

Element					Reference
U	**Th**	**Ra**	**Pb**	**Po**	
62-150	0.64-21	170-520	12-110	2.4	**NNR, 2013**
12	0.31	11	43	21	Staven *et al.*, 2003
61.8	20.5	171	107	2.24	VandenHove *et al.*, 2009b
LEAFY VEGETABLES (lettuce, spinach, brussel sprouts)					
2.2-80	-	40-250	-	-	Bain *et al.*, 1994
30-570	-	-	240-1430	280-2100	Al-Masri *et al.*, 2010
50	50	600	1000	400	Ewers *et al.*, 2003
-	-	200	120	12	IAEA, 2010a
100	100	400	300	20	NNR, 1997
200	12	910	800	74	**NNR, 2013**
17	3.6	98	20	2.4	Staven *et al.*, 2003
197	12.2	907	803	74.3	VandenHove *et al.*, 2009b
ROOT VEGETABLES (carrot, radish, turnip)					
40-47	-	22-50	-	-	Bain *et al.*, 1994
30	20	300	200	600	Ewers *et al*, 2003
-	8	180	-	-	IAEA, 2010a
300	8	400	200	20	NNR, 1997
84	8	700	150	58	**NNR, 2013**
30	0.85	5	15	18	Staven *et al.*, 2003
84.3	8.04	697	146	58	VandenHove *et al.*, 2009b
FRUIT					
20-170			110-7030	430-6560	Al-Masri *et al.*, 2010
4	4	400	100	10	NNR, 1997
150	7.8	170	150	-	**NNR, 2013**
40	2.5	61	100	12	Staven *et al.*, 2003
120		115	77.2		VandenHove *et al.*, 2009b

Remarks NNR RG-002:

- Transfer factors in RG-002 are more specific.
- For cereals and maize there are different values for stem & shoots and grain. Values in above table are for grain.
- Separate values are listed for different types of soil (sand, loam, clay). Values in above table are the values for "All Soil"
- Grass and pasture separate; range is listed above.
- Fruit/head/berries/buds were classified as non-leafy vegetables
- Seeds and pods were classified as leguminous vegetables

Table A-16: Typical radionuclide activity concentrations in products and waste from mineral sands mining and processing

Th (Bq.kg^{-1})	U (Bq.kg^{-1})	Country	Reference
MINERALS			
Ore			
20-280	30-120	Australia	Collett *et al.*, 2014
200-1000	30-200	World	IAEA, 2012
Heavy mineral concentrate (HMC)			
500-600	300-2500	Australia	Calytrix, 2013
300-3000	<100-800	Australia	Collett *et al.*, 2014
300-8000	100-2000	World	IAEA, 2012
Ilmenite			
500-1900	100-500	Australia	Calytrix, 2013
200-2000	<100-400	Australia	Collett *et al.*, 2014
40-2000	30-400	World	IAEA, 2012
Rutile			
200-600	100-800	Australia	Calytrix, 2013
<200-1400	<100-300	Australia	Collett *et al.*, 2014
60-400	<100-700	World	IAEA, 2012
163±6	485±84	South Africa	Masok *et al*., 2016
Zircon			
800-1100	3200-3800	Australia	Calytrix, 2013
600-1200	1000-4000	Australia	Collett *et al.*, 2014
500-1000	2000-4000	South Africa	Harlow, 2017
500-1000	1000-4000	World	IAEA, 2012
174±5	158±9	South Africa	Masok *et al*., 2016
600	3000	World	UNSCEAR, 2008
Zirconia			
100-26000	3000-13000	South Africa	Harlow, 2017
9000-10000	9000-10000	South Africa	Selby, 2007
300	7000	World	UNSCEAR, 2008
Monazite concentrate			
82000-143500	9500-20000	Australia	Calytrix, 2013
40000-250000	6000-30000	Australia	Collett *et al.*, 2014
14000-250000	6000-40000	World	IAEA, 2012
5000-350000	10000-50000	World	UNSCEAR, 2008
UPGRADED FEEDSTOCK			
Synthetic rutile			
400-1900	100-500	Australia	Calytrix, 2013
>200-1500	<100-300	Australia	Collett *et al.*, 2014
100-1900	90-700	World	IAEA, 2012
Chloride slag			
1-910	2-250	World	IAEA, 2012
Sulphate slag			
1-120	2-80	World	IAEA, 2012
Intermediate products and tailings			
2400-7200	900-2000	Australia	Calytrix, 2013
50-20000	10-1000	World	IAEA, 2012
Iron oxide			
<400	<300	Australia	Collett *et al.*, 2014
<1000	<1000	World	IAEA, 2012

Table A-17: Typical measured activities of natural radioactivity in water worldwide (mBq.L^{-1}) and dose (µSv.a^{-1})

Country	n	^{238}U	^{234}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	Dose	Reference
Groundwater and wells										
Australia	-	150	-	70	-	-	-	140	-	Kleinschmidt *et al.*, 2011
Brazil	44	0.36-180	-	3-530	<10- 320	-	0.03-0.049	20-1800	-	Lauria *et al.*, 2012
Brazil	210	-	-	1-3790	9-980	-	-	2-3800	-	Godoy & Godoy, 2006
Finland	-	1200-20900	20-350	20-50	13-40	7-48	-	-	410	Vesterbacka, 2007
Saudi Arabia	37	<10-1110	60 -2200	<30-1560	-	-	-	<50-460	-	Shabana &Kinsara, 2014
USA	-	551-69290	-	< - 1154	< - 844	-	-	< -533	-	Hughes *et al.*, 2005
USA	26	-	-	-	2-555	4- 1480	-		-	Ruberu *et al.*, 2007
Bottled, spring and mineral water										
Austria	-	-	-	37-225	<2-34	-	-	-	2- 40	Kralik *et al.*, 2003
Brazil	-	-	-	<2- 647	<5- 85	-	-	12-741	-	De Oliveria *et al.*, 2001
Croatia	12	2.1.-14.6	4.7-36.5	0.67-52.1	0.25-3	0.7-7.6	-	<0.05-35.8	-	Rozmaric *et al.*, 2012
Hungary	18	5-274	7-742	-	-	-	-	-	0.07-32.4	Jobbagy *et al.*, 2010
Hungary	-	-	-	4- 601	-	-	-	-	14-119	Kovacs *et al.*, 2003
Italy	-	<3-122	-	<2- 200	-	-	-	-	1-50	Rusconi *et al.*, 2004
Poland	-	-	4± 2	-	-	4±3	-	-	-	Skwarzec *et al*, 2003
Slovenia	15	1-28	3-71	0.4-32	0.6-13.2	0.24-2.1	-	0.05-5.3	-	Benedik & Jeran, 2012
Drinking water, tap water, water works and Surface water										
Belgium	11	0.3-26.1	0.3-54.4	<2-328	0.2-3.1	<10	-	>9-35.9	-	Vasile *et al.*, 2016
Brazil	-	-	-	<2-235	-	-	-	<4-131	-	De Oliveria *et al.*, 2001
Finland	-	1200	20	3	3	3	-	-	20	Vesterbacka, 2007
Ghana	-	14-70	24-72	8-12	4.1-10	-	0.9-23.2	-	0.020	Gbadago *et al*., 2011
Italy	-	2-103	2-135	5-61	-	1-11	-	-	1.8-36.2	Jia & Tori, 2007
Italy	-	21±30	26±36	9±15	3±4	26±36	1±1	-	2.81-38.5	Jia *et al.*, 2009
Jordan	-	-	-	-	-	-	-	-	0.15	Al-Amir *et al.*, 2012
EU reference		3000	2800	500	200	100	600	200	100	EU, 2013a
World		**1**	**-**	**0.5**	**10**	**5**	**0.05**	**0.5**	-	UNSCEAR, 2010

Table A-18: Literature values for Activity concentration of radionuclides in food (Bq.kg^{-1} fresh weight), annual intake (Bq.a^{-1}) and committed effective dose for the adult age group (mSv.a^{-1})

Category	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	Reference
ANIMAL PRODUCTS							
Milk	**0.001**	**0.005**	**0.015**	**0.015**	**0.0003**	**0.005**	UNSCEAR, 2000
	-	-	-	0.020	-	-	Arunanchalam *et al*, 2014
	-	-	0.24	0.28	-	-	Carvalho, 1995
	-	0.0218	-	-	0.0027	0.041	Choi *et al.*,2008
	-	-	-	0.02-0.07	-	-	Cunha *et al.*,2001
	0.002	0.015	0.038	-	0.024	0.060	Lauria *et al.*, 2012
	0.0026	0.01	0.018	0.016	0.0024	-	Pietrzak-Flik *et al.*,1997
	0.048	0.015	-	-	-	0.03	Santos *et al.*,2002
MEAT							
Meat	**0.002**	**0.015**	**0.08**	**0.06**	**0.001**	**0.01**	UNSCEAR, 2000
	-	-	-	0.09-0.25	-	-	Cunha *et al.*,2001
	0.012	0.006	0.063	-	0.007	0.020	Lauria *et al.*, 2012
Beef	-	-	-	0.053	-	-	Arunanchalam *et al*, 2014
	-	-	0.55	0.86	-	-	Carvalho, 1995
	-	0.036	-	-	0.0078	0.025	Choi *et al.*,2008
	0.015	0.008	0.048	-	-	0.029	Yu & Mao, 1999
Mutton	-	-	-	0.041-0.066	-	-	Kannan *et al.*, 2001
Poultry	-	-	0.12	0.15	-	-	Carvalho, 1995
	-	0.0257	-	-	0.0008	0.0244	Choi *et al.*,2008
	-	-	-	0.050-0.100	-	-	Kannan *et al.*, 2001
	0.010	0.058	0.056	-	0.020	0.200	Lauria *et al.*, 2012
	0.0009	0.006	0.047	-	-	0.027	Yu & Mao, 1999
FISH AND SEAFOOD							
Fish	**0.03**	**0.1**	**0.2**	**2 (0.08-12)**	**0.01**	-	UNSCEAR, 2000
	-	-	0.3	0.6-13.5	-	-	Carvalho, 1995
	-	-	1.3-1.8	0.17-6.7	-	-	Cunha *et al.*,2001
	-	-	-	1.41- 32.2	-	-	Kannan *et al.*,2001
	-	-	-	0.51-5.56	-	-	Kim *et al.*, 2017
	-	-	2.8	0.6- 26	-	-	Yamamoto *et al.*,1994
	0.018	0.005	0.047	-	-	0.047	Yu & Mao, 1999

Category	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	Reference
Shellfish	-	0.151	-	-	0.052	0.193	Choi *et al.*,2008
	2.2	0.059	-	0.12	-	-	Fisenne *et al.*,1987
	-	-	-	17- 122	-	-	Kannan *et al.*,2001
	-	-	-	47.8	-	-	Kim *et al.*, 2017
	-	-	-	19.1 – 33	-	-	Lee *et al.*,2009
	-	-	-	0.2 - 43	-	-	Yamamoto *et al.*,1994
CEREAL AND GRAIN							
Grain	**0.02**	**0.08**	**0.05**	**0.06**	**0.003**	**0.06**	UNSCEAR, 2000
	-	-	-	0.294	-	-	Arunanchalam *et al*, 2014
	0.005	0.177	0.224	-	0.068	0.440	Lauria *et al.*, 2012
Barley	-	-	-	0.15	-	-	Lee *et al.*,2009
	0.0106	-	-	0.1	0.0465	-	Pietrzak-Flik *et al.*,1997
Wheat	-	-	0.09	0.14	-	-	Carvalho, 1995
	-	0.112	-	-	0.104	0.125	Choi *et al.*,2008
	3.2	-	-	-	-	-	Misdaq & Elamyn, 2006
	0.0106	0.0871	-	-	0.0505	-	Pietrzak-Flik *et al.*,1997
Maize	0.021	0.0215	-	-	-	-	Arogunjo *et al.*,2009
	-	-	0.066	0.049	-	-	Carvalho, 1995
LEAFY VEGETABLE							
Leafy veg	**0.02**	**0.05**	**0.08**	**0.05**	**0.015**	**0.04**	UNSCEAR, 2000
	-	-	0.33	0.054	-	-	Carvalho, 1995
	-	-	-	0.07-0.31	-	-	Cunha *et al.*,2001
	0.681	2.201	**2.705**	-	0.967	8.195	Lauria *et al.*, 2012
Spinach	-	0.0156	-	-	0.0134	0.174	Choi *et al.*,2008
	-	-	-	0.10-0.65	-	-	Kannan *et al.*,2001
	-	-	-	0.27	-	-	Lee *et al.*,2009
	0.014	0.03	-	-	-	0.21	Santos *et al.*,2002
Cabbage	0.0324	-	-	-	-	-	Arogunjo *et al.*,2009
	-	0.015	-	-	0.0197	0.0129	Choi *et al.*,2008
	-	-	-	0.028-0.13	-	-	Kannan *et al.*,2001
	0.0002	0.137	-	-	-	0.304	Santos *et al.*,2002
Lettuce	-	0.137	-	-	0.0033	0.196	Choi *et al.*,2008
	-	-	-	0.36	-	-	Lee *et al.*,2009
	0.0154	0.0597	0.051	0.067	0.0073	-	Pietrzak-Flik *et al.*,1997

Category	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	Reference
	0.0041	0.07	-	-	-	0.089	Santos *et al.*,2002
ROOT VEGETABLE							
Root veg	**0.003**	**0.03**	**0.03**	**0.04**	**0.0005**	**0.02**	UNSCEAR, 2000
	-	-	-	0.251	-	-	Arunanchalam *et al*, 2014
	-	-	0.23	0.025	-	-	Carvalho, 1995
	0.020	0.300	0.300	-	0.030	1.2	Lauria *et al.*, 2012
Carrot	-	-	-	0.020-0.070	-	-	Kannan *et al.*,2001
	0.0077	0.04	0.044	0.028	0.0252	-	Pietrzak-Flik *et al.*,1997
	0.0013	-	-	-	-	0.694	Santos *et al.*,2002
Red beet	-	-	-	0.020-0.180	-	-	Kannan *et al.*,2001
	0.0033	0.054	0.046	0.049	0.0163	-	Pietrzak-Flik *et al.*,1997
Onion	-	0.013	-	-	0.007	0.0056	Choi *et al.*,2008
	0.00259	0.021	0.029	0.031	0.0095	-	Pietrzak-Flik *et al.*,1997
	0.0002	0.065	-	-	-	0.112	Santos *et al.*,2002
OTHER VEGETABLE							
Tomatoes	-	-	-	0.019-0.029	-	-	Kannan *et al.*,2001
	2.8	-	-	-	-	-	Misdaq & Elamyn, 2006
	0.0009	0.013	0.012	0.028	0.0013	-	Pietrzak-Flik *et al.*,1997
	0.0013	0.157	-	-	-	0.158	Santos *et al.*,2002
Legumes	0.455	-	-	-	-	-	Arogunjo *et al.*,2009
	-	-	0.11	0.04-0.17	-	-	Cunha *et al.*,2001
	3.3	-	-	-	-	-	Misdaq & Elamyn, 2006
	0.00338	0.179	-	-	0.0102	-	Pietrzak-Flik *et al.*,1997
	0.004	0.131	-	-	-	0.262	Santos *et al.*,2002
FRUIT							
Apple	-	0.0007	-	-	0.0073	0.0066	Choi *et al.*,2008
	-	-	0.1	0.05-0.07	-	-	Cunha *et al.*,2001
	0.0002	0.035	0.020	-	0.0001	0.067	Lauria *et al.*, 2012
	0.0015	0.016	-	0.05	0.0038	-	Pietrzak-Flik *et al.*,1997
	0.023	0.002	0.029	-	-	0.014	Yu & Mao, 1999
Orange	-	0.0007	-	-	0.0082	0.0078	Choi *et al.*,2008
	-	-	0.42	-	-	-	Lee *et al.*,2009
	0.004	0.021	-	-	-	0.048	Santos *et al.*,2002

Category	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	Reference
	0.013	0.001	0.021	-	-	0.021	Yu & Mao, 1999
WATER							
Water	**0.001**	**0.0005**	**0.01**	**0.005**	**0.0001**	**0.0005**	UNSCEAR, 2000
ANNUAL RADIOACTIVITY INTAKE (Bq.a^{-1})							
	5.7	**22**	**30**	**58**	**1.7**	**1.5**	UNSCEAR, 2000
	2.9 – 56.9	**8.8 – 39.8**	**16 - 110**	**18-131**	**0.73-9.1**	**1.3-66**	UNSCEAR, 2000
COMMITTED DOSE (mSv.a^{-1})							
Total dose	**0.29[0.14** excluding K-40**]**						UNSCEAR, 2000
	0.00025	**0.008**	**0.028**	**0.085**	**0.00036**	**0.021**	UNSCEAR, 2000

Table A-19: Literature values for activity concentrations of soil, sediment, tailings (Bq.kg^{-1} dry weight)

Country	N	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{40}K	Ra_{eq}	Reference
Soil									
Brazil	3	-	241±15	-	-	249±8	-	-	Linsalata *et al.*, 1991
England	-	-	1.9-99	2.9-153	2.8-154	2.2-115	94-1025	-	Beresford *et al.*, 2008
Egypt	-	13.7-27.9	-	-	-	15.4-53.1	176-407	54.3-117	Ebaid *et al.*, 2000
Ghana	12	7.54-42.3	-	-	-	4.18-54.9	84.6-479	-	Adukpo *et al.*, 2014
Greece	-	<1-1420	21-101	-	-	26-94	458-1796	-	Florou *et al.*, 2007
India	24	-	19.5-96.0	-	-	30.2-136	189-508	-	Mehra & Singh, 2011
	3		0-6.49			3.95-19.0	221-423	22.7-57.9	Ravisankar *et al.*, 2012
Malaysia	21	-	51±4	-	-	119±6	158±321	59-530	Saleh *et al.*, 2015
Namibia	100	10.8-26.4	-	-	-	12.8-52.3	212-684	-	Oyedele,2006
Norway	-	-	-	39.4	39.8	-	-	-	Brown *et al.*, 2011
Poland	2	-	-	16.0±0.4	16.7±0.6	-	-	-	Pietrzak & Skowronska,1995
SA, Paarl E	-	27±7	27±7	-	-	30±6	124±14	-	Lindsay *et al.*, 2008
SA, Paarl W	-	78±7	78±7	-	-	96±1	276±95	-	Lindsay *et al.*, 2008
South Africa	10	17.0± 0.4	-	-	-	22.2 ± 0.5	497± 15	86.9± 1.4	Kamunda *et al.* 2016
South Africa	70	28.9±16.0	28.0 ±19.3	65.5±33.2	-	22.9 ±21.2	150 ± 151	70.9±49.4	This study
United States	4	-	40.5±6.5	-	-	37.6±1.2	-	-	Linsalata *et al.*, 1989

Country	N	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{40}K	Ra_{eq}	Reference
Sediment									
Ghana	13	2.59-32.3	-	-	-	2.23-60.6	20.7-384	-	Adukpo *et al.*, 2014
South Africa	246	934 ± 14	260 ± 10	270 ± 20	-	45.4 ± 0.9	176 ± 2	-	Faanhof *et al.*, 2010
SA, baseline	24	19.7±16.7	17.5 ±14.9	24.5±21.9	-	18.6 ±11.9	168 ± 150	57.0±35.6	This study
SA, gold area	41	156 ± 150	155 ± 153	161 ± 140	-	28.4 ±15.9	176 ± 2	229±181	This study
SA, other	20	41.6±33.2	45.5 ±32.9	107 ± 92	-	105 ± 131	366 ± 333	216±194	This study
								-	
Tailings									
South Africa	56	785± 14	-	-	-	43.9 ± 1.0	427± 13	881± 14	Kamunda *et al.*,2016
South Africa	45	272± 4	-	-	-	47.6 ± 3.7	87.2 ± 5.2	-	Njinga & Tshivhase, 2016
South Africa	49	338±160	349 ±185	467±245	-	23.3 ±8.53	195 ± 74	395±195	This study
Worldwide									
Europe soil	-	-	36(0-1000)	-	-	34(1-258)	483(0-3200)	-	Trevisi *et al.*, 2012
Global soil	AVE	**33(16-110)**	**32(17-60)**	-	-	**45(11-64)**	**420(140-850)**	-	UNSCEAR, 2000
Global soil	MED	**35**	**35**	-	-	**30**	**400**	-	UNSCEAR, 2000
Soil	AVE	**37±4**	-	-	-	**33±3**	**400±24**	**<370**	UNSCEAR, 2008

Table A-20: Literature values for activity concentrations and radium equivalent activities of cement and products used for manufacturing of cement (Bq.kg^{-1})

Country	N	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	I_{γ}	Reference
Bricks							
Australia	25	40.7	88.8	681	78-181	-	Beretka & Mathew,1985
Brazil	13	12.7-48	49.7-793	144±514	-	-	Malanca *et al.*, 1993
India	-	25.3-62.0	84.8-137	342-4059	-	0.63-0.99	Viruthagari & Ponnarais,2011
Europe	1676	47(2-148)	48(2-164)	598(12-1169)	-	-	Trevisi *et al.*, 2012
EU	-	**50(200)**	**50(200)**	**670(2000)**	-	-	EU, 1999
Worldwide	-	1-200	-		-	-	IAEA, 2014a
South Africa	5	76±17	24±4	160±45	117±26	0.41±0.09	This study
Cement							
Australia	7	51.8	77.7-181	114.7	-	0.31	Beretka & Mathew,1985

Country	N	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	I_γ	Reference
Cameroon	24	16.6-47.6	12.5-32.5	182-286	53.6-106	0.20-0.39	Ndontchueng *et al.*, 2013
China	46	68.3±3.6	51.7±5.4	174±9	163	-	Xinwei, 2005
Ghana	4	5.9±0.8	25.4±0.8	233±3.93	90.1±13.5	-	Kpeglo *et al.*, 2011
Greece	20	4.6-25.4	8.1-16.4	141-3201	-	-	Papastefanous *et al.*, 2005
Ireland	3	26.9-107	3.3-15.1	65.7-252	-	0.19-0.40	Lee *et al.*, 2004
India	3	28.6-54.0	23.5-41.7	150-233	76.1-122	0.27-0.43	Ravisankar *et al.*, 2012
India	15	20.3-60.1	18.8-60.1	161-248	64.1-151	0.23-0.43	Sharma *et al.*, 2016
Nigeria	1	20±3	8.4±0.2	51±7	36	-	Arabi *et al.*, 2015
Serbia	22	37±22	15±29	43±64	10-282	0.03-0.76	Pantelic *et al.*, 2015
Sweden	-	55	47	241	-	-	OECD, 1979
Turkey	145	40.5±26.7	26.1±18.9	267±102	98.3±53.8	0.35±0.19	Turhan, 2008
UK	-	22	18	155	-	-	OECD, 1979
Europe	2013	45(4-422)	31(3-266)	216(4-846)	-	-	Trevisi *et al.*, 2012
Worldwide	-	7-180	-	-	-	-	IAEA, 2014a
South Africa	10	23±16	23±7	153±83	67±27	0.24±1.0	This study
Concrete							
Australia	5	14.8	40.7	199	55.5-104	0.23	Beretka & Mathew,1985
Finland	-	49	36	359	-	-	OECD, 1979
Greece	15	2-53.8	7.9-25.1	140-5838	-	-	Papastefanous *et al.*, 2005
Nigeria	130	4.3-66.8	12.4-266	86.2-1073	51-446	0.39	Farai & Ademola, 2005
Norway	-	26	36	721	-	-	OECD, 1979
Turkey	10	28.3±13.3	15.9±3.2	219±45.2	68.0±18.8	0.25±0.07	Turhan, 2008
Europe	2727	60(1-1300)	35(1-152)	392(7-1450)	-	-	Trevisi *et al.*, 2012
EU	-	40(240)	30(190)	400(1600)	-	-	EU, 1999
Worldwide	-	1-250	-	-	-	-	IAEA, 2014a
South Africa	6	47±23	50±27	94±67	125±35	0.43±0.12	This study
Fly-ash							
See Table A-21							
Granite							
Germany	-	100	80	1229	-	-	OECD, 1979
Greece	16	64±53	81±79	1104±407	-	0.01-2.15	Pavlidou *et al.*, 2006
Italy	6	11.7-153	19-360	240-1600	-	0.22-2.84	Righi & Bruzzi, 2006
*Italy	1	11.7±1.0	19±2	24±26	-	0.20-0.27	Righi & Bruzzi, 2006
Japan	6	10.2-322	29.2-201	742-10990	-		Hassan *et al.*, 2010

Country	N	^{226}Ra	^{232}Th	^{40}K	Ra_{eq}	I_{γ}	Reference
Serbia	211	38±52	43±57	660±540	84-879	0.23-2.37	Pantelic *et al.*, 2015
World	**-**	**77**	**84**	**1200**			UNSCEAR, 2008
Gypsum							
Australia	4	-	11.1	-	3.7-25.9	0.04	Beretka & Mathew,1985
Brazil	1	6.3	-	154	18.1	-	Malanca *et al.*, 1993
Serbia	265	20±26	0.4±3	23±55	11-260	0.03-0.70	Pantelic *et al.*, 2015
Turkey	29	10.8±12.2	3.6±2.7	44.5±23.2	17.5±16.0	0.06±0.05	Turhan, 2008
Europe	502	15(1-70)	9(1-100)	91(5-279)	-	-	Trevisi *et al.*, 2012
EU	-	10(70)	10(100)	80(200)	-	-	EU, 1999
Worldwide	-	<1-70	-	-	-	-	IAEA, 2014a
South Africa	20	110±109	91±42	68±20	214±123	0.73±0.42	This study
Phosphogypsum							
Australia	9	11.1	270-418	451	-	1.28	Beretka & Mathew, 1985
Germany	-	592	<16	96	-	-	OECD, 1979
Greece	9	109-688	2.7-11.1	5.0-92.1	-	-	Papastefanous *et al.*, 2005
Sweden	-	15	62	48	-	-	OECD, 1979
Turkey	2	564±92.5	14.9±2.8	10.4±1.0	575±77.9	1.92±0.26	Turhan, 2008
UK	-	629	18	41	-	-	OECD, 1979
Europe	290	407(18-1406)	21(2-118)	78(0-569)	-	-	Trevisi *et al.*, 2012
EU	-	390(1100)	20(160)	60(300)	-	-	EU, 1999
Worldwide	-	4-700	-	-	-	-	IAEA, 2014a
South Africa	55	87±17	42±21	104±35	151±39	0.52±0.14	This study
Zircon sand							
Australia	3	2249	503	326	1728-3704	8.08	Beretka & Mathew, 1985
BM average values		50	50	500	-	-	OECD,1979

*Imported from South Africa

Table A-21: Literature values for activity concentrations of coal and coal fly ash (Bq.kg^{-1})

Country	N	^{40}K	^{232}Th	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	Ra_{eq}	Reference
Coal									
Belgium	10	-	20	-	20	-	-	-	Zeevaert *et al.*, 2006
(from SA)	4		25-30		25-30				
China	7	-	-	-	-	-	25-62	-	Chuangao *et al.*, 2017
India	-	-	19.5	-	16.8	-	12.3-43	-	Sahu *et al.*, 2014
Serbia	-	45-243	13-32	18-71	14-52	-	-	-	Jankovic *et al.*, 2011
Serbia	9	-	-	-	-	22.7-116	-	-	Seslak *et al.*, 2016
South Africa	-	15.8 ± 1.1	27.8 ± 1.5	18.4 ± 1.2	-	-	-	-	Duliu *et al.*, 2005
	6	148 ± 31	51 ± 24	54 ± 27	59 ± 23	-	-	142 ± 60	This study
Spain(SA)	-	<20	25 ± 3	-	30 ± 3	-	-	-	Baeza *et al.*, 2007
Turkey	4	136-322	15.6-22.6	-	36-110	-	-	78-150	Akkurt *et al.*, 2009
Worldwide	-	**50**	**20 (10-25)**	**20(10-25)**	**20**	**20**	**20**	-	UNSCEAR, 2008
Lignite									
Greece	6	173±14	19±8.5	306±4.2	346±2.4	361±9.6	-	-	Karangelos *et al.*, 2004
Fly ash									
Australia	15	203	170	-	96.2	-	-	137-633	Beretka & Mathew, 1985
China	12	357 ± 67	56.4 ± 24.6	-	87±36	-	-	195	Xinwei, 2005
China	7	-	-	-	-	-	64-181	-	Chuangao *et al.*, 2017
Greece	6	454±11	53±4.7	964±6.6	904±8.6	1158±11	-	-	Karangelos *et al.*, 2004
India	-	-	95-230	19 -121	40.7-152	25.7-69.6	-	93-300	Pandit *et al.*, 2011
India	-	-	61.7		78.8	-	-	25.7-69.6	Sahu *et al.*, 2014
Serbia	-	174-489	29-121	21-246	45-270	-	-	102-405	Jankovic *et al.*, 2011
Serbia	9	-	-	-	-	84.3-153	-	-	Seslak *et al.*, 2016
Spain (SA)	-	-	-	150	250	-	-		Font *et al.*, 1993
South Africa	-	330±29	156±3	186±2	161±9	320±32	-	-	Madzivire *et al.*, 2014
South Africa	30	229 ± 88	146 ± 49	152 ± 40	147 ± 48	154 ± 64	-	370 ± 114	This study
Turkey	20	466±148	117± 45	-	232±107	-	-	429±151	Turhan *et al.*, 2011
EU	-	650 (1500)	100 (300)	-	180 (1100)	-	-	-	EU, 1999
Worldwide	-	**265**	**70**	**200**	**240**	**930**	**1700**	**200**	UNSCEAR, 2008
Slag (bottom ash)									
Australia	3	141	181±10	-	340	-	-	-	Beretka & Mathew, 1985
China	6	324 ± 56	91.3 ± 13.6	-	63.2± 18.2	-	-	207	Xinwei, 2005

Country	N	^{40}K	^{232}Th	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	Ra_{eq}	Reference
	7	-	-	-	-	-	2.3-64	-	Chuangao *et al.*, 2017
Greece	6	405±11	44±4.6	681±3.5	662±9.3	275±5.9	-	-	Karangelous *et al.*, 2004
India	-		24.4	-	41.4	-	-	14.2-49	Sahu *et al.*, 2014
Serbia	-	67-375	14-73	26-145	17-114	-	-	-	Jankovic *et al.*, 2011
Serbia	10	-	-	-	-	20.1-60.8	-	-	Seslak *et al.*, 2016
South Africa	-	193 ± 76	132 ± 23	-	77 ± 12	-	-	256 ± 34	This study
Turkey	12	243 ± 114	178±96	-	148 ± 109	-	-	393 ± 234	Turhan *et al*.,, 2011
EU	-	240 (1000)	270 (1100)	-	70 (340)	-	-	-	EU, 1999

Table A-22: Typical radionuclide activity concentrations in products and waste from the phosphate industry (Bq.kg^{-1})

Country	**^{238}U**	**^{226}Ra**	**^{210}Pb**	**^{210}Po**	**^{232}Th**	**^{228}Ra**	**Reference**
Phosphate ore							
South Africa[1]	200	200	-	-	400	400	IAEA, 2013
Worldwide	**200-1500**	-	-	-	**20**		UNSCEAR, 2000
Phosphate rock							
Brazil	158-1868	139-1518	373-1698	-	246-577	-	Saueia & Mazzilli, 2006
Egypt	-	666±33	-	-	329±17	-	Abbady *et al.*, 2005
South Africa	118	44.5	270	-	783	-	Masok *et al.*, 2016
South Africa	110-180	110-180	100-130	-	330-610	400-620	Van der Westhuizen,2007
Spain	1600	-	-	-	-	-	Mola *et al.*, 2013
Worldwide	**30-300**	-	-	-	-	-	IAEA, 2006
Worldwide	**50-2400**	-	-	-	low	-	UNSCEAR, 2016
Phosphate tailings							
South Africa	220-300	190-280	-	-	260-440	220-450	Van der Westhuizen,2007
Worldwide	**900-1300**				**20**		UNSCEAR, 2000
Phosphoric acid							
South Africa	140-190	<LOD	140-180	-	280-470	<LOD	IAEA, 2013

Country	^{238}U	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	Reference
Worldwide	**140-2600**	-	-	-	-	-	IAEA, 2013
Phosphogypsum							
Brazil	900	2000	-	2700	-	-	Martinez-Aguirre & Garcia-Leon,1994
Brazil	40-58	122-940	136-1163	-	60-257	-	Saueia & Mazzilli,2006
Florida	-	900-1100	-	-	-	-	Silva *et al*., 2001
Greece	-	261-688	-	-	-	-	Papastefanou *et al*., 2006
Netherlands	-	800	-	-	-	-	Silva *et al*., 2001
South Africa[1]	50-70	90-120	<LOD	<LOD	130-590	350-500	IAEA, 2013
South Africa[2]	10-80	80-330	80-330	80-330	10-170	10-170	IAEA, 2013
South Africa	31±20	109±18	135±70	-	253±160	404±70	Msila *et al*., 2016
Spain	-	518	-	-	-	-	Silva *et al*., 2001
Syria	-	310	-	471	-	-	Al-Masri & Al-Bich,2002
Turkey	-	31-563	-	-	5.6-27	-	Gezer *et al*., 2012
Worldwide	**<100**	**200-3000**	-	-	-	-	IAEA, 2013
Worldwide[1]	**<100**	**10-700**	-	-	-	-	IAEA, 2013
Phosphate fertilizer							
Brazil[3]	<850	-	-	-	-	-	Saueia & Mazzilli,2006
Brazil[4]	264-1158	<1.3-879	19-1225	-	81-546	-	Saueia & Mazzilli,2006
Brazil[5]	182-861	<1.3-548	101-964	-	109-521	-	Saueia & Mazzilli,2006
Serbia	35±8	4-452	-	-	8-226	-	Todorovic *et al*., 2015
Worldwide	**31-2640**	**400-2000**	-	-	-	-	IAEA, 2006
Worldwide[3]	**300-3000**	**10-100**	-	-	**8-40**	-	UNSCEAR, 2000

[1]Igneous origin; [2]75% igneous and 24% sedimentary; [3]MAP/DAP; [4]SSP; [5]DAP

APPENDIX B

CALCULATIONS

Appendix B contains a summary of the calculations used for data reduction in the thesis. These calculations are based on the formulae described in section 2.13.

B.1 General for all radiochemical (alpha spectrometry) methods

Efficiency calibration

The counting efficiency for α-spectrometry depends on the detector used (*i.e.* diameter and thickness of the active volume), the diameter of the sample (*i.e.* the radioactive deposit), and the geometry rig used to position the sample in front of the detector (*i.e.* area of the radioactive deposit exposed and the distance between sample and detector.

This value has been determined by counting a calibration standard for the same geometry as used for the samples. In the methods where an internal tracer is added, the efficiency value cancels out in the equations below, and is only required if the exact recovery has to be calculated.

Counting Protocols

When analyzing the samples a specific counting protocol is selected on the instrument. The regions of interest in the spectra are pre-defined in the counting protocols as follows:

Method	ROI	Nuclide	Energy (MeV)
Polonium	1	Po-209	4.51 - 4.91
	2	Po-210	4.92 - 5.39
Uranium	1	U-238	3.82 - 4.28
	2	U-235	4.31- 4.51
	3	U-234	4.56 - 4.91
	4	U-232	5.11 - 5.45
	5	Test area	7.35 - 7.70
Thorium	1	Th-232	3.71 - 4.02
	2	Th-230	4.37 - 4.69
	3	Th-229	4.73 - 5.08
	4	Th-228	5.09 - 5.45
	5	Th-227	5.46 - 6.09
	6	Test area 1	6.10 - 6.82
	7	Test area 2	7.04 - 7.39
	8	Test area 3	8.43 - 8.78
	9	Test area 4	7.40 - 7.70
Radium	1	Ra-226	3.70-4.80
	2	Ra-223,Rn-222,Po-218	4.82-6.09
	3	Rn-220, Bi-211, Po-216	6.10-6.82
	4	Po-215	6.84-7.70
	5	Po-212	7.80-8.80

Parameters used in calculations

t_0	reference date tracer solution/time of sampling	[a]
t_1	time of separation	[a]
t_2	time of counting	[a]
t_m	midpoint of sample count	[a]
t	decay time (t_m- t_1) or (t_m- t_0)	[a]
λ	decay constant of nuclide ($\lambda = \ln 2 / t_{½}$)	[-]
T	counting period (nominally 24 hrs, or 86400 seconds)	[s]
T_S	counting period sample	[s]
T_b	counting period background	[s]
ε	efficiency of α-detector used for this sample	[-]
C	decay factors as defined in B2 to B5	[-]
V	volume of sample taken for analysis	[l]
R	fractional chemical yield	[-]
I	nett count of sample *i.e* the integral over the relevant ROI of the α spectrum, corrected for background and blank	[-]
B	background counts, normalised to counting period t_s	[-]
Bl	nett count of blank over the same ROI, corrected for background	[-]
A_0	activity of tracer added (at reference date)	[$mBq.ml^{-1}$]
A_t	activity of tracer added, decay corrected	[$mBq.ml^{-1}$]
A_m	activity of tracer measured	[$mBq.ml^{-1}$]
C_s	beta counts of ^{133}Ba tracer added to sample	[cps]
C_c	beta counts of ^{133}Ba calibration source	[cps]
A_s	activity concentration of the sample at time of counting	[$mBq.L^{-1}$]
CU	Counting uncertainty of the sample	[$mBq.L^{-1}$]
S	Probable error	[$mBq.L^{-1}$]
MDA	Minimum Detectable Activity	[$mBq.L^{-1}$]

Chemical yield

The chemical yield (for Po, U and Th) is calculated from the fraction of the tracer that was recovered during the analytical procedure.

$$R = \frac{A_m}{A_t}$$ ....*Equation B1*

Measured tracer activity concentration, A_m

$$A_m = \left(\frac{I}{\varepsilon.T} - \frac{B}{\varepsilon.T}\right) * 1000$$ ....*Equation B2*

Added tracer activity, decay corrected, A_t

$$A_t = A_0 * \left(e^{-\lambda.(t_m - t_0)}\right)$$ ....*Equation B3*

The chemical yield (for Ra) is calculated from the fraction of the ^{133}Ba tracer that was recovered during the precipitation procedure, and is a relative measurement.

$$R = \frac{C_s}{C_c}$$ ....*Equation B4*

Activity concentration, A_s

The activity concentration of the analyte in the sample ($mBq.L^{-1}$) at time of counting is calculated from the following equation.

$$A_s = \left(\frac{I}{\varepsilon.T.V.R.C} - \frac{Bl}{\varepsilon.T.V.R.C}\right) * 1000 \ldots\ldots\ldots \textit{Equation B5}$$

Counting uncertainty, CU

The probable error is calculated from counting statistics using the equation:

$$S = \left(\frac{\sqrt{I+B}}{\varepsilon.T.V.R.C}\right) * 1000 \ldots\ldots\ldots \textit{Equation B6}$$

Minimum detectable activity, MDA

Both the calculated activity value (even if negative) and the minimum detectable activity value, is reported. The MDA is calculated from:

$$MDA = \left(\frac{2.71+3.29*\sqrt{B*(1+T_s/T_B}}{\varepsilon.T_s.V.R.C}\right) * 1000 \ldots\ldots\ldots \textit{Equation B7}$$

B.2 Data reduction for ^{210}Po and ^{210}Pb

For ^{210}Po the activity concentration in the sample, counting uncertainty and MDA at times of first and second deposition is calculated from equations B5 to B7 with relative contribution factor, C=1.

The activity of ^{210}Pb and ^{210}Po at time of sampling is calculated using Bateman equations, as shown below.

Parameters used in calculations

t_0	time of sampling	[a]
t_1	time of first deposition	[a]
t_2	time of second deposition	[a]
t_{c1}	time of first count	
t_{c2}	time of second count	
T	counting period	[s]
A_1, A_2	^{210}Po activity at time of first and second depositions respectively	[$mBq.L^{-1}$]
A_{Po}	^{210}Po activity at time of sampling	[$mBq.L^{-1}$]
A_{Pb}	^{210}Pb activity at time of sampling	[$mBq.L^{-1}$]
MDA_1	MDA calculated at time of first deposition	[$mBq.L^{-1}$]
MDA_2	MDA calculated at time of second deposition	[$mBq.L^{-1}$]
MDA_{Po}	MDA of ^{210}Po at time of sampling	[$mBq.L^{-1}$]
MDA_{Pb}	MDA of ^{210}Pb at time of sampling	[$mBq.L^{-1}$]

C_1-C_4	decay factors as defined in equations B12 to B16
λ_1	decay constant of ^{210}Pb (half life 22 a)
λ2:	decay constant of ^{210}Bi (half life 5 d)
λ_3	decay constant of ^{210}Po (half life138.38 d)

Activity of ^{210}Pb and ^{210}Po at time of sampling

The activity concentrations of Pb and Po at time of sampling are only calculated after the second deposition has been performed after an ingrowth period of at least 4-6 months.

The following IF statement applies:

IF A_2 is within the range $A_1 \pm 3s$; take average of A_1 and A_2; else Bateman equations apply.

Formulas for calculation of the Po and Pb activities at time of sampling were obtained by solving the two equations:

At time t_1: $A_1 = A_{Pb}.\ \exp(-\lambda_{Pb}.(t_1 - t_0))\ .(1-\exp(-\lambda_{Po}.(t_1 - t_0))) + (A_{Po}.\ \exp(-\lambda_{Po}.(t_1 - {}_0)))$

At time t_2: $A_2 = A_{Pb}.\ \exp(-\lambda_{Pb}.(t_2 - t_0))\ .(1-\exp(-\lambda_{Po}.(t_2 - t_0))) + (A_{Po}.\ \exp(-\lambda_{Po}.(t_2 - t_0)))$

$$A_{Po} = \frac{C_1 * A_2 - C_3 * A_1}{C_1 * C_4 - C_2 * C_3}$$ ……*Equation B8*

$$A_{Pb} = \frac{C_4 * A_1 - C_2 * A_2}{C_1 * C_4 - C_2 * C_3}$$ ……*Equation B9*

MDA of ^{210}Pb and ^{210}Po at time of sampling

$$MDA_{Po} = \frac{MDA_2 * C_1 + MDA_1 * C_3}{C_1 * C_4 - C_2 * C_3}$$ ……*Equation B10*

$$MDA_{Pb} = \frac{MDA_1 + MDA_{Po} * C_2}{C_1}$$ ……*Equation B11*

Decay Factors

In order to apply Bateman equations, decay factors are calculated.

C_1 : ingrowth of Po from Pb in time t_1 - t_0; $(e^{-\lambda Pb.t})(1 - e^{-\lambda Po.t})$

$$C_1 = e^{-\lambda_1.(t_1 - t_0)} * \lambda_2 \lambda_3 * \left(\frac{e^{-\lambda_1.(t_1 - t_0)}}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)} + \frac{e^{-\lambda_2.(t_1 - t_0)}}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)} + \frac{e^{-\lambda_3.(t_1 - t_0)}}{(\lambda_1 - \lambda_3)(\lambda_2 - \lambda_3)} \right)$$ …*Equation B12*

C_2 : decay of Po in time t_1 - t_0; $(e^{-\lambda Po.t})$

$$C_2 = \left(1 * e^{-\lambda_3.(t_1 - t_0)}\right)$$ ……*Equation B13*

C_3 : ingrowth of Po from Pb in time t_2 - t_1.

$$C_3 = e^{-\lambda_1.(t_2 - t_1)} * \lambda_2\lambda_3 * \left(\frac{e^{-\lambda_1.(t_2 - t_1)}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)} + \frac{e^{-\lambda_2.(t_2 - t_1)}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} + \frac{e^{-\lambda_3.(t_2 - t_1)}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)}\right) \quad \text{...Equation B14}$$

C_4 : decay of Po in time t_2 - t_1.

$$C_4 = \left(1 * e^{-\lambda_3.(t_2 - t_1)}\right) \quad \text{.....Equation B15}$$

B.3 Data reduction for U isotopes

For ^{238}U, ^{235}U and ^{234}U the activity concentration in the sample, counting uncertainty and MDA is calculated from equations B5 to B7 with relative contribution factor, C=1.

Mathematics based on equilibrium assumption

The activity ratios of U-238/235 and U-234/238 are calculated. Based on the equilibrium assumption and a ratio U-238/235 = 21.7 a correction is made to the U-234 and U-235 activity concentrations whenever the U-238/235 ratio is more than 23.9 or less than 19.5.

When 19.5 < ratio < 23.9, the activity concentration, uncertainty and MDA as calculated in B.1 are reported. If not, the following applies**:**

If A_{U-238} as calculated in B.1 is < 1 then: $A_{U-234} = A_{U-234} + A_{U-235}$

If $A_{U-238} > 1$ then: $A_{U-234} = A_{U-234} + A_{U-235} – A_{U-238} / 21.7$ and $A_{U-235} = A_{U-238} / 21.7$

B.4 Data reduction for thorium isotopes

Equations B5 to B7 are used to calculate the activity concentration, counting uncertainty and MDA for the Th isotopes. The decay factor C is defined in equations B19 to B22.

For estimation of the ^{227}Th activity concentration the contribution of ^{228}Th in the ROI has to be subtracted:

$$A_s = \left(\frac{(I-Bl)-I_2}{\varepsilon.T.V.R.C}\right) * 1000 \quad \text{.....Equation B16}$$

where

$$I_2 = I_{(228)} * \frac{C_5}{C_3} \quad \text{.....Equation B17}$$

For ^{230}Th the total propagated uncertainty (mBq.L^{-1}) is reported and calculated as:

$$TPU = A * \sqrt{(\frac{S}{A})^2 * {F_p}^2} \quad \text{.....Equation B18}$$

where F_p is the uncertainty associated with the procedure (=1 at concentrations lower than 10 mBq.L^{-1}and =0.15 at higher concentrations)

Decay factors, C

A correction factor can be calculated from the relative contribution of the nuclide to the peak area in a specific region of interest.

^{232}Th ROI (3.71 – 4.02 MeV)

$$C_1 = \left(0.23 * e^{-\lambda_1 t}\right) + \left(0.77 * e^{-\lambda_1 t}\right) \quad \textit{Equation B19}$$

where 0.23 and 0.77 is the percentage distribution of ^{232}Th at α-energies of 3.96 and 4.02 MeV respectively and λ_1 is the decay constant of ^{232}Th with half-life 1.41×10^{10} a.

^{230}Th ROI (4.37 – 4.69 MeV)

$$C_2 = \left(0.23 * e^{-\lambda_1 t}\right) + \left(0.76 * e^{-\lambda_1 t}\right) \quad \textit{Equation B20}$$

where 0.23 and 0.76 is the percentage distribution of ^{230}Th at α-energies of 4.62 and 4.69 MeV respectively and λ_1 is the decay constant of ^{230}Th with half-life 7.5×10^5 a.

^{228}Th ROI (5.09 – 5.45 MeV)

Counts in this area are due to ^{228}Th as well as 6 % of the ingrowth activity of ^{224}Ra

$$C_3 = \left(0.27 * e^{-\lambda_1 t}\right) + \left(0.73 * e^{-\lambda_1 t}\right) + \left[0.06 * \lambda_2 * \left(\frac{e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1 - \lambda_2)}\right) \quad \textit{Equation B21}$$

where 0.27 and 0.73 is the percentage distribution of ^{228}Th at α-energies of 5.34 and 5.42 MeV respectively and λ_1, λ_2 are the decay constant of ^{228}Th (1.91 a) and ^{224}Ra (3.66 d).

^{227}Th ROI (5.46 – 6.09 MeV)

Counts in this area are due to ^{227}Th (3%, 39%, 3% and 55% at 5.67, 5.76, 5.86 and 6.03 MeV respectively) as well as ingrowth activity of ^{223}Ra (35% and 63% at 5.61 and 5.75 MeV respectively, parent ^{227}Th), ^{224}Ra (94% at 5.69 MeV, parent ^{228}Th) and ^{212}Bi (70 % and 27% at 6.05 and 6.09 MeV respectively, parent ^{228}Th).

Contribution: ^{227}Th nuclides

$$C_4 = \left[0.98 * \lambda_8 * \left(\frac{e^{-\lambda_7 t}}{(\lambda_8 - \lambda_7)} + \frac{e^{-\lambda_8 t}}{(\lambda_7 - \lambda_8)}\right)\right] + \left(1 * e^{-\lambda_7 t}\right) \quad \textit{Equation B22}$$

Contribution: ^{228}Th nuclides

$$C_5 = \left[0.94 * \lambda_2 * \left(\frac{e^{-\lambda_1 t}}{(\lambda_2 - \lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1 - \lambda_2)}\right)\right] + (0.36 * 0.97 * \lambda_2\lambda_3\lambda_4\lambda_5\lambda_6 * \left(\frac{e^{-\lambda_1 t}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)(\lambda_5-\lambda_1)(\lambda_6-\lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)(\lambda_5-\lambda_2)(\lambda_6-\lambda_2)} + \frac{e^{-\lambda_3 t}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)(\lambda_5-\lambda_3)(\lambda_6-\lambda_3)} + \frac{e^{-\lambda_4 t}}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)(\lambda_5-\lambda_4)(\lambda_6-\lambda_4)} +\right.$$

$$\frac{e^{-\lambda_5 t}}{(\lambda_1-\lambda_5)(\lambda_2-\lambda_5)(\lambda_3-\lambda_5)(\lambda_4-\lambda_5)(\lambda_6-\lambda_5)} + \frac{e^{-\lambda_6 t}}{(\lambda_1-\lambda_6)(\lambda_2-\lambda_6)(\lambda_3-\lambda_6)(\lambda_4-\lambda_6)(\lambda_5-\lambda_6)}\Bigg) \text{ ....} \textit{Equation B23}$$

where λ_1-λ_6 are decay constants for Th-228 and daughters with half-lifes ^{228}Th (1.91 a), ^{224}Ra (3.66 d), ^{220}Rn (55.6 s), ^{216}Po (0.15 s), ^{212}Pb (10.6 h) and ^{212}Bi (60.6 m); and λ_7, λ_8 are decay constants for ^{227}Th (18.7 d) and ^{223}Ra (11.4 d).

B.5 Data reduction for radium isotopes

Equations B5 to B7 are used to calculate the activity concentration, counting uncertainty and MDA for the Ra isotopes using the ROI indicated and decay factors as defined in equations B26 to B28. Activities for ^{224}Ra and ^{223}Ra are only estimated.

^{226}Ra: ROI 1, C=1

^{224}Ra: Use data for ^{212}Po – ROI 5, C_6 (equation B26)

^{223}Ra: Use data for ^{215}Po – ROI 4, C_7 (equation B27), corrected for ingrowth of ^{214}Po from ^{226}Ra – ROI 4, C_8 (equation B28)

For estimation of the ^{223}Ra activity concentration the contribution of ^{226}Ra in the ROI has to be subtracted:

$$A = \left(\frac{(I-Bl)-I_2}{\varepsilon.\text{T.V.R.}C_7}\right) * 1000 \text{ ....} \textit{Equation B24}$$

where

$$I_2 = I_{(226)} * C_8 \text{ ....} \textit{Equation B25}$$

Decay factors, C

A correction factor or ingrowth factor can be calculated from the relative contribution of the nuclide to the peak area in a specific region of interest.

^{212}Po in ROI 5 (7.80 – 8.80 MeV)

Counts in this area are used for calculation of ^{224}Ra activity and come from the ingrowth of series:

Ra-224→Rn-220→Po-216→Pb-212→Bi-212→Po-212

$$C_6 = 0.64 * \lambda_2\lambda_3\lambda_4\lambda_5\lambda_6 * \Bigg(\frac{e^{-\lambda_1 t}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)(\lambda_5-\lambda_1)(\lambda_6-\lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)(\lambda_5-\lambda_2)(\lambda_6-\lambda_2)} + \frac{e^{-\lambda_3 t}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)(\lambda_5-\lambda_3)(\lambda_6-\lambda_3)} + \frac{e^{-\lambda_4 t}}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)(\lambda_5-\lambda_4)(\lambda_6-\lambda_4)} + \frac{e^{-\lambda_5 t}}{(\lambda_1-\lambda_5)(\lambda_2-\lambda_5)(\lambda_3-\lambda_5)(\lambda_4-\lambda_5)(\lambda_6-\lambda_5)} + \frac{e^{-\lambda_6 t}}{(\lambda_1-\lambda_6)(\lambda_2-\lambda_6)(\lambda_3-\lambda_6)(\lambda_4-\lambda_6)(\lambda_5-\lambda_6)}\Bigg) \text{ ....} \textit{Equation B26}$$

where λ_1-λ_6 are decay constants for Ra-224 and daughters with half-life ^{224}Ra (3.66 d), ^{220}Rn (55.6 s), ^{216}Po (0.15 s), ^{212}Pb (10.6 h), ^{212}Bi (60.6 m) and ^{212}Po (45.1 s).

^{215}Po in ROI 4 (7.80 – 8.80 MeV)

Counts in this area are used for calculation of ^{223}Ra activity and come from the ingrowth of series:

Ra-223→Rn-219→Po-215

$$C_7 = \lambda_2\lambda_3 * \left(\frac{e^{-\lambda_1 t}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} + \frac{e^{-\lambda_3 t}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)}\right) \text{……………….} \textit{Equation B27}$$

where λ_1-λ_3 are decay constants for Ra-223 and daughters with half-life ^{223}Ra (11.43 d), ^{219}Rn (3.96 s) and ^{215}Po (1.62 ms).

^{214}Po in ROI 4 (7.80 – 8.80 MeV)

Counts in this area are used for correction of ^{223}Ra activity and come from the ingrowth of series:

Ra-226→Rn-222→Po-218→Pb-214→Bi-214→Po-214

$$C_8 = \lambda_2\lambda_3\lambda_4\lambda_5\lambda_6 * \left(\frac{e^{-\lambda_1 t}}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)(\lambda_5-\lambda_1)(\lambda_6-\lambda_1)} + \frac{e^{-\lambda_2 t}}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)(\lambda_5-\lambda_2)(\lambda_6-\lambda_2)} + \frac{e^{-\lambda_3 t}}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)(\lambda_5-\lambda_3)(\lambda_6-\lambda_3)} + \frac{e^{-\lambda_4 t}}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)(\lambda_5-\lambda_4)(\lambda_6-\lambda_4)} + \frac{e^{-\lambda_5 t}}{(\lambda_1-\lambda_5)(\lambda_2-\lambda_5)(\lambda_3-\lambda_5)(\lambda_4-\lambda_5)(\lambda_6-\lambda_5)} + \frac{e^{-\lambda_6 t}}{(\lambda_1-\lambda_6)(\lambda_2-\lambda_6)(\lambda_3-\lambda_6)(\lambda_4-\lambda_6)(\lambda_5-\lambda_6)}\right) \text{…….} \textit{Equation B28}$$

where λ_1-λ_6 are decay constants for Ra-226 and daughters with half-life ^{226}Ra (1600 a), ^{222}Rn (3.82 d), ^{218}Po (3.11 m), ^{214}Pb (26.8 m), ^{214}Bi (19.9 m) and ^{214}Po (0.164 s).

APPENDIX C

ANALYTICAL DATA

Appendix C contains the raw data of the radioactivity measurements.

Table C-1: Activity concentration of radionuclides in food in $Bq.kg^{-1}$ wet weight and Committed Effective Dose for the adult age group ($mSv.a^{-1}$).

Table C-2: Results for samples from the building industry - Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (I_γ)

Table C-3: Results for sediment samples: Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (H_{ex}), External gamma dose rate, D ($nGy.h^{-1}$) and Annual effective dose, AED ($mSv.a^{-1}$)

Table C-4: Results for soil samples: Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (H_{ex}), External gamma dose rate, D ($nGy.h^{-1}$) and Annual effective dose, AED ($mSv.a^{-1}$)

Table C-5: Results for tailings and waste rock from gold mine area - Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (H_{ex}), Absorbed dose, D ($nGy.h^{-1}$) and Annual effective dose rate, AED ($mSv.a^{-1}$)

Table C-6: Results for samples from the coal industry: Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (I_γ), External gamma dose rate, D ($nGy.h^{-1}$) and Annual effective dose, AED ($mSv.a^{-1}$)

Table C-7: Results for solids from the phosphate industry - Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (H_{ex}), Absorbed dose, D ($nGy.h^{-1}$) and Annual effective dose rate, AED ($mSv.a^{-1}$)

Table C-8: Results for solids from mineral sands industry - Activity concentration in $Bq.kg^{-1}$and Annual effective dose, AED ($mSv.a^{-1}$)

Table C-9: Results for water samples in area impacted by phosphate industry (Activity concentrations $mBq.L^{-1}$; Dose $\mu Sv.a^{-1}$)

Table C-10: Results for water samples from baseline area, monazite area and area impacted by gold mining (Activity concentrations $mBq.L^{-1}$; Dose $\mu Sv.a^{-1}$)

Table C-11: Nuclide specific analysis of water from Catchment C (Activity concentrations $mBq.L^{-1}$; Dose $\mu Sv.a^{-1}$)

Table C-1: Activity concentration of radionuclides in food in Bq.kg^{-1} wet weight and Committed Effective Dose for the adult age group (mSv.a^{-1}).

**Analysed by high energy gamma spectrometry on ashed samples; **Older data*

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
1: GOLD MINING INDUSTRY										
G1	Fish	0.660 ± 0.130	**1.40** ± 0.10	0.240 ± 0.090	0.240 ± 0.090	< 0.044	< 0.38	0.0250 ± 0.0040	0.028	
G2	Fish	0.350 ± 0.100	0.820 ± 0.130	< 0.046	< 0.046	< 0.022	< 0.024	< 0.025	0.012	
G3	Fish	**3.02** ± 0.12	**4.38** ± 0.21	< 0.22	0.826 ± 0.180	< 0.28	< 1.4	< 0.42	0.12	
G4	Fish	0.258 ± 0.065	< **2.3**	< 1.2	0.241 ± 0.077	< 0.79	< 0.80	0.637 ± 0.098	0.04	
G5	Fish	0.13 ± 0.059	< **1.9**	< 1.1	0.991 ± 0.61	< 0.68	< 0.72	0.341 ± 0.056	0.042	
G6	Fish	**1.07** ± 0.03	**1.59** ± 0.41	< 0.76	0.206 ± 0.062	< 0.17	< 0.32	0.139 ± 0.027	0.036	16
G7	Fish	< 1.2	< 0.14	-	0.431 ± 0.113	< 0.15	< 0.15	< 0.15	0.023	**55**
G8	Fish	< 3.5	0.35 ± 0.12	0.588 ± 0.153	0.762 ± 0.126	< 0.49	0.75 ± 0.31	< 0.50	0.066	**35**
G9	Fish	**1.1** ± 0.55	< 0.84	-	0.775 ± 0.121	< 0.47	< 1.5	< 0.93	0.082	**28**
G10	Fish**	**4.74** ± 0.05	< **9.8**	< 1.7	< 1.1	< 0.65	< 15	< 10	**0.48**	
G11	Fish	< 0.15	< **2.8**	< 0.48	< 0.42	< 1.6	< 4.9	< 6.1	0.16	
G12	intestines**	**38.5** ± 1.7	< **5.7**	< 4.1	**19.0** ± 0.2	< **2.2**	< 9.5	< 6.2	**0.96**	
G13	bones**	**12.1** ± 5.4	< **6.1**	< 4.8	**4.00** ± 0.04	< **2.0**	< 8.4	< 4.9	**0.54**	
G14	Chicken*	< **21**	**2.73** ± 0.55	**1.33** ± 0.46	**1.63** ± 0.31	< **2.5**	< **3.5**	< **1.9**	**0.72**	**20**
G15	Chicken	0.0385 ± 0.0085	0.327 ± 0.056	< 0.69	**3.84** ± 1.07	< 0.34	< 0.25	< 0.13	**0.51**	**91**
G16	Meat*	< 3.3	< 0.58	< **17**	0.13 ± 0.047	< 0.45	0.82 ± 0.39	< 0.64	**0.75**	11
G17	Meat*	< 2.8	< 0.92	-	0.250 ± 0.076	< 0.47	< 1.7	< 1.0	0.24	12
G18	Meat*	< 2.8	< 0.94	-	0.17 ± 0.076	< 0.45	-	< 1.0	0.16	13
G19	Meat*	< 3.4	< 0.61	-	0.17 ± 0.058	< 0.41	< 1.2	< 0.69	0.20	11
G20	Meat*	< 3.7	< 0.79	-	0.573 ± 0.110	< 0.35	< 1.4	< 0.89	**0.26**	**27**
G21	Meat*	< 2.7	< 0.53	0.11 ± 0.080	0.12 ± 0.040	< 0.14	< 0.93	< 0.59	0.11	12
G22	Meat	0.0215 ± 0.0059	< 0.14	< 0.66	0.90 ± 0.42	0.086 ± 0.034	< 0.28	0.097 ± 0.012	0.062	39
G23	Meat	0.0284 ± 0.0061	< 0.16	< 0.70	**1.06** ± 0.35	< 0.23	< 0.30	0.076 ± 0.011	0.078	49
G24	Meat	0.0452 ± 0.0087	< 0.28	< 1.1	**3.87** ± 0.53	< 0.22	< 0.61	< 0.17	**0.53**	87
G25	Pork	0.0144 ± 0.0029	0.324 ± 0.059	< 0.76	**2.71** ± 0.50	< 0.11	< 0.42	< 0.13	**0.38**	86
G26	Liver	< 4.3	< 0.74	-	**13.1** ± 0.7	< 0.41	< 1.3	< 1.1	**2.7**	**59**
G27	Liver*	< 3.0	< 0.5	-	**6.93** ± 0.52	< 0.47	-	< 0.89	**1.7**	**71**
G28	Liver&Kidney	0.20 ± 0.11	< 2.7	1.2 ± 0.48	**3.87** ± 0.49	< 0.30	< 0.95	0.341 ± 0.040	**0.60**	

	Category	Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
Leafy Vegetables										
G29	Spinach*	< **30**	**1.0** ± 0.30	0.762 ± 0.155	0.648 ± 0.103	**3.93** ± 0.64	< 1.3	0.82 ± 0.25	**0.57**	8
G30	Spinach	0.289 ± 0.027	< 0.84	1.41 ± 0.23	-	0.40 ± 0.15	< 0.35	0.153 ± 0.014	0.17	
G31	Spinach	0.276 ± 0.019	0.916 ± 0.186	0.430 ± 0.150	0.155 ± 0.148	< 4.2	0.341 ± 0.066	0.0800 ± 0.0230	0.25	11
G32	Spinach	0.059 ± 0.008	0.393 ± 0.063	**1.84** ± 0.35	**1.12** ± 0.19	0.366 ± 0.019	0.438 ± 0.079	0.203 ± 0.023	0.17	**42**
G33	Spinach	0.051 ± 0.006	< 0.52	< 0.41	0.135 ± 0.035	0.19 ± 0.041	< 0.20	0.077 ± 0.009	0.046	19
G34	Spinach	0.063 ± 0.006	0.662 ± 0.054	0.926 ± 0.25	0.233 ± 0.068	0.069 ± 0.013	**0.847** ± 0.066	0.11 ± 0.023	**0.39**	11
G35	Cabbage*	< 12	0.30 ± 0.16	0.039 ± 0.023	0.054 ± 0.020	**2.67** ± 0.49	< 0.59	**1.3** ± 0.50	0.21	2
G36	Cabbage	0.242 ± 0.026	< 0.60	< 0.35	-	0.08 ± 0.038	< 0.24	< 0.062	0.034	
G37	Cabbage	0.0565 ± 0.0161	< 0.99	0.39 ± 0.22	-	0.21 ± 0.066	< 0.41	0.0969 ± 0.0140	0.018	
G38	Cabbage	0.0217 ± 0.0036	< 0.28	< 0.19	0.140 ± 0.043	< 0.014	< 0.11	0.017 ± 0.0035		
G39	Cabbage	0.0043 ± 0.0023	< 0.49	< 0.53	0.094 ± 0.042	0.335 ± 0.014	< 0.32	< 0.11	0.034	18
G40	Lettuce	0.0791 ± 0.0178	< 0.36	< 0.24	-	0.14 ± 0.039	< 0.38	0.0279 ± 0.0049	0.025	
G41	Lettuce	0.0513 ± 0.0158	< 0.31	< 0.20	-	0.06 ± 0.025	< 0.13	0.0247 ± 0.0041	0.017	
Root Vegetables										
G42	Turnip	0.32 ± 0.12	< 0.16	< 0.14	< 0.140	0.01 ± 0.002	< 0.088	0.0211 ± 0.0050	0.055	27
G43	Turnip	0.0848 ± 0.0179	< 0.66	< 0.42	-	< 0.23	< 0.23	< 0.069	0.11	
G44	Turnip	0.0765 ± 0.0174	< 0.70	< 0.43	-	< 0.22	< 0.22	< 0.0700	0.11	
G45	Beetroot*	< **21**	0.46 ± 0.19	0.147 ± 0.053	0.281 ± 0.053	**3.0** ± 0.90	< 0.72	< 0.44	**0.73**	8
G46	Beetroot	0.714 ± 0.191	< 0.21	0.255 ± 0.065	0.255 ± 0.065	0.07 ± 0.0039	0.17 ± 0.021	0.122 ± 0.006	0.16	32
G47	Beetroot	0.239 ± 0.026	< 0.99	< 0.58	-	< 0.310	< 0.40	0.0772 ± 0.0129	0.16	
G49	Beetroot	0.255 ± 0.024	0.506 ± 0.114	0.525 ± 0.107	2.11 ± 0.24	0.20 ± 0.010	0.48 ± 0.040	0.289 ± 0.014		
G50	Beetroot	0.197 ± 0.01	0.984 ± 0.085	0.685 ± 0.187	0.777 ± 0.192	0.117 ± 0.011	**1.05** ± 0.09	0.19 ± 0.018	**1.0**	10
G51	Spring Onions	0.340 ± 0.120	0.780 ± 0.015	0.610 ± 0.130	0.600 ± 0.130	0.07 ± 0.0030	0.27 ± 0.070	0.370 ± 0.020	0.097	41
G52	Carrots	0.0588 ± 0.0158	< 0.59	< 0.37	-	0.19 ± 0.053	< 0.23	0.215 ± 0.014	0.10	
G53	Carrots	0.0820 ± 0.0083	< 0.29	0.18 ± 0.071	0.230 ± 0.060	0.05 ± 0.0035	0.19 ± 0.030	0.0937 ± 0.0054		
G54	Tomato	0.0078 ± 0.0023	< 0.037	< 0.16	0.038 ± 0.017	0.039 ± 0.004	< 0.076	< 0.021	0.008	**31**
G55	Lemon	< 0.61	**2.94** ± 0.63	-	0.136 ± 0.038	0.13 ± 0.050	**3.83** ± 0.83	< 2.8	**0.35**	3
G56	Peaches	0.0398 ± 0.0030	< 0.62	< 0.037	0.533 ± 0.17	0.308 ± 0.010	< 0.21	< 0.068	0.076	**63**
G57	Peaches	0.0323 ± 0.0031	0.055 ± 0.021	0.19 ± 0.098	0.063 ± 0.045	0.018 ± 0.002	0.045 ± 0.022	0.025 ± 0.0051	0.037	**19**
G58	Maize*	< **35**	< 2.8	-	0.28 ± 0.14	< **6.0**	< **5.0**	**7.6** ± 3.9	**1.6**	12
G59	Cereal	0.013 ± 0.0025	< 0.14	< 0.39	**1.1** ± 0.37	0.101 ± 0.009	< 0.24	< 0.07	0.24	**83**
G60	Cereal	0.0156 ± 0.0023	< 0.38	**1.17** ± 0.18	**1.9** ± 0.47	0.057 ± 0.009	< 0.12	< 0.037	**0.89**	**63**

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
G61	Cereal	0.014 ± 0.0091	< 2.50	< 2.1	0.47 ± 0.41	0.319 ± 0.043	< 0.83	< 0.25	**1.4**	**27**
G62	Cereal	0.0085 ± 0.0017	< 0.33	**3.57** ± 0.45	**1.1** ± 0.37	0.038 ± 0.009	< 0.11	< 0.03	**1.1**	**35**
G63	Cereal	0.0956 ± 0.0185	< 2.90	< 2.3	**2.6** ± 0.74	0.25 ± 0.045	< 0.97	0.245 ± 0.038	**1.8**	**23**
G64	Cereal	0.0041 ± 0.002	< 0.44	**1.59** ± 0.023	0.54 ± 0.29	0.042 ± 0.01	< 0.14	< 0.043	**1.2**	**67**
G66	Asparagus	0.0370 ± 0.0140	0.250 ± 0.100	0.210 ± 0.080	0.213 ± 0.084	< 0.0070	0.03 ± 0.008	0.0100 ± 0.0080	0.028	**50**
G67	Oats	< 0.27	0.390 ± 0.280	**1.40** ± 0.30	**1.39** ± 0.34	< 0.034	< 0.012	0.0120 ± 0.0290	0.42	**60**
G68	Rye*	< 8.5	**11** ± 5.0	**9.82** ± 1.30	**9.55** ± 0.93	0.39 ± 0.090	< **16**	**27.3** ± 9.0	**4.9**	**34**
G69	Barley leaves*	< 2.6	< 1.9	-	0.375 ± 0.110	0.38 ± 0.053	< 3.5	6.9 ± 2.3	0.21	12
G70	Luzern	1.90 ± 1.21	**3.80** ± 0.44	-	0.498 ± 0.083	0.22 ± 0.033	**3.99** ± 0.68	< 1.9	**0.94**	9
G71	Milk	0.0143 ± 0.0016	< 0.086	< 0.032	0.073 ± 0.0368	< 0.095	< 0.052	< 0.19	0.068	
G72	Milk	0.0029 ± 0.0009	0.068 ± 0.025	< 0.24	0.036 ± 0.009	0.028 ± 0.009	< 0.15	< 0.044	0.070	**21**
G73	Milk	0.0055 ± 0.0011	< 0.033	< 0.23	0.009 ± 0.002	0.126 ± 0.012	< 0.12	< 0.035	0.086	4
G74	Milk	0.0011 ± 0.0003	0.014 ± 0.004	< 0.064	0.066 ± 0.025	0.010 ± 0.002	< 0.024	< 0.03	0.023	**41**
G75	Milk	0.0014 ± 0.0003	0.028 ± 0.005	< 0.07	0.072 ± 0.014	0.011 ± 0.002	< 0.051	< 0.05	0.025	**41**
G76	Milk	0.0075 ± 0.0017	< 0.19	< 0.13	0.050 ± 0.0250	0.12 ± 0.010	0.02 ± 0.0028	< 0.078	0.062	**35**
G77	Milk	0.0103 ± 0.0019	< 0.14	< 0.10	0.083 ± 0.0418	0.10 ± 0.011	0.01 ± 0.0017	< 0.062	0.071	**49**
G78	Milk	0.0108 ± 0.0018	< 0.18	< 0.13	0.067 ± 0.0340	0.10 ± 0.010	< 0.019	< 0.075	0.12	**23**
G79	Milk	0.0102 ± 0.0013	< 0.53	< 0.33		0.17 ± 0.013	< 0.17	< 0.057	0.17	
G80	Milk	0.0058 ± 0.0010	< 0.55	< 0.33		0.13 ± 0.012	< 0.18	< 0.058	0.17	

2: PHOSPHATE INDUSTRY

Older data

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
P1	Fish**	0.550 ± 0.069	< 1.9	< **42**	**1.90** ± 0.02	< 1.4	< 3.1	< 2.2	**1.3**	5
P2	Fish**	8.83 ± 0.28	24.3 ± 1.0	< **39**	**8.20** ± 0.08	1.62 ± 0.13	29.6 ± 1.0	10.7 ± 0.7	**1.2**	**21**
P3	Fish**	7.94 ± 0.20	21.3 ± 0.8	< **53**	**19.0** ± 0.2	3.76 ± 0.17	23.2 ± 1.2	11.3 ± 1.5	**1.6**	**36**
P4	Fish**	9.61 ± 0.23	23.1 ± 0.8	< **54**	**23.2** ± 0.2	5.56 ± 0.20	27.5 ± 1.3	12.5 ± 0.3	**1.8**	**43**
P5	Fish**	1.74 ± 0.11	< 2.1	< **36**	**4.20** ± 0.04	< 1.5	7.66 ± 0.86	< 1.3	**1.1**	12
P6	Fish**	8.68 ± 0.23	35.2 ± 1.0	< **45**	**12.8** ± 0.1	3.05 ± 0.16	38.6 ± 1.6	12.9 ± 0.9	**1.4**	**28**
P7	Fish**	0.357 ± 0.059	< 1.8	< **34**	**4.00** ± 0.04	< 1.5	4.50 ± 0.85	< 2.1	**1.0**	12

Newer data

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
P8	Fish*	0.175 ± 0.042	< 4.3	< 1.9	0.284 ± 0.072	0.40 ± 0.076	< 1.5	0.485 ± 0.063	0.071	12
P9	Fish*	0.198 ± 0.042	< 4.5	< 2.0	0.470 ± 0.027	0.12 ± 0.038	< 1.7	0.520 ± 0.067	0.062	**23**

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
P10	Fish*	0.587 ± 0.122	< 3.2	< 1.5	**4.49** ± 0.45	0.36 ± 0.054	< 1.1	0.549 ± 0.072	0.18	**76**
P11	Fish	0.036 ± 0.0063	< 0.56	< 0.32	0.704 ± 0.128	0.05 ± 0.0110	< 0.16	0.349 ± 0.016	0.045	**47**
P12	Fish	0.053 ± 0.012	< 0.15	0.680 ± 0.410	0.277 ± 0.093	0.12 ± 0.020	< 0.54	0.486 ± 0.031	0.055	15
P13	Fish	0.026 ± 0.012	< 0.21	< 0.87	0.8 ± 0.193	0.17 ± 0.026	< 0.47	< 0.31	0.038	**63**
P14	Fish	0.021 ± 0.0094	< 0.13	< 0.89	1.11 ± 0.32	< 0.15	0.248 ± 0.64	< 0.08	0.085	**39**
P15	Fish	0.013 ± 0.0098	0.16 ± 0.061	< 1.2	1.48 ± 0.36	< 0.15	< 0.34	< 0.11	0.085	**52**
Discharge point										
P16	Fish*	0.157 ± 0.066	< 6.1		**6.40** ± 0.70	< 0.66	< 10	< 5.4	**0.31**	**64**
P17	Fish	0.133 ± 0.063	< 4.9	**2.83** ± 1.67	2.52 ± 0.25	< 0.48	**2.55** ± 1.41	< 5.2	0.13	**58**
P18	Fish*	-	-	-	**6.60** ± 0.62	-	-	-	**0.34**	**58**
P19	Fish	< 1.9	< 0.32	-	2.21 ± 0.17	< 0.29	-	< 0.36	0.13	**52**
P20	Fish	0.037 ± 0.0079	< 2.0	< 1.2	3.59 ± 0.42	< 0.28	0.24 ± 0.13	0.14 ± 0.027	0.13	**83**
P21	Crayfish/Crab*	0.066 ± 0.0103	< 0.67	**3.42** ± 0.22	**10.8** ± 0.8	0.12 ± 0.039	< 0.74	< 1.7	**0.46**	**71**
P22	Crayfish/Crab*	0.112 ± 0.075	0.702 ± 0.319	**3.16** ± 2.92	**8.08** ± 0.40	< 0.86	**1.21** ± 0.53	**1.78** ± 0.30	**0.33**	**74**
Background										
P23	Fish*	0.0735 ± 0.0636	0.718 ± 0.272	-	2.24 ± 0.19	< 0.70	**1.99** ± 0.38	**1.32** ± 0.30	0.091	**74**
P24	Fish*	0.0978 ± 0.0607	< 5.0	1.10 ± 0.31	1.15 ± 0.31	< 0.44	**4.49** ± 1.41	**3.15** ± 1.38	0.12	**28**
P25	Fish	-	-	-	3.17 ± 0.42	-	-	-	0.21	**46**
P26	Fish*	-	-	-	1.65 ± 0.25	-	-	-	0.14	**36**
P27	Fish	-	-	-	0.627 ± 0.102	-	-	-	0.032	**63**
P28	Fish	-	-	-	1.18 ± 0.18	-	-	-	0.038	**94**
P29	Fish	-	-	-	0.698 ± 0.151	-	-	-	0.038	**55**
P30	Fish	0.035 ± 0.0077	< 2.1	< 1.2	2.94 ± 0.48	< 0.28	< 0.72	< 0.22	0.11	**78**
P31	Fish	0.054 ± 0.0086	< 0.3	< 1.3	0.973 ± 0.183	< 0.31	< 0.51	< 1.1	0.089	**33**
P32	Chicken	0.0780 ± 0.0118	< 0.45	**1.14** ± 0.15	0.177 ± 0.067	< 0.23	0.02 ± 0.0110	0.0077 ± 0.0019	0.10	15
P33	Chicken	0.0843 ± 0.0138	0.330 ± 0.150	< 0.34	0.310 ± 0.160	< 0.34	0.16 ± 0.040	0.0480 ± 0.0063	0.10	**27**
P34	Chicken	0.0859 ± 0.0257	< 0.29	**1.2** ± 0.36	0.697 ± 0.248	< 0.35	< 0.6	< 0.38	0.15	**45**
P35	Meat	0.028 ± 0.0034	< 0.62	< 0.42	**2.33** ± 0.6	0.204 ± 0.017	< 0.25	< 0.07	**0.32**	**88**
P36	Meat	0.011 ± 0.0042	< 1.2	< 0.81	0.356 ± 0.161	0.483 ± 0.032	< 0.45	< 0.13	0.12	**45**
P37	Green beans	0.0287 ± 0.0035	< 0.41	0.721 ± 0.129	0.260 ± 0.066	< 0.045	**2.25** ± 0.09	**0.849** ± 0.037	0.048	**36**
P38	PawPaw	0.0084 ± 0.0014	< 0.17	< 0.11	0.027 ± 0.0120	< 0.017	0.08 ± 0.0136	0.0350 ± 0.003	0.015	12
P39	Tomatoes	0.0072 ± 0.0009	< 0.14	< 0.10	0.025 ± 0.0097	0.06 ± 0.0012	**1.30** ± 0.07	**0.162** ± 0.011	0.008	21
P40	Lemons	0.0089 ± 0.0009	< 0.15	0.112 ± 0.035	0.057 ± 0.0240	< 0.013	**2.02** ± 0.08	**1.58** ± 0.07	0.018	21

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
P41	Maize	0.0084 ± 0.0024	< 0.39	0.250 ± 0.095	0.360 ± 0.150	< 0.054	< 0.062	< 0.018	0.092	**70**

3. BASELINE STUDY

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
B1	Calamary	< 0.73	< 0.53	0.695 ± 0.160	**32.2** ± 2.1	-	< 0.54	0.047 ± 0.01	**0.99**	**98**
B2	Mussel	-	< 0.32	2.79 ± 0.37	**59.3** ± 2.4	-	< 0.57	0.355 ± 0.075	**1.8**	**97**
B3	Mussel	-	-	-	**28.7** ± 1.8	-	-	-	**0.86**	
B4	Mussel	-	-	-	**12.0** ± 1.0	-	-	-	**0.36**	
B5	Milk	-	-	-	0.035 ± 0.0110	-	-	-	0.015	
B6	Milk				0.013 ± 0.0037	< 0.38			0.025	**21**
B7	Milk	0.0087 ± 0.0013	< 0.004	-	0.013 ± 0004	< 0.38	< 0.48	< 0.18		
B8	Mutton	0.0466 ± 0.0095	0.588 ± 0.087	< 1.1	1.26 ± 0.45	< 0.12	< 0.48	< 0.18		
B9	Mutton	0.0073 ± 0.0051	0.211 ± 0.033	< 0.5	1.3 ± 0.49	< 0.08	< 0.23	< 0.07		
B10	Mutton	0.0081 ± 0.0052	0.167 ± 0.029	< 0.44	1.21 ± 0.55	< 0.07	< 0.19	< 0.06		
B11	Mutton	0.015 ± 0.0051	0.128 ± 0.042	< 0.55	1.34 ± 0.45	< 0.09	< 0.22	0.017 ± 0.066		
B12	Mutton rib	0.016 ± 0.011	0.505 ± 0.079	0.96 ± 0.51	0.4 ± 0.29	< 0.2	1.31 ± 0.17	0.416 ± 0.047		
B13	Liver	0.0284 ± 0.0053	0.095 ± 0.042	0.51 ± 0.19	1.84 ± 0.62	< 0.07	< 0.18	0.058 ± 0.018		
B14	Liver	0.19 ± 0.011	0.45 ± 0.14	< 2.2	1.82 ± 0.7	< 0.08	< 0.7	< 0.28		
B15	Liver	0.0265 ± 0.0043	0.995 ± 0.245	< 4	0.727 ± 0.365	< 0.07	< 1.3	< 0.49		
B16	Springbok	0.012 ± 0.0068	0.209 ± 0.048	< 0.79	2.1 ± 0.59	< 0.11	0.22 ± 0.07	< 0.11		

4: MINERAL SANDS INDUSTRY

Category		Uranium-238	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Dose	%Po
M1	Meat	0.0463 ± 0.0032	< 1.5	< 0.97	0.307 ± 0.104	< 0.051	< 0.52	< 0.17	0.11	**33**
M2	Meat	0.016 ± 0.0032	< 0.98	< 0.64	0.564 ± 0.255	< 0.072	< 0.39	0.3 ± 0.098	0.12	**56**
M3	Meat	0.0152 ± 0.0026	< 0.92	0.59 ± 0.2	0.481 ± 0.126	< 0.051	< 0.33	< 0.1	0.11	**52**
M4	Grapes	0.059 ± 0.012	0.44 ± 0.16	< 0.3	0.36 ± 0.129	0.21 ± 0.008	< 0.19	0.0825 ± 0.0072	0.062	**40**
M5	Grapes	< 0.25	< 0.6	< 0.21	0.07 ± 0.074	0.015 ± 0.003	< 1.2	< 0.38	0.053	**6**
M6	Grapes	< 0.029	< 0.5	< 0.17	0.063 ± 0.024	0.011 ± 0.004	< 1.1	< 0.32	0.048	**11**
M7	Grapes	0.0109 ± 0.0025	0.151 ± 0.014	< 0.33	0.317 ± 0.113	0.072 ± 0.005	0.107 ± 0.03	0.0319 ± 0.0062	0.097	**29**
M8	Oats	**1.27** ± 0.07	**2.14** ± 0.37	**5** ± 0.5	**5.36** ± 0.65	**1.39** ± 0.04	**1.72** ± 0.13	**1.44** ± 0.06	**1.9**	**51**

Table C-2: Results for samples from the building industry - Activity concentration in Bq.kg^{-1}, Radium equivalent dose, Ra_{eq} in Bq.kg^{-1}, Gamma Index (I_γ)

Uranium-238	Thorium-230	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_m
Bricks										
141 ± 5	-	157 ± 14	106 ± 24	-	75.9 ± 1.2	92.4 ± 10	86.0 ± 6.6	167 ± 33	278	0.96
-	-	72.5 ± 5.7	-	-	-	31.8 ± 6.1	27.3 ± 9.4	236 ± 32	91	0.32
86.2 ± 3.1	-	94.2 ± 5.9	-	-	29.8 ± 1.7	28.0 ± 5.4	36.0 ± 5.0	117 ± 23	146	0.50
79.6 ± 3.3	-	99.8 ± 6.1	-	-	27.7 ± 1.1	29.9 ± 5.9	31.0 ± 4.0	189 ± 26	154	0.53
53.1 ± 2.2	-	57.7 ± 4.7	-	-	21.1 ± 1.1	20.4 ± 4.9	32.1 ± 8.3	136 ± 22	98	0.34
142 ± 5	-	66.1 ± 4.8	-	-	23.0 ± 1.1	25.7 ± 4.7	19.8 ± 3.4	155 ± 22	111	0.39
56.7 ± 2.1	-	65.6 ± 4.4	-	-	19.8 ± 1.2	22.0 ± 4.6	20.9 ± 3.3	125 ± 20	103	0.36
Cement										
10.7 ± 3	27.8 ± 3.7	11.6 ± 4.3	< 140	13.5 ± 2.0	22.1 ± 3.4	24.7 ± 7.1	15.6 ± 2.8	131 ± 33	53	0.19
11.9 ± 2.6	34.7 ± 3.5	13.5 ± 4.8	< 120	15.9 ± 2.0	19.7 ± 2.6	11.2 ± 6.5	26.9 ± 3.1	245 ± 39	60	0.23
18.6 ± 3.4	30.0 ± 3.4	24.4 ± 5.5	< 140	14.3 ± 2.7	21.5 ± 2.9	39.5 ± 8	25.6 ± 3.2	184 ± 37	69	0.25
38.3 ± 4.8	85.4 ± 7.1	53.7 ± 7.5	< 130	47.7 ± 4.2	39.1 ± 4.8	40.6 ± 8.7	48.3 ± 5.3	362 ± 49	137	0.50
< 11	16.6 ± 2.3	10.5 ± 4.3	< 120	59.9 ± 4.4	15.3 ± 2.2	< 29	15.1 ± 2.1	122 ± 29	42	0.15
36.0 ± 4.6	67.4 ± 4.4	56.0 ± 6.9	< 78	15.4 ± 2.3	17.8 ± 2.3	21.7 ± 7.2	19.5 ± 2.3	111 ± 34	90	0.31
10.3 ± 2.8	98.4 ± 7.4	11.1 ± 4.8	< 130	18.7 ± 2.0	15.0 ± 2.9	< 32	34.4 ± 4.3	100 ± 32	40	0.15
17.8 ± 2.5	59.6 ± 5.4	18.4 ± 4.9	< 130	15.2 ± 1.7	31.9 ± 4.0	25.0 ± 8.8	34.7 ± 4.1	97 ± 31	71	0.25
5.03 ± 2.7	34.2 ± 4.3	21.1 ± 5.4	< 130	18.0 ± 3.4	20.1 ± 3.3	16.2 ± 8.0	18.7 ± 3.1	135 ± 36	60	0.22
16.7 ± 3.3	51.7 ± 4.3	18.2 ± 4.9	< 130	25.8 ± 3.5	19.6 ± 2.6	19.2 ± 6.9	21.9 ± 2.7	116 ± 32	55	0.20
19.2 ± 0.9	33.4 ± 3.8	17.0 ± 3.8	< 110	14 ± 2.2	26.7 ± 3.4	12.6 ± 4.5	32.5 ± 3.9	84 ± 22	62	0.22
Ceramic										
779 ± 15	-	710 ± 18	817 ± 57	-	200 ± 3	180 ± 13	166 ± 10	< 130	996	3.37
Concrete										
26.9 ± 1	80.0 ± 6.4	24.9 ± 4.1	< 110	15.2 ± 2.2	69 ± 6	26.3 ± 5.9	47.8 ± 5.2	43 ± 20	127	0.44
59.6 ± 1.6	85.7 ± 5.6	53.7 ± 6.1	67.6 ± 23	81.7 ± 6.5	93 ± 5.8	75.6 ± 9.8	99.2 ± 6.1	42 ± 28	190	0.66

Uranium-238	Thorium-230	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_m
28.5 ± 1.1	42.3 ± 3.7	28.2 ± 4.6	< 110	20.6 ± 4.5	44.4 ± 3.9	51.8 ± 8.1	49.3 ± 4.0	< 120	92	0.32
23.7 ± 1.0	61.1 ± 5.8	29.3 ± 4.1	< 130	29.5 ± 4.1	46.9 ± 5.2	32.8 ± 7.0	60.2 ± 5.8	56 ± 23	101	0.35
53.3 ± 1.0	-	74.1 ± 4.2	181 ± 35	-	23.6 ± 2.0	38.9 ± 5.6	33.7 ± 3.5	189 ± 24	122	0.43
54.4 ± 1.1	-	73.4 ± 4.2	159 ± 36	-	22.8 ± 2.1	28.8 ± 5.1	30.1 ± 3.5	141 ± 21	117	0.41
Gypsum										
10.8 ± 3.0	55.8 ± 4.7	44.6 ± 7.9	< 120	42.7 ± 3.6	9.98 ± 1.96	< 41	13 ± 2.2	< 160	59	0.20
31.9 ± 4.1	91.3 ± 8.6	87.8 ± 10.7	< 180	105 ± 6	14.3 ± 3.4	13.9 ± 8.3	18.1 ± 4.1	< 180	108	0.36
22.8 ± 3.0	110 ± 11	104 ± 9	132 ± 34	113 ± 10	6.03 ± 2.46	< 36	17.7 ± 4.2	< 160	113	0.38
15.1 ± 2.7	24.3 ± 2.9	< 23	< 160	7.1 ± 1.9	35.9 ± 3.5	< 34	27.9 ± 3.1	< 140	51	0.18
17.5 ± 4.1	48.9 ± 4.7	29.9 ± 5.7	< 120	20.6 ± 3.7	25.5 ± 3.4	22.5 ± 6.7	35.8 ± 3.9	75 ± 33	72	0.25
10.1 ± 0.4	-	62.5 ± 14.2	< 140	-	99 ± 6.1	313 ± 32	119 ± 16	< 380	204	0.70
-	-	79.8 ± 7.2	-	-	-	43.1 ± 9.2	34.5 ± 6.4	< 160	79	0.27
-	-	75.0 ± 6.9	-	-	-	182 ± 14	187 ± 11	< 140	75	0.25
9.33 ± 1.03	-	108 ± 8	161 ± 39	-	< 8.6	438 ± 20	92.4 ± 8	< 150	108	0.36
-	-	77.2 ± 7.3	-	-	-	89.3 ± 10.3	79.9 ± 7.7	< 140	77	0.26
-	-	90.0 ± 7.6	-	-	-	157 ± 13	159 ± 11	< 150	90	0.30
-	-	71.5 ± 6.4	-	-	-	29.8 ± 8	48.4 ± 6.9	< 130	71	0.24
-	-	83.2 ± 7	-	-	-	56.3 ± 8.8	60.2 ± 7.5	< 140	83	0.28
-	-	93.6 ± 7.3	-	-	-	80.9 ± 10	61.9 ± 7.5	< 140	93	0.31
6.68 ± 0.86	-	86.4 ± 16.2	< 140	89.5 ± 5.2	110 ± 2	251 ± 34	210 ± 58	< 420	244	0.84
7.32 ± 0.88	-	72.3 ± 15.4	< 140	86.5 ± 5.6	98.6 ± 1.6	202 ± 30	188 ± 48	< 400	213	0.73
4.96 ± 0.77	-	103 ± 16	125 ± 37	66 ± 4.4	54 ± 1.2	320 ± 35	159 ± 55	< 370	180	0.61
16.2 ± 1.2	-	74.6 ± 16.4	117 ± 33	85.3 ± 5	112 ± 2	182 ± 29	152 ± 51	< 380	235	0.81
8.47 ± 0.94	-	59.6 ± 13.2	< 110	30.9 ± 2.2	12.3 ± 0.7	189 ± 29	< 65	< 360	77.2	0.26
6.79 ± 0.87	-	84.0 ± 15.7	168 ± 32	80.2 ± 4.5	72.2 ± 1.2	142 ± 27	149 ± 19	< 360	187	0.64
8.62 ± 0.95	-	72.0 ± 16.0	147 ± 35	72.5 ± 4.9	95.7 ± 1.6	162 ± 29	200 ± 24	< 430	209	0.72
7.21 ± 0.88	-	71.8 ± 14.8	< 110	87.8 ± 7.1	74.2 ± 1.2	97.8 ± 24.2	160 ± 22	< 370	178	0.61
10.4 ± 1.0	-	78.9 ± 16.3	179 ± 37	87.5 ± 5.2	92.9 ± 1.6	157 ± 29	187 ± 22	< 450	212	0.73

Uranium-238	Thorium-230	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_m
11.4 ± 1.1	-	94.0 ± 17.3	< 140	70.2 ± 4.5	164 ± 3	125 ± 28	131 ± 19	< 460	328	1.13
8.94 ± 0.95	-	70.3 ± 18.8	140 ± 32	81.6 ± 4.9	64.9 ± 1.2	189 ± 33	207 ± 24	< 450	163	0.56
16.5 ± 1.2	-	121 ± 9	114 ± 110	-	84 ± 1.6	329 ± 19	175 ± 12	< 160	241	0.82
32.0 ± 1.6	-	209 ± 12	109 ± 110	-	161 ± 3	476 ± 24	331 ± 17	< 42	439	1.50
24.8 ± 1.5	-	212 ± 13	127 ± 110	-	154 ± 2	531 ± 27	295 ± 17	< 210	432	1.48
21.9 ± 1.4	-	191 ± 11	140 ± 210	-	142 ± 2	427 ± 23	261 ± 15	< 180	394	1.35
8.17 ± 0.94	-	< 14	< 86	-	< 1.4	< 21	6.2 ± 3.7	< 110		
10.3 ± 1.0	-	< 14	< 73	-	< 1.5	6.3 ± 4.1	6.5 ± 3.9	< 93		
47.4 ± 4.7	-	209 ± 11	217 ± 35	-	34.3 ± 1.7	382 ± 20	92.1 ± 8.7	< 160	258	0.87
144 ± 9	-	110 ± 9	117 ± 30	-	143 ± 4	433 ± 21	125 ± 10	< 160	314	1.08
40.3 ± 2.3	-	46.8 ± 4.1	-	76.9 ± 5.6	104 ± 4	76.8 ± 7.4	82.4 ± 5.8	< 88	196	0.68
42.1 ± 2.5	-	79.8 ± 7.6	-	74.9 ± 4.5	118 ± 4	168 ± 14	204 ± 62	< 140	249	0.86
38.2 ± 2.3	-	71.7 ± 7.3	-	79.8 ± 5.8	98.6 ± 3.7	133 ± 13	157 ± 10	< 120	213	0.73
38.0 ± 2.6	-	79.7 ± 7.7	-	71.4 ± 6.1	112 ± 3	183 ± 14	212 ± 11	< 140	240	0.83
42.0 ± 2.5	-	82.0 ± 7.7	-	79.1 ± 4.9	101 ± 4	133 ± 13	156 ± 10	< 150	226	0.78
40.9 ± 2.6	-	72.7 ± 7.7	-	84.9 ± 4.7	118 ± 4	173 ± 14	205 ± 11	< 150	241	0.83
33.8 ± 2.3	-	73.4 ± 6.9	-	70.4 ± 3.9	97.4 ± 3.7	121 ± 12	150 ± 9	< 150	213	0.73
22.0 ± 3.5	-	90.6 ± 7.7	-	76.9 ± 4.6	123 ± 3	176 ± 14	205 ± 11	< 150	267	0.92
< 29	-	97.3 ± 8.0	-	84.4 ± 6.6	99.4 ± 2.4	174 ± 14	181 ± 11	< 140	240	0.82
20.0 ± 3.5	-	79.2 ± 7.6	-	82.4 ± 7.3	121 ± 3	178 ± 14	201 ± 11	62 ± 33	257	0.89
26.3 ± 3.3	-	73.1 ± 7.1	-	64 ± 5.1	110 ± 2	120 ± 12	144 ± 10	< 150	230	0.79
32.5 ± 3.6	-	84.4 ± 7.6	-	86 ± 4.7	102 ± 2	167 ± 13	216 ± 12	< 140	230	0.79
8.16 ± 0.49	-	77.8 ± 6.7	45 ± 25	-	83.2 ± 2	144 ± 12	184 ± 10	< 110	197	0.68
7.24 ± 0.47	-	93.9 ± 7.3	152 ± 37	-	66.5 ± 1.6	198 ± 14	227 ± 11	66 ± 27	194	0.67
17.5 ± 0.6	-	103 ± 8	94.1 ± 13	-	127 ± 2	245 ± 15	256 ± 12	76 ± 31	291	1.00
17.9 ± 0.6	-	83.0 ± 7.1	70.5 ± 11	-	126 ± 2	200 ± 14	238 ± 12	< 130	263	0.91
17.3 ± 0.6	-	91.7 ± 7.8	57.9 ± 12	-	131 ± 2	256 ± 16	258 ± 12	53 ± 31	283	0.98
21.6 ± 0.7	-	110 ± 9	56.3 ± 11	-	141 ± 2	249 ± 15	246 ± 11	< 130	312	1.07

Uranium-238	Thorium-230	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_m
18.4 ± 0.6	-	100 ± 7	67.4 ± 12	-	127 ± 2	254 ± 15	257 ± 12	99 ± 29	289	1.00
19.0 ± 0.6	-	109 ± 8	71.9 ± 13	-	140 ± 2	254 ± 16	291 ± 13	< 140	309	1.06
44.4 ± 5.4	-	79.3 ± 7.1	54.0 ± 28	-	153 ± 6	199 ± 14	210 ± 11	109 ± 28	307	1.07
9.40 ± 0.4	-	84.8 ± 7.1	97.0 ± 35	-	71 ± 2.8	300 ± 16	157 ± 9	< 130	186	0.64
9.33 ± 0.4	-	92.8 ± 7.2	83.0 ± 31	-	55.2 ± 2.4	346 ± 17	182 ± 10	< 130	172	0.59
9.52 ± 0.4	-	93.1 ± 7.3	< 190	-	55.6 ± 2.4	351 ± 17	170 ± 10	< 130	173	0.59
10.8 ± 0.4	-	71.7 ± 7.5	< 140	-	61.3 ± 2.4	321 ± 18	134 ± 9	< 130	159	0.55
22.3 ± 0.6	-	48.3 ± 4.9	-	-	< 2.3	< 25	4.2 ± 1.7	56 ± 23	53	0.18
35.2 ± 0.8	-	88.8 ± 6.0	-	-	< 2.5	< 24	4.8 ± 1.7	75 ± 22	94	0.32
110 ± 2	-	264 ± 10	-	-	< 3.2	< 34	< 22	40 ± 22	267	0.89
157 ± 2	-	444 ± 14	-	-	< 3.6	< 21	< 37	< 140	444	1.48
322 ± 4	-	836 ± 22	-	-	4.87 ± 0.69	12 ± 6.5	20 ± 6.7	73 ± 33	849	2.84
11.5 ± 0.5	-	112 ± 8	-	-	< 2.5	< 35	< 23	60 ± 30	117	0.39
13.1 ± 0.5	-	86.0 ± 7.0	58.0 ± 28	-	107 ± 6	202 ± 13	216 ± 11.0	< 110	239	0.82
10.5 ± 0.4	-	82.6 ± 7.3	135 ± 36	-	75.5 ± 4.5	184 ± 14	196 ± 10	46 ± 28	194	0.67
5.01 ± 0.37	-	91.9 ± 6.9	100 ± 38	-	53.1 ± 1.2	235 ± 13	262 ± 19	< 96	168	0.57
7.54 ± 0.54	-	79.9 ± 5.8	58.6 ± 16	-	64.5 ± 2.1	166 ± 11	188 ± 16	< 92	172	0.59
Phosphogypsum										
4.64 ± 0.4	-	71.3 ± 6.1	134 ± 32	-	4.04 ± 0.31	16 ± 7.1	25.9 ± 4.5	96 ± 26	102	0.29
3.98 ± 0.37	-	52.9 ± 5.2	< 84	-	6.09 ± 0.29	29.3 ± 6.7	31.2 ± 4.7	110 ± 27	70	0.24
10.5 ± 0.6	-	98.3 ± 7.9	125 ± 37	-	7.43 ± 0.29	147 ± 14	152 ± 10	123 ± 36	118	0.41
14.8 ± 0.7	-	67.9 ± 6.2	< 130	-	35.7 ± 0.7	16 ± 7.9	40.9 ± 5.4	70 ± 27	124	0.43
13 ± 0.6	-	74 ± 6.9	< 85	-	10.7 ± 0.3	45.1 ± 8.1	49.6 ± 6.7	93 ± 30	96	0.33
10 ± 0.6	-	76.8 ± 6.2	< 92	-	8.18 ± 0.29	46.8 ± 8.3	48.8 ± 5.8	114 ± 30	97	0.33
69.6 ± 1.5	-	153 ± 10	131 ± 36	-	67.4 ± 1.1	464 ± 20	471 ± 18	195 ± 37	265	0.91
30 ± 1	-	121 ± 8	120 ± 34	-	37.8 ± 0.6	364 ± 19	336 ± 14	102 ± 30	183	0.63
16.3 ± 0.7	-	112 ± 8	108 ± 31	-	61.4 ± 1	447 ± 20	407 ± 16	142 ± 32	211	0.73
23.1 ± 0.8	-	104 ± 8	< 110	-	42.9 ± 0.7	312 ± 17	307 ± 13	59 ± 27	170	0.58

Uranium-238	Thorium-230	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_m
9.72 ± 0.56	-	64.8 ± 6.2	84.2 ± 25	-	41.7 ± 0.7	222 ± 14	239 ± 11	141 ± 27	135	0.47
20.5 ± 0.8	-	105 ± 8	125 ± 31	-	51.3 ± 0.8	310 ± 17	337 ± 14	157 ± 31	191	0.66
20.7 ± 0.8	-	94.4 ± 8.8	< 140	-	43.2 ± 0.9	268 ± 15	301 ± 13	69 ± 27	162	0.55
17 ± 0.7	-	85.1 ± 6.8	< 100	-	32.2 ± 0.8	246 ± 15	281 ± 12	51 ± 26	135	0.46
13.6 ± 0.7	-	93.8 ± 7	< 97	-	20.3 ± 0.6	163 ± 13	194 ± 11	72 ± 26	128	0.44
17.8 ± 0.7	-	96.3 ± 6.8	< 110	-	31.4 ± 0.8	197 ± 13	231 ± 11	156 ± 29	153	0.53
12.6 ± 0.6	-	84.9 ± 6.8	150 ± 32	-	47.9 ± 0.9	210 ± 14	255 ± 12	121 ± 27	163	0.56
19 ± 0.8	-	66.2 ± 5.4	< 140	-	57 ± 1	194 ± 12	214 ± 10	46 ± 21	151	0.52
11.5 ± 0.6	-	85.1 ± 7	< 130	-	21.3 ± 0.6	155 ± 12	186 ± 10	93 ± 25	123	0.42
16.4 ± 0.7	-	90.9 ± 6.9	126 ± 38	-	28.9 ± 0.5	258 ± 16	298 ± 13	97 ± 27	140	0.48
23.1 ± 0.8	-	94.5 ± 7.4	< 120	-	48.2 ± 0.9	285 ± 16	295 ± 13	139 ± 31	174	0.60
28.2 ± 0.9	-	101 ± 7	< 130	-	33.9 ± 0.8	198 ± 19	249 ± 11	102 ± 28	157	0.54
24.9 ± 0.9	-	82.5 ± 6.9	< 81	-	35 ± 0.8	198 ± 14	223 ± 11	134 ± 31	143	0.49
15.3 ± 0.7	-	74.5 ± 6.7	< 130	-	20 ± 0.5	140 ± 12	172 ± 10	139 ± 29	114	0.39
17.4 ± 0.8	-	83.8 ± 6.7	< 140	-	28.1 ± 0.5	175 ± 13	184 ± 10	< 120	124	0.42
34.3 ± 1.2	-	96 ± 7.5	< 150	-	101 ± 2	418 ± 19	412 ± 16	154 ± 32	252	0.88
17.4 ± 0.8	-	93.3 ± 6.8	< 130	-	34.1 ± 0.8	259 ± 14	284 ± 12	131 ± 26	152	0.53
17.3 ± 0.8	-	96 ± 7.4	< 100	-	37 ± 0.8	243 ± 15	266 ± 12	62 ± 27	154	0.53
29.6 ± 1.1	-	92 ± 6.9	< 140	-	32 ± 0.7	213 ± 13	216 ± 11	105 ± 27	146	0.50
18.6 ± 0.8	-	99 ± 11.7	67 ± 29	-	34.7 ± 0.8	198 ± 14	243 ± 12	133 ± 30	159	0.55
18.9 ± 0.8	-	77.5 ± 6.3	< 110	-	48 ± 1	226 ± 13	228 ± 10	111 ± 25	155	0.54
66.3 ± 1.9	-	91.8 ± 7	< 100	-	58.5 ± 1	245 ± 15	291 ± 12	97 ± 28	183	0.63
42.5 ± 1.4	-	77.4 ± 6.4	< 150	-	67.9 ± 1.2	255 ± 15	258 ± 12	61 ± 25	179	0.62
47.5 ± 1.5	-	78.4 ± 6.1	< 110	-	60.2 ± 1.1	236 ± 14	255 ± 11	39 ± 24	168	0.58
15.8 ± 0.8	-	75.3 ± 6.1	< 120	-	36.9 ± 0.8	193 ± 13	181 ± 10	90 ± 28	135	0.47
45.7 ± 1.5	-	79.1 ± 6.7	< 130	-	63.9 ± 1.1	251 ± 14	271 ± 12	96 ± 25	178	0.62
27.4 ± 1.1	-	66 ± 6.5	100 ± 32	-	43.9 ± 0.9	182 ± 14	206 ± 10	64 ± 28	134	0.46
55.2 ± 1.7	-	107 ± 8	148 ± 34	-	59.6 ± 1.1	299 ± 18	304 ± 13	175 ± 33	206	0.71

Uranium-238	Thorium-230	Radium-226	Lead-210	Polonium-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_m
26.3 ± 1	-	82.7 ± 6.9	74 ± 27	-	61.3 ± 1.1	208 ± 14	265 ± 12	103 ± 27	178	0.62
14.3 ± 0.7	-	85.1 ± 6.7	< 130	-	26.5 ± 0.6	131 ± 12	155 ± 9	67 ± 25	128	0.44
39.5 ± 1.3	-	90.3 ± 6.7	< 120	-	55.7 ± 1	211 ± 13	251 ± 11	89 ± 26	177	0.61
13 ± 0.7	-	79.5 ± 6	64 ± 24	-	23.3 ± 0.6	126 ± 11	137 ± 8	86 ± 27	119	0.41
44.1 ± 1.4	-	71.8 ± 6.6	< 130	-	70.3 ± 1.2	266 ± 15	261 ± 11	133 ± 27	183	0.64
20.6 ± 0.9	-	76.2 ± 6.4	71 ± 29	-	36.2 ± 0.7	147 ± 12	171 ± 9	89 ± 28	135	0.46
12.3 ± 0.7	-	86.7 ± 6.4	77 ± 25	-	20.3 ± 0.5	123 ± 11	127 ± 8	66 ± 24	121	0.41
52.4 ± 1.6	-	88.4 ± 7.2	< 120	-	57.9 ± 1	256 ± 16	262 ± 12	93 ± 29	178	0.62
23.6 ± 1	-	86.1 ± 6.2	126 ± 31	-	39.7 ± 0.7	172 ± 12	203 ± 10	107 ± 26	151.	0.52
5.43 ± 0.4	-	134 ± 20	165 ± 25	-	47.1 ± 2.4	283 ± 46	154 ± 8	< 106	201	0.68
15.8 ± 0.7	-	86.1 ± 8.5	90 ± 29	-	64.9 ± 1.6	350 ± 18	97.8 ± 9.1	< 140	179	0.61
5.07 ± 0.67	-	70.7 ± 6.1	< 100	-	53.4 ± 1.8	68.5 ± 8.8	75.7 ± 7.3	< 130	147	0.50
3.75 ± 0.59	-	75.2 ± 6.4	77.6 ± 23	-	116 ± 2	124 ± 12	145 ± 9	< 130	241	0.83
5.1 ± 0.67	-	59.7 ± 6.5	109 ± 26	-	25.8 ± 1.6	37.3 ± 7.4	42.7 ± 5.4	< 130	97	0.33
4.93 ± 0.68	-	72.4 ± 6.6	105 ± 27	-	32.5 ± 1.6	55.8 ± 9	56.1 ± 6.6	< 130	119	0.40
3.63 ± 0.57	-	80.5 ± 6.4	106 ± 25	-	39.6 ± 1.8	70.2 ± 9	55 ± 6.4	< 130	137	0.47
-	-	104 ± 9	-	-	-	271 ± 17	323 ± 14	< 140	104	0.35
-	-	100 ± 8	-	-	-	300 ± 17	182 ± 14	< 150	100	0.33
64.3 ± 4.7	-	75.9 ± 7.8	105 ± 33	-	27.4 ± 1	34.7 ± 8.6	34.8 ± 6	< 150	115	0.39
Plasterboard										
-	-	91.4 ± 7.9	-	-	-	85.8 ± 11.3	75.1 ± 8.5	73 ± 37	220	0.76
-	-	67.7 ± 7.6	-	-	-	85.3 ± 11.9	95.3 ± 8.4	191 ± 42	204	0.72
-	-	92.5 ± 7.9	-	-	-	52.2 ± 10.8	75.7 ± 7.4	< 170	167	0.57
Sand										
28.9 ± 5.6	-	96.8 ± 5.1	225 ± 29	-	9.49 ± 1.83	12.6 ± 4.1	5.5 ± 1.53	55 ± 21	115	0.39
Silica fume										
< 6.1	23.8 ± 3.8	47.4 ± 8.7	< 200	121 ± 7	2.8 ± 1.25	57.5 ± 13.6	6.05 ± 2.12	599 ± 79	97	0.37

Table C-3: Results for sediment samples: Activity concentration in Bq.kg^{-1}, Radium equivalent dose, Ra_{eq} in Bq.kg^{-1}, Gamma Index (H_{ex}), External gamma dose rate, D (nGy.h^{-1}) and Annual effective dose, AED (mSv.a^{-1})

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
Baseline 1										
17.4 ± 2.5	17.8 ± 2.7	< 72	26.2 ± 1.2	30.0 ± 4.7	29.2 ± 3.5	121 ± 19	64.6	0.17	29.1	0.04
11.3 ± 0.52	13.3 ± 2.5	< 60	13.1 ± 0.51	16.1 ± 3.7	15.7 ± 2.6	114 ± 18	40.8	0.11	18.8	0.02
10.8 ± 0.43	10.9 ± 2.7	< 76	17.7 ± 0.72	16.9 ± 3.6	16.4 ± 3.2	56.2 ± 16.2	40.5	0.11	18.1	0.02
22.2 ± 3.1	21.5 ± 3.1	< 74	33.9 ± 1.3	54.3 ± 5.6	44.1 ± 4.3	337 ± 29	96.0	0.26	44.5	0.05
17.7 ± 0.66	17.0 ± 2.9	< 70	22.7 ± 0.74	25.7 ± 5.3	32.9 ± 3.9	418 ± 34	81.7	0.22	39.0	0.05
21.4 ± 0.64	19.9 ± 3.2	< 80	45.0 ± 1.2	47.8 ± 6.4	44.9 ± 4.7	329 ± 32	110	0.30	50.1	0.06
13.2 ± 2.3	15.2 ± 2.9	< 82	26.6 ± 1.1	15.2 ± 4.5	25.3 ± 3.7	75.9 ± 18	59.0	0.16	26.2	0.03
12.9 ± 0.52	15.1 ± 2.6	< 78	9.49 ± 0.42	15.6 ± 4.2	12.2 ± 2.6	66.8 ± 18.3	33.8	0.09	15.5	0.02
17.3 ± 0.51	12.0 ± 2.4	< 68	22.1 ± 0.73	18.7 ± 4.4	17.3 ± 3.4	67.7 ± 17.1	48.9	0.13	21.7	0.03
20.5 ± 3.1	21.8 ± 3.1	< 80	17.9 ± 0.72	29.6 ± 5.1	25.3 ± 3.8	290 ± 29	69.7	0.19	33.0	0.04
13.6 ± 0.56	14.3 ± 2.7	< 68	8.39 ± 0.41	10.8 ± 4.2	11.7 ± 2.7	411 ± 32	57.9	0.16	28.8	0.04
16.0 ± 0.55	10.1 ± 2.6	< 72	10.6 ± 0.58	11.0 ± 3.5	8.73 ± 2.7	287 ± 28	47.3	0.13	23.0	0.03
Baseline 2										
42.1 ± 0.91	6.19 ± 0.41	11.0 ± 2.3	16.3 ± 1.1	10.96 ± 0.77	9.84 ± 0.52	102 ± 4.9	37.4	0.10	17.0	0.02
24.7 ± 1.9	25.2 ± 0.72	32.6 ± 2.9	21.6 ± 0.91	18.25 ± 0.93	18.6 ± 0.51	53.6 ± 2.5	60.1	0.16	26.8	0.03
82.9 ± 4.3	73.0 ± 1.7	76.4 ± 5.9	38.2 ± 1.7	41.02 ± 1.4	40.3 ± 1.4	59.5 ± 3.2	132	0.36	59.3	0.07
14.6 ± 1.2	10.1 ± 0.42	15.4 ± 1.7	7.55 ± 0.43	8.286 ± 0.64	8.57 ± 0.32	36.4 ± 2.1	23.7	0.06	10.7	0.01
Baseline 3										
5.11 ± 0.42	3.57 ± 0.22	9.46 ± 2.3	2.57 ± 0.22	4.12 ± 0.51	3.94 ± 0.27	5.74 ± 1.5	7.7	0.02	3.4	0.004
38.0 ± 0.91	38.7 ± 11.2	49.6 ± 4.5	23.9 ± 1.5	33.01 ± 1.3	28.5 ± 0.75	352 ± 8.8	100	0.27	47.0	0.06
34.6 ± 2.6	36.4 ± 1.2	42.9 ± 3.7	39.6 ± 1.7	44.0 ± 1.7	41.9 ± 1.1	473 ± 12	130	0.35	60.4	0.07
5.19 ± 0.88	2.54 ± 0.33	7.05 ± 1.1	3.18 ± 0.22	3.41 ± 0.41	3.82 ± 0.24	8.62 ± 1.1	7.7	0.02	3.4	0.004
Baseline 4										
6.56 ± 0.41	10.3 ± 0.42	22.6 ± 3.1	8.34 ± 0.51	8.14 ± 0.61	7.25 ± 0.31	28.2 ± 2.1	24.4	0.07	11.0	0.01

Uranium-238	**Radium-226**	**Lead-210**	**Thorium-232**	**Radium-228**	**Thorium-228**	**Potassium-40**	**Ra_{eq}**	**H_{ex}**	**D**	**AED**
7.68 ± 0.44	7.07 ± 0.36	7.16 ± 2.2	2.91 ± 0.34	7.79 ± 0.57	6.84 ± 0.20	66.4 ± 2.8	16.3	0.04	7.8	0.01
5.01 ± 1.1	6.53 ± 0.34	6.83 ± 1.3	10.4 ± 0.52	12.0 ± 0.74	9.11 ± 0.34	65.2 ± 2.7	26.4	0.07	12.0	0.01
12.6 ± 1.6	10.5 ± 0.48	13.4 ± 1.8	17.9 ± 0.87	18.2 ± 0.92	18.7 ± 0.68	222 ± 6	53.2	0.14	24.9	0.03
Phosphate Industry 1										
180 ± 2	777 ± 27	776 ± 194	5800 ± 280	3020 ± 60	7020 ± 170	311 ± 76	9095	24.6	3875	4.8
131 ± 10	547 ± 45	763 ± 89	4580 ± 120	3100 ± 120	3490 ± 200	370 ± 180	7125	19.2	3034	3.7
Phosphate Industry 2										
24.1 ± 0.74	34.5 ± 5.8	63.2 ± 25.6	552 ± 8	125 ± 10	484 ± 16	< 110	824	2.22	349	0.43
20.1 ± 0.63	19.9 ± 3.6	< 84	95.7 ± 2.8	43.7 ± 6.6	75 ± 12	64 ± 20	162	0.44	69.7	0.09
36.3 ± 1.1	60.6 ± 5.8	< 120	224 ± 5	164 ± 11	200 ± 19	158 ± 28	393	1.06	170	0.21
37.5 ± 1.1	64.2 ± 12.1	< 170	306 ± 5	< 55	238 ± 19	< 410	502	1.35	214	0.26
Phosphate Industry 3										
26.5 ± 0.78	19.1 ± 4.4	< 75	46.7 ± 0.81	63.1 ± 6.6	37.2 ± 5.2	< 92	85.9	0.23	37.0	0.05
47.8 ± 0.96	49.0 ± 4.4	< 82	65.3 ± 2.8	88.2 ± 7.6	88.3 ± 6.1	114 ± 25	151	0.41	66.8	0.08
92.5 ± 1.3	67.2 ± 6.4	< 120	129 ± 4	118 ± 11	127 ± 19	137 ± 31	262	0.71	115	0.14
72.2 ± 3.2	100 ± 19	82.0 ± 35,5	167 ± 5	103 ± 30	197 ± 44	310 ± 120	363	0.98	160	0.20
5.75 ± 0.44	12.7 ± 4.1	< 120	10.6 ± 0.62	29.9 ± 6.7	17.1 ± 4.4	< 100	27.9	0.08	12.3	0.02
6.65 ± 0.43	25.0 ± 9.9	< 110	7.02 ± 0.31	< 63	< 100	< 310	35.0	0.09	15.8	0.02
Phosphate Industry 4										
16.2 ± 1.2	21.0 ± 7.3	< 110	14.5 ± 0.72	< 52	18.2 ± 7.4	716 ± 72	96.9	0.26	48.3	0.06
18.1 ± 0.75	12.7 ± 3.8	< 99	21.1 ± 1.2	< 27	19.3 ± 4.2	284 ± 31	64.7	0.17	30.5	0.04
66.3 ± 1.1	98.2 ± 19.1	280 ± 34	57.2 ± 2.4	< 120	39.6 ± 16.1	300 ± 120	203	0.55	92.4	0.11
Mineral Sands 1										
50.6 ± 1.6	53.2 ± 4.6	252 ± 32	47.9 ± 1.2	40.3 ± 7	59.7 ± 10.3	902 ± 52	191	0.52	91.1	0.11
149 ± 4	132 ± 7	92.4 ± 47.1	146 ± 3	169 ± 11	158 ± 14	173 ± 24	354	0.96	156	0.19
36.1 ± 1.3	29.5 ± 4.2	< 87	33.2 ± 1.1	22.2 ± 6.5	45.4 ± 9.2	126 ± 24	86.7	0.23	38.9	0.05
26.9 ± 1.4	21.9 ± 3.2	48.6 ± 23.5	28.8 ± 0.86	20.8 ± 4.5	22.8 ± 6.6	43 ± 17	66.4	0.18	29.3	0.04
32.5 ± 1.2	31.7 ± 3.6	45.4 ± 20.2	29.8 ± 0.93	25.8 ± 5.3	35.1 ± 3.9	< 76	74.3	0.20	32.6	0.04

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
Mineral Sands 2										
32.1 ± 0.85	23.6 ± 3.4	37.4 ± 19.1	57.6 ± 1.2	84.8 ± 7.8	74.5 ± 5.1	938 ± 50	178	0.48	84.8	0.10
34.4 ± 0.82	33.1 ± 3.7	59.7 ± 16.3	65.7 ± 1.2	87.0 ± 7.7	89.7 ± 5.5	860 ± 47	193	0.52	90.8	0.11
Mineral Sands 3										
419 ± 4.3	435 ± 20	424 ± 70	3830 ± 69	4486 ± 77	4712 ± 117	1172 ± 81	6002	16.2	2563	3.1
505 ± 5	478 ± 19	479 ± 110	5842 ± 122	6279 ± 97	6359 ± 152	148 ± 84	8843	23.9	3755	4.6
Gold Mines 1										
185 ± 5.1	217 ± 9	< 110	49.5 ± 2.4	51.6 ± 8.9	45.6 ± 14.1	568 ± 44	331	0.89	153	0.19
154 ± 5.6	155 ± 16	61.8 ± 32.3	66.1 ± 2.4	79.9 ± 19.1	81.2 ± 14.2	592 ± 108	295	0.80	136	0.17
138 ± 2.3	182 ± 181	< 108	60.9 ± 2.4	47.2 ± 8.8	55.5 ± 5.7	656 ± 51	319	0.86	148	0.18
175 ± 4.2	372 ± 12	< 108	54.8 ± 1.2	59.5 ± 8.9	67.8 ± 16.2	734 ± 52	507	1.37	236	0.29
122 ± 4.1	204 ± 9	< 108	48.7 ± 0.81	45.5 ± 9.2	52.1 ± 13.4	660 ± 47	324	0.88	151	0.19
114 ± 1.4	**183** ± 13	< 108	47.9 ± 0.82	77.6 ± 12.1	45.1 ± 8.9	748 ± 77	309	0.84	145	0.18
125 ± 1.6	200 ± 16	< 108	47.1 ± 1.2	66.2 ± 16.2	40.1 ± 10.1	830 ± 94	331	0.89	155	0.19
Gold Mines 2										
51.9 ± 1.7	54.2 ± 4.6	61.1 ± 17.2	11.5 ± 1.3	22.5 ± 4.5	10.1 ± 3.2	212 ± 27	87.0	0.23	40.8	0.05
279 ± 9.7	196 ± 16	313 ± 40	18.5 ± 1.3	< 75	30.5 ± 5.6	132 ± 84	233	0.63	107	0.13
101 ± 1.7	85.2 ± 8.6	112 ± 33	35.9 ± 1.4	42.3 ± 6.3	40.9 ± 10.2	275 ± 32	159	0.43	72.9	0.09
139 ± 3.4	99.0 ± 6.1	72.8 ± 32	33.3 ± 0.71	35.9 ± 6.7	33.7 ± 8.9	223 ± 29	164	0.44	75.1	0.09
139 ± 4.7	102 ± 6	100 ± 41	30.9 ± 0.72	32.8 ± 6.5	27.9 ± 5.5	159 ± 28	159	0.43	72.6	0.09
237 ± 2	199 ± 14	< 108	28.4 ± 0.74	36.7 ± 10.1	52.1 ± 9.4	112 ± 56	248	0.67	114	0.14
Gold Mines 3										
54.9 ± 1.8	50.6 ± 15	48.8 ± 23.2	22.2 ± 1.8	89.3 ± 11	56.6 ± 16.2	513 ± 45	122	0.33	58.2	0.07
98.4 ± 3.7	124 ± 13	< 108	43.8 ± 1.2	66.1 ± 15	56.9 ± 12.1	< 321	186	0.50	83.8	0.10
104 ± 1.7	123 ± 12	77.2 ± 28.1	52.7 ± 1.6	38.5 ± 7.2	52.0 ± 9.8	96.1 ± 23.1	206	0.56	92.9	0.11
154 ± 3.8	137 ± 11	105 ± 27	37.1 ± 0.82	63.2 ± 8.9	47.7 ± 12.2	92.6 ± 24.3	397	1.07	182	0.22
53.9 ± 2.5	69.5 ± 5.6	51.2 ± 29.9	20.4 ± 0.61	10.2 ± 5.4	19.8 ± 4.1	229 ± 31	116	0.31	54.0	0.07
110 ± 1.4	305 ± 13	< 108	35.9 ± 0.82	71.3 ± 11	48.9 ± 7.5	133 ± 43	367	0.99	168	0.21

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
Gold Mines 4										
667 ± 17	265 ± 10	178 ± 26	16.6 ± 1.9	19.9 ± 5.8	22.1 ± 4.7	133 ± 26	299	0.81	138	0.17
289 ± 10	101 ± 13	126 ± 40	12.8 ± 0.92	< 64	9.45 ± 8.3	< 324	119	0.32	54.6	0.07
454 ± 3.8	162 ± 16	141 ± 28	14.9 ± 0.53	17.3 ± 6.4	10.1 ± 3.3	110 ± 23	191	0.52	88.3	0.11
333 ± 7.7	191 ± 8	144 ± 24	13.1 ± 0.45	20.7 ± 6.4	20.4 ± 5.8	137 ± 27	220	0.60	102	0.13
370 ± 12	233 ± 9	189 ± 45	16.1 ± 0.51	< 44	13.5 ± 5.7	191 ± 29	270	0.73	125	0.15
519 ± 3	427 ± 21	245 ± 68	23.2 ± 1.1	34.3 ± 12.1	32.8 ± 9.6	281 ± 73	482	1.30	223	0.27
Gold Mines 5										
27.8 ± 1.1	44.9 ± 4.1	< 108	22.4 ± 1.5	28.3 ± 5.1	25.9 ± 3.8	62.9 ± 18.2	81.8	0.22	36.9	0.05
31.9 ± 1.4	25.4 ± 8.8	< 108	12.2 ± 0.61	< 61	20.7 ± 7.4	< 318	42.9	0.12	19.1	0.02
23.7 ± 0.81	24.2 ± 2.4	< 108	10.6 ± 0.52	9.97 ± 4.8	7.96 ± 3.5	< 86	39.4	0.11	17.6	0.02
22.2 ± 0.87	20.3 ± 3.2	< 108	9.89 ± 0.35	9.44 ± 4.2	9.44 ± 3.4	< 78	34.5	0.09	15.4	0.02
23.1 ± 1.2	26.6 ± 3.5	< 108	11.1 ± 0.47	9.43 ± 4.3	13.3 ± 4.1	< 78	42.4	0.11	19.0	0.02
16.1 ± 0.57	16.0 ± 5.4	< 108	9.00 ± 0.35	< 40	17.8 ± 4.8	63.3 ± 40.1	33.8	0.09	15.5	0.02
30.3 ± 0.85	36.9 ± 8.2	< 108	13.4 ± 0.51	25.5 ± 9.9	25.3 ± 7.4	210 ± 59	72.3	0.20	33.9	0.04
Gold Mines 6										
55.2 ± 1.6	42.1 ± 10.3	67.7 ± 18.1	40.4 ± 1.1	< 80	75.3 ± 29.1	130 ± 70	110	0.30	49.3	0.06
370 ± 4.1	718 ± 29	517 ± 34	41.8 ± 1.2	68.6 ± 20.2	44.2 ± 13.6	437 ± 106	811	2.19	375	0.46
207 ± 2.7	602 ± 26	533 ± 29	37.8 ± 1.1	< 90	42.0 ± 6.3	< 384	656	1.77	301	0.37
234 ± 5.2	177 ± 13	82.3 ± 16.2	28.5 ± 0.91	26.9 ± 14.1	39.6 ± 8.9	183 ± 67	232	0.63	107	0.13
Gold Mines 7										
25.7 ± 0.62	33.2 ± 3.7	< 108	16.0 ± 1.3	16.8 ± 4.4	19.7 ± 3.5	133 ± 23	66.3	0.18	30.6	0.04
26.9 ± 0.71	22.2 ± 3.3	< 108	16.4 ± 1.1	25.4 ± 4.1	14.0 ± 3.5	103 ± 20	53.6	0.14	24.5	0.03
31.4 ± 0.74	43.3 ± 4.2	< 108	18.5 ± 1.1	23.7 ± 5.2	36.2 ± 4.3	172 ± 25	83.0	0.22	38.4	0.05
41.1 ± 0.86	29.5 ± 3.5	< 108	16.7 ± 1.1	22.3 ± 4.8	22.3 ± 3.5	111 ± 22	61.9	0.17	28.4	0.03
44.8 ± 0.91	46.0 ± 4.1	< 108	18.9 ± 1.2	19.7 ± 4.8	18.9 ± 3.8	187 ± 26	87.6	0.24	40.5	0.05

Table C-4: Results for soil samples: Activity concentration in Bq.kg^{-1}, Radium equivalent dose, Ra_{eq} in Bq.kg^{-1}, Gamma Index (H_{ex}), External gamma dose rate, D (nGy.h^{-1}) and Annual effective dose, AED (mSv.a^{-1})

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
Baseline 1										
20.1 ± 2.7	17.4 ± 3.1	< 75.9	16.7 ± 0.72	16.4 ± 4.4	18.0 ± 3.3	117 ± 21	50.5	0.14	23.1	0.03
13.9 ± 0.52	16.3 ± 3.2	< 65.8	11.1 ± 0.41	21.2 ± 4.3	19.5 ± 3.2	86.6 ± 19.2	38.8	0.10	17.8	0.02
17.2 ± 0.51	14.9 ± 2.3	< 76.8	23.9 ± 0.90	21.4 ± 4.2	21.1 ± 2.8	135 ± 22	59.4	0.16	26.9	0.03
< 19.6	17.1 ± 3.1	< 76.2	16.9 ± 0.71	23.1 ± 4.9	21.7 ± 3.4	195 ± 25	56.2	0.15	26.2	0.03
17.0 ± 0.51	12.2 ± 2.4	< 71.3	16.7 ± 0.72	14.1 ± 3.9	12.2 ± 2.3	< 70.7	36.0	0.11	15.7	0.02
24.1 ± 3.3	17.5 ± 3.4	< 86.4	24.0 ± 1.2	15.5 ± 4.9	28.1 ± 3.7	100 ± 20	59.6	0.16	26.8	0.03
18.4 ± 0.57	26.6 ± 3.4	< 73.5	22.0 ± 0.81	33.3 ± 4.9	28.0 ± 4.1	133 ± 22	68.3	0.18	31.1	0.04
18.8 ± 0.53	13.2 ± 2.3	< 70.3	23.9 ± 0.92	12.3 ± 3.7	16.3 ± 2.6	< 62.5	47.3	0.14	20.5	0.03
16.9 ± 2.7	17.9 ± 3.1	< 78.3	14.0 ± 0.63	11.5 ± 4.1	13.9 ± 3.4	106 ± 21	46.1	0.12	21.2	0.03
32.1 ± 0.75	34.8 ± 3.7	43.5 ± 16.1	31.1 ± 1.1	29.1 ± 4.9	35.1 ± 3.8	134 ± 21	89.5	0.24	40.4	0.05
11.2 ± 0.41	12.2 ± 2.2	< 71.0	12.8 ± 0.52	13.5 ± 3.4	13.3 ± 2.3	< 56.7	30.5	0.09	13.4	0.02
Baseline 2										
14.2 ± 0.55	11.7 ± 0.41	17.5 ± 2.6	5.88 ± 0.42	6.95 ± 0.51	7.58 ± 0.38	30.7 ± 2.0	22.4	0.06	10.2	0.01
26.2 ± 0.72	19.3 ± 0.52	26.9 ± 3.1	13.1 ± 0.91	17.2 ± 0.82	16.9 ± 0.55	51.2 ± 2.5	42.1	0.11	19.0	0.02
13.2 ± 1.4	11.4 ± 0.40	25.2 ± 2.3	10.3 ± 0.52	11.7 ± 0.71	11.1 ± 0.46	35.9 ± 2.0	28.8	0.08	13.0	0.02
Baseline 3										
3.05 ± 0.31	2.07 ± 0.21	13.4 ± 2.4	2.26 ± 0.21	3.06 ± 0.41	3.24 ± 0.12	6.23 ± 1.3	5.8	0.02	2.6	0.00
11.2 ± 0.49	11.3 ± 0.42	17.8 ± 2.5	4.62 ± 0.44	8.32 ± 0.61	8.09 ± 0.33	12.6 ± 1.6	18.8	0.05	8.5	0.01
-	5.94 ± 0.21	10.9 ± 1.4	-	4.89 ± 0.52	4.39 ± 0.27	144 ± 14	17.0	0.05	8.7	0.01
-	5.81 ± 0.22	8.92 ± 1.3	-	1.54 ± 0.30	1.92 ± 0.22	42.9 ± 2.3	9.1	0.02	4.4	0.01
-	4.88 ± 0.22	13.9 ± 1.5	-	-	1.42 ± 0.26	25.4 ± 1.7	6.8	0.02	3.3	0.00
13.9 ± 1.3	8.99 ± 0.51	27.8 ± 3.1	17.2 ± 0.72	17.6 ± 1.3	16.8 ± 0.61	51.6 ± 3.7	37.5	0.10	16.7	0.02
6.08 ± 0.80	3.65 ± 0.33	15.3 ± 1.8	2.90 ± 0.31	2.92 ± 0.51	3.56 ± 0.22	49.2 ± 2.7	11.5	0.03	5.5	0.01
11.2 ± 0.49	11.3 ± 0.42	17.8 ± 2.5	4.62 ± 0.44	8.32 ± 0.61	8.09 ± 0.33	12.6 ± 1.6	18.8	0.05	8.5	0.01

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
-	5.94 ± 0.21	10.9 ± 1.4	-	4.89 ± 0.52	4.39 ± 0.27	144 ± 14	17.0	0.05	8.7	0.01
-	5.81 ± 0.22	8.92 ± 1.3	-	1.54 ± 0.30	1.92 ± 0.22	42.9 ± 2.3	9.1	0.02	4.4	0.01
-	4.88 ± 0.22	13.9 ± 1.5	-	-	1.42 ± 0.26	25.4 ± 1.7	6.8	0.02	3.3	0.00
13.9 ± 1.3	8.99 ± 0.51	27.8 ± 3.1	17.2 ± 0.72	17.6 ± 1.3	16.8 ± 0.61	51.6 ± 3.7	37.5	0.10	16.7	0.02
6.08 ± 0.80	3.65 ± 0.33	15.3 ± 1.8	2.90 ± 0.31	2.92 ± 0.51	3.56 ± 0.22	49.2 ± 2.7	11.5	0.03	5.5	0.01
16.9 ± 1.4	10.9 ± 0.40	18.6 ± 1.9	13.8 ± 0.63	16.6 ± 0.82	15.5 ± 0.59	48.6 ± 2.4	34.3	0.09	15.4	0.02
Baseline 4										
9.36 ± 0.38	8.59 ± 0.41	-	4.34 ± 0.31	6.28 ± 1.2	6.89 ± 0.52	78.5 ± 6.1	20.8	0.06	9.8	0.01
8.78 ± 0.38	6.97 ± 0.42	-	5.59 ± 0.42	7.21 ± 1.2	5.35 ± 0.41	92.3 ± 5.9	22.1	0.06	10.4	0.01
6.90 ± 0.34	6.11 ± 0.41	-	3.02 ± 0.21	4.03 ± 0.81	4.54 0.23	68.2 ± 5.3	15.7	0.04	7.5	0.01
9.42 ± 0.39	7.82 ± 0.44	-	5.84 ± 0.40	9.85 ± 1.1	7.42 ± 0.52	65.3 ± 5.7	21.2	0.06	9.9	0.01
14.9 ± 0.49	14.2 ± 0.61	-	8.39 ± 0.62	10.9 ± 1.3	11.7 ± 0.44	101 ± 17	34.0	0.09	15.8	0.02
7.19 ± 0.34	7.59 ± 0.42	-	3.91 ± 0.34	7.03 ± 1.2	5.09 ± 0.51	32.6 ± 4.2	15.6	0.04	7.2	0.01
12.5 ± 0.45	12.6 ± 0.51	-	8.32 ± 0.62	13.4 ± 1.2	11.2 ± 0.62	47.2 ± 4.7	28.1	0.08	12.8	0.02
15.8 ± 0.56	12.5 ± 0.41	15.5 ± 2.5	6.65 ± 0.51	10.7 ± 0.71	10.2 ± 0.33	77.8 ± 2.9	27.9	0.08	13.0	0.02
Baseline 5										
39.1 ± 1.5	37.3 ± 4.3	114 ± 29	76.7 ± 2.1	88.5 ± 7.7	90.6 ± 13.1	36.5 ± 18.8	150	0.40	65.0	0.08
29.6 ± 1.2	23.7 ± 3.5	< 108	46.7 ± 1.2	38.1 ± 5.5	48.8 ± 8.9	< 76	90.4	0.26	39.1	0.05
31.5 ± 1.3	29.2 ± 3.9	< 113	50.7 ± 1.2	53.1 ± 6.7	46.3 ± 9.9	< 87	102	0.29	44.1	0.05
16.9 ± 0.82	12.8 ± 2.1	< 98	23.9 ± 0.72	19.2 ± 3.1	24.5 ± 5.3	< 40	47.0	0.14	20.4	0.02
32.1 ± 1.3	27.5 ± 3.5	< 96	48.3 ± 1.2	53.3 ± 5.9	50.1 ± 8.7	50.9 ± 16.2	100	0.27	44.0	0.05
49.9 ± 1.9	53.9 ± 5.1	53.8 ± 25	86.0 ± 2.0	80.3 ± 8.5	79.8 ± 11.5	< 92	177	0.50	76.8	0.09
33.8 ± 1.4	52.7 ± 5.0	< 119	51.5 ± 1.2	78.2 ± 8.3	78.2 ± 11.4	< 90	126	0.36	55.5	0.07
Baseline 6										
28.2 ± 1.1	31.9 ± 3.6	48.6 ± 6.7	15.2 ± 0.61	24.8 ± 4.1	16.3 ± 3.8	147 ± 21	64.7	0.17	29.9	0.04
28.5 ± 1.1	55.3 ± 4.5	51.1 ± 9.4	15.1 ± 0.61	31.1 ± 5.9	33.8 ± 4.7	629 ± 41	125	0.34	60.9	0.07
57.7 ± 2.1	34.6 ± 3.7	38.7 ± 6.8	30.8 ± 1.4	8.72 ± 3.6	20.9 ± 3.3	182 ± 23	92.7	0.25	42.2	0.05
39.3 ± 1.5	28.2 ± 3.5	44.1 ± 7.8	14.8 ± 0.61	19.7 ± 4.3	17.1 ± 2.9	257 ± 27	69.2	0.19	32.7	0.04

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
38.8 ± 1.5	20.6 ± 3.0	22.0 ± 7.1	17.9 ± 0.72	14.9 ± 4.4	18.9 ± 3.8	145 ± 20	57.4	0.15	26.4	0.03
Mineral Sands Industry										
64.9 ± 1.1	44.8 ± 4.6	84.1 ± 19.3	85.2 ± 7.3	55.1 ± 7.3	49.3 ± 5.4	734 ± 47	223	0.60	103	0.13
5.71 ± 0.45	13.4 ± 1.7	< 80	9.49 ± 0.51	13.3 ± 2.3	10.3 ± 1.6	485 ± 23	64.3	0.17	32.1	0.04
10.2 ± 0.61	16.6 ± 1.8	< 85	5.61 ± 0.43	12.3 ± 2.4	12.0 ± 1.6	227 ± 15	42.1	0.11	20.5	0.03
40.1 ± 0.82	28.6 ± 3.7	± 100	30.6 ± 1.1	26.3 ± 5.3	22.3 ± 8.3	567 ± 40	116	0.31	55.3	0.07
41.1 ± 0.81	34.6 ± 4.5	< 97	43.4 ± 1.2	28.5 ± 6.1	43.5 ± 11.2	691 ± 46	150	0.40	71.0	0.09
87.5 ± 3.3	81.5 ± 9.8	95.3 ± 23.8	128 ± 2.4	111 ± 17	108 ± 25	< 264	265	0.77	115	0.14
17.3 ± 0.71	22.4 ± 3.8	< 85	22.8 ± 0.92	24.3 ± 5.5	16.2 ± 3.8	123 ± 25	64.5	0.17	29.2	0.04
Gold Mines 1										
31.5 ± 1.8	36.4 ± 3.6	110 ± 22	20.0 ± 0.91	16.1 ± 4.9	27.9 ± 7.4	191 ± 24	79.8	0.22	36.9	0.05
41.9 ± 2.2	41.9 ± 3.6	47.4 ± 20.5	23.7 ± 1.2	21.7 ± 5.3	25.0 ± 3.2	187 ± 24	90.2	0.24	41.5	0.05
44.2 ± 2.2	36.2 ± 3.5	33.2 ± 16.1	22.8 ± 1.3	28.1 ± 5.2	25.5 ± 3.5	168 ± 23	81.8	0.22	37.5	0.05
47.9 ± 2.3	94.2 ± 3.9	98.9 ± 21.2	17.2 ± 0.92	25.8 ± 3.2	19.1 ± 4.7	208 ± 15	135	0.36	62.6	0.08
48.3 ± 2.4	53.3 ± 3.1	114 ± 28	23.6 ± 1.1	32.9 ± 3.5	27.5 ± 5.8	290 ± 18	109	0.30	51.0	0.06
44.1 ± 2.2	42.4 ± 2.7	< 100	24.9 ± 1.1	21.3 ± 3.2	21.0 ± 4.7	282 ± 17	99.7	0.27	46.4	0.06
40.9 ± 2.1	36.7 ± 2.9	< 98	25.9 ± 1.2	24.8 ± 4.1	27.2 ± 6.3	254 ± 22	93.4	0.25	43.2	0.05
43.3 ± 2.2	81.1 ± 4.2	117 ± 25	15.9 ± 0.90	8.81 ± 3.6	16.6 ± 2.5	234 ± 22	122	0.33	56.8	0.07
34.3 ± 1.9	32.8 ± 2.9	52.2 ± 16.6	22.9 ± 1.2	17.6 ± 3.7	26.2 ± 5.8	287 ± 23	87.7	0.24	41.0	0.05
37.2 ± 2.0	38.5 ± 3.1	< 93	29.0 ± 1.1	18.6 ± 4.1	27.5 ± 6.7	348 ± 26	107	0.29	49.9	0.06
43.7 ± 2.2	50.7 ± 3.6	66.2 ± 30.3	21.3 ± 1.1	25.8 ± 4.5	26.3 ± 7.1	63.6 ± 15.6	85.9	0.23	38.9	0.05
38.8 ± 2.0	52.5 ± 3.1	72.1 ± 23.1	21.8 ± 0.91	25.2 ± 3.5	29.5 ± 6.1	131 ± 14	93.7	0.25	42.8	0.05
Gold Mines 2										
25.7 ± 0.65	33.2 ± 3.7	-	16.0 ± 1.1	16.8 ± 4.4	19.7 ± 3.5	133 ± 24	66.3	0.18	30.6	0.04
26.9 ± 0.66	22.2 ± 3.2	-	16.4 ± 1.1	25.4 ± 4.1	14.0 ± 3.5	103 ± 20	53.6	0.14	24.5	0.03
31.4 ± 0.70	43.3 ± 4.2	-	18.5 ± 1.1	23.7 ± 5.2	36.2 ± 4.3	172 ± 25	83.0	0.22	38.4	0.05
41.1 ± 0.81	29.5 ± 3.5	-	16.7 ± 1.1	22.3 ± 4.8	22.3 ± 3.5	111 ± 22	61.9	0.17	28.4	0.03
44.8 ± 0.86	46.0 ± 4.1	-	18.9 ± 1.2	19.7 ± 4.8	18.9 ± 3.8	187 ± 26	87.6	0.24	40.5	0.05

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
Gold Mines 3										
30.3 ± 0.78	23.8 ± 3.3	34.6 ± 16.6	14.9 ± 0.42	20.2 ± 4.2	12.6 ± 3.2	97.3 ± 21.8	52.6	0.14	24.1	0.03
31.6 ± 0.80	33.2 ± 3.5	36.2 ± 17.4	15.2 ± 0.42	22.3 ± 4.8	14.4 ± 3.5	57.5 ± 19.7	59.2	0.16	26.8	0.03
31.8 ± 0.82	35.0 ± 3.6	67.1 ± 17.6	15.8 ± 0.51	17.7 ± 4.9	16.3 ± 3.1	49.1 ± 20.2	61.3	0.17	27.7	0.03
39.9 ± 0.89	13.1 ± 1.7	70.2 ± 18.2	15.6 ± 0.51	7.26 ± 2.1	9.02 ± 1.4	34.2 ± 9.77	38.1	0.10	16.9	0.02
50.4 ± 1.0	60.2 ± 5.3	113 ± 25	18.8 ± 0.52	20.6 ± 5.8	23.0 ± 3.9	74.5 ± 24.1	92.7	0.25	42.2	0.05
42.9 ± 0.93	45.5 ± 4.1	82.4 ± 21.4	18.0 ± 0.51	17.9 ± 5.1	22.7 ± 3.4	47.8 ± 20.9	74.9	0.20	33.9	0.04
40.1 ± 0.91	39.9 ± 3.8	57.2 ± 15.8	17.5 ± 0.52	23.1 ± 5.2	23.6 ± 3.3	73.2 ± 20.9	70.7	0.19	32.1	0.04

Table C-5: Results for tailings and waste rock from gold mine area - Activity concentration in Bq.kg^{-1}, Radium equivalent dose, Ra_{eq} in Bq.kg^{-1}, Gamma Index (H_{ex}), Absorbed dose, D (nGy.h^{-1}) and Annual effective dose rate, AED (mSv.a^{-1})

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
TAILINGS										
Tailings 1										
553 ± 2.8	592 ± 17	641 ± 38	41.2 ± 1.2	34.4 ± 8.2	40.1 ± 6.2	307 ± 41	674	1.82	311	0.38
302 ± 8.2	333 ± 20	398 ± 35	29.7 ± 0.93	34.1 ± 17.4	40.2 ± 6.5	257 ± 102	395	1.07	183	0.22
201 ± 5.5	231 ± 17	273 ± 37	22.8 ± 1.6	< 83	39.2 ± 11.6	< 406	264	0.71	121	0.15
456 ± 14	525 ± 25	597 ± 39	31.1 ± 1.3	60.3 ± 20.2	< 137	169 ± 90	582	1.57	268	0.33
465 ± 31	507 ± 24	798 ± 75	33.4 ± 0.73	56.4 ± 19.1	36.4 ± 6.3	388 ± 96	585	1.58	271	0.33
251 ± 2.1	372 ± 23	591 ± 70	29.5 ± 0.65	37.6 ± 16.2	34.2 ± 7.5	< 457	414	1.12	190	0.23
388 ± 11	395 ± 22	647 ± 63	27.9 ± 1.3	< 81	28.3 ± 10.8	205 ± 83	451	1.22	208	0.26
Tailings 2										
236 ± 1.9	277 ± 11	373 ± 34	30.3 ± 1.8	34.5 ± 7.9	33.1 ± 5.4	192 ± 32	335	0.91	154	0.19
290 ± 9.1	285 ± 18	385 ± 29	32.1 ± 0.93	< 71	30.2 ± 6.4	< 375	331	0.89	151	0.19
321 ± 21	349 ± 20	578 ± 57	31.3 ± 0.69	< 87	34.1 ± 5.9	245 ± 8.4	412	1.11	190	0.23

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
382 ± 2.7	435 ± 25	708 ± 72	26.8 ± 0.61	< 110	26.1 ± 10.7	260 ± 105	494	1.33	228	0.28
323 ± 9.2	342 ± 20	499 ± 59	29.3 ± 1.1	29.1 ± 16.2	31.8 ± 10.5	182 ± 82	398	1.07	183	0.22
Tailings 3										
94.1 ± 2.3	82.4 ± 4.7	120 ± 25	9.37 ± 1.6	6.21 ± 3.5	7.53 ± 2.5	127 ± 19	106	0.29	49.0	0.06
114 ± 2.8	83.7 ± 4.7	92.3 ± 25.6	10.1 ± 1.4	4.88 ± 3.1	9.06 ± 2.6	95.7 ± 18	105	0.28	48.7	0.06
82.5 ± 2.9	60.2 ± 4.1	70.2 ± 21.4	10.2 ± 0.73	13.8 ± 4.2	11.8 ± 2.5	147 ± 20	85.9	0.23	40.0	0.05
205 ± 4.3	198 ± 7.9	230 ± 27	16.1 ± 0.69	1.95 ± 4.7	9.88 ± 4.8	146 ± 25	232	0.63	107	0.13
94.1 ± 4.7	158 ± 7.4	189 ± 24	12.1 ± 0.85	12.1 ± 5.6	13.7 ± 2.2	146 ± 27	186	0.50	86.2	0.11
181 ± 12	166 ± 16	207 ± 36	12.3 ± 1.5	< 74	< 119	< 369	184	0.50	84.2	0.10
161 ± 2.1	97.1 ± 5.7	100 ± 20	13.8 ± 0.69	< 26	8.95 ± 3.1	123 ± 24	126	0.34	58.3	0.07
184 ± 6.1	167 ± 7.7	150 ± 23	12.8 ± 0.41	10.7 ± 5.4	13.3 ± 4.1	137 ± 27	196	0.53	90.7	0.11
235 ± 2.1	156 ± 14	188 ± 50	12.7 ± 0.41	< 66	18.1 ± 4.9	154 ± 72	185	0.50	86.1	0.11
110 ± 1.8	165 ± 7.1	176 ± 42	11.6 ± 0.57	15.2 ± 5.4	16.8 ± 3.3	199 ± 26	197	0.53	91.5	0.11
Tailings 4										
241 ± 7.7	215 ± 7.6	247 ± 30	21.7 ± 0.69	11.7 ± 4.3	23.6 ± 8.2	153 ± 23	258	0.70	119	0.15
209 ± 4.4	197 ± 8.2	280 ± 20	28.5 ± 1.0	23.4 ± 6.8	26.8 ± 9.9	149 ± 26	249	0.67	114	0.14
163 ± 8.3	154 ± 7.4	190 ± 22	19.8 ± 0.85	12.1 ± 6.3	17.7 ± 2.3	165 ± 28	195	0.53	90.1	0.11
574 ± 6.9	513 ± 16	608 ± 47	42.6 ± 1.6	53.7 ± 11.2	29.9 ± 6.3	268 ± 41	594	1.61	274	0.34
452 ± 10	243 ± 9.8	341 ± 87	17.2 ± 0.45	12.2 ± 6.8	17.6 ± 4.5	151 ± 27	279	0.75	129	0.16
326 ± 11	589 ± 17	693 ± 39	37.9 ± 0.81	< 48	35.4 ± 9.1	323 ± 44	668	1.80	308	0.38
282 ± 2.3	202 ± 15	463 ± 60	18.1 ± 0.49	37.9 ± 13.5	28.5 ± 4.9	121 ± 65	238	0.64	109	0.13
283 ± 3.4	230 ± 8.8	366 ± 52	16.8 ± 0.81	23.1 ± 6.3	20.3 ± 5.2	171 ± 27	267	0.72	124	0.15
Tailings 5										
510 ± 9.5	316 ± 21	600 ± 37	22.9 ± 0.89	30.3 ± 7.2	28.6 ± 6.7	280 ± 30	371	1.00	172	0.21
668 ± 31	623 ± 16	777 ± 46	29.5 ± 1.3	17.7 ± 7.7	24.1 ± 5.6	174 ± 30	679	1.83	313	0.38
420 ± 9.6	552 ± 9.9	649 ± 38	19.1 ± 0.53	19.7 ± 5.4	14.7 ± 3.4	129 ± 20	590	1.59	272	0.33
609 ± 18	591 ± 16	796 ± 42	26.5 ± 1.1	17.1 ± 8.4	16.7 ± 5.6	171 ± 30	642	1.73	296	0.36

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
612 ± 41	591 ± 30	810 ± 56	24.9 ± 1.0	< 112	< 160	185 ± 112	641	1.73	296	0.36
584 ± 23	507 ± 23	686 ± 47	26.3 ± 1.4	25.3 ± 14.9	< 113	114 ± 74	553	1.49	255	0.31
449 ± 9.1	368 ± 19	582 ± 42	24.4 ± 0.93	< 77	29.5 ± 8.9	117 ± 75	412	1.11	190	0.23
412 ± 23	454 ± 22	753 ± 78	21.9 ± 2.6	< 98	< 135	342 ± 93	512	1.38	237	0.29
Tailings 6										
482 ± 22	464 ± 14	707 ± 40	26.2 ± 1.1	12.8 ± 7.5	26.4 ± 12.4	193 ± 3.4	516	1.39	238	0.29
556 ± 13	542 ± 12	555 ± 41	23.9 ± 0.65	26.8 ± 5.8	23.2 ± 9.6	173 ± 24	589	1.59	272	0.33
342 ± 10	359 ± 11	445 ± 32	22.2 ± 0.85	16.9 ± 7.3	13.6 ± 6.1	199 ± 29	406	1.10	188	0.23
426 ± 23	395 ± 21	785 ± 68	20.5 ± 2.3	< 80	< 141	191 ± 83	439	1.19	203	0.25
Tailings 7										
390 ± 2.9	442 ± 12	446 ± 36	32.4 ± 0.85	23.6 ± 7.4	22.7 ± 5.3	225 ± 27	506	1.37	233	0.29
527 ± 1.9	545 ± 23	838 ± 42	11.6 ± 0.43	< 85	< 114	< 324	562	1.52	259	0.32
398 ± 2.9	819 ± 35	901 ± 50	33.3 ± 2.7	35.5 ± 24.6	< 174	< 487	867	2.34	399	0.49
444 ± 14	662 ± 28	696 ± 43	31.3 ± 1.6	35.8 ± 17.2	28.2 ± 15.8	< 397	707	1.91	325	0.40
231 ± 7.3	290 ± 19	356 ± 37	23.2 ± 0.88	< 88	28.6 ± 9.9	405 ± 94	355	0.96	165	0.20
WASTE ROCK										
Waste Rock 1										
51.2 ± 1.6	49.3 ± 3.7	< 99	12.6 ± 0.45	9.71 ± 4.7	12.9 ± 2.9	333 ± 28	93.0	0.25	44.3	0.05
45.8 ± 1.9	37.6 ± 4.4	< 103	13.7 ± 0.69	37.6 ± 5.7	12.0 ± 3.9	501 ± 38	95.8	0.26	46.6	0.06
42.2 ± 2.2	39.3 ± 4.6	< 86	13.5 ± 0.69	15.2 ± 5.6	16.1 ± 3.8	369 ± 39	86.9	0.23	41.6	0.05
47.3 ± 1.7	43.1 ± 4.8	< 102	11.7 ± 0.65	< 29	7.34 ± 3.16	301 ± 36	83.0	0.22	39.5	0.05
46.1 ± 1.3	43.2 ± 9.8	< 122	14.2 ± 0.73	< 68	< 99.2	139 ± 74	74.3	0.20	34.4	0.04
46.9 ± 2.7	< 46.8	89.3 ± 38	18.4 ± 2.3	< 79	< 103	457 ± 91	61.5	0.17	30.2	0.04
Waste Rock 2										
37.8 ± 2.1	22.6 ± 2.2	< 110	30.2 ± 1.3	30.4 ± 3.8	32.7 ± 6.3	441 ± 25	99.5	0.27	47.0	0.06
50.3 ± 2.2	44.7 ± 4.2	68.9 ± 21	27.3 ± 1.0	18.0 ± 5.8	14.6 ± 3.8	275 ± 29	105	0.28	48.6	0.06
35.6 ± 1.3	28.4 ± 3.6	< 92	15.9 ± 0.77	20.6 ± 5.2	15.2 ± 3.5	333 ± 34	76.7	0.21	36.6	0.04

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
28.0 ± 1.7	21.7 ± 2.1	< 93	12.9 ± 0.73	18.1 ± 2.8	13.0 ± 1.9	428 ± 23	73.0	0.20	35.6	0.04
52.0 ± 2.3	66.7 ± 4.9	86.2 ± 25	13.3 ± 0.61	31.6 ± 5.8	12.3 ± 3.3	291 ± 31	108	0.29	51.0	0.06
26.5 ± 0.9	28.3 ± 3.6	< 89	12.9 ± 0.65	< 25	14.7 ± 3.7	388 ± 35	76.6	0.21	37.0	0.05
16.3 ± 1.3	9.93 ± 1.8	< 88	12.8 ± 0.73	19.4 ± 2.6	13.5 ± 4.3	209 ± 16	44.3	0.12	21.0	0.03
15.6 ± 0.8	21.6 ± 3.5	< 88	11.9 ± 0.57	20.4 ± 5.1	10.0 ± 3.3	297 ± 31	61.5	0.17	29.5	0.04
21.7 ± 0.8	16.9 ± 3.4	< 88	11.6 ± 0.57	< 24	10.9 ± 3.4	250 ± 30	52.8	0.14	25.3	0.03
Waste Rock 3										
34.9 ± 0.8	36.6 ± 4.2	± 102	12.9 ± 0.57	17.0 ± 5.2	17.1 ± 3.43	459 ± 39	90.4	0.24	43.9	0.05
56.8 ± 1.2	42.9 ± 4.1	130 ± 26	13.1 ± 0.65	20.5 ± 4.6	12.7 ± 2.95	319 ± 31	86.1	0.23	41.0	0.05
39.0 ± 0.8	32.5 ± 4.1	< 86	13.5 ± 0.61	10.9 ± 4.8	20.8 ± 3.93	471 ± 38	88.0	0.24	42.8	0.05
27.1 ± 0.7	29.9 ± 3.7	47.5 ± 22	12.2 ± 0.57	19.6 ± 4.5	20.9 ± 3.52	462 ± 37	82.7	0.22	40.3	0.05
53.7 ± 1	61.5 ± 4.71	36.8 ± 21	12.4 ± 0.49	19.1 ± 4.9	19.3 ± 3.4	272 ± 30	100	0.27	47.3	0.06
65.1 ± 1.1	69.7 ± 4.92	64.7 ± 19	15.8 ± 0.61	18.3 ± 5.2	16.3 ± 3.6	340 ± 31	118	0.32	55.9	0.07
50.9 ± 1	30.2 ± 3.68	< 105	12.6 ± 0.57	16.9 ± 4.4	18.6 ± 3.6	391 ± 34	78.3	0.21	37.9	0.05
Waste Rock 4										
31.1 ± 1.1	81.7 ± 4.2	76.9 ± 9.9	22.3 ± 2.4	13.2 ± 6.1	21.7 ± 2.2	187 ± 30	128	0.35	59.0	0.07
19.1 ± 0.8	5.83 ± 1.9	11.7 ± 7.3	16.2 ± 2.8	< 20	5.16 ± 3.3	376 ± 33	58.0	0.16	28.2	0.03
20.7 ± 0.8	19.1 ± 2.9	26.2 ± 6.2	19.4 ± 2.3	< 25	12.8 ± 2.8	186 ± 31	61.1	0.17	28.3	0.03
90.7 ± 2.8	84 ± 4.1	175 ± 17	27.5 ± 2.8	18 ± 6	22.2 ± 2.3	303 ± 35	147	0.40	68.1	0.08
17.8 ± 0.7	7.87 ± 2.6	< 24	15.6 ± 1.9	< 33	14.6 ± 2.9	813 ± 57	92.8	0.25	47.0	0.06
Waste Rock 5										
30.6 ± 0.8	29.7 ± 4.2	< 83	12.1 ± 0.77	14.8 ± 5.3	21.4 ± 3.9	476 ± 40	83.7	0.23	40.9	0.05
15.6 ± 1.2	16 ± 2.5	< 86	9.25 ± 0.49	5.47 ± 2.9	11.8 ± 2.4	198 ± 22	44.5	0.12	21.2	0.03
24.2 ± 1.4	22.5 ± 3.0	< 84	14.2 ± 0.61	11.8 ± 3.5	12.9 ± 2.6	302 ± 26	65.7	0.18	31.4	0.04
23.8 ± 1.4	22.8 ± 3.0	< 93	11.7 ± 0.53	< 19	12.4 ± 2.5	389 ± 29	69.4	0.19	33.8	0.04
16.1 ± 1.1	13.3 ± 2.8	< 86	8.76 ± 0.41	< 18	10.8 ± 2.9	371 ± 29	54.4	0.15	26.9	0.03

Table C-6: Results for samples from the coal industry: Activity concentration in Bq.kg^{-1}, Radium equivalent dose, Ra_{eq} in Bq.kg^{-1}, Gamma Index (I_γ), External gamma dose rate, D (nGy.h^{-1}) and Annual effective dose, AED (mSv.a^{-1})

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	I_γ	D	AED
Coal										
89.0 ± 1.2	70.5 ± 5.9	< 130	80.3 ± 4.9	79.4 ± 9.4	87.3 ± 7.3	150 ± 29	197	0.69	87.3	0.11
89.1 ± 1.2	100 ± 8	< 120	82 ± 5.3	97.6 ± 11	112 ± 9	202 ± 35	233	0.81	104	0.13
35.9 ± 0.8	37.4 ± 5.5	< 120	34.5 ± 2.2	53.8 ± 8.5	45.1 ± 6.5	113 ± 32	95	0.33	42.8	0.05
37.4 ± 0.8	55.7 ± 6	< 110	35.8 ± 2.3	44.2 ± 8.5	58.5 ± 7.7	141 ± 33	118	0.41	53.2	0.07
38.5 ± 0.8	46.1 ± 6.6	< 110	36 ± 2.3	44.1 ± 9.2	60.1 ± 7.2	127 ± 34	107	0.38	48.3	0.06
35.4 ± 0.8	42.4 ± 5.4	< 100	35 ± 2.2	49.6 ± 8.4	56.6 ± 6.8	155 ± 32	104	0.37	47.2	0.06
Fly ash										
222 ± 2	237 ± 18	-	180 ± 3	221 ± 28	254 ± 19	438 ± 75	528	1.84	236	0.29
172 ± 2	178 ± 13	-	161 ± 3	178 ± 19	189 ± 14	389 ± 59	438	1.53	196	0.24
204 ± 2	223 ± 15	-	182 ± 3	260 ± 25	250 ± 17	328 ± 63	509	1.76	227	0.28
184 ± 3	229 ± 18	-	161 ± 3	245 ± 28	237 ± 19	255 ± 79	479	1.65	214	0.26
218 ± 4	76.9 ± 6.2	-	187 ± 3	87.5 ± 9.5	79.8 ± 6.4	< 120	344	1.19	148	0.18
246 ± 4	205 ± 19	-	187 ± 3	234 ± 28	243 ± 20	< 360	472	1.62	208	0.25
159 ± 3	195 ± 14	-	173 ± 3	153 ± 20	224 ± 16	311 ± 60	466	1.62	208	0.25
186 ± 2	161 ± 9	320 ± 32	156 ± 3	182 ± 13	184 ± 10	330 ± 39	409	1.43	182	0.22
144 ± 2	125 ± 9	138 ± 34	107 ± 4	127 ± 13	152 ± 11	213 ± 46	294	1.02	131	0.16
104 ± 1	116 ± 8	93 ± 33	81.1 ± 2.8	139 ± 13	128 ± 9	230 ± 41	250	0.87	112	0.14
163 ± 2	160 ± 11	127 ± 25	168 ± 6	180 ± 16	187 ± 12	163 ± 40	413	1.43	182	0.22
146 ± 2	144 ± 9	166 ± 29	151 ± 5	150 ± 13	186 ± 11	201 ± 35	375	1.30	166	0.20
144 ± 2	141 ± 9	184 ± 27	149 ± 5	161 ± 14	173 ± 10	240 ± 39	373	1.30	165	0.20
116 ± 2	107 ± 7	86.4 ± 20	121 ± 4	117 ± 11	114 ± 8	265 ± 33	300	1.05	134	0.16
104 ± 2	103 ± 7	< 110	108 ± 4	104 ± 10	107 ± 8	194 ± 30	272	0.95	121	0.15
108 ± 2	97.4 ± 6.9	63 ± 23	110 ± 3	124 ± 11	107 ± 8	262 ± 35	275	0.96	122	0.15
164 ± 3	158 ± 8	183 ± 27	148 ± 9	197 ± 13	176 ± 10	296 ± 34	392	1.37	175	0.21
114 ± 8	122 ± 8	125 ± 32	138 ± 6	120 ± 11	151 ± 18	248 ± 34	338	1.18	150	0.18
183 ± 9	169 ± 16	188 ± 37	212 ± 8	157 ± 24	177 ± 38	170 ± 74	485	1.68	213	0.26
203 ± 3	152 ± 10	148 ± 33	166 ± 14	166 ± 15	175 ± 14	176 ± 36	403	1.40	178	0.22
162 ± 3	146 ± 10	181 ± 35	178 ± 11	195 ± 17	186 ± 12	125 ± 38	410	1.42	180	0.22

Uranium-238			Radium-226			Lead-210			Thorium-232			Radium-228			Thorium-228			Potassium-40			Ra_{eq}	I_γ	D	AED
146	±		171	±			-		187	±		197	±		223	±		50	±		442	1.52	194	0.24
137	±		175	±			-		185	±		193	±		214	±		168	±		452	1.56	200	0.24
123	±		146	±			-		147	±		201	±		208	±		187	±		371	1.28	164	0.20
154	±		175	±			-		197	±		215	±		179	±		110	±		465	1.61	204	0.25
133	±		183	±			-		179	±		208	±		153	±		238	±		457	1.58	203	0.25
110	±		112	±			<	314	65	±			-		52	±		-			205	0.70	91.0	0.11
112	±		67	±			<	114	18	±			-		20	±		-			93	0.31	41.8	0.05
113	±		113	±			-		158	±		121	±		146	±		146	±		350	1.22	154	0.19
98	±		35	±			<	168	11	±			-		24	±		-			51	0.17	22.8	0.03
Slag																								
84.9	±	6.9	106	±	10		<	140	65.2	±	4.6	88.5	±	13	76.5	±	4.9	97	±	46	206	0.71	92.4	0.11
101	±	8	121	±	11		<	150	84.2	±	5.2	92	±	13	95.1	±	5.5	281	±	45	263	0.92	118	0.15
119	±	9	**141**	±	11		<	150	90	±	4.9	79.3	±	16	88.3	±	4.8	207	±	40	285	0.99	128	0.16
204	±	20	158	±	9	144	±	39	66.9	±	6.5	191	±	14	176	±	11	187	±	38	268	0.92	121	0.15

Table C-7: Results for solids from the phosphate industry - Activity concentration in $Bq.kg^{-1}$, Radium equivalent dose, Ra_{eq} in $Bq.kg^{-1}$, Gamma Index (H_{ex}), Absorbed dose, D ($nGy.h^{-1}$) and Annual effective dose rate, AED ($mSv.a^{-1}$)

Uranium-238			Radium-226			Lead-210			Thorium-232			Radium-228			Thorium-228			Potassium-40			Ra_{eq}	H_{ex}	D	AED
Phosphate rock																								
127	±	2	119	±	12	114	±	30	511	±	32	459	±	30	523	±	186		<	220	850	2.29	364	0.45
137	±	2	127	±	7		<	130	483	±	8	509	±	17	517	±	16	156	±	25	830	2.24	350	0.43
122	±	4	97.3	±	11.1	100	±	37	527	±	12	506	±	31	537	±	41	317	±	57	875	2.36	363	0.45
133	±	8	131	±	13	214	±	38	515	±	16	534	±	30	594	±	46		<	270	868	2.34	372	0.46
Phosphogypsum – results in Table C-5																								

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	Potassium-40	Ra_{eq}	H_{ex}	D	AED
Fertilizer SSP										
84.5 ± 1.1	65.7 ± 15.4	< 140	316 ± 9	313 ± 32	333 ± 53	< 410	518	1.40	221	0.27
92.4 ± 1.2	90.0 ± 14.7	100 ± 34	327 ± 9	273 ± 31	343 ± 42	< 350	558	1.51	239	0.29
97.9 ± 1.2	54.6 ± 13.5	79 ± 28	317 ± 9	233 ± 29	311 ± 44	< 350	508	1.37	217	0.27
Fertilizer MAP										
202 ± 2	36 ± 16	< 130	383 ± 12	< 120	298 ± 48	< 560	584	1.58	248	0.30
202 ± 2	< 60	< 110	410 ± 12	35.1 ± 16.0	327 ± 46	< 450	586	1.58	248	0.30
215 ± 2	< 50	< 110	343 ± 11	< 90	270 ± 44	< 380	490	1.32	207	0.25
Dust/Scale in plant										
56.5 ± 9.1	56.0 ± 7.4	5280 ± 90	35.4 ± 0.9	51.5 ± 10.9	36.5 ± 7.2	55 ± 34	111	0.30	47.3	0.06
232 ± 9.2	229 ± 26	7640 ± 140	207 ± 3	303 ± 42	244 ± 27	< 520	525	1.42	231	0.28
7.01 ± 0.34	15.0 ± 9.0	< 170	2450 ± 60	643 ± 27	1050 ± 50	128 ± 38	3528	9.53	1486	1.82
Tailings and waste										
42.6 ± 1.4	38.6 ± 4.6	< 91	90.9 ± 1.6	114 ± 8	99.8 ± 6.3	190 ± 29	183	0.49	72.7	0.09
16.1 ± 0.5	13.5 ± 2.6	< 75	38.9 ± 0.9	37.8 ± 5.5	48.9 ± 3.8	343 ± 28	95.5	0.26	29.7	0.04
91.4 ± 2.6	75.6 ± 4.8	150 ± 36	92.1 ± 1.6	89.4 ± 6.4	79.1 ± 5.1	< 64	207	0.56	90.6	0.11
50.6 ± 0.9	49.9 ± 3.2	< 130	55.2 ± 1.2	63.3 ± 5	55.0 ± 3.8	28 ± 10	131	0.35	56.4	0.07
47.4 ± 1.5	25.4 ± 5.6	< 96	31.3 ± 0.7	30.8 ± 7.3	29.8 ± 6.1	572 ± 52	114	0.31	30.6	0.04
16.1 ± 0.5	16.3 ± 2.8	< 65	44.2 ± 0.8	48.3 ± 5.6	47.8 ± 4.2	371 ± 30	108	0.29	34.2	0.04
10.7 ± 0.7	39.3 ± 30	< 120	13.2 ± 0.7	< 83	8.3 ± 8.6	390 ± 190	88.2	0.24	26.1	0.03
Soil										
12.7 ± 0.5	4.6 ± 1.8	9.52 ± 1.8	10.2 ± 0.4	12.2 ± 0.8	12.4 ± 0.5	827 ± 19	82.9	0.22	8.3	0.01
12.7 ± 0.9	< 42	< 96	19.8 ± 1.5	< 79	< 100	170 ± 83	41.4	0.11	12.0	0.01

Table C-8: Results for solids from mineral sands industry - Activity concentration in $Bq.kg^{-1}$ and Annual effective dose, AED ($mSv.a^{-1}$)

Uranium-238			Radium-226			Lead-210			Thorium-232			Radium-228			Thorium-228			AED
TiO_2 production																		
Heavy mineral concentrate; intermediate products and tailings																		
1900	±	20	2230	±	180	444	±	33	1410	±	20	1710	±	50	1610	±	60	0.73
3970	±	40	4300	±	360	781	±	57	1440	±	20	1920	±	50	1740	±	70	1.09
4090	±	260	3470	±	60	2790	±	120	1910	±	60	2130	±	40	1960	±	50	1.01
1840	±	20	1560	±	30	1650	±	100	807	±	20	676	±	22	667	±	36	0.40
5270	±	120	4010	±	70	2910	±	130	2970	±	80	2950	±	70	2710	±	110	1.27
6420	±	150	4830	±	80	4860	±	260	2810	±	80	2390	±	70	2370	±	100	1.31
5100	±	50	4550	±	80	6180	±	320	3570	±	100	3480	±	90	3380	±	140	1.50
5630	±	60	4650	±	80	4900	±	260	3120	±	90	2890	±	80	2870	±	120	1.39
4070	±	60	3450	±	66	5680	±	520	1750	±	30	1660	±	70	1670	±	90	0.92
3500	±	40	3680	±	310	605	±	44	2190	±	20	2640	±	70	2500	±	100	1.17
7860	±	80	7500	±	660	944	±	69	4710	±	80	5580	±	150	5090	±	200	2.39
Ilmenite																		
291	±	3	201	±	8	344	±	63	605	±	16	500	±	15	488	±	23	0.15
193	±	2	210	±	8	371	±	48	536	±	16	466	±	14	436	±	21	0.14
118	±	1	97	±	5	120	±	44	282	±	9	260	±	9	245	±	14	0.07
252	±	10	210	±	12	331	±	74	840	±	20	678	±	28	730	±	45	0.20
19.3	±	0.8	20.1	±	5.5		<	110	30.3	±	1.1	25	±	10	27.2	±	6.1	0.01
344	±	6	280	±	15	443.2	±	113	564	±	8	532	±	27	550	±	41	0.17
Byproducts																		
Gypsum																		
277	±	3	326	±	39	310	±	32	953	±	16	881	±	27	1010	±	40	0.27
186	±	2	153	±	11	272	±	43	1310	±	30	811	±	28	1050	±	50	0.25
377	±	21		<	97	618	±	96	674	±	16	404	±	36	433	±	45	0.10

Uranium-238	Radium-226	Lead-210	Thorium-232	Radium-228	Thorium-228	AED
Slag						
60.5 ± 1.0	44.1 ± 3.4	< 25	83.6 ± 3.2	76.9 ± 5.9	72.6 ± 4.6	0.02
30.9 ± 0.7	22.1 ± 2.6	< 18	33.8 ± 1.4	30.3 ± 4.1	36.8 ± 3.2	0.01
40.4 ± 1.4	33.6 ± 7.6	< 110	63.3 ± 1.6	67.7 ± 12.8	78.2 ± 9.3	0.02
45.6 ± 1.5	47.5 ± 8.7	< 120	73.0 ± 2	97.5 ± 14.6	75 ± 10	0.03
Quartz						
2510 ± 30	2990 ± 240	650 ± 48	771 ± 12	987 ± 26	942 ± 38	0.65
4690 ± 50	5000 ± 420	784 ± 57	1530 ± 20	1830 ± 50	1670 ± 70	1.12
2940 ± 30	2280 ± 40	2500 ± 140	1660 ± 50	1540 ± 30	1490 ± 50	0.67
2770 ± 40	2490 ± 60	3420 ± 300	970 ± 16	882 ± 53.96	927 ± 73	0.57
Zirconia production						
Fumed silica						
1130 ± 10	5600 ± 100	8030 ± 580	52.1 ± 0.5	94.5 ± 1.6	879 ± 55	0.96
3410 ± 160	6660 ± 120	4710 ± 340	157 ± 7	177 ± 8	787 ± 55	1.11
Zirconia						
4900 ± 50	1690 ± 30	< 21	226 ± 2	824 ± 12	332 ± 13	0.36
5510 ± 270	1430 ± 30	< 75	254 ± 13	694 ± 32	234 ± 12	0.30
3900 ± 40	2490 ± 40	421 ± 32	180 ± 2	669 ± 12	495 ± 16	0.49
5140 ± 250	3110 ± 50	< 75	236 ± 11	690 ± 32	439 ± 23	0.58
Zircon						
6190 ± 60	6470 ± 550	710 ± 52	4090 ± 40	4800 ± 130	4370 ± 180	1.95
9760 ± 100	10900 ± 900	1130 ± 80	6490 ± 80	8120 ± 210	7460 ± 300	3.31
7220 ± 70	5770 ± 100	3590 ± 210	5920 ± 160	6240 ± 90	5520 ± 120	2.13
9220 ± 200	9380 ± 140	10400 ± 600	4830 ± 160	8200 ± 140	8360 ± 190	3.21
8840 ± 200	7480 ± 120	5050 ± 290	3810 ± 110	3540 ± 90	3540 ± 140	1.89
5990 ± 90	5250 ± 90	7600 ± 810	3640 ± 60	3550 ± 80	3630 ± 540	1.57
Monazite						
3910 ± 360	6700 ± 120	4690 ± 1380	92100 ± 5300	132100 ± 1800	118500 ± 2600	19.5

Uranium-238			Radium-226			Lead-210			Thorium-232			Radium-228			Thorium-228			AED
1640	±	50	1230	±	60	1120	±	370	28600	±	600	18200	±	300	18100	±	425	2.9
6150	±	40	7140	±	160	4160	±	190	92500	±	3200	150400	±	1600	145000	±	2572	231
3540	±	30	3520	±	80	4270	±	270	36190	±	3000	51500	±	700	49700	±	1136	8.0
2540	±	100	2840	±	70	3690	±	190	30600	±	900	35500	±	500	36000	±	779	5.7
2010	±	60	2350	±	80	3800	±	190	27900	±	600	29500	±	400	29000	±	626	4.7
2740	±	20	3620	±	100	5330	±	410	36200	±	900	43800	±	600	43900	±	900	7.0
4770	±	180	7440	±	150	5580	±	390	62100	±	2400	96200	±	1200	91400	±	1700	15
7890	±	50	9980	±	220	11900	±	650	98600	±	3700	173800	±	2100	165000	±	300	27

Table C-9: Results for water samples in area impacted by phosphate industry (Activity concentrations $mBq.L^{-1}$; Dose $\mu Sv.a^{-1}$)

	U-238			U-234			Th-230			Ra-226			Pb-210			Po-210			Th-232			Th-228			< 1 a	> 17 a
Surface water 1																										
Mar 2011	56.1	±	10.8	129	±	17	23.4	±	4.7	5.1	±	2.1	3.2	±	2.4	3.2	±	2.4	4.9	±	1.3	1.9	±	0.8	100	21
Oct 2011	30.0	±	4.3	50.2	±	5.6	16.2	±	4.0	2.9	±	0.9	0.7	±	0.8	0.7	±	0.8	2.8	±	1.2	6.6	±	2.1	94	14
Oct 2013	12.7	±	3.2	56.8	±	6.8	11.6	±	2.9	3.2	±	1.1	2.0	±	1.8	2.0	±	1.8	0.6	±	0.7	2.6	±	1.1	79	13
Feb 2014	104	±	9.5	120	±	10	115	±	10	0.0	±	0.7	1.0	±	1.4	1.0	±	1.4	24.7	±	4.7	7.6	±	2.8	240	43
Jul 2014	37.0	±	9.6	109	±	15	50.2	±	9.4	1.4	±	0.7	13.4	±	4.1	13.4	±	4.1	6.2	±	2.0	3.1	±	1.6	320	69
Nov 2014	56.8	±	8.6	68.6	±	9.4	20.7	±	5.2	10.2	±	2.1	9.2	±	4.1	9.2	±	4.1	1.7	±	1.7	7.6	±	3.5	180	31
Mar 2015	26.9	±	4.8	66.0	±	7.5	36.0	±	9.3	1.4	±	0.6	29.1	±	13.8	1.5	±	5.8	9.3	±	3.8	9.2	±	4.8	240	43
Surface water 2																										
Mar 2011	32.8	±	6.2	76.5	±	10.1	30.9	±	5.7	4.4	±	1.6	2.7	±	2.0	2.7	±	2.0	0.7	±	0.5	1.1	±	0.6	92	18
Oct 2011	63.8	±	5.8	70.3	±	6.2	22.8	±	5.3	12.5	±	1.9	1.6	±	1.5	1.6	±	1.5	2.0	±	1.1	11.9	±	2.8	150	23
Oct 2013	38.8	±	5.1	75.1	±	7.2	13.7	±	3.1	3.4	±	1.1	2.3	±	1.9	2.3	±	1.9	0.0	±	0.5	1.8	±	0.8	86	16

	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228	< 1 a	> 17 a
Feb 2014	58.4 ± 7.5	134 ± 11	98.6 ± 40.7	2.4 ± 1.0	0.6 ± 1.6	0.6 ± 1.6	3.6 ± 5.8	12.2 ± 3.9	480	79
Nov 2014	23.7 ± 4.9	58.7 ± 8.0	12.5 ± 3.2	2.3 ± 0.8	6.4 ± 3.3	6.4 ± 3.3	1.0 ± 0.7	3.6 ± 1.8	140	23
Mar 2015	63.5 ± 10.9	88.6 ± 13.1	49.2 ± 10.3	2.8 ± 0.9	16.5 ± 7.8	-2.0 ± 3.1	9.0 ± 3.0	4.9 ± 3.3	190	36
Surface water 3										
Mar 2011	69.5 ± 12.7	148 ± 19	30.1 ± 6.0	6.9 ± 2.3	9.7 ± 3.9	9.7 ± 3.9	2.4 ± 1.1	6.8 ± 1.8	190	36
Oct 2011	75.8 ± 13.6	200 ± 23	36.1 ± 7.6	3.2 ± 0.9	1.9 ± 1.6	1.9 ± 1.6	-0.7 ± 1.7	6.7 ± 3.0	110	22
Oct 2013	46.9 ± 5.8	71.7 ± 7.2	42.0 ± 8.3	13.4 ± 2.1	0.7 ± 1.1	0.7 ± 1.1	5.3 ± 2.2	17.0 ± 3.9	240	33
Feb 2014	58.9 ± 7.8	66.5 ± 8.5	49.3 ± 9.0	4.0 ± 1.2	9.6 ± 3.5	17.1 ± 3.7	6.3 ± 1.8	5.7 ± 2.2	240	43
Jul 2014	59.1 ± 6.5	87.3 ± 8.1	73.9 ± 13.9	16.3 ± 3.1	1.5 ± 1.1	1.5 ± 1.1	17.1 ± 4.0	8.4 ± 3.1	290	46
Nov 2014	71.8 ± 12.7	78.2 ± 12.9	14.6 ± 3.8	0.9 ± 0.5	13.7 ± 5.8	0.0 ± 2.6	4.4 ± 1.7	11.9 ± 3.0	190	31
Surface water 4										
Mar 2011	24.1 ± 8.0	47.2 ± 11.4	9.0 ± 9.2	1.6 ± 1.4	6.2 ± 2.6	0.4 ± 1.3	2.4 ± 0.9	3.7 ± 1.3	100	17
Oct 2011	40.3 ± 8.2	46.8 ± 8.2	15.1 ± 4.3	4.3 ± 1.1	1.6 ± 1.5	1.6 ± 1.5	4.7 ± 1.9	5.5 ± 2.6	100	17
Oct 2013	21.9 ± 4.2	36.4 ± 5.5	32.0 ± 6.2	0.4 ± 0.4	1.2 ± 8.5	1.2 ± 6.2	6.9 ± 1.8	14.1 ± 2.5	210	35
Jul 2014	32.3 ± 7.2	58.1 ± 9.0	22.8 ± 5.6	3.3 ± 1.2	9.4 ± 2.6	9.4 ± 2.6	13.4 ± 3.4	10.7 ± 3.4	310	46
Nov 2014	31.3 ± 21.9	46.9 ± 14.7	20.9 ± 4.8	7.6 ± 1.5	10.7 ± 4.4	10.7 ± 4.4	4.3 ± 1.6	6.6 ± 2.2	250	49
Borehole 1										
Mar 2011	20.7 ± 9.1	58.5 ± 12.5	17.0 ± 4.2	14.4 ± 3.3	7.6 ± 3.4	7.6 ± 3.4	10.9 ± 1.2	7.7 ± 2.1	250	43
Oct 2011	13.0 ± 3.4	58.3 ± 7.6	11.3 ± 3.8	17.3 ± 2.4	5.0 ± 2.6	5.0 ± 2.6	1.7 ± 1.7	6.0 ± 2.8	140	24
Oct 2013	9.3 ± 2.6	30.2 ± 4.7	14.6 ± 3.3	11.0 ± 2.3	24.6 ± 6.0	-0.8 ± 4.8	4.1 ± 1.5	15.2 ± 2.7	200	31
Jul 2014	39.3 ± 5.7	115 ± 10	42.8 ± 8.2	19.0 ± 2.6	3.9 ± 1.8	3.9 ± 1.8	1.2 ± 1.1	6.8 ± 2.3	400	63
Mar 2015	35.8 ± 5.0	74.2 ± 7.3	25.5 ± 5.6	21.3 ± 2.9	14.4 ± 7.0	14.4 ± 7.0	11.3 ± 2.9	36.9 ± 4.9	440	59
Borehole 2										
Mar 2011	32.7 ± 9.1	81.1 ± 13.8	7.1 ± 7.3	3.6 ± 1.3	2.8 ± 2.0	2.8 ± 2.0	1.1 ± 0.6	3.4 ± 1.3	74	13
Oct 2011	42.8 ± 9.1	83.6 ± 12.9	30.5 ± 6.2	3.4 ± 1.0	3.7 ± 2.2	3.7 ± 2.2	9.5 ± 2.3	1.1 ± 1.6	130	23
Oct 2013	21.3 ± 4.7	46.8 ± 7.0	89.6 ± 15.4	2.7 ± 1.1	1.6 ± 1.6	1.6 ± 1.6	7.8 ± 2.2	31.3 ± 4.3	340	42
Jul 2014	69.3 ± 7.7	175 ± 12	48.3 ± 9.6	2.8 ± 1.1	3.6 ± 1.9	3.6 ± 1.9	10.0 ± 2.8	7.6 ± 2.8	290	57

	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	Th-232	Th-228	< 1 a	> 17 a
Mar 2015	35.9 ± 5.8	94.6 ± 9.5	10.9 ± 3.0	1.8 ± 0.8	22.1 ± 1.6	22.1 ± 6.1	2.6 ± 1.5	7.1 ± 2.3	200	44
Borehole 3										
Mar 2011	27.3 ± 6.9	44.9 ± 8.2	27.2 ± 5.4	4.4 ± 1.9	1.7 ± 1.6	1.7 ± 1.6	1.4 ± 0.8	8.1 ± 2.1	160	22
Oct 2011	147 ± 16	130 ± 15	5.3 ± 5.6	8.1 ± 1.9	2.9 ± 1.9	2.9 ± 1.9	1.4 ± 1.3	5.2 ± 1.8	120	25
Oct 2013	16.9 ± 3.5	21.8 ± 4.0	38.0 ± 6.9	10.1 ± 2.2	1.3 ± 1.4	1.3 ± 1.4	1.2 ± 1.1	4.3 ± 1.3	140	22
Feb 2014	192 ± 23	152 ± 23	122 ± 5.3	2.2 ± 0.8	6.1 ± 2.9	6.1 ± 2.9	37.2 ± 6.7	8.4 ± 3.6	320	95
Jul 2014	18.4 ± 4.2	38.4 ± 5.9	35.8 ± 7.3	9.2 ± 2.1	3.3 ± 1.7	3.3 ± 1.7	3.2 ± 1.4	14.0 ± 3.1	240	35
Borehole 4										
Mar 2011	60.3 ± 11.6	96.0 ± 15.1	22.5 ± 6.2	4.2 ± 1.9	2.1 ± 1.6	2.1 ± 1.6	4.4 ± 2.2	5.8 ± 3.1	110	19
Oct 2011	27.4 ± 6.1	89.1 ± 11.1	24.1 ± 5.5	3.7 ± 1.1	0.8 ± 0.9	0.8 ± 0.9	1.9 ± 1.1	5.0 ± 1.8	100	17
Oct 2013	79.1 ± 7.4	242 ± 13	19.0 ± 3.9	4.0 ± 1.2	31.3 ± 8.8	1.4 ± 6.3	1.1 ± 0.6	2.8 ± 1.1	190	44
Feb 2014	45.9 ± 6.1	146 ± 11	66.3 ± 11.5	7.8 ± 2.4	4.4 ± 3.7	4.4 ± 3.7	34.3 ± 6.1	7.2 ± 3.4	310	61
Jul 2014	85.0 ± 13.2	372 ± 26	56.4 ± 10.6	7.0 ± 1.8	5.1 ± 2.1	5.1 ± 2.1	16.5 ± 3.4	6.4 ± 2.7	260	52
Mar 2015	43.8 ± 6.0	148 ± 11	35.4 ± 8.1	7.6 ± 2.0	19.6 ± 10.2	0.3 ± 4.5	5.8 ± 2.4	5.8 ± 3.3	160	33
Impounding Dam										
	8400 ± 170	6240 ± 150	5150 ± 800	188 ± 8	197 ± 26	891 ± 58	17800 ± 300	17400 ± 300	-	-
	9830 ± 140	9560 ± 140	3020 ± 460	3060 ± 170	218 ± 20	381 ± 32	7990 ± 80	7540 ± 80	-	-
	5270 ± 80	5130 ± 80	2530 ± 390	538 ± 76	164 ± 16	164 ± 16	9450 ± 170	7770 ± 150	-	-
	1900 ± 50	1790 ± 50	670 ± 110	103 ± 12	40 ± 11	174 ± 25	2240 ± 90	1990 ± 80	-	-
	7480 ± 80	7190 ± 80	1850 ± 280	1070 ± 30	±	212 ± 15	6300 ± 70	5690 ± 70	-	-
	7030 ± 70	6550 ± 70	3680 ± 570	341 ± 37	1000 ± 70	1480 ± 50	11600 ± 300	9360 ± 230	-	-
	3390 ± 110	3840 ± 110	1630 ± 250	235 ± 10	1250 ± 80	1250 ± 80	6450 ± 70	5690 ± 70	-	-

Table C-10: Results for water samples from baseline area, monazite area and area impacted by gold mining (Activity concentrations mBq.L^{-1}; Dose μSv.a^{-1})

Activity Concentration							Dose		Ratios				
U-238	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Th-232**	**Th-228**	**< 1 a**	**> 17 a**	**234/238**	**238/226**	**226/210**	**228/232**	**226/228**
Background Surface water													
2.47	8.01	18.2	3.10	0.782	1.20	6.37	89	11	3.24	0.80	3.96	5.31	0.49
2.85	17.7	13.6	1.47	1.40	2.18	2.53	56	8.9	6.20	1.93	1.05	1.16	0.58
2.96	19.6	16.5	5.59	9.70	2.72	3.35	150	26	6.62	0.53	0.58	1.23	1.67
3.73	6.54	43.7	7.30	1.93	1.94	2.37	200	30	1.75	0.51	3.78	1.22	3.08
11.3	38.5	23.2	10.6	10.5	6.89	24.4	440	62	3.42	1.07	1.01	3.55	0.43
2.38	8.21	17.5	0.771	25.8		1.54	180	32	3.45	3.08	0.03	-	0.50
10.9	13.4	12.2	0.936	1.67	3.37	7.33	97	12	1.23	11.6	0.56	2.18	0.13
Background Groundwater													
2.13	5.93	20.3	5.70	2.44	2.05	3.60	140	20	2.79	0.37	2.34	1.75	1.58
6.50	4.49	33.4	7.87	2.72	0.459	4.48	160	23	0.69	0.83	2.90	9.75	1.76
5.91	6.42	27.4	1.50	4.16	1.43	1.86	180	27	1.09	3.93	0.36	1.30	0.81
2.23	3.08	15.8	0.708	1.75	3.03	14.8	160	18	1.38	3.14	0.40	4.87	0.05
7.65	32.5	24.6	7.55	59.2	5.30	10.5	260	51	4.25	1.01	0.13	1.97	0.72
8.08	11.8	11.2	6.28	9.96	0.854	4.21	150	25	1.45	1.29	0.63	4.93	1.49
Monazite area													
187	559	51.1	42.7	7.63	10.9	7.09	266	61	2.99	4.37	5.60	0.65	6.02
470	1360	56.7	16.7	2.44	12.7	11.2	334	94	2.88	28.2	6.84	0.88	1.49
177	524	28.6	29.7	29.4	2.62	6.79	235	59	2.97	5.94	1.01	2.59	4.38
380	979	27.7	485	31.9	2.11	13.1	810	188	2.57	0.78	15.2	6.22	37.0
536	1090	33.6	345	68.8	1.07	36.9	959	205	2.03	1.56	5.01	34.3	9.35
694	2070	32.0	92.8	2.84	3.85	6.69	429	137	2.98	7.47	32.7	1.74	13.9
331	377	26.6	6.5	7.46	5.57	13.1	348	66.6	1.14	50.9	0.87	2.35	0.50
286	996	54.8	31.4	9.89	18.3	5.35	288	79.2	3.48	9.11	3.18	0.29	5.88

Activity Concentration							Dose		Ratios				
U-238	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Th-232**	**Th-228**	**< 1 a**	**> 17 a**	**234/238**	**238/226**	**226/210**	**228/232**	**226/228**
112	881	16.1	2.4	12.8	2.85	8.50	262	64	7.85	46.0	0.19	2.98	0.29
490	1170	46.0	112	49.5	3.50	17.4	581	141	2.39	4.35	2.27	4.97	6.46
Gold mine Surface 1													
84.5	138	26.0	4.37	1.95	2.94	3.66	140	26	1.63	19.3	2.23	1.24	1.19
78.7	101	51.9	3.69	37.4	8.12	13.3	260	48	1.28	21.3	0.10	1.64	0.28
135	191	262	5.80	7.46	43.2	17.2	500	88	1.41	23.2	0.78	0.40	0.34
102	172	47.8	5.69	5.65	15.8	13.7	440	69	1.69	17.9	1.01	0.87	0.41
195	244	94.9	1.00	12.8	24.3	6.16	310	61	1.25	-	-	0.25	0.16
50.7	71.6	41.0	3.34	21.9	4.06	7.91	470	75	1.41	15.2	0.15	1.95	0.42
152	239	59.6	1.74	28.1	29.5	5.39	-	106	1.57	-	-	0.18	0.32
99.9	150	117	3.87	6.31	35.0	13.6	-	133	1.50	25.8	0.61	0.39	0.28
Gold mine Surface 2													
835	745	25.9	6.61	4.29	7.82	10.6	370	93	0.89	126	1.54	1.36	0.62
1450	1420	61.3	6.47	4.62	2.55	10.7	460	140	0.98	224	1.40	4.19	0.60
1614	1390	71.0	12.2	16.2	12.9	7.73	580	160	0.87	132	0.75	0.60	1.58
992	919	69.5	7.44	4.38	22.2	8.69	370	100	0.93	133	1.70	0.39	0.86
1121	1010	87.4	4.80	1.34	21.0	8.42	360	110	0.90	234	3.59	0.40	0.57
1370	1250	45.3	4.60	20.1	9.27	24.2	520	140	0.91	298	0.23	2.61	0.19
362	314	29.3	18.6	46.9	6.37	20.3	-	180	0.87	19.5	0.40	3.18	0.92
225	217	495	8.22	3.18	57.4	8.16	-	119	0.96	27.4	2.59	0.14	1.01
638	591	20.0	3.63	8.99	14.3	4.67	-	77	0.93	176	0.40	0.33	0.78
Gold mine Surface 3													
1510	1330	140	103	43.7	9.91	15.8	820	210	0.88	14.7	2.35	1.59	6.50
1090	989	16.7	192	8.92	2.06	3.07	490	140	0.90	5.69	21.6	1.49	62.6
1840	1690	57.5	257	31.1	4.74	12.8	1300	300	0.91	7.17	8.28	2.69	20.1
346	335	59.5	178	6.35	9.82	21.6	540	100	0.97	1.94	28.1	2.20	8.24

Activity Concentration							Dose		Ratios				
U-238	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Th-232**	**Th-228**	**< 1 a**	**> 17 a**	**234/238**	**238/226**	**226/210**	**228/232**	**226/228**
2040	1880	103	79.6	13.3	28.0	12.3	-	235	0.92	25.6	6.00	0.44	6.50
729	790	60.6	85.0	6.32	14.1	8.03	-	115	1.08	8.58	13.5	0.57	10.6
1440	1420	28.8	150	2.20	17.4	4.65	-	153	0.98	9.56	68.5	0.27	32.3
Gold mine Surface 4													
286	294	36.8	3.57	1.14	4.23	0.00	290	57	1.03	80.2	3.12	0.00	-
1530	1450	44.8	3.46	10.3	3.89	2.28	460	150	0.95	-	0.33	0.58	1.52
1690	1500	16.1	5.46	1.60	4.13	11.3	400	140	0.89	309	3.42	2.73	0.48
1990	1800	21.8	10.3	8.22	4.63	15.1	690	200	0.90	193	1.26	3.27	0.68
570	539	62.3	3.48	29.5	48.9	28.9	-	251	0.95	164	0.12	0.59	0.12
1080	1140	28.9	3.02	8.74	3.98	2.57	-	100	1.05	357	0.35	0.65	1.17
Gold mine Surface 5													
74.1	103	30.1	181	2.66	0.00	8.14	640	110	1.40	0.41	68.1	-	22.2
87.0	94.8	83.5	165	11.4	3.59	17.9	490	86	1.09	0.53	14.5	4.97	9.23
165	179	41.4	139	7.55	1.52	6.04	520	94	1.08	1.18	18.5	3.97	23.1
258	225	43.6	185	9.31	3.20	34.5	580	98	0.87	1.40	19.9	10.8	5.36
205	228	39.1	112	14.6	14.4	19.9	-	141	1.11	1.83	7.67	1.38	5.62
Gold mine Surface 6													
5760	4950	368	91	5.87	39.9	23.0	1900	560	0.86	63.1	15.5	0.58	3.96
6600	6100	24.8	130	27.3	0.94	4.63	1400	540	0.92	50.9	4.75	4.92	28.1
7290	6620	20.4	370	18.1	8.41	6.12	1600	610	0.91	19.7	20.4	0.73	60.4
1900	1770	57.8	201	5.09	36.3	20.5	-	288	0.94	9.44	39.4	0.57	9.80
Gold mine Surface 7													
22.3	35.4	71.7	1.82	4.48	3.00	10.9	220	33	1.59	12.2	0.41	3.65	0.17
42.4	47.6	63.5	1.61	7.92	3.49	9.53	300	48	1.12	26.4	0.20	2.73	0.17
54.2	89.7	73.2	5.49	17.0	2.59	11.6	460	73	1.65	9.88	0.32	4.47	0.47
105	167	197	17	16.9	25.9	16.3	920	160	1.59	6.29	0.99	0.63	1.03

Activity Concentration							Dose		Ratios				
U-238	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Th-232**	**Th-228**	**< 1 a**	**> 17 a**	**234/238**	**238/226**	**226/210**	**228/232**	**226/228**
34.0	36.5	31.1	3.67	27.0	11.9	11.6	350	57	1.07	9.25	0.14	0.97	0.32
32.9	49.6	123	4.97	22.4	41.7	34.2	-	231	1.51	6.63	0.22	0.82	0.15
13.6	36.9	76.3	1.53	3.84	10.6	3.18	-	39	2.72	8.86	0.40	0.30	0.48
58.0	73.6	30.7	4.14	3.83	10.6	6.47	-	47	1.27	14.0	1.08	0.61	0.64
Gold mine Surface 8													
10300	9230	31.4	245	3.80	7.10	12.4	2100	810	0.89	42.1	64.6	1.74	19.9
8730	7500	97.3	226	12.9	5.40	14.0	1900	700	0.86	38.6	17.5	2.60	16.1
11400	9970	58.4	352	16.3	5.33	7.06	2200	890	0.87	32.4	21.7	1.32	49.9
2090	1900	22.6	206	18.5	5.26	8.97	700	220	0.91	10.2	11.1	1.71	22.9
5740	4920	71.5	226	21.0	34.1	11.3	-	478	0.86	25.5	10.8	0.33	20.0
5390	419	61.0	190	4.78	13.4	5.11	-	364	0.78	28.4	39.7	0.38	37.1
8540	7460	23.3	228	2.37	11.9	6.86	-	549	0.87	37.4	96.3	0.58	33.3
Gold mine Surface 9													
5640	5090	26.3	91.8	11.6	2.79	36.1	1400	470	0.90	61.4	7.92	12.9	2.55
5100	4490	84.4	84.9	11.3	2.63	8.33	1200	420	0.88	60.0	7.52	3.17	10.2
890	850	50.0	44.3	10.3	7.33	8.90	510	120	0.96	20.1	4.31	1.21	4.98
227	221	126	8.66	1.79	23.2	27.0	630	96	0.98	26.2	4.84	1.17	0.32
625	505	14.2	15.3	35.4	3.20	15.9	360	82	0.81	40.9	0.43	4.97	0.96
Gold mine Groundwater													
23.4	69.2	24.4	2.99	5.15	2.27	3.76	120	21	2.95	7.84	0.58	1.66	0.80
75.3	128	58.2	3.12	4.24	7.20	7.01	280	46	1.71	24.1	0.74	0.97	0.44
25.4	90.6	71.6	3.06	8.00	1.92	1.91	290	46	3.57	8.30	0.38	1.00	1.60
25.2	83.8	74.1	1.31	4.78	33.3	14.5	410	61	3.32	19.3	0.27	0.44	0.09
22.7	46.7	44.8	1.63	13.7	8.74	9.36	190	31	2.06	13.9	0.12	1.07	0.17
18.1	53.4	40.1	4.88	17.5	7.95	23.4	380	58	2.95	3.71	0.28	2.94	0.21
38.4	89.9	93.6	3.19	12.5	37.4	14.7	-	100	2.34	12.1	0.26	0.39	0.22

Activity Concentration							Dose		Ratios				
U-238	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Th-232**	**Th-228**	**< 1 a**	**> 17 a**	**234/238**	**238/226**	**226/210**	**228/232**	**226/228**
49.0	92.6	36.0	3.45	2.93	44.0	42.2	550	69	1.89	14.2	1.17	0.96	0.08
56.1	86.8	28.7	1.16	2.43	2.48	7.20	160	25	1.55	48.3	0.48	2.90	0.16
47.6	350	26.8	18.9	18.4	3.54	13.9	320	58	7.35	2.52	1.03	3.92	1.36
68.0	248	47.2	9.11	5.04	16.7	5.03	-	51	3.65	7.46	1.81	0.30	1.81
30.1	292	64.5	5.59	5.06	3.68	5.84	-	46	9.71	5.38	1.10	1.59	0.96
31.3	322	30.4	10.9	11.9	29.1	4.75	-	82	10.3	2.88	0.91	0.16	2.29
Gold mine drinking water													
26.2	60.8	11.7	1.09	15.1	1.75	2.39	180	30	2.32	24.1	0.07	1.36	0.45
26.2	68.2	76.3	2.39	7.31	39.4	11.3	431	72	2.60	11.0	0.33	0.29	0.21
4.61	14.4	4.88	2.48	4.76	2.16	1.48	58	10	3.12	1.86	0.52	0.68	1.68
46.5	89.1	25.6	57.0	28.9	2.50	3.95	258	43	1.92	0.82	1.98	1.58	-
15.4	31.7	45.3	0.93	11.6	23.8	5.47	292	49	2.06	16.5	0.08	0.23	0.17
87.2	118	88.6	3.85	10.3	26.3	17.3	792	132	1.35	22.7	0.37	0.66	0.22
19.4	27.4	47.9	1.39	6.99	21.4	9.23	266	44	1.42	13.9	0.20	0.43	0.15
85.9	102	26.2	9.05	5.84	5.45	9.34	540	90	1.18	9.49	1.55	1.71	0.97
27.9	30.4	32.6	1.29	7.59	6.79	5.05	233	39	1.09	21.7	0.17	0.74	0.26
51.5	346	39.9	14.7	3.59	19.4	10.8	594	99	6.70	3.51	4.10	0.55	1.36
65.1	108	35.5	1.41	36.0	19.2	21.0	740	123	1.66	46.2	0.04	1.09	0.07
62.6	95.2	78.1	1.92	8.65	49.5	6.04	504	84	1.52	32.6	0.22	0.12	0.32
Gold mine process water													
6610	5780	100	275	9.48	26.9	16.4	1900	610	0.87	24.0	29.0	0.61	16.8
7530	7060	96.4	211	29.3	6.49	11.4	1800	660	0.94	35.7	7.19	1.75	18.5
326	364	62.9	128	27.2	5.35	2.19	470	110	1.12	2.54	4.71	0.41	58.6
878	833	80.2	69.3	2.49	13.8	14.0	640	140	0.95	12.7	27.8	1.02	4.96
204	280	35.9	39.7	8.24	2.72	6.89	416	69	1.37	5.15	4.82	2.53	5.76
10100	8280	92.6	263	7.43	9.73	18.3	2100	780	0.82	38.2	35.4	1.88	14.4

Activity Concentration							Dose		Ratios				
U-238	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Th-232**	**Th-228**	**< 1 a**	**> 17 a**	**234/238**	**238/226**	**226/210**	**228/232**	**226/228**
5590	5150	134	233	66.4	13.7	20.0	1600	530	0.92	23.9	3.51	1.46	11.6
6170	5480	164	211	8.82	19.5	10.7	2889	481	0.89	29.2	23.9	0.55	19.7
4780	4400	18.0	175	4.22	1.41	6.13	2104	351	0.92	27.3	41.5	4.34	28.6
4260	3950	46.4	139	63.1	11.5	13.4	2300	383	0.93	30.7	2.20	1.17	10.3
6360	6020	137	200	21.1	4.46	21.7	1800	590	0.95	31.8	9.50	4.87	9.21
7870	7010	107	362	6.39	12.2	16.8	2200	700	0.89	21.7	56.6	1.38	21.5
4560	4190	24.4	183	18.4	18.3	17.9	1200	410	0.92	24.9	9.98	0.98	10.3
9850	8990	24.8	269	28.2	2.66	14.3	2000	790	0.91	36.5	9.55	5.37	18.8
9650	8690	25.0	245	19.3	3.23	3.75	1800	740	0.90	39.4	12.7	1.16	65.3
3780	3460	63.2	106	53.8	10.6	7.78	1860	310	0.92	35.6	1.97	0.73	13.6
8480	7840	23.8	267	8.27	2.69	9.87	3750	624	0.92	31.8	32.3	3.66	27.1
8350	7420	12.8	149	10.3	19.8	5.41	1600	640	0.89	56.1	14.5	0.27	27.5
8440	7570	82.9	234	8.75	4.77	6.99	1700	670	0.90	36.1	26.8	1.47	33.5
12500	11000	169	242	5.62	11.3	11.7	2500	970	0.88	51.7	43.1	1.03	20.7
4440	4010	19.6	298	32.3	5.24	5.21	1300	420	0.90	14.9	9.25	0.99	57.2
6350	5260	67.1	166	9.41	13.1	5.32	2550	425	0.83	38.3	17.6	0.41	31.2
12400	11790	13.0	197	6.69	1.68	9.29	5041	840	0.95	62.9	29.5	5.53	21.2
4140	3870	172	203	11.2	29.2	17.4	1300	410	0.93	20.4	18.1	0.60	11.6
7070	6370	1800	220	29.5	39.5	17.1	3500	920	0.90	32.1	7.47	0.43	12.9
8130	7230	75.1	208	14.2	9.29	16.6	1700	650	0.89	39.1	14.6	1.79	12.5
9600	7870	51.9	80.3	34.7	3.90	12.1	2300	780	0.82	119	2.31	3.10	6.63
3570	3220	18.0	115	86.5	7.41	7.23	1764	294	0.90	30.9	1.33	0.97	15.9
6710	5970	144	190	10.3	19.7	6.99	1500	570	0.89	35.4	18.4	0.35	27.1
7060	6410	163	153	23.9	28.2	22.4	1800	630	0.91	46.1	6.40	0.80	6.82
11500	10100	41.3	454	43.9	4.77	6.09	2600	960	0.88	25.2	10.3	1.28	74.6
6990	6150	245	276	11.5	33.5	53.9	2900	750	0.88	25.3	23.9	1.61	5.13

Activity Concentration							Dose		Ratios				
U-238	U-234	Th-230	Ra-226	Pb-210	Th-232	Th-228	< 1 a	> 17 a	234/238	238/226	226/210	228/232	226/228
4420	4010	32.3	114	25.1	7.53	14.7	2140	357	0.91	38.8	4.54	1.95	7.77
3680	3070	40.6	146	6.92	4.53	36.2	2410	402	0.83	25.1	21.1	7.99	4.04
5860	5260	44.9	172	9.50	25.8	7.83	2580	430	0.90	33.9	18.1	0.30	22.0
13300	12800	44.8	202	8.82	8.40	7.74	5370	896	0.96	65.9	22.9	0.92	26.1

Table C-11: Nuclide specific analysis of water from Catchment C (Activity concentrations mBq.L^{-1}; Dose µSv.a^{-1})

	Activity concentrations (mBq.L^{-1})									Measured		Calculated		Dose		Isotopic ratios			
Date	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	U-235	Th-232	Th-228	GA	GB	GA	GB	< 1a	17a	234:238	210:226	230:232	228:232
Sampling Point 1																			
20100420	5.83	18	36.4	2.82	7.71	7.71	0.268	2.06	3.6	-140	-180	112	30	130	24	3.09	2.73	17.6	1.75
20100807	24.1	35.3	15	0.27	1.8	1.8	1.09	4.79	6.14	-91	-330	137	58	130	18	1.46	6.67	3.13	1.28
20101203	22.6	50.5	21	2.77	11	0.061	1.04	< 9	2.9	28	-21	167	75	120	20	2.23	0.02	-	-
20110203	20.1	33.4	29.3	4.56	1.0	1.0	0.926	1.23	3.25	42	390	123	53	100	16	1.66	0.22	23.8	2.64
20110310	19.4	37.2	17	1.93	2.43	2.43	0.891	2.5	0.81	0.1	-51	115	51	140	22	1.92	1.26	6.80	0.32
20110603	9.82	29.6	33.8	116*	1.7	1.7	0.452	5.18	6.87	32	100	453	253	310	52	3.01	-	6.53	1.33
20110701	5.64	27.9	88.4	-0.9	2.01	2.01	0.259	12.8	4.8	18	620	163	17	180	30	4.95	-2.23	6.91	0.38
20110824	9.36	22.7	16	1.37	17.1	31.8	0.431	5.5	5.48	38	330	130	41	310	53	2.43	23.2	2.91	1.00
20110923	29	65.1	55	0.91	10.3	10.3	1.33	6.98	2.74	-160	-190	244	79	280	47	2.24	11.3	7.88	0.39
20111020	1050	1090*	28.6	59.9*	2.81	2.81	48.2	3.39	4.50	1580*	440	2420	2260	340	110*	-	-	8.44	1.33
20111124	10.4	28	19.5	3.11	2.92	2.92	0.477	0.44	1.3	-24	89	126	46	140	22	2.69	0.94	44.3	2.95
20111209	18.8	28.4	10	2.1	22.6	-10	0.865	1.36	3.57	-120	81	102	63	150	27	1.51	-4.76	7.35	2.63
20120213	12.9	23.0	119	2.74	1.2	1.2	0.593	4.1	11.4	799	1290	253	33	450	66	1.78	0.44	29.0	2.78

	Activity concentrations (mBq.L^{-1})									Measured		Calculated		Dose		Isotopic ratios			
Date	**U-238**	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Po-210**	**U-235**	**Th-232**	**Th-228**	**GA**	**GB**	**GA**	**GB**	**< 1a**	**17a**	**234:238**	**210:226**	**230:232**	**228:232**
20120267	103	123	11	4.22	1.0	1.0	4.73	0.8	1.58	34	240	272	222	61	15	1.19	0.24	13.7	1.98
20120307	7.02	13.7	17	1.37	0.76	0.76	0.323	0.75	0.74	-270	460	56	21	56	8.8	1.95	0.55	22.6	0.99
Sampling Point 2																			
20100807	5.12	15.1	9.2	-0.1	3.81	3.81	0.236	-0.62	3.1	-110	-270	63	20	72	12	2.95	-38.1	-14.8	-5.00
20110310	50.6	60.0	18	1.61	2.74	2.74	2.33	2.96	1.77	130	94	161	111	84	16	1.19	1.70	6.08	0.60
20110923	73.4	86.8	38.6	3.34	1.4	1.4	3.38	4.87	0.026	60	120	272	161	290*	46	1.18	0.42	7.93	0.01
20111209	6.14	24.3	12.0	1.00	1.4	1.4	0.283	1.37	2.3	-160	9.3	64	13	84	13	3.96	1.40	8.76	1.68
20120307	11.9	24.6	33.3	1.62	0.86	0.86	0.548	1.5	2.95	-320	40	99	33	89	14	2.07	0.53	22.2	1.97
20120620	11.0	27.3	5.2	2.08	11	0.56	0.506	< 1.8	4.5	190	250	95	44	92	16	2.48	0.27	-	-
20121030	5.34	23.8	13	0.68	2.77	2.77	0.246	< 1.9	4.8	-110	-5.4	82	20	77	12	4.46	4.07	-	-
Sampling Point 3																			
20100807	102	111	83.6	0.38	7.49	7.49	4.71	3.07	2.6	-3.9	-210	341	220	180	36	1.09	19.7	27.2	0.85
20110310	43	77.1	11	1.60	1.3	1.3	1.98	2.1	4.80	160	260	181	99	120	19	1.79	0.81	5.24	2.29
20110824	222	234	21	1.88	2.62	2.62	10.8	2.65	2.63	290	280	551	467	180	37	1.05	1.39	7.92	0.99
20110923	158	190	37.5	3.09	2.54	2.54	7.28	4.0	3.31	73	-92	483	337	320	56	1.20	0.82	9.38	0.83
20111209	61	70.1	10.1	2.0	3.51	3.51	2.81	3.21	2.8	-110	170	200	139	140	24	1.15	1.76	3.15	0.87
20120307	73.9	71.9	26	2.27	6.41	6.41	3.40	0.97	2.40	-190	170	214	166	120	23	0.97	2.82	26.8	2.47
20120620	321	340	7.2	4.83	4.67	0.11	14.8	1.3	19.4	462	-110	796	674	250	47	1.06	0.02	5.54	14.9
20121030	156	180	18.8	3.86	7.5	0.42	7.33	2.43	4.03	130	49	435	340	190	37	1.15	0.11	7.74	1.66
Sampling Point 4																			
20100807	838	844	35.1	2.4	5.04	5.04	38.5	3.08	7.39	1040	310	1830	1723	280	84	1.01	2.10	11.4	2.40
20101203	739	779	11.3	2.92	13.3	0.35	34	1.5	7.36	781	629	1670	1534	290	81	1.05	0.12	7.53	4.91
20110203	157	162	8.6	3.44	1.4	1.4	7.25	4.0	12	220	515	410	335	150	25	1.03	0.41	2.15	3.00

	Activity concentrations ($mBq.L^{-1}$)									Measured		Calculated		Dose		Isotopic ratios			
Date	**U-238**	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Po-210**	**U-235**	**Th-232**	**Th-228**	**GA**	**GB**	**GA**	**GB**	**< 1a**	**17a**	**234:238**	**210:226**	**230:232**	**228:232**
20110310	264	272	4.3	4.26	3.86	3.86	12.2	-0.88	2.5	210	400	616	557	180	40	1.03	0.91	-4.89	-2.84
20110420	206	206	225*	4.12	3.31	3.31	9.49	5.6	18.8	54	120	915	439	1100*	180*	1.00	0.80	-	3.36
20110603	328	352	43.6	4.05	5.36	5.36	15.1	10.2	7.92	310	320	818	689	230	51	1.07	1.32	4.27	0.78
20110701	406	402	46.4	2.2	2.7	2.7	18.7	9.44	3.8	390	400	955	850	160	46	0.99	1.23	4.92	0.40
20110824	623	643	28.9	4.58	3.04	3.04	27.7	3.58	4.99	485	410	1410	1290	230	66	1.03	0.66	8.07	1.39
20110923	773	793	37.4	2.99	3.54	3.54	35.6	1.5	12.6	764	260	1750	1590	350	88	1.03	1.18	24.9	8.40
20111020	953	912	8.5	5.7	25	-2.7	43.9	-0.70	4.8	735	450	2390	2170	310	95	0.96	-0.47	-12.1	-6.86
20111124	924	953	15.5	6.42	3.75	3.75	42.6	1.6	5.62	1080	580	2140	1950	350	98	1.03	0.58	9.69	3.51
20111209	704	737	13	2.7	5.57	5.57	32.4	4.86	18.1	1060	1490	1640	1460	410	90	1.05	2.06	2.67	3.72
20120267	419	464	12.6	4.09	19.3	-0.52	19.3	1.8	1.4	630	724	995	890	170	51	1.11	-0.13	7.00	0.78
20120307	251	285	9.1	3.36	2.19	2.19	11.2	4.9	4.9	120	520	627	527	160	37	1.14	0.65	1.86	1.00
20120524	479	440	23	1.94	1.0	1.0	22.0	< 2.2	0.82	261	351	1030	988	200	54	0.92	0.52	-	-
20120620	586	623	34	2.37	1.96	1.96	24.7	2.4	6.30	1010	570	1350	1210	200	58	1.06	0.83	14.17	2.63
20121030	421	420	5.0	1.82	19.1	0.70	19.4	1.6	10.6	490	360	957	890	220	54	1.00	0.38	3.13	6.63
Sampling Point 5																			
20100807	1350	1370	19.2	147	7.77	7.77	61.3	2.3	6.02	2800	600	3370	3070	500	150	1.01	0.05	8.35	2.62
20101203	2070	1960	18	184	4.02	-0.73	95.4	3.28	5.87	2370	1200	4850	4620	570	200	0.95	0.00	5.49	1.79
20110203	957	893	11	82.3	2.66	2.66	44.1	0.82	5.69	1290	840	2240	2130	320	98	0.93	0.03	13.41	6.94
20110310	1890	1790	7.2	207	6.74	6.74	79.2	2.4	2.95	2860	1000	4520	4290	660	200	0.95	0.03	3.00	1.23
20110824	1370	1240	23	104	2.67	2.67	63.1	3.8	3.36	1890	710	3110	3020	400	130	0.91	0.03	6.05	0.88
20110923	161	174	19	258*	14.4	-0.55	7.41	10.5	36.2*	1600	678	1250	855	630	110	1.08	-	1.81	-
20111124	771	762	16.8	117	2.06	2.06	39.4	0.44	2.2	1200	682	2050	1830	420	110	0.99	0.02	38.1	5.00
20111209	827	822	6.7	272*	2.67	2.67	38.1	1.96	5.44	1310	1260	2690	2290	540	140	0.99	-	3.42	2.78

	Activity concentrations (mBq.L[-1])									Measured		Calculated		Dose		Isotopic ratios			
Date	**U-238**	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Po-210**	**U-235**	**Th-232**	**Th-228**	**GA**	**GB**	**GA**	**GB**	**< 1a**	**17a**	**234:238**	**210:226**	**230:232**	**228:232**
20120213	755	705	12	77.0	1.98	1.98	34.8	1.11	2.5	633	590	1790	1700	340	92	0.93	0.03	10.8	2.25
20120267	526	513	*392	43.8	2.31	2.31	24.2	43.1*	24.2*	712	616	1750	1170	740	140	0.98	0.05	-	-
20120307	859	912	26.9	116	2.67	2.67	39.6	1.1	12.6	1210	1100	2290	1990	400	110	1.06	0.02	24.4	11.4
20120404	511	539	7.3	27.2	3.29	3.29	23.5	0.76	1.5	350	590	1220	1110	210	59	1.05	0.12	9.61	1.97
20120524	815	802	20	61.2	6.64	6.64	37.5	< 5.7	6.20	948	837	1950	1810	320	92	0.98	0.11	-	-
20120620	908	848	159	67.4	3.57	3.57	44.3	34.1	18.7	1150	530	2320	2000	620	140	0.93	0.05	4.66	0.55
20121030	420	418	2.6	23.4	15	3.09	19.8	0.014	1.90	320	340	994	927	170	49	1.00	0.13	-	-
Sampling Point 6																			
20110701	438	528	79.2	33.4	1.7	1.7	20.2	9.07	5.12	849	580	1250	975	260	66	1.21	0.05	8.73	0.56
20111020	747	754	25.3	42.9	4.42	4.42	34.4	1.71	3.40	1150	370	1710	1610	260	80	1.01	0.10	14.8	1.99
20101847	703	769	21.9	30.8	2.2	2.2	29.9	12.7	2.0	881	50	1680	1500	210	70	1.09	0.07	1.72	0.16
20101203	974	1000	18	60.4	3.8	3.8	44.8	4.14	4.1	1100	514	2290	2120	320	100	1.03	0.06	4.35	0.99
20110203	275	311	16.9	47.6	174*	-3.3	12.7	1.0	2.53	865	500	962	836	440	130	1.13	-0.07	16.9	2.53
20110310	755	818	14	76.3	4.77	4.77	35.4	-0.13	12	1330	590	1920	1690	400	100	1.08	0.06	-	-
20110603	596	708	31.1	41.8	3.04	3.04	27.5	2.87	13.6	686	160	1580	1310	340	81	1.19	0.07	10.8	4.74
20110923	845	828	31.6	40.8	1.1	1.1	38.9	3.3	4.9	1280	220	1940	1810	280	87	0.98	0.03	9.58	1.48
20111124	810	926	8.4	55.4	3.75	3.75	37.3	1.59	1.6	1470	501	2020	1780	310	93	1.14	0.07	5.28	1.01
20111209	924	957	23.5	49.5	1.3	1.3	42.5	0.38	1.14	1390	1040	2170	2000	290	93	1.04	0.03	61.8	3.00
20120213	919	949	46.5	54.0	10.5	0.66	42.3	4.46	3.91	1570	1230	2250	2010	460	120	1.03	0.01	10.4	0.88
20120267	767	937	46.2	53.8	1.2	1.2	35.3	3.89	6.71	1240	665	2040	1680	350	97	1.22	0.02	11.8	1.72
20120307	692	826	25.5	45.9	6.20	6.20	30.6	1.4	4.21	778	920	1760	1510	310	87	1.19	0.14	18.2	3.01
20120404	700	788	7.7	53.7	3.88	3.88	32.3	1.7	1.7	1040	500	1750	1550	240	77	1.13	0.07	4.53	1.00
20120524	610	607	40.2	27.6	95.8*	0.61	28.1	2.5	4.01	547	432	1563	1402	600	140	1.00	0.02	16.0	1.60

	Activity concentrations (mBq.L^{-1})									Measured		Calculated		Dose		Isotopic ratios			
Date	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	U-235	Th-232	Th-228	GA	GB	GA	GB	< 1a	17a	234:238	210:226	230:232	228:232
20120620	462	550	24	42.9	2.98	0.11	21.3	1.2	6.07	497	11	1250	1040	250	64	1.19	0.00	20.0	5.06
20121030	785	824	12	41.4	17.1	3.25	36.1	3.08	8.46	1040	340	1890	1710	310	90	1.05	0.08	3.90	2.75
Sampling Point 7																			
20100807	472	434	17	38.5	16.8	-2.6	21.7	5.16	5.1	580	250	1130	1060	230	63	0.92	-0.07	3.29	0.99
20101203	776	747	196*	25.7	6.71	6.71	35.7	2.1	8.13	803	375	1930	1650	490*	120*	0.96	0.26	-	3.87
20110203	566	536	23.1	33.9	2.3	2.3	26	1.0	5.7	775	641	1320	1230	200	60	0.95	0.07	23.1	5.70
20110310	667	609	66.5	47.6	3.10	3.10	28.3	6.07	7.0	765	530	1510	1350	340	86	0.91	0.07	10.9	1.15
20110420	331	322	15	24.8	3.82	3.82	15.2	2.0	14	200	220	831	732	230	47	0.97	0.15	7.50	7.00
20110603	855	855	45.6	14.1	3.11	3.11	39.4	4.44	4.38	919	748	1960	1780	320	93	1.00	0.22	10.2	0.99
20110701	869	895	41.3	9.78	1.5	1.5	40	2.8	1.4	939	520	1930	1810	250	83	1.03	0.15	14.7	0.50
20110824	837	869	33	22	2.63	2.63	38.5	5.01	7.13	780	360	1940	1770	290	85	1.04	0.12	6.59	1.42
20110923	931	860	82.3*	20.1	3.8	3.8	42.9	8.69	20.7	804	210	2143	1960	500*	110*	0.92	0.19	-	2.38
20111124	348	360	12.8	26.1	8.42	-2.1	17.8	3.26	11.0	634	495	923	789	290	60	1.03	-0.08	3.93	3.37
20111209	516	480	18.3	35.8	1.2	1.2	23.8	1.16	1.9	430	621	1190	1130	180	53	0.93	0.03	15.7	1.64
20120267	215	264	29.4	20.8	4.16	4.16	9.92	0.86	3.8	410	663	630	492	140	36	1.36	0.20	34.1	4.42
20120307	332	357	15.5	13.4	0.35	0.35	14.2	1.92	1.6	290	710	780	704	110	35	0.98	0.03	8.07	0.83
20120404	231	206	16.7	24.2	5.13	5.13	11.5	15.4	3.74	170	250	592	529	170	38	0.89	0.21	1.08	0.24
20120524	431	473	32.6	13.0	4.26	4.26	19.9	1.4	19.3	381	568	1110	913	400	76	1.10	0.33	23.2	13.7
20120620	859	968	120*	15.5	2.11	2.11	39.5	34.2*	13.9	1120	600	2190	1790	520*	120*	1.13	0.14	-	-
20121030	305	325	55.5	18.7	2.1	2.1	14.1	0.91	8.2	190	350	820	668	190	46	1.07	0.11	60.9	9.01
Sampling Point 8																			
20100807	452	502	16.7	7.52	3.34	3.34	22.9	2.41	6.0	390	200	1110	954	210	55	1.11	0.44	6.93	2.49
20101203	97.2	128	83.9	6.32	14.8	-1.3	4.47	6.21	10.7	100	429	378	224	230	41	1.32	-0.21	13.5	1.72

	Activity concentrations ($mBq.L^{-1}$)									Measured		Calculated		Dose		Isotopic ratios			
Date	**U-238**	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Po-210**	**U-235**	**Th-232**	**Th-228**	**GA**	**GB**	**GA**	**GB**	**< 1a**	**17a**	**234:238**	**210:226**	**230:232**	**228:232**
20110203	188	185	25.2	5.59	1.5	1.5	8.64	3.0	6.05	170	656	472	401	150	30	0.98	0.27	8.40	2.02
20110310	166	199	7.2	6.51	3.83	0.56	7.67	1.0	3.0	310	330	444	359	150	32	1.20	0.09	7.20	3.00
20110420	168	166	155*	12.6	6.43	6.43	7.72	71.1*	26.1*	130	86	737	375	640*	100*	0.99	0.51	-	-
20110603	241	276	47.1	12.4	0.38	0.38	11.1	1.94	3.9	210	260	671	524	170	39	1.15	0.03	24.2	2.01
20110701	319	320	59.5	0.3	0.95	0.95	14.7	8.04	4.76	200	430	745	649	180	43	1.00	3.17	7.40	0.59
20110824	367	381	21	9.53	5.5	5.5	16.9	3.84	6.54	250	180	880	780	190	47	1.04	0.58	5.47	1.70
20110923	535	516	43	9.97	5.43	0.24	24.6	16	19.4	556	200	1290	1130	330	71	0.96	0.02	2.69	1.21
20111020	561	595	10	4.6	3.75	3.75	25.9	0.56	5.35	535	360	1290	1180	200	58	1.06	0.82	17.8	9.55
20111124	368	381	11	10.5	3.66	3.66	16.9	1.1	3.94	451	470	964	821	260	57	1.04	0.35	10.0	3.58
20111209	370	407	28	12.2	3.78	3.78	17.0	-0.38	4.13	590	854	959	797	280	61	1.10	0.31	-73.6	-10.8
20120213	407	398	93.9	9.69	13.6	0.61	18.8	3.7	5.51	578	630	1090	880	470	94	0.98	0.06	25.3	1.49
20120267	356	365	33.9	14.8	17.8	-0.33	16.4	10.0	5.8	612	552	905	785	190	51	1.03	-0.02	3.39	0.58
20120307	275	282	30.8	5.92	0.14	0.14	12.7	1.10	6.88	47	560	659	575	170	37	1.03	0.02	28.0	6.25
20120404	326	326	24.6	14.5	3.87	-0.12	15	1.26	5.02	200	210	784	703	170	42	1.00	-0.01	19.5	3.98
20120524	506	545	8.5	3.20	29.6	3.77	23.3	3.87	5.00	519	566	1200	1080	300	76	1.08	1.18	2.20	1.29
20120620	457	474	69.7	19.3	3.31	3.31	21.0	15.9	34.4	668	330	1240	985	480	84	1.04	0.17	4.38	2.16
20121030	377	400	13	8.42	11.0	0.30	17.4	0.74	11.0	180	210	931	807	240	53	1.06	0.04	17.5	14.8
Sampling Point 9																			
20100420	1710	1790	13	122	15.4	15.4	78.6	1.48	7.35	1600	1070	4480	3840	1000	240	1.05	0.13	8.78	4.97
20101203	52.8	65.7	19	6.52	11.3	-0.06	2.43	6.33	7.3	-66	45	231	135	170	30	1.24	-0.01	3.00	1.15
20110203	5250	5170	175	95.1	5.94	5.94	242	9.91	9.43	4850	2420	11700	11000	1700	510	0.98	0.06	17.6	0.95
20110310	1610	1720	30	74.7	27.9	10.1	74.0	3.7	15	1750	660	4360	3540	1900	360	1.07	0.14	8.11	4.05
20110824	721	801	14	34.2	22.4	2.04	33.2	1.93	6.1	791	420	1900	1590	520	120	1.11	0.06	7.25	3.16

	Activity concentrations (mBq.L^{-1})									Measured		Calculated		Dose		Isotopic ratios			
Date	**U-238**	**U-234**	**Th-230**	**Ra-226**	**Pb-210**	**Po-210**	**U-235**	**Th-232**	**Th-228**	**GA**	**GB**	**GA**	**GB**	**< 1a**	**17a**	**234:238**	**210:226**	**230:232**	**228:232**
20111020	33.5	46	27.8	25.4	5.21	5.21	1.54	4.29	4.29	-24	92	276	141	180	31	1.37	0.21	6.48	1.00
20111124	36.9	44.5	8.9	10.3	24.5	-11	1.70	0.80	3.18	90	22	262	164	220	39	1.21	-1.07	11.1	3.98
20111209	72.9	75.8	40.8	22.9	27.5	-12	3.36	3.6	4.51	61	140	357	231	300	55	1.04	-0.52	11.3	1.25
20120213	48.7	65.5	18.8	20.6	8.89	-0.81	2.24	2.21	7.43	587	1060	356	164	460	69	1.34	-0.04	8.51	3.36
20120267	216	229	29.1	24.1	2.42	2.42	9.95	2.1	10.8	252	462	618	497	190	38	1.06	0.10	13.8	5.14
20120307	206	180	20.1	8.39	9.48	-0.47	9.49	0.85	2.5	30	300	480	450	120	31	0.87	-0.06	23.6	2.94
20120404	105	106	4.6	15.7	3.43	0.085	4.82	3.85	5.57	-120	96	336	257	170	29	1.01	0.01	1.19	1.45
20120524	39.4	39.7	27	7.38	1.85	1.85	1.82	6.29	13.5	-140	51	222	102	240	33	1.01	0.25	4.29	2.15
20120620	24.0	23.7	93.0	6.37	6.4	6.4	1.11	19.2	4.0	5.7	-230	245	77	260	42	0.99	1.00	4.84	0.21
20121030	40.1	45.6	18.2	6.89	7.97	-0.10	1.85	3.28	6.51	-200	0.65	193	112	170	28	1.14	-0.01	5.55	1.98
Sampling Point 10																			
20100420	742	805	13	45	3.9	3.9	34.2	3.38	2.8	608	140	1810	1620	260	81	1.08	0.09	3.85	0.83
20100807	683	732	22.2	36.5	7.203	-2.1	31.4	1.37	3.2	581	120	1610	1480	220	72	1.07	-0.06	16.2	2.34
20101203	991	1040	10	44.7	4.1	4.1	45.6	1.49	10.3	1110	552	2330	2130	330	99	1.05	0.09	6.71	6.91
20110203	849	898	34.2	53.5	1.6	1.6	39.1	5.57	5.54	893	561	2060	1850	280	88	1.06	0.03	6.14	0.99
20110310	765	830	19	46.5	5.10	0.61	35.2	1.97	4.47	1430	310	1880	1670	330	92	1.08	0.01	9.64	2.27
20110603	736	869	133*	42.9	1.2	1.2	33.9	31.4	17	778	230	2020	1590	440*	110*	1.18	0.03	-	0.54
20110824	804	880	23	54.5	7.48	1.84	34.9	0.42	6.25	1050	190	1990	1770	280	86	1.09	0.03	54.7	14.88
20110923	756	863	64.3	46.4	3.12	3.12	34.8	3.88	6.1	1020	76	1960	1650	330	94	1.14	0.07	16.5	1.57
20111020	18.6	38.6'	19.3	4.57	2.86	2.86	0.856	3.2	18.1	22	-20	171	59	190	24'	2.08	0.63	6.03	5.66
20111124	710	827	13	39.2	1.93	1.93	32.7	1.3	3.87	1030	300	1770	1530	360	92	1.16	0.05	10.0	2.98
20111209	928	1040	10.8	42.4	2.58	2.58	42.7	-0.86	3.41	1220	879	2260	2010	270	91	1.12	0.06	-12.5	-3.97
20120213	938	1030	38.4	39.4	4.14	4.14	43.2	5.21	7.71	612	1010	2290	2010	420	110	1.10	0.11	7.37	1.48

	Activity concentrations (mBq.L^{-1})									Measured		Calculated		Dose		Isotopic ratios			
Date	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	U-235	Th-232	Th-228	GA	GB	GA	GB	< 1a	17a	234:238	210:226	230:232	228:232
20120267	851	972	25.4	102	3.27	3.27	39.2	0.74	2.94	1210	812	2270	1950	320	100	1.14	0.03	34.3	3.97
20120307	909	948	8.5	51.6	6.13	6.13	44.1	2.3	9.84	1070	510	2200	1980	450	110	1.04	0.12	3.70	4.28
20120404	871	895	5.8	52.2	2.80	2.80	40.1	1.3	0.94	1260	670	2020	1890	240	84	1.03	0.05	4.46	0.72
20120524	713	811	20	35.9	3.82	3.82	32.8	2.3	6.56	1160	694	1770	1540	260	78	1.14	0.11	8.70	2.85
20120620	647	735	70.9	39.0	26.6	2.60	29.8	4.6	17.2	902	290	1750	1430	480	110	1.14	0.07	15.4	3.74
20121030	880	911	10	42.9	4.6	4.6	40.5	5.0	16.4	1200	410	2100	1900	350	93	1.04	0.11	2.00	3.28
Sampling Point 11																			
20100807	116	130	23.4	9.51	15.7	-5.1	5.32	-0.51	3.4	41	-42	348	276	120	28	1.12	-0.54	-45.8	-6.67
20101203	29.2	57.8	33.4	4.55	4.67	4.67	1.34	4.88	8.99	-41	-27	208	73	280	42	1.98	1.03	6.84	1.84
20110203	59.3	80.9	11	2.82	2.26	2.26	2.73	1.0	2	36	330	249	133	350	55	1.36	0.80	11.0	2.00
20110310	72.2	70.7	9.4	12.1	5.36	5.36	3.33	3.1	3.1	53	130	233	182	150	27	0.98	0.44	3.03	1.00
20110420	144	153	8.8	2.18	3.22	3.22	6.64	0.86	6.95	-76	-150	369	308	140	27	1.06	1.48	10.3	8.08
20110603	174	172	47.2	2.67	2.96	2.96	8.02	19.2	7.15	230	160	484	367	230	42	0.99	1.11	2.46	0.37
20110701	193	204	47.1	1.5	3.77	3.77	8.89	11.9	6.14	82	170	519	404	200	39	1.06	2.51	3.96	0.52
20110824	233	259	9.6	4.88	3.2	3.2	10.7	2.53	7.49	-36	180	582	490	190	38	1.11	0.66	3.79	2.96
20110923	1490	1410*	-1.1	1.57	2.0	2.0	68.7	7.26	11.9	62	7.3	3140	3060	490*	140*	-	1.27	-0.15	1.64
20111020	86.2	87.5	21	3.37	2.28	2.28	3.97	4.00	6.25	11	-3.9	247	188	110	20	1.02	0.68	5.25	1.56
20111124	36.7	52.6	12	2.79	2.23	2.23	1.69	0.50	4.0	21	100	168	84	240	37	1.43	0.80	24.0	8.00
20111209	51.0	62.8	8.9	0.75	1.2	1.2	2.35	2.75	7.66	-100	170	198	115	180	26	1.23	1.60	3.24	2.79
20120213	43.7	58.5	21.1	0.81	2.18	0.034	2.01	0.89	6.59	1520	848	178	94	200	30	1.34	0.04	23.7	7.40
20120267	55.5	75	27.9	3.08	1.3	1.3	2.56	2.52	6.08	89	320	205	124	97	16	1.35	0.42	11.0	2.41
20120307	54.3	72.0	15	1.76	3.08	3.08	2.50	1.04	3.1	-140	230	180	123	68	14	1.33	1.75	14.4	2.98
20120404	129	164	18.5	1.84	2.12	2.12	5.96	5.85	20.0	46	270	413	274	210	31	1.27	1.15	3.16	3.42

Date	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	U-235	Th-232	Th-228	Measured GA	Measured GB	Calculated GA	Calculated GB	Dose < 1a	Dose 17a	234:238	210:226	230:232	228:232
	Activity concentrations (mBq.L^{-1})															Isotopic ratios			
20120524	403	344	11	1.31	1.7	1.7	18.6	2.98	4.5	150	320	839	832	140	40	0.85	1.30	3.69	1.51
20120620	279	302	16	4.26	3.90	0.71	12.9	< 2.2	3.11	420	76	675	591	140	35	1.08	0.17	-	-
20121030	201	212	9.7	2.64	6.81	6.81	9.25	1.9	4.80	-0.34	78	503	429	170	35	1.05	2.58	5.11	2.53
Sampling Point 12																			
20100420	19.3	31.3	21.2	0.57	7.22	7.22	0.887	1.7	6.04	-220	-160	126	52	140	22	1.62	12.6	12.4	3.55
20100807	11.4	26.6	32.2	0.38	2.71	2.71	0.525	2.48	2.5	-99	-230	101	30	91	16	2.33	7.13	12.9	1.01
20101203	31.9	51.8	26.7	0.23	7.7	-0.2	1.47	4.14	6.09	-31	26	147	73	130	22	1.62	-0.87	6.45	1.47
20110203	47.1	84.7	68	1.05	1.5	1.5	2.17	8.4	27.2	30	400	303	105	380	50	1.80	1.43	8.10	3.24
20110310	23.4	36.1	19	2.53	3.78	3.78	1.08	1.6	6.48	31	-3	160	70	140	20	1.54	1.49	11.8	4.05
20110603	39.6	61.9	81.6	2.25	4.12	4.12	1.82	14	35	46	-36	360	93	510	66	1.56	1.83	5.83	2.50
20110701	39.7	46.4	73.9	2.5	0.22	0.22	1.67	14.5	9.5	-61	250	215	86	210	33	1.17	0.09	5.10	0.66
20110824	71.1	96.5	24	1.54	1.88	1.88	3.28	1.52	4.49	326	17	236	152	99	18	1.36	1.22	15.7	2.95
20110923	53.2	64	26.5	1.2	4.38	4.38	2.45	1.2	11.1	-9.9	-66	225	127	190	29	1.20	3.65	22.0	9.25
20111020	37.0	56.4	44	1.8	5.08	5.08	1.7	11	15	-71	-50	269	90	360	54	1.52	2.82	4.00	1.36
20111124	19.6	38.3	14.8	0.91	1.9	1.9	0.903	0.94	3.5	41	68	152	61	170	26	1.95	2.09	15.7	3.72
20111209	16.1	39.5	13	3.46	11.8	-5.3	0.73	0.46	2.3	-140	82	131	64	100	19	2.45	-1.53	28.2	5.00
20120213	15.9	35.4	10	3.5	4.74	4.74	0.733	1.81	1.8	-6.1	170	125	42	260	40	2.23	1.35	5.52	0.99
20120307	26.9	47.6	10	3.65	2.06	2.06	1.24	0.77	3.79	-260	140	130	70	75	12	1.77	0.56	12.9	4.92
20120404	52.4	63.2	10	2.15	3.19	3.19	2.41	0.32	4.77	-220	110	180	118	140	22	1.21	1.48	31.2	14.91
20120524	54.2	68.9	23	1.04	1.4	1.4	2.49	7.99	5.7	-180	57	200	120	100	17	1.27	1.35	2.88	0.71
20120620	63.8	89.0	95.8	0.32	6.12	0.22	2.94	5.99	0.98	15	-250	294	140	200	36	1.39	0.69	15.9	0.16
20121030	33.6	49.5	10	4.39	7.5	0.57	1.54	3.44	4.1	-140	-7.5	130	86	98	17	1.47	0.13	2.91	1.19
Sampling Point 13																			

	Activity concentrations (mBq.L^{-1})									Measured		Calculated		Dose		Isotopic ratios			
Date	U-238	U-234	Th-230	Ra-226	Pb-210	Po-210	U-235	Th-232	Th-228	GA	GB	GA	GB	< 1a	17a	234:238	210:226	230:232	228:232
20100807	181	198	48	7.51	3.22	3.22	7.79	2.1	1.4	250	370	493	390	110	24	1.09	0.43	22.8	0.67
20101203	217	221	42.1	10.8	8.88	8.88	10.3	2.49	6.07	260	370	593	473	210	52	1.02	0.82	16.9	2.44
20110824	147	164	15	11.2	13.7	3.47	6.78	2.6	4.58	110	420	422	340	160	35	1.12	0.31	5.77	1.76
20110923	149	154	31.5	9.66	23.5	-1.5	6.87	16.7	10.9	95	180	471	354	240	46	1.03	-0.16	1.89	0.65
20111020	177	224	29	5.97	4.05	4.05	8.15	5.2	3.0	150	400	521	394	160	35	1.27	0.68	5.58	0.58
20111124	199	205	56.3	18.9	6.19	6.19	9.36	2.2	3.2	380	511	619	471	240	49	1.03	0.33	25.5	1.45
20111209	130	143	25.4	17.8	3.79	3.79	5.5	3.60	5.9	120	1060	420	312	190	36	1.10	0.21	7.06	1.64
20120213	161	168	50.5	14.6	5.65	5.65	7.43	2.1	5.72	1230	887	527	368	390	66	1.04	0.39	24.0	2.72
20120307	57.7	67.5	17	17.7	1.97	1.97	2.65	1.80	1.3	212	280	210	157	100	19	1.17	0.11	9.44	0.72
Sampling Point 14																			
20100807	951	944	68.9	7.21	7.12	-0.24	43.8	10.5	7.5	1060	800	2138	1976	110	24	0.99	-0.03	6.56	0.71
20101203	813	759	29.6	3.6	3.84	3.84	37.4	-1.5	3.1	1050	610	1701	1675	270	79	0.93	1.07	-19.7	-2.07
20110203	186	215	6	8.2	4.35	4.35	8.57	2.47	8.86	100	441	487	403	150	31	1.16	0.53	2.43	3.59
20110310	266	276	69.8	4.67	4.01	4.01	12.2	11.5	32.2	442	450	761	564	420	66	1.04	0.86	6.07	2.80
20100420	200	220	50.5	4.56	4.7	4.7	9.19	2.63	3.83	110	1040	562	427	270	52	1.10	1.03	19.2	1.46
20110824	630	692	17	9.14	4.73	4.73	29	3.1	4.82	240	370	1479	1320	230	68	1.10	0.52	5.48	1.55
20120404	320	336	13	8.48	8.02	-0.31	14.7	3.22	4.41	290	460	768	683	180	44	1.05	-0.04	4.04	1.37
20120524	421	423	29	13.4	5.66	5.66	19.4	6.15	19.4	318	524	1056	900	320	63	1.00	0.42	4.72	3.15
20120620	766	746	42.8	3.89	3.51	3.51	36.2	8.2	11.7	1020	700	1698	1586	350	87	0.97	0.90	5.22	1.43
20121030	461	446	20	7.58	12.2	20.4	21.2	1.8	24.4	250	1210	1128	979	470	88	0.97	2.69	11.1	13.56
min	5.12	13.7	-1.1	-0.9	0.14	-12	0.236	-1.5	0.026	-320	-330	55.84	13.06	56	8.8	0.85	-38.1	-107	-92.3
max	5250	5170	175	207	29.6	31.8	242	34.1	35	4850	2420	11663	10979	1900	510	4.95	23.2	186	136

APPENDIX D

VALIDATION OF IMPLEMENTED ANALYTICAL METHODS

Appendix D contains some of the full validation reports of the radiochemical methods implemented by the author of the thesis during this study.

D.1 Validation of the method for the determination of ^{210}Po and ^{210}Pb in water

1. OBJECTIVE

To validate the method for the determination of Polonium-210 and Lead-210 in water.

2. SCOPE

The specifications set for the method is as follows:

- The chemical yield should be better than 20%;
- The precision and accuracy should be better than 20%; and
- The minimum detectable activity (MDA) should be 5 mBq.L^{-1}.

3. STANDARDS AND SAMPLES

3.1. Standards

^{209}Po tracer (ca 0.085 Bq ^{209}Po/g)

The activity concentration of the solution was (0.0928 ± 0.0020) Bq.g^{-1}

A second tracer solution with activity (0.0932 ± 0.002) Bq.g^{-1} was prepared.

^{210}Pb control solution (ca 0.300 Bq ^{210}Pb/g)

The activity concentration of the solution was (0.315 ± 0.010) Bq.g^{-1}.

3.2. Samples

Samples which were spiked with a known activity of ^{209}Po, ^{210}Pb or ^{226}Ra were used for method development and validation.

The accuracy of the method was determined by analyses of control samples. The control sample should be analysed at least once a month and the results reported on a datasheet for quality control purposes.

4. OPTIMIZATION OF PLATING CONDITIONS

The method of determining ^{210}Po by spontaneous deposition has been thoroughly investigated through the years and used in determining polonium in biological and environmental samples.

4.1 Physical Aspects

Under ideal conditions, transport of an electro-active species to a rotating disc electrode is diffusion-controlled (3.3 g). The theoretical rate of polonium deposition on a rotating silver disc can be expressed as

$$dN/dt = K_1(A\ \omega^{0.5} / V)(N_0 - N_s)\ exp\ (K_2T)$$

where dN/dt is the rate of deposition; K_1 and K_2 are constants; T is the absolute temperature; A is the active disc area; V is the volume of solution; ω is the angular velocity of rotation of the disc; and N_0 and N_s are the concentrations of polonium in the bulk liquid and at the disc surface respectively.

Following from the above expression it is clear that the rate of deposition is directly proportional to: (i) the ratio of disc area to solution volume (A/V); (ii) the concentration difference between the bulk solution and the solution at the disc surface ($N_0 - N_s$); (iii) the square root of the angular velocity of rotation of the disc and (iv) the exponential of the absolute temperature. This indicates that optimum plating conditions would require high temperatures and angular velocity, and small solution volume.

4.1.1 Reaction vessel

The use of plastic beakers instead of glass is recommended in the literature to prevent the possible adsorption of Po on glass surfaces. When using plastic beakers it is not possible to use hot plates and the yields were much lower (20-37%) when heating on a water bath, maybe because of inefficient stirring.

Slightly higher yields were obtained by using 200 mL of sample (60-77%) in a narrow-mouth 250 ml beaker than in a 400 ml beaker (45-67%). The narrow-mouth beaker also lessens the evaporation rate (see 4.1.3). When using glass a problem was experienced with variance in blank values (see 5.1) which was thought to be due to either adsorption or leaching of Pb/Po out of the glass.

4.1.2 Temperature

From all the reports it is evident that rapid and effective deposition depends on elevated temperature and low volume. The rate of deposition increases with increasing temperature up to 85 ^{O}C, above which bubble formation at the disc reduces recovery. Temperatures < 85 ^{O}C are required for quantitative recovery.

Deposition was not quantitative at room temperature. The yield was 20% after 48 h. Yields of 50-70 % were obtained at a temperature of 80-90 ^{O}C. Po is volatile at a temperature of 150 ^{O}C and losses will occur at very high temperatures. The temperature should be set to ensure even boiling of the solution without spattering.

4.1.3 Volume

According to the literature the rate of polonium deposition varies directly with the surface area of the disc, and inversely with the volume of the solution. The recovery increases linearly from 55 to 90% with a decrease in sample volume from 900 to 300 ml. Smith & Hamilton also found that recovery improved from 60-95% with decreasing volume from 100 to 25 ml.

Experimentally it was found (see Table 1) that the yield stayed fairly constant for a volume of 50 to 200 ml. The yield in 400 ml was 43 % which is still within the normal range of the method (see 5.2), and can also be the effect of the larger beaker used (see 4.1.1).

To reduce loss by evaporation, constant refilling is necessary to keep the volume between 100 and 150 ml. In the literature constant volume is retained by means of a drip valve set to equal the loss by evaporation.

Table 1: Volume

Volume (ml)	Yield (%)
50	70
100	62
150	59
200	70
400	43

It was found that a solution which had been refilled with 0.25 M HCl during the first extraction had a yellow colour after plating and a black precipitate formed in the stored solution in the two months in-growth period. The solution had to be filtered before a second extraction could be carried out. As it was suspected that the precipitate could be $PbCl_2$ which is only slightly soluble in diluted HCl, the precipitate was α and β counted but didn't contain any activity. When refilling with distilled water the solution remained clear throughout the plating procedure and no precipitate formed in the in-growth period. The pH at the start and end of the plating period was about 1 and 0.5 respectively.

Evaporation of samples and re-dissolving of the residue in HCl didn't cause any losses. Pre-concentration of samples volumes of up to 1 litre is therefore in principle possible. For direct determination of Po in volumes of more than a litre pre-concentration as follows is recommended in the literature: A suspension of Ni fillings or powder or a Ag ribbon is stirred in the heated solution. After separation by filtration the metal is dissolved in HCl or HNO_3. This resulted in a small volume of solution, from which the Po is plated on a silver disc.

4.1.4 Disc size

Polonium may be deposited on both sides of a silver disc simultaneously by suspending the disc in the plating solution. The same counting precision can be obtained in half the time if all the polonium is plated on one side of the disc. To achieve this one face of the disc can be protected by coating with enamel or by retaining the disc in a holder with a srew-on-cap. In the present work, it proved impossible to find a paint that gave reliable coating in hot HCl. Covering one side of the disc with plastic worked well to prevent plating. No activity higher than background was measured under or on the plastic side. Other possible methods include melting a thin coating of polyethylene on the unpolished side of the disc or preparation of a thin plastic foil from poly(vinyl formaldehyde) available as Formvar.

The maximum theoretical geometric counting efficiency of 50% would be achieved with a sample disc diameter equal to, or smaller than that of the detector, and with the sample in contact with detector surface. In practice, some distance is necessary to avoid contamination of the detector. In the present study the detector diameter was 24 mm. A source 20 mm in diameter was counted 6 mm from the detector. When using a larger disc (32 mm diameter) the yield improved slightly, but this gain was neutralized by the lower counting efficiency when using another geometry (30 mm i.d. rig and not 20 mm). Increasing the surface area by not covering one side and counting both sides of the disc also didn't improve the yields.

Washing of the disc (cleaning mechanically, heat and stir for 1 h in detergent, rinse with acetone and airdry) as described by Clayton & Bradley didn't prove to be necessary, as it had no effect on the yields or the blank values. Hamilton & Smith reported that resolution improves when polishing the disc to a bright finish with alumina paste. Since the resolution of the spectra usually was quite good, polishing in our case didn't seem necessary.

The possibility of re-using the discs after cleaning as suggested by Flynn was investigated. Two discs with Po-210 activity of 65 mBq were mechanically cleaned by polishing the plated sides and recounted. There was, however, still a significant amount of Po present after cleaning (38.5, 47.3

mBq).

4.1.5 Stirring

In the literature variable recoveries are found when using a non-stirred silver bottom apparatus or with stationary hanging silver disks in stirred solution, where as spinning silver disks give good yields (90 % at 85 ^{O}C for 1.5 h in 0.5 M HCl). Too fast rotational velocities may cause turbulence which reduces recovery. It was confirmed experimentally that stirring of the solution during extraction is very important to obtain sufficient yields. Without stirring yields of less than 20% were often obtained. Mechanical stirring with a glass rod caused excessive splashing owing to the difficulty of regulation at low speed, hence a combined hot-plate magnetic stirrer was used.

Periodic additions of H_2O were required to compensate for volume loss during plating. Bubbles must be removed from the face of the disc periodically during plating. The low yields obtained in a water bath (see 4.1.1), was probably due to inefficient stirring of the solution.

4.1.6 Time

Plating of polonium from solution onto a silver disc is initially rapid, but the rate decreases with time. Plating times vary depending on the polonium activity (75-150 min) for activities of 200-1500 mBq. Up to 300 mBq of polonium is usually recovered in less than 2 h. Flynn found that full recovery of polonium is possible in 60 minutes and that recoveries are unaffected by further plating time up to 3 hours.

As can be seen in Table 2 a 2-hour extraction time was marginally adequate to achieve maximum deposition. As a precautionary measure, extractions were usually for 3 to 4 h. Quantitative yields were not obtained, however, even when the deposition was continued for 6 hours. Plating times longer than 2 hours didn’t cause tailing as mentioned in the literature.

Table 2: Extraction time

time (h)	yield (%)
1	33
2	68
3	77
4	71
5	73
6	76

4.1.7 Stability of the prepared disc

The half-life of ^{210}Po is 138 d. After decay correction it was found that the activity on the prepared discs remained stable for at least 7 days after preparation. No discoloration of the discs occurred.

4.2 Chemical Aspects

4.2.1 pH

A series of solutions were spiked with ^{209}Po tracer and the pH adjusted with HCl to cover a range from pH 0.5 to 3. The effect of pH on the yield is shown in Figure 1. The results clearly indicate that the yield decreases with an increase in pH and that the pH of the solution should be between 0.5 and 1.5 (acid concentration 0.1 N HCl) for optimal recovery. According to the literature for a deposition time of 4 hours, the recovery of ^{209}Po decreases when the HCl concentration exceeded 0.5 N. The optimum pH range is 1.5 to 2.0. At lower pH the silver is etched, which reduces recovery and decreases the peak resolution.

Acidifying the solution with HNO_3 gave yields of 40-60% for the pH range 0.75-2. At low pH the presence of HNO_3 caused discoloration of the disc and at a pH of 0.5 the disc dissolved.

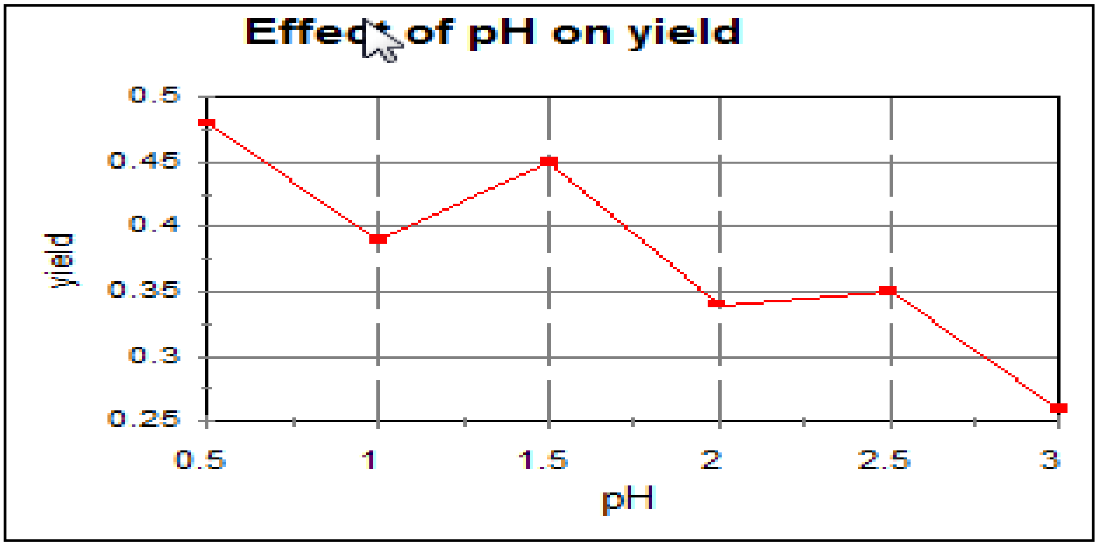

Figure 1: Effect of pH on yield

4.2.2 Interferences

The number of radioactive cations in the environment which will spontaneously deposit on silver from a 0.1 M HCl solution is very limited.

According to the literature the presence of nitrate ions in solution will decrease the yields and may also cause discoloration of the disc. Samples received for Po-analysis should therefore be preserved with HCl and not with HNO_3. Samples that are acidified with HNO_3 should be evaporated and re-dissolved in 0.2 M HCl. The yields obtained for samples plated in a solution of HCl, HNO_3 or HNO_3 evaporated and re-dissolved in HCl were found to be comparable. The presence of HNO_3 did however cause discoloration of the disc, especially at lower pH because it attacked the silver disc. Spectra obtained by counting this "black" disc, showed self-absorption and loss of resolution (spread 3.2 to 5.4 MeV).

Table 3: Effect of iron concentration on yield

Fe(III) concentration (mg)	yield (%)	
	ascorbic acid	no ascorbic
0	53	47
2.5	42	
5	41	
7.5	23	Spectrum spread
10	29	No plating

As can be seen in Table 3 plating of polonium was inhibited in the presence of Fe(III). A concentration of 7.5 mg Fe/ml reduced the recovery of Po to 20%, compared to a recovery of 50% for control solutions containing no iron. For samples containing more than 7.5 mg Fe/ml no plating occurred without addition of ascorbic acid. A dark deposit on the silver surface was also evident, and coincided with severe degradation of the α-peak resolution.

According to Flynn the polonium deposition method is subject to interference from oxidants, organic materials and elements that also deposit on silver. He also mentions the slight possibility of small amounts of ^{232}Th and ^{212}Bi plating at pH = 1, which can be prevented by addition of a small quantity of sulphide. Interference of Fe(III), Cr(VI) and other oxidants can be eliminated by addition of hydroxylamine hydrochloride, excess of which does not interfere with plating efficiency. Tellerium and selenium in milligram quantities deposit on silver and decrease plating efficiency but as much as 10 mg of these metals can be tolerated by raising the pH to 2.0. Smith&Hamilton found ascorbic acid to be more effective than hydroxylamine hydrochloride as reducing agent. A 2 g excess of ascorbic acid does not reduce plating efficiency.

Since occasional problems had been experienced with the yields obtained for some routine field samples, it was considered worthwhile to investigate some of Flynn's suggestions, even though he is the only author mentioning any interfering element other than Fe.

A solution containing ^{232}Th was plated. The α-spectrum indicated no presence of either ^{232}Th or ^{212}Bi. The addition of hydroxylamine hydrochloride as a reducing agent to avoid interference by ions such as iron, as well as addition of citric acid and Bi-carrier, was also investigated.

Four samples for which very low yields had previously been obtained (RA 1833), were re-analysed using 2 g of hydroxylamine hydrochloride and not ascorbic acid. The effect of the addition of citric acid and Bi-carrier was also studied. These problem samples were usually yellowish in colour. The results can be seen in Table 4.

Table 4: Analysis of field samples

Reagent added	**Yield (%)**			
	x126	**x146**	**x108**	**x164**
100 mg ascorbic acid	13 07	12	11 04 07	13
2g hydroxylamine hydrochloride + 1 g citric acid + 40 mg bismuth carrier	57	64		51 49
2g hydroxylamine hydrochloride + 1 g citric acid (no Bi carrier)	69			
2g hydroxylamine hydrochloride+ 40 mg bismuth carrier (no citric acid)		59		
2g hydroxylamine hydrochloride (no citric acid or Bi-carrier)		62		

Addition of hydroxylamine hydrochloride greatly improved the yield of the problem samples. Addition of citric acid and Bi-carrier didn't seem to have any effect. The recovery of Po for normal field samples was affected little by the addition of hydroxylamine hydrochloride. It can, therefore, be omitted in the procedure unless problems had been experienced with the first analysis.

4.3 Efficiency of extraction

The yields obtained under optimum conditions varied between 40-80% (see 7.2) with a maximum of 80%. All attempts to further increase the yield failed. A second extraction directly after the first plating gave yields of 5-8 % to give a total maximum of 85%. The failure of the other 20% of Po to deposit could not be explained, and may be a result of adsorption of Po on the glass wall.

Polonium solutions at trace concentrations under various alkaline, neutral and weakly acidic conditions are known to be unstable being readily hydrolyzed, chemically deposited, or volatilized, exhibiting "radio-collodial" behaviour; and undergoing "plate-out" or adsorption onto glass surfaces. Stored polonium solutions, however, are generally considered to be stable in the acid range 0.1 to 1 N.

Normally when calculating the Po/Pb content on the day of sampling corrections are made for the Po remaining in the sample after first extraction. Because of the very incorrect results that were sometimes obtained when assuming that polonium remains in the solution (see 5.3), it was experimentally investigated. Six samples containing only ^{209}Po was extracted and left for six weeks before a second extraction was done. 2 g of silver filings were added to two of the samples before storage to ensure total removal of all Po.

Table 5: Efficiency of extraction

Sample	Yield % (1st)	Yield % (2nd)
1	49	00
2*	47	02
3	64	02
4*	57	00
5	21^{L}	04
6#	59	59

** Ag filings added; # ^{209}Po added with 2 nd extraction; ^{L} low yield - sample not stirred*

As can be seen from Table 5 none of the samples contained any Po higher than background activity after six weeks. When a second extraction was done directly after the first, the yield was also less than 10% which means that the low polonium concentration in the solution after six weeks is most probably not as result of polonium adsorbing on the walls of the plastic container during storage. The rest of the polonium activity (20%) is therefore unaccounted for and are lost during the plating process. It also cannot be assumed that Po is totally extracted at all times, because yields higher than 1 (as high as 1.31) were sometimes obtained during second extraction which is a clear indication that some Po does sometimes remain in the solution.

The activity of the tracer solution was verified (see 5.4) and was accurate to within 4 %.

To improve yields pre-concentration of Po on Ni filings which adsorb Po and Bi, dissolution and then plating with Ag can be investigated. Residual polonium can be stripped from solution by letting the solution stand in a water bath overnight in contact with a large silver disc.

5. CAPABILITY STUDY

5.1 Blank samples and detection limits

Three groups of four blank samples each were spiked with 0.5 ml of ^{209}Po and analysed on three different days (Tables 6 and 7).

As can be seen from Table 6 the average blank value differed significantly from day to day and show ^{210}Po contamination of the order 2-5 mBq.L^{-1}. The average blank values were lower than the value of (1.57 ± 0.51) counts/h mentioned in the literature.

The blank values (in the region of interest for ^{210}Po) obtained by counting clean silver discs, silver discs after plating in a solution of HNO_3 or HCl and a solution containing ^{209}Po were compared with detector background values.

Table 6: Analysis of blank samples (counts in 24 h)

DAY 1		DAY 2		DAY 3	
counts	**yield**	**counts**	**Yield**	**counts**	**Yield**
8	0.55	15	0.57	6	0.58
28	0.62	7	0.59	3	0.51
15	0.59	15	0.56	3	0.49
19	0.59	6	0.62	4	0.58
*Avg=0.73 ± 0.35		0.45 ± 0.20		0.17 ± 0.06	

** Avg in counts per hour*

Table 7: Identification of factors causing blank values

Detector background			Background Ag disc only	Blank (200 ml water + 0.5 ml ^{209}Po)			
Initial	**after cleanup**	**current**		**new glass**	**old glass**	**deionized water**	**Dist water**
58	9	3	1	20	14	6	25^{n}
38	4	2	2	21	9	4	17
35	2	1				9^{n}	
45	1	0				12^{n}	
1.84 ± 0.43	0.17± 0.15	0.06 ± 0.05		0.85 ± 0.03	0.48 ± 0.15	0.32 ± 0.14	0.88 ± 0.24

*** Avg in counts per hour; ^{n} new beaker*

The original high detector background values were the result of detector contamination. After clean-up as in RA-PFT-107(01) the values decreased. Recoil of ^{226}Ra results in ^{210}Po contamination of the detectors. As recommended in RA-PFT-107(02) samples for ^{210}Po determination should never be counted on the same detectors as ^{226}Ra samples, except where recoil suppression is available on the detectors.

It was found (Table 7) that the blank value increased when new beakers were being used for the first time. Beakers that had been re-used a few times tended to give lower values except in cases of contamination of the beaker itself. Water quality also had an effect on the blank value. The distillation unit is installed in the same laboratory where some of the analyses on the natural nuclides are performed. It may be that the water is contaminated in some way. The difference between the three days (Table 6) can most probably be ascribed to a combination of the water quality and the beakers used.

Addition of ascorbic acid did not increase the blank value. Background values for discs were 3 - 8 counts in 24 h regardless whether the disc had been cleaned or not.

Because of the significant difference between the background and blank values, distilled water spiked with ^{209}Po should be used as blank samples to compensate for the risk that the water or beakers might be contaminated. Doing a blank with every new beaker used may be an option, but will waste a lot of time. Higher contamination than 20 counts seldom occurs if all precautions are followed and beakers are soaked in a solution of nitric acid and contrad for at least three days. Some authors recommend storing the beakers until reused filled with 0.5 N HCl and scraps of silver foil.

The lowest and highest average values of (0.17 ± 0.06) and (0.73 ± 0.35) counts/h were used for calculation of the MDA for ^{210}Po. The minimum detectable activities were calculated from the sample blank counts for a counting period of 24 hours, volume 200 ml, chemical yield 0.4 and detector efficiency 0.3. The MDA varies between 5.8 and 10.7 $mBq.L^{-1}$. By counting for 48 hours the MDA can be decreased to 3.8 $mBq.L^{-1}$.

5.2 Chemical yield

The average yields for samples spiked with ^{209}Po are presented in Table 8. The yields were determined for solutions acidified with HNO_3 (pH=1), HNO_3 (pH=2) and HCl (pH=0.5). The yields were much better when plating in a solution of HCl.

Table 8: Chemical yield of the analytical procedure

	yield	rsd	n
HNO_3 (pH = 1)	0.40 ± 0.08	20.7	8
HNO_3 (pH = 2)	0.36 ± 0.06	16.6	4
HCl (pH = 0.5)	0.66 ± 0.10	15.5	74

For a total of 88 samples analysed during development and validation the average yield was 0.64±0.14 (rsd 22.5). Of these 10 values were lower than 0.4 and only 4 lower than 0.3. These were usually a result of insufficient stirring or spillage losses. Another 4 values were higher than 0.8 which was during second extractions and mostly a result of the Po still present in the solution unaccounted for. Rejecting this outliers gave an average yield of 0.66 ± 0.10 with a range of 0.42-0.80.

According to the literature deposition should be quantitative (> 90%) under the conditions as in par 4. The relatively low average yield found couldn't be explained. All attempts to improve yields by optimizing experimental conditions failed (see 4.3). A possible error with expected activity value by certifying the tracer solution was also excluded (see 5.4).

5.3 Precision and Accuracy

The accuracy of the method was determined using samples spiked with a ^{210}Pb-^{210}Bi-^{210}Po standard (ref data 96-01-01). The reference solution has been stored long enough to expect radioactive equilibrium between ^{210}Pb, ^{210}Bi and ^{210}Po. Three sets of four samples each were prepared and analysed on different days. A second extraction was done after an in-growth period of 6 weeks. The expected activity of the samples is 314.97 mBq ^{210}Pb-^{210}Po. The results are presented in Table 9.

The precision for the Po-values determined at time of first and second extraction was good. Although the results obtained for Pb-210 at sampling were acceptable it can clearly be seen from Table 9 that the results for Po-210 were atrocious. The data were manipulated by changing the time of sampling (t_0) in the spreadsheet and the yields obtained. Results are presented in Table 10.

By taking $t_0 = t_1$ and not as the real reference date (96-01-01) the values obtained for Po was more accurate. The erroneous results first obtained can be ascribed to the relatively small in-growth period of 6 weeks allowed between the two extractions compared to the long time between sampling and first extraction. For more accurate values the in-growth period should be extended to at least 6 months which will result in much longer turnaround times at RadioAnalysis.

In the original spreadsheet the yield for the second extraction is calculated assuming that Po is not quantitatively removed during the first extraction. The effect of manipulating yield values can be seen from Table 10. It is clear that the assumption that the Po not extracted at time t_0 was still present after 6 weeks is incorrect (see 4.3). Although the measured yield with the first extraction was accurate (see 5.4), it seems as if some of the Po (not necessarily all because sometimes yields > 1 are obtained) remaining in the solution is lost somewhere (either during the plating process itself or during the standing period, maybe sticking to the sides of the containers, the sides of the Ag disc itself, etc). The Po residue in the stored sample probably lies somewhere between 40 and 10 %, and may differ from sample to sample. More accurate results were obtained when expecting only 10 % of Po to remain in the solution.

Table 9: Control samples

Set	Yield		Activity concentration mBq.L^{-1}			
	1st	2 nd	Po 1st extraction	Po 2nd extraction	Po sampling	Pb sampling
1	0.73	0.60	409	120	71727	182
	0.74	0.64	372	122	41874	252
	0.70	0.60	357	120	51923	198
	0.79	0.72	361	109	40044	246
2	0.76	0.74	349	118	25775	287
	0.80	0.75	365	112	29020	294
	0.69	0.63	343	123	41476	225
	0.76	0.74	374	121	40822	260
3	0.76	0.77	344	96.5	56797	180
	0.93	0.71	248	90.2	-51629	446
	0.76	0.50	341	108	30641	266
	0.83	0.63	358	115	4836	372
average			352	113	31 859	267
standard deviation			38	10	31 210	78
relative std deviation			10.7	9.3	98.0	29.1
percentage error					10 014	- 15.1

Table 10: Manipulation of control sample data

Manipulation	Po-210 at sampling			Pb-210 at sampling (mBq.L^{-1})		
	mBq.L^{-1}	rsd %	Err %	mBq.L^{-1}	rsd %	Err %
current spreadsheet t_0 = 96-01-01	31859 ± 31210	98.0	10014	267 ± 78	29.1	- 15.1
current spreadsheet $t_0 = t_1$	352 ± 38	10.7	11.7	242 ± 70	29.0	- 23.0
use real yields; assume all Po extracted with 1st extraction; $t_0 = t_1$	352 ± 38	10.7	11.7	445 ± 28	6.2	41.4
assume R = 0.9 for 1 st extraction $t_0 = t_1$	352 ± 38	10.7	11.7	360 ± 29	7.9	14.4

Table 11: Control samples using independent fractions

Set	Yield		Activity concentration mBq.L-1			
	1st	2 nd	Po 1st extraction	Po 2nd extraction	Po sampling	Pb sampling
1	0.73	0.54	409	380	20786	405
	0.74	0.67	372	352	13915	390
	0.70	0.58	357	381	-26388	533
	0.79	0.39	361	378	-21188	517
2	0.76	0.79	349	320	23569	325
	0.80	0.93	365	292	66207	178
	0.69	0.42	343	412	-70544	688
	0.76	0.57	374	363	5715	425
average			366	360	1509	433
standard deviation			39	38	40884	152
relative std deviation			5.5	10.7	2709	35
percentage error					379	37

Note: Sets 1 and 2 in Table 9 were used for calculation of data on first extraction

To eliminate the uncertainties with the yield determination, and also the problem of having to repeat a sample after a second extraction mess-up (which implicates a 6-week extension of deadlines), it was decided to do two separate independent extractions on samples with at least a six-week time lapse in between. Another two sets of control samples were analysed about three months after the first sets in Table 9. The mathematics was changed to provide for independent extractions. The results are summarized in Table 11.

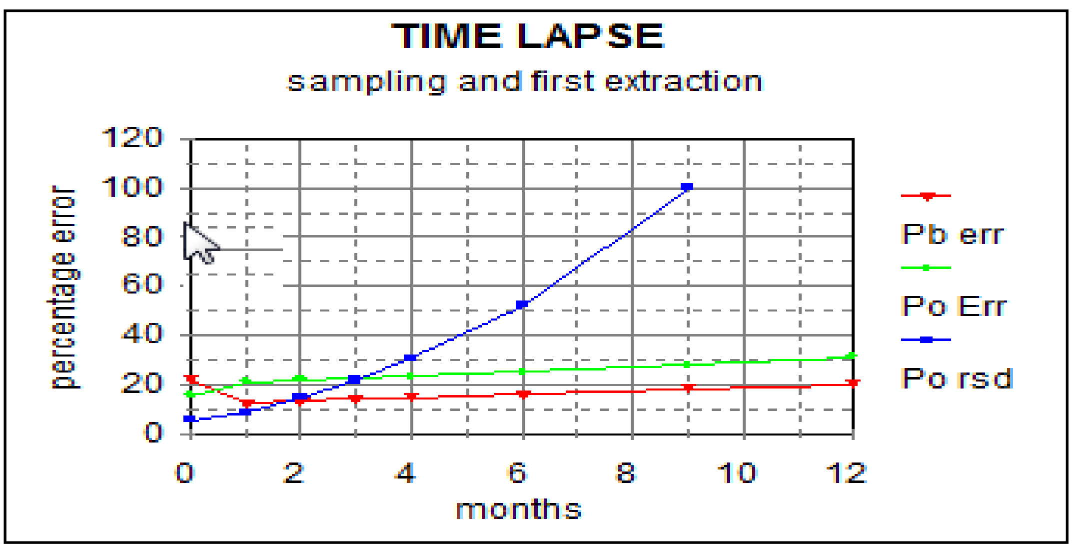

Figure 2: Precision and accuracy as function of time interval between sampling and first extraction

The value for Po at sampling was again erroneous because of the short time lapse between first and second extractions. As can be seen from Figure 2 the accuracy for both Po and Pb decreases with an increase in time interval. The first extraction should preferably be performed within four months (more or less one t½ Po) after sampling for the error for Pb to be less than 15% and for Po to be less than 25%. Although the precision for Pb stays constant at 30% regardless of the time interval, the precision for Po also decreases (with a rsd of 5 to 30 %) with an increase in time interval. With $t_1 - t_0$ = 4 months the precision for both Pb and Po is 30%. The accuracy and precision compares well with those obtained by using the method where extraction is done twice on the same fraction (see Table 9). The precision is poor compared to counting statistics. This can be due to contribution of the deposition step itself or other inherent variances in the method.

5.4. Certification of tracer solution

Since the optimum yield obtained was only 0.8 (see 4.3) and because of the uncertainty regarding the yield determination (see 5.3), the activity concentration of the solution was verified experimentally.

Preparation of drip standards was unsuccessful because of the volatility of Polonium when evaporating under infrared.

A 0.1 g fraction of the ^{209}Po stock solution (17.31 $Bq.g^{-1}$) was counted with liquid scintillation. A experimental value of 1.856 Bq was obtained for the expected value of 1.933 Bq. This corresponds to a relative percentage error of -3.98%. The tracer is suitable for determining the chemical yield of the procedure and the measured yields can be assumed to be correct.

6. CONCLUSIONS

The method gives an average yield of 0.64 for deposition in HCl solutions at a temperature of $95^{O}C$. There is a large fluctuation in yield. The analysis should be repeated for yields lower than 0.2.

The accuracy of the method is acceptable with a percentage error of less than 15 % for ^{210}Pb and less than 20% for ^{210}Po provided that the first extraction is done within 2 months after sampling.

The precision of the method is poor (30%) with $t_1 - t_0$ = 4 months.

The minimum detectable activity of the method is 5-10 $mBq.L^{-1}$ for a counting period of 24 hours depending on the blank raw counts. By counting for 48 hours the MDA can be decreased to less than 4 $mBq.L^{-1}$.

Advantages of the plating method are many: relatively little operator time needed, few chemical reactions or manipulations are involved, material costs are low, a high degree of analytical expertise is not necessary to perform the simple method, suitable sensitivity is available from α-spectrometry giving good accuracy for the measurements of Pb and Po.

The main disadvantage of the plating method is the period of time necessary to allow in-growth of ^{210}Po from ^{210}Pb (2 years to reach equilibrium. However, the limits of detection for α-spectrometry enable measurements to be made before equilibrium has been reached.

By doing two independent extractions on two separate aliquots six weeks apart, accurate results are obtained. Uncertainties regarding the yield and problems with a second extraction mess-up are eliminated.

7. RECOMMENDATIONS

The method is adequate for the determination of ^{210}Po and ^{210}Pb in water samples at a level of 5 $mBq.L^{-1}$ for a counting period of 24 hours.

The control sample should be analysed at least once a month to monitor the reproducibility of the method.

For further improvement of the method the following aspects need to be investigated:

- The unexplained "loss" of polonium during plating as explained in paragraphs 4.3 and 5.3.
- Plating in a closed reaction vessel to prevent losses due to evaporation of the sample.
- Further improvement of the method precision.
- Evaluation of the repeatability of disk-mounting in the α-spectrometers to minimize counting efficiency uncertainties.
- Evaluation of the homogeneity of distribution over the disk surface.
- Revalidation of the method when adding hydroxylamine hydrochloride to samples.

D.2 Validation of the method for the determination of the thorium isotopes in water

1. OBJECTIVE

To validate the method for the determination of each of the individual radionuclides ^{232}Th, ^{230}Th, ^{228}Th and ^{227}Th in water using ^{229}Th as yield tracer.

2. SCOPE

This document must be read together with the validation reports RA-VAL-142(01) and RA-VAL-142(02). Several aspects which had been validated previously are fully covered there.

The specifications set for the method is as follows:

- The chemical yield should be better than 20%;
- The precision and accuracy should be better than 20%; and
- The minimum detectable activity (MDA) should be ≤ 5 $mBq.L^{-1}$ for each individual nuclide.

Changes to RA-WIN-142 as a result of experimental problems experienced during routine use of the method, are also discussed in this validation report.

The method is validated for each of the individual Th nuclides. Once proven to be accurate for each of the nuclides, use of only the ^{232}Th control sample will be sufficient for future quality control purposes.

3. BACKGROUND

During an audit performed by SANAS for accreditation of the method RA-WIN-142 a non-conformance was registered stating that the results for ^{228}Th are of unknown accuracy and that no validation data has been presented for ^{230}Th and ^{227}Th. The purpose of this validation report is to report data showing the accuracy of RA-WIN-142 for determination of each of the individual thorium nuclides ^{232}Th, ^{230}Th, ^{228}Th and ^{227}Th.

Since it also became clear during routine use of the method that use of ^{234}Th as yield tracer is not ideal, it was decided that the validation of the method will be performed using ^{229}Th as yield tracer.

The literature survey which was carried out for thorium separation and determination is described in RA-VAL-142(01). This contains details of the options available for preconcentration, chemical separation, sample preparation for α-spectrometry and data reduction. Preparation of the ^{234}Th tracer is also described in detail. RA-VAL-142(02) gives further theoretical background especially regarding cation separation of Th, U and Pa.

Reverse phase partition chromatography using extraction resins had proved excellent for separation of the actinides since development. The sorption coefficient of the actinide resin is extremely high with respect to tetravalent actinides ($k > 10^6$) even if strong acidic solutions are analysed. Since Th is generally in the 4+ state, high chemical recoveries can be expected. According to the literature Thorium cannot be eluted from Truspec with any concentration of HNO_3 , but can easily be stripped using dilute HCl. Burnett obtained yields of 80 - 90% when using 1 M HCl and 98% with 0.5 M HCl. U is very strongly held irrespective of HNO_3 or HCl concentrations, and is only eluted with a HCl/HF mixture. Cations such as Fe, Ca, and Ra are not retained by the resin.

Thorium is very strongly absorbed on cation resins, but can be quantitatively eluted using 5 M HNO_3 if a resin with a low degree of cross-linking (AG50X4) is used, or with 5M HNO_3 - 0.1 M HF.

Because of problems experienced with non-reproducible and low yields during routine use of RA-WIN-142 (revision 0) where only Truspec separation was performed, it was concluded during further investigation (RA-VAL-142(02)) that the best possible option is to use Truspec to get rid of interfering cations and elute Th, Pa and U as one fraction which is then further separated on a cation exchange column.

4. TECHNICAL

Samples for analyses were prepared and analysed as in RA-WIN-142 (revision 3). Control samples for each of the Th nuclides were prepared by adding a suitable amount of each of the different control solutions listed underneath to 10 ml 2 M HNO_3. To determine the chemical yield, 1 ml of ^{229}Th tracer was added.

The following control solutions and standards were used (see paragraph 5 for detail on preparation):

^{234}Th tracer	323 ± 30 $Bq.g^{-1}$
^{229}Th tracer	126.6 ± 3.2 $mBq.g^{-1}$
^{232}Th control	18.9 ± 1.8 $mBq.g^{-1}$ (nitrate salt)
^{232}Th control	73.8 ± 2.8 $mBq.g^{-1}$ (AAS standard)
^{230}Th control	33.9± 1.1 $mBq.g^{-1}$
^{228}Th control	112.3 ± 1.1 $mBq.g^{-1}$
^{227}Th control	24.8 ± 2.1 $mBq.g^{-1}$

5. PREPARATION OF SUITABLE CONTROL SOLUTIONS

5.1 Th-234 tracer (ca 1000 Bq ^{234}Th/g)

A ^{234}Th tracer solution was prepared by milking a column loaded with U_3O_8 as set out in RA-WIN-142, revision 1. The activity concentration of the solution as measured with LSC was 323 $Bq.g^{-1}$.

5.2 Th-229 tracer (ca 100 mBq ^{229}Th/g)

A ^{229}Th tracer solution was prepared by diluting 1.0665 g of the certified solution ACS/DC/38 (12.25 ± 0.31 $Bq.g^{-1}$) to a final mass of 103.16 g. The activity concentration of the solution was (0.1266 ± 0.0032) $Bq.g^{-1}$.

5.3 Th-232 control solutions

^{232}Th is available as the thorium nitrate salt of which the activity is not certified. Certified standards used for AAS and ICP-MS analysis can be purchased. In natural thorium ores and compounds, ^{228}Th is generally found in equilibrium with its indirect parent ^{232}Th.

It was decided to prepare ^{232}Th control solutions using both the thorium nitrate salt as well as a AAS standard solution routinely used at Radioanalysis for preparation of neutron activation standards This standard has a certified content of 970 μg Th/ml.

5.3.1 Nitrate salt

The $Th(NO_3)_4.5H_2O$ control solution was prepared as in RA-WIN-142. The calculated activity was 18.91 mBq ^{232}Th/g.

5.3.2 AAS standard

1.0296 g of the Atomic Absorption standard solution ACS/L003/00 (Aldrich chemicals; 970 $\mu g.ml^{-1}$ = 3.93 ± 0.15 Bq,ml^{-1}) was diluted to 54.8405 g. The expected activity was 73.8 $mBq.g^{-1}$ ^{232}Th.

5.4 Th-230 control solution

^{230}Th is present in the decay series of ^{238}U and can be expected to be in equilibrium with ^{238}U in an uranium ore.

During previous experimental work an anion column loaded with uranium was used as a source for preparation of ^{234}Th tracer (see RA-VAL-142(01), par 6.1). It was found that the NBS 950b standard (ACS/F18/2) used, contained high levels of ^{230}Th, and it was therefore not suitable for use as a source for preparation of ^{234}Th. A prepared tracer solution of 1 kBq ^{234}Th contained approximately 2 Bq ^{230}Th (0.2%) and 100 mBq of ^{232}Th and ^{228}Th. A 1 kBq ^{234}Th tracer prepared from a U_3O_8 salt contained only 10 mBq.g^{-1} ^{230}Th impurity.

U and Th can be separated using either anion or cation exchange. When a solution containing U and Th is loaded onto a cation column, U can be eluted with 2 M HCl while Th is retained. On an anion column Th will be retained when loaded in 8 M HNO_3, while uranium is not. Th can be eluted with 1 M HCl. When loaded in 8 M HCl uranium forms anion complexes and will be retained. Typical yields expected are 80%.

Based on this, it was decided to prepare ^{230}Th by anion separation of a U-solution prepared from the NBS-standard. The Th fraction is expected to contain mainly ^{234}Th and ^{230}Th.

5.4.1 Preparation and standardization

0.4257 g U_3O_8 (NBS 950b) was dissolved by heating with 20 ml 1:1 HNO_3 and loaded onto a 30 cm anion exchange (Ag1X8) column (1 cm diameter) in 6 M HNO_3. U was eluted with 80 ml HNO_3 and Th with 60 ml 8 M HCl.

After separation the solution was standardized. 0.5 ml fractions of the solution were pipetted into vials and the activity determined with liquid scintillation counting. The activity of the solution was about 80 Bq.g^{-1} which can mainly be attributed to ^{234}Th. This activity corresponds well with the activity previously found in RA-VAL-142(01) of approximately 100 Bq ^{234}Th and 0.2 Bq ^{230}Th when loading 0.4 g U_3O_8.

Fractions of the prepared solution were analysed by α-spectrometry to determine the purity thereof. LaF_3 precipitation was done on fractions with and without addition of $TiCl_3$ (for reduction of U). Uranium contamination of about 4 - 6 mBq.g^{-1} was observed in samples to which $TiCl_3$ was added. Uranium in oxidation state (VI) will however not co-precipitate with LaF_3 if no reducing agent is added. In the α-spectra of samples prepared without $TiCl_3$ only the Th-230 peak at 4.66 MeV was observed.

Since it was not possible to prepare drip standards directly from the concentrated 8 M HCl solution, the solution was evaporated to dryness and made up to volume with 0.1 M HCl. Three standards were prepared by evaporating small volumes of solution directly onto a planchette under an infrared lamp. The activity of the three standards was 32.6, 34.6 and 34.4 mBq.g^{-1} respectively. The activity of the prepared ^{230}Th control solution was therefore certified to be 33.9 ± 1.1 mBq.g^{-1}.

The activity value for ^{230}Th was confirmed by α-counting of LaF_3 precipitates of the solution (see results in Table 4). The average of 35.6 ± 1.8 compares very well with the value obtained for the drip standards and can be assumed to be the expected value for ^{230}Th.

5.5 Th-228 control solution (ca 100 mBq ^{228}Th/g)

^{228}Th is present in the ^{232}U solution (ACS/DC21/01) purchased as a reference solution. ^{228}Th is certified to be in equilibrium with ^{232}U.

A ^{228}Th control solution was prepared as in RA-WIN-145 by diluting 0.1150 g of the ^{232}U certified solution ACS/DC21/01 (103.4 ± 1.0 Bq.g^{-1}) to a final mass of 105.8865 g with 2 M HNO_3. The activity concentration of the solution was (112.3. ± 1.1) mBq.g^{-1}.

^{228}Th as a daughter of ^{232}Th will also be present in any solution of ^{232}Th. The ^{228}Th activity is however not certified and is not necessarily in equilibrium, although it can be expected to be the case for solutions prepared from natural thorium ores. The activity of ^{228}Th can be determined by gamma spectrometry.

^{228}Th spectra will show higher energetic alpha-particle peaks from short-lived daughter products (i.e. ^{224}Ra, 3.66 d) if counted a few days after preparation. Although this is corrected for by counting ^{212}Po (8.78 MeV), it is better to count the sample as soon as possible after column separation.

5.6 Th-227 control solution

Significant problems exist to obtain known quantities of ^{227}Th.

Radioactive equilibrium between the radionuclides can be expected in a very old uranium ore sample such as UREM-6 (ACS/B15/01). The daughters of the U-235 series e.g. ^{231}Pa and ^{227}Th will be in equilibrium with ^{235}U and ^{230}Th will be in equilibrium with ^{238}U. The natural isotopic ratio of ^{238}U / ^{235}U = 21.45 can also be expected.

UREM 6 is certified as containing 1906 µg.g^{-1} U (23.7 Bq ^{238}U/g). The ^{227}Th activity was calculated assuming that all radionuclides are in equilibrium and the natural isotopic ratio of 21.45 between ^{238}U/^{235}U exists. A ratio of 21.45 can also be expected between ^{230}Th/^{227}Th.

The solution was prepared as in RA-WIN-146. 2.6555 g of UREM-6 was dissolved by microwave digestion and diluted to a final volume of 116.9763 g with 2 M HNO_3. The expected activity was calculated as 24.8 mBq ^{227}Th/g and 537.9 mBq.g^{-1} ^{230}Th.

^{223}Ra will grow into the sample very quickly and will interfere with the ^{227}Th α-spectra. Interference can be corrected for by counting of ^{215}Po (7.39MeV). This is included in the calculations used in the spreadsheet for data reduction

6. YIELD TRACER: Th-234 versus Th-229

Th-234

In RA-VAL-142(02) the chemical yield for recovering thorium from the sample was determined by adding a known amount of the β-emitting isotope ^{234}Th (in excess of the activity that might be present as daughter of ^{238}U), and determining the gross β-activity of the final lanthanum fluoride precipitate by liquid scintillation counting (LSC). The method does not provide any selectivity for the analyte, and all β-activity is ascribed to ^{234}Th. Using the αβ-discrimination facility of the LSC it is possible to discriminate against α-emitters to a limited extent. Because of a certain amount of overflow between the two channels a significant error is however still made when the α-activity in the samples is higher than 10 Bq.L^{-1}.

The use of liquid scintillation vials and Ultima Gold scintillation cocktail result in extra costs as well as extra waste which has to be exposed of. The uranium columns used for milking of ^{234}Th have to be discarded as radioactive waste. The procedure for preparation and purification of the ^{234}Th tracer is also quite tedious.

During original preparation of the ^{234}Th tracer solution it was thought that a pure solution, which contains mainly the four radionuclides, ^{238}U, ^{234}U, ^{234}Th and ^{234}Pa, could be obtained, because of the long half-life of ^{230}Th. In RA-VAL-142(02), Table 2, it was shown that considerable amounts of impurities were present in the prepared ^{234}Th tracer. (^{232}Th: 0.38 ± 0.59 mBq.L^{-1}; ^{230}Th: 4 ± 2.4 mBq.L^{-1}; ^{228}Th: 18.8 ± 5.8 mBq.L^{-1} and ^{227}Th: 2.8 ± 3.4 mBq.L^{-1}).

Monitoring of the tracer blank value over the period January 2000 to June 2001 confirms that the tracer is not suitable for use if ^{228}Th has to be determined as well. Contamination values for 40 samples were an average of 0.75 ± 0.99 (^{232}Th), 3.2 ± 2.6 (^{230}Th), 27.5 ± 21.4 (^{228}Th) and 1.8 ± 3.8 (^{227}Th) mBq absolute. The contamination level of ^{228}Th did not decrease with repeated elution of the column as would have been expected and the quality of the routinely produced ^{228}Th results was poor.

Th-229

Although original purchase of ^{229}Th is quite expensive, long term savings as a result of reduced costs due to waste disposal and consumables will be significant. Preparation of ^{229}Th is uncomplicated and involves dilution of the certified standard solution. ^{229}Th also acts as carrier to prevent insufficient separation of the short lived nuclide (^{227}Th) due to a possible mass-effect.

Addition of tracer may deteriorate the limit of detection and accuracy of adjacent, lower energy peaks in the α-spectrum when the energy resolution of the source, i.e. the source purity (thickness) is not optimal. This is the case for ^{229}Th ($t_{½}$ = 7340 a) which has its main energy of 4.84 MeV rather close to the peak of ^{230}Th at 4.69 MeV. For this reason the use of ^{234}Th has always been preferred.

Disadvantages of using ^{229}Th include recoil contamination of the detector with short-lived, alpha-emitting progeny (^{225}Ac and its daughters). Also, low probability (0.3%) ^{229}Th alpha emissions are present in the ^{230}Th region of interest which must be accounted for to preclude bias for low activity measurements. ^{229}Th progeny (^{225}Ac) will also interfere with determination of ^{227}Th if samples are not counted directly after preparation.

As a final evaluation samples were analysed using ^{234}Th and ^{229}Th as yield tracers. The results are shown in Table 1. It is clear that the results when using ^{229}Th are more accurate (error < 10%), while values obtained when using ^{234}Th as tracer are on average higher with a positive bias of 15-30%.

Table 1: Comparison of results obtained for ^{232}Th using ^{234}Th or ^{229}Th as tracer

	^{232}Th (mBq.g^{-1})	**% Error**	**Yield**
Use of Th-234 as tracer	84.4	14.4	0.83
	85.4	15.7	0.23
	96.3	30.5	0.52
	86.7	17.5	0.61
Use of Th-229 as tracer	71	-3.8	0.28
	79.3	7.4	0.63
	75.7	2.6	0.69
	75.5	2.3	0.70

Expected value is 73.8 mBq.g^{-1}

7. DEVELOPMENT

7.1 Problems experienced with low yields

During routine-use of the method (RA-WIN-142) it was found that the yield was very low and inconsistent. A non-conformance (RA-NC-086) was registered to investigate this problem. During this investigation the following possible causes were eliminated (see RA-VAL-142(02), par 6.1): Incorrectly prepared reagents or tracer, variance in separation capability of different batches of resin and losses during precipitation due to fast flow-rate. It was concluded that a shift in elution curve resulted in the Th peak to be missed and caused the low yields. RA-WIN-142 was revised to incorporate a cation exchange separation as well as a Truspec separation. The method has worked fine since implementation. Later problems were again experienced with yields being very inconsistent and often lower than 5% and therefore unusable. It was decided to reinvestigate the elution behaviour of Th on the Truspec resin.

7.2 Evaluation of the current method

Samples were analysed with the current method (WIN-142; revision 2): Truspec and cation separation, 10 ml 1 M HCl discarded before elution of Th, U and Pa with HCl/HF. The method was modified to discard only the first 5 ml of 1 M HCl. Results obtained using only Truspec (elution with 30 ml 1 M HCl, discarding the first 5 ml) and using both Truspec and cation separation were also compared. ^{229}Th was added as yield tracer.

When using the current method very low yields were obtained for almost all the samples (see Table 2). This resulted in large, but still acceptable, errors. During routine use this was very inconsistent with some batches having fairly good yields and others very poor. Poor yields were obtained for both samples containing only ^{234}Th (short half-life) or only ^{232}Th (long half-life) which makes the possibility of it being a result of mass-effect (different masses of Th reacting differently on the column) highly improbable.

Yields were higher when discarding only 5 ml 1 M HCl than when 10 ml 1 M HCl was discarded which indicates that the main portion of Th most probably elutes in the second 5 ml of 1 M HCl.

Good yields were obtained when performing only the Truspec separation (basically this is exactly the same method as has been used in the first revision RA-WIN-142). Because of the problems experienced at that time when the method had been in operation for almost two years (see NC-086) is was decided to continue performing both a Truspec and cation separation, even though the cation separation takes an extra hour.

It was found that small differences observed in the column flow rate through the Truspec column do not have a significant influence on the yield. Incorrect elution volumes may however cause losses and liquids should preferably be measured by using a pipette or a automatic dispenser.

Although the flow rate through the cation columns does sometimes vary, Th is retained very strongly on the cation column and the variance in flow rate did not appear to have any effect on the yield.

Yields were acceptable with use of cation resins from different manufactures (Eichrom, Biorad and even for different mesh size; 100-200 and 200-400).

Table 2: Comparison of the yields obtained with different volumes of 1 M HCl

	^{232}Th (mBq.g^{-1})	% Error	Yield
10 ml 1 M discarded; Tru + cation separation (method as in WIN-142(02))	64.8	-12.2	0.05
	87.4	18.4	0.12
	92.7	25.6	0.04
	65.3	-11.5	0.04
5 ml 1 M discarded; Tru + cation separation (resins from different manufacturers)	71	-3.8	0.28
	79.3	7.4	0.63
	75.7	2.6	0.69

5 ml 1 M discarded; Th eluted with 25 ml 1 M HCl; only Tru separation	76.5	3.7	0.91
	79.9	8.3	0.52
	74.4	0.8	0.32
	83.7	16.5	0.62

Expected value is 73.8 mBq.g^{-1}

7.3 Elution curves

In previously obtained elution curves the following was observed:

RA-VAL-142(01): (use 30 ml 1M HCl). No activity was found in the first 10 mℓ, but 72-76 % of Th eluted in the next 15 ml 1 M HCl with a further 19-22% being retained on the column and only eluted with HCl/HF. When using 40 ml of 1 M HCl 84% of Th was eluted. It was decided to use 30 ml of 1 M HCl and discard the first 5 ml.

RA-VAL-142(02): (50 ml 1 M HCl). The yield for Th in the 1 M HCl fraction was just 14%, while 84% was retained on the column and eluted with 0.1 M Cl/ 0.1 M HF. Based on this it was assumed that the 10 ml of 1 M HCl can be discarded without resulting in significant losses of Th. Th was eluted together with U and Pa with HCl/HF and further separated on a cation column.

The effect of lower concentrations of HCl on the elution of Th from the column was investigated. It was found that only 24%, 27% and 32% was eluted with 35 ml of 1 M, 0.5 M and 0.1 M HCl respectively. 100% of Th was eluted with 0.1 M HCl / 0.1 M HF.

RA-VAL-142(03): Separate samples of ^{234}Th tracer (± 20 Bq) and ^{232}Th (± 8 Bq) in 10 ml 2 M HNO_3 were loaded onto TruSpec columns to investigate the elution behaviour of Th. The column was eluted with 10 mℓ 2 M HNO_3, 2 mℓ 9 M HCl, 10 mℓ 4 M HCl, 10 ml 1 M HCl and 15 ml 0.1 M HCl/ 0.1 M HF. Fractions of the column effluent were collected and counted by LSC.

The yield for Th in the 1 M HCl fraction was about 80%, while only 2-3 % was retained on the column and eluted with 0.1 M Cl/ 0.1 M HF.

The elution curves were repeated, but this time eluted with only 35 ml of 1 M HCl. The yield for Th in the 1 M HCl fraction was about 95 %, of which about 82% was eluted in the second 5 ml fraction.

This is in contradiction with the previous elution curves (see RA-VAL-142(01) and RA-VAL-142(02)). The new elution curves show that discarding of the first 10 ml (especially the second 5 ml portion) of the 1 M HCl will result in great losses of Th.

It is clear that the low yields are caused by inefficient column separation. Th is now sharply eluted from the column in 1 M HCl, as would have been expected from the literature, and not retained as previously found in RA-VAL-142(02).

7.4 Mass Effect

The different Th isotopes have different half- lifes which range from relatively short lived e.g. ^{227}Th (18.7 d), ^{234}Th (24.1 d), intermediate e.g ^{228}Th (1.912 a), long lived ^{229}Th (7880 a) and ^{230}Th (75380 a) and very long lived ^{232}Th (1.405E10 a).

At first it was thought that the inconsistent yields may be a result of different behaviour of nuclides of different masses on the separation column. The almost similar elution curves obtained for both ^{232}Th and ^{234}Th contradicts this. However, in VAL-142(02) the average chemical yield for control samples (0.29 ± 0.13; range 0.06-0.45) was lower than the yield of the blank samples (0.44 ± 0.22;

range 0.27-0.84)) and the field samples (0.36 ± 0.08; range 0.27-0.49). The reason for this may be matrix-related or a result of a difference in column behaviour of ^{234}Th and ^{232}Th.

The effect on column separation of a possible mass-effect is investigated in more detail in the method for the separation of the actinides (see RA-VAL-183). It is not important in the method for determination of the Th-nuclides, since the addition of ^{229}Th (which has significant mass) has the added advantage that it acts as a carrier to prevent separation differences due to different masses of the short- and long lived nuclides.

8. CAPABILITY STUDY

Elution curves showed that Th is now again eluted as a sharp peak with 1 M HCl, as expected according to the literature. Discarding a large volume of 1 M HCl will therefore result in losses of Thorium. Since it was found (see §6.3, RA-VAL-142(02)) that Th can also be eluted from the TruSpec column with HCl /HF, and to prevent the possibility of retention of Th in diluted HCl as had happened before, it was decided to keep to the separation scheme in which Th, Pa and U are eluted as a batch and then further separated on a cation column. The only change to the method is that 3 ml and not 10 ml of 1 M HCl is used before elution with HCl/HF.

Truspec:

- load sample in 2 M HNO_3
- elute Ra, Ca and other cations with 2 M HNO_3
- convert resin to HCl form
- elute Ac with 4 M HCl
- rinse with 3 ml 1 M HCl
- elute Pa, Th and U with 0.1 M HCl / 0.1 M HF

Cation:

- load eluted fraction directly
- elute Pa with 0.1 M HCl / 0.01 M HF
- elute U with 2 M HCl
- elute Th with 2 M H_2SO_4

8.1 Blank samples

Distilled water, spiked with ^{229}Th, was used as blank samples and analysed as in RA-WIN-142.

As can be seen from Table 3 the impurity level for ^{228}Th is much lower than previously found in the ^{234}Th tracer (see par 6). Relatively high counts (40-60 counts in 24 h) are still present in the ^{230}Th region mainly as a result of tailing of the ^{229}Th peak. Blank determinations are described in detail in RA-PFT-162.

If only reagents are used (no added tracer), the blanks are comparable to detector background values (maximum 4 counts in 24 h). Addition of ^{229}Th tracer causes an increase in the blank value. The filtering equipment was eliminated as a source of the positive blank value since a blank filtered immediately after a high activity sample was clean. ^{229}Th α-active progeny will also contribute to the blank determinations if samples are not counted immediately after preparation.

The calculated MDA's for the different nuclides are about 1 mBq.L^{-1} when calculated using detector background values for a counting period of 24 hours, volume 200 ml and detector efficiency 0.2. The limiting factor to actual low level determination of the Th nuclides is however the higher counts obtained for the blank samples. MDA should be calculated using detector background and the blanks used as a control measure for levels of contamination. An MDA calculated by using the blank value will be an indication of the real measurement capability of the method.

Table 3: Analysis of blank samples

	yield	Activity concentration and MDA values $mBq.L^{-1}$							
		232		230		228		227	
	0.5	0.7	0.8	12.1	0.7	0.3	0.8	0.6	0.8
	0.55	0.1	1.1	3.1	0.9	1.1	0.9	0.4	0.9
	0.47	1.1	0.3	5.7	0.5	1.3	0.5	1.8	0.5
	0.69	0.5	0.2	1.4	0.6	0	0.9	2.4	0.6
	0.39	0.7	0.5	4	1.2	-0.4	1.7	3.3	1.2
	0.5	1.1	0.4	10.7	0.9	0.9	1.3	4.1	0.9
avg	0.5	0.7	0.6	6.2	0.8	0.5	1.0	2.1	0.8
std	0.1	0.4	0.3	4.3	0.3	0.7	0.4	1.5	0.2
rsd %	19.3	54.2	61.7	69.9	31.6	125.9	41.5	69.9	30.4

8.2 Control samples

8.2.1 LaF_3 precipitation

Fractions of the different control solutions were precipitated directly, without performing a column separation.

Percentage error for ^{232}Th and ^{228}Th was calculated assuming equilibrium of the radionuclides in the solution. The expected value was 73.8 $mBq.g^{-1}$

Average for ^{230}Th is 35.6 ± 1.8 which corresponds very well with the value of 33.9 obtained for the drip standards (see par 5.4).

^{227}Th cannot be determined in a solution containing ^{229}Th without performing a column separation because of the presence of daughters of ^{229}Th in the ROI of ^{227}Th.

Table 4: LaF_3 precipitation of Th control solutions

Sample	yield	Activity concentration $mBq.g^{-1}$				Error		
		232	230	228	227	232	230	228
232	1.0	77.2	10.4	74	71.5	4.61		0.27
232+229	1.06	78.8	11.4	76.5	NAD	6.78		3.66
230+229	0.33	1	37.3	4.7	NAD		10.0	
230+229	0.47	0.8	34	1.4	NAD		0.3	
230+229	0.96	0.7	35.1	2	NAD		3.5	

NAD = not able to determine

8.2.2 Th-232

Two types of thorium control solutions, an AAS standard and a thorium nitrate source, were compared to ensure that the origin of the standard did not affect thorium determination.

For the AAS-standard (Table 5) results for ^{232}Th and ^{228}Th are very good, with the error smaller than 10% for most of the samples. The precision for both ^{232}Th and ^{228}Th is also very good. Results for ^{227}Th are negative if counted too long after column separation, because of interference of daughters of ^{229}Th in the ^{227}Th area.

Results for ^{232}Th, ^{228}Th and ^{230}Th compared well with samples which were precipitated directly (see Table 4).

Although radioactive equilibrium can not necessarily be assumed in cases where chemical preparation has been performed to produce $Th(NO_3)_3$ the results in Tables 5 and 6 show that equilibrium does in all probability exists. This will be expected for $Th(NO_3)_3$ which is older than 4 years. The ^{228}Th content of the AAS-stock solution was determined with γ-spectrometry to be 4.0076 ± 0.1455 $Bq.g^{-1}$ which seems to be in equilibrium with ^{232}Th (3.9 ± 0.15 $Bq.g^{-1}$). The expected activity for ^{228}Th after dilution is 75.2 $mBq.g^{-1}$

^{232}Th has a long half-life (> 10^9 y) and is the only one of the Th-nuclides which has significant mass and can be readily determined with good precision and accuracy by instrumental techniques such as ICP-MS. INAA is also a reference method of proven accuracy for ^{232}Th which provides an added element of quality assurance to the overall results. Because good results were obtained, it was not thought necessary to do any additional analysis.

Table 6: Test results for ^{232}Th (thorium nitrate salt)

Sample	yield	Activity concentration $mBq.g^{-1}$				Error	
		232	230	228	227	232	228
1	0.49	35.3	6.7	35.1	-3.6	-6.7	-7.2
2	0.49	40.3	8.9	39.1	-5.2	6.6	3.4
3	0.71	32.4	6	32.3	-1.8	-14.3	-14.6
4	0.51	36.9	8.3	32.9	-2.4	-2.4	-13.0
avg		36.2	7.5	34.9	-3.3		
std		3.3	1.4	3.1	1.5		
rsd %		9.1	18.1	8.8	-46.2		

Expected value 37.82 mBq (use 2 mℓ of solution)

For the thorium nitrate salt (Table 6) accuracy for both ^{232}Th and ^{228}Th were very good (if equilibrium is assumed for ^{228}Th). The inaccurate results for ^{228}Th found during routine use of the method (Table 7) was probably a result of the high contamination levels of ^{228}Th in the ^{234}Th tracer which was subtracted as a blank value.

Nothing can be said about the accuracy for ^{230}Th and ^{227}Th. Precision on results for ^{230}Th is fairly good. ^{227}Th is negative and lower than MDA limits.

The results obtained using ^{229}Th as tracer were much better for all four the nuclides, than the results obtained for the same control sample during routine use of the method using ^{234}Th as tracer (see Table 7).

Three of a total of 30 samples were discarded because of very high error for ^{232}Th. The average error for ^{232}Th was small. There was no bias and the error varied between -30 and +30%. The results for the rest of the nuclides were poor with a range of -200 to 120 $mBq.g^{-1}$ for ^{228}Th. These values were calculated after subtraction of a ^{234}Th blank value which varied and resulted in inconsistent and very high negative values.

Table 7: Results for control sample using ^{234}Th as yield tracer

	Activity concentration mBq.g^{-1}				Error
	232	**230**	**228**	**227**	**232**
avg	36.8	-5.2	-59.4	2.1	-2.7
stds	8.7	8.5	91.0	17.0	
min	26.3	-25.5	-204	-39.9	
max	47.7	17.7	119	43.2	

expected value for Th-232 is 37.82 mBq (use 2 ml of solution)

8.2.3 Th-230

Table 8: Results for ^{230}Th

Sample	yield	Activity concentration mBq.g^{-1}				Error
		232	**230**	**228**	**227**	**230**
1	0.65	0.5	37.7	0.4	1.5	5.9
2	0.26	0	28.9	1.9	2.3	-18.8
3	0.74	0.5	39.3	0.6	7	10.4
4	0.18	0.4	32.1	-0.5	1.5	-9.8
avg		0.4	34.5	0.6	3.1	
std		0.2	4.8	1.0	2.6	
rsd %		68	14	165	86	

Expected value for ^{230}Th is 33.9 mBq.g^{-1}

Results for ^{230}Th are accurate even though low-energy tailing of ^{229}Th sometimes interferes in this region. Resolution between the ^{230}Th and ^{229}Th peaks was good.

8.2.4 Th-228

The samples were prepared from control solution U232-018 (112.3 mBq.g^{-1}; expected value after decay 92.6 mBq.g^{-1}). The error is higher than for any of the other Th nuclides, but still acceptable (less than 25%). The error for ^{228}Th in the ^{232}Th solutions (see Tables 5, 6) was less than 15%.

Table 9: Results for ^{228}Th

Sample	yield	Activity concentration mBq.g^{-1}				Error
		232	**230**	**228**	**227**	**228**
1	0.62	1	13.7	112	-16	21.0
2	0.63	0.7	10.4	106	-13.5	14.9
3	0.63	0.5	10.6	113	-16.4	22.3
4	0.81	1.1	14.6	109	-15.2	18.0
5	0.37	0.6	5.4	115	-3.9	24.3
avg		0.8	10.9	111	-13.0	
std		0.3	3.6	3.4	5.2	
rsd %		33.2	33.0	3.1	-40.1	

Expected value for ^{228}Th is 92.6 mBq.g^{-1}

8.2.5 Th-227

Table 10: Results for ^{227}Th

Sample	yield	Activity concentration mBq.g^{-1}				Ratio	Error	
		232	230	228	227	230:227	227	230
1	0.34	37.4	420	22.1	19.6	21.4	-20.9	-21.8
2	0.30	18.9	422	23.3	18.4	22.9	-25.8	-21.4
3	0.7	16.6	399	14.9	17.7	22.5	-28.6	-25.9
4	0.71	19.2	412	17.9	19.2	21.5	-22.6	-23.3
5	0.5	21.2	442	20.8	20.8	21.2	-16.1	-17.7
avg		22.7	419	19.8	19.1	21.9	-22.8	-22.0
std		8.4	16	3.4	1.2	0.8	4.8	3.0
rsd %		37.1	3.8	17.2	6.2	3.4	-20.9	-13.6

expected activities for ^{227}Th is 24.8 and for ^{230}Th is 537.9

The calculated activity for ^{227}Th is very dependent on the time delay between column separation and counting. To minimize errors due to ^{229}Th daughters present in the ^{227}Th area, samples should be counted as soon as possible after preparation.

Errors for both ^{227}Th and ^{230}Th are slightly higher than for some of the other isotopes, with a negative bias. Preparation of the control solution involves dissolution of small fractions of a uranium ore which is then combined as a final solution. It is highly probable that small losses occurred during preparation of the control solution which resulted in the real activity value to be lower than the calculated value. The ^{230}Th:^{227}Th ratio shows excellent correspondence with the expected natural ratio (21.45) which confirms that both ^{230}Th and ^{227}Th are measured accurately.

8.2.6 Th-234

The results obtained for ^{234}Th which has a short half-life are very good which confirms that the column separation is working well for both short- and long half-life nuclides and that a possible mass-effect is prevented by addition of ^{229}Th as tracer (and carrier).

Table 11: Results for ^{234}Th

Sample	yield	Activity concentration mBq.g^{-1}	Error
1	0.91	148	- 8.9
2	0.28	135	-16.9
3	0.63	133	-18.1
4	0.69	143	-11.2
avg		140	
std		7	
rsd %		4.9	

expected activities for ^{234}Th is 162.1

9. CONCLUSIONS

RA-WIN-142 was changed according to the new elution curves. This method gives an average yield of 0.6 ± 0.2 (n=26). A shift in elution curves occurs from time to time and must be reinvestigated when yields lower than 10 % are obtained consistently, to confirm the position of the Th peak.

The results obtained by using ^{229}Th as tracer are more accurate than those using ^{234}Th.

The accuracy of the method is very good for ^{232}Th and ^{228}Th (error < 15%) and acceptable for ^{230}Th and ^{227}Th (error < 30 %).

The calculated MDA's for the different nuclides are about 1 $mBq.L^{-1}$ when calculated using detector background values for a counting period of 24 hours, volume 200 ml and detector efficiency 0.2. The limiting factor to actual low level determination of the Th nuclides is however the higher counts obtained for the blank samples. MDA should be calculated using detector background and the blanks used as a control measure for levels of contamination

The precision of the method is better than 10 % for ^{232}Th and ^{228}Th and better than 20% for ^{230}Th.

10. RECOMMENDATIONS

The method using ^{229}Th as yield tracer is adequate for the determination of all of the Th nuclides at a level of 5 $mBq.L^{-1}$ for a counting period of 24 hours.

The ^{232}Th control sample should be analysed at least once a month to monitor the reproducibility of the method.