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RADIOACTIVE EQUILIBRIUM

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SCIENCE / TECHNICAL

An Explanation of Radioactive Equilibrium

Michael Kitto

Radioactive secular equilibrium occurs when the half-life of the parent isotope is much longer than the half-life of the progeny. As the decay rate of the parent isotope, and hence the production rate of the progeny, occurs at a constant rate, eventually the progeny decay rate equals the production rate, and the activities reach a constant value. In our case, radium-226 is the long-lived parent (half-life 1600 yr), followed by radon and its radon decay products (RDPs). In solids, when radon is created it is either trapped until it decays, or it may be able to migrate through the particle matrix and escape into the open air before it decays back to a solid atom (e.g., Po-218). The "freed" radon disrupts the equilibrium, resulting in a lower concentration of the RDPs in the matrix. The radon that is created on or near the particle surface is much more likely to escape into the air than the radon trapped inside the matrix. The portion of radon that escapes into

(half-lives of 29 and 20 minutes, respectively) for gamma measurements as well as the alpha-emitting Po-218 and Po-214 isotopes detected by continuous radon monitors. Thus, once the radon is collected as a grab sample or onto charcoal, at least 3 hours (six half-lives) is commonly allowed for RDPs to re-establish equilibrium with the trapped radon so that count rates are maximized and counting error minimized.

The degree of radon equilibrium in effluent is important in regard to exposure and dose. Active subslab depressurization (SSD) systems extract soil gas containing radon, RDPs, and moisture. The ER of the emission is likely low due to air movement, but as several alpha-emitting isotopes exist in the effluent, disposal above the roof line is warranted. As a vast majority of the dose is from the RDPs, and not the radon itself, the ER value is important regarding dose. In contrast, emissions

Naturally occurring radioactive decay series

Parent of series	Parent half-life
Thorium-232	14 billion years
Uranium-238	4.5 billion years
Uranium-235	0.7 billion years
Neptunium-237 (extinct)	2 million years

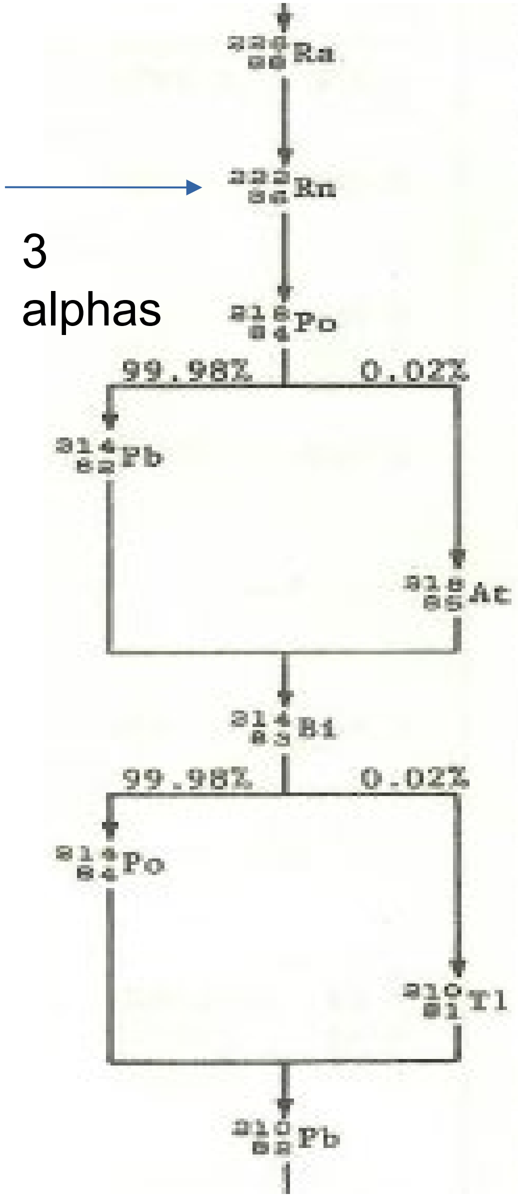
U-238 decay series

14 decay products

Uranium Series (4n + 2)*

Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†		
			α	β	γ
$^{238}_{92}U$	Uranium I	4.51×10^{9} y	4.15 (25%) 4.20 (75%)	---	---
$^{234}_{90}Th$	Uranium X_1	24.1d	---	0.103 (21%) 0.193 (79%)	0.063c‡ (3.5%) 0.093c (4%)
$^{234}_{91}Pa^{m}$	Uranium X_2	1.17m	---	2.29 (98%)	0.765 (0.30%) 1.001 (0.60%)
99.87% 0.13%					
$^{234}_{91}Pa$	Uranium Z	6.75h	---	0.53 (66%) 1.13 (13%)	0.100 (50%) 0.70 (24%) 0.90 (70%)
$^{234}_{92}U$	Uranium II	2.47×10^{5} y	4.72 (28%) 4.77 (72%)	---	0.053 (0.2%)
$^{230}_{90}Th$	Ionium	8.0×10^{4} y	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
$^{226}_{88}Ra$	Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
$^{222}_{86}Rn$	Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
$^{218}_{84}Po$	Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
99.98% 0.02%					
$^{214}_{82}Pb$	Radium B	26.8m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{218}_{85}At$	Astatine	~2s	6.65 (6%) 6.70 (94%)	? (~0.1%)	---
$^{214}_{83}Bi$	Radium C	19.7m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
99.98% 0.02%					
$^{214}_{84}Po$	Radium C'	164μs	7.69 (100%)	---	0.799 (0.014%)
$^{210}_{81}Tl$	Radium C"	1.3m	---	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
$^{210}_{82}Pb$	Radium D	21y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)
$^{210}_{83}Bi$	Radium E	5.01d	4.65 (.00007%) 4.69 (.00005%)	1.161 (~100%)	---
~100% .00013%					
$^{210}_{84}Po$	Radium F	138.4d	5.305 (100%)	---	0.803 (0.0011%)
$^{206}_{81}Tl$	Radium E"	4.19m	---	1.571 (100%)	---
$^{206}_{82}Pb$	Radium G	Stable	---	---	---

U-238 chain continued



		Alpha (MeV)		
Radium	1602y	4.60 (6%) 4.78 (95%)	---	0.186 (4%)
Emanation Radon (Rn)	3.823d	5.49 (100%)	---	0.510 (0.07%)
Radium A	3.05m	6.00 (~100%)	0.33 (~0.019%)	---
Radium B	26.8m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
Astatine	~2s	6.65 (6%) 6.70 (94%)	? (~0.1%)	---
Radium C	19.7m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
Radium C'	164μs	7.69 (100%)	---	0.799 (0.014%)
Radium C''	1.3m	---	1.3 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.31 (21%)
Radium D	21y	3.72 (.000002%)	0.016 (85%) 0.061 (15%)	0.047 (4%)

Th-232 decay series

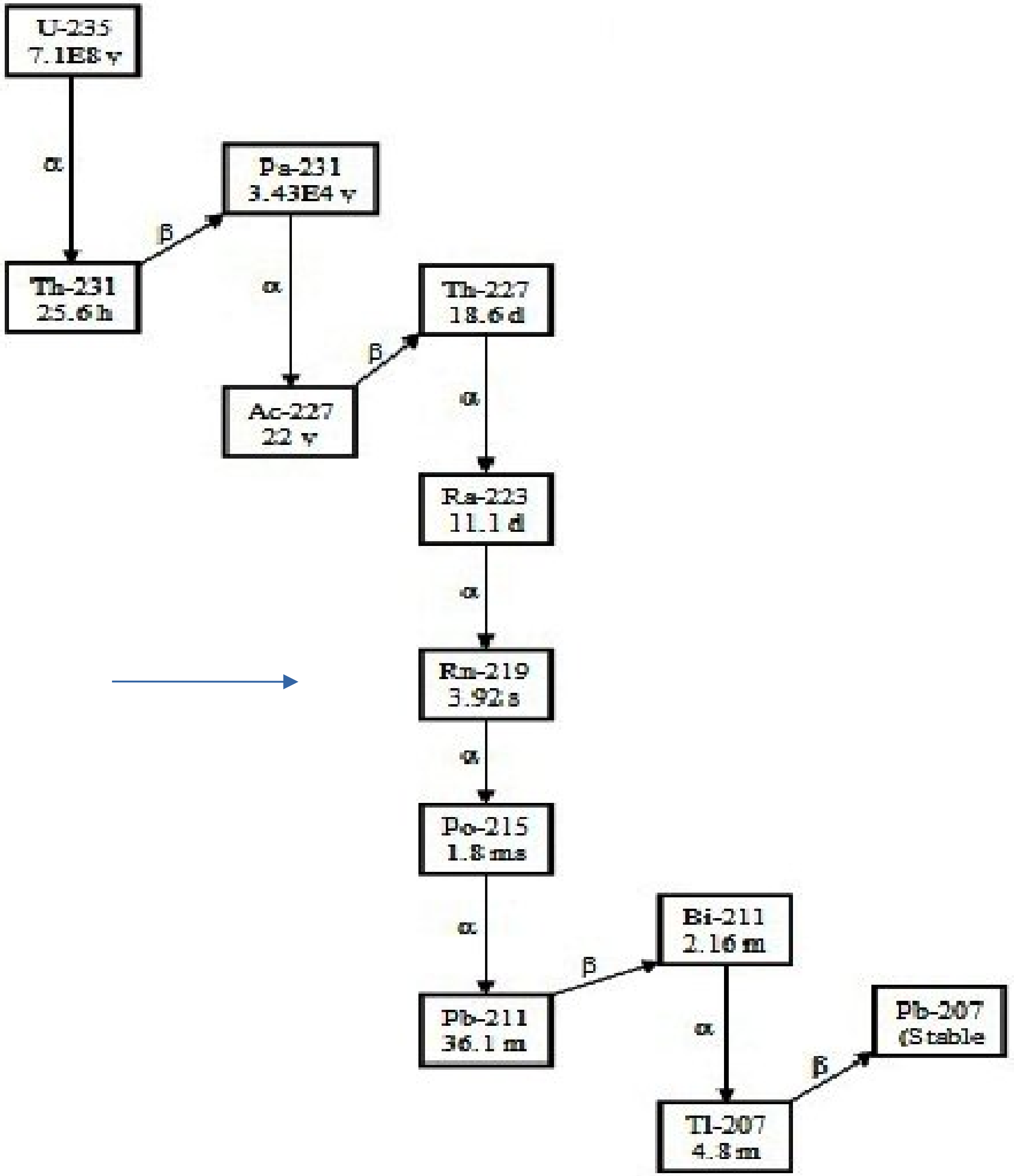
10 decay products

3 alphas

Thorium Series (4n)*

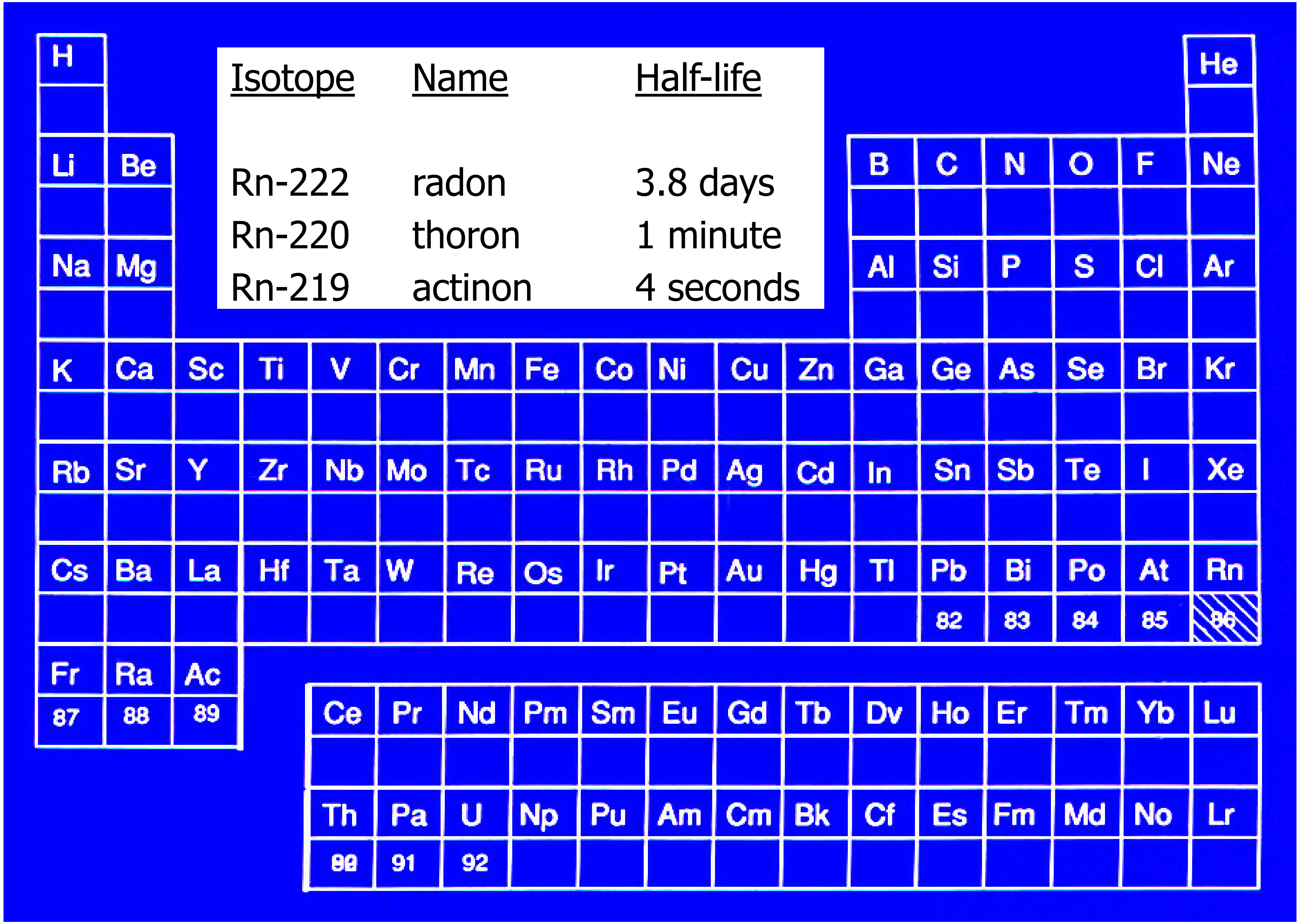
Nuclide	Historical name	Half-life	Major radiation energies (MeV) and intensities†					
			α		β		γ	
$^{232}_{90}Th$	Thorium	1.41×10^{10}y	3.95 4.01	(24%) (76%)	---		---	
$^{228}_{88}Ra$	Mesothorium I	6.7y	---		0.055	(100%)	---	
$^{228}_{89}Ac$	Mesothorium II	6.13h	---		1.18 1.75 2.09	(35%) (12%) (12%)	0.34c‡ 0.908 0.96c	(15%) (25%) (20%)
$^{228}_{90}Th$	Radiothorium	1.910y	5.34 5.43	(28%) (71%)	---		0.084 0.214	(1.6%) (0.3%)
$^{224}_{88}Ra$	Thorium X	3.64d	5.45 5.68	(6%) (94%)	---		0.241	(3.7%)
$^{220}_{86}Rn$	Emanation Thoron (Tn)	55s	6.29	(100%)	---		0.55	(0.07%)
$^{216}_{84}Po$	Thorium A	0.15s	6.78	(100%)	---		---	
$^{212}_{82}Pb$	Thorium B	10.64h	---		0.346 0.586	(81%) (14%)	0.239 0.300	(47%) (3.2%)
$^{212}_{83}Bi$ 64.0% 36.0%	Thorium C	60.6m	6.05 6.09	(25%) (10%)	1.55 2.26	(5%) (55%)	0.040 0.727 1.620	(2%) (7%) (1.8%)
$^{212}_{84}Po$	Thorium C'	304ns	8.78	(100%)	---		---	
$^{208}_{81}Tl$	Thorium C''	3.10m	---		1.28 1.52 1.80	(25%) (21%) (50%)	0.511 0.583 0.860 2.614	(23%) (86%) (12%) (100%)
$^{208}_{82}Pb$	Thorium D	Stable	---		---		---	

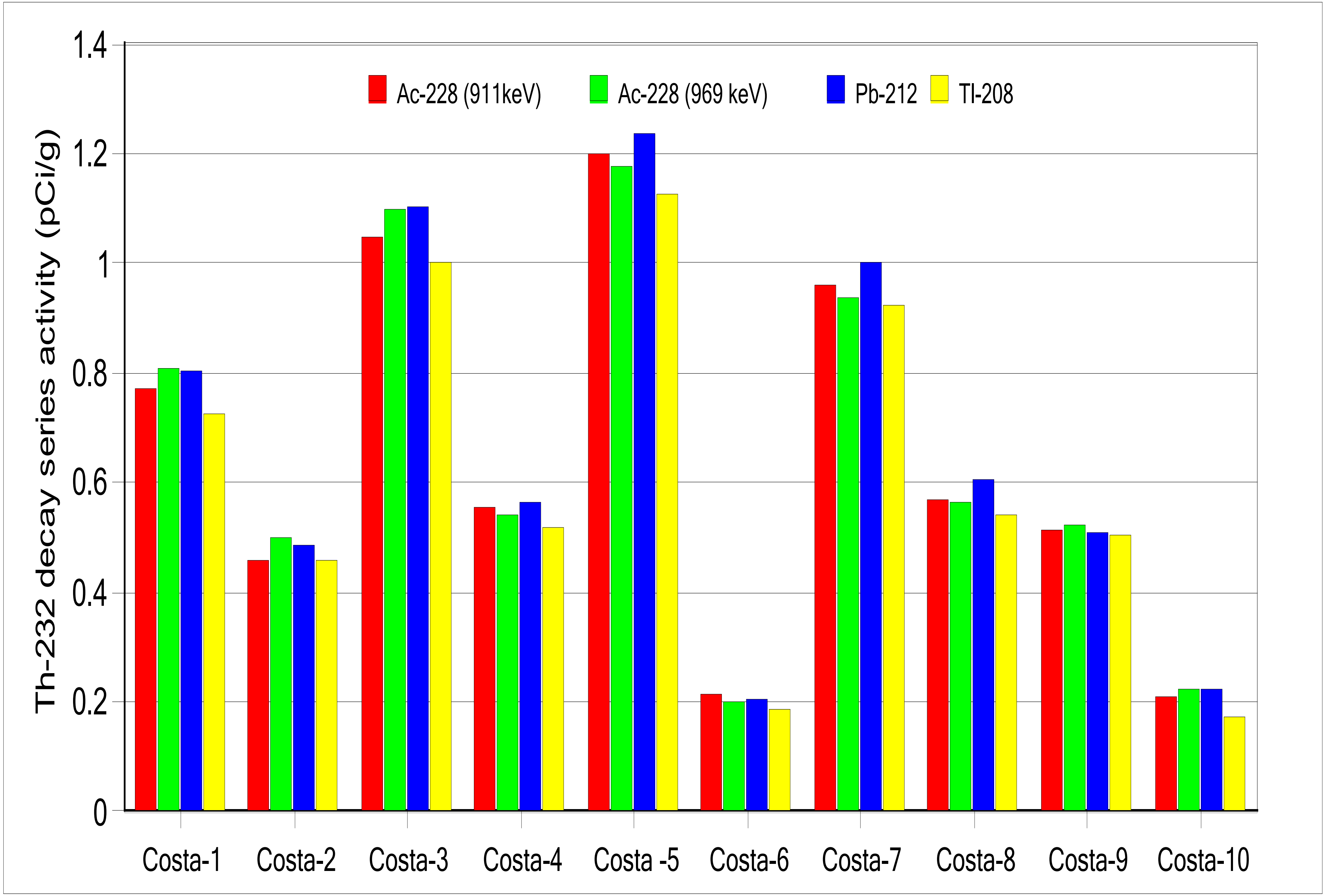
U-235
decay
series

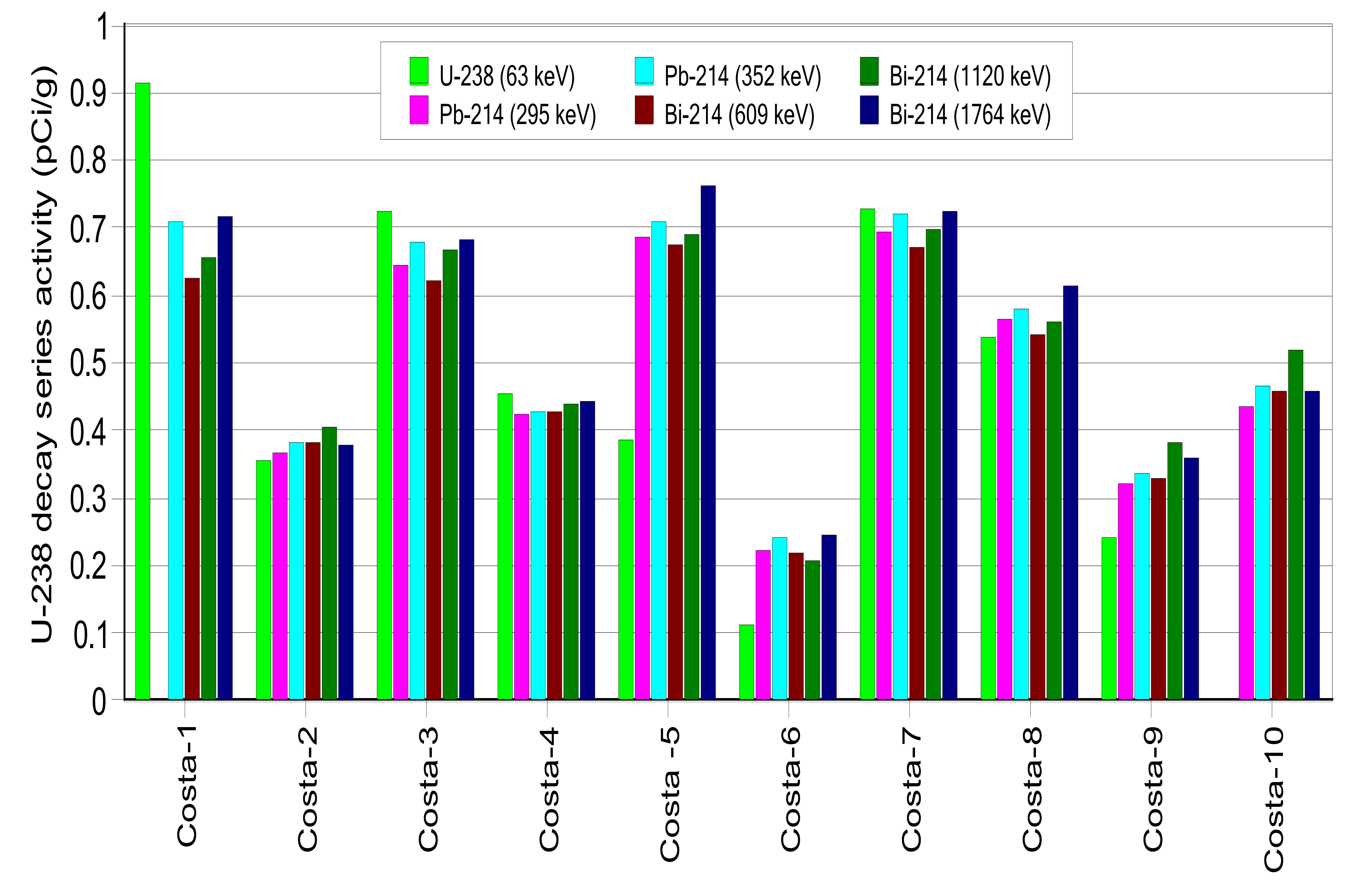


3
alphas

Isotope	Name	Half-life
Rn-222	radon	3.8 days
Rn-220	thoron	1 minute
Rn-219	actinon	4 seconds

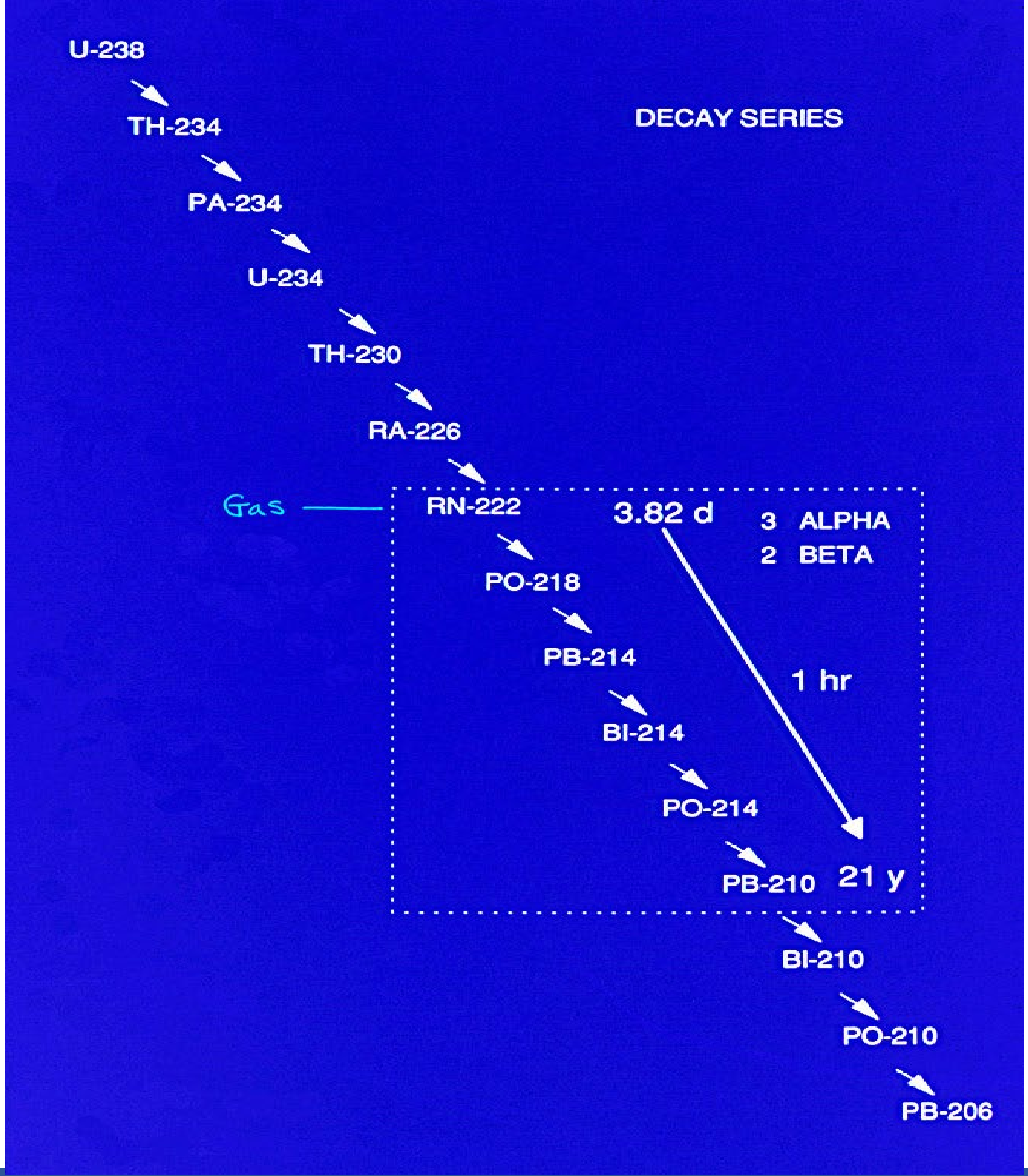



Ac-228 (911keV)
Ac-228 (969 keV)
Pb-212
Tl-208
Th-232 decay series activity (pCi/g)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Costa-1
Costa-2
Costa-3
Costa-4
Costa -5
Costa-6
Costa-7
Costa-8
Costa-9
Costa-10


U-238 (63 keV)
Pb-214 (352 keV)
Bi-214 (1120 keV)
Pb-214 (295 keV)
Bi-214 (609 keV)
Bi-214 (1764 keV)
U-238 decay series activity (pCi/g)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Costa-1
Costa-2
Costa-3
Costa-4
Costa -5
Costa-6
Costa-7
Costa-8
Costa-9
Costa-10

At equilibrium,
all isotopes in
decay series have
the same activity.

Need to measure
any one isotope to
know other’s activity



		MAJOR RADIATION (MeV)		
↓	HALF-LIFE	ALPHA	BETA	GAMMA
RN-222	3.8 days	5.5		
↓				
PO-218	3 min	6.0		
↓				
PB-214	27 min		0.67 0.73 1.02	0.30 0.35
↓				
BI-214	20 min		1.0 1.51 3.26	0.61 1.12
↓				
PO-214	0.2 msec	7.7		
↓				
PB-210	22 years		0.02 0.06 1.16	0.05
↓				

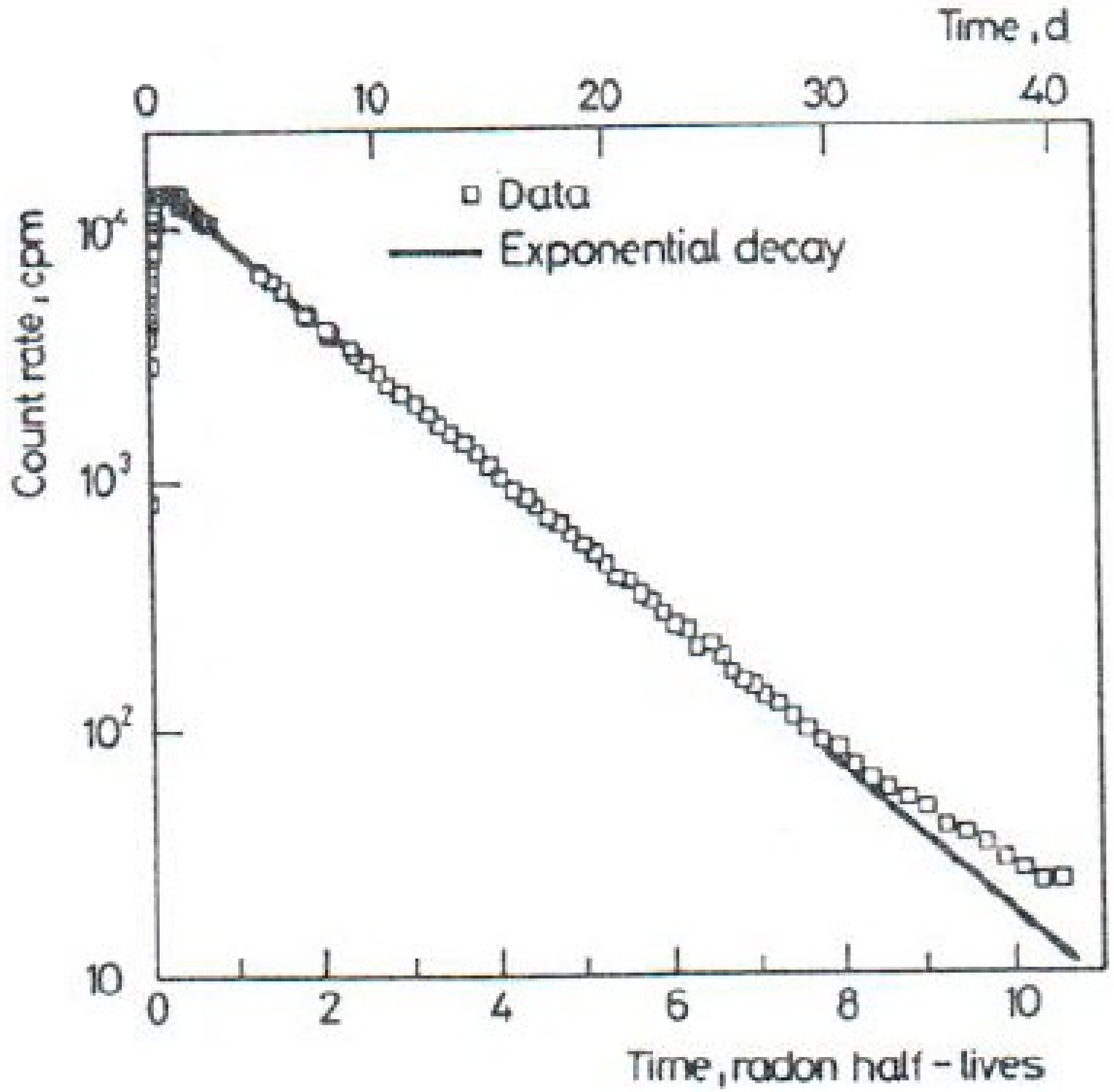
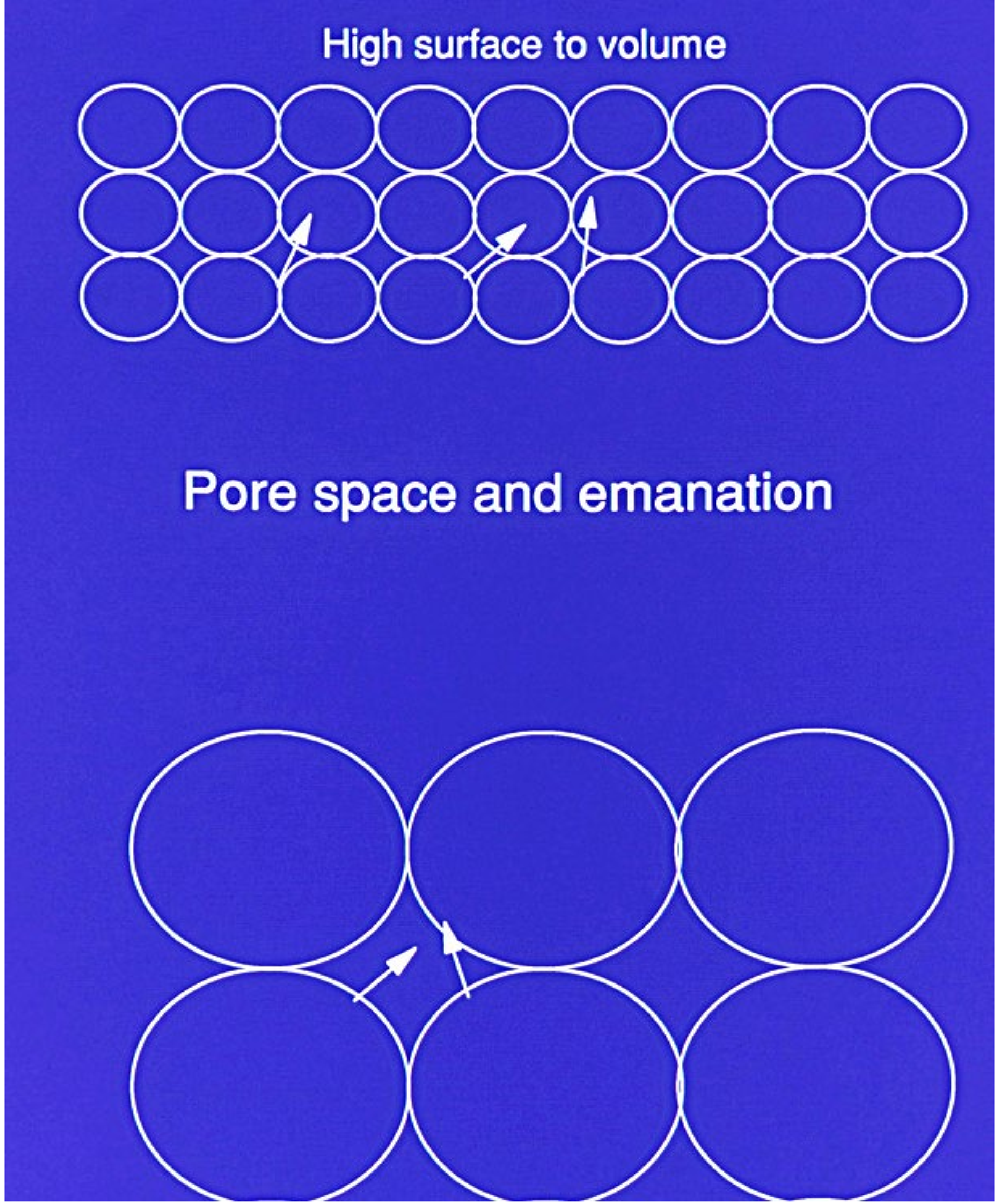
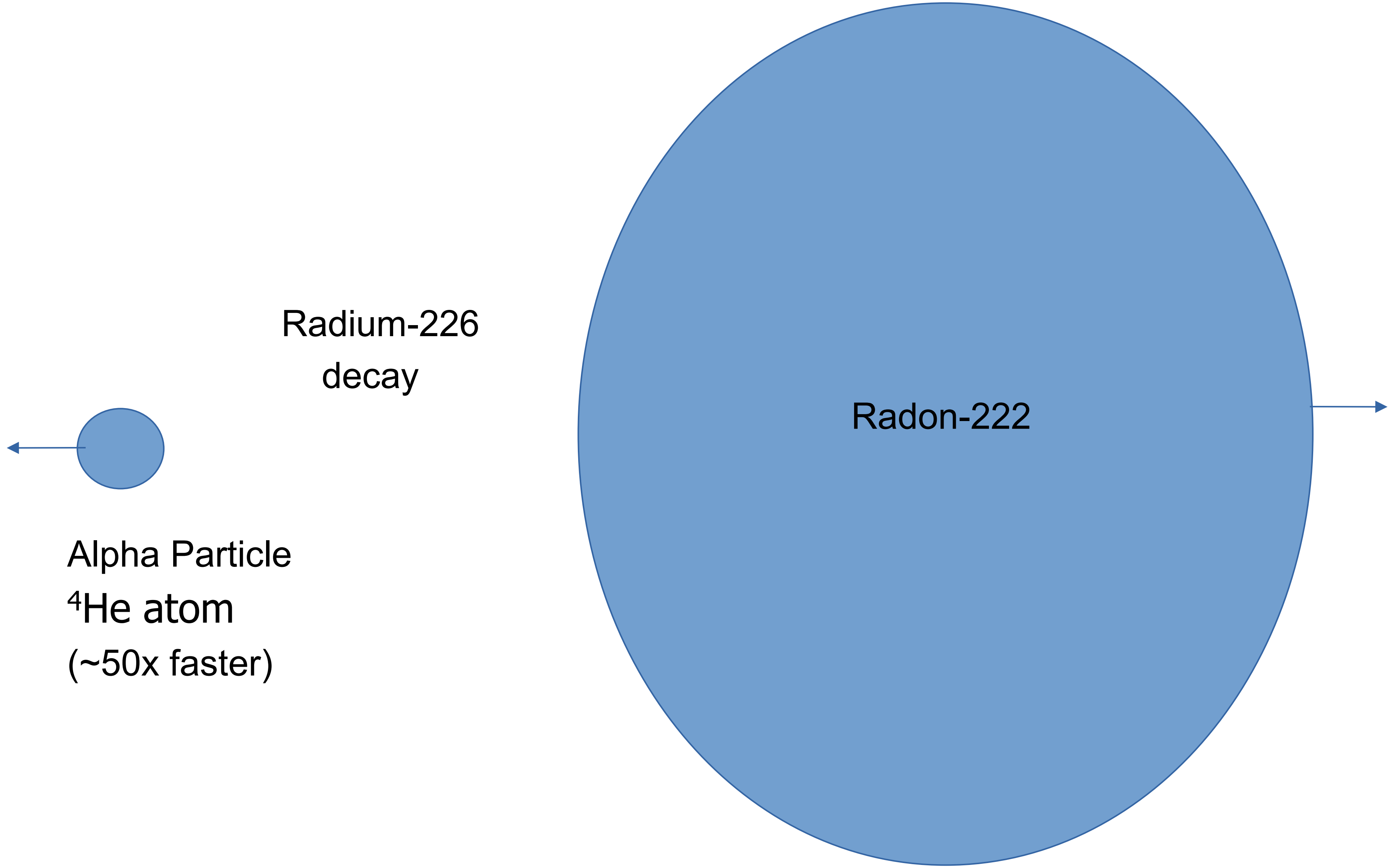
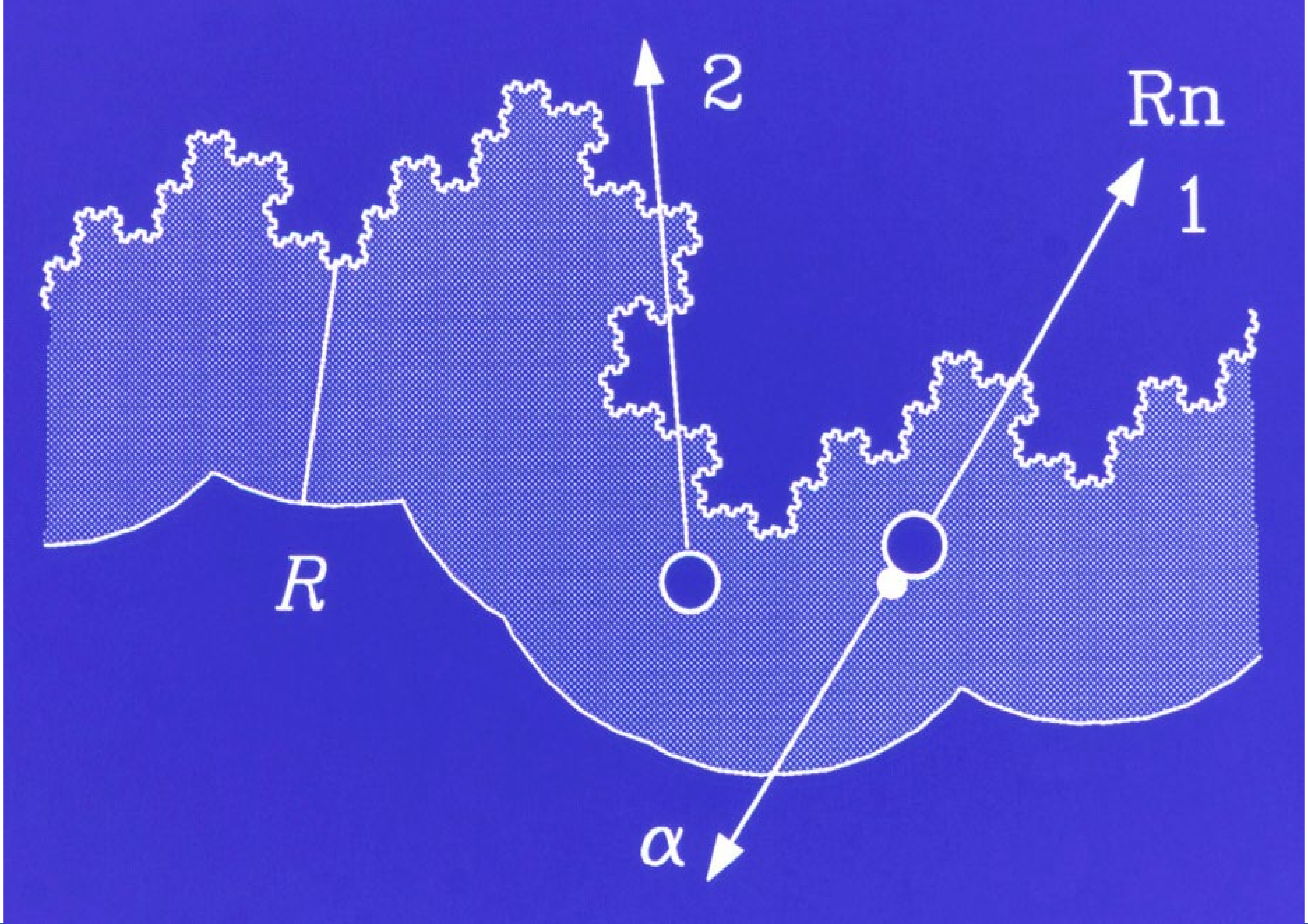
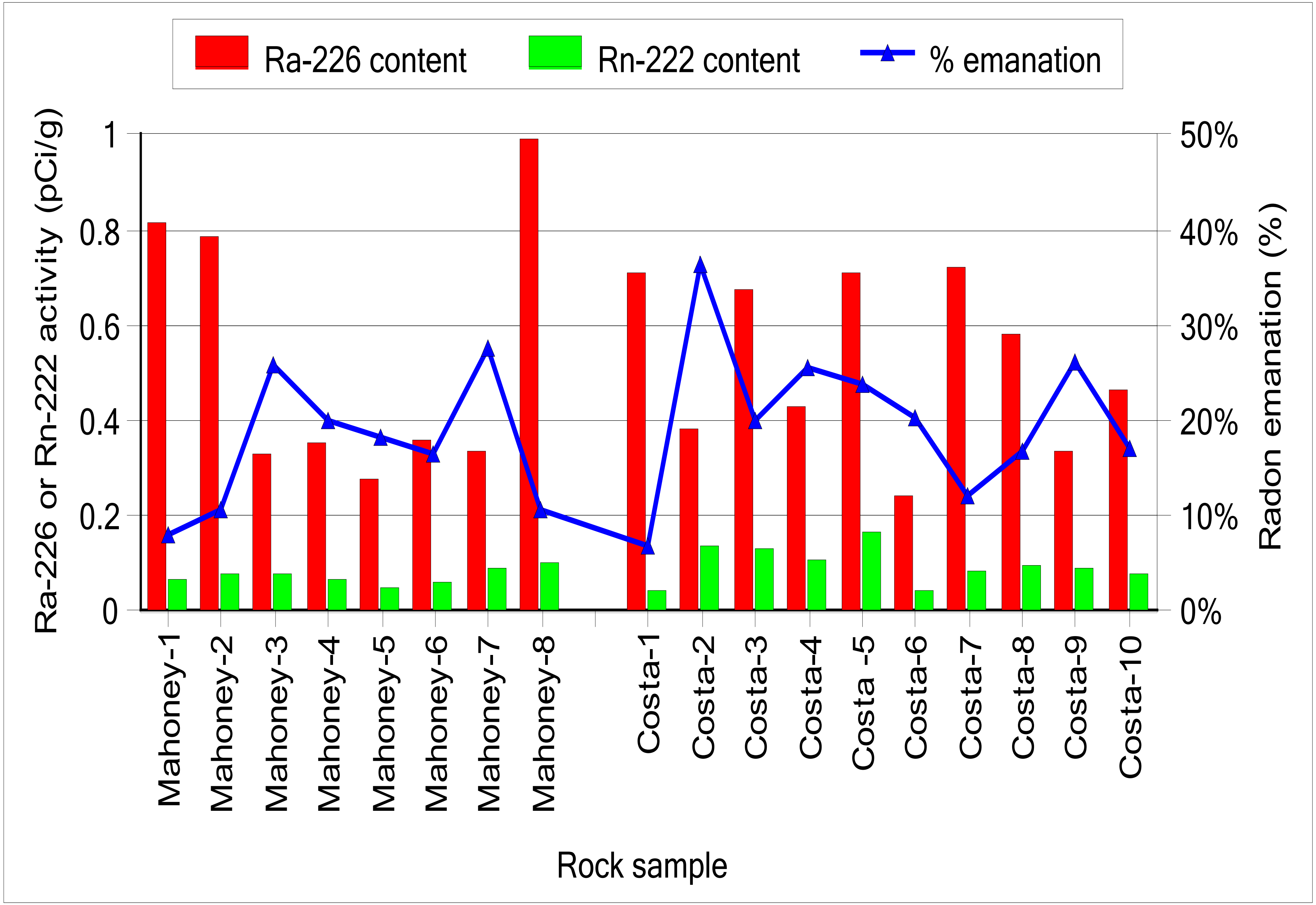


Fig. 1. Observed count rates from LS measurements of a single cocktail. Deviation beyond 30 days is due to ^{210}Po ingrowth

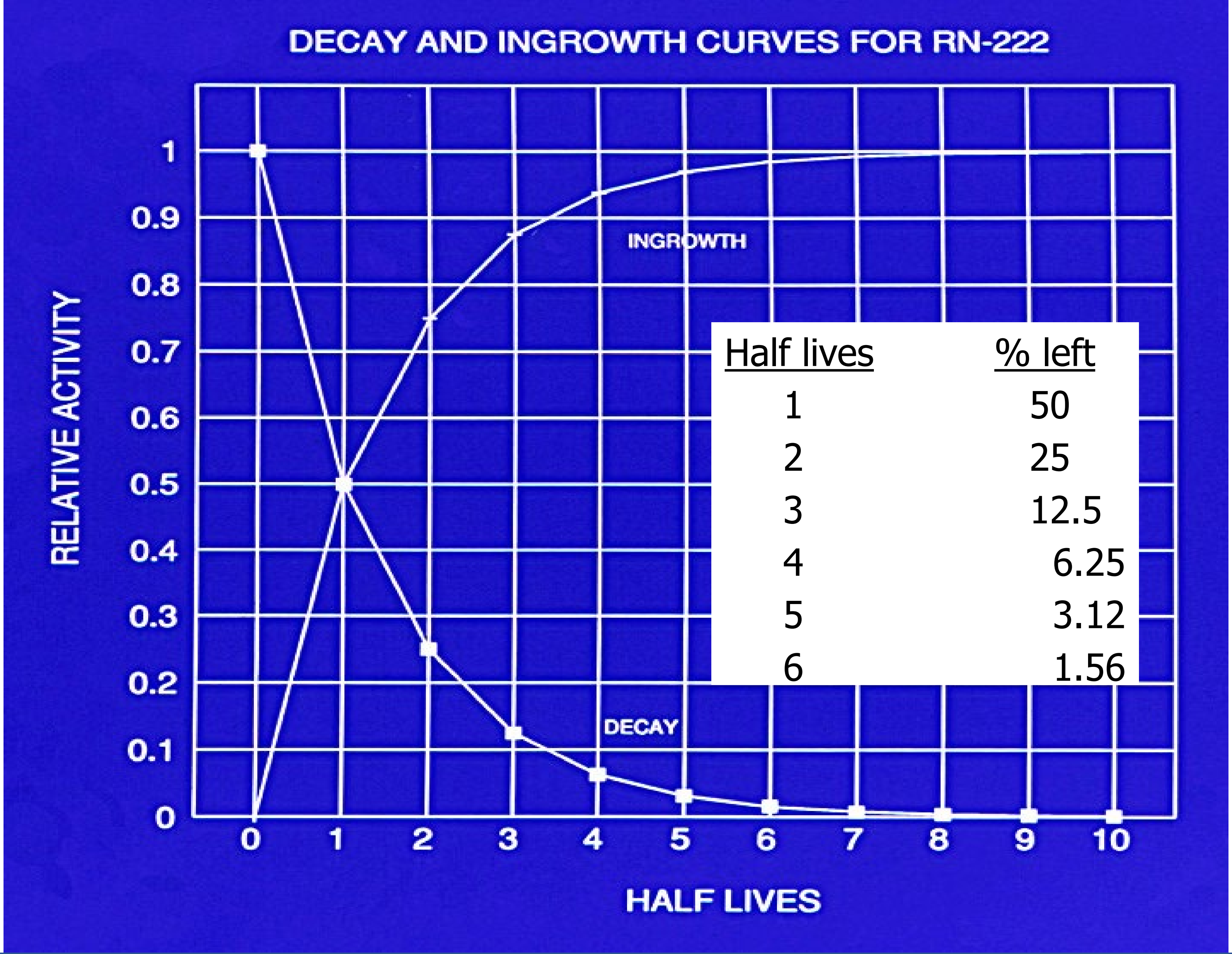

High surface to volume
Pore space and emanation


Radium-226
decay
Radon-222
Alpha Particle
^{4}He atom
(~50x faster)


2
Rn
1
R
α

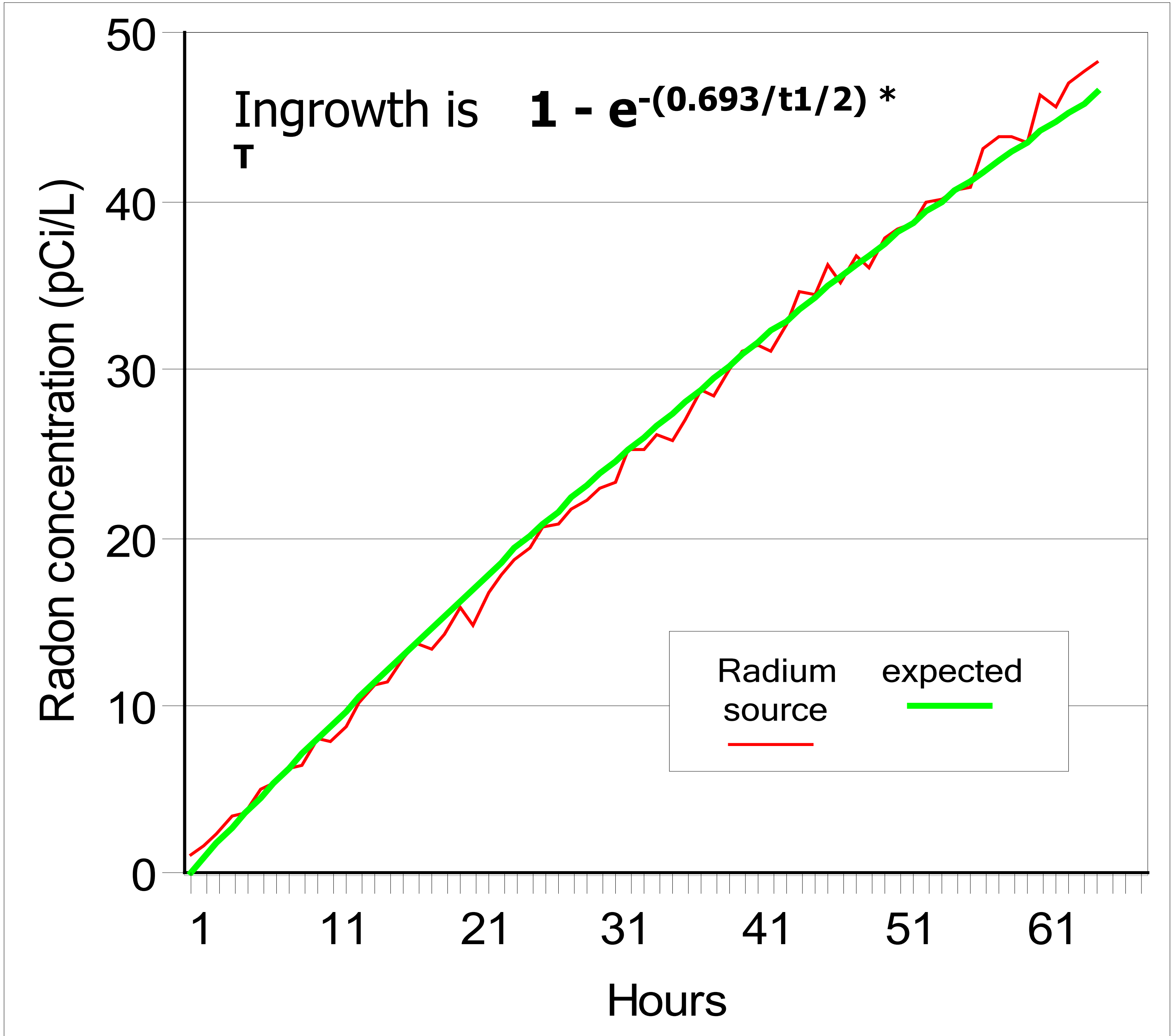


Ra-226 content
Rn-222 content
% emanation
Ra-226 or Rn-222 activity (pCi/g)
Radon emanation (%)
1
0.8
0.6
0.4
0.2
0
50%
40%
30%
20%
10%
0%
Mahoney-1
Mahoney-2
Mahoney-3
Mahoney-4
Mahoney-5
Mahoney-6
Mahoney-7
Mahoney-8
Costa-1
Costa-2
Costa-3
Costa-4
Costa -5
Costa-6
Costa-7
Costa-8
Costa-9
Costa-10
Rock sample

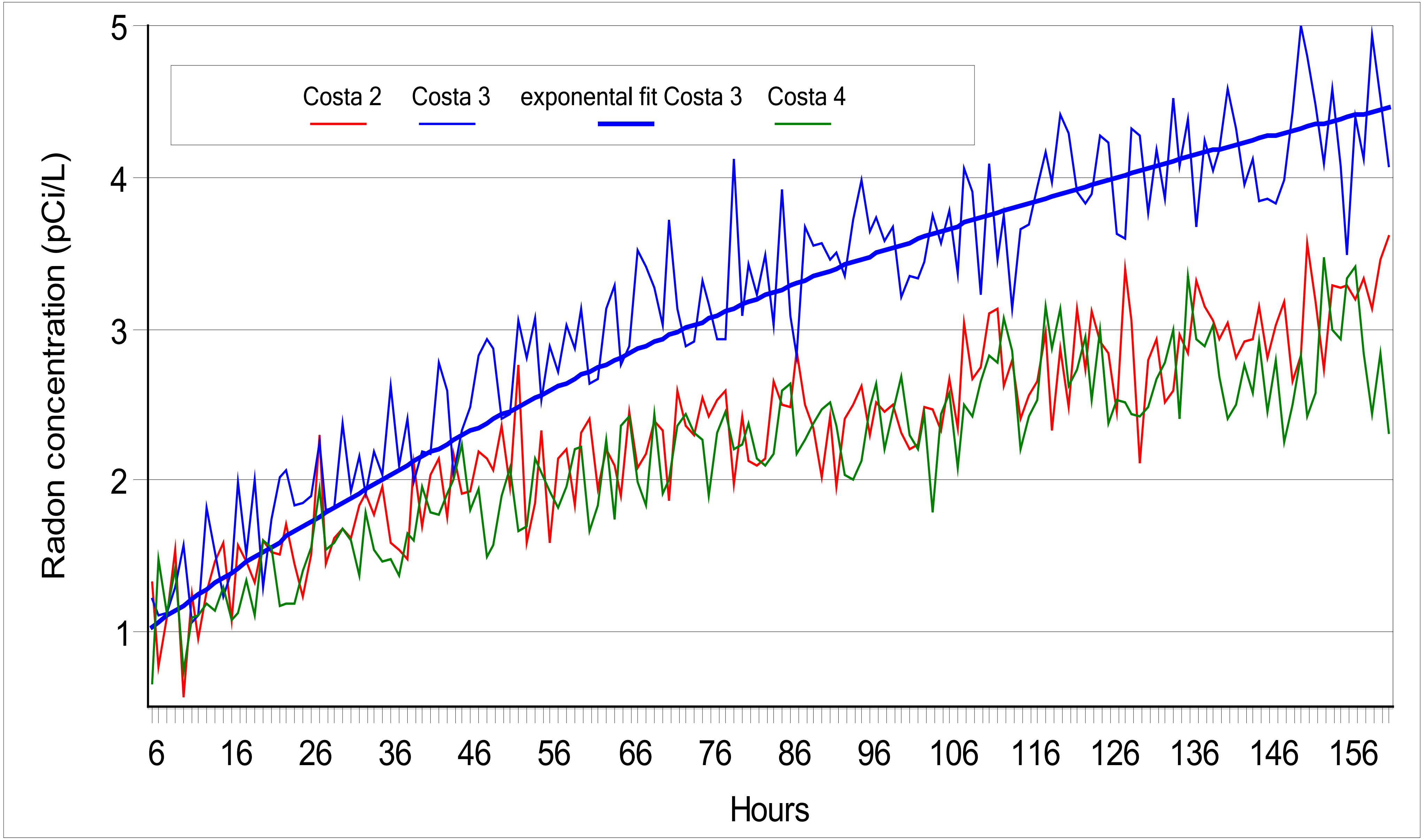


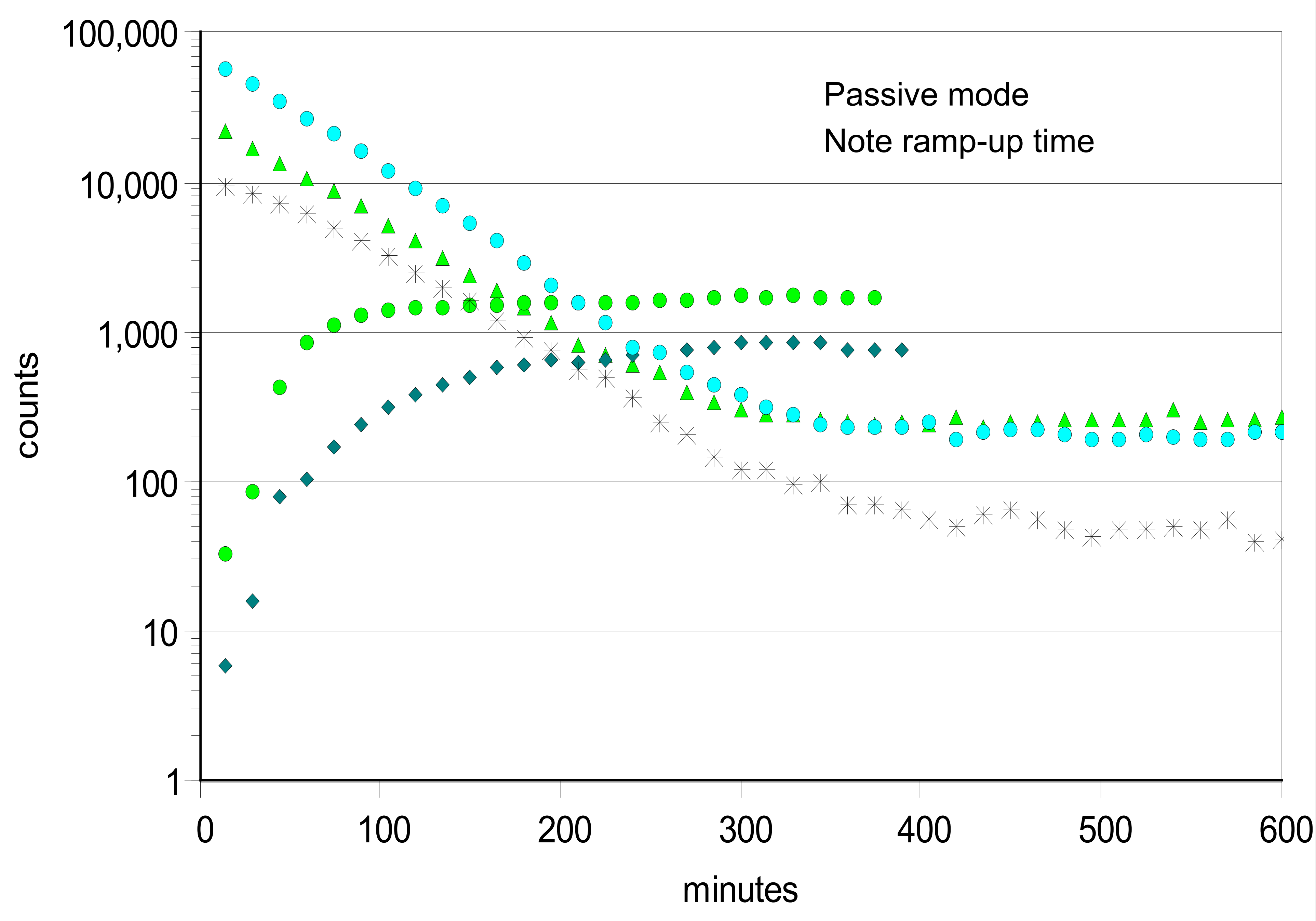
Half lives	% left
1	50
2	25
3	12.5
4	6.25
5	3.12
6	1.56

Ra-226 source in airtight box follows expected ingrowth

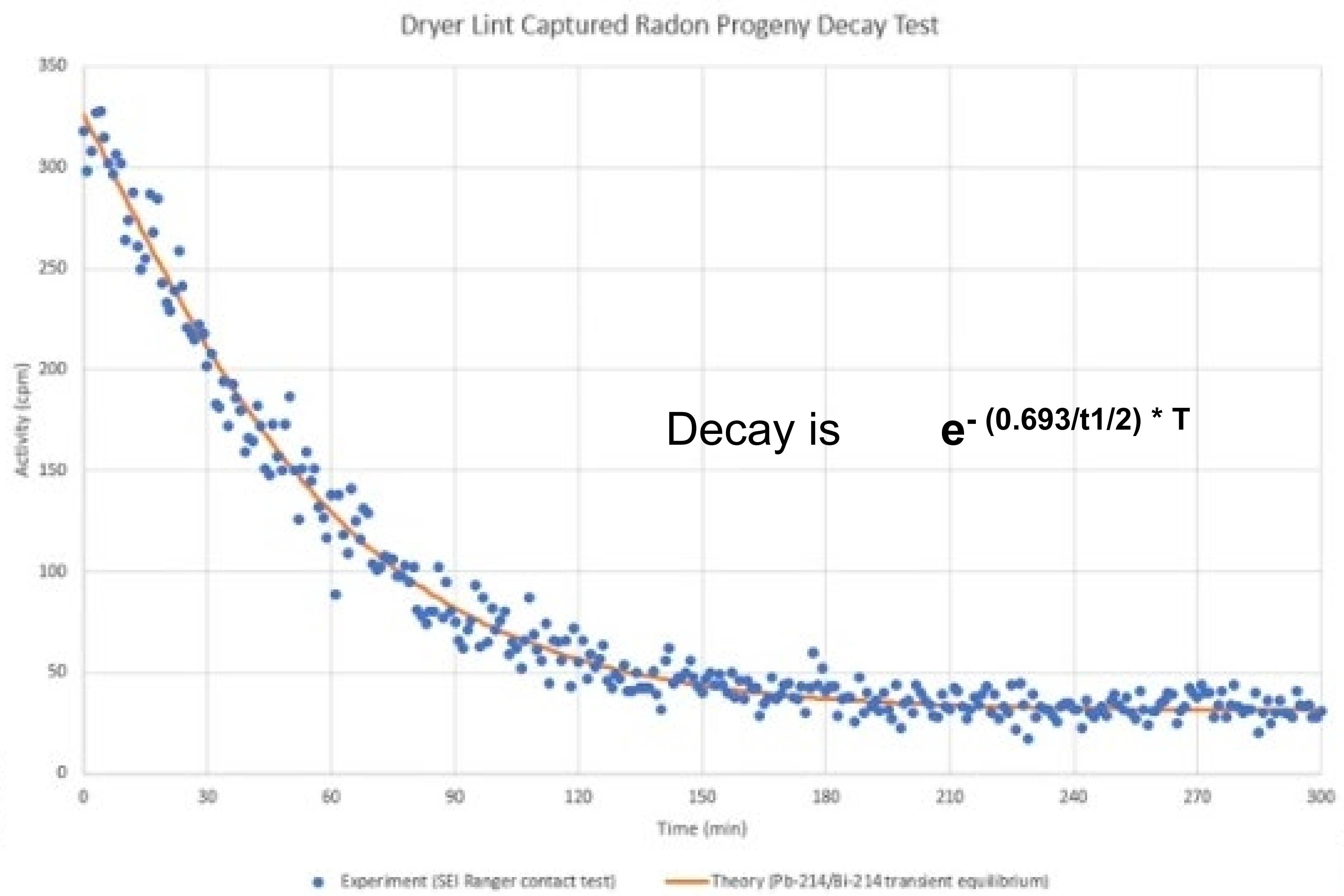


Ingrowth is $1 - e^{-(0.693/t1/2) * T}$





100,000
10,000
1,000
100
10
1
counts
0
100
200
300
400
500
600
minutes
Passive mode
Note ramp-up time



Decay is $e^{-(0.693/t1/2) * T}$

Decay time, h

Fig. 3. Comparison of time required to establish equilibrium in LS cocktails

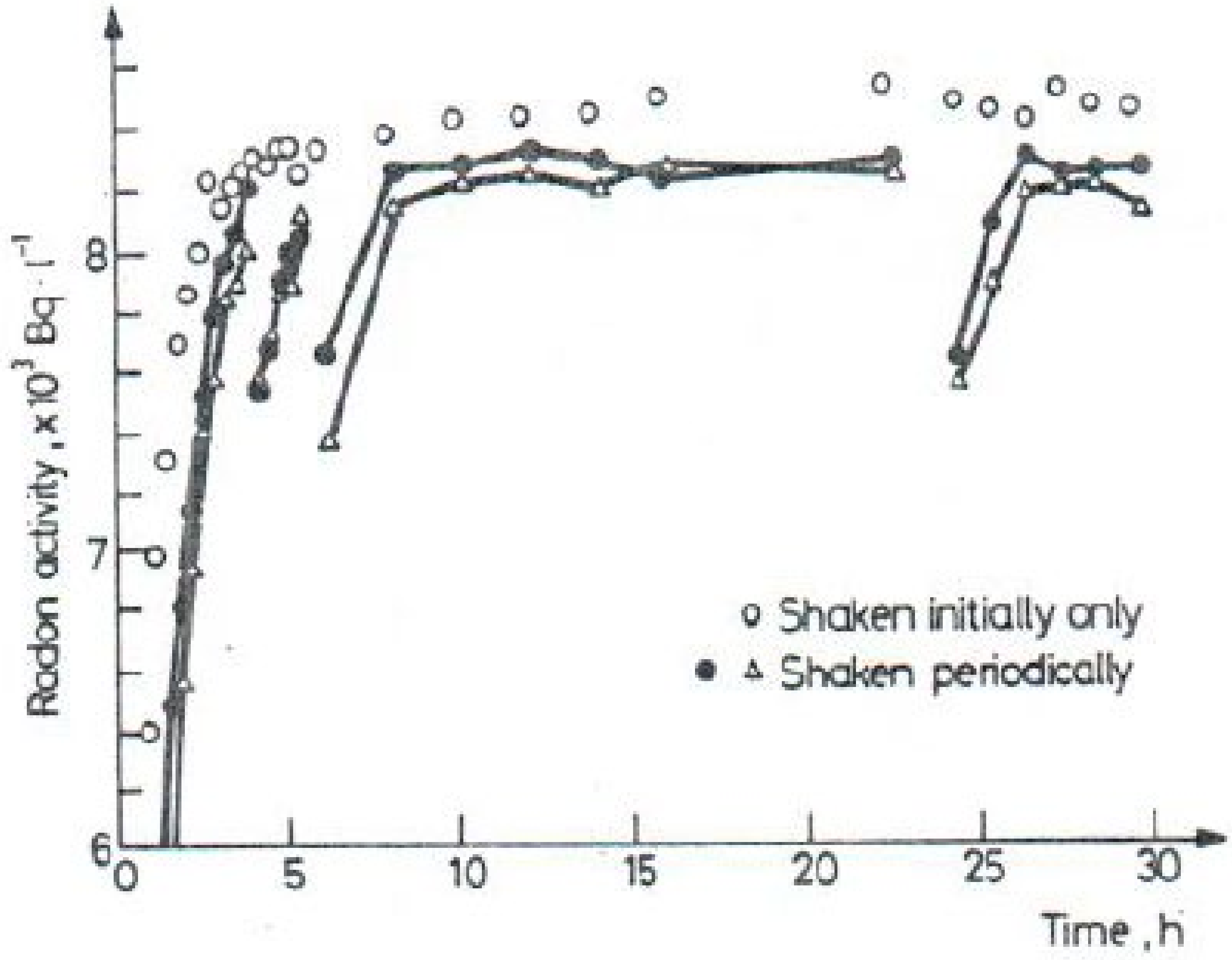


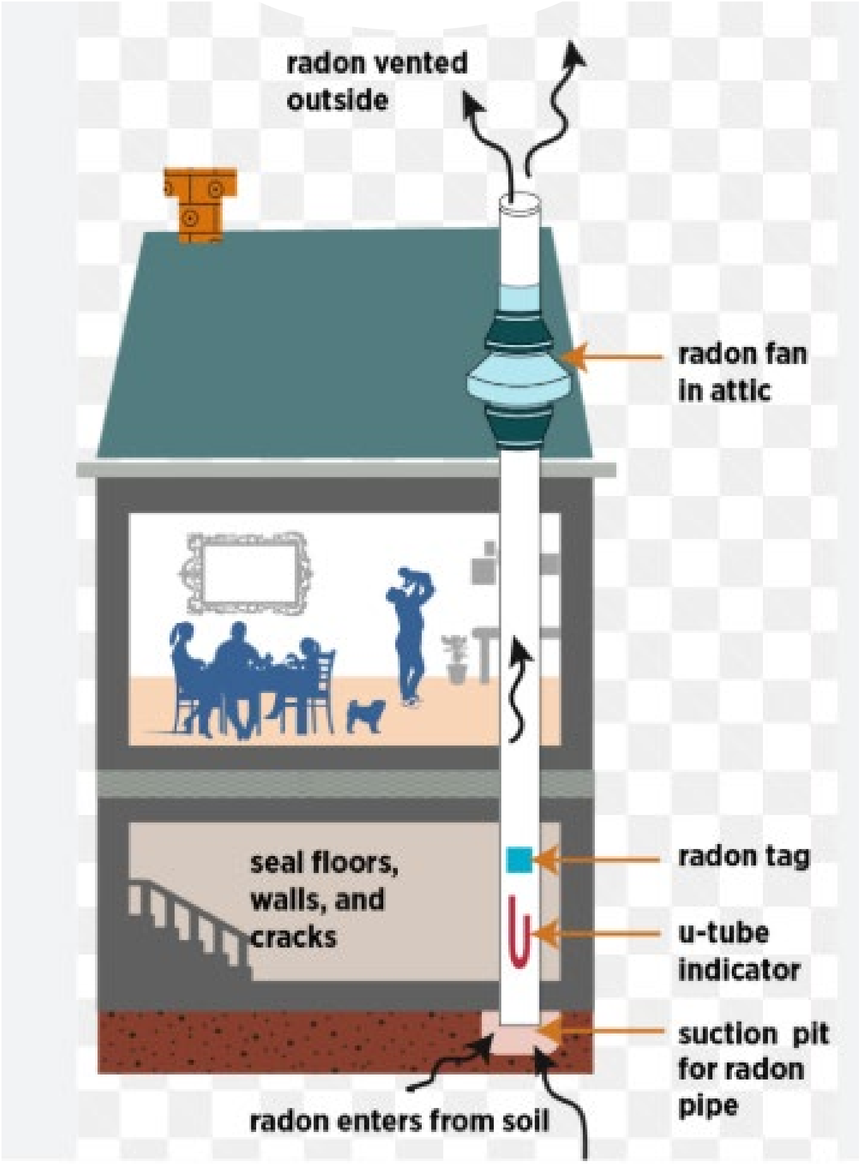
Fig. 4. Observed radon activity in LS cocktails shaken once compared with those shaken periodically

Uranium glazed tableware (e.g., Fiesta, Vistosa)

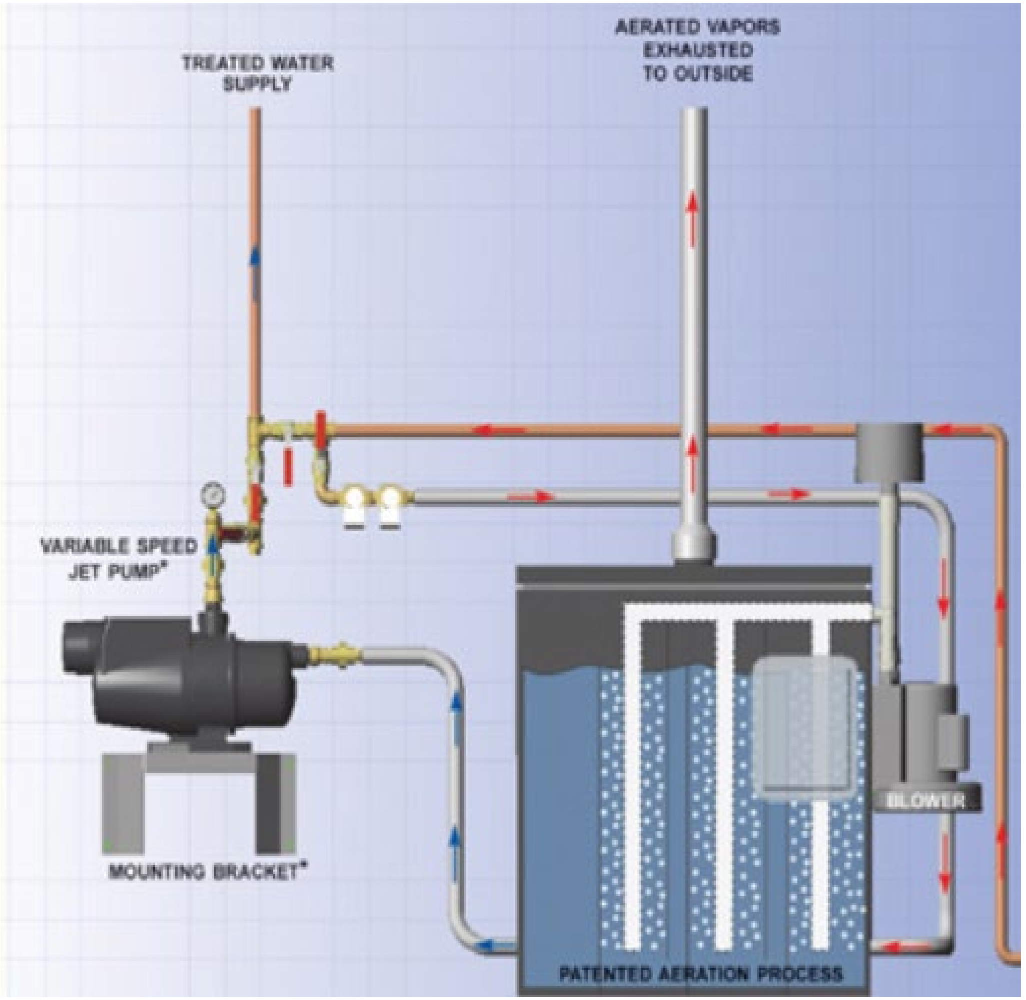
Contain Uranium but emit no radon

Different radioactive dose potential from each

Radon and RDPs



Radon only



Half-lives:

Strontium-90 is 28.8 years

Yttrium-90 (Y-90) is 64 hours

			Sr-90			
** Y-90 INGROWTH **						
Sample No.	335001	335002	335003	335004	335005	335006
count time	50	50	50	50	50	50
GROSS CTS						
GP15_00748	18214	14533	19195	16529	13813	14550
thru	24547	20264	23397	20354	19398	20369
GP15_00756	40150	35070	32738	29310	23847	24525
			33006	28923	27238	27832
date 1@ midi	02/05/13 01:29 PM	02/05/13 02:20 PM	02/05/13 05:44 PM	02/05/13 06:35 PM	02/05/13 03:21 PM	02/05/13 04:12 PM
date 2@ midi	02/06/13 12:49 PM	02/06/13 01:40 PM	02/06/13 10:41 AM	02/06/13 11:32 AM	02/06/13 02:36 PM	02/06/13 03:27 PM
date 3@ midi	02/11/13 10:20 AM	02/11/13 11:11 AM	02/08/13 01:32 PM	02/08/13 02:23 PM	02/07/13 11:47 AM	02/07/13 12:38 PM
date 4@ midpt			02/08/13 03:17 PM	02/08/13 04:08 PM	02/08/13 10:56 AM	02/08/13 11:47 AM
CERT DATE	01/21/09 12:00 PM	01/21/09 12:00 PM	01/21/09 12:00 PM	01/21/09 12:00 PM	01/21/09 12:00 PM	01/21/09 12:00 PM
DPM	1093	1093	1093	1093	1093	1093
Y SEPAR	8:35:00 AM	8:35:00 AM	8:35:00 AM	8:35:00 AM	8:35:00 AM	8:35:00 AM
SR RECOV	0.9807	0.9842	0.9806	0.9344	0.9900	0.9800
SR PPT WT	33.05	49.75	66.09	78.72	100.09	115.59
DPM*REC	1072	1076	1072	1021	1082	1071
* Y INGROW*						
count 1	0.0516	0.0603	0.0942	0.1025	0.0705	0.0790
count 2	0.2631	0.2698	0.2459	0.2528	0.2771	0.2837
count 3	0.7931	0.7950	0.5648	0.5688	0.4251	0.4303
count 4			0.5729	0.5769	0.5524	0.5565
[redacted]						
effic 1	0.3125	0.2389	0.3105	0.2727	0.2211	0.2341
effic 2	0.3201	0.2382	0.3129	0.2735	0.2252	0.2466
effic 3	0.3343	0.2447	0.3273	0.2930	0.2365	0.2554
effic 4			0.3282	0.2814	0.2381	0.2579
AVG of 3	0.3223	0.2406	0.3169	0.2797	0.2231	0.2404
STD DEV	0.0111	0.0035	0.0091	0.0115	0.0080	0.0107

Harmless Cumulative Natural Radiation Hits to the Body

2-year old: more than 60 trillion

4-year old: more than 120 trillion

6-year old: more than 180 trillion

8-year old: more than 250 trillion

10-year old: more than 300 trillion

20-year old: more than 630 trillion

Based on L.E. Feinendegen, Health Phys. 100:274–276, 2011

Natural Radioactivity in the Body of A Typical 70kg Adult Human

Nuclide	Approx. Total Mass	Disintegrations per day
Uranium isotopes	90 micrograms	95 thousand
Thorium isotopes	30 micrograms	9.5 thousand
Potassium-40	17 miligrams	380 million
Radium isotopes	31 picograms	95 thousand
Carbon-14	22 nanograms	320 million
Tritium	0.06 picograms	2 million
Polonium isotopes	0.2 picograms	3.2 million

Based on information from http://physics.isu.edu/radinf/natural.htm