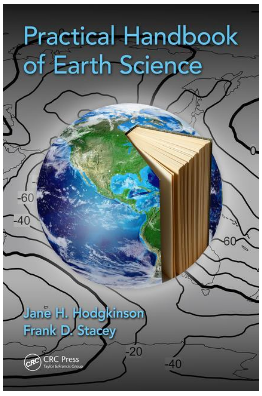

Practical Handbook of Earth Science

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Elements, Isotopes and Radioactivity

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Chapter 3

Elements, Isotopes and Radioactivity

3.1 PERIODIC TABLE OF ELEMENTS: A GEOCHEMICAL CLASSIFICATION (Figure 3.1)

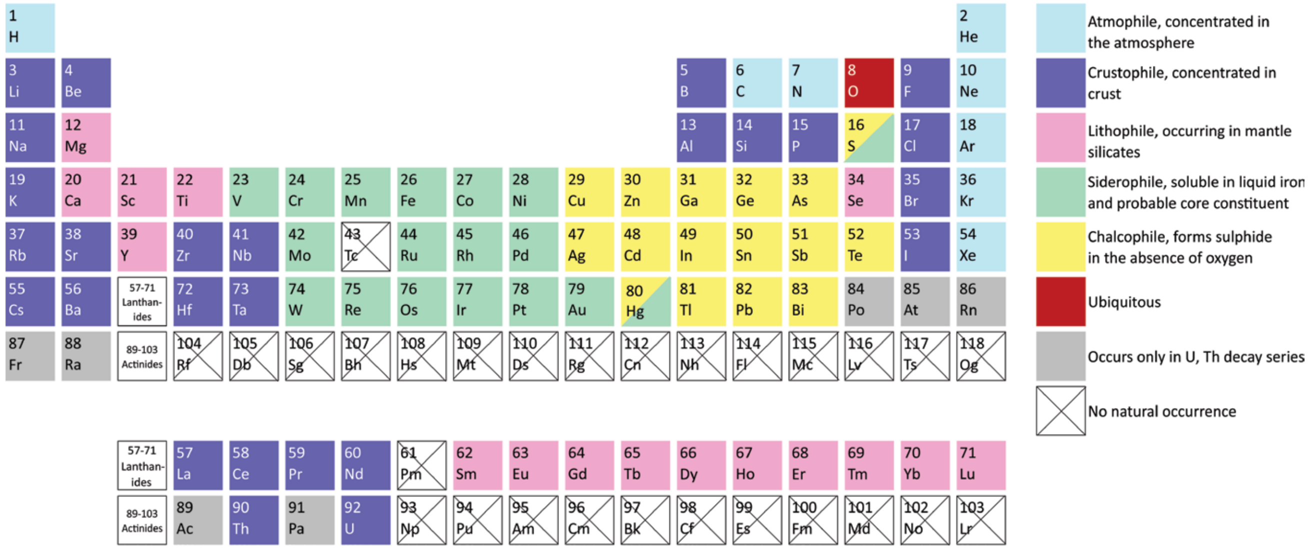

Figure 3.1 A geochemical classification of the elements.

3.2 PERIODIC TABLE OF ELEMENTS: A BIOLOGICAL CLASSIFICATION (Figure 3.2)

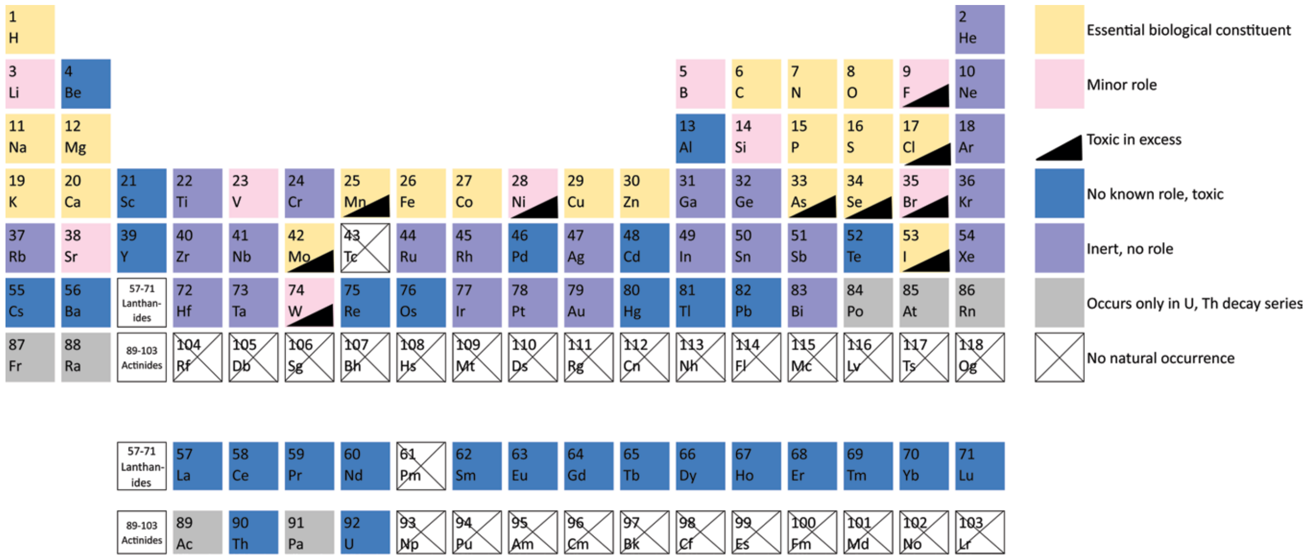

Figure 3.2 A biological classification of the elements.

3.3 ISOTOPES OF THE NATURALLY OCCURRING ELEMENTS

TABLE 3.1 ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
0	Neutron	n[a] (1.0886)	
1	Hydrogen	H (1.0079)	1 (99.985), 2 (0.015), 3[a] (atmospheric trace from cosmic ray bombardment)
2	Helium	He (4.00260)	3 (0.00013), 4 (99.99987)
3	Lithium	Li (6.940)	6 (7.59), 7 (92.41)
4	Beryllium	Be (9.01218)	9 (100), 10[a] (atmospheric trace from cosmic ray bombardment)
5	Boron	B (10.811)	10 (19.9), 11 (80.1)
6	Carbon	C (12.0107)	12 (98.93), 13 (1.07), 14[a] (1.6 × 10^{-10} in atmosphere)
7	Nitrogen	N (14.0067)	14 (99.635), 15 (0.365)
8	Oxygen	O (15.9994)	16 (99.757), 17 (0.038), 18 (0.205)
9	Fluorine	F (18.99480)	19 (100)
10	Neon	Ne (20.1797)	20 (90.48), 21 (0.27), 22 (9.25)
11	Sodium	Na (22.9898)	23 (100)
12	Magnesium	Mg (24.3050)	24 (78.99), 25 (10.00), 26 (11.01)
13	Aluminium	Al (26.98154)	27 (100)
14	Silicon	Si (28.0855)	28 (92.22), 29 (4.69), 30 (3.09)
15	Phosphorus	P (30.97376)	31 (100)
16	Sulphur	S (32.065)	32 (94.93), 33 (0.76), 34 (4.29), 36 (0.02)
17	Chlorine	Cl (35.453)	35 (75.76), 37 (24.24)
18	Argon		
	Atmosphere	Ar (39.948)	36 (0.337), 38 (0.063), 40 (99.600)
	Solar wind	Ar (36.67)	36 (75.3), 38 (14.2), 40 (10.5)

(Continued)

TABLE 3.1 *(Continued)* ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
19	Potassium	K (39.0983)	39 (93.258), 40[a] (0.01167), 41 (6.730)
20	Calcium	Ca (40.078)	40 (96.94), 42 (0.65), 43 (0.13), 44 (2.09), 46 (0.0041), 48[b] (0.19)
21	Scandium	Sc (44.95591)	45 (100)
22	Titanium	Ti (47.867)	46 (8.25), 47 (7.44), 48 (73.72), 49 (5.41), 50 (5.18)
23	Vanadium	V (50.9415)	50[b] (0.25), 51 (99.75)
24	Chromium	Cr (51.996)	50 (4.35), 52 (83.79), 53 (9.50), 54 (2.36)
25	Manganese	Mn (54.93804)	55 (100)
26	Iron	Fe (55.845)	54 (5.84), 56 (91.75), 57 (2.12), 58 (0.28)
27	Cobalt	Co (58.93319)	59 (100)
28	Nickel	Ni (58.6934)	58 (68.077), 60 (26.223), 61 (1.140), 62 (3.634), 64 (0.926)
29	Copper	Cu (63.546)	63 (69.2), 65 (30.8)
30	Zinc	Zn (65.409)	64 (48.27), 66 (27.98), 67 (4.10), 68 (19.02), 70 (0.63)
31	Gallium	Ga (69.723)	69 (60.108), 71 (39.892)
32	Germanium	Ge (72.63)	70 (20.38), 72 (27.31), 73 (7.76), 74 (36.72), 76[b] (7.83)
33	Arsenic	As (74.9216)	75 (100)
34	Selenium	Se (78.96)	74 (0.89), 76 (9.37), 77 (7.63), 78 (23.77), 80 (49.61), 82[b] (8.73)
35	Bromine	Br (79.904)	79 (50.69), 81 (49.31)
36	Krypton	Kr (83.798)	78 (0.35), 80 (2.29), 82 (11.59), 83 (11.50), 84 (56.99), 86 (17.28)
37	Rubidium	Rb (85.4678)	85 (72.165), 87[a] (27.835)
38	Strontium	Sr (87.62)	84 (0.56), 86 (9.86), 87 (7.00), 88 (82.58)

(Continued)

TABLE 3.1 *(Continued)* ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
39	Yttrium	Y (88.90585)	89 (100)
40	Zirconium	Zr (91.224)	90 (51.45), 91 (11.22), 92 (17.15), 94 (17.38), 96[b] (2.80)
41	Niobium	Nb (92.90638)	93 (100)
42	Molybdenum	Mo (95.96)	92 (14.77), 94 (9.23), 95 (15.90), 96 (16.68), 97 (9.56), 98 (24.19), 100[a] (9.67)
43	Technetium	Tc	No naturally occurring isotope
44	Ruthenium	Ru (101.07)	96 (5.44), 98 (1.87), 99 (12.76), 100 (12.60), 101 (17.06), 102 (31.55), 104 (18.62)
45	Rhodium	Rh (102.90550)	103 (100)
46	Palladium	Pd (106.42)	102 (1.02), 104 (11.14), 105 (22.33), 106 (27.33), 108 (26.46), 110 (11.72)
47	Silver	Ag (106.8682)	107 (51.839), 109 (48.161)
48	Cadmium	Cd (112.411)	106 (1.25), 108 (0.89), 110 (12.49), 111 (12.80), 112 (24.13), 113[b] (12.22), 114[b] (28.72), 116[b] (7.49)
49	Indium	In (114.818)	113 (4.29), 115[b] (95.71)
50	Tin	Sn (118.71)	112 (0.97), 114 (0.66), 115 (0.34), 116 (14.54), 117 (7.68), 118 (24.22), 119 (8.59), 120 (32.58), 122 (4.63), 124 (5.79)
51	Antimony	Sb (121.60)	121 (57.21), 123 (47.79)
52	Tellurium	Te (127.60)	120 (0.09), 122 (2.55), 123 (0.89), 124 (4.74), 125 (7.07), 126 (18.84), 128[b] (31.74), 130[b] (30.08)
53	Iodine	I (126.90448)	127 (100)
54	Xenon	Xe (131.293)	124 (0.095), 126 (0.089), 128 (1.910), 129 (26.401), 130 (4.071), 131 (21.232), 132 (26.909), 134 (10.436), 136[b] (8.857)

(Continued)

TABLE 3.1 ***(Continued)*** **ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS**

Atomic No. z	Element	Symbol (mean atomic wt., in units of u = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
55	Caesium	Cs (132.90552)	133 (100)
56	Barium	Ba (137.327)	130[b] (0.106), 132 (0.101), 134 (2.417), 135 (6.592), 136 (7.854), 137 (11.232), 138 (71.698)
57	Lanthanum	La (138.90547)	138[a] (0.090), 139 (99.910)
58	Cerium	Ce (140.116)	136 (0.190), 138 (0.251), 140 (88.450), 142 (11.114)
59	Praseodymium	Pr (140.90765)	141 (100)
60	Neodymium	Nd (144.242)	142 (27.2), 143 (12.2), 144[b] (23.8), 145 (8.23), 146 (17.2), 148 (5.72), 150[b] (5.60)
61	Promethium	Pm	No naturally occurring isotope
62	Samarium	Sm (150.36)	144 (3.07), 146[a] (trace), 147[a] (14.99), 148[b] (11.24), 149 (13.82), 150 (7.38), 152 (26.75), 154 (22.75)
63	Europium	Eu (151.964)	151[b] (47.81), 153 (52.19)
64	Gadolinium	Gd (157.25)	152[b] (0.20), 154 (2.18), 155 (14.80), 156 (20.47), 157 (15.65), 158 (24.84), 160 (21.86)
65	Terbium	Tb (158.92535)	159 (100)
66	Dysprosium	Dy (162.500)	156 (0.056), 158 (0.095), 160 (2.329), 161 (18.889), 162 (25.475), 163 (24.896), 164 (28.260)
67	Holmium	Ho (164 93032)	165 (100)
68	Erbium	Er (167.259)	162 (0.139), 164 (1.601), 166 (33.503), 167 (22.869), 168 (26.978), 170 (14.910)
69	Thulium	Tm (168.9342)	169 (100)
70	Ytterbium	Yb (173.04)	168 (0.13), 170 (3.04), 171 (14.28), 172 (21.83), 173 (16.13), 174 (31.83), 176 (12.76)
71	Lutetium	Lu (174.967)	175 (97.41), 176[a] (2.59)
72	Hafnium	Hf (178.49)	174[b] (0.162), 176 (5.26), 177 (18.60), 178 (27.28), 179 (13.63), 180 (35.08)

(Continued)

TABLE 3.1 *(Continued)* ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
73	Tantalum	Ta (180.9479)	180 (0.012), 181 (99.988)
74	Tungsten	W (183.84)	180[b] (0.12), 182 (26.55), 183 (14.31), 184 (30.64), 186 (28.45)
75	Rhenium	Re (186.207)	185 (37.40), 187[a] (62.60)
76	Osmium	Os (190.23)	184 (0.02), 186[b] (1.59), 187 (1.96), 188 (13.24), 189 (16.15), 190 (26.26), 192 (40.78)
77	Iridium	Ir (192.217)	191 (37.3), 193 (62,7)
78	Platinum	Pt (195.089)	190[a] (0.014), 192 (0.782), 194 (32.967), 195 (33.832), 196 (25.242), 198 (7.163)
79	Gold	Au (196.966569)	197 (100)
80	Mercury	Hg (200.592)	196 (0.15), 198 (9.97), 199 (16.87), 200 (23.10), 201 (13.18), 202 (29.86), 204 (6.87)
81	Thallium	Tl (204.3833)	203 (29.52), 205 (70.48)
82	Lead	Pb (207.21) (variable)	204[b] (1.347), 206 (25.03). 207 (21.25), 208 (52.37) (averages in marine sediments)
83	Bismuth	Bi (208.9804)	209[b] (100)
84	Polonium	Po	Intermediate daughters in uranium and thorium decay series
85	Astatine	At	
86	Radon	Rn	
87	Francium	Fr	
88	Radium	Ra	
89	Actinium	Ac	
90	Thorium	Th (232.0381)	232[a] (100)
91	Protactinium	Pa	Intermediate daughter in uranium decay
92	Uranium	U (238.0289)	234[a] (0.0055), 235[a] (0.7200), 238[a] (99.2745)

[a] Radioactive isotopes.
[b] Isotopes with half-lives exceeding the age of the universe.

3.4 NATURALLY OCCURRING LONG-LIVED RADIOACTIVE ISOTOPES

This list recognises half-lives exceeding the age of the universe for isotopes that have generally been regarded as stable. The possibility that β decay rates are affected by neutrino flux is under consideration. It is not clear whether any of the following numbers are seriously affected.

TABLE 3.2 DECAY MECHANISMS AND HALF-LIVES

Isotope	% of Element	Decay Mechanism	Half-Life (years)	Decay Product
^{40}K	0.01167	89.28% β 10.72% K 0.001% $β^+$	1.248×10^9	^{40}Ca ^{40}Ar ^{40}Ar
^{48}Ca	0.19	2β	4×10^{19}	^{48}Ti
^{50}V	0.25	β	1.4×10^{17}	^{50}Cr
^{76}Ge	7.83	2β	1.8×10^{21}	^{26}Se
^{82}Se	8.73	2β	9.7×10^{19}	^{82}Kr
^{87}Rb	27.835	β	4.92×10^{10}	^{87}Sr
^{96}Zr	2.80	2β	2×10^{19}	^{96}Mo
^{100}Mo	9.67	2β	8.5×10^{18}	^{100}Ru
^{113}Cd	12.22	β	8.04×10^{15}	^{113}I
^{116}Cd	7.49	2β	2.8×10^{19}	^{116}Sn
^{115}In	95.71	β	4.4×10^{14}	^{115}Sn
^{128}Te	31.74	2β	2.2×10^{24}	^{128}Xe
^{130}Te	30.08	2β	7.9×10^{20}	^{130}Xe
^{130}Ba	0.106	2K	$\sim 10^{21}$	^{130}Xe
^{136}Xe	8.857	2β	2.38×10^{21}	^{136}Ba
^{138}La	0.090	33.6% β 66.4% $β^+$	1.02×10^{11}	^{138}Ce ^{138}Ba
^{142}Ce	11.05	α	5.0×10^{15}	^{138}Ba
^{144}Nd	23.8	α	2.3×10^{15}	^{140}Ce
^{146}Sm	trace	α	6.8×10^7	^{142}Nd
^{147}Sm	14.99	α	1.06×10^{11}	^{143}Nd
^{148}Sm	11.24	α	7×10^{15}	^{144}Nd→^{140}Ce

(Continued)

TABLE 3.2 *(Continued)* DECAY MECHANISMS AND HALF-LIVES

Isotope	% of Element	Decay Mechanism	Half-Life (years)	Decay Product
^{150}Nd	5.6	2β	6.7×10^{18}	^{150}Sm
^{151}Eu	47.81	α, β	5×10^{18}	^{147}Pm→^{147}Sm
^{152}Gd	0.2	2α	1.08×10^{14}	^{148}Sm→^{144}Nd
^{156}Dy	0.0524	α	2×10^{14}	^{152}Gd
^{174}Hf	0.162	α	2.0×10^{15}	^{170}Yb
^{176}Lu	2.59	β	3.85×10^{10}	^{176}Hf
^{180}W	0.12	α	1.8×10^{18}	^{176}Hf
^{186}Os	1.89	α	2×10^{15}	^{182}W
^{187}Re	62.6	99.99% β 0.01% α	4.12×10^{10}	^{187}Os ^{183}Ta
^{190}Pt	0.014	α	6.5×10^{11}	^{186}Os
^{204}Pb	1.35	α	1.4×10^{17}	^{200}Hg
^{209}Bi	100	α	1.9×10^{19}	^{205}Tl
^{232}Th	100	6α + 4β	1.4010×10^{10}	^{208}Pb (final)
^{235}U	0.7201	7α + 4β	7.0381×10^{8}	^{207}Pb (final)
^{238}U	99.2743	8α + 6 β 5.4×10^{-5}% fission	4.4683×10^{9}	^{206}Pb (final)

Note: α, alpha particle emission; β, electron emission; β⁺, positron emission; K, electron capture [normally from the innermost (K) shell of orbital electrons].

3.5 SOME EXTINCT ISOTOPES

TABLE 3.3 EXTINCT ISOTOPES WITH DECAY PRODUCTS THAT ARE IDENTIFIABLE IN METEORITES OR PROVIDE ISOTOPIC CLUES TO EARLY SOLAR SYSTEM PROCESSES

Isotope	Decay Mechanism	Half-Life (years)	Decay Product
^{22}Na	$β^+$	2.603	^{22}Ne
^{26}Al	85% $β^+$ 15% K	7.17×10^{5}	^{26}Mg
^{60}Fe	2β	3×10^{5}	^{60}Ni via ^{60}Co

(Continued)

TABLE 3.3 *(Continued)* EXTINCT ISOTOPES WITH DECAY PRODUCTS THAT ARE IDENTIFIABLE IN METEORITES OR PROVIDE ISOTOPIC CLUES TO EARLY SOLAR SYSTEM PROCESSES

Isotope	Decay Mechanism	Half-Life (years)	Decay Product
^{107}Pd	β	6.5×10^5	^{107}Ag
^{129}I	β	1.6×10^7	^{129}Xe
^{146}Sm	α	1.03×10^8	^{142}Nd
^{182}Hf	2β	8.9×10^6	^{182}W via ^{182}Ta
^{236}U	α	2.4×10^7	^{208}Pb via ^{232}Th
^{244}Pu	0.3% fission 99.7% α	8.3×10^7	0.3% fission products 99.7% ^{208}Pb via ^{232}Th

3.6 SHORT-LIVED ISOTOPES

TABLE 3.4 ISOTOPES PRODUCED BY COSMIC RAYS OR RADIOACTIVE DECAY

Isotope	Decay Mechanism	Half-Life	Decay Product
Neutron	β	611 s (10.18 minutes)	^{1}H
^{3}H, tritium	β	12.32 years	^{3}He
^{7}Be	K	53.22 days	^{7}Li
^{10}Be	β	1.39×10^6 years	^{10}B
^{14}C	β	5730 years	^{14}N
^{22}Na	β	2.603 years	^{22}Ne
^{32}Si	2β	153 years	^{32}S via ^{32}P
^{32}P	β	14.263 days	^{32}S
^{33}P	β	25 days	^{33}S
^{35}S	β	87.5 days	^{35}Cl
^{36}Cl	98.1% β 1.9% K	3.01×10^5 years	^{36}Ar ^{36}S
^{37}Ar	K	35 days	^{37}Cl

(Continued)

TABLE 3.4 *(Continued)* ISOTOPES PRODUCED BY COSMIC RAYS OR RADIOACTIVE DECAY

Isotope	Decay Mechanism	Half-Life	Decay Product
^{39}Ar	β	270 years	^{39}K
^{41}Ca	K	1.02×10^5 years	^{41}K
^{53}Mn	K	3.7×10^6 years	^{53}Cr
^{234}U	α	2.47×10^5 years	$^{230}Th \rightarrow ^{206}Pb$

3.7 FISSION PRODUCTS

Nuclear fission, principally of ^{235}U and ^{239}Pu, results in fragments with unequal atomic masses in ranges 85–110 and 125–155. Statistics of the fragments depend somewhat on the fissioning isotopes and on conditions such as energies of incident neutrons. Each fission event also produces two or three neutrons and, in a few cases, other small fragments such as tritium (^3H). The products are all neutron-rich, making them radioactive emitters of β particles (energetic electrons). There is a very wide range of radioactive fission products. Table 3.5 lists the ones of particular environmental concern on account of their abundances and likelihood of ingestion.

Releases from nuclear accidents also include isotopes of the actinides (elements close to thorium, uranium and plutonium in the periodic table), as well as unfissioned ^{235}U and ^{239}Pu (half-life 24,100 years).

The total intensity of radiation from fission products, R, decreases with time as a sum of numerous exponential decays, with complications arising from secondary decays. A rough empirical representation for fallout radiation at an open site, derived largely from Chernobyl data, is

$$R = R_1 t^{-1/2} \quad (3.1)$$

where t is time in days, starting at day 1, when the intensity was R_1. This simple equation is a useful approximation for $t = 1$ day to 10,000 days (27.4 years). In the

TABLE 3.5 ENVIRONMENTALLY PROBLEMATIC FISSION PRODUCTS

Isotope	^{90}Sr	^{137}Cs	^{89}Sr	^3H	^{140}Ba	^{131}I
Half-life	28 years	30 years	15 days	13 years	128 days	8.05 days
Ingestion	30%	~100%	30%	High[a]	5%	100%

[a] Readily absorbed but also generally quickly excreted.

much longer term, this relationship will fail because fission products all have half-lives of either less than 100 years or more than 200,000 years and the half-life distribution of still active isotopes will change dramatically.

3.8 RADIOGENIC HEAT

TABLE 3.6 THERMALLY IMPORTANT RADIOACTIVE ISOTOPES

Isotope	μW/kg	μW/kg of Element	Total Earth Content (kg)	Heat (10^{12} W) Now	Heat (10^{12} W) 4.5×10^9 years ago	Heat (10^{12} W) In 10^9 Years' Time
^{238}U	95.0	94.35	15.02×10^{16}	14.25	28.6	12.2
^{235}U	562.0	4.05	0.11×10^{16}	0.60	50.1	0.22
^{232}Th	26.6	26.6	55.98×10^{16}	14.87	18.6	14.1
^{40}K	30.0	0.00350	8.06×10^{20} (total K)	2.82	34.2	1.6
	Total heat			31.2	132	28.1

TABLE 3.7 AVERAGE RADIOGENIC HEAT IN EARTH MATERIALS

Material		Concentration (ppm by mass) U	Th	K	K/U	Heat (10^{-12} W/kg)
Igneous rocks	Granites	4.6	18	33,000	7000	1050
	Alkali basalts	0.75	2.5	12,000	16,000	180
	Tholeiitic basalts	0.11	0.04	1500	13,600	27
	Eclogites	0.035	0.15	500	14,000	9.2
	Peridotites	0.006	0.02	100	17,000	1.5
Meteorites	Carbonaceous Chondrites	0.020	0.070	400	20,000	5.2
	Ordinary Chondrites	0.015	0.046	900	60,000	5.8
	Iron Meteorites	Nil	Nil	Nil	–	$<3 \times 10^{-4}$
Moon	Apollo samples	0.23	0.85	590	2500	47
Global averages	Crust	1.2	4.5	15,500	13,000	293
	Mantle	0.029	0.109	81	2800	5.7
	Core	0	0	29	–	0.1
	Whole Earth	0.025	0.093	135	5400	5.2