RADIOLOGICAL EMERGENCY RESPONSE

Write in Your Emergency Phone Numbers

Supervisor:

Team Office:

Group Office:

Division Office:

Emergency Response Team:

Fire Department:

Hospital:

Guidelines for Control of Emergency Exposures

Use a dose limit of:	(EPA-400)
5 rem (50 mSv)	for all emergency procedures
10 rem (100 mSv)	only for protecting major property
25 rem (250 mSv)	for lifesaving or protection of large populations
> 25 rem (250 mSv)	for lifesaving or protection of large populations only by volunteers and where the risks have been evaluated

EMERGENCY RESPONSE

SWIMS for Radiological and Other Emergencies
Only under extreme radiological conditions such as external radiation greater than 100 rem / hr (1 Sv/h) or airborne radioactivity concentrations greater than 100,000 DAC would the radiological emergency take precedence over serious personnel injuries. Hazardous conditions such as atmospheres that are IDLH (Immediately Dangerous to Life or Health) would require you to implement controls to protect the emergency responders. Therefore, you would not attempt to move a seriously injured person before medical personnel arrived unless the radiological or other hazardous condition presented a greater danger to that person and yourself.

Stop or **S**ecure operations in the area. If applicable, secure the operation causing the emergency.

Warn others in the area as you are evacuating. Do not search for potentially missing personnel at this stage of the emergency.

Isolate the source of the radiation or radioactivity or other contaminant or hazard only if you understand the operation and are qualified to isolate the source.

Minimize individual exposure and contamination. Control the entry points to the area if possible.

Secure unfiltered ventilation. Evaluate the radiological or other hazardous condition and advise facility personnel on ventilation control.

HAZARD CONTROL PRIORITIES DURING MEDICAL EMERGENCIES

Immediate treatment by trained medical personnel should be sought for any serious injuries such as those involving profuse bleeding or broken bones.

The order of priority should be to protect lives, protect property, and then to control the spread of contamination.

Identifying a Major Injury

Consider the following points in determining if the injury should be handled as a major injury.

- Any head injury (from base of neck to top of head)
- Any loss of consciousness
- Any disorientation
- Any convulsion
- Any loss of sensation
- Any loss of motor function
- Limbs at abnormal angles
- Amputations
- Any burn of the face, hands, feet, or genitals (chemical, thermal, or radiation)
- Any burn larger than the palm of your hand
- Any inhalation of any abnormal substance
- Profuse bleeding
- Abnormal breathing patterns

Major Injuries Occurring in Hazardous Areas

Protect yourself - consider the magnitude of any radiation field, airborne contamination, or other hazard.

Stay with the injured person unless doing so puts you at immediate risk to life or health.

Don’t move the injured person unless there is a danger from some environmental emergency such as fire, explosion, hazardous material spill, or radiation field.

If you must move the injured person, drag them by either the hands or the feet to a safe area.

Apply First Aid Only to the extent you are trained to do so.

Secure help - yell or phone, but don’t leave the injured person unless necessary.

Send someone to meet the ambulance to guide the medical personnel to the injured person.

Prepare the area for access by the medical team.

Begin a gross hazard evaluation of the immediate area near the injured person, beginning with the injured person.

Be sure to survey any object that caused the injury.

Provide information to medical personnel about the injured person (what happened, how, when, location of phone and exits, indicate which areas on the injured person are contaminated and include contamination values).

ACUTE RADIATION EFFECTS

0 – 25 REM (0 - 0.25 Sv)

minimal decrease in white blood cell count for ~ 2 weeks

increase in risk of dying from cancer from US average risk of ~ 14 persons per 100 population to ~ 17 persons per 100 population (3 additional persons per 100 population will experience the onset of terminal cancer ~25 years after the acute exposure

> 25 REM - ≤ 100 REM (0.25 - 1 Sv)

small decrease in white blood cell count for > 2 weeks

increase in risk of dying from cancer to ~ 26 in 100

> 100 REM - ≤ 200 REM (1 - 2 Sv)

moderate decrease in white blood cell count

25% of those exposed will experience nausea within a few hours

less than 5% of those exposed require hospitalization

increase in risk of dying from cancer to ~ 38 in 100

> 200 REM - ≤ 600 REM (2 - 6 Sv)

major decrease in white blood cell count

~ 100% of those exposed will experience nausea within a few hours

appearance of bruises on skin (purpura); pneumonia symptoms; hair loss; 90% of those exposed require hospitalization; decrease in thinking ability for ~ 2 weeks; increase in risk of dying from cancer to ~ 74 in 100

600 REM - ≤800 REM (6 – 8 Sv)

all of the above symptoms will be present

100% of those exposed will require hospitalization

~ 100% of those exposed will die within a few weeks without medical treatment; increase in risk of dying from cancer to ~98 in 100

800 REM - ≤ 2000 REM (8 – 20 Sv)

All of the above symptoms will be present

Diarrhea, fever, electrolytes imbalance, GI tract and respiratory system failure

100% of those exposed will be incapacitated within hours

Very few of those exposed will survive

>2000 REM (>20 Sv)

100% mortality within a few days

DEFINITIONS

Acute	any dose in a short period of time
Chronic	any dose in a long period of time
Somatic	effects in the exposed individual
Genetic	effects in the offspring of the exposed individual
Teratogenic	effects in the exposed unborn embryo/fetus
Stochastic	effects for which a probability exists and increases with increasing dose
Non-Stochastic (deterministic)	effects for which a threshold exists - effects do not occur below the threshold
(examples;	cataracts, erythema, epilation, acute radiation syndrome)

TERMS

Lymphocyte - white blood cells
Leukopenia - abnormally low white blood cell count
Purpura - purple discoloration of skin caused by blood bleeding into the skin tissue
Pneumonia - inflammation of lung tissue, accompanied by fever, chills, cough, and difficulty in breathing
Hematopoietic – decrease in the formation of blood cells
Ataxia - inability to coordinate voluntary muscular movements

BEIR V 1990 800 excess deaths per 100,000 persons at 10 rem
(4,000 Hiroshima survivors in excess of 50 rem dose had an extra 300 incidences of cancer)
(~ 7500 excess deaths per 100,000 at 50 rem)
(~ 1500 excess deaths per 100,000 at 10 rem)

TABLE OF THE ELEMENTS

Z			Density g/cc	Z			Density g/cc
1	Hydrogen	H	9E-5	31	Gallium	Ga	5.9
2	Helium	He	1.8E-4	32	Germanium	Ge	5.32
3	Lithium	Li	0.534	33	Arsenic	As	5.727
4	Beryllium	Be	1.848	34	Selenium	Se	4.5
5	Boron	B	2.37	35	Bromine	Br	0.0031
6	Carbon	C	2.05	36	Krypton	Kr	0.0037
7	Nitrogen	N	0.00125	37	Rubidium	Rb	1.532
8	Oxygen	O	0.00143	38	Strontium	Sr	2.54
9	Fluorine	F	0.0017	39	Yttrium	Y	4.47
10	Neon	Ne	0.0009	40	Zirconium	Zr	6.06
11	Sodium	Na	0.97	41	Niobium	Nb	8.57
12	Magnesium	Mg	1.738	42	Molybdenum	Mo	10.22
13	Aluminum	Al	2.6989	43	Technetium	Tc	11.5
14	Silicon	Si	2.33	44	Ruthenium	Ru	12.2
15	Phosphorus	P	2.2	45	Rhodium	Rh	12.41
16	Sulfur	S	2.0	46	Palladium	Pd	12.02
17	Chlorine	Cl	0.002165	47	Silver	Ag	10.5
18	Argon	Ar	0.0018	48	Cadmium	Cd	8.65
19	Potassium	K	0.862	49	Indium	In	7.31
20	Calcium	Ca	1.55	50	Tin	Sn	6.5
21	Scandium	Sc	2.989	51	Antimony	Sb	6.618
22	Titanium	Ti	4.54	52	Tellurium	Te	2.64
23	Vanadium	V	6.11	53	Iodine	I	4.93
24	Chromium	Cr	7.19	54	Xenon	Xe	0.0059
25	Magnesium	Mn	7.43	55	Cesium	Cs	1.873
26	Iron	Fe	7.87	56	Barium	Ba	3.51
27	Cobalt	Co	8.9	57	Lanthanum	La	6.15
28	Nickel	Ni	8.9	58	Cerium	Ce	6.67
29	Copper	Cu	8.96	59	Praseodymium	Pr	6.773
30	Zinc	Zn	7.13	60	Neodymium	Nd	7.008

Z			Density g/cc
61	Promethium	Pm	7.264
62	Samarium	Sm	7.54
63	Europium	Eu	5.244
64	Gadolinium	Gd	7.90
65	Terbium	Tb	8.27
66	Dysprosium	Dy	8.54
67	Holmium	Ho	8.795
68	Erbium	Er	9.066
69	Thulium	Tm	9.321
70	Ytterbium	Yb	6.98
71	Lutetium	Lu	9.84
72	Hafnium	Hf	13.31
73	Tantalum	Ta	16.6
74	Tungsten	W	19.3
75	Rhenium	Re	21.02
76	Osmium	Os	22.57
77	Iridium	Ir	22.42
78	Platinum	Pt	21.45
79	Gold	Au	19.32
80	Mercury	Hg	13.546
81	Thallium	Tl	11.85
82	Lead	Pb	11.35
83	Bismuth	Bi	9.747
84	Polonium	Po	9.32
85	Astatine	At	~ 15
86	Radon	Rn	0.0097
87	Francium	Fr	~ 15
88	Radium	Ra	5.5
89	Actinium	Ac	10.07
90	Thorium	Th	11.70
91	Protactinium	Pa	15.37
92	Uranium	U	16.95
93	Neptunium	Np	20.25
94	Plutonium	Pu	19.84
95	Americium	Am	13.67
96	Curium	Cm	13.51
97	Berkelium	Bk	14.78
98	Californium	Cf	15.1
99	Einsteinium	Es	
100	Fermium	Fm	
101	Mendelevium	Mv	
102	Nobelium	No	
103	Lawrencium	Lr	
104	Rutherfordium	Rf	
105	Hahnium	Ha	
106	Seaborgium	Sg	
107	Bohrium	Bh	
108	Hassium	Hs	
109	Meitnerium	Mt	
110	Darmstadtium	Ds	
111	Roentgenium	Rg	
112	Copernicium	Cn	
113	Nihonium	Nh	
114	Flerovium	Fl	
115	Moscovium	Mc	
116	Livermorium	Lv	
117	Tennessee	Ts	
118	Oganesson	Og	

Relative Locations of Products of Nuclear Processes

			^{3}He in	α in
	β$^-$ out	p in	d in	t in
	η out	Original Nucleus	η in	
t out	d out	p out	β$^+$ out ε	
α out	^{3}He out			

η neutron p proton d deuteron
t triton (^{3}H) ^{3}He α alpha β$^-$ beta
β$^+$ positron ε electron capture

Use this chart along with the Table of the Elements to determine the progeny (and ancestor) of an isotope. For example; we know Pu^{238} is an alpha emitter. The alpha decay mode tells us the mass # decreases by 4 (238 goes to 234) and the Z # decreases by two (94 goes to 92). The element with a Z # of 92 is Uranium. Pu^{238} decays to U^{234}.

$_ZX^A$ Z = atomic # (number of protons)
X = element
A = mass # (number of protons and neutrons)

Decay Modes

Alpha $_ZX^A \rightarrow {}_{Z-2}X^{A-4} + \alpha$
Beta Minus $_ZX^A \rightarrow {}_{Z+1}X^{A} + \beta^-$
Beta Plus (Positron) $_ZX^A \rightarrow {}_{Z-1}X^{A} + \beta^+$
Electron Capture $_ZX^A \rightarrow {}_{Z-1}X^{A}$

Radioactive Decay Calculation

$A_t = A_0 e^{-\lambda t}$ $A_0 = A_t / e^{-\lambda t}$

$t = \ln(A_t / A_0) / -\lambda$ half-life $= -t \times 0.693 / \ln(A_t / A_0)$

Where; A_t is the activity at the end of time 't'

A_0 is the activity at the beginning

λ is 0.693 divided by the half-life

t is the decay time

Example: What is the % activity of Co-60 remaining 12 years after it was produced ?

Co-60 half-life is 5.271 years

$A_t = A_0 e^{-\lambda t}$

$A_t = 100e^{-0.693/5.271 \times 12} = 100e^{-1.578} = 100 \times 0.206 = 20.6\%$

Calculating the Activity of Progeny

$$A_{dt} = A_{p(0)} \times \lambda_d / (\lambda_d - \lambda_p) \times (e^{-\lambda pt} - e^{-\lambda dt}) + A_{d(0)} e^{-\lambda dt}$$

$A_{d(t)}$ is the activity of the progeny at the end of time 't'

$A_{p(0)}$ is the activity of the parent at the beginning

$A_{d(0)}$ is the activity of the progeny at the beginning

Example: What is the activity of Tc-99m 14 hours after its parent Mo-99 was produced ?

Mo-99 half-life is 66.02 hours, initial activity is 100 uCi

Tc-99m half-life is 6.0058 hours, initial activity is 0 uCi

$A_{dt} = 100$ uCi $\times 0.693/6.0058/(0.693/6.0058-0.693/66.02) \times$
$(e^{-0.693/66.02 \times 14} - e^{-0.693/6.0058 \times 14}) + A_{d(0)} e^{-\lambda dt}$

$A_{dt} = 100$uCi $\times 1.149 \times (e^{-0.1470} - e^{-1.615}) = 76.3$uCi Tc-99m

Note: IF the progeny has activity at time '0', the decrease in activity of the progeny must be accounted for with an additional calculation.

COMMONLY ENCOUNTERED RADIONUCLIDES

Only the most abundant energies are listed. ‘S’ is “Stable’

	Progeny		**kev and % abundance**
H^3	He^3	β^-	18.6 (100)
12.32y	S		
Be^7	Li^7	EC	
53.44d	S	γ	478 (10.42)
C^{14}	N^{14}	β^-	157 (100)
5730y	S		
O^{15}	N^{15}	β^+	1732 (99.9)
122.24s	S	γ	511 (200)
N^{16}	O^{16}	β^-	3302 (4.9), 4288 (68), 10418 (26)
7.13s	S	γ	6129 (69), 7115 (5)
F^{18}	O^{18}	β^+	634 (96.73)
109.74m	S	γ	511 194)
Na^{22}	Ne^{22}	β^+	546 (89.84)
2.602y	S	γ	1275 (99.94)
		Ne x-rays	1 (0.12)
Na^{24}	Mg^{24}	β^-	1390 (99.935)
15.00h	S	γ	1369 (99.9991), 2754 (99.862)
Al^{26}	Mg^{26}	β^+	1174 (81.81)
7.17E5y	S	γ	130 (2.5), 1809 (99.96), 2938 (0.24)
		Mg x-rays	1 (0.44)
P^{32}	S^{32}	β^-	1710 (100)
14.29d	S		
Cl^{36}	Ar^{36}	β^-	710 (99.0)
3.01E5y	S		

K^{40}	Ca^{40}	β^-	1312 (89.33)
1.27E9y	S		
	Ar^{40}	EC	
	S	γ	1461 (10.67)
		Ar x-rays	3 (0.94)
Ar^{41}	K^{41}	β^-	1198 (99.17), 2492 (0.78)
1.827h	S	γ	1294 (99.16)
K^{42}	Ca^{42}	β^-	1684(0.32), 1996(17.5), 3521(82.1)
12.36h	S	γ	313(0.3), 1525 (18)
K^{43}	Ca^{43}	β^-	422 (2.24), 827 (92.2), 1224 (3.6)
22.6h	S	γ	373 (87.3), 397 (11.43), 593 (11.0), 617 (80.5)
Sc^{46}	Ti^{46}	β^-	357 (99.996)
83.83d	S	γ	889 (99.983), 1121 (99.987)
Sc^{47}	Ti^{47}	β^-	441 (68), 601 (32)
3.351d	S	γ	159 (68)
Sc^{48}	Ti^{48}	β^-	482 (10.01), 657 (89.99)
43.7h	S	γ	984 (100), 1037 (97.5), 1312 (100)
V^{48}	Ti^{48}	β^+	697 (50.1)
16.238d	S	γ	944 (7.76), 984 (100), 1312 (97.5)
		Ti x-rays	0.45 (0.15), 5 (9.74)
Cr^{51}	V^{51}	EC	
27.704d	S	γ	320 (9.83)
		V x-rays	1 (0.33), 5 (22.31)
Mn^{52}	Cr^{52}	β^+	575 (29.4)
5.591d	S	γ	511(67), 744(82), 935(84), 1434(100)
		Cr x-rays	1 (0.26), 5 (15.5), 6 (2.94)
Mn^{54}	Cr^{54}	EC	
312.5d	S	γ	835 (99.975
		Cr x-rays	1 (0.37), 5 (22.13), 6 (2.94)

Fe^{55}	Mn^{55}	EC	
2.7y	S	Mn x-rays	1 (0.42), 6 (24.5), 6 (3.29)
Mn^{56}	Fe^{56}	β^-	736 (14.6), 1038 (27.8), 2849 (56.2)
2.5789h	S	γ	847 (98.9), 1811 (27.2), 2113 (14.3)
Co^{56}	Fe^{56}	β^+	423 (1.05), 1461 (18.7)
78.76d	S	γ	847 (99.958), 10381 (14.03), 1238 (67), 1771 (15.5), 2598 (16.9)
		Fe x-rays	1 (0.34), 6 (21.83), 7 (2.92)
Ni^{57}	Co^{57}	β^+	463 (0.87), 716 (5.7), 843 (33.1)
35.60h	S	γ	127 (12.9), 1378 (77.9), 1919 (14.7)
		Co x-rays	1 (0.29), 7 (18.1), 8 (2.46)
Co^{57}	Fe^{57}	EC	
270.9d	S	γ	14 (9.54), 122 (85.51), 136 (10.6)
		Fe x-rays	1 (0.8), 6 (49.4), 7 (6.62)
Co^{58}	Fe^{58}	β^+	475 (14.93)
70.8d	S	γ	811 (99.4), 864 (0.74), 1675 (0.54)
		Fe x-rays	0.7 (0.36), 6 (23.18), 7 (3.1)
Ni^{59}	Co^{59}	EC	
7.5E4y	S	Co x-rays	1 (0.47), 7 (29.8)
Fe^{59}	Co^{59}	β^-	131 (1.37), 273 (45.2), 466 (53.1)
44.53d	S	γ	192 (3.11), 1099 (56.5). 1292 (43.2)
Co^{60}	Ni^{60}	β^-	318 (100)
5.271y	S	γ	1173 (100), 1332 (100)
Cu^{62}	Ni^{62}	β^-	1754 (0.132), 2927 (97.59)
9.673m	S	γ	876 (0.148), 1173 (0.336)
		Ni x-rays	7 (0.7)
Ni^{63}	Cu^{63}	β^-	66.98 (100)
98.7y	S		

Zn^{65}	Cu^{65}	EC	
243.66d	S	β^+	330 (1.415)
		γ	1116 (50.75)
		Cu x-rays	1 (0.57), 8 (34.1), 9 (4.61)
Ni^{65}	Cu^{65}	β^-	2130 (100)
2.520h	S	γ	368 (4.5), 1115 (16), 1481 (25)
Ge^{68}	Ga^{68}	EC	
270.9d		Ga x-rays	1 (0.67), 9 (38.7), 10 (5.46)
Ga^{68}	Zn^{68}	β^+	822 (0.012), 1899 (0.8794)
67.7m	S	γ	1077 (0.032), 1883 (0.0014)
		Zn x-rays	9 (0.049), 10 (0.00579)
As^{74}	Se^{74}	β^-	1353 (34.0)
17.77d	S	γ	634 (15.4)
	Ge^{74}	EC	
	S	β^+	1540 (66.0)
		γ	596 (59.9), 608 (0.55), 1204 (0.287)
		Ge x-rays	1 (0.26), 10 (15), 11 (2.22)
Se^{75}	As^{75}	EC	
119.78d	S	γ	136 (59.2), 265 (59.8), 280 (25.2)
		As x-rays	1 (0.9), 11 (47.5), 12 (7.3)
Kr^{85}	Rb^{85}	β^-	173 (0.437), 687 (99.563)
10.72y	S	γ	514 (0.434)
Rb^{88}	Sr^{88}	β^-	2581 (13.3), 3479 (4.1), 5315 (7.8)
17.772m	S	γ	898 (14), 1836 (21.4), 2678 (1.98)
Rb^{89}	Sr^{89}	β^-	1275 (33), 2223 (34), 4503 (25)
15.15m		γ	1031 (58), 1248 (42), 2196 (13.3)
Sr^{89}	Y^{89}	β^-	1491 (99.985)
50.53m	S	γ	av. 909 (0.02)
Sr^{90}	Y^{90}	β^-	546 (100)
28.9y			
Y^{90}	Zr^{90}	β^-	519 (0.0115), 2284 (99.9885)
64.00h	S		

Nb^{94}	Mo^{94}	β^-	471 (100)
20.3E4y	S	γ	703 (100), 871 (100)
Zr^{95}	Nb^{95}	β^-	366 (55.4), 399 (43.7), 887 (0.78)
63.98d		γ	724 (43.7), 757 (55.3)
Nb^{95}	Mo^{95}	β^-	160 (99.97)
34.991d	S	γ	766 (100)
Mo^{99}	decays 88.6% of the time to Tc^{99m} & 11.4% to Tc^{99}		
66.0h		β^-	436 (17.3), 848 (1.36), 1214 (82.7)
		γ	181 (6.2), 740 (12.8), 778 (4.5)
		Tc x-rays	2 (0.2), 18 (2.63), 21 (0.52)
Tc^{99m}	Tc^{99}	γ	141 (89.07)
6.0058h		Tc x-rays	2 (0.48), 18 (6.1), 21 (1.2)
Tc^{99}	Ru^{99}	β^-	294 (99.998)
2.13E5y	S		
Ru^{106}	Rh^{106}	β^-	39 (100)
371.8d			
Rh^{106}	Pd^{106}	β^-	1979(1.77), 2410(10.6), 3541(86.8)
29.9s	S	γ	616(0.75), 62 (9.93), 873(0.439), 1050(1.56), 1128(0.404), 1562(0.163)
Cd^{109}	Ag^{109}	EC	
1.264y	S	γ	88.03 (100)
		Ag x-rays	11.28 (12), 12.34 (13)
I^{125}	Te^{125}	EC	
60.1d	S	γ	35 (6.49)
		Te x-rays	4 (15), 27 (112.2), 31 (25.4)
I^{126}	Xe^{126}	β^-	1258 (47.3)
12.928d	S	γ	389 (32.1), 491 (2.43), 754 (3.7)
		Xe x-rays	29 (0.115), 30 (0.213)
	Te^{126}	β+	1132 (52.7)
	S	Te x-rays	4 (4.8), 27 (36.4), 31 (8.2)
I^{129}	Xe^{129}	β^-	194 (100)
1.57E7y	S	γ	40 (7.52)
		Xe x-rays	4(12), 29(29.71), 30(55), 34(19.5)

I^{131} 8.025d	Xe^{131} S	β^-	248 (2.1), 334 (7.4), 606 (89.3)
		γ	80 (2.5), 284 (6.05), 364 (81.2), 637 (7.26), 723 (1.8)
		Xe x-rays	4 (0.6), 29 (1.3), 30 (2.5), 34 (0.5)
I^{133} 20.8h	Xe^{133} 5.248d	β^-	371 (1.24), 460 (3.75), 521 (3.12), 882 (4.16), 1013(1.81), 1227(83.42), 1524 (1.07)
		γ	511 (1.81), 530 (86.3), 707 (1.49), 856(1.23), 875(4.47), 1236(1.49), 1298(2.33)
		Xe x-rays	29 (0.151), 30 (0.281)
	Cs^{133} S	β^-	267 (0.69), 346 (99.3)
		γ	530 (86.3), 707 (1.49), 856 (1.23), 875 (4.47), 1236 (1.49), 1298 (2.33)
		Cs x-rays	81 (37)
Ba^{133} 10.518y	Cs^{133} S	EC	
		γ	53 (2.14), 80 (35.55), 276 (6.9), 303 (17.8), 356 (60), 384 (8.7)
		Cs x-rays	4 (17), 31 (97.6), 35 (22.8)
I^{134} 52.6m	Xe^{134} S	β^-	1280(32.5), 1560(16.3), 1800(11.2), 2420 (11.5)
		γ	847 (95.41), 884 (65.3), 1073 (15.3)
		Xe x-rays	4(0.17), 29(0.43), 30(0.8), 34(0.3)
I^{135} 6.583h	Xe^{135} 9.139h	β^-	300 (1.08), 340 (0.91), 350 (1.39), 460 (4.73), 480 (7.33), 620 (1.57), 670 (1.10), 740 (7.9), 920 (8.7), 1030 (21.8), 1150 (7.9), 1250 (7.4), 1450 (23.6), 1580 (1.2), 2180 (1.9)
		γ	1132 (22.5), 1260 (28.6), 1678 (9.5)
		Xe x-rays	30 (0.127)
	Cs^{135} 2.31E6y	β^-	551 (3.13), 751 (0.59), 909 (96.1)
		γ	158 (0.29), 249 (89.9), 358 (0.22), 408 (0.36), 608 (2.89)
		Cs x-rays	4 (0.66), 31 (4.13), 35 (0.96)
	Ba^{135} S	β^-	269 (100)
		γ	268 (16.0)
		Ba x-rays	4 (8.6), 32 (43.6), 36 (10.3)

Cs^{137}	Ba^{137m}	β^-	512 (94.6), 1173 (5.4)
30.187y	2.552m		
	Ba^{137}	IT	
	S	γ	662 (89.98)
		Ba x-rays	4 (1), 32 (5.89), 36 (1.39)
Ba^{140}	La^{140}	β^-	454 (26), 991 (37.4), 1005 (22)
12.75d	1.68d	γ	30 (14), 163 (6.7), 537 (25)
		La x-rays	5 (15), 33 (1.51), 38 (0.36)
	Ce^{140}	β^-	1239 (11.11), 1348 (44.5), 1677 (20.7)
	S	γ	329 (20.5), 487 (45.5), 816 (23.5)
		Ce x-rays	5 (0.25), 34 (0.47), 35 (0.9), 39 (0.9)
Gd^{148}	Sm^{144}	α	3180 (100)
74.52y	S		
Ir^{192}	Pt^{192}	β^-	256 (5.65), 536 (41.4), 672 (48.3)
73.83d	S	γ	296(29.02), 308(29.68), 317(82.85), 468 (48.1), 589 (4.57), 604 (8.20), 612 (5.34)
		Pt x-rays	9 (4.1), 65 (2.6), 67 (4.5), 76 (1.97)
	Os^{192}	EC (4.69)	
	S	Os x-rays	9(1.46), 61(1.1), 63(1.96), 71(0.8)
Tl^{204}	Pb^{204m}	β^-	763 (97.42)
3.779y	66.9m		
	Hg^{204}	EC (2.58)	
	S	Hg x-rays	10(0.8), 69(0.4), 71(0.7), 80(0.3)
	Pb^{204}	IT	
	S	γ	375 (94.11), 899 (99.2), 912 (91.1)
		Pb x-rays	11(4.9), 73(2.8), 75(4.36), 85(1.94)

Pb-208 (S), Tl-208, Po-212, Bi-212, Pb-212, Po-216, Rn-220, Ra-224, Th-228, Ac-228, Ra-228, Th-232 are in the Thorium-232 decay chain.

Pb-206 (S), Tl-206, Po-210, Bi-210, Pb-210, Tl-210, Po-214, Bi-214, Pb-214, At-218, Po-218, Rn-222, Ra-226, Th-230, U-234, Pa-234, Pa-234m, Th-234, U-238 are in the Uranium-238 decay chain.

Bi-209 (S), Tl-209, Pb-209, Po-213, Bi-213, At-217, Fr-221, Ac-225, Ra-225, Th-229, U-233, Pa-233, U-237, Np-237, Am-241, Pu-241 are in the Neptunium (4n+1) decay chain.

Pb-207 (S), Tl-207, Po-211, Bi-211, Pb-211, At-215, Po-215, Rn-219, Ra-223, Fr-223, Th-227, Ac-227, Pa-231, Th-231, U-235 are in the Actinium (4n+3) decay chain.

Pu^{236}	U^{232}	α	5614 (0.2), 5722 (31.8), 5770 (68.1)
2.851y		γ	av. 61 (0.08)
		U x-rays 14 (13)	
U^{232}	Th^{228}	α	5414 (100)
68.81y			
Pu^{242}	U^{238}	α	4984 (100)
3.742E5y		U x-rays 14 (9.1)	
Cm^{242}	Pu^{238}	α	6070 (25.9), 6113 (74.1)
162.85d		γ	av. 59 (0.04)
		Pu x-rays 14 (11.5)	
Pu^{238}	U^{234}	α	5358 (0.1), 5456 (29.0), 5499 (70.9)
87.84y		γ	43 (0.04), 100 (0.007), 153 (0.0009)
		U x-rays 14 (4.0)	
Am^{243}	Np^{239}	α	5181 (1), 5234 (10.6), 5275 (87.9)
7.388E3y		γ	43 (5.5), 75 (66), 118 (0.55)
		Np x-rays 14 (39)	
Np^{239}	Pu^{239}	β^-	330 (35.7), 391 (7.1), 436 (52)
2.3565d		γ	106 (22.7), 228 (10.7), 278 (14.1)
		Pu x-rays 14 (62), 100 (14.7), 104 (23.7), 117 (11.1)	
Pu^{239}	U^{235}	α	5105(11.5), 5143(15.1), 5155(73.3)
24,125y		γ	52(0.02), 129(0.0062), 375(0.0015), 414 (0.0015)
		U x-rays 14 (4.4)	
Cm^{244}	Pu^{240}	α	5763 (23.6), 5805 (76.4)
18.11y		γ	av. 57 (0.03)
		Pu x-rays 14 (10.3)	

Pu^{240}	U^{236}	α	5123 (26.4), 5168 (73.5)
6567.1y		γ	av. 54 (0.05)
		U x-rays 14(11)	
Bk^{249}	Cf^{249}	β^-	124 (100)
320d			
Cf^{249}	Cm^{245}	α	5760(3.66), 5814(84.4), 5946(4)
350.6y		γ	253 (2.7), 333 (15.5), 388 (66)
		Cm x-rays 15(30), 105 (2.19), 109 (3.5), 123 (1.66)	
Cm^{245}	Pu^{241}	α	5392(5.0), 5451(93.2), 5580(0.8)
8.56E3y		Pu x-rays 42 (38.2), 133 (34.7), 175 (61)	
Cf^{252}	Cm^{248}	α	5977(0.2), 6076(15.2), 6118(81.6)
2.639y		γ	av. 68 (0.03)
		Cm x-rays 15 (7.3)	
		spontaneous fission (3)	
Cm^{248}	Pu^{244}	α	5162 (91.61)
333.5d		spontaneous fission (8.39)	
Pu^{244}	U^{240}	α	4666 (100)
7.93E7y		spontaneous fission (0.121)	
U^{240}	Np^{240}	β^-	440 (100)
14.1h		γ	44 (1.65)
		Np x-rays 14 (4.4)	
Np^{240}	Pu^{240}	β^-	2188 (100)
7.4m			

Thorium-232 Decay Chain (including Thoron Progeny)

	1st Progeny		**kev and % abundance**
Th^{232}	Ra^{228}	α	3830(0.2), 3953 (23), 4010 (77)
1.41E10y		γ	59 (0.19), 125 (0.04)
		Ra x-rays 12 (8.4)	
Ra^{228}	Ac^{228}	β^-	39 (100)
5.75y			
Ac^{228}	Th^{228}	β^-	606 (8), 1168 (32), 1741 (12)
6.13h		γ	338(11.4), 911(27.7), 969(16.6)
		Th x-rays 13 (39), 90 (2.1), 93 (3.5), 105 (1.6)	
Th^{228}	Ra^{224}	α	5212(0.4), 5341(26.7), 5423(72.7)
1.91y		γ	84 (1.2), 132 (0.12), 216 (0.24)
		Ra x-rays 12 (9.6)	
Ra^{224}	Rn^{220}	α	5449 (4.9), 5686 (95.1)
3.62d		γ	241 (3.95)
		Rn x-rays 12(0.4), 81 (0.126), 84 (0.209)	

Rn^{220} is “thoron” gas, usually included with “radon” gas

Rn^{220}	Po^{216}	α	6288 (99.9), 5747 (0.1)
56s		γ	av. 550 (0.1)
Po^{216}	Pb^{212}	α	6779 (99.998)
0.15s			
Pb^{212}	Bi^{212}	β^-	158(5.22), 334 (85.1), 573 (9.9)
10.64h		γ	115 (0.6), 239 (44.6), 300 (3.4)
		Bi x-rays 11 (15.5), 75 (10.7), 77 (18), 87 (8)	

Bi^{212} decays 64.7% of the time by β^- to Po^{212} and 35.93% by α to Tl^{208}

Bi^{212}	Tl^{208}	α	5767 (0.6), 6050 (25.2), 6090 (9.6)
60.6m	Po^{212}	β^-	625 (3.4), 1519 (8), 2426 (48.4)
		γ	727 (11.8), 785 (1.97), 1621 (2.75)
		Tl x-rays 10 (7.7)	

Tl^{208}	Pb^{208}	β^-	1283(23.2), 1517(22.7), 1794(49.3)
3.05m	S	γ	511 (21.6), 583 (84.2), 860(12.46), 2614 (99.8)
	Pb x-rays 11 (2.9), 73 (2.0), 75 (3.4), 85 (1.5)		
Po^{212}	Pb^{208}	α	8785 (100)
304ns	S		

Pb^{208} is Stable

Uranium-238 Decay Chain (including Radon Progeny)

	1st Progeny		**kev and % abundance**
U^{238}	Th^{234}	α	4039(0.2), 4147(23.4), 4196(77.4)
4.47E9y		γ	av. 66 (0.1)
		Th x-rays 13 (8.8)	
Th^{234}	Pa^{234m}	β^-	76 (2), 96 (25.3), 189 (72.5)
24.1d		γ	63 (3.8), 92 (2.7), 93 (2.7)
		Pa x-rays 13 (9.6)	

Pa^{234m} decays 99.87% of the time by β^- to U^{234} and 0.13% of the time by IT to Pa^{234}

Pa^{234m}	U^{234}	β^-	1236(0.7), 1471(0.6), 2281(98.6)
1.17m		γ	766 (0.2), 926 (0.4), 1001 (0.6)
		U x-rays 14(0.44), 95(0.115), 98(0.187)	
	Pa^{234}	IT	
Pa^{234}	U^{234}	β^-	484 (35), 654 (0.6), 1183(10)
6.70h		γ	131 (20.4), 882 (24), 946 (12)
		U x-rays 14(144), 95(15.7), 98(25.4), 111(11.8)	
U^{234}	Th^{230}	α	4605(0.2), 4724(27.4), 4776(72.4)
2.45E5y		γ	53 (0.118), 121 (0.04)
Th^{230}	Ra^{226}	α	4476(0.12), 4621(23.4), 4688(76.3)
7.7E4y			
Ra^{226}	Rn^{222}	α	4602 (5.6), 4785 (94.4)
1600y		γ	186 (3.28)
		Rn x-rays 12(0.4), 81(0.18), 84(0.3), 95(0.14)	

Rn^{222} is “radon” gas

Rn^{222}	Po^{218}	α	5490 (99.92), 4986 (0.08)
3.82d		γ	av. 512 (0.08)

Po^{218} decays 99.98% of the time by α to Pb^{214} and 0.02% of the time by β^- to At^{218}

Po^{218}	Pb^{214}	α	6003 (99.98)
3.05	At^{218}	β^-	330 (0.02)
At^{218}	Bi^{214}	α	6650 (6), 6700
2s			
Pb^{214}	Bi^{214}	β^-	672(48), 729 (42.5), 1024 (6.3)
26.8m		γ	242(7.49), 295(19.2), 352(37.2)
		Bi x-rays	11(13.5), 75(6.2), 77(10.5), 87(4.7)

Bi^{214} decays 99.979% of the time by β^- to Po^{214} and 0.021% of the time by α to Tl^{210}

Bi^{214}	Po^{210}	β^-	1505(17.7), 1540(17.9), 3270(17.2)
19.9m		γ	609(46.3), 1120(15.1), 1764(15.8)
		Po x-rays	11(0.5), 77(0.36), 79(06), 90(0.3)
Po^{214}	Pb^{210}	α	7687 (99.989), 6892 (0.01)
146us		γ	797 (0.013)
Tl^{210}	Pb^{210}	β^-	1320 (25), 1870 (56), 2340 (19)
1.30m		γ	298 (79), 800 (99), 1310(21)
		Pb x-rays	11(13), 73(2.5), 75(4.3), 85(1.9)
Pb^{210}	Bi^{210}	β^-	17 (80.2), 63 (19.8)
22.3y		γ	47 (4.05)
		Bi x-rays	11 (24.3)

Bi^{210} decays ~100% of the time by β^- to Po^{210} and 0.000013% of the time by α to Tl^{206}

Bi^{210}	Po^{210}	β^-	1161 (99.9998)
5.01d	Tl^{206}	α	4650 (0.00007), 4690 (00005)
Po^{210}	Pb^{206}	α	5350(99.9989)
138.4d	S		
Tl^{206}	Pb^{206}	β^-	1520 (100)
4.19m	S		

Pb^{206} is Stable

Neptunium-232 Decay Chain (4n+1)

Pu^{241} decays ~100% of the time by β^- to Am^{241} and 0.0023% of the time by α to U^{237}

	1st Progeny		kev and % abundance
Pu^{241}	Am^{241}	β^-	21 (~100)
14.4y	U^{237}	α	4850 (0.0003), 4900 (0.0019)
Am^{241}	Np^{237}	α	5440 (13), 5490 (85)
432.2y		γ	26 (2.4), 33 (0.1), 59.5 (36)
		Np x-rays	14 (43)
Np^{237}	Pa^{233}	β^-	248 (96)
6.75d		γ	30 (14), 86 (14), 208 (22)
		Pa x-rays	13.3 (59), 92 (1.58), 108 (1.2)
Pa^{233}	U^{233}	β^-	145 (37), 257 (58), 568 (5)
27.0d		γ	75 (1.2), 87 (1.9), 311 (49)
		U x-rays	14 (49), 96 (28), 111 (8)
U^{233}	Th^{229}	α	4780 (15), 4820 (83)
1.592E5y		Th x-rays	13 (3.9)
Th^{229}	Ra^{225}	α	4840 (58), 4900 (11), 5050 (7)
7.34E3y		β^-	31 (4), 137 (2), 211 (3.3)
		Ra x-rays	12 (81), 85 (16), 100 (12)
Ra^{225}	Ac^{225}	β^-	320 (100)
14.8d		γ	40 (31)
Ac^{225}	Fr^{221}	α	5935 (100)
10.0y			
Fr^{221}	At^{217}	α	6126(15), 6242(1.4), 6340(83.4)
4.8m		γ	100 (0.2), 218 (12.5), 412 (0.1)
		At x-rays	11 (2.3), 80 (2), 92 (0.6)
At^{217}	Bi^{213}	α	7066 (99.9)
0.0323s		γ	595 (004)

Bi^{213} decays 97.84% of the time by β$^-$ to Po^{213} and 2.16% of the time by α to Tl^{209}

Bi^{213}	Po^{213}	β$^-$	320 (1.06), 980 (32), 1420(64)
45.65m		γ	293 (0.7), 440 (28), 1100 (0.5)
		Po x-rays	11 (1.8), 78 (3.4), 90 (1)
	Tl^{209}	α	5549 (0.16), 5870 (2)
Po^{213}	Pb^{209}	α	8377 (~100)
4.2E-6s			
Tl^{209}	Pb^{209}	β$^-$	1825 (100)
2.20m		γ	117(77), 465(96.6), 1567(99.7)
		Pb x-rays	10.6 (8.7), 74 (16), 85 (4.4)
Pb^{209}	Bi^{209}	β$^-$	645 (100)
3.253h	S	Bi^{209} is Stable	

Actinium Decay Chain (4n + 3)

	1st Progeny		kev and % abundance
U^{235}	Th^{231}	α	4370 (18), 4400 (57), 4580 (8)
7.08E8y		γ	143 (11), 185 (54), 204 (5)
Th^{231}	Pa^{231}	β^-	140 (45), 220 (15), 305 (40)
25.5h		γ	26 (2), 84 (10)
Pa^{231}	Ac^{227}	α	4950 (22), 5010 (24), 5020(23)
3.48E4y		γ	27 (6), 29 (6)

Ac^{227} decays 98.62% of the time by β^- to Th^{227} and 1.38% of the time by α to Fr^{223}

Ac^{227}	Th^{227}	β^-	43 (98.6)
21.77y		γ	70 (0.08)
	Fr^{223}	α	4860 (0.18), 4950 (1.2)
Th^{227}	Ra^{223}	α	5760 (21), 5980 (24), 6040 (23)
18.72d		γ	50 (8), 237 (15), 310 (8)
Fr^{223}	Ra^{223}	β^-	1150 (~100)
21.8m		γ	50 (8), 80 (13), 234 (4)
Ra^{223}	Rn^{219}	α	5610 (26), 5710 (54), 5750 (9)
11.435d		γ	33 (6), 149 (10), 270 (10)
Rn^{219}	Po^{215}	α	6420 (8), 6550 (11), 6820 (81)
3.96s		γ	272 (9), 401 (5)

Po^{215} decays ~100% of the time by α to Pb^{211} and 0.00023% of the time by β^- to At^{215}

Po^{215}	Pb^{211}	α	7380 (~100)
1.778ms	At^{215}	β^-	740 (0.00023)
At^{215}	Bi^{211}	α	8010 (100)
0.1ms			

Pb^{211}	Bi^{211}	β^-	290(1.4), 560 (9.4), 1390 (87.5)
36.1m		γ	405 (3.4), 427 (1.8), 832 (3.4)

Bi^{211} decays 99.73% of the time by α to Tl^{207} and 0.273% of the time by β^- to Po^{211}

Bi^{211}	Tl^{207}	α	6280 (16), 6620 (84)
2.13m		γ	351 (14)
	Po^{211}	β^-	600 (0.28)

Po^{211}	Pb^{207}	α	7450 (99)
0.516s	S	γ	570 (0.5), 900 (0.5)

Tl^{207}	Pb^{207}	β^-	1440 (99.8)
4.77m	S	γ	897 (0.16)

Pb^{207} is Stable

Activity, Half-Life, and Gamma Constants at 30cm

Ci/g = 3.578E5/($T_{1/2}$ in yr x atomic mass)
GBq/g = 1.324E7/($T_{1/2}$ in yr x atomic mass)

	Half-Life	**Ci/g**	**Rem/hr/Ci @ 30 cm**	**GBq/g**	**Sv/hr/GBq @ 30cm**
Ac-227	21.77y	72.40	N/A	2.68E3	N/A
Ac-228	6.15h	2.24E6	2.82	8.29E7	7.62E-4
Ag-110	24.6s	4.17E9	0.18	1.54E11	4.79E-5
Ag-110m	249.79d	13.03	14.66	482	3.97E-3
Ag-111	7.45d	65.79	0.16	2.43E3	4.20E-5
Al-26	7.3E5y	0.019	16.6	0.699	4.49E-3
Am-241	432.7y	3.43	0.19	127	5.04E-5
Am-242	16.02h	8.08E5	0.23	2.99E7	6.25E-5
Am-243	7370y	0.20	0.23	7.40	6.22E-5
Ar-37	35.04d	1.01E5	N/A	3.73E6	N/A
Ar-39	269.0y	34.14	N/A	1.26E3	N/A
Ar-41	1.82h	4.20E7	7.73	1.55E9	2.09E-3
Ar-42	32.90y	259.20	N/A	9.59E3	N/A
As-74	17.8d	9.91E4	0.586	3.67E6	1.58E-4
At-215	0.100us	5.25E14	N/A	1.94E16	N/A
At-216	300us	1.74E14	N/A	6.44E15	N/A
At-218	1.6s	3.23E10	N/A	1.20E12	N/A
Au-198	2.695d	2.12E10	0.279	7.84E11	7.55E-5
Ba-131	11.5d	8.68E4	2.15	3.21E6	5.82E-4
Ba-133	10.52y	255.90	2.22	9.47E3	6.01E-4
Ba-137m	2.552m	5.37E8	4.44	1.99E10	1.20E-3
Ba-139	83.06m	1.63E7	0.173	6.03E8	4.68E-5
Ba-140	12.75d	7.32E4	0.871	2.71E6	2.36E-4
Ba-141	18.27m	7.31E7	2.4	2.70E9	6.50E-4
Ba-142	10.6m	1.25E8	1.01	4.63E9	2.73E-4
Be-7	53.28d	3.50E5	0.38	1.30E7	1.03E-4
Be-10	1.51E6y	0.024	N/A	0.875	N/A
Bi-210	5.01d	1.24E5	N/A	4.59E6	N/A
Bi-210m	3.04E6y	5.61E-4	2.124	0.0207	5.75E-4
Bi-211	2.14m	4.17E8	0.273	1.54E10	7.39E-5
Bi-212	60.6m	1.47E7	N/A	5.44E8	N/A
Bi-213	45.59m	1.94E7	0.739	7.17E8	2.00E-4
Bi-214	19.9m	4.41E7	9.31	1.63E9	2.52E-3
Bk-249	320d	1.64E3	N/A	6.07E4	N/A

	Half-Life	**Ci/g**	**Rem/hr/Ci @ 30 cm**	**GBq/g**	**Sv/hr/GBq @ 30cm**
Br-82	17.68m	1.33E8	2.15	4.92E9	5.82E-4
Br-84	31.8m	7.05E7	0.172	2.61E9	4.66E-5
C-11	20.38m	8.38E8	6.815	3.10E10	1.84E-3
C-14	5730y	4.46	N/A	165	N/A
Ca-41	1.03E5y	0.085	N/A	3.14	N/A
Ca-47	4.536d	6.13E5	0.198	2.27E7	5.36E-5
Cd-109	1.264y	2.6E3	0.528	9.62E4	1.43E-4
Cd-113	7.70E15y	4.12E-13	N/A	1.52E-11	N/A
Cd-118	50.3m	3.17E7	N/A	1.17E9	N/A
Ce-141	32.5d	2.85E4	0.422	1.06E6	1.14E-4
Ce-143	33.1h	6.63E5	1.19	2.45E7	3.22E-4
Cf-249	351y	4.09	1.98	151	5.35E-4
Cf-252	2.638y	538	N/A	1.99E4	N/A
Cf-255	85.0m	8.67E6	N/A	3.21E8	N/A
Cf-256	12.3m	5.97E7	N/A	2.21E9	N/A
Cl-36	3.01E5y	0.033	N/A	1.22	N/A
Cl-38	37.24m	1.33E8	8.92	4.92E9	2.41E-3
Cm-242	162.8d	3.31E3	N/A	1.22E5	N/A
Cm-243	29.1y	50.59	0.675	1.87E3	1.83E-4
Cm-244	18.1y	81.0	N/A	3.00E3	N/A
Cm-245	8500y	0.17	0.325	6.36	8.80E-5
Cm-247	1.56E7y	9.28E-5	1.87	3.43E-3	5.06E-4
Co-56	77.3d	3.02E4	21.36	1.12E6	5.77E-3
Co-57	271.8d	8.43E3	0.713	3.12E5	4.54E-4
Co-58	70.88d	3.18E4	6.81	1.18E6	1.84E-3
Co-60	5.271y	1.13E3	15.19	4.18E4	4.11E-3
Cr-51	27.70d	9.24E4	0.207	3.42E6	5.61E-5
Cs-134	2.0648y	1.29E3	10.25	4.79E4	2.77E-3
Cs-134m	2.903h	8.06E6	0.0986	2.98E8	2.67E-5
Cs-135	2.30E6y	1.15E-3	N/A	0.0427	N/A
Cs-136	13.16d	7.30E4	6.85	2.70E6	1.85E-3
Cs-137	30.17y	86.6	See Ba137m	3.20E3	N/A
Cs-138	33.41m	4.08E7	2.31	1.51E9	6.25E-4
Cu-61	3.333h	1.54E7	1.05	5.71E8	2.84E-4
Cu-62	9.74m	3.11E8	7.85	3.39E7	2.12E-3
Cu-64	12.7h	3.86E6	1.228	1.43E8	3.33E-4
Dy-154	3.00E6y	7.75E-4	N/A	0.0287	N/A

	Half-Life	**Ci/g**	**Rem/hr/Ci @ 30 cm**	**GBq/g**	**Sv/hr/GBq @ 30cm**
Dy-165	2.334h	8.14E6	0.0918	3.01E8	2.49E-5
Es-253	20.47d	2.52E4	N/A	9.32E5	N/A
Es-256	25.4m	2.89E7	N/A	1.07E9	N/A
Eu-152	13.537y	174.0	5.82	6.44E3	1.58E-3
Eu-154	8.589y	270.6	7.06	1.00E4	1.91E-3
Eu-155	4.7611y	485.1	0.319	1.79E4	8.64E-5
Eu-156	15.19d	5.51E4	1.3	2.04E6	3.52E-4
F-18	1.830h	9.52E7	7.72	3.52E9	2.09E-3
Fe-55	2.73y	2.38E3	N/A	8.81E4	N/A
Fe-59	44.51d	4.97E4	7.34	1.84E6	1.98E-3
Fe-60	1.50E6y	3.98E-3	N/A	0.147	N/A
Fm-256	157.6m	4.66E6	N/A	1.72E8	N/A
Fr-219	20.0ms	2.58E12	N/A	9.53E13	N/A
Fr-221	4.9m	1.74E8	0.163	6.43E9	4.41E-5
Fr-223	21.8m	3.87E7	0.0952	1.43E9	2.58E-5
Ga-67	3.2612d	5.98E5	0.9381	2.21E7	2.54E-4
Gd-148	75y	32.2	N/A	1.19E3	N/A
Gd-150	1.79E6y	1.33E-3	N/A	0.0493	N/A
Gd-152	1.08E14y	2.18E-11	N/A	8.07E-10	N/A
Ge-68	270.8d	7.09E3	N/A	2.62E5	N/A
H-3	12.3y	9.70E3	N/A	3.59E5	N/A
Hf-174	2.00E15y	1.03E-12	N/A	3.81E-11	N/A
Hg-203	46.612d	1.38E4	1.29	5.11E5	3.49E-4
Ho-163	4.57E3y	0.48	N/A	17.8	N/A
Ho-166	26.8h	7.05E5	0.1164	2.61E7	3.15E-5
Ho-166m	1200y	1.80	5.39	66.5	1.46E-3
I-123	13.27h	1.92E6	0.796	7.11E7	2.15E-4
I-124	4.176d	2.52E5	5.53	9.34E6	1.50E-3
I-125	60.1d	1.74E4	1.664	6.44E5	4.50E-4
I-126	12.93d	7.97E4	4.34	2.95E6	1.17E-3
I-129	1.57E7y	1.77E-4	0.736	6.55E-3	1.99E-4
I-130	12.36h	1.55E6	4.76	5.74E7	1.29E-3
I-131	8.040d	1.24E5	3.14	4.59E6	8.49E-4
I-132	2.295h	1.04E7	5.17	3.83E8	1.40E-3
I-133	20.8h	1.13E6	4.54	4.18E7	1.23E-3
I-134	52.6m	2.67E7	17.47	9.88E8	4.72E-3
I-135	6.57h	3.53E6	9.57	1.31E8	2.59E-3

	Half-Life	Ci/g	Rem/hr/Ci @ 30 cm	GBq/g	Sv/hr/GBq @ 30cm
In-111	2.8047d	4.20E5	3.717	1.55E7	1.01E-3
In-113m	1.6582h	1.69E7	1.53	6.25E8	4.14E-4
In-115	4.41E14y	7.06E-12	N/A	2.61E-10	N/A
Ir-192	73.83d	9.21E3	6.56	3.41E5	1.77E-3
K-40	1.28E9y	6.99E-6	0.91	2.59E-4	2.46E-4
K-42	12.36h	6.04E6	1.4	2.23E8	3.78E-4
K-43	22.3h	3.27E6	5.6	1.21E8	1.51E-3
Kr-85	10.73y	392.0	0.02	1.45E4	5.40E-6
Kr-85m	4.48h	8.24E6	0.96	3.05E8	2.60E-4
Kr-87	76.3m	2.84E7	3.18	1.05E9	8.61E-4
Kr-88	2.84h	1.26E7	8.9	4.64E8	2.41E-3
Kr-89	3.15m	6.71E8	3.96	2.48E10	1.07E-3
La-140	1.678d	5.56E5	13.61	2.06E7	3.68E-3
La-142	91.1m	1.46E7	0.675	5.38E8	1.83E-4
Lu-177	6.73d	1.10E5	0.170	4.06E6	4.61E-5
Mn-52	5.591d	4.49E5	18.6	1.66E7	5.03E-3
Mn-52m	21.2m	1.72E8	1.48	6.35E9	4.01E-4
Mn-53	3.74E6y	1.81E-3	N/A	0.0669	N/A
Mn-54	312.2d	7.75E3	5.67	2.87E5	1.53E-3
Mn-56	2.578h	2.17E7	10.24	8.03E8	2.77E-3
Mo-99	67h	4.80E5	1.25	1.78E7	3.38E-4
N-13	9.965m	1.45E9	6.814	5.37E10	1.84E-3
N-16	7.13s	9.89E10	16.57	3.66E12	4.48E-3
Na-22	2.605y	6.24E3	14.85	2.31E5	4.01E-3
Na-24	14.96h	8.73E6	20.55	3.23E8	5.55E-3
Nb-94	2.03E5y	0.19	10.20	6.94	2.76E-3
Nb-95	34.975d	3.93E4	4.74	1.46E6	1.28E-3
Nd-144	2.29E15y	1.09E-12	N/A	4.02E-11	N/A
Ni-57	35.6h	1.54E6	12	5.70E7	3.24E-3
Ni-59	7.60E4y	0.080	12.5	2.95	3.38E-3
Ni-63	101y	56.23	N/A	2.08E3	N/A
Ni-65	2.52h	1.91E7	3.4	7.07E8	9.19E-4
Ni-66	54.6h	8.71E5	N/A	3.22E7	N/A
Np-237	2.14E6y	7.05E-4	0.0868	0.0261	2.35E-5
Np-238	2.117d	2.59E5	0.018	9.59E6	4.87E-6
Np-239	2.355d	2.32E5	0.594	8.58E6	1.61E-4
Np-240	61.9m	1.27E7	0.863	4.68E8	2.34E-4

	Half-Life	Ci/g	Rem/hr/Ci @ 30 cm	GBq/g	Sv/hr/GBq @ 30cm
O-15	122.2s	6.15E9	7.98	2.29E11	2.16E-3
Os-186	2E15y	9.62E-13	0.613	3.56E-11	1.66E-4
P-32	14.28d	2.86E5	N/A	1.06E7	N/A
P-33	25.34d	1.56E5	N/A	5.78E6	N/A
Pa-231	3.28E4y	0.047	0.104	1.75	2.81E-5
Pa-233	26.967d	2.08E4	1.27	7.69E5	3.44E-4
Pa-234	6.69h	2.00E6	7.03	7.40E7	1.90E-3
Pa-234m	1.17m	6.86E8	0.05	2.54E10	1.35E-5
Pb-209	3.253h	4.61E6	N/A	1.71E8	N/A
Pb-210	22.3y	76.4	0.0203	2.83E3	5.50E-6
Pb-211	36.1m	2.47E7	0.248	9.14E8	6.71E-5
Pb-212	10.64h	1.39E6	0.732	5.14E7	1.98E-4
Pb-214	27m	3.25E7	1.155	1.20E9	3.12E-4
Pd-107	6.50E6y	5.15E-4	N/A	0.0191	N/A
Pm-147	2.6234y	928.3	3.15E-5	3.43E4	8.53E-9
Pm-149	53.08h	3.97E5	0.0532	1.47E7	1.44E-5
Pm-151	4.12m	7.31E5	1.2	2.71E7	3.25E-4
Po-210	138.38d	4.49E3	N/A	1.66E5	N/A
Po-212	304ns	1.78E17	N/A	6.59E18	N/A
Po-214	164us	3.22E14	6.71E-4	1.19E16	1.81E-7
Po-216	145ms	3.60E11	9.95E-5	1.33E13	2.69E-9
Po-218	3.10m	2.78E8	N/A	1.03E10	N/A
Pr-142m	14.6m	9.08E7	N/A	3.36E9	N/A
Pt-190	6.50E11y	2.90E-9	N/A	1.07E-7	N/A
Pt-202	44.0h	3.53E5	N/A	1.30E7	N/A
Pu-236	2.87y	528	N/A	1.95E4	N/A
Pu-238	87.7y	17.1	0.877	633	2.37E-4
Pu-239	2.41E4y	0.062	0.335	2.30	9.05E-5
Pu-240	6560y	0.227	N/A	8.40	N/A
Pu-241	14.4y	103	N/A	3.81E3	N/A
Pu-242	3.75E5y	3.94E-3	N/A	0.146	N/A
Ra-223	11.435d	5.12E4	0.37	1.89E6	1.00E-4
Ra-224	3.66d	1.59E5	0.054	5.88E6	1.46E-5
Ra-225	14.9d	3.90E4	0.07	1.44E6	1.89E-5
Ra-226	1600y	0.99	0.045	36.6	1.22E-5
Ra-228	5.76y	272	N/A	1.01E4	N/A
Rb-81	4.576h	8.47E6	3.628	3.13E8	9.82E-4

	Half-Life	Ci/g	Rem/hr/Ci @ 30 cm	GBq/g	Sv/hr/GBq @ 30cm
Rb-82	1.273m	1.80E9	7.452	6.67E10	2.02E-3
Rb-83	86.2d	1.83E4	3.135	6.76E5	8.49E-4
Rb-87	4.75E10y	8.67E-8	N/A	3.21E-6	N/A
Rb-88	17.7m	1.21E8	3.58	4.48E9	9.68E-4
Rb-89	15.4m	1.37E8	12.17	5.07E9	3.29E-3
Re-187	4.35E10y	4.40E-8	N/A	1.63E-6	N/A
Re-188	16.98h	9.82E5	0.2096	3.63E7	5.67E-5
Rh-105	35.36h	8.45E5	0.462	3.13E7	1.25E-4
Rh-106	29.8s	3.58E9	0.644	1.32E11	1.74E-4
Rn-212	23.9m	3.71E7	N/A	1.37E9	N/A
Rn-216	45.0us	1.16E15	N/A	4.30E16	N/A
Rn-219	3.96s	1.30E10	0.329	4.81E11	8.91E-5
Rn-220	55.6s	9.21E8	3.99E-3	3.41E10	1.08E-6
Rn-222	3.8235d	1.54E5	3.03E-3	5.70E6	8.19E-7
Ru-97	2.9d	4.65E5	1.32	1.72E7	3.57E-4
Ru-103	39.26d	3.23E4	2.65	1.20E6	7.17E-4
Ru-105	4.44h	6.73E6	1.93	2.49E8	5.22E-4
Ru-106	1.02y	3.31E3	N/A	1.22E5	N/A
S-35	87.51d	4.27E4	N/A	1.58E6	N/A
Sb-122	2.7238d	3.93E5	2.991	1.46E7	8.10E-4
Sb-124	60.2d	1.75E4	9.62	6.48E5	2.60E-3
Sb-125	1007.4d	1.04E3	2.57	3.84E4	6.96E-4
Sb-126	12.46d	8.33E4	11.5	3.08E6	3.11E-3
Sc-44	3.927h	1.82E7	0.579	6.72E8	1.57E-4
Sc-46	83.81d	3.39E4	10.9	1.25E6	2.95E-3
Sc-47	3.349d	8.30E5	0.56	3.07E7	1.51E-4
Sc-48	43.7h	1.49E6	21	5.51E7	5.68E-3
Se-75	119.78d	1.45E4	9.53	5.37E5	2.58E-3
Se-79	6.50E5y	6.98E-3	N/A	0.258	N/A
Si-32	132y	84.77	N/A	3.14E3	N/A
Sm-146	1.031E8y	2.38E-5	N/A	8.80E-4	N/A
Sm-147	1.06E11y	2.30E-8	N/A	8.50E-7	N/A
Sm-148	7.00E15y	3.46E-13	N/A	1.28E-11	N/A
Sm-153	46.27h	4.43E5	0.175	1.64E7	4.74E-5
Sn-121	27.06h	9.58E5	N/A	3.54E7	N/A
Sn-125	9.64d	1.09E5	0.33	4.01E6	8.93E-5
Sr-85	64.84d	2.37E4	3.06	8.78E5	8.28E-4

	Half-Life	**Ci/g**	**Rem/hr/Ci @ 30 cm**	**GBq/g**	**Sv/hr/GBq @ 30cm**
Sr-87m	2.803h	1.32E7	1.92	4.87E8	5.20E-4
Sr-89	50.52d	2.90E4	5.29E-3	1.07E6	1.43E-6
Sr-90	29.1y	137.0	N/A	5.07E3	N/A
Sr-91	9.63h	3.58E6	0.635	1.32E8	1.72E-4
Sr-92	2.71h	1.26E7	7.8942	4.65E8	2.14E-3
Tb-160	72.3d	1.13E4	0.635	4.18E5	1.72E-4
Tc-99	2.13E5y	0.017	N/A	0.629	N/A
Tc-99m	6.01h	5.27E6	0.896	1.95E8	2.42E-4
Tc-101	14.2m	1.31E8	1.71	4.85E9	4.63E-4
Te-123m	119.7d	8.88E3	1.365	3.28E5	3.69E-4
Te-127	9.35h	2.64E6	0.0335	9.78E7	9.06E-6
Te-129	69.6m	2.10E7	0.5717	7.76E8	1.55E-4
Te-129m	33.6d	3.02E4	0.137	1.12E6	3.71E-5
Te-131	25m	5.75E7	1.57	2.13E9	4.25E-4
Te-131m	30h	7.98E5	2.18	2.95E7	5.90E-4
Te-132	3.204d	3.09E5	2.124	1.14E7	5.75E-4
Te-133	12.5m	1.13E8	2.32	4.19E9	6.28E-4
Te-133m	55.4m	2.55E7	3.11	9.45E8	8.42E-4
Te-134	41.8m	3.36E7	1.77	1.24E9	4.79E-4
Te-135	19s	4.40E9	0.195	1.63E11	5.28E-5
Th-227	18.72d	3.07E4	0.39	1.14E6	1.05E-4
Th-228	1.913y	820.0	0.014	3.03E4	3.78E-6
Th-229	7300y	0.214	0.145	7.92	3.92E-5
Th-230	7.54E4y	0.021	2.07E-3	0.762	5.60E-7
Th-231	25.55h	5.32E5	0.0480	1.97E7	1.30E-5
Th-232	1.40E10y	1.10E-7	7.62E-4	4.07E-6	2.06E-7
Th-234	24.10d	2.32E4	0.0356	8.58E5	9.62E-6
Tl-201	72.912h	2.14E5	0.122	7.91E6	3.30E-5
Tl-204	3.78y	464.0	0.0124	1.72E4	3.35E-6
Tl-206	4.20m	2.17E8	N/A	8.03E9	N/A
Tl-208	3.053m	2.96E8	18.89	1.10E10	5.11E-3
Tl-209	2.161m	4.16E8	4.17	1.54E10	1.13E-3
U-237	6.75d	8.16E4	0.561	3.02E6	1.52E-4
U-238	4.47E9y	3.36E-7	N/A	1.24E-5	N/A
V-48	15.98d	1.70E5	15.6	6.29E6	4.22E-3
V-49	330d	8.09E3	N/A	2.99E5	N/A
W-187	23.72d	7.07E5	2.82	2.62E7	7.63E-4

Xe-131m	11.84d	8.69E4	0.5664	3.22E6	1.53E-4
Xe-133	5.243d	1.87E5	0.6248	6.93E6	1.69E-4
Xe-133m	2.19d	4.49E5	0.7027	1.66E7	1.90E-4
Xe-135	9.14h	2.54E6	1.6178	9.41E7	4.38E-4
Xe-135m	15.29m	9.12E7	2.9736	3.37E9	8.05E-4
Xe-138	14.08m	9.69E7	1.36	3.58E9	3.68E-4
Y-88	106.65d	1.39E4	14.83	5.15E5	4.01E-3
Y-90	64.1h	5.43E5	N/A	2.01E7	N/A
Y-92	3.54h	9.63E6	0.126	3.56E8	3.41E-5
Y-93	10.18h	3.31E6	0.11	1.23E8	2.98E-5
Yb-169	32.026d	2.41E4	1.219	8.93E5	3.30E-4
Zn-65	243.8d	8.24E3	3.575	3.05E5	9.68E-4
Zr-89	78.41h	4.50E5	5.65	1.66E7	1.53E-3
Zr-93	1.53E6y	2.52E-3	N/A	0.0931	N/A
Zr-95	64.02d	2.15E4	5.16	7.96E5	1.39E-3
Zr-97	16.91h	1.91E6	0.236	7.08E7	6.39E-5

The exposure rate from these radionuclides do not include their short-lived progeny. Spontaneous fission, isotopic mixtures, impurities in mixtures, and shielding (including self shielding) should also be taken into account when estimating exposure rate.

Gamma exposure at 30 cm vs Particle Size

in microns for commonly encountered radionuclides

	mRem/hr			**mSv/hr**		
	1µ	**10µ**	**100µ**	**1µ**	**10µ**	**100µ**
Be-7	1.3E-4	1.3E-1	1.3E2	1.3E-6	1.3E-3	1.3
Na-22	4.7E-5	4.7E-2	4.7E1	4.7E-7	4.7E-4	0.47
Na-24	9.5E-2	9.5E1	9.5E4	9.5E-4	0.95	9.5E2
Al-26	4.5E-10	4.5E-7	4.5E-4	4.5E-12	4.5E-9	4.5E-7
Mg-28	4.8E-2	4.8E1	4.8E4	4.8E-4	0.48	4.8E2
Sc-46	6.9E-4	6.9E-1	6.9E2	6.9E-6	6.9E-4	6.9
V-48	1E-2	1E1	1E4	1E-4	0.10	1E2
Cr-51	9E-5	9E-2	9E1	9E-7	9E-4	0.9
Mn-52	3.8E-2	3.8E1	3.8E4	3.8E-4	0.38	3.8E2
Mn-54	1.7E-4	1.7E-1	1.7E2	1.7E-6	1.7E-3	1.7
Mn-56	8.3E-1	8.3E2	8.3E5	8.3E-3	8.3	8.3E3
Co-56	2.9E-3	2.9	2.9E3	2.9E-5	2.9E-2	29
Co-57	6.6E-5	6.6E-2	6.6E1	6.6E-7	6.6E-4	0.66
Co-58	1E-3	1	1E3	1E-5	1E-2	10
Fe-59	1.5E-3	1.5	1.5E3	1.5E-5	1.5E-2	15
Co-60	8E-5	8E-2	8E1	8E-7	8E-4	0.8
Zn-65	1.1E-4	1.1E-1	1.1E2	1.1E-6	1.1E-3	1.1
Se-75	3.5E-4	3.5E-1	3.5E2	3.5E-6	3.5E-3	3.5
Y-88	6.3E-4	6.3E-1	6.3E2	6.3E-6	6.3E-3	6.3
Sr/Y-90	N/A	N/A	N/A	N/A	N/A	N/A
Zr-95	3.8E-4	3.8E-1	3.8E2	3.8E-6	3.8E-3	3.8
Mo-99	3.2E-3	3.2	3.2E3	3.2E-5	3.2E-2	32
Cd-109	2.4E-5	2.4E-2	2.4E1	2.4E-7	2.4E-4	0.24
Cs-137	3.6E-7	3.6E-4	3.6E-1	3.6E-9	3.6E-6	3.6E-3
Ba-140	2.4E-4	2.4E-1	2.4E2	2.4E-6	2.4E-3	2.4
W-187	1.1E-3	1.1	1.1E3	1.1E-5	1.1E-2	11
Os-191	3.9E-4	3.9E-1	3.9E2	3.9E-6	3.9E-3	3.9
Ir-192	7.1E-4	7.1E-1	7.1E2	7.1E-6	7.1E-3	7.1
Au-198	8E-3	8	8E3	8E-5	8E-2	80
Ra-226	3.5E-10	3.5E-7	3.5E-4	3.5E-12	3.5E-9	3.5E-6
U-234	5.4E-11	5.4E-8	5.4E-5	5.4E-13	5.4E-10	5.4E-7
U-235	8.1E-14	8.1E-11	8.1E-8	8.1E-16	8.1E-13	8.1E-10
Np-237	3.9E-11	3.9E-8	3.9E-5	3.9E-13	3.9E-10	3.9E-7

Pu-238	1.6E-7	1.6E-4	1.6E-1	1.6E-9	1.6E-6	1.6E-3
Pu-239	2.2E-10	2.2E-7	2.2E-4	2.2E-12	2.2E-9	2.2E-6
Pu-240	2E-9	2E-6	2E-3	2E-11	2E-8	2E-5
Am-241	1.3E-7	1.3E-4	1.3E-1	1.3E-9	1.3E-6	1.3E-3

1000 μ = 1 mm (millimeter) = 0.03937 inches
100 μ is easily discernible with the naked eye
50 μ is not easily discernible with the naked eye
< 10 μ is typical size for airborne particles

Activity in DPM vs Particle Size in microns for oxide form of various isotopes

	0.5µ	**1µ**	**5µ**	**10µ**	**50µ**
U-234	8.7E-3	0.07	9	69.7	8700
U-235	3.0E-6	2.4E-5	3E-3	0.02	3
U-238	4.7E-7	3.8E-6	5E-4	3.8E-3	0.47
Np-237	1.0E-3	8.0E-3	1.0	8	1.0E3
Pu-238	25	201	2.5E4	2E5	2.5E7
Pu-239	0.09	0.73	91	730	9.1E4
Pu-240	0.33	2.7	333	2.67E3	3.3E5
Pu-241	151	1.21E3	1.5E5	1.2E6	1.5E8
Am-241	5.1	41.1	5.14E3	4.1E4	5.14E6

Calculating Activity vs Particle Size

1. Volume of the particle is $V = 1/6\pi d^3$.
2. Use the density of the isotope listed in this reference.
3. Mass of the particle is M = V x density.
4. Activity of the particle is A = M x specific activity.

Correct the activity of the particle for the oxide form if you need that; the molecular weight of Pu-238 is 238, the activity of the dioxide form must be reduced by the ratio of the molecular weight of the dioxide form to the molecular weight of Pu-238. Multiply the calculated activity by 238/270 to get the activity of the dioxide form.

For particles larger than about 1µ the aerodynamic diameter is approximately equal to the physical diameter times the square root of the density. The 10µ diameter particle in our example would have an equivalent aerodynamic diameter of 34µ (10µ x the square root of 11.46). This must be taken into account in air sampling/monitoring situations.

RADIATION BIOLOGY

Maximum survivable dose: 1000 rem (10 Sv)

Cancer mortality rate ~ 900 excess deaths per 100,000 persons at 0.1 Sv (10 rem)

Radiation Dose Risk

Report	Additional Cancer Deaths
BEIR III 1980	3 in 10,000 per 1 rem (10 mSv)
(also Reg Guide 8.29)	
BEIR V 1990	800 in 100,000 per 10 rad (0.1 Gy)

Hiroshima Survivors Incidence of Cancer

4,000 Hiroshima survivors who received doses greater than 50 rem showed an extra 300 incidences of cancer.

COMPOSITION OF THE HUMAN BODY

O	65 %	Rb	0.00046 %	I	1.6E-5 %
C	18	Sr	0.00046	Au	1.4E-5
H	10	Br	0.00029	Ni	1.4E-5
N	3	Pb	0.00017	Mo	1.3E-5
Ca	1.5	Nb	0.00016	Ti	1.3E-5
P	1.0	Cu	0.00010	Te	1.2E-5
S	0.25	Al	0.000087	Sb	1.1E-5
K	0.20	Cd	0.000072	Li	3.11E-6
Cl	0.15	B	0.000069	Cr	2.4E-6
Na	0.15	Ba	0.000031	Cs	2.1E-6
Mg	0.05	As	0.000026	Co	2.1E-6
Fe	0.006	V	0.000026	Ag	1.0E-6
F	0.0037	Sn	0.000024	U	1.3E-7
Zn	0.0032	Hg	0.000019	Be	5E-8
Si	0.0020	Se	0.000019	Ra	1E-13
Zr	0.0006	Mn	0.00001		

DOSIMETRY

1 Bq = 1 dps = 2.7 E-11 Ci
1 Gy = 1 joule / kg = 100 rads

H_T (Sv) = D(Gy) x Q (Sv / Gy)

Quality Factors (Q) values:
x-rays, beta, gamma = 1
neutrons: thermal = 2
fast = 10
alpha = 20

DOSE EQUIVALENT CALCULATIONS

1 Roentgen = 2.58E-4C / kg or 1 esu / cm^3
= 87 ergs / g or 2.082 E9 ip / cm^3
= 7.02 E4 MeV / cm^3 in air @ STP
or = 98 ergs / g in tissue
1 R/hr ~ 1 E-13 Amperes / cm^3
1 rad = 100 ergs / g in any absorber
ρ_{air} = 0.001293 g / cm^3
W_{air} = 33.7 eV
1 Ampere = 1 Coulomb / sec
STP_{air} = 760mm Hg @ 0^0C or 14.7lb / in^2 @32^0 F

INTERNAL DOSIMETRY

Calculating CDE and CEDE ICRP 26/30
CDE = I/nALI x 50 rem (0.5 Sv) nALI is the non-stochastic ALI
CDE = 50 yr committed dose equivalent to irradiated tissue
I = Intake
nALI = non-stochastic ALI = 50 rem (0.5 Sv)/ h_{max}
h_{max} = greatest dose equivalent found in the exposure-to-dose conversion tables
CEDE = I / sALI x 5 rem (50 mSv) sALI is the stochastic ALI
CEDE = 50 yr committed effective dose equivalent
OR CEDE = $\Sigma^n_{i=1} W_T$
CEDE = 50 yr committed effective dose equivalent to individual tissue
W_T = tissue weighting factor
Effective Dose Equivalent EDE = H_Σ = $\Sigma W_T H_T$
D.E. rate (Sv / hr) = 0.15 A(TBq)E / r^2

Calculating DAC and DAC-hours

DAC = ALI / 2000 hr at 1.2 E6 ml / hr

1 DAC-h = 2.5 mrem (25 μSv) CEDE if based on sALI **OR** 25 mrem (0.25 mSv) ref ICRP 26 CDE to an organ or tissue if based on nALI

DAC Fraction = Σ_i(concentration / DAC)/PF

DAC fraction x time (hours) = DAC-hours

INTERNAL DOSIMETRY

Intake I(Bq) = A_t(Bq) / IRF_t

Body burden q = $q_0 e^{-\lambda \text{ eff } t}$

CEDE or H_{50} = 50 mSv (5 rem) x I / ALI

TEDE = CEDE + Deep Dose Equivalent

Effective Half-Life

$t_{eff} = t_r \times t_b \,/\, (t_r + t_b)$

where; t_r = radioactive half-life
t_b = biological half-life

Effective Removal Constant

$\lambda_{eff} = \lambda_r + \lambda_b$

where; λ_r = decay constant = -0.693 / $t_{1/2}$
λ_b = biological removal constant -0.693/ t_b

Calculating Internal Dose (ICRP 30)

H_{50} (T-S) = (1.6E-10)U_S SEE(T-S)

H_{50} = 50 year dose equivalent commitment in sieverts

where SEE is the Specific Effective Energy modified by a quality factor for radiation absorbed in the target organ (T) for each transformation in the source organ (S) expressed in MeV/g.

SEE = $\Sigma Y \bullet E \bullet AF \bullet Q / M_T$

where;

Y = yield of radiations per transformation

E = average energy of the radiation

AF = absorbed fraction of energy absorbed in the target organ (T) per emission of radiation in the source organ (S)

Q = quality factor

M_T = mass of the target organ

U_S = number of nuclear transformations in the source organ (S) during the time interval for which the dose is to be calculated

EQUIVALENT DOSE, EFFECTIVE DOSE, and COMMITTED EFFECTIVE DOSE

ICRP 60 Equivalent Dose

H_T = $\Sigma_R W_R D_{T,R}$
H_T = equivalent dose in tissue T
W_R = radiation weighting factor
$D_{T,R}$ = absorbed dose averaged over tissue T due to radiation R

ICRP 60 Effective Dose

E = $\Sigma_T W_T H_T$
W_T = tissue weighting factor
H_T = equivalent dose in tissue(s) T

ICRP 60 Committed Effective Dose

E(50) = $\Sigma^{T=j}_{T=i}\, W_T H_T(50) + (W_{remainder}\, \Sigma^{T=1}_{T=K}\, M_T H_T(50) / \Sigma^{T=1}_{T=K}\, M_T)$
W_T = tissue weighting factor for tissues & organs T_i to T_j
M_T = mass of the remainder tissues T_K to T_1
$W_{remainder}$ = 0.05 (the W_T assigned to the remainder tissues)

ICRP 23 REFERENCE MAN

Daily Water Intake = 2.2 liters / day
Breathing Rate = 2 E4 ml / min
Skin surface area = 18,000 cm^2

There are approximately 10^{13} cells in the human body.

There are 140 g of potassium in reference man, 125 nCi (4.625 kBq) is K^{40} which results in 0.25 mrem/wk or 13 mrem/yr (2.5 μ Sv/wk or 0.13 mSv/yr) to the whole body.

RADIATION WEIGHTING FACTORS[1] (ICRP 60)

Type and Energy Range[2]	Radiation Weighting Factor, W_R
Photons, all energies	1
Electrons & muons, all energies[3]	1
Neutrons, <10 keV	5
10 keV to 100 keV	10
100 keV to 2 MeV	20
2 MeV to 20 MeV	10
> 20 MeV	5
Protons, other than recoil protons, energy > 2MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[1] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

[2] The choice of values for other radiation is discussed in Annex A of Publication 60.

[3] Excluding Auger electrons emitted from nuclei bound to DNA

ICRP 60 Tissue Weighting Factors

Tissue or organ	Tissue weighting factor, W_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

CALCULATING TODE AND TEDE

TEDE = DDE + CEDE
TODE = DDE + CDE
TEDE = total effective dose equivalent
TODE = total organ dose equivalent
DDE = deep dose equivalent
CDE = 50 year committed dose equivalent to a tissue or organ
CEDE = 50 year committed effective dose equivalent

DOSE EQUIVALENT LIMITS & POSTING REQUIREMENTS (10CFR20 & 10CFR835)

Dose Equivalent	Annual Limit
TEDE	5 rem 50 mSv
TODE	50 rem 0.5 Sv
LDE (Lens Dose Equivalent)	15 rem 0.15 Sv
SDE,WB	50 rem 0.5 Sv
SDE, ME	50 rem 0.5 Sv
TEDE (general public)	0.1 rem 1 mSv

DOSE EQUIVALENT MEASUREMENT

Abbreviations from USNRC Reg. Guide 8.7

	Measurement Depth for External Sources (cm)	Density Thickness (mg / cm^2)
TEDE	1	1000
TODE	1	1000
LDE	0.3	300
SDE, WB[1]	0.007	7
SDE, ME[2]	0.007	7

[1] SDE, WB is the shallow dose equivalent to the skin of the whole body

[2] SDE, ME the shallow dose equivalent to a major extremity.

RADIATION INTERACTIONS

Charged Particles
Ionization, Excitation, *Bremsstrahlung* (β^-), Annihilation (β^+)

Neutrons
Scattering ($E > 0.025$ eV)
- Elastic (energy & momentum are conserved)
- Inelastic (photon emitted)
- Absorption ($E < 0.025$ eV)
- Radiative Capture (η, γ)
- Particle Emission (η, α) (η, p) (η, η)
- Fission (η, f)

Gamma or X-ray photons
- Photoelectric Effect (generally $\leq$ 1 MeV)
- Compton Scattering (generally 200 keV - 5 MeV)
- Pair Production (min 1.022 MeV)

Scattered Photon
$T' = T / [1 + T(1 - \cos \Theta) / m_0c_2]$
where: $c_2 = 931.5$ MeV/amu

Bremsstrahlung
emitted energy is ~ 1/3 of the electron energy

Photon Attenuation: $I_x = I_0e^{-\mu x}$
Interaction Probability per gram:
- Photoelectric ~ Z^4 / E^3
- Compton independent of Z
- Pair Production ~ Z^1

$\mu_{Total} = \mu_{pe} + \mu_{cs} + \mu_{pp}$
$W_{Air} = 33.9$ eV per ion pair
Specific Ionization = S/W (i.p. / cm)

SHIELDING MATERIALS

α	N/A (7 mg/cm^2)
β^-	low Z, such as plastic or aluminum
γ	high Z, such as tungsten
mixed β^-/ γ	low Z, then high Z
neutron	hydrogenous material to thermalize (such as polyethylene) then neutron absorber (such as Cd, B, Li, Hf), then high Z to absorb "capture gammas"

Photon Half-Value Layers in CM

MeV	0.10	0.60	1.00	2.00	6.00	15.00
U	0.005	0.25	0.48	0.78	0.80	0.62
W	0.008	0.35	0.58	0.82	0.85	0.67
Pb	0.012	0.52	0.90	1.35	1.39	1.08
Sn	0.06	1.20	1.38	1.80	2.65	2.20
Cu	0.18	1.01	1.70	1.65	2.49	2.38
Fe	0.25	1.15	1.32	1.55	2.88	2.85
Al	1.12	3.30	4.45	5.90	9.67	11.7
Concrete	1.8	3.8	4.6	6.2	11.2	10.4
Water	4.20	7.80	9.60	14.2	25.0	35.7

This table applies to a thin shield and no provision is made for buildup factor. Always perform a radiation measurement to confirm adequacy of shield.

Tenth-value Thickness

Simply multiply the half-value thickness by the square root of 10 (3.162) to get the tenth-value thickness.

Example: A half-value tikness of concrete for Cs-137 gamma radiation is 3.8 cm. The tenth-value thickness is 3.8 cm x 3.162 = 12 cm.

Photon Shielding Buildup Factors

MeV	Water	Aluminum	Concrete	Iron	Lead
0.5	2.52	2.37	2.19	1.98	1.24
1.0	2.13	2.02	1.94	1.87	1.37
2.0	1.83	1.75	1.75	1.76	1.39

Incorporating Photon Buildup Factors

$I = I_0 \times B \times 0.5^n$

$I = I_0 \times B \times e^{-\mu x}$

μ is the linear attenuation coefficient in cm^{-1}

x is the shield thickness in cm

B is the buildup factor taken from tables, obtained by measurements, or calculations such as MCNP.

Neutron and Gamma Shielding
Simplified Shield Thickness Calculation

perform radiation measurements to verify these calculations

I = shielded exposure rate

I_0 = unshielded exposure rate

n = number of shielding layers (tenth or half)

$I = I_0 \times 0.1^n$ for tenth value thickness

$I = I_0 \times 0.5^n$ for half value thickness

Radiation Streaming

Consider the potential for radiation streaming thru gaps in the shielding. Design the shielding to minimize gaps and perform a comprehensive survey after the shielding is in place.

Stay-Time Calculation

Stay-time calculations are typically used to determine how long an individual can remain in an area with elevated radiation fields until they reach some pre-determined dose limit. The principles can also be applied to airborne areas.

Stay-time = Allowable exposure/exposure rate

Example: allowable exposure is 100 mR and exposure rate is 25 mR/hr

Stay-time = 100 mR / 25 mR/hr = 4 hours

Beta Dose Rates

	rad/h per mCi			Gy/h per MBq		
MeV	1 cm	10 cm	30 cm	1 cm	10 cm	30 cm
0.15	1,200	1.7	0	444	0.6	0
0.25	1,000	2.2	0.1	370	0.81	0.037
0.30	900	3.6	0.1	333	1.33	0.037
0.50	750	5.2	0.4	278	1.92	0.148
0.75	650	5.0	0.5	241	1.85	0.185
1.0	550	4.6	0.4	204	1.70	0.148
1.25	450	4.3	0.4	167	1.59	0.148
1.50	400	4.0	0.4	148	1.48	0.148
1.75	350	3.4	0.4	130	1.26	0.148
2.00	340	3.6	0.4	126	1.33	0.148
2.25	320	3.3	0.4	118	1.22	0.148

Beta dose should be treated as a “shallow” dose and should not be summed with “deep” doses. This chart should also be used to determine beta$^+$ doses from positron emitters.

Half-value Thickness vs Beta Energy

Isotope	Emax (MeV)	Half-Value Thickness mg / cm^2
C-14	0.156	2
Tc-99	0.292	7.5
Cl-36	0.714	15
Sr/Y-90	0.546 / 2.284	150
U-238 Betas from short lived progeny	0.191 / 2.281	130
P-32	1.710	150

Estimate the half-value thickness for a beta emitter.

mg/cm^2 = 50 x E^2

where E is Emax

This equation tends to underestimate the half-value thickness for low energy betas and overestimate the half-value thickness for high energy betas.

Positron Emitters Beta$^+$ Energy and % Abundance

	Half-life	**MeV** (%)		**Half-life**	**MeV** (%)
C-11	20.3m	0.960 (99.8%)	V-48	15.98d	0.697 (50.1%)
N-13	9.97m	1.199 (99.8%)	Mn-52	5.591d	2.633 (94.9%)
O-15	122s	1.732 (99.9%)	Co-56	77.3d	1.458 (19.0%)
F-18	1.83h	0.634 (96.7%)	Co-58	70.88d	0.475 (14.9%)
Na-22	2.605y	0.546 (89.8%)	Cu-62	9.74m	2.926 (97.2%)
Al-26	7.3E5y	3.210 (100%)	Zn-65	243.8d	0.330 (1.4%)
Ga-68	67.7m	0.822 (1.2%), 1.899 (89.1%)			
As-74	17.8d	0.945 (26.1%), 1.540 (3.0%)			
Rb-82	1.26m	2.601 (13.1%), 3.378 (81.8%)			
Ni-57	35.6h	0.737 (7.0%), 0.865 (35.3%)			

Several of the positron emitters are useful in PET studies. That usefulness is somewhat offset by the cost of producing the radionuclides and the added complexity of radiation protection. For all of the positron emitters the energy of the Beta+ must be considered. Refer to the table of Beta Dose Rates for estimates of beta$^+$ radiation exposure. Also, consider the annihilation photons when the positron comes into contact with a beta-, annihilating their masses and producing two 511 KeV photons. These photons present an external radiation hazard. For the patient undergoing a PET scan the combination of the positron energy and the photon energy must be considered.

Combining Radiation Types to Determine Total Dose

An individual radionuclide may have several different types of emissions. Those different types of emissions and the shortlived progeny of the individual radionuclide must be considered when determining a total dose.

Particulate radiation should be treated as a “shallow” dose while photons and neutrons should be treated as a “deep” dose and these two types of doses should not be summed.

This example with sodium-22 will clarify this concept.
Na-22 2.605y Beta$^+$ 0.546 MeV (89.8% Abundance)
1 mCi Gamma 1.275 MeV (99.9% Abundance)
From the table of Beta Dose Rates we find 320 rad/hr at 1 cm and 0.4 rad/hr at 30 cm. The near contact dose rate is much higher than the dose rate at 30 cm.

Using 6CEN for the gamma dose rate we find;

6CEN = 6 x 1 mCi x 1.275 MeV x 0.999
= 7.64 mRem/hr at 1 foot (~30 cm).

We can also use 6CEN for the annihilation photons from the positron.

6CEN = 6 x 1 mCi x 0.511 MeV x 2 x 0.898
= 5.51 mRem/hr at 1 foot (~ 30 cm).
6CEN = 6 x 1 mCi x 0.511 MeV x 2 x 0.898

The “shallow” dose from the positron at 30 cm is 400 mrad/hr and the “deep” dose from the gamma and photon radiation is
7.64 mRem/hr + 5.51 mRem/hr = 13.15 mRem/hr.

Shallow Dose Correction Factor

In accordance with 10CFR20 and 10CFR835 deep dose equivalent shall be used for posting of radiation areas. Shallow dose equivalent shall be reported separate from deep dose equivalent. Deep dose equivalent is the sum of the gamma and neutron deep dose equivalents. Shallow dose includes low-energy photons and charged particles such as betas, positrons, and protons. Alpha particles are not included in shallow dose.

The following applies to vented air ionization chambers with a window density thickness of 7 mg/cm^2 and a moveable shield with a density thickness of 1,000 mg/cm^2.

Determining the need to report a shallow dose;
If the Open Shield Reading divided by the Closed Shield Reading is equal to or greater than 1.2, then perform a shallow dose survey.

Calculate the shallow dose rate using this equation;
(Open Shield Reading - Closed Shield Reading) x CF
Obtain the **CF** (Correction Factor) from experimental or published data for the specific detector and radiation source(s).

Typical correction factors for betas range between 2 and 5 (multipliers). Typical correction factors for low energy photons range between 0.1 and 1 (multipliers).

Low energy photons that penetrate the closed shield of the ion chamber and produce a response in the instrument are part of the “deep” dose.

NEUTRON SHIELD THICKNESS

$I = I_0e^{-\sigma Nx}$

where; I = final neutron flux rate

I_0 = initial neutron flux rate

σ = shield cross section in cm^2

N = number of atoms per cm^3 in the shield

X = shield thickness in centimeters

Example: A dosimetry phantom is designed to simulate the composition of the human body. Ten % by weight is hydrogen. Assume a density of 1 and a shield cross section of hydrogen of 0.1 barns. A barn is 1E-24 cm^2. N, the number of atoms per cm^3, is 10% of Avogadro's number, so N equals 6E22 hydrogen atoms per cm^3. Assume the phantom thickness is 30 cm.

I^0 = 5,000 n/cm^2 /s

σ = 1E-25 cm^2 (0.1 barns)

N = 6E22 atoms per cm^3

x = 30 centimeters thick

$-\sigma Nx$ = 1E-25 times 6E22 times 30 = -0.18

$I = I_0e^{-\sigma Nx}$

I = 5,000 n/cm^2 /s $e^{-0.18}$

I = 5,000 n/cm^2 /s x 0.835 = 4,175 n/cm^2 /s

Initial neutron flux rate reduced from 5,000 n/cm^2/s to 4,175 n/cm^2/s

The attenuation of the neutron flux by the phantom is about 16%.

Neutron Half-Value Layers in centimeters

Energy in MeV	1	5	10	15
Polyethylene	3.7	6.1	7.7	8.8
Water	4.3	6.9	8.8	10.1
Concrete	6.8	11	14	16
Damp soil	8.8	14.3	18.2	20.8

Example: How many half-value layers of polyethylene are needed to attenuate a 100 mRem/hr 5 MeV neutron source to 5 mRem/hr? How thick does the polyehylene need to be?

$I = I_0 \times 0.5^n$ = 5 mRem/hr

I_0 = 100 mRem/hr n = the number of half-value layers

$I/I_0 = 0.5^n$

$5/100 = 0.05 = 0.5^n$

$\ln 0.05 = n \times \ln 0.5$

$n = \ln 0.05/\ln 0.5 = -2.996/-0.693 = 4.32$ half-value layers

cm = 4.32 half-value layers x 6.1 cm = 26.4 cm thick

Exposure Rate in an Air-Filled Ion Chamber

X = I / m[1 / (2.58E-4 C / kg)-R]
X = exposure rate (R / sec)
I = current (amperes)
M = mass of air in chamber (kg)

% Resolution of a Gamma Spec System

% R = FWHM / peak energy x 100 = % resolution
FWHM = peak energy width at full width half-max height
peak energy = photopeak energy of interest

True Count Rate Based on the Resolving Time of a Gas-Filled Detector

R_C = $R_O / (1 – R_O Y)$ = true count rate
R_O = observed count rate
Y = resolving time

Specific Gamma-Ray Constant Γ for Source Activity A

Γ = $\varphi E_\gamma (\mu_{en}/\rho)_{air}$ e / W
Γ = specific gamma constant (R-cm^2 / hr-A)
φ = photon fluence rate (γ / cm^2-hr)
Eγ = gamma photon energy (MeV)
(μ_{en}/ρ) = density thickness of air (g / cm^2)
e = electron charge (Coulombs)
W = average amount of energy to produce an ion pair in air (eV)

Photon Fluence Rate φ from a Point Source

Φ = $AY / 4\pi D^2$ = photon fluence rate (γ / cm^2-hr)
A = source activity (decay per hr)
Y = photon yield (γ / decay)
D = distance from point source (cm)

Exposure Rate (X) from a Point Source

X (R/hr) = $\Gamma A / D^2$
Γ = specific gamma ray constant (R/hr @ 1 meter per Ci)
A = activity of source in curies
D = distance from source in meters

Exposure Rate (X) from a Line Source

Inside L / 2: $X_1 (D_1) = X_2 (D_2)$

Outside L / 2: $X_1 (D_1)^2 = X_2 (D_2)^2$

D_1 = distance from source at location 1

D_2 = distance from source at location 2

L = length of line

Note: outside of L/2 the equation is the same as the inverse square rule.

Exposure Rate (X) from a Disk Source

$X \text{ (R/hr)} = \pi R^2 A_a \Gamma \times \ln[(R^2 + D^2) / D^2]/R^2$

Γ = R/hr @ 1 meter per Ci

A_a = activity per unit area (curies per sq. meter)

R = radius of source surface in meters

D = distance from source surface in meters

Simplify the formula by canceling the R^2s

$X \text{ (R/hr)} = \pi A_a \Gamma \times \ln[(R^2 + D^2) / D^2]$

Inverse Square Rule

$X_1 (D_1)^2 = X_2 (D_2)^2$

X_1 = Measured exposure rate

D_1 = Distance from source for the measured exposure rate

X_2 = Exposure rate to be calculated

D_2 = New distance from the source

Applying the Inverse Square Law to Dose Reduction

Given: A high activity source at an unknown distance.

Find: Exposure rate from the source at 30 cm without approaching closer to the source.

X_1 is measured exposure rate at distance Y

X_2 is measured exposure rate at distance Y + 100 cm

$X_1 (Y)^2 = X_2 (Y + 100 \text{ cm})^2$

$Y^2 = X_2 (Y + 100 \text{ cm})^2 / X_1$

Setup this equation by entering the exposure rates you measured at distances Y and Y + 100 cm.

Let us assume 100 mr/hr and 50 mr/hr for those two points.

$Y^2 = 50 (Y + 100 \text{ cm})^2 / 100 = 0.5Y^2 + 100Y + 5{,}000$

simplify this to $Y^2 - 200Y - 10{,}000 = 0$

This quadratic equation can be factored into two answers.

The positive answer for Y is 241.42 cm.

Now we know the distance for exposure rate X_2 and we can calculate the exposure rate at any distance.
The exposure rate at 30 cm would be 6,476 mR/hr but we were able to calculate that exposure rate without entering the High Radiation Area.

A simpler method without having to factor a quadratic equation is to back AWAY from the source until the exposure rate is ¼ of the initial rate. The distance you moved away is equal to the original distance to the source. Now you can use the inverse square rule to calculate the 30 cm exposure rate.

Signal levels for counting gases

Counting Gas	ω Factor (eV / ion pair)	Gas Density (g / L)
Air	33.8	1.2928
Ar	26.4	1.8
He	41.3	0.183
H_2	36.5	0.09
N_2	34.8	1.25
O_2	30.8	1.43
CH_4	27.3	0.717
Ne	36.2	0.9
Xe	21.5	5.9
Ne + 0.5 % Ar	25.3	0.909
Ar + 0.5 % C_2H_2	20.3	1.75
Ar + 0.8 % CH_4	26.0	1.78
Ar + 10 % CH_4 (P-10)	26.0	1.616

Use this equation to calculate the current flow in femto-amps for an ion chamber at 1 mR/hr exposure rate.

(0.871 x V x P x fill gas g / L) / (T x ω for fill gas)

where; V is chamber volume in cc, P is chamber pressure in mm Hg, fill gas g/l, T is 273.15 + ^{0}C, ω for fill gas

Table 1 of DOE 5400.5 Surface Activity Guidelines

Radionuclides	Ave	Max	Removable
Group 1: Transuranics, I-125, I-129, Ac-227, Ra-226, Ra-228, Th-228, Th-230, Pa-231	100	300	20
Group 2: Th-natural, Sr-90, I-126, I-131, I-133, Ra-223, Ra-224, U-232, Th-232	1,000	3,000	200
Group 3: U-natural, U-235, U-238, and associated decay products, alpha emitters	5,000	15,000	1,000
Group 4: Beta/gamma emiters[1]	5,000	15,000	1,000
Tritium[2]	N/A	N/A	10,000

[1] radionuclides with decay modes other than alpha emission or spontaneous fission except Sr-90 and others noted above

[2] applicable to surface and subsurface

Appendix D of 10CFR835

Nuclide	Removable	Total (fixed + removable)
Natural U, U-235, U-238, and associated decay products	1,000 alpha	5,000 alpha
Transuranics, Ra-226, Ra-228, Th-230, Th-228, Pa-231, Ac-227, I-125, I-129	20	500
Natural Th, Th-232, Sr-90, Ra-223, Ra-224, U-232, I-126, I-131, I-133	200	1,000
Beta/gamma emitters[1]	1,000	5,000
Tritium[2]	10,000	10,000

[1] nuclides with decay modes other than alpha emission or spontaneous fission except 90Sr and others noted above

[2] Tritium organic compounds, surfaces contaminated by HT, HTO, and metal tritide aerosols

Contamination levels in dpm/100 cm^2

INSTRUMENT SELECTION AND USE

Exposure/Absorbed Dose Rates (photon) - Ion Chamber, Energy Compensated GM, Tissue-Equivalent Plastic
Dose Equivalent Rates (neutron) - BF_3 or He^3 moderated, Neutron-Proton Recoil (Rossi Detector, Liquid Plastic Scintillator, Plastic/ZnS Scintillator) , $LiGdBO_3$-loaded Plastic, CLYC, Bubble Dosimeter
Beta and activity - Proportional Counter, GM pancake, Plastic Scintillator
Alpha activity - Proportional Counter, ZnS Scintillator, Air Proportional, Solid-state Silicon, Plastic Scintillator
Alpha + beta activity - Proportional Counter, Plastic/ZnS Scintillator, Plastic Scintillator, Solid-state Silicon
Gross gamma activity - NaI, CsI
X-ray spectroscopy - Si(Li)
Gamma spectroscopy - HPGe, CZT, HgI, CsI, LaBr
Alpha spectroscopy - Frisch Grid, Solid-state Silicon
Beta spectroscopy - BGO, Plastic Scintillator, Silicon

INSTRUMENT USE

Select an instrument appropriate for the isotope(s) to be surveyed for.

Check instrument for a valid calibration sticker and for damage that would prevent it from operating acceptably.

Check the battery condition.

Perform an operational (or performance) check.

Determine the isotope(s) correction factor to be applied to the measurement.

Calculate the instrument's MDA and compare to survey criteria. Go to the STATISTICS section of this document for MDA calculations.

IF the instrument does not meet all of the above criteria, then replace the instrument (or change/charge the batteries) or change your survey technique so that the instrument's MDA will meet the survey criteria.

Perform and then document the survey.

6CEN

The 6CEN equation can be used to calculate the exposure rate in R/hr at 30 cm for x-ray and gamma radiation point sources with energies between 60 KeV and 2 MeV.

R/hr at 30 cm = 6CEN

where;
C = curies of radioactive material
E = photon energy in MeV
N = abundance of that photon expressed as a decimal

1.6TBqEN

The same formula in Sv/h is given by 1.6 TBqEN,
where TBq is the number of terabecquels.

Sv/hr at 30 cm = 1.6TBqEN
where; TBq = quantity of radioactive material

Airborne Activity General Dispersion Model

Assume a 1 μCi (37 kBq) release of respirable Pu-239 inside a large room measuring 12 x 12 x 3 meters with a ventilation turnover rate of 7 volumes per hour. The General Dispersion Model uses this formula for volume.

$V = 2/3 \times \pi \times R^3$

Volume in cm^3	30 cm	1 M	10 M
@ distance R	5.65E4	2.09E6	2.09E9
Concentration @ distance R			
in μCi / cc	1.77E-5	4.78E-7	4.78E-10
in Bq / M^3	6.55E5	1.77E4	17.7
in DAC	8.85E6	2.39E5	239
Time for airborne wave front to reach distance R	13 sec	43 sec	7.15 min

1 CFM sample for 1 week equals 10,080 CF (285.4 M^3)

2 CFM sample for 1 week equals 20,160 CF (571 M^3)

Airborne Radioactivity (long-lived)

C_S = $R_N / (V \times \varepsilon \times SA \times CE \times CF)$
C_S = activity concentration at end of sample run time
R_N = net counting rate
V = sample volume
ε = detector efficiency
SA = self-absorption factor
CE = collection efficiency
CF = conversion from disintegrations per unit time to activity

Airborne Radioactivity (short-lived)

C_S = $R_N / [V \times \varepsilon \times SA \times CE \times CF \times (1-e^{-\lambda ts}) \times (e^{-\lambda td})]$
t_s = sample count time
t_d = time elapsed between end of sample run time and start of sample count time

RESPIRATORY PROTECTION FACTORS (PF) 10CFR20

Device	**Mode**	**Particulates**	**Vapors**	**PF**
Air-purifying half-mask	D	Y	N	10
Air-purifying full-face	D	Y	N	50
Air-purifying full-face	PP	Y	N	1000
Supplied-air hood	PP	Y	Y	1000*
Supplied-air full-face	PP	Y	Y	2000
SCBA	D	Y	N	50
SCBA	PD	Y	Y	10,000

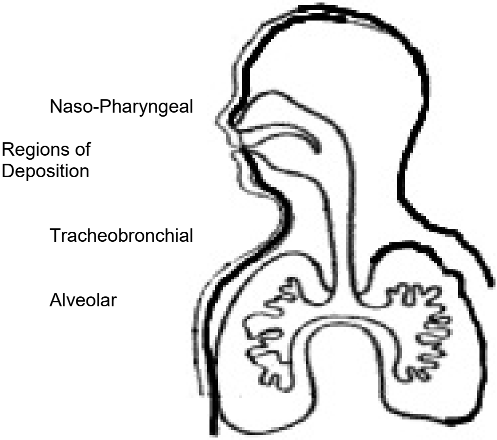
* 2000 for supplied-air hood if run at max flow with calibrated flow gauge. Bubble suits have been used in Pu atmospheres as high as 2,000,000 DAC. Supplied-air respirators are worn inside the bubble suits and real-time air monitoring INSIDE the bubble suits is performed.

Ventilation Rates

Ventilation rates of work areas for health physics and industrial hygiene requirements is typically 6 to 7 volume turnovers per hour.
Calculate the ventilation rate in CFM to ventilate a room at 7 volume turnovers per hour given room dimensions of 30 feet by 30 feet by 10 feet.
Volume of the room is 30 x 30 x 10 = 9,000 cubic feet. Seven volume turnovers per hour would be 7 times 9,000 cubic feet or 63,000 cubic feet per hour (1,050 CFM) room ventilation rate.

Lung Deposition from ICRP 30

AMAD	NP	TB	
μ	Naso-pharanx	Trachea-bronchus	Alveolar
0.1	0.01	0.08	0.61
1	0.3	0.08	0.25
10	0.9	0.08	0.04



AIR MONITORING

Concentration

Concentration is activity per volume of air and may be stated as dpm / cubic meter, uCi / ml, or Bq / cubic meter. DAC (**D**erived **A**ir **C**oncentration) is another way to express airborne radioactivity concentrations as relative hazards.

DPM = Sample CPM / Eff (CPM / DPM)
1 uCi = 2.22 E6 DPM
1 DPM / M^3 = 4.5 E-13 uCi / ml
1 uCi / ml = 2.22 E12 DPM / M^3
1 Bq = 1 DPS
DPM / M^3 = CPM/(Eff x total sample volume in M^3)
uCi / ml = CPM/(Eff x 2.22 E6 DPM/uCi x total sample volume in ml)
Bq / M^3 = CPM / (Eff x 60 DPM / Bq x total sample volume in M^3)
DAC = uCi/ml divided by (uCi/ml per DAC {DAC Factor})
1 DAC-h = 1 DAC exposure for 1 hour
1 DAC-h = 2.5 mrem = 25 uSv

Calculate the number of DAC-h on a filter by this formula
DAC-h = DPM on filter / (Sample LPM x 1.332E11 x DAC factor)

Calculate the DPM on a filter to reach 8 DAC-h
DPM = 8 DAC-h x LPM x 1.33E11 x DAC factor

Calculate the DAC level on a filter from the # of DPM
DAC = # of DPM / (DAC factor x LPM x time in minutes x 2.22E9)

AIR FLOW METER CORRECTIONS

Mass Flow Meters

$Q_S = Q_A (P_A / P_S \times T_S / T_A)$
$Q_A = Q_S (P_S / P_A \times T_A / T_S)$
where; Q_S is the STP flow rate
Q_A is the ambient flow rate
P_S is STP pressure
P_A is the ambient pressure
T_S is STP temperature
T_A is the ambient temperature

Rotameter Corrections

$Q_S = Q_I \times P_S / P_A \times T_S / T_A / \sqrt{(P_S / P_I \times T_A / T_S)}$

where; Q_I is the rotameter flow indication
P_I is the actual pressure inside the rotameter.

This correction assumes the rotameter markings are correct at STP. The actual pressure inside the rotameter should be used in the calculations.

For personnel protection against particulate airborne radioactivity ambient sample volumes instead of volumes corrected to STP should be used for calculations. The ambient respiratory rate will remain the same as atmospheric pressure changes from STP up to an elevation of approximately 12,000 feet (3,660 Meters).

Filter Media Characteristics for Alpha CAMs

Type		Pore Size	Filter DP	FWHM keV
Millipore	Fluoropore	5 μ	0.5"Hg	370
	Fluoropore	3 μ	0.8"Hg	300
	SMWP	5 μ	2.0"Hg	450
	SSWP	3 μ	3.1"Hg	350
	RW19	1.2 μ	3.8"Hg	450
	Durapore	5 μ	4.3"Hg	490
	AP40	0.7 μ	2.6"Hg	490
Bladewerx	Speclon 1.5	1.5 μ	2.6"Hg	300
	Speclon 5.0	5 μ	0.4"Hg	370
Whatman	GFA	0.3 μ	2.8"Hg	490
	EPM 2000	0.6 μ	1.8"Hg	1,000
Gelman	A/E Glass	1.0 μ	2.3"Hg	1,000
	Versapor 3000	3.0 μ	2.3"Hg	450
Hollingsworth & Vose				
	HV LB5211	0.3 μ	1.0"Hg	650

The rated pore size is for >99.99% collection efficiency for that size particle and greater. All of these filters have >99% collection efficiency for particles as small as 0.3 μm. The stated pressure drop is for a 40 mm collection diameter with an air flow rate of 2 ACFM and barometric pressure of 23.1"Hg. The FWHM is for Po-214 at 7.68 MeV and was determined using a 25 mm collection diameter and a 25 mm diameter diffused junction detector with a spacing of 4 mm. The pressure drop will be higher and the FWHM will be broader at higher barometric pressures.

DAC factors from 10CFR20 and 10CFR835
ALIs (Annual Limit on Intake) for Ingestion and Inlation from 10CFR20

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	µCi/mL	Bq/M³	Ingestion	Inhalation
H-3[1]	X	2E-05	7E+5	X	X
H-3[2]	X	2E-01	9E+9	X	X
H-3[3]	2E-05	X	X	8E+4	8E+4
STCs[4]	X	2E-06	8E+4	X	X
STCs[5]	X	1E-05	5E+5	X	X
Be-7	8E-06	1E-05	4E+5	4E+4	2E+4
Be-10	6E-09	2E-08	1E+3	1E+3	2E+2
C-11[6, 38]	X	1E-04	6E+6	X	X
C-11[7]	5E-04	4E-04	1E+7	X	1E+6
C-11[8]	3E-04	2E-04	9E+6	X	6E+5
C-11[9]	2E-04	X	X	4E+5	4E+5
C-14[6]	X	9E-07	3E+4	X	X
C-14[7]	7E-04	7E-04	2E+7	X	2E+6
C-14[8]	9E-05	8E-05	3E+6	X	2E+5
C-14[9]	1E-06	X	X	2E+3	2E+3
F-18[38]	3E-05	3E-06	1E+5	5E+4	7E+4
Na-22	3E-07	2E-07	1E+4	4E+2	6E+2
Na-24	2E-06	4E-07	1E+4	4E+3	5E+3
Mg-28	5E-07	3E-07	1E+4	7E+2	1E+3
Al-26	3E-08	4E-08	1E+3	4E+2	60
Si-31	1E-06	5E-06	1E+5	9E+3	3E+4
Si-32	2E-09	1E-08	3E+2	2E+3	5
P-32	2E-07	5E-07	7E+3	6E+2	4E+2
P-33	1E-06	4E-06	1E+4	6E+3	3E+3
S-35[10]	6E-06	4E-06	1E+5	X	1E+4
S-35	9E-07	5E-07	1E+4	6E+3	2E+3
Cl-36	1E-07	1E-07	4E+3	2E+3	2E+2
Cl-38[38]	2E-05	5E-06	2E+5	2E+4	4E+4
Cl-39[38]	2E-05	2E-06	1E+5	2E+4	5E+4
K-40	2E-07	1E-07	6E+3	3E+2	4E+2
K-42[38]	2E-06	2E-06	1E+5	5E+3	5E+3
K-43	4E-06	9E-07	3E+4	6E+3	9E+3
K-44	3E-05	8E-06	2E+5	2E+4	7E+4
K-45[38]	5E-05	9E-06	3E+5	3E+4	1E+5
Ca-41	2E-06	2E-06	8E+4	3E+3	4E+3

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Ca-45	4E-07	2E-07	9E+3	2E+3	8E+2
Ca-47	4E-07	2E-07	9E+3	8E+2	9E+2
Sc-43	9E-06	2E-06	7E+4	7E+3	2E+4
Sc-44m	3E-07	2E-07	1E+4	5E+2	7E+2
Sc-44	5E-06	1E-06	4E+4	4E+3	1E+4
Sc-46	1E-07	1E-07	4E+3	9E+2	2E+2
Sc-47	1E-06	7E-07	2E+4	2E+3	3E+3
Sc-48	6E-07	2E-07	1E+4	8E+2	1E+3
Sc-49[38]	2E-05	8E-06	3E+5	2E+4	5E+4
Ti-44	2E-09	7E-09	2E+2	3E+2	6
Ti-45	1E-05	2E-06	1E+5	9E+3	3E+4
V-47[38]	3E-05	6E-06	2E+5	3E+4	8E+4
V-48	3E-07	2E-07	7E+3	6E+2	6E+2
V-49	8E-06	1E-05	7E+5	7E+4	2E+4
Cr-48	3E-06	2E-06	8E+4	6E+3	7E+3
Cr-49[38]	4E-05	5E-06	2E+5	3E+4	8E+4
Cr-51	8E-06	1E-05	5E+5	4E+4	2E+4
Mn-51[38]	2E-05	7E-06	2E+5	2E+4	5E+4
Mn-52m[38]	4E-05	5E-06	2E+5	3E+4	9E+4
Mn-52	4E-07	2E-07	8E+3	7E+2	9E+2
Mn-53	5E-06	1E-05	2E+5	5E+4	1E+4
Mn-54	3E-07	4E-07	1E+4	2E+3	8E+2
Mn-56	6E-06	2E-06	8E+4	5E+3	2E+4
Fe-52	1E-06	5E-07	2E+4	9E+2	2E+3
Fe-55	8E-07	6E-07	2E+4	9E+3	2E+3
Fe-59	1E-07	1E-07	6E+3	8E+2	3E+2
Fe-60	3E-09	1E-09	60	30	6
Co-55	1E-06	5E-07	2E+4	1E+3	3E+3
Co-56	8E-08	1E-07	4E+3	4E+2	2E+2
Co-57	3E-07	9E-07	3E+4	4E+3	7E+2
Co-58m	3E-05	3E-05	1E+6	6E+4	6E+4
Co-58	3E-07	3E-07	1E+4	1E+3	7E+2
Co-60m[38]	1E-03	4E-04	1E+7	1E+6	3E+6
Co-60	1E-08	3E-08	1E+3	2E+2	30
Co-61[38]	2E-05	6E-06	2E+5	2E+4	6E+4
Co-62m[38]	6E-05	6E-06	2E+5	4E+4	2E+5
Ni-56	5E-07	X	X	1E+3	1E+3

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	µCi/mL	Bq/M^3	Ingestion	Inhalation
Ni-56[11]	X	4E-07	1E+4	X	X
Ni-56[12]	X	4E-07	1E+4	X	X
Ni-57	1E-06	X	X	2E+3	3E+3
Ni-57[11]	X	5E-07	2E+4	X	X
Ni-57[12]	X	7E-07	2E+4	X	X
Ni-59	8E-07	X	X	2E+4	2E+3
Ni-59[11]	X	2E-06	9E+4	X	X
Ni-59[12]	X	6E-07	2E+4	X	X
Ni-63	3E-07	X	X	9E+3	2E+3
Ni-63[11]	X	1E-06	4E+4	X	X
Ni-63[12]	X	2E-07	1E+4	X	X
Ni-65	7E-06	X	X	8E+3	2E+4
Ni-65[11]	X	4E-06	1E+5	X	X
Ni-65[12]	X	8E-07	3E+4	X	X
Ni-66	3E-07	X	X	4E+2	6E+2
Ni-66[11]	X	2E-07	1E+4	X	X
Ni-66[12]	X	2E-07	1E+4	X	X
Cu-60[38]	4E-05	4E-06	1E+5	3E+4	9E+4
Cu-61	1E-05	3E-06	1E+5	1E+4	3E+4
Cu-64	9E-06	3E-06	1E+5	1E+4	2E+4
Cu-67	2E-06	2E-06	3E+4	5E+3	5E+3
Zn-62	1E-06	9E-07	3E+4	1E+3	3E+3
Zn-63[38]	3E-05	8E-07	2E+5	2E+4	7E+4
Zn-65	1E-07	5E-06	7E+3	4E+2	3E+2
Zn-69m	3E-06	2E-07	6E+4	4E+3	7E+3
Zn-69[38]	6E-05	1E-06	2E+5	6E+4	1E+5
Zn-71m	7E-06	7E-06	5E+4	6E+3	2E+4
Zn-72	5E-07	1E-06	1E+4	1E+3	1E+3
Ga-65[38]	7E-05	3E-07	3E+5	5E+4	2E+5
Ga-66	1E-06	7E-07	2E+4	1E+3	3E+3
Ga-67	4E-06	2E-06	7E+4	7E+3	1E+4
Ga-68[38]	2E-05	4E-06	1E+5	2E+4	4E+4
Ga-70[38]	7E-05	1E-05	4E+5	5E+4	2E+5
Ga-72	1E-06	5E-07	2E+4	1E+3	3E+3
Ga-73	6E-06	2E-06	1E+5	5E+3	2E+4
Ge-66	8E-06	2E-06	9E+4	2E+4	2E+4
Ge-67[38]	4E-05	7E-06	2E+5	3E+4	9E+4

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Ge-68	4E-08	7E-08	2E+3	5E+3	1E+2
Ge-69	3E-06	1E-06	3E+4	1E+4	8E+3
Ge-71	2E-05	5E-05	1E+6	5E+5	4E+4
Ge-75[38]	3E-05	7E-06	2E+5	4E+4	8E+4
Ge-77	2E-06	1E-06	4E+4	9E+3	6E+3
Ge-78[38]	9E-06	3E-06	1E+5	2E+4	2E+4
As-69[38]	5E-05	9E-06	3E+5	3E+4	1E+5
As-70[38]	2E-05	2E-06	8E+4	1E+4	5E+4
As-71	2E-06	1E-06	4E+4	4E+3	5E+3
As-72	6E-07	4E-07	1E+4	9E+2	1E+3
As-73	7E-07	8E-07	3E+4	8E+3	2E+3
As-74	3E-07	3E-07	1E+4	1E+3	8E+2
As-76	6E-07	6E-07	2E+4	1E+3	1E+3
As-77	2E-06	1E-06	4E+4	4E+3	5E+3
As-78[38]	9E-06	3E-06	1E+5	8E+3	2E+4
Se-70[38]	2E-05	2E-06	9E+4	1E+4	4E+4
Se-73m[38]	6E-05	1E-05	4E+5	3E+4	1E+5
Se-73	5E-06	1E-06	5E+4	3E+3	1E+4
Se-75	3E-07	3E-07	1E+4	5E+2	6E+2
Se-79	2E-07	1E-07	6E+3	6E+2	6E+2
Se-81m[38]	3E-05	6E-06	2E+5	2E+4	7E+4
Se-81[38]	9E-05	1E-05	4E+5	6E+4	2E+5
Se-83[38]	5E-05	5E-06	1E+5	3E+4	1E+5
Br-74m[38]	2E-05	2E-06	1E+5	1E+4	4E+4
Br-74[38]	3E-05	4E-06	1E+5	2E+4	7E+4
Br-75[38]	2E-05	3E-06	1E+5	3E+4	5E+4
Br-76	2E-06	5E-07	2E+4	4E+3	4E+3
Br-77	8E-06	2E-06	7E+4	2E+4	2E+4
Br-80m	6E-06	5E-06	2E+5	2E+4	1E+4
Br-80[38]	8E-05	2E-05	7E+5	5E+4	2E+5
Br-82	2E-06	3E-07	1E+4	3E+3	4E+3
Br-83	3E-05	6E-06	2E+5	5E+4	6E+4
Br-84[38]	2E-05	5E-06	2E+5	2E+4	6E+4
Rb-79[38]	5E-05	8E-06	2E+5	4E+4	1E+5
Rb-81m[38]	1E-04	1E-05	6E+5	2E+5	3E+5
Rb-81	2E-05	2E-06	1E+5	4E+4	5E+4
Rb-82m	7E-06	8E-07	3E+4	1E+4	2E+4

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Rb-83	4E-07	5E-07	2E+4	6E+2	1E+3
Rb-84	3E-07	3E-07	1E+4	5E+2	8E+2
Rb-86	3E-07	4E-07	1E+4	5E+2	8E+2
Rb-87	6E-07	7E-07	2E+4	1E+3	2E+3
Rb-88[38]	3E-05	1E-05	5E+5	2E+4	6E+4
Rb-89[38]	6E-05	1E-05	3E+5	4E+4	1E+5
Sr-80[38]	5E-06	2E-06	9E+4	4E+3	1E+4
Sr-81[38]	3E-05	5E-06	2E+5	2E+4	8E+4
Sr-82	4E-08	7E-08	2E+3	2E+2	90
Sr-83	1E-06	9E-07	3E+4	2E+3	4E+3
Sr-85m[38]	3E-04	3E-05	1E+6	2E+5	6E+5
Sr-85	6E-07	8E-07	3E+4	3E+3	2E+3
Sr-87m	5E-05	9E-06	3E+5	4E+4	1E+5
Sr-89	6E-08	1E-07	3E+3	5E+2	1E+2
Sr-90	2E-09	7E-09	2E+2	30	4
Sr-91	1E-06	9E-07	3E+4	2E+3	4E+3
Sr-92	3E-06	1E-06	6E+4	3E+3	7E+3
Y-86m[38]	2E-05	6E-06	2E+5	2E+4	5E+4
Y-86	1E-06	4E-07	1E+4	1E+3	3E+3
Y-87	1E-06	8E-07	3E+4	2E+3	3E+3
Y-88	1E-07	1E-07	6E+3	1E+3	2E+2
Y-90m	5E-06	4E-06	1E+5	8E+3	1E+4
Y-90	3E-07	3E-07	1E+4	4E+2	6E+2
Y-91m[38]	7E-05	2E-05	7E+5	1E+5	2E+5
Y-91	5E-08	9E-08	3E+3	5E+2	1E+2
Y-92	3E-06	2E-06	7E+4	3E+3	8E+3
Y-93	1E-06	9E-07	3E+4	1E+3	2E+3
Y-94[38]	3E-05	8E-06	3E+5	2E+4	8E+4
Y-95[38]	6E-05	1E-05	4E+5	4E+4	1E+5
Zr-86	1E-06	5E-07	2E+4	1E+3	2E+3
Zr-88	9E-08	1E-07	5E+3	4E+3	2E+2
Zr-89	1E-06	6E-07	2E+4	2E+3	2E+3
Zr-93	3E-09	3E-09	1E+2	1E+3	6
Zr-95	5E-08	9E-08	3E+3	1E+3	1E+2
Zr-97	5E-07	4E-07	1E+4	6E+2	1E+3
Nb-88[38]	9E-05	5E-06	1E+5	5E+4	2E+5
Nb-89m[13]	2E-05	3E-06	1E+5	1E+4	4E+4

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Nb-89[14]	6E-06	2E-06	1E+5	5E+3	2E+4
Nb-90	1E-06	3E-07	1E+4	1E+3	2E+3
Nb-93m	7E-08	6E-07	2E+4	9E+3	2E+2
Nb-94	6E-09	2E-08	8E+2	9E+2	20
Nb-95m	9E-07	6E-07	2E+4	2E+3	2E+3
Nb-95	5E-07	4E-07	1E+4	2E+3	1E+3
Nb-96	1E-06	4E-07	1E+4	1E+3	2E+3
Nb-97[38]	3E-05	5E-06	1E+5	2E+4	7E+4
Nb-98[38]	2E-05	3E-06	1E+5	1E+4	5E+4
Mo-90	2E-06	7E-07	2E+4	2E+3	5E+3
Mo-93m	6E-06	1E-06	3E+4	4E+3	1E+4
Mo-93	8E-08	2E-07	7E+3	2E+4	2E+2
Mo-99	6E-07	5E-07	1E+4	1E+3	1E+3
Mo-101[38]	6E-05	6E-06	2E+5	4E+4	1E+5
Tc-93m[38]	6E-05	7E-06	2E+5	3E+4	2E+5
Tc-93	3E-05	3E-06	1E+5	3E+4	7E+4
Tc-94m[38]	2E-05	4E-06	1E+5	2E+4	4E+4
Tc-94	8E-06	1E-06	3E+4	9E+3	2E+4
Tc-95m	8E-07	6E-07	2E+4	4E+3	2E+3
Tc-95	8E-06	1E-06	5E+4	1E+4	2E+4
Tc-96m[38]	1E-04	2E-05	1E+6	2E+5	2E+5
Tc-96	9E-07	3E-07	1E+4	2E+3	2E+3
Tc-97m	5E-07	2E-07	7E+3	5E+3	1E+3
Tc-97	2E-06	3E-06	1E+5	4E+4	6E+3
Tc-98	1E-07	9E-08	3E+3	1E+3	3E+2
Tc-99m	6E-05	1E-05	4E+5	8E+4	2E+5
Tc-99	3E-07	1E-07	6E+3	4E+3	7E+2
Tc-101[38]	1E-04	1E-05	4E+5	9E+4	3E+5
Tc-104[38]	3E-05	7E-06	2E+5	2E+4	7E+4
Ru-94[38]	2E-05	5E-06	1E+5	2E+4	4E+4
Ru-97	5E-06	2E-06	8E+4	8E+3	1E+4
Ru-103	3E-07	2E-07	9E+3	2E+3	6E+2
Ru-105	5E-06	2E-06	8E+4	5E+3	1E+4
Ru-106	5E-09	1E-08	5E+2	2E+2	10
Rh-99m	2E-05	3E-06	1E+5	2E+4	6E+4
Rh-99	8E-07	6E-07	2E+4	2E+3	2E+3
Rh-100	2E-06	5E-07	1E+4	2E+3	4E+3

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	µCi/mL	Bq/M^3	Ingestion	Inhalation
Rh-101m	3E-06	1E-06	6E+4	6E+3	8E+3
Rh-101	6E-08	1E-07	6E+3	2E+3	2E+2
Rh-102m	5E-08	1E-07	4E+3	1E+3	1E+2
Rh-102	2E-08	6E-08	2E+3	6E+2	60
Rh-103m[38]	5E-04	2E-04	8E+6	4E+5	1E+6
Rh-105	2E-06	1E-06	4E+4	4E+3	6E+3
Rh-106m	1E-05	1E-06	5E+4	8E+3	3E+4
Rh-107[38]	1E-04	9E-06	3E+5	7E+4	2E+5
Pd-100	5E-07	5E-07	2E+4	1E+3	1E+3
Pd-101	1E-05	3E-06	1E+5	1E+4	3E+4
Pd-103	1E-06	1E-06	6E+4	6E+3	4E+3
Pd-107	2E-07	1E-06	7E+4	3E+4	4E+2
Pd-109	2E-06	1E-06	4E+4	2E+3	5E+3
Ag-102[38]	8E-05	7E-06	2E+5	5E+4	2E+5
Ag-103[38]	4E-05	7E-06	2E+5	4E+4	1E+5
Ag-104m[38]	4E-05	6E-06	2E+5	3E+4	9E+4
Ag-104[38]	3E-05	3E-06	1E+5	2E+4	7E+4
Ag-105	4E-07	7E-07	2E+4	3E+3	1E+3
Ag-106m	3E-07	2E-07	9E+3	8E+2	7E+2
Ag-106[38]	8E-05	1E-05	4E+5	6E+4	2E+5
Ag-108m	1E-08	2E-08	1E+3	6E+2	20
Ag-110m	4E-08	7E-08	2E+3	5E+2	90
Ag-111	4E-07	3E-07	1E+4	9E+2	9E+2
Ag-112	3E-06	2E-06	8E+4	3E+3	8E+3
Ag-115[38]	3E-05	8E-06	3E+5	3E+4	8E+4
Cd-104[38]	3E-05	4E-06	1E+5	2E+4	7E+4
Cd-107	2E-05	4E-06	1E+5	2E+4	5E+4
Cd-109	1E-08	1E-07	9E+2	3E+2	50
Cd-113m	1E-09	1E-09	60	20	2
Cd-113	9E-10	1E-09	50	20	2
Cd-115m	2E-08	3E-08	1E+3	3E+2	50
Cd-115	5E-07	4E-07	1E+4	9E+2	1E+3
Cd-117m	5E-06	1E-06	4E+4	5E+3	1E+4
Cd-117	5E-06	2E-06	7E+4	5E+3	1E+4
In-109	2E-05	4E-06	1E+5	2E+4	4E+4
In-110[15, 38]	2E-05	4E-06	1E+5	2E+4	4E+4
In-110[16]	7E-06	9E-07	3E+4	5E+3	2E+4

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
In-111	3E-06	1E-06	5E+4	4E+3	6E+3
In-112	3E-04	1E-05	6E+5	2E+5	6E+5
In-113m[38]	6E-05	1E-05	3E+5	5E+4	1E+5
In-114m	3E-08	5E-08	1E+3	3E+2	60
In-115m	2E-05	6E-06	2E+5	1E+4	4E+4
In-115	6E-10	1E-09	40	40	10
In-116m[38]	3E-05	4E-06	1E+5	2E+4	8E+4
In-117m[38]	1E-05	5E-06	1E+5	1E+4	3E+4
In-117[38]	7E-05	5E-06	2E+5	6E+4	2E+5
In-119m[38]	5E-05	1E-05	4E+5	4E+4	1E+5
Sn-110	5E-06	1E-06	6E+4	4E+3	1E+4
Sn-111[38]	9E-05	1E-05	5E+5	7E+4	2E+5
Sn-113	2E-07	2E-07	1E+4	2E+3	5E+2
Sn-117m	5E-07	2E-07	9E+3	2E+3	1E+3
Sn-119m	4E-07	3E-07	1E+4	3E+3	1E+3
Sn-121m	2E-07	1E-07	6E+3	3E+3	5E+2
Sn-121	5E-06	2E-06	7E+4	6E+3	1E+4
Sn-123m[38]	5E-05	7E-06	2E+5	5E+4	1E+5
Sn-123	7E-08	1E-07	3E+3	5E+2	2E+2
Sn-125	1E-07	2E-07	7E+3	4E+2	4E+2
Sn-126	2E-08	3E-08	1E+3	3E+2	60
Sn-127	8E-06	2E-06	7E+4	7E+3	2E+4
Sn-128[38]	1E-05	2E-06	8E+4	9E+3	3E+4
Sb-115[38]	1E-04	1E-05	4E+5	8E+4	2E+5
Sb-116m[38]	3E-05	2E-06	1E+5	2E+4	7E+4
Sb-116[38]	1E-04	1E-05	3E+5	7E+4	3E+5
Sb-117	9E-05	1E-05	3E+5	7E+4	2E+5
Sb-118m	8E-06	1E-06	4E+4	5E+3	2E+4
Sb-119	1E-05	6E-06	2E+5	2E+4	3E+4
Sb-120[17]	2E-04	2E-05	7E+5	1E+5	4E+5
Sb-120[18]	5E-07	3E-07	1E+4	9E+2	1E+3
Sb-122	4E-07	4E-07	1E+4	7E+2	1E+3
Sb-124m[38]	2E-04	3E-05	1E+6	2E+5	6E+5
Sb-124	1E-07	1E-07	4E+3	5E+2	2E+2
Sb-125	2E-07	1E-07	6E+3	2E+3	5E+2
Sb-126m[38]	8E-05	7E-06	2E+5	5E+4	2E+5
Sb-126	2E-07	1E-07	6E+3	5E+2	5E+2

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Sb-127	4E-07	3E-07	1E+4	7E+2	9E+2
Sb-128[19]	1E-06	5E-07	2E+4	8E+4	4E+5
Sb-128[20]	2E-04	9E-06	3E+5	1E+3	3E+3
Sb-129	4E-06	1E-06	5E+4	3E+3	9E+3
Sb-130[38]	3E-05	2E-06	1E+5	2E+4	6E+4
Sb-131[38]	1E-05	4E-06	1E+5	1E+4	2E+4
Te-116	9E-06	2E-06	7E+4	8E+3	2E+4
Te-116[10]	X	6E-06	1E+3	X	X
Te-121m	8E-08	1E-07	4E+3	5E+2	2E+2
Te-121m[10]	X	4E-08	1E+3	X	X
Te-121	1E-06	1E-06	4E+4	3E+3	3E+3
Te-121[10]	X	1E-06	3E+4	X	X
Te-123m	9E-08	1E-07	4E+3	6E+2	2E+2
Te-123m[10]	X	5E-08	2E+3	X	X
Te-123	8E-08	2E-08	1E+3	5E+2	2E+2
Te-123[10]	X	1E-08	4E+2	X	X
Te-125m	2E-07	1E-07	7E+3	1E+3	4E+2
Te-125m[10]	X	1E-07	3E+3	X	X
Te-127m	1E-07	9E-08	3E+3	6E+2	3E+2
Te-127m[10]	X	6E-08	2E+3	X	X
Te-127	7E-06	3E-06	1E+5	7E+3	2E+4
Te-127[10]	X	7E-06	2E+5	X	X
Te-129m	1E-07	1E-07	3E+3	5E+2	2E+2
Te-129m[10]	X	1E-07	5E+3	X	X
Te-129[38]	3E-05	7E-06	2E+5	3E+4	6E+4
Te-129[10]	X	1E-05	5E+5	X	X
Te-131m	2E-07	3E-07	1E+4	3E+2	4E+2
Te-131m[10]	X	1E-07	5E+3	X	X
Te-131[38]	2E-06	7E-06	2E+5	3E+3	5E+3
Te-131[10]	X	6E-06	2E+5	X	X
Te-132	9E-08	1E-07	6E+3	2E+2	2E+2
Te-132[10]	X	7E-08	2E+3	X	X
Te-133m[10]	X	1E-06	6E+4	X	X
Te-133m[38]	2E-06	2E-06	1E+5	3E+3	5E+3
Te-133[38]	9E-06	9E-06	3E+5	1E+4	2E+4
Te-133[10]	X	7E-06	2E+5	X	X
Te-134[10]	X	6E-06	2E+5	X	X

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Te-134[38]	1E-05	2E-06	1E+5	2E+4	2E+4
I-120m[38]	9E-06	2E-06	1E+5	1E+4	2E+4
I-120m[10]	X	3E-06	5E+4	X	X
I-120m[21]	X	4E-06	8E+4	X	X
I-120[38]	4E-06	2E-06	6E+4	4E+3	9E+3
I-120[10]	X	1E-06	5E+4	X	X
I-120[21]	X	1E-06	1E+5	X	X
I-121	8E-06	8E-06	3E+5	1E+4	2E+4
I-121[10]	X	4E-06	1E+5	X	X
I-121[21]	X	5E-06	2E+5	X	X
I-123	3E-06	2E-06	1E+5	3E+3	6E+3
I-123[10]	X	1E-06	5E+4	X	X
I-123[21]	X	1E-06	7E+4	X	X
I-124	3E-08	4E-08	1E+3	50	80
I-124[10]	X	2E-08	9E+2	X	X
I-124[21]	X	3E-08	1E+3	X	X
I-125	3E-08	3E-08	1E+3	40	60
I-125[10]	X	2E-08	7E+2	X	X
I-125[21]	X	2E-08	9E+2	X	X
I-126	1E-08	2E-08	7E+2	20	40
I-126[10]	X	1E-08	4E+2	X	X
I-126[21]	X	1E-08	5E+2	X	X
I-128	5E-05	1E-05	6E+5	4E+4	1E+5
I-128[10]	X	8E-06	3E+5	X	X
I-128[21]	X	3E-05	1E+6	X	X
I-129	4E-09	5E-09	2E+2	50	90
I-129[10]	X	2E-09	1E+2	X	X
I-129[21]	X	3E-09	1E+2	X	X
I-130	3E-07	3E-07	1E+4	4E+2	7E+2
I-130[10]	X	1E-07	6E+3	X	X
I-130[21]	X	2E-07	7E+3	X	X
I-131	2E-08	2E-08	9E+2	30	50
I-131[10]	X	1E-08	5E+2	X	X
I-131[21]	X	1E-08	6E+2	X	X
I-132m[38]	4E-06	3E-06	1E+5	4E+3	8E+3
I-132m[10]	X	1E-06	6E+4	X	X
I-132m[21]	X	1E-06	7E+4	X	X

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
I-132	3E-06	2E-06	7E+4	4E+3	8E+3
I-132[10]	X	1E-06	5E+4	X	X
I-132[21]	X	1E-06	6E+4	X	X
I-133	1E-07	1E-07	5E+3	1E+2	3E+2
I-133[10]	X	7E-08	2E+3	X	X
I-133[21]	X	9E-08	3E+3	X	X
I-134[38]	2E-05	3E-06	1E+5	2E+4	5E+4
I-134[10]	X	3E-06	1E+5	X	X
I-134[21]	X	8E-06	2E+5	X	X
I-135	7E-07	6E-07	2E+4	8E+2	2E+3
I-135[10]	X	3E-07	1E+4	X	X
I-135[21]	X	4E-07	1E+4	X	X
Cs-125[38]	6E-05	1E-05	4E+5	5E+4	1E+5
Cs-127	4E-05	4E-06	1E+5	6E+4	9E+4
Cs-129	1E-05	2E-06	9E+4	2E+4	3E+4
Cs-130[38]	8E-05	1E-05	6E+5	6E+4	2E+5
Cs-131	1E-05	7E-06	2E+5	2E+4	3E+4
Cs-132	2E-06	9E-07	3E+4	3E+3	4E+3
Cs-134m	6E-05	8E-06	2E+5	1E+5	1E+5
Cs-134	4E-08	5E-08	2E+3	70	1E+2
Cs-135m[38]	8E-05	8E-06	2E+5	1E+5	2E+5
Cs-135	5E-07	5E-07	2E+4	7E+2	1E+3
Cs-136	3E-07	2E-07	1E+4	4E+2	7E+2
Cs-137	6E-08	8E-08	3E+3	1E+2	2E+2
Cs-138[38]	2E-05	5E-06	2E+5	2E+4	6E+4
Ba-126[38]	6E-06	4E-06	1E+5	6E+3	2E+4
Ba-128	7E-07	4E-07	1E+4	5E+2	2E+3
Ba-131m	6E-04	4E-05	1E+6	4E+5	1E+6
Ba-131	3E-06	1E-06	4E+4	3E+3	8E+3
Ba-133m	4E-06	2E-06	7E+4	2E+3	9E+3
Ba-133	3E-07	3E-07	1E+4	2E+3	7E+2
Ba-135m	5E-06	2E-06	9E+4	3E+3	1E+4
Ba-139[38]	1E-05	1E-05	3E+5	1E+4	3E+4
Ba-140	6E-07	3E-07	1E+4	5E+2	1E+3
Ba-141[38]	3E-05	1E-05	4E+5	2E+4	7E+4
Ba-142[38]	6E-05	9E-06	3E+5	5E+4	1E+5
La-131[38]	5E-05	8E-06	3E+5	5E+4	1E+5

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
La-132	4E-06	1E-06	5E+4	3E+3	1E+4
La-135	4E-05	1E-05	4E+5	4E+4	9E+4
La-137	3E-08	4E-08	1E+3	1E+4	60
La-138	1E-09	3E-09	1E+2	9E+2	4
La-140	5E-07	3E-07	1E+4	6E+2	1E+3
La-141	4E-06	2E-06	9E+4	4E+3	9E+3
La-142[38]	9E-06	2E-06	8E+4	8E+3	2E+4
La-143[38]	4E-05	1E-05	4E+5	4E+4	9E+4
Ce-134	3E-07	3E-07	1E+4	5E+2	7E+2
Ce-135	2E-06	5E-07	2E+4	2E+3	4E+3
Ce-137m	2E-06	9E-07	3E+4	2E+3	4E+3
Ce-137	5E-05	1E-05	7E+5	5E+4	1E+5
Ce-139	3E-07	4E-07	1E+4	5E+3	7E+2
Ce-141	2E-07	1E-07	6E+3	2E+3	6E+2
Ce-143	7E-07	5E-07	2E+4	1E+3	2E+3
Ce-144	6E-09	1E-08	7E+2	2E+2	10
Pr-136[38]	9E-05	1E-05	3E+5	5E+4	2E+5
Pr-137[38]	6E-05	9E-06	3E+5	4E+4	1E+5
Pr-138m	2E-05	2E-06	7E+4	1E+4	4E+4
Pr-139	5E-05	1E-05	2E+5	4E+4	1E+5
Pr-142m[38]	6E-05	5E-05	2E+6	8E+4	1E+5
Pr-142	8E-07	7E-07	2E+4	1E+3	2E+3
Pr-143	3E-07	2E-07	9E+3	9E+2	7E+2
Pr-144[38]	5E-05	1E-05	4E+5	3E+4	1E+5
Pr-145	3E-06	2E-06	8E+4	3E+3	8E+3
Pr-147[38]	8E-05	9E-06	3E+5	5E+4	2E+5
Nd-136[38]	2E-05	4E-06	1E+5	1E+4	5E+4
Nd-138	2E-06	1E-06	5E+4	2E+3	5E+3
Nd-139m	6E-06	1E-06	5E+4	5E+3	1E+4
Nd-139[38]	1E-04	1E-05	6E+5	9E+4	3E+5
Nd-141	3E-04	3E-05	1E+6	2E+5	6E+5
Nd-147	4E-07	2E-07	9E+3	1E+3	8E+2
Nd-149[38]	1E-05	4E-06	1E+5	1E+4	2E+4
Nd-151[38]	8E-05	9E-06	3E+5	7E+4	2E+5
Pm-141[38]	7E-05	1E-05	4E+5	5E+4	2E+5
Pm-143	2E-07	5E-07	2E+4	5E+3	6E+2
Pm-144	5E-08	1E-07	3E+3	1E+3	1E+2

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Pm-145	7E-08	1E-07	1E+4	1E+4	2E+2
Pm-146	2E-08	4E-08	1E+3	2E+3	40
Pm-147	5E-08	1E-07	4E+3	4E+3	1E+2
Pm-148m	1E-07	1E-07	4E+3	7E+2	3E+2
Pm-148	2E-07	2E-07	9E+3	4E+2	5E+2
Pm-149	8E-07	6E-07	2E+4	1E+3	2E+3
Pm-150	7E-06	2E-06	8E+4	5E+3	2E+4
Pm-151	1E-06	8E-07	3E+4	2E+3	3E+3
Sm-141m[38]	4E-05	5E-06	2E+5	3E+4	1E+5
Sm-141[38]	8E-05	1E-05	4E+5	5E+4	2E+5
Sm-142[38]	1E-05	4E-06	1E+5	8E+3	3E+4
Sm-145	2E-07	4E-07	1E+4	6E+3	5E+2
Sm-146	1E-11	2E-11	1	10	4E-2
Sm-147	2E-11	2E-11	1	20	4E-2
Sm-151	4E-08	7E-08	2E+3	1E+4	1E+2
Sm-153	1E-06	8E-07	3E+4	2E+3	3E+3
Sm-155[38]	9E-05	1E-05	3E+5	6E+4	2E+5
Sm-156	4E-06	2E-06	7E+4	5E+3	9E+3
Eu-145	8E-07	5E-07	2E+4	2E+3	2E+3
Eu-146	5E-07	3E-07	1E+4	1E+3	1E+3
Eu-147	7E-07	5E-07	2E+4	3E+3	2E+3
Eu-148	1E-07	2E-07	9E+3	1E+3	4E+2
Eu-149	1E-06	2E-06	9E+4	1E+4	3E+3
Eu-150[22]	4E-06	2E-06	7E+4	3E+3	8E+3
Eu-150[23]	8E-09	1E-08	6E+2	8E+2	20
Eu-152m	3E-06	1E-06	6E+4	3E+3	6E+3
Eu-152	1E-08	2E-08	7E+2	8E+2	20
Eu-154	8E-09	1E-08	5E+2	5E+2	20
Eu-155	4E-08	7E-08	2E+3	4E+3	90
Eu-156	2E-07	1E-07	6E+3	6E+2	5E+2
Eu-157	2E-06	1E-06	4E+4	2E+3	5E+3
Eu-158[38]	2E-05	5E-06	1E+5	2E+4	6E+4
Gd-145[38]	6E-05	7E-06	2E+5	5E+4	2E+5
Gd-146	5E-08	1E-07	4E+3	1E+3	1E+2
Gd-147	1E-06	6E-07	2E+4	2E+3	4E+3
Gd-148	3E-12	5E-12	0.2	10	8E-3

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Gd-149	9E-07	7E-07	2E+4	3E+3	2E+3
Gd-151	2E-07	2E-07	9E+3	6E+3	4E+2
Gd-152	4E-12	7E-12	0.2	20	1E-2
Gd-153	6E-08	9E-08	3E+3	5E+3	1E+2
Gd-159	2E-06	1E-06	5E+4	3E+3	6E+3
Tb-147[38]	1E-05	2E-06	1E+5	9E+3	3E+4
Tb-149	3E-07	1E-07	6E+3	5E+3	7E+2
Tb-150	9E-06	2E-06	8E+4	5E+3	2E+4
Tb-151	4E-06	1E-06	4E+4	4E+3	9E+3
Tb-153	3E-06	2E-06	8E+4	5E+3	7E+3
Tb-154	2E-06	5E-07	2E+4	2E+3	4E+3
Tb-155	3E-06	2E-06	8E+4	6E+3	8E+3
Tb-156m[24]	3E-06	2E-06	9E+4	2E+4	3E+4
Tb-156m[25]	1E-05	4E-06	1E+5	7E+3	8E+3
Tb-156	6E-07	4E-07	1E+4	1E+3	1E+3
Tb-157	1E-07	2E-07	8E+3	5E+4	3E+2
Tb-158	8E-09	1E-08	6E+2	1E+3	20
Tb-160	9E-08	1E-07	3E+3	7E+2	2E+2
Tb-161	7E-07	4E-07	1E+4	2E+3	2E+3
Dy-155	1E-05	2E-06	1E+5	9E+3	3E+4
Dy-157	3E-05	5E-06	1E+5	2E+4	6E+4
Dy-159	1E-06	2E-06	8E+4	1E+4	2E+3
Dy-165	2E-05	6E-06	2E+5	1E+4	5E+4
Dy-166	3E-07	3E-07	1E+4	6E+2	7E+2
Ho-155[38]	6E-05	1E-05	4E+5	4E+4	2E+5
Ho-157[38]	6E-04	2E-05	1E+6	3E+5	1E+6
Ho-159[38]	4E-04	2E-05	9E+5	2E+5	1E+6
Ho-161	2E-04	3E-05	1E+6	1E+5	4E+5
Ho-162m[38]	1E-04	9E-06	3E+5	5E+4	3E+5
Ho-162[38]	1E-03	5E-05	2E+6	5E+5	2E+6
Ho-164m[38]	1E-04	3E-05	1E+6	1E+5	3E+5
Ho-164[38]	3E-04	2E-05	8E+5	2E+5	6E+5
Ho-166m	3E-09	7E-09	2E+2	6E+2	70
Ho-166	7E-07	6E-07	2E+4	9E+2	2E+3
Ho-167	2E-05	4E-06	1E+5	2E+4	6E+4
Er-161	3E-05	3E-06	1E+5	2E+4	6E+4
Er-165	8E-05	2E-05	1E+6	6E+4	2E+5

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Er-169	1E-06	6E-07	2E+4	3E+3	3E+3
Er-171	4E-06	1E-06	6E+4	4E+3	1E+4
Er-172	6E-07	4E-07	1E+4	1E+3	1E+3
Tm-162[38]	1E-04	9E-06	3E+5	7E+4	3E+5
Tm-166	6E-06	1E-06	4E+4	4E+3	1E+4
Tm-167	8E-07	5E-07	2E+4	2E+3	2E+3
Tm-170	9E-08	1E-07	4E+3	8E+2	2E+2
Tm-171	1E-07	2E-07	9E+3	1E+4	3E+2
Tm-172	5E-07	4E-07	1E+4	7E+2	1E+3
Tm-173	5E-06	2E-06	8E+4	4E+3	1E+4
Tm-175[38]	1E-04	8E-06	2E+5	7E+4	3E+5
Yb-162[38]	1E-04	1E-05	5E+5	7E+4	3E+5
Yb-166	8E-07	5E-07	2E+4	1E+3	3E+3
Yb-167[38]	3E-04	3E-05	1E+6	3E+5	7E+5
Yb-169	3E-07	2E-07	8E+3	2E+3	7E+2
Yb-175	1E-06	8E-07	2E+4	3E+3	3E+3
Yb-177[38]	2E-05	5E-06	2E+5	2E+4	5E+4
Yb-178[38]	2E-05	5E-06	1E+5	1E+4	4E+4
Lu-169	2E-06	9E-07	3E+4	3E+3	4E+3
Lu-170	8E-07	4E-07	1E+4	1E+3	2E+3
Lu-171	8E-07	6E-07	2E+4	2E+3	2E+3
Lu-172	5E-07	3E-07	1E+4	1E+3	1E+3
Lu-173	1E-07	2E-07	8E+3	5E+3	3E+2
Lu-174m	9E-08	2E-07	7E+3	2E+3	2E+2
Lu-174	5E-08	9E-08	3E+3	5E+3	1E+2
Lu-176m	9E-06	3E-06	1E+5	8E+3	2E+4
Lu-176	2E-09	3E-09	1E+2	7E+2	50
Lu-177m	3E-08	4E-08	1E+3	7E+2	80
Lu-177	9E-07	5E-07	1E+4	2E+3	2E+3
Lu-178m[38]	7E-05	4E-06	1E+5	5E+4	2E+5
Lu-178	5E-05	8E-06	3E+5	4E+4	1E+5
Lu-179	6E-06	3E-06	1E+5	6E+3	2E+4
Hf-170	2E-06	1E-06	4E+4	3E+3	5E+3
Hf-172	4E-09	6E-09	2E+2	1E+3	90
Hf-173	5E-06	2E-06	8E+4	5E+3	1E+4
Hf-175	4E-07	5E-07	2E+4	3E+3	9E+2
Hf-177m[38]	2E-05	1E-06	6E+4	2E+4	6E+4

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Hf-178m	5E-10	8E-10	30	3E+2	10
Hf-179m	1E-07	1E-07	6E+3	1E+3	3E+2
Hf-180m	9E-06	1E-06	6E+4	7E+3	2E+4
Hf-181	7E-08	1E-07	4E+3	1E+3	2E+2
Hf-182m[38]	4E-05	4E-06	1E+5	4E+4	9E+4
Hf-182	3E-10	5E-10	20	2E+2	0.8
Hf-183[38]	2E-05	4E-06	1E+5	2E+4	5E+4
Hf-184	3E-06	1E-06	4E+4	2E+3	6E+3
Ta-172[38]	4E-05	5E-06	1E+5	4E+4	1E+5
Ta-173	7E-06	3E-06	1E+5	7E+3	2E+4
Ta-174[38]	4E-05	5E-06	2E+5	3E+4	9E+4
Ta-175	6E-06	1E-06	6E+4	6E+3	1E+4
Ta-176	5E-06	1E-06	3E+4	4E+3	1E+4
Ta-177	7E-06	4E-06	1E+5	1E+4	2E+4
Ta-178	3E-05	3E-06	1E+5	2E+4	7E+4
Ta-179	4E-07	1E-06	7E+4	2E+4	9E+2
Ta-180m	2E-05	9E-06	3E+5	2E+4	6E+4
Ta-180	1E-08	4E-08	1E+3	1E+3	20
Ta-182m[38]	2E-04	6E-06	2E+5	2E+5	4E+5
Ta-182	6E-08	7E-08	2E+3	8E+2	1E+2
Ta-183	4E-07	2E-07	1E+4	9E+2	1E+3
Ta-184	2E-06	8E-07	3E+4	2E+3	5E+3
Ta-185[38]	3E-05	5E-06	1E+5	3E+4	6E+4
Ta-186[38]	9E-05	7E-06	2E+5	5E+4	2E+5
W-176	2E-05	3E-06	1E+5	1E+4	5E+4
W-177	4E-05	5E-06	2E+5	2E+4	9E+4
W-178	8E-06	3E-06	1E+5	5E+3	2E+4
W-179[38]	7E-04	1E-04	5E+6	5E+5	2E+6
W-181	1E-05	1E-05	4E+5	2E+4	3E+4
W-185	3E-06	2E-06	9E+4	2E+3	7E+3
W-187	4E-06	1E-06	5E+4	2E+3	9E+3
W-188	5E-07	6E-07	2E+4	4E+2	2E+3
Re-177[38]	1E-04	1E-05	4E+5	9E+4	3E+5
Re-178[38]	1E-04	1E-05	3E+5	7E+4	3E+5
Re-181	4E-06	1E-06	4E+4	5E+3	8E+3
Re-182[26]	9E-07	3E-07	1E+4	1E+3	1E+4
Re-182[27]	5E-06	1E-06	4E+4	1E+3	2E+3

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Re-184m	2E-07	1E-07	4E+3	2E+3	4E+2
Re-184	6E-07	3E-07	1E+4	2E+3	2E+3
Re-186m	6E-08	7E-08	2E+3	1E+3	2E+2
Re-186	7E-07	4E-07	1E+4	2E+3	2E+3
Re-187	4E-05	1E-04	4E+6	6E+5	1E+5
Re-188m	6E-05	2E-05	1E+6	8E+4	1E+5
Re-188	2E-06	7E-07	2E+4	2E+3	3E+3
Re-189	2E-06	9E-07	3E+4	3E+3	4E+3
Os-180[38]	2E-04	1E-05	3E+5	1E+5	4E+5
Os-181[38]	2E-05	3E-06	1E+5	1E+4	4E+4
Os-182	2E-06	9E-07	3E+4	2E+3	4E+3
Os-185	2E-07	4E-07	1E+4	2E+3	5E+2
Os-189m	7E-05	7E-05	2E+6	8E+4	2E+5
Os-191m	7E-06	4E-06	1E+5	1E+4	2E+4
Os-191	6E-07	3E-07	1E+4	2E+3	1E+3
Os-193	1E-06	8E-07	3E+4	2E+3	3E+3
Os-194	3E-09	1E-08	4E+2	4E+2	8
Ir-182[38]	5E-05	7E-06	2E+5	4E+4	1E+5
Ir-184	1E-05	1E-06	6E+4	8E+3	2E+4
Ir-185	4E-06	1E-06	7E+4	5E+3	1E+4
Ir-186[28]	X	7E-07	2E+4	X	X
Ir-186[29]	X	4E-06	1E+5	X	X
Ir-186	2E-06	X	X	2E+3	6E+3
Ir-187	1E-05	3E-06	1E+5	1E+4	3E+4
Ir-188	1E-06	6E-07	2E+4	2E+3	3E+3
Ir-189	1E-06	1E-06	4E+4	5E+3	4E+3
Ir-190m[38]	8E-05	X	X	2E+5	2E+5
Ir-190m[30]	X	2E-06	7E+4	X	X
Ir-190m[31]	X	5E-05	1E+6	X	X
Ir-190	4E-07	2E-07	8E+3	1E+3	9E+2
Ir-192m	6E-09	1E-07	1E+3	3E+3	90
Ir-192	9E-08	1E-07	4E+3	3E+2	2E+2
Ir-194m	3E-08	8E-08	2E+3	6E+2	90
Ir-194	8E-07	7E-07	2E+4	1E+3	2E+3
Ir-195m	9E-06	2E-06	7E+4	8E+2	2E+4
Ir-195	2E-05	4E-06	1E+5	1E+4	4E+4
Pt-186	2E-05	3E-06	1E+5	1E+4	4E+4

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	µCi/mL	Bq/M^3	Ingestion	Inhalation
Pt-188	7E-07	8E-07	3E+4	2E+3	2E+3
Pt-189	1E-05	3E-06	1E+5	1E+4	3E+4
Pt-191	4E-06	1E-06	7E+4	4E+3	8E+3
Pt-193m	3E-06	2E-06	8E+4	3E+3	6E+3
Pt-193	1E-05	2E-05	7E+5	4E+4	2E+4
Pt-195m	2E-06	1E-06	5E+4	2E+3	4E+3
Pt-197m[38]	2E-05	7E-06	2E+5	2E+4	4E+4
Pt-197	4E-06	3E-06	1E+5	3E+3	1E+4
Pt-199[38]	6E-05	1E-05	4E+5	5E+4	1E+5
Pt-200	1E-06	1E-06	5E+4	1E+3	3E+3
Au-193	8E-06	3E-06	1E+5	9E+3	2E+4
Au-194	2E-06	9E-07	3E+4	3E+3	5E+3
Au-195	2E-07	4E-07	1E+4	5E+3	4E+2
Au-198m	5E-07	2E-07	1E+4	1E+3	1E+3
Au-198	7E-07	5E-07	1E+4	1E+3	2E+3
Au-199	2E-06	7E-07	2E+4	3E+3	4E+3
Au-200m	1E-06	4E-07	1E+4	1E+3	3E+3
Au-200	3E-05	7E-06	2E+5	3E+4	6E+4
Au-201	9E-05	9E-06	3E+5	7E+4	2E+5
Hg-193m[32]	5E-06	1E-06	4E+4	4E+3	1E+4
Hg-193m	3E-06	1E-06	4E+4	3E+3	8E+3
Hg-193m[10]	4E-06	1E-07	6E+3	X	8E+3
Hg-193[32]	3E-05	5E-06	1E+5	2E+4	6E+4
Hg-193	2E-05	4E-06	1E+5	2E+4	4E+4
Hg-193[10]	1E-05	5E-07	1E+4	X	3E+4
Hg-194[32]	1E-08	2E-08	1E+3	20	30
Hg-194	2E-05	3E-08	1E+3	8E+2	40
Hg-194[10]	1E-08	1E-08	5E+2	X	30
Hg-195m[32]	3E-06	1E-06	5E+4	3E+3	6E+3
Hg-195m	2E-06	8E-07	3E+4	2E+3	4E+3
Hg-195m[10]	2E-06	6E-08	2E+3	X	4E+3
Hg-195[32]	2E-05	6E-06	2E+5	2E+4	5E+4
Hg-195	1E-05	6E-06	2E+5	1E+4	3E+4
Hg-195[10]	1E-05	4E-07	1E+4	X	3E+4
Hg-197m[32]	4E-06	1E-06	5E+4	4E+3	9E+3
Hg-197m	2E-06	8E-07	3E+4	3E+3	5E+3
Hg-197m[10]	2E-06	9E-08	3E+3	X	5E+3

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Hg-197[32]	6E-06	4E-06	1E+5	7E+3	1E+4
Hg-197	4E-06	2E-06	7E+4	6E+3	9E+3
Hg-197[10]	4E-06	1E-07	4E+3	X	8E+3
Hg-199m[32]	7E-05	8E-06	3E+5	6E+4	2E+5
Hg-199m[38]	6E-05	5E-06	1E+5	6E+4	1E+5
Hg-199m[10]	3E-05	3E-06	1E+5	X	8E+4
Hg-203[32]	3E-07	7E-07	2E+4	5E+2	8E+2
Hg-203	5E-07	2E-07	1E+4	2E+3	1E+3
Hg-203[10]	4E-07	8E-08	2E+3	X	8E+2
Tl-194m[38]	6E-05	5E-06	2E+5	5E+4	2E+5
Tl-194[38]	2E-04	2E-05	8E+5	3E+5	6E+5
Tl-195[38]	5E-05	6E-06	2E+5	6E+4	1E+5
Tl-197	5E-05	8E-06	2E+5	7E+4	1E+5
Tl-198m[38]	2E-05	2E-06	9E+4	3E+4	5E+4
Tl-198	1E-05	1E-06	5E+4	2E+4	3E+4
Tl-199	4E-05	5E-06	2E+5	6E+4	8E+4
Tl-200	5E-06	8E-07	3E+4	8E+3	1E+4
Tl-201	9E-06	4E-06	1E+5	2E+4	2E+4
Tl-202	2E-06	1E-06	5E+4	4E+3	5E+3
Tl-204	9E-07	9E-07	3E+4	2E+3	2E+3
Pb-195m[38]	8E-05	7E-06	2E+5	6E+4	2E+5
Pb-198	3E-05	2E-06	9E+4	3E+4	6E+4
Pb-199[38]	3E-05	4E-06	1E+5	2E+4	7E+4
Pb-200	3E-06	1E-06	4E+4	3E+3	6E+3
Pb-201	8E-06	2E-06	7E+4	7E+3	2E+4
Pb-202m	1E-05	1E-06	6E+4	9E+3	3E+4
Pb-202	2E-08	4E-08	1E+3	1E+2	50
Pb-203	4E-06	2E-06	7E+4	5E+3	9E+3
Pb-205	6E-07	9E-07	3E+4	4E+3	1E+3
Pb-209	2E-05	9E-06	3E+5	2E+4	6E+4
Pb-210	1E-10	1E-10	5	0.6	0.2
Pb-211[38]	3E-07	4E-08	1E+3	1E+4	6E+2
Pb-212	2E-08	5E-09	2E+2	80	30
Pb-214[38]	3E-07	4E-08	1E+3	9E+3	8E+2
Bi-200[38]	4E-05	4E-06	1E+5	3E+4	8E+4
Bi-201[38]	1E-05	2E-06	1E+5	1E+4	3E+4
Bi-202[38]	2E-05	2E-06	9E+4	1E+4	4E+4

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	µCi/mL	Bq/M^3	Ingestion	Inhalation
Bi-203	3E-06	7E-07	2E+4	2E+3	6E+3
Bi-205	5E-07	4E-07	1E+4	1E+3	1E+3
Bi-206	4E-07	2E-07	8E+3	6E+2	9E+2
Bi-207	1E-07	1E-07	6E+3	1E+3	4E+2
Bi-210m	3E-10	2E-10	9	40	0.7
Bi-210	1E-08	9E-09	3E+2	8E+2	30
Bi-212[38]	1E-07	8E-09	3E+2	5E+3	2E+2
Bi-213[38]	1E-07	7E-09	2E+2	7E+3	3E+2
Bi-214[38]	3E-07	1E-08	4E+2	2E+4	8E+2
Po-203[38]	3E-05	4E-06	1E+5	3E+4	6E+4
Po-205[38]	2E-05	3E-06	1E+5	2E+4	4E+4
Po-207	1E-05	1E-06	6E+4	8E+3	3E+4
Po-210	3E-10	2E-10	9	3	0.6
At-207[38]	2E-08	2E-07	1E+4	6E+3	2E+3
At-211	2E-08	5E-09	1E+2	1E+2	50
Rn-220[33]	X	1E-08	6E+2	X	X
Rn-220[34]	7E-06	X	X	X	2E+4
Rn-220[35]	9E-09	X	X	X	20
Rn-222[33]	X	8E-08	3E+3	X	X
Rn-222[34]	4E-06	X	X	X	1E+4
Rn-222[35]	3E-08	X	X	X	1E+2
Fr-222[38]	2E-07	1E-08	3E+2	2E+3	5E+2
Fr-223[38]	3E-07	4E-07	1E+4	6E+2	8E+2
Ra-223	3E-10	9E-11	3	50	0.7
Ra-224	7E-10	2E-10	8	8	2
Ra-225	3E-10	1E-10	4	8	0.7
Ra-226	3E-10	2E-10	9	2	0.6
Ra-227[38]	6E-06	8E-07	3E+4	2E+4	1E+4
Ra-228	5E-10	1E-10	5	2	1
Ac-224	1E-08	5E-09	2E+2	2E+3	30
Ac-225	1E-10	8E-11	3	50	0.3
Ac-226	1E-09	5E-10	20	1E+2	3
Ac-227	2E-13	2E-13	1E-2	0.2	4E-4
Ac-228	4E-09	6E-09	2E+2	2E+3	9
Th-226[38]	6E-08	4E-09	1E+2	5E+3	1E+2
Th-227	1E-10	7E-11	2	1E+2	0.3
Th-228	4E-12	2E-11	0.7	6	1E-2

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Th-229	4E-13	2E-12	7E-2	0.6	9E-4
Th-230	3E-12	3E-12	0.1	4	6E-3
Th-231	3E-06	1E-06	5E+4	4E+3	6E+3
Th-232	5E-13	3E-12	0.1	0.7	1E-3
Th-234	6E-08	9E-08	3E+3	3E+2	2E+2
Pa-227[38]	4E-08	4E-09	1E+2	4E+3	1E+2
Pa-228	5E-09	1E-08	3E+2	1E+3	10
Pa-230	1E-09	9E-10	30	6E+2	40
Pa-231	6E-13	1E-12	4E-2	0.2	2E-3
Pa-232	9E-09	1E-08	6E+2	1E+3	20
Pa-233	2E-07	1E-07	6E+3	1E+3	6E+2
Pa-234	3E-06	7E-07	2E+4	2E+3	7E+3
U-230	1E-10	4E-11	1	4	0.3
U-231	2E-06	1E-06	4E+4	4E+3	5E+3
U-232	3E-12	2E-11	0.7	2	8E-3
U-233	2E-11	7E-11	2	10	4E-2
U-234	2E-11	7E-11	2	10	4E-2
U-235	2E-11	8E-11	3	10	4E-2
U-236	2E-11	7E-11	2	10	4E-2
U-237	6E-07	3E-07	1E+4	2E+3	2E+3
U-238	2E-11	8E-11	3	10	4E-2
U-239[38]	7E-05	9E-06	3E+5	7E+4	2E+5
U-240	1E-06	6E-07	2E+4	1E+3	2E+3
U-Natural	2E-11	X	X	10	5E-2
Np-232[38]	7E-07	3E-06	1E+5	1E+5	5E+2
Np-233[38]	1E-03	7E-05	2E+6	8E+5	3E+6
Np-234	1E-06	5E-07	2E+4	2E+3	3E+3
Np-235	3E-07	1E-06	4E+4	2E+4	8E+2
Np-236[36]	9E-12	4E-11	1	3	5E-2
Np-236[37]	1E-08	5E-08	1E+3	3E+3	30
Np-237	2E-12	8E-12	0.3	0.5	4E-3
Np-238	3E-08	1E-07	4E+3	1E+3	60
Np-239	9E-07	5E-07	1E+4	2E+3	2E+3
Np-240[38]	3E-05	2E-06	8E+4	2E+4	6E+4
Pu-234	8E-08	3E-08	1E+3	8E+3	2E+2
Pu-235[38]	1E-03	8E-05	3E+6	9E+5	3E+6
Pu-236	8E-12	1E-11	0.6	20	2E-2

	10CFR20	**10CFR835**		**10CFR20 ALIs in uCi**	
	µCi/mL	**µCi/mL**	**Bq/M^3**	**Ingestion**	**Inhalation**
Pu-237	1E-06	1E-06	6E+4	1E+4	3E+3
Pu-238	3E-12	6E-12	0.2	0.9	7E-3
Pu-239	3E-12	5E-12	0.2	0.83	6E-3
Pu-240	3E-12	5E-12	0.2	0.8	6E-3
Pu-241	1E-10	2E-10	10	40	0.3
Pu-242	3E-12	5E-12	0.2	0.8	7E-3
Pu-243	2E-05	5E-06	1E+5	2E+4	4E+4
Pu-244	3E-12	5E-12	0.2	0.8	7E-3
Pu-245	2E-06	8E-07	3E+4	2E+3	4E+3
Pu-246	1E-07	8E-08	3E+3	4E+2	3E+2
Am-237[38]	1E-04	8E-06	3E+5	8E+4	3E+5
Am-238[38]	1E-06	2E-06	9E+4	4E+4	3E+3
Am-239	5E-06	1E-06	6E+4	5E+3	1E+4
Am-240	1E-06	7E-07	2E+4	2E+3	3E+3
Am-241	3E-12	5E-12	0.1	0.8	6E-3
Am-242m	3E-12	5E-12	0.1	0.8	6E-3
Am-242	4E-08	4E-08	1E+3	4E+3	80
Am-243	3E-12	5E-12	0.1	0.8	6E-3
Am-244m[38]	2E-06	3E-06	1E+5	6E+4	4E+3
Am-244	8E-08	1E-07	5E+3	3E+3	2E+2
Am-245	3E-05	5E-06	2E+5	3E+4	8E+4
Am-246m[38]	8E-05	6E-06	2E+5	5E+4	2E+5
Am-246[38]	4E-05	2E-06	9E+4	3E+4	1E+5
Cm-238	5E-07	1E-07	4E+3	2E+4	1E+3
Cm-240	2E-10	2E-10	7	60	0.6
Cm-241	1E-08	2E-08	8E+2	1E+3	30
Cm-242	1E-10	1E-10	5	30	0.3
Cm-243	4E-12	7E-12	0.2	10	9E-3
Cm-244	5E-12	9E-12	0.3	10	1E-2
Cm-245	3E-12	5E-12	0.1	0.7	6E-3
Cm-246	3E-12	5E-12	0.1	0.7	6E-3
Cm-247	3E-12	5E-12	0.2	0.8	6E-3
Cm-248	7E-13	1E-12	5E-2	0.2	2E-3
Cm-249[38]	7E-06	8E-06	3E+5	5E+4	2E+4
Cm-250	1E-13	2E-13	8E-3	4E-2	3E-4
Bk-245	5E-07	3E-07	1E+4	2E+3	1E+3
Bk-246	1E-06	8E-07	3E+4	3E+3	3E+3

	10CFR20	10CFR835		10CFR20 ALIs in uCi	
	µCi/mL	µCi/mL	Bq/M^3	Ingestion	Inhalation
Bk-247	2E-12	3E-12	0.1	0.5	4E-3
Bk-249	7E-10	1E-09	50	2E+2	20
Bk-250	1E-07	2E-07	9E+3	9E+3	3E+2
Cf-244[38]	2E-07	1E-08	5E+2	3E+4	6E+2
Cf-246	4E-09	1E-09	50	4E+2	90
Cf-248	3E-11	5E-11	2	80	6E-2
Cf-249	2E-12	3E-12	0.1	0.5	4E-3
Cf-250	4E-12	7E-12	0.2	10	9E-3
Cf-251	2E-12	3E-12	0.1	0.5	4E-3
Cf-252	8E-12	1E-11	0.6	20	2E-2
Cf-253	7E-10	5E-10	20	2E+2	20
Cf-254	7E-12	2E-11	0.8	20	2E-2
Es-250	2E-07	4E-07	1E+4	4E+4	5E+2
Es-251	4E-07	3E-07	1E+4	7E+3	9E+2
Es-253	6E-10	2E-10	9	2E+2	10
Es-254m	4E-09	1E-09	50	3E+2	10
Es-254	3E-11	6E-11	2	80	7E-2
Fm-252	5E-09	2E-09	80	5E+2	10
Fm-253	4E-09	1E-09	60	1E+3	10
Fm-254	4E-08	6E-09	2E+2	3E+3	90
Fm-255	9E-09	2E-09	80	5E+2	20
Fm-257	7E-11	1E-10	4	20	0.2
Md-257	4E-08	2E-08	1E+3	7E+3	80
Md-258	1E-10	1E-10	4	30	0.2

External Exposure in a Cloud of Airborne Material

	10CFR835		10CFR20
	uCi/mL	Bq/M^3	uCi/mL
Ar-37	10	4E+10	10
Ar-39	4E-04	1E+07	4E-04
Ar-41	1E-06	3E+04	3E-06
Kr-74	1E-06	4E+04	3E-06
Kr-76	3E-06	1E+05	9E-06
Kr-77	1E-06	5E+04	4E-06
Kr-79	5E-06	2E+05	2E-05
Kr-81	2E-04	9E+06	7E-04
Kr-83m	2E-02	9E+08	1E-02
Kr-85	2E-04	9E+06	1E-04
Kr-85m	9E-06	3E+05	2E-05
Kr-87	1E-06	5E+04	5E-06
Kr-88	6E-07	2E+04	2E-06
Xe-120	3E-06	1E+05	1E-05
Xe-121	7E-07	2E+04	2E-06
Xe-122	2E-05	1E+06	7E-05
Xe-123	2E-06	8E+04	6E-06
Xe-125	5E-06	2E+05	2E-05
Xe-127	5E-06	2E+05	1E-05
Xe-129m	6E-05	2E+06	2E-04
Xe-131m	1E-04	6E+06	4E-04
Xe-133	4E-05	1E+06	1E-04
Xe-133m	4E-05	1E+06	1E-04
Xe-135	5E-06	2E+05	1E-05
Xe-135m	3E-06	1E+05	9E-06
Xe-138	1E-06	4E+04	4E-06

STCs = Special Tritium Compounds

1 = Water (HTO) form
2 = Elemental (HT form)
3 = water and elemental
4 = Insoluble
5 = Soluble
6 = Vapor form
7 = As CO
8 = As CO_2
9 = compounds
10 = Vapor
11 = Inorganic
12 = Carbonyl
13 = 66 min half-life
14 = 122 min half-life
15 = 69 min half-life
16 = 5 h half-life
17 = 16 min half-life
18 = 6 d half-life
19 = 9 h half-life
20 = 10 min half-life
21 = Methyl
22 = 12 h half-life
23 = 34 yr half-life
24 = 24 h half-life
25 = 5 h half-life
26 = 64 h half-life
27 = 12 h half-life
28 = 16 h half-life
29 = 2 h half-life
30 = 3 h half-life
31 = 1 h half-life
32 = Organic
33 = radon-220/222 with short-lived progeny
34 = with progeny removed
35 = with progeny present
36 = 1E+05 yr half-life
37 = 22 h half-life
38 = half-life less than 2 h

For any radionuclide not listed in these tables with decay mode other than alpha emission or spontaneous fission and with radioactive half-life less than two hours, the DAC value shall be 6E-06 µCi/mL (2E+04 Bq/M^3).

The DAC values listed for both 10CFR20 and 10CFR835 were truncated after being calculated from the appropriate ALI values. For 10CFR835 the ALI values were taken from ICRP 68.

I TYPES OF AIR SAMPLES

Particulates

Air sampling for particulates includes both solid and liquid aerosols. The particulates may be radioactive, toxic, nuisance, or a combination of these characteristics. It is important to know the particle size distribution of the aerosols. Further the density of the particles must be taken into account.

Gases

Air sampling for gases may be for radioactive, toxic, nuisance, or oxygen deficiencent atmospheres or a combination of these characteristics. The gases sampled are single molecules but may be heavier than air.

Special Cases

Air sampling may involve both particulates and gases in the same sample.

There are radioactive isotopes that are gases but have particulate progeny. Those progeny initially exist as single molecules but will quickly agglomorate onto dust particles in the air, then they react as true particulates for air sampling purposes. However, before those particulate progeny do agglomorate onto dust particles they will react more like gas molecules which will affect the sampling technique required.

Vapors of metals or organics may change to particles as they cool or as they react with the atmosphere.

II AIR SAMPLE COLLECTIOM & ANALYSIS METHODS

A. Passive and Diffusion
B. Flow Through
C. Grab
D. Filtration
E. Absorption and Adsorption
F. Bubblers
G. Impactors
H. Particle Separators
I. Affect of Sample Inlets on Collection

A. Passive and Diffusion

Passive and diffusion sampling of air requires the substance being sampled to come into contact (or near contact) with the container, collection media, or detection assembly.

Examples of this sampling method are; smoke, CO, and CO_2 monitors where the substance in the air (in this case the smoke or CO or CO_2) migrate throughout the space where the detectors are located and when the substance enter into the active volume of the detector an alarm is generated.

Another example is the Electret for sampling radon and thoron. A charged disc is placed inside a container which has an opening through which air can migrate. The radon and thoron in the air will ionize the air inside this container due to the radioactive decay of these gases and their progeny. The ionization of the air then causes the charged disc to lose part of its charge. When the Electret is collected later the remaining charge on the disc is determined and the amount of charge lost is related to the radon and thoron concentration of the air the Electret was exposed to.

Colorimetric detectors are also used in a passive mode for the detection of toxic airborne substances. A color change or color intensity change indicates the detector has reacted to the toxic substance. The substances detected by this method are gases such as chlorine and ammonia and for military and homeland security applications colorimetric detectors for biological and chemical weapons are used.

B. Flow Through

Flow through chambers generally are combined with some detection method. Applications include sampling for radioactive substances, both gas and particulate, and sampling for toxic substances.

When sampling for radioactive substances the typical flow through chamber is a version of the air ionization chamber used for the detection of gamma detection. The actual gamma radiation background must be subtracted from the total signal level to determine the actual concentration of the radioactive substance.

Sampling for toxic substances using a flow through chamber generally requires an electrochemical detection method. Some flow through detectors for toxic substances have the capability of detecting more than one type of toxic substance.

Sampling for oxygen deficient atmospheres is another application for flow through chambers.

C. Grab

The basic technique in grab sampling is to cause the air to be sampled to flow through or into the collection container.

This can be accomplished by using a pump and when the container is sufficiently purged simply close the outlet and inlet valves on the container.

Another technique is to fill the sampling container water and when the inlet and outlet valves are opened the water flowing out draws the air to be sampled into the container.

Sampling containers can be evacuated using a vacuum pump before sampling the air and when the sample needs to be collected the technician simply opens the inlet valve on the sampling container.

D. Filtration

Filtration is the most widely used method for collecting samples of aerosols.

The methods and equipment range from high volume samplers (up to about 40 cfm) for environmental or short-term workplace sampling, to low-volume lapel samplers (1 lpm or less) for collecting aerosols in the breathing zone of individual workers.

Low-pressure-drop, cellulose filters are commonly used, and samples can be easily reduced to ash or dissolved for analysis without the filter material interferring with the analysis.

Concerns for penetration of particles into the filter matrix are a function of the type of filter and the filter analysis method. Membrane filters with their superior front-surface collecting characteristics are preferred over fiber-type filters when alpha particle spectroscopy is applied. Shielding by the filter media is seldom a concern for detection of gamma particulate radiation.

E. Absorption and Adsorption

Absorption and adsorption are both used in air sampling and are sometimes hard to distinguish from each other.

Absorption is a process in which atoms, molecules, or ions enter some bulk phase - a gas, liquid, or solid material.

Adsorption is a process in which a gas or liquid aerosol accumulates on the surface of a solid or liquid, forming a film of molecules or atoms.

Sorption refers to both absorption and adsorption while desorption is the reverse of either process.

Anhydrous calcium sulfate is an example of absorption where water vapor (or tritium oxide) is collected by passing an air stream through a cartridge containing the anhydrous calcium sulfate. The moisture content of air can then be measured by gravimetric or other methods and tritium oxide in the air can be measured directly or indirectly using either a radiation detector or liquid scintillation counting.

Silica gel, zeolites, and activated charcoal are examples of adsorption where toxic or radioactive substances are collected by passing an air stream through a cartridge containing one of these materials. The radioactive substances collected by these materials can be measured directly or indirectly using radiation detectors. Toxic substances collected by these materials are typically extracted from the materials before they are measured.

F. Bubblers

Bubblers consist of an air pump and a liquid container which has an inlet tube going to near the bottom of the bubbler. The air pump pulls air to be sampled into the inlet tube and the air goes through the tube to the bottom of the liquid container where the air “bubbles” into the liquid and rises to the top of the liquid container where the air is drawn off by the air pump. Water is the typical liquid used but other liquids may be used depending on what substance is desired to be collected.

Bubblers are used to collect both gases and aerosols and these may be radioactive or toxic gases and aerosols.

In some cases real-time analysis of the substances being collected are possible by using chemicals in the liquid which will react with the substances being collected.

The substance collected in the liquid may be analyzed at some later time also.

An example of a bubbler sample collection technique is the elemental tritium and tritium oxide bubbler. Elemental tritium is used in several applications and must be adequately monitored for in order to apply safety controls. Elemental tritium is not as hazardous as tritium oxide but elemental tritium quickly converts to the oxide form upon exposure to the atmosphere. Typically the air being sampled is drawn through a series of collection vials with an appropriate liquid in them and the tritium oxide is effectively collected in those vials but the elemental tritium passes through them.

The air stream is then directed to a catalyst and heater section where the elemental tritium is converted into tritium oxide. From there the tritium oxide (which was elemental tritium just before) is drawn through another set of collection vials identical to the first set. The first set of vials contains the tritium oxide from the original sample while the second set of vials contains the elemental tritium which was converted to the oxide form. When the contents of the vials are analyzed a measurement of elemental tritium and tritium oxide can be derived.

G. Impactors

Impactors are used to collect aerosols, either solid or liquid particles.

An air pump pulls air through a opening small enough to increase the velocity of the air stream to a level such that large particles in the air cannot deviate from their straight flight and therefore “impact” on a plate. Smaller particles can go around the impactor plate because they have less kinetic energy than the larger particles. Multiple impactor plates in series and with higher and higher air velocities separate the particles in distinct size ranges.

The cascade impactor and the Andersen sampler are examples of impactor particle collection techniques.

H. Particle Separators

Cyclone separators use a method similar to impactors in that the larger particles cannot follow the main air stream at some velocities. The large particles then drop out the bottom of the cyclone separator while the air stream with much smaller particles go out the top of the cyclone separator. Just as with multi-stage impactors, multi-stage cyclone separators can be used to collect a range of particle sizes.

I. Affect of Sample Inlets on Collection

The design of the sample inlet is critical to the efficacy of the collection system.

The use of non-conductive materials should be avoided for the collection of aerosol particles due to electrostatic collection of those particles on the sample inlet before they get to the point of collection.

The use of non-reactive materials should always be used regardless of whether sampling for gases or aerosols.

The length, inside diameter, and bends in the sample inlet should be sized so as to minimize loss of any of the sample in the sample inlet itself.

Calculations should be performed on transport velocities to ensure that the collection of aerosols remains isokinetic throughout the sampling system.

III AIR SAMPLE PUMPS

INTRODUCTION

Equipment used to generate vacuum is similar to air compressors. It's even possible to generate compressed air or vacuum with the same machine, depending on how it is installed. Vacuum pumps generally can be considered as compressors in which the discharge rather than the intake is at atmospheric pressure. The vacuum in a chamber is created by physically removing air molecules and exhausting them from the system. Removing air from the enclosed system progressively decreases air density within the confined space, thus causing the absolute pressure of the remaining gas to drop and a vacuum is created. Because the absolute maximum pressure difference that can be produced is equal to atmospheric pressure (nominally 29.92"Hg at sea level), it is important to know this value at the work site.

For example, a pump with a maximum vacuum capability of 24"Hg cannot generate a 24" vacuum when the atmospheric pressure is 22" Hg (as in Mexico City, for instance). The proportion of the air evacuated will be the same, however. This pump therefore will pull
22 X 24/29.92 = 17.6” Hg vacuum in Mexico City.

- The maximum pressure difference produced by pump action can never be higher than 29.92"Hg (14.7 psi), since this represents a perfect vacuum.
- The mass of air drawn into the pump on each suction stroke, and hence the absolute pressure change, decreases as the vacuum level increases.
- At high vacuum levels, there is significantly less air passing through the pump. Therefore, virtually all the heat generated by pump operation will have to be absorbed and dissipated by the pump structure itself.

Positive Displacement Vacuum Pumps

Vacuum pumps fall into the same categories as air compressors do. They are either positive displacement or non-positive displacement machines. A positive displacement pump draws a relatively constant volume of air despite variations in the vacuum levels. The principle types of positive displacement vacuum pumps are the piston, diaphragm, rocking piston, rotary vane, lobed rotor, and rotary screw designs.

Reciprocating Piston Pumps -The primary advantage of the piston design is that it can generate relatively high vacuums from 27 to 28.5"Hg and do so continuously under all kinds of operating conditions. The major disadvantages are somewhat limited capacities and high noise levels, accompanied by vibrations that may be transmitted to the base structure. In general, the reciprocating piston design is best suited to pulling relatively small volumes of air through a high vacuum range.

Diaphragm Pumps -The diaphragm unit creates vacuum by flexing of a diaphragm inside a closed chamber. Small diaphragm pumps are built in both one- and two-stage versions. The single stage design provides vacuums up to 24"Hg, while the two stage unit is rated for 29"Hg.

Rocking Piston Pumps -This design combines the light weight and compact size of the diaphragm unit with the vacuum capabilities of reciprocating piston units. Vacuums to 27.5"Hg are available with a single stage; two-stage units can provide vacuums to 29"Hg.

Rotary Vane Pumps -Most rotary vane pumps have lower vacuum ratings than can be obtained with the piston design: only 20 to 28"Hg maximum. However, some two stage oil- lubricated designs have vacuum capabilities up to 29.5"Hg. The rotary vane design offers significant advantages: compactness; larger flow capacities for a given size; lower cost (about 50 percent less for a given displacement and vacuum level); lower starting and running torques; and quiet, smooth, vibration free, continuous air evacuation without a receiver tank.

Rotary Screw and Lobed Rotor Pumps - Vacuum capabilities of rotary screw pumps are similar to those of piston pumps, but evacuation is nearly pulse-free. Lobed rotor vacuum pumps, like the corresponding compressors, bridge the gap between positive and non-positive displacement units. Air flow is high but vacuum capabilities are limited to about 15"Hg. Capabilities can be improved with staging.

Non-positive Displacement Vacuum Pumps

Non-positive displacement vacuum pumps use changes in kinetic energy to remove air from a system. The most significant advantage of this design is its ability to provide very high volume flow rates, much higher than possible with any of the positive displacement designs. But because of their inherent leakage, these machines may not be practical for applications requiring higher vacuum levels and low flow rates. The principle types of non-positive displacement vacuum pumps are the **centrifugal, axial-flow, and regenerative** designs. Single-stage regenerative blowers can provide vacuums up to 7"Hg with flows to several hundred cfm. Vacuum capabilities of these designs are improved when they are multi-stage.

Evaluating Vacuum Pump Performance

The primary performance criteria cover three characteristics:

Vacuum level that can be produced.
Rate of air removal.
Power required.

Somewhat less critical are temperature effects and certain other characteristics. In general, the best pump for a specific job is the one having the greatest pumping capacity at the required vacuum level and operating within an acceptable horsepower range.

Vacuum Level - A pump's vacuum rating is the maximum vacuum level for which it is recommended. The rating is expressed in “Hg and is specified for either continuous or intermittent duty cycles.

Most vacuum pumps can't come near the theoretical maximum vacuum (29.92"Hg at sea level) because of internal leakage. For a reciprocating piston pump the upper vacuum limit may be 28 or 28.5"Hg, roughly 93 to 95 % of the maximum theoretical value. Internal leakage and clearance volume establish the highest vacuum a pump can produce.

For some pumps, this is also the vacuum rating. In other types, however, heat dissipation is a problem. For these, the maximum vacuum rating might be based on allowable temperature rise. For example, good wear life for some rotary vane pumps requires a maximum 180 F (82 C) rise in casing temperature at the exhaust port. Vacuum ratings will be based on this temperature rise. The vacuum rating listed for a pump is based on operation at 29.92"Hg. Operating where atmospheric pressure is lower will reduce the vacuum the pump can produce. An adjusted vacuum rating for such locations can be determined by multiplying actual atmospheric pressure by the ratio of the nominal vacuum rating to standard atmospheric pressure:

$$\text{Adjusted Vacuum Rating} =$$
$$\text{Actual Atmospheric Pressure} \times \frac{\text{Nominal Vacuum Rating}}{\text{Standard Atmospheric Pressure}}$$

Air Removal Rate -Vacuum pumps are rated according to their open capacity, which is the volume of air (expressed in cfm) exhausted when there is no vacuum or pressure load on the pump. Effectiveness of the vacuum pump in removing air from the closed system is given by its volumetric efficiency, a measure of how close the pump comes to delivering its calculated volume of air.

This equation is applied in two different ways:

- **True (or Intake) Volumetric Efficiency** -The volume of air removed during a given time period is converted to an equivalent volume at the temperature and absolute pressure existing at the intake.
- **Atmospheric Volumetric Efficiency** -The volume of air removed by the pump is converted to an equivalent volume at standard conditions (14.7 psi and 68 F). The displacement is the total volume swept by the repetitive movement of the pumping element during the same time period (usually one revolution). With various vacuum pumps having the same displacement, it is the difference in volumetric efficiencies that accounts for the difference in free air capacities.

Since these differences exist, pump selection should be based on actual free air capacity rather than on displacement. In short, the air removal rate is a measure of vacuum pump capacity and the capacity of standard machines must be determined from the manufacturers' tables or curves showing cfm of free air delivered at rated speed for vacuum levels ranging from 0 “Hg (open capacity) to the maximum vacuum rating. Free air capacity at different speeds for a given vacuum also may be included in the manufacturers' performance curves. The rated capacity of any pump is highest at 0 “Hg and will drop rapidly as the vacuum level increases. This reflects a drop in both volumetric efficiency and the volume of air that can be drawn into the pumping chamber. To repeat, a basic characteristic of positive displacement pumps is that capacity drops as the vacuum level increases. The same principle holds for diaphragm pumps.

Effects of Temperature Rise

Vacuum pump performance is significantly affected by heating of the pump itself. At higher vacuum levels, there is very little air flow through the pump. There is thus very little transfer of internal heat to this remaining air. Much of the heat generated by friction must be absorbed and dissipated by the pump casing. Since some pumps generate heat faster than it can be dissipated, a gradual rise in pump temperature results, drastically reducing service life. One solution is to give careful consideration to pump ratings. For example, a continuous-duty pump should have a high maximum vacuum rating.

Summary of Vacuum Pump Selection Factors

These basic questions should be answered before deciding which vacuum pump is best suited for a particular application:

What degree of vacuum is required?
What flow capacity (cfm) is required?
What horsepower and speed requirements are needed to meet vacuum level and capacity values?
What power is available?
Will duty cycle be continuous or intermittent?
What is the atmospheric pressure at the work site?
What is the ambient temperature?
Are there any space limitations?

Vacuum Ratings and Typical Pump Capacities

Maximum Vacuum Rating (“Hg)	CFM Range	
27.5 to 28.5	1 to 1,000	Piston (multi-stage)
25.5 to 29	0.1 to 2	Rocking piston
24 to 29	0.1 to 8	Diaphragm (single & multi-stage)
10 to 28	0.5 to 50	Rotary vane
14 to 22	5 to 2,000	Multi-stage Centrifugal
14 to 22	5 to 200	Multi-stage Regerative
5 to 7	5 to 200	Single-stage Regerative
1 to 2	1 to 10,000	Single-stage Centrifugal

Nomenclature

V_{VC} = volume of expanded air, cu ft
V = volume of free air, cu ft
P = pressure (psi)
Pa = absolute pressure (psia)
P1 = inlet (or original) absolute pressure
P2 = discharge (or final) absolute pressure
V1 = inlet (or original) volume
V2 = discharge (or final) volume
T1 = inlet (or original) absolute temperature
T2 = discharge (or final) absolute temperature m = mass
T = absolute temperature Kelvin
R = 0.08207 lit-atm per mole-K

Positive Gauge Pressure is the pressure above atmospheric pressure (measured in psig).

Negative Gauge Pressure (vacuum) is the difference between atmospheric pressure and the pressure remaining in the evacuated system (measured in “Hg or negative psig).

Absolute Pressure is the pressure above a perfect vacuum condition measured in psia. When using gas laws, pressure must be absolute pressure values.

Metric Units -in metric systems pressures are given in "bars" equal to 14.50 psi. The unit of force is the newton, and the unit of area is the square meter. One bar is 10,000 newtons per square meter

Absolute Temperature is the temperature above absolute zero, the point where all thermal activity ceases. Such a perfect gas would exert no pressure if kept at a constant volume. In SI units, absolute zero is - 273 C, and absolute temperatures are given in degrees Kelvin (K).

Volume Measurements for Gas Laws

For the General Gas Law, the volume unit must correspond to the value of R used. For example, when the value 53.3 is used, volume must be in cubic feet. For other laws, the only requirement is that all volumes be given in the same units.

Gas Laws

The relationships of pressure, volume, and temperature of a quantity of air are interrelated. The first three laws cover conditions where the quantity or mass of air is constant. The fourth law (General Law) provides for computation involving change in the mass of air.

Boyle's Law - P1V1 = P2V2

This basic law covers the relationship between changes in pressure and volume when temperature remains constant.

Charles' Law - P1/P2 = T1/T2: V1/V2 = T1/T2

The basic forms above cover changes in pressure and volume caused by temperature changes. A pressure change is calculated for a system where the volume is constant. A volume change is calculated where the pressure remains constant.

Combined Gas Law
$P1V1/T1 = P2V2/T2$

General Gas Law or Equation of State of an Ideal Gas
$mR = PV/T$
The above basic form includes the effect of mass (in pounds). The right hand portion of the equation is the same as the Combined Gas Law. R is a constant that varies with the gas being considered and the units used. For air in units of the U.S. system (T in degrees Rankine, V in cubic feet, m in pounds mass, and P in pounds per square foot absolute-to obtain psfa, multiply psia by 144), R has the value 53.3.

Variation: $PV = nRT$
In this variation, n represents the amount of gas in moles. A mole is 6.02E+21 molecules; its weight in grams equals the molecular weight of the gas. This makes R independent of the gas involved. In metric units (T in degrees Kelvin, V in liters, and P in atmospheres), R has the value 0.08207.

Flow Measurements - The volume of air delivered by a compressor or removed by a vacuum pump is given in cubic feet per minute (cfm). This may be either cfm at actual temperature and pressure or standard cubic feet of air per minute (scfm)-that is, cfm at atmospheric pressure and a standard temperature of 68 F (20 C). For utmost accuracy, scfm also requires correction to a standard humidity of 36 percent.) The term "free air" is often used interchangeably with "standard air." Strictly speaking, "free air" refers to air at ambient conditions - the conditions at a compressor's intake or a vacuum pump's discharge port.

Power - The units of power are horsepower (hp) and watts (w) or kilowatts (kw). One U.S. horsepower equals 0.746 kw and 1.014 metric horsepower.

Absolute Pressure - In pressure or vacuum systems, absolute pressure is the pressure above a perfect vacuum condition (zero pressure). In a pressure system, it is equal to the positive gauge pressure plus atmospheric pressure. In a vacuum system, it is equal to the negative gauge pressure subtracted from atmospheric pressure. U.S. units for absolute pressure are pounds per square inch, absolute (psia).

Adiabatic - A change, such as expansion or compression, without loss or gain of heat. Any sufficiently fast process is approximately adiabatic.

Atmosphere - Unit of pressure that will support a column of mercury 29.92 inches high at 0 C, sea-level, and latitude 45. Actual day-to-day atmospheric pressure fluctuates about this value.

Atmospheric Pressure - Pressure exerted by the atmosphere in all directions, equal at sea level to about 14.7 psi.

Back Pressure - Resistance to flow in a system.

Barometer - Device for measuring atmospheric pressure at a specific location.

Barometric Pressure - The reading, in inches of mercury ("Hg), showing atmospheric pressure at a given location.

Differential Pressure - Difference in pressure between two points in a system or component.

Displacement - The total volume swept by the repetitive motion of the pumping element. Displacement per revolution is determined by size of the pumping chamber(s). Displacement per minute also depends on compressor speed. Displacement is meaningful only in positive displacement compressors.

Efficiency, Volumetric - Ratio of actual capacity to theoretical displacement multiplied by 100 percent.

Free Air - Air under the atmospheric conditions (including temperature) at any specific location.

Gauge Pressure (Positive) - The pressure differential above atmospheric pressure (see pressure gauge).

Gauge Pressure (Negative) - The difference between pressure remaining in an evacuated system and atmospheric pressure (see vacuum gauge). Also known as -gauge vacuum" or "vacuum level." In effect, it is the pressure drop produced by evacuating the system. Measured in inches of mercury (“Hg). Caution: It is a potentially misleading term which must be carefully defined when used; negative pressure (absolute) doesn't exist.

Maximum Vacuum Rating - Highest vacuum level recommended for a vacuum pump.

Non-positive Displacement - (Of a compressor or vacuum pump). One that uses kinetic energy to create pressure gradients (slopes) for moving air. This applies to Regenerative, Axial flow, and Centrifugal pumps.

Open Capacity - The volume of air exhausted per minute when there is no vacuum or pressure load on the pump, expressed in cfm.

PSIG - Pounds per square inch gauge-pressure above or below (vacuum) atmospheric pressure.

Positive Displacement - (Of a compressor or vacuum pump.) One that moves a specific volume of air for each cycle of operation.

Pressure Differential - Difference in pressure between two points in a system or component.

Pressure Drop - Any reduction in pressure from normal value.

Pressure Gauge - A device that displays the pressure level in a system. Most gauges use atmospheric pressure as a reference level and measure the difference between the actual pressure and atmospheric pressure; the readout is called "gauge pressure." (A gauge that reads below atmospheric is called a vacuum gauge).

Rated Capacity (Vacuum) - The cfm of free air exhausted by a vacuum pump at rated speed. Usually given for vacuums ranging from 0 “Hg to the maximum vacuum rating.

Vacuum Receiver Tank - Container in which gas is stored under vacuum as a source of pneumatic fluid power.
Accommodates sudden or unusually high system demands.
Prevents frequent on/off cycling of an air compressor or vacuum pump and absorbs pulsations.

Regulator - Device to control flow of gases, thus controlling the magnitude of the force and torque produced by the actuator.

Standard Air - Air at a temperature of 68 F, a pressure of 14.70 psia, and a relative humidity of 36 percent.

Vacuum - A space containing air or other gas at less than atmospheric pressure; usually expressed in “Hg.

Vacuum Gauge - Device for determining the pressure level in a partial vacuum.

Vacuum Pump - A device that pulls air out of a closed container or system.

Vacuum Relief Valve - A valve that controls system vacuum level. It operates by providing a modulated flow of atmospheric air into the system.

Volumetric Efficiency - The ratio of a pump's actual delivery to its computed fluid delivery multiplied by 100 percent.

The author expresses gratitude to the Gast Manufacturing Corporation who provided much of the information in this section.

IV AIR SAMPLE PUMP POWER SOURCES

A. AC Powerline

B. Battery

C. Generator

D. Solar

E. Wind

A. AC Powerline

This section applies to those portable or temporary AC powerline operated vacuum pumps. Permanently installed systems must conform to building codes. Use the following table and equations as guidance in determining electrical wiring requirements for your system.

AWG Gauge	Ohms per 100 feet of wire	Maximum Amps
0000	0.0049	302
000	0.0062	239
00	0.0078	190
0	0.0098	150
1	0.012	119
2	0.016	94
4	0.025	60
6	0.040	37
8	0.063	24
10	0.10	15
12	0.16	9.3

Determine what size of electric motor you need for your vacuum system. You can refer to the vacuum pump manufacturers data sheets after you determine your vacuum and air flow rate requirements to determine the power requirements. If the manufacturer states the electric motor rating in horsepower convert that to watts by multiplying # Horsepower by 746 watts per horsepower to calculate the watts required.

Example: A 5 horsepower pump needs 5 x 746 = 3,730 watts of electric power. If you use 120 VAC power use this equation to determine your motor's running current. Amps = Watts / Volts = 3730/120 = 31 amps

Use Ohm's Law to determine if your powerline is causing an unacceptable voltage drop on your system. V is Volts, I is Amps, R is Ohms
$V = I \times R \qquad I = V/R \qquad R = V/I$

Example: If you use a 100 foot length of 12 gauge powerline to operate a vacuum pump that uses 31 amps calculate the voltage loss using this equation; $V = I \times R$
$V = 31 \times 0.16 = 5$ Volts less than the standard 120 VAC at the source. This causes your vacuum pump to operate with lower efficiency and greater heat generation. You must also consider the starting current of your vacuum pump which may be three times its running current.

B. Battery Systems

When using batteries to power vacuum pumps you must consider the continuous run time you need to get from your battery system.

Use the following table and equation to determine your battery requirements after you establish how many watt-hours of power you need from the system.

Example: You have a DC operated vacuum pump that uses 250 watts per hour. Your want to continuously operate your vacuum pump for 8 hours. The watt-hrs you need from your battery system is 250 watts times 8 hours (2,000 watt-hrs).

Battery Type	Watt-hrs per kg battery weight
Li-Ion	135
NiMH	78
NiZn	52
NiCd	47
Alkaline	80
Lead Acid	37

The batteries with the highest power density will be the lightest for your application but the price will be the highest. The lowest price for a battery system will be Lead Acid but will be the heaviest battery system.

If your vacuum pump is AC operated then you must factor in a DC to AC converter which increase the system cost and weight. You will also have a power conversion factor of around 90% so you will need extra battery power.

C. Generators

Generators can be an effective way of powering portable or temporary electrical equipment.

Use the following table and equation to determine your generator capacity requirements and time between refueling of your generator fuel tank.

Example: You have a water irrigation pump that uses 750 watts per hour. You want to continuously operate your irrigation pump for 8 hours. You need a generator with more than 750 watts generating capacity and the watt-hrs you need from your generator is 750 watts times 8 hours (6,000 watt-hrs).

Typical gasoline generators will deliver about 3,000 watt-hrs per gallon of fuel. If you choose a gasoline generator with a capacity of 1,000 watts or more your generator would use about 2 gallons of fuel to operate your vacuum pump for 8 hours continuously.

Typical diesel generators will deliver about 10,000 watt-hrs per gallon of fuel. If you choose a diesel generator with a capacity of 1,000 watts or more your generator would use less than 1 gallon of fuel to operate your vacuum pump for 8 hours continuously.

Gasoline powered generators are readily available with capacities from less than 1,000 watts up to 10,000 watts. Diesel powered generators are readily available with capacities from about 5,000 watts up to 20,000 watts. Diesel generators tend to be heavier and more expensive than the gasoline equivalent.

D. Solar Power

Solar power panels can be an effective way to power a remote air monitoring system.

If you want to operate the system continuously you need to add a battery system. Use previous guidance from the section on battery systems to determine the required size of the battery system.

Solar cells produce 12 to 17 watts per square foot of panel depending on the quality of the panels, orientation of the panels, geographic location, and season of the year. The purchase cost of solar power panels ranges from about $1 per watt to $2 per watt. The installation cost of your system must also be considered.

Example: You have an air monitoring system that uses 250 watts per hour. Your sunlight availability at the location is 6 hours per day. You want to continuously operate your system and you want to plan for a lack of useable sunlight for only one day. You need a battery system that will operate the vacuum pump for 36 or more hours, but then you must also size the solar panel system to generate enough power to operate the system and recharge the battery system. You need 250 watts per hour times 24 hours or 6,000 watt-hours per day from your solar panels. You also need to store a minimum of 18 hours in the battery system in order to operate your air sample pump when there is no sunlight. Your battery system needs to store 250 watts times 18 hours or 4,500 watt-hours just to operate overnight. You must double that battery storage capacity if you need to operate for an extra day without useable sunlight for your solar panels.

How many square feet of solar panel do you need?

Example: From our previous example you need a minimum of 6,000 watt-hours per day from your solar panels. With 6 hours per day of available sunlight you need to collect 1,000 watts per hour. Your solar panels may have a capacity of 15 watts per square foot. Therefore you need 67 square feet of solar panels for this example.

Refer to the National Renewable Energy Laboratory website at WWW.NREL.GOV for a map depicting solar power availability in the US.

E. Wind Power

Wind power systems are an attractive option as a way to power a remote air monitoring system.

If you want to operate the system when there is not enough wind you need to add a battery system. Use previous guidance from the section on battery systems and solar panels to determine the required size of the battery system.

Wind power systems are readily available in capacities from a few hundred watts to several thousand watts.

Power from a wind system varies with the square of the rotor diameter and the cube of the wind speed. The wind speed typically is higher at 50 feet and higher above the ground surface than it is at 20 feet above the ground surface.

Wind power can be estimated by squaring the diameter of the rotor and multiplying that be the cube of the wind speed.

Example: You have a wind machine with a 12 foot diameter rotor and your wind speed is 20 mph.
Watts = 12 squared x 20 cubed divided by 500 = 2,300 watts

If this wind system generated this much power for 3 hours per day you could operate the air sampling system in the previous example continuously with the appropriate battery system.

Refer to the National Renewable Energy Laboratory website at WWW.NREL.GOV for a map depicting wind power availability in the US.

AIR POLLUTION SAFE LIMITS (mg / m^3)

Pollutant	Limit	Pollutant	Limit
Benzene **	0.3	Iron oxide (fume)	5
Bromine	0.66	Isopropyl alcohol	980
Cadmium *	0.002	Lead (dust & fume)	0.2
CO_2	9,000	Manganese	0.2
Carbon disulfide	31	Mercury	0.01
CO	29	Methanol	0.2
Carbon tetrachloride***	31	Nitric oxide	30
Chlorine	1.5	NO_2	5.6
Chloroform*	49	Selenium	0.2
Cresol	22	SO_2	5.2
Ethanol	1,880	Sulfuric acid	1
Fluorine	1.6	Tellurium	0.1
Formaldehyde*	0.37	Tetraethyl lead	0.1
Gasoline	890	Toluene	188
Hydrogen cyanide	11	Turpentine	560
Iodine	1	Vinyl chloride**	13
		Zinc oxide (fume)	5
Asbestos **	0.2 fibers / cc		

* Suspected human carcinogen
** Animal carcinogen
*** Confirmed human carcinogen

ELEVATION VS AIR PRESSURE

Elevation		Barometric Pressure		Boiling Point of Water		Speed of Sound	
FT	**M**	**mm Hg**	**kPa**	**^{0}C**	**^{0}F**	**M/S**	**MPH**
-500	-152	774	103.2	100.5	212.9	340.9	763
0	0	760	101.3	100	212.0	340.3	761
500	152	746	99.5	99.5	211.1	339.7	760
1,000	305	732	97.6	99.0	210.2	339.1	759
1,500	457	720	96.0	98.4	209.2	338.6	757
2,000	610	707	94.3	97.9	208.3	338.0	756
2,500	762	694	92.5	97.4	207.4	337.4	755
3,000	914	681	90.8	97.0	206.6	336.7	753
3,500	1,067	668	89.1	96.4	205.6	336.2	752
4,000	1,219	656	87.5	95.9	204.6	335.6	751
4,500	1,372	644	85.9	95.4	203.7	334.8	749
5,000	1,524	632	84.3	94.9	202.9	334.4	748
5,500	1,676	619	82.5	94.4	202.0	333.8	747
6,000	1,829	609	81.2	93.9	201.1	333.2	745
6,500	1,981	597	79.6	93.3	200.0	332.6	744
7,000	2,134	586	78.1	92.8	199.1	332.2	743
7,500	2,286	575	76.7	92.4	198.3	331.4	741
8,000	2,438	564	75.2	91.8	197.4	330.8	740
9,000	2,743	543	72.4	90.9	195.6	330.1	738
10,000	3,048	523	69.7	89.8	193.7	328.5	735
11,000	3,353	504	67.1	88.8	191.4	327.3	732
12,000	3,658	484	64.5	87.8	190.1	326.0	729
13,000	3,962	464	62.0	86.8	188.2	324.6	726
14,000	4,267	444	59.5	85.8	186.4	323.2	723
15,000	4,572	424	57.0	84.8	184.6	321.8	720
16,000	4,877	404	54.6	83.7	182.7	320.4	717

ELEVATIONS OF MAJOR US AIRPORTS AND FACILITIES

		Feet			Feet
AK	Anchorage	144	IL	Bloomington	875
AK	Fairbanks	434	IL	Moline	589
AL	Birmingham	644	IN	Bloomington	845
AL	Dothan	401	IN	Evansville	416
AL	Huntsville	630	KS	Wichita	1,332
AR	Little Rock	260	KY	Lexington	980
AR	Fort Smith	469	KY	Paducah	410
AZ	Flagstaff	7,011	LA	New Orleans	6
AZ	Phoenix	1,133	LA	Shreveport	248
AZ	Tucson	2,641	MA	Boston	20
CA	Imperial	-24	MA	Worcester	1,009
CA	Lake Tahoe	6,264	MD	Hagerstown	704
CA	Sacramento	24	MD	Salisbury	52
CA	Los Angeles	126	ME	Portland	74
CO	Denver	5,431	ME	Presque Island	534
CO	Leadville	9,927	MI	Detroit	626
CO	Pueblo	4,726	MI	Hancock	1,095
CT	Bridgeport	10	MN	Duluth	1,428
CT	New Haven	14	MN	Minneapolis	841
DC	Washington	313	MO	Saint Louis	605
FL	Gainesville	152	MO	Springfield	1,267
FL	Miami	11	MS	Biloxi	28
GA	Atlanta	1,026	MS	Tupelo	346
GA	Savannah	51	MT	Yellowstone	6,644
HI	Honolulu	13	MT	Wolf Point	1,986
HI	Lanai City	1,308	NC	Asheville	2,165
IA	Burlington	698	NC	New Bern	19
IA	Mason City	1,213	ND	Grand Forks	844
ID	Idaho Falls	4,741	ND	Williston	1,962
ID	Lewiston	1,438	NE	Lincoln	1,214

NE	Omaha	983
NH	Lebanon	598
NH	Manchester	234
NJ	Atlantic City	76
NJ	Trenton	213
NM	Albuquerque	5,352
NM	Carlsbad	3,293
NM	Los Alamos	7,200
NM	White Sands	4,197
NV	Ely	6,255
NV	Las Vegas	2,175
NY	Jamestown	1,724
NY	New York	13
OH	Akron	1,228
OH	Cincinnati	897
OH	Cleveland	584
OK	Oklahoma City	1,295
OK	Tulsa	677
OR	Portland	27
OR	Redmond	3,077
PA	Johnstown	2,284
PA	Philadelphia	21
RI	Providence	55
SC	Columbia	236
SC	Myrtle Beach	28
SD	Huron	1,288
SD	Rapid City	3,202
TN	Bristol	1,519
TN	Memphis	332
TX	Dallas	487
TX	El Paso	3,956

UT	Cedar City	5,623
UT	Saint George	2,936
UT	Salt Lake City	4,227
VA	Norfolk	27
VA	Roanoake	1,176
VT	Burlington	334
WA	Bellingham	166
WA	Pullman	2,551
WA	Richland	195
WI	La Crosse	654
WI	Oshkosh	808
WI	Rhinelander	1,623
WV	Bluefield	2,857
WV	Huntington	828
WY	Laramie	7,276
WY	Sheridan	4,021

Lowest Spot in the US
Death Valley, CA -282

Highest Spot in the US
Mt. McKinley, AK 20,320

Lowest Spot in the World
Dead Sea, Israel/Jordan -1,371

Highest Spot in the World
Mt. Everest, Nepal/China 29,035

INTERNATIONAL AIRPORT ELEVATIONS (FEET)

Addis-Ababa, Ethiopia	7,625
Algiers, Algeria	826
Amsterdam, Netherlands	-13
Athens, Greece	90
Bagdad, Iraq	113
Beijing, China	15
Berlin, Germany	164
Bogota, Columbia	8,355
Bombay, India	27
Buenos Aires, Argentina	66
Cairo, Egypt	366
Calgary, Canada	3,557
Cape Town, South Africa	151
Casablanca, Morocco	656
Damascus, Syria	2,020
Darwin, Australia	94
Dublin, Ireland	222
Geneva, Switzerland	1,411
Helsinki, Finland	167
Istanbul, Turkey	92
Jakarta, Indonesia	86
Johannesburg, South Africa	5,557
Karachi, Pakistan	100
Khartoum, Sudan	1,256
La Paz, Bolivia	13,354
Lima, Peru	105
Lisbon, Portugal	374
London, England	80
Madrid, Spain	1,998
Manila, Phillipines	74
Melbourne, Australia	392
Mexico City, Mexico	7,341
Montreal, Canada	117
Moscow, Russia	623
Nairobi, Kenya	5,327
New York, NY	13
Osaka, Japan	39
Panama City, Panama	135
Paris, France	292
Perth, Australia	53
Port Moresby, Papua New Guinea	125
Quito, Ecuador	9,228
Recife, Brazil	36
Reykjavik, Iceland	169
Rio de Janeiro, Brazil	16
Rome, Italy	7
Santiago, Chili	1,554
Seoul, South Korea	58
Shanghai, China	15
Shannon, Ireland	47
Singapore, Singapore	65
Stockholm, Sweden	123
Sydney, Australia	6
Taipei, Taiwan	21
Tehran, Iran	3,949
Tel Aviv, Israel	135
Tokyo, Japan	8
Toronto, Canada	569
Tunis, Tunisia	20
Vancouver, Canada	8
Warsaw, Poland	361
Washington, DC USA	313

COMPOSITION OF AIR

	Symbol	% Volume	Density g / l
Air	-	100.00	1.2928
Nitrogen	N_2	78.084	1.2506
Oxygen	O_2	20.947	1.4290
Argon	Ar	0.934	1.7840
Carbon Dioxide	CO_2	0.033	1.9770
Neon	Ne	18.2 PPM	0.9002
Helium	He	5.2 PPM	0.1785
Methane	CH_4	2.0 PPM	0.66
Krypton	Kr	1.1 PPM	3.7
Sulfur Dioxide	SO_2	1.0 PPM	2.927
Hydrogen	H_2	0.5 PPM	0.0899
Nitrous Oxide	N_2O	0.5 PPM	1.977
Xenon	Xe	0.09 PPM	5.9
Ozone	O_3	0.0 to 0.07 PPM	2.144
Ozone - winter	O_3	0.0 to 0.02 PPM	2.144
Nitrogen Dioxide	NO_2	0.02 PPM	1.4494
Iodine	I_2	0.01 PPM	4.93
Carbon Monoxide	CO	0.0 to trace	1.2500
Ammonia	NH_3	0.0 to trace	0.7710

RADON FACTS

1 working level = 3 DAC Rn^{222} (including progeny)
= 1.3E5 MeV / liter of air alpha energy
= 100 pCi / liter (1E-7 uCi / mL)
= 20.8 uJoules / M^3
1 working level-month = 1 pCi / L in air thru evaporation

EPA ACTION LEVELS FOR RADON GAS IN HOMES

Concentration (pCi / L)	Sampling Frequency
0 - 4	initial and no follow up

EPA Recommends Mitigation at ≥ 4 pCi / L

4 -20 one year and follow up
20 -200 3 months and follow up
> 200 Implement radon reduction methods 4 pCi / L in living area = 1.03 working level-month = 1 rem

PROPOSED EPA ACTION LEVELS FOR RADON IN DRINKING WATER

Maximum Contaminant Level (MCL) is 300 pCi / L of radon in water of community water systems (CWS).
Alternative Maximum Contaminant Level (AMCL) is 4,000 pCi / L of radon in water of community water systems.

To comply with the AMCL limit the state or the CWS (Community Water System) must implement a Multi-Media Mitigation plan to address the radon in the air of residences. The proposed rule would not apply to CWSs that use solely surface water.

The proposed rule requires monitoring for radon in drinking water. The monitoring frequency varies from once per quarter to once in 9 years based on radon concentrations.

SI and US “Traditional” Units

Activity

1 TBq = 27 Ci
1 GBq = 27 mCi
1 MBq = 27 µCi
1 kBq = 27 nCi
1 Bq = 27 pCi
1 Bq = 1 dps
1 Bq = 60 dpm
1 kCi = 37 TBq
1 Ci = 37 GBq
1 mCi = 37 MBq
1 µCi = 37 kBq
1 nCi = 37 Bq
1 nCi = 37 dps
1 nCi = 2220 dpm
1 pCi = 0.037 Bq
1 pCi = 2.22 dpm

Dose Equivalent

1 Sv = 100 rem
1 mSv = 100 mrem
1 mSv = 0.10 rem
1 µSv = 100 µrem
1 µSv = 0.10 mrem
1 nSv = 0.10 µrem

1 krem = 10 Sv
1 rem = 10 mSv
1 mrem = 10 µSv
1 mrem = 0.01 mSv
1 µrem = 0.01 µSv
1 µrem = 10 nSv

Absorbed Dose

1 kGy = 100 krad
1 Gy = 100 rad
1 mGy = 100 mrad
1 µGy = 100 µrad
1 krad = 10 Gy
1 rad = 10 mGy
1 mrad = 10 µGy
1 µrad = 10 nGy

Dose Rate

1 Sv/h = 100 rem/h
1 mSv/h = 100 mrem/h
1 µSv/h = 100 µrem/h
1 nSv/h = 100 nrem/hr
1 krem/h = 10 Sv/h
1 rem/h = 10 mSv/h
1 mrem/h = 10 µSv/h
1 µrem/h = 0.01 µSv/h

ABBREVIATIONS

ampere	A, or amp
angstrom unit	A, or Å
atmosphere	atm
atomic weight	at. wt.
becquerel	Bq
cubic foot	ft^3, or cu ft
cubic feet per minute	ft^3/min, or cfm
cubic inch	in^3, or cu. in.
cubic meter	m^3, or cu m
curie	Ci
degree	deg, or ^{0}
disintegrations per minute	dpm
gallon	gal
gallons per minute	gpm
gram	g or gm
liter	liter, or L
meter	m
micron	μ, μm, or mu
pounds per square inch	lb/in^2, or psi
roentgen	R
square centimeter	cm^2, or sq cm
square foot	ft^2, sq ft
square meter	m^2, or sq m
volt	V, or v
watt	W, or w

CONVERSION OF UNITS

Length

1 angstrom (Å)	=	1E-8 cm	1 cm	=	1E8 Å
1 inch	=	2.54 cm	1 cm	=	0.3937 in
1 meter	=	3.2808 feet	1 foot	=	0.3048 m
1 kilometer	=	0.6214 miles	1 mile	=	1.609 km
1 mile	=	5,280 feet	1 foot	=	1.894E-4 mi
1 micron (µm)	=	1E-6 meters	1 m	=	1E6 µm
1 mil	=	1E-3 inches	1 inch	=	1E3 mil
1 thousandth of an inch (0.001")	=	2.54E-2 mm	1 mm	=	0.03937 in
1 yard	=	0.9144 meters	1 m	=	1.0936 yard

Area

1 acre	=	43,560 ft^2	1 ft^2	=	2.296E-5 acre
1 barn	=	1E-24 cm^2	1 cm^2	=	1E24 barn
1 cm^2	=	0.1550 in^2	1 in^2	=	6.452 cm^2
1 m^2	=	10.764 ft^2	1 ft^2	=	0.0929 m^2
1 m^2	=	3.861E-7 mile^2	1 mile^2	=	2.59E6 m^2
1 mile^2	=	640 acres	1 acre	=	1.5625E-3 mi^2

Volume

1 cm^3 (cc)	=	3.5315E-5 ft^3	1 ft^3	=	28,316 cm^3
1 cm^3	=	1E-6 m^3	1 m^3	=	1E6 cm^3
1 cm^3	=	0.03381 ounces	1 ounce	=	29.58 cm^3
1 92ft^3	=	28.316 liters	1 liter	=	0.035315 ft^3
1 ft^3	=	7.481 gallons	1 gal	=	0.1337 ft^3
1 liter	=	1.057 quarts	1 quart	=	0.946 liter
1 liter	=	0.2642 gallons	1 gal	=	3.785 liter
1 liter	=	61.0237 in^3	1 in^3	=	0.016387 liter
1 m^3	=	35.315 ft^3	1 ft^3	=	0.028316 m^3
1 m^3	=	1,000 liters	1 liter	=	1E-3 m^3
1 milliliter (ml)	=	1 cm^3	1 cm^3	=	1 ml

Mass

1 gram	=	0.03527 ounces	1 ounce	=	28.35 g
1 kilogram	=	2.2046 pounds	1 lb	=	0.4536 kg
1 pound	=	16 ounces	1 ounce	=	0.0625 lb
1 pound	=	453.59 grams	1 gram	=	2.2046E-3 lb

Density

1 gram / cm^3 = 62.428 lbs / ft^3 1 lb/ft^3 = 0.016018 g/cm^3
1 gram / cm^3 = 8.345 lbs / gal 1 lb/gal = 0.1198 g/cm^3

Concentration

1 Bq / M^3 = 60 DPM / M^3 1 DPM/M^3 = 0.0167 Bq/M^3
1 Bq / M^3 = 0.027027pCi/L 1 pCi / L = 37 Bq / M^3
1 pCi / L = 1E-9 µCi / cc 1 µCi / cc = 1E9 pCi / L
1 µCi / cc = 2.22E12 DPM/M^3
1 DPM / M^3 = 4.5045E-13 µCi/cc
1 µCi / cc = 3.7E10 Bq / M^3
1 Bq / M^3 = 2.7027E-11 µCi/cc
1 pCi / ft^3 = 3.5315E-11 µCi / cc
1 µCi / cc = 2.8316E10 pCi / ft^3

Pressure

1 atmosphere = 1.01325 bars 1 bar = 0.9869 atm
1 atmosphere = 101.325 kPa 1 kPa = 0.009869 atm
1 atmosphere = 14.696 lbs / in^2 1 lbs / in^2 = 0.06805 atm
1 atmosphere = 760 mm Hg 1 mm Hg = 0.001316 atm
1 atmosphere = 29.9213 “Hg 1 “Hg = 0.033421 atm
1 atmosphere = 33.8995 feet H_2O 1 ft H_2O = 0.0295 atm
1 bar = 1E6 dynes / cm^2 1 dyne/cm^2 = 1E-6 bar
1 dyne/cm^2 = 0.1 Pascals 1 Pascal = 10 dyne/cm^2
1 Torr = 1 mm Hg 1 mm Hg = 1 Torr
1 dyne/cm^2 = 1.0197E-3 g/cm^2 1 g/cm^2 = 980.68 dyne/cm^2

Power

1 joule/sec = 1E7 ergs/sec 1 erg/sec = 1E-7 joule/sec
1 watt = 1E7 ergs/sec 1 erg/sec = 1E-7 watt
1 watt = 1 joule/sec 1 joule/sec = 1 watt
1 watt = 0.001341 hp 1 hp = 745.7 watts
1 BTU/min = 0.01757 kW 1 kW = 56.9 BTU/min
1 BTU/min = 0.023575 hp 1 hp = 42.4 BTU/min
1 joule = 9.478E-4 BTU 1 BTU = 1.055E3 joules
1 joule = 1E7 ergs 1 erg = 1E-7 joule
1 calorie, g = 0.003971 BTU 1 BTU = 251.8 calories, g

Radiological

1 roentgen = 1.61E12 ion pairs/g of air
1 roentgen = 0.98 rads (in soft tissue)
1 roentgen = 87.7 ergs / g of air
1 roentgen = 5.47E13 eV / g of air
1 ion pair / g of air = 6.21E-13 roentgen
1 rad (in soft tissue) = 1.02 roentgen
1 eV / g tissue = 1.602E-13 roentgen
1 erg / g of air = 0.0114 roentgen
1 eV / g of air = 1.828E-14 roentgen
1 rad = 100 ergs / g
1 rad = 6.242E13 eV / g
1 μCi / m^2 = 222 dpm / cm^2
1 dpm / cm^2 = 0.0045 μCi / m^2
1 megaCi/sq mile = 0.386 Ci / m^2
1Ci / m^2 = 2.59 mega Ci/sq mile
1 μCi / cm^3 = 2.22E12 dpm / m^3
1 dpm / m^3 = 4.5E-13 μCi / cm^3
1 becquerel (Bq) = 2.7027E-11 Ci
1 g U^{235} fissioned = 7.81E7 BTU
1 fission = 3.04E-14 BTU
1 g U^{235} fissioned = 1 megawatt-days
1 g U^{235} fissioned = 1.8E-2 kilotons TNT
1 kW-hrs = 1.123E17 fissions
1 fission = 3.204E-4 ergs
1 erg = 3.121E3 fissions
1 Megatons TNT = 1.45E20 fissions

1 erg / g = 0.01 rad
1 erg /g in tissue = 0.01 rem
1 rem = 0.01 Sv
1 curie (Ci) = 3.7E10 dps
1 curie = 2.22E12 dpm
1 Ci = 3.7E10 Bq
1 dps = 1 Bq
1 rad = 0.01 gray
1 eV = 1.602E-19 joule

1 rem = 100 ergs / g in tissue
1 sievert (Sv) = 100 rem
1 sievert = 1 J / kg
1 dps = 2.7027E-11 Ci
1 dpm = 4.5045E-13 Ci
1 becquerel = 1 dps
1 gray = 100 rads
1 joule (J) = 6.24E18 eV

Others

1 ampere = 2.998E9 electrostatic units/sec
3.336E-10 amp = 1 electrostatic unit/sec
1 ampere = 6.242E18 electronic charges/sec
1.602E-19 amp = 1 electronic charge/sec
1 coulomb = 6.242E18 electronic charges
1 electronic charge = 1.602E-19 coulomb

MULTIPLES AND SUBMULTIPLES

1E18	Exa	E	1E2	hecto	h	1E-6	micro	µ
1E15	Peta	P	1E1	deka	da	1E-9	nano	n
1E12	tera	T	1E0	1	1	1E-12	pico	p
1E9	giga	G	1E-1	deci	d	1E-15	femto	f
1E6	mega	M	1E-2	centi	c	1E-18	atto	a
1E3	kilo	k	1E-3	milli	m			

GREEK ALPHABET

Α α	Alpha	Ι ι	Iota	Ρ ρ	Rho
Β β	Beta	Κ Κ	Kappa	Σ σ	Sigma
Γ γ	Gamma	Λ λ	Lambda	Τ τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
Ε ε	Epsilon	Ν ν	Nu	Φ φ	Phi
Ζ ζ	Zeta	Ξ ξ	Xi	Χ χ	Chi
Η η	Eta	Ο ο	Omicron	Ψ ψ	Psi
Θ θ	Theta	Π π	Pi	Ω ω	Omega

CONSTANTS

Avogadro's number (N_0)	6.02252E23
electron charge (e)	4.80298E-10 esu
e electron rest mass (m)	9.1091E-28 g
acceleration of gravity (g)	32.1725 ft / sec^2
@ sea level & 45^0 latitude	980.621 cm / sec^2
Planck's constant (h)	6.625E-27 erg-sec
velocity of light (c)	2.9979E10 cm/sec
	186,280 miles / sec
ideal gas volume (V_0)	22,414 cm3 / mole (STP)
neutron mass	1.67482E-24 g
proton mass	1.67252E-24 g
ratio of proton to electron mass	1836.13
natural base of logarithms (e)	2.71828
pi	3.14159
1C	6.2418E18 esus
1A	1 C/sec
1 barn (b)	1E-24 cm^2
charge (e-1)	1.6E-19 C
W for air	33.8 eV / ion pair
Universal gas constant (R)	8.32E7 ergs/^{0}C gram mol

A gram-molecular weight of any gas contains Avogadro's number, N_0 (6.02252E23) atoms and occupies a volume of 22,414 cm^3 at STP.

Temperature

^{0}C = (^{0}F - 32)(5/9)

^{0}F = ^{0}C x 1.8 + 32

K (Kelvin) = ^{0}C + 273.15

^{0}R (Rankine) = ^{0}F + 459.58

Absolute zero is 0 Kelvin, 0 Rankine, -273.15 ^{0}C, and -459.67 ^{0}F

Surface Area & Volume Calculations

Triangle A (area) = ½ x b x h;
where b is the base and h is the height of the triangle

Rectangle A (area) = a x b;
where a and b are the lengths of the sides

Rectangular Box V (volume) = w x l x h;
where w is the width, l is the length, and h is the height

Parallelogram (a 4-sided figure with opposite sides parallel)
A (area) = a x h; or a x b x sin Θ
where a and b are the length of the sides, h is the altitude (or vertical height), and Θ is the angle between the sides

Trapezoid (a 4-sided figure with two sides parallel)
A (area) = ½ x h (a + b);
where a and b are the length of the sides and h is the height

Regular polygon of *n* sides
A (area) = 1/4 x *n* x a^2 x cotangent (180^0 / *n*);
where a is the length of a side and *n* is the number of sides

Circle A (area) = πr^2; or $1/4 \pi d^2$;
where r is the radius and d is the diameter

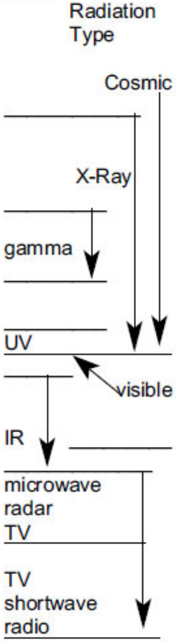
Cube A (area) = 6 x a^2; V (volume) = a^3;
where a is the length of a side

Cylinder A (area) = $2 \pi r h$; V (volume) = $\pi r^2 h$;
where r is the radius and h is the length of the height

Sphere A (area) = $4 \pi r^2$; or πd^2; V (volume) = $4/3 \pi r^3$ **or** $1/6 \pi d^3$
where r is the radius and d is the diameter

ELECTROMAGNETIC SPECTRUM

Wavelength Meters	Frequency MHz	Energy keV
1E-8	3E20	1.24E9
1E-14	3E16	1.24E5
1E-10	3E12	1.24E1
1E-6	3E8	1.24E-3
1E-2	3E4	1.24E-7
1E2	3	1.24E-11
1E6	3E-4	1.24E-15



λ (meters wavelength) = 300 / F = 1.24E-9 / keV
F (frequency MHz) = 300 / λ = 2.419E11 x keV
E (keV) = 1.24E-9 / λ = F / 2.419E11

Rules of Thumb for Alpha Particles

1. An alpha particle of at least 7.5 MeV energy is needed to penetrate the nominal protective layer of the skin (7 mg / cm^2 or 0.07 mm).

2. The alpha emissions and energies of the predominant particles from 1 µg of several common materials are:

	DPM per µg	**Alpha Energy (MeV)**
Pu-238	39,000,000	5.50 (72%)
Pu-239	140,000	5.15 (72.5%)
Pu-240	500,000	5.16 (76%)
Pu-242	8,700	4.90 (76%)
[a]Natural U	1.5	4.20 (37%), 4.77 (36%)
Oralloy (93% 235U)	160	4.39 (~ 80%)
[b]Natural Th	0.5	4.01 (38%), 5.43 (36%)
[c]D-38 (DU, tuballoy)	1	4.20 (~ 60%)

[a] Includes 234U in equilibrium

[b] Includes 228Th in equilibrium. Depending upon the time since chemical separation, 228Th can decay to give a net disintegration rate lower than 0.5.

[c] With 2pi (50%) geometry, the surface of a thick uranium metal (tuballoy) source gives ~ 2400 alpha counts/min per cm^2.
Depleted uranium (D-38) gives ~ 800 alpha cpm/cm^2.

3. Alpha particles lose about 0.8 MeV per mg/cm^2 density thickness of the attenuating material.

4. Detector window thicknesses cause alpha particles to lose energy at about 0.8 MeV per mg/cm^2 of window thickness.
Therefore, a detector with a window thickness of 3 mg/cm^2 (such as sealed gas-proportional pancake alpha/beta detectors and pancake GM detectors) will not detect alpha emitters of less than 3 MeV.

5. Air-proportional alpha detectors have a flatter energy response vs efficiency response than sealed gas-proportional, alpha scintillator, alpha/beta scintillator, or GM detectors. This is due to several factors. One factor is the typically thinner entrance windows on air-proportional alpha detectors compared to beta detectors and alpha and beta scintillator detectors whereby more of the initial alpha particle energy enters the active volume of the air-proportional detector compared to other detectors. A second factor is the relatively shallow depth of the air-proportional detector compared to the path length of the alpha particle in air which leads to the alpha pulses being of similar height for any alpha particle energy above a threshold.

6. Alpha particle energy transfer to air
6 MeV alpha particles produce 40,000 Ion Pairs per cm
4 MeV alpha particles produce 55,000 Ion Pairs per cm
therefore;
6 MeV alpha particles lose 1.18 MeV per cm of air
4 MeV alpha particles lose 1.87 MeV per cm of air

Alpha particle range in cm of air at 1 atmosphere
$R = 0.56\ E\ (E < 4\ \text{MeV})$
$R = 1.24\ E - 2.62\ (E > 4\ \text{MeV})$

Alpha particles lose about 60 KeV of energy per mm of air at STP.

RULES OF THUMB FOR BETA PARTICLES

1. Beta particles of at least 70 keV energy are required to penetrate the nominal protective layer of the skin.

2. The average energy of a beta-ray spectrum is approximately one-third the maximum energy.

3. The range of beta particles in air is ~12 ft (3.6 m) / MeV.

4. The range of beta particles (or electrons) in grams / cm^2 (thickness in cm multiplied by the density in g / cm^3) is approximately half the maximum energy in MeV. This rule overestimates the range for low energies (0.5 MeV) and low atomic numbers, and underestimates for high energies and high atomic numbers.

5. The exposure rate in rads per hour in an infinite medium uniformly contaminated by a beta emitter is 2.12 EC / ρ where E is the average beta energy per disintegration in MeV, C is the concentration in μCi / cm^3, and ρ is the density of the medium in grams / cm^3. The dose rate at the surface of the object is one half the value given by this relationship. In such a large object, the relative beta and gamma dose rates are related to the average energies released per disintegration.

6. The surface dose rate through 7 mg / cm^2 of shielding from a thin deposition of 1 mCi / cm^2 is about 9 rad/h (90 mGy/h) for energies above about 0.6 MeV. Note that in a thin layer, the beta dose rate exceeds the gamma dose rate for equal energies released by a factor of 100.

7. The bremsstrahlung from a 1 Ci P-32 aqueous solution in a glass bottle is ~ 3 mrad/h (30 μGy/h) at 1 m.

8. Half-value thickness vs beta energy

Isotope	β$^-$ max energy (KeV)	Half-Value Thickness
Tc-99	292	7.5 mg / cm^2
Cl-36	714	15 mg / cm^2
Sr/Y-90	546 / 2270	150 mg / cm^2
U-238	Betas from short lived progeny 191, 2290	130 mg / cm^2

9. Estimating beta energy using a paper shield

a) The density thickness of typical notepaper of 20 pound weight is 7.5 mg/cm^2.

b) Take a reading with your beta detector of the surface contamination you wish to estimate the energy of.

c) A single sheet of notepaper will stop all but the most energetic of alpha particles, will have virtually no effect on gamma radiation, and will only stop very low energy beta particles such as C-14.

d) A single sheet of notepaper will reduce the count rate from Tc-99 by ½.

e) Continue adding more sheet of notepaper until the net count rate is less than ½ the unshielded count rate.

f) Multiply the number of sheet of notepaper necessary to reduce the count rate to ½ by 7.5 mg/cm^2. That density thickness is your half-value layer and you can compare the required density thickness with the table in step 8 or some other reference.

RULES OF THUMB FOR GAMMA RADIATION

1. The range of gamma rays (any photon) for energies from eV to 10 MeV in air is from a few mm to 100 meters. The range of those photons in water is from a few mm to several cm.

2. The dose rate 1 m above a flat, infinite plane contaminated with a thin layer (1 Ci / m^2) of gamma emitters is:

Energy (MeV)	0.4	0.6	0.8	1.0	1.2
Rem/h	7.2	10	13	16	19
mSv/h	72	100	130	160	190

3. The dose rate in rem/h per hour in an infinite medium uniformly contaminated by a gamma emitter is 2.12 EC / ρ, where C is the number of microcuries per cubic centimeter, E is the average gamma energy per disintegration in MeV, and ρ is the density of the medium. At the surface of a large body, the dose rate is about half of this. At ground level (one-half of an infinite cloud), the dose rate from a uniformly contaminated atmosphere is 1,600 EC rem/h per mCi / cm^3.

4. The radiation scattered from the air (skyshine) from a 100 Ci Co-60 source 30 cm behind a 1 m high shield is ~ 100 mR/h (1 mSv/h) at 15 cm from the outside of the shield.

RULES OF THUMB FOR NEUTRONS

1. The number of neutrons per square centimeter per second at distance R from a small source emitting Q neutrons per second without shielding is given by;

$n / cm^2\text{-sec} = Q / 4\pi R^2 = 0.08Q / R^2$

2. For α, neuron sources use the following equation to approximate the number of neutrons per second per Ci (Q).

$Q = 5.6E3 \times (\text{alpha particle energy in MeV})^{3.65}$

This holds true for Be; multiply by 0.16 for Boron, by 0.05 for F, by 0.015 for Li, and 0.003 for O.

3. For neutron energies from 1 to 10 MeV the neutron exposure rate is approximately equal to 1 mrem/hr at 1 meter for each 1E6 neutrons per second.

Multiply the neutron mrem/hr at 1 meter by 11.1 to calculate the neutron exposure rate for the same source at a distance of 30 cm.

4. For spontaneous fission the gamma exposure rate for an unshielded source is approximately twice the neutron exposure rate.

5. The range of neutrons in air for energies from 0 to 10 MeV is from a few centimeters to 100 meters.

6. The range of neutrons in water (or tissue) for energies from 0 to 10 MeV is from a few millimeters to 1 meter.

7. Neutron flux to dose rate conversion:

Fast: 1 mrem (0.01 mSv) / hr per 6 n / cm^2-sec
Slow: 1 mrem (0.01 mSv) / hr per 272 n / cm^2-sec

APPROXIMATE NEUTRON ENERGIES

cold neutrons	0 - 0.025 eV
thermal	0.025 eV
epithermal	0.025 - 0.4 eV
cadmium	0.4 - 0.6 eV
epicadmium	0.6 - 1 eV
slow	1 eV - 10 eV
resonance	10 eV - 300 eV
intermediate	300 eV - 1 MeV
fast	1 MeV - 20 MeV
relativistic	> 20 MeV

Note: A thermal neutron is one which has the same energy and moves at the same velocity as a gas molecule does at a temperature of 20 degrees C. The velocity of a thermal neutron is 2200 m / sec (~5,000 mph).

Neutron Fluence per mrem (10CFR20)

MeV	n/cm^2 per mrem	n/cm^2/s per mrem/hr	MeV	n/cm^2 per mrem	n/cm^2/s per mrem/hr
thermal	....	......	10	2.4E4	6.7
to	9E5	250	14	1.7E4	4.7
1E-2	....	....	20	1.6E4	4.4
1E-1	1.7E5	47	40	1.4E4	6.7
5E-1	3.9E4	11	60	1.6E4	4.4
1	2.7E4	7.5	100	2E4	5.6
2.5	2.9E4	8	200	1.9E4	5.3
5	2.3E4	6.4	300	1.6E4	4.4
7	2.4E4	6.7	400	1.4E4	6.7

Spontaneous Fission Neutron and Gamma Yields

	SF (years) half-life	**n/s/Ci**	**n/s/GBq**	**mrem / hr per Ci @ 30 cm neutron**	**gamma**
Es-253	6.7E5	7.14E3	1.92E2	0.1	0.1
Cf-252	85	2.64E9	7.14E7	2.93E4	1E4
Bk-249	6E8	1.25E2	3.38	<0.1	<0.1
Cm-244	1.38E7	1.11E5	3.0E3	1.2	0.4
Cm-242	7.2E6	5.28E3	1.43E2	<0.1	0.1
Am-241	2E14	0.18	4.86E-3	<0.1	<0.1
Pu-242	7E10	4.56E5	1.23E4	5.0	2.0
Pu-240	1.39E11	4.01E3	1.08E2	<0.1	0.1
Pu-239	5.5E15	0.37	1.0E-2	<0.1	<0.1
Pu-238	4.9E10	1.52E2	4.1	<0.1	<0.1
Pu-236	3.5E9	69.7	1.88	<0.1	<0.1
Np-237	1E18	0.18	4.86E-3	<0.1	<0.1
U-238	7E15	5.44E4	1.47E3	0.6	0.2
U-235	1.9E17	3.15E2	8.51	<0.1	<0.1
U-234	2E16	1.05	2.84E-2	<0.1	<0.1
U-232	8E13	0.07	1.89E-3	<0.1	<0.1
Th-232	1E21	1.18	3.19E-2	<0.1	<0.1

These neutron and gamma exposure rates are approximate values for the spontaneous fission process. When you are making exposure rate measurements you should take into account shielding of the source (including self-shielding), individual instrument response to both neutron and gamma radiation, isotopic mixtures, age of the material (for both decay and ingrowth), homogeneity of the material, and impurities.
Refer to the Specific Activity and Characteristic Radiations of Commonly Encountered Radionuclides sections for information on gamma exposure rates and radiations from primary decay modes of these isotopes.

Energy & Yield of neutrons from the alpha, n reaction

	η energy MeV	n/s/GBq	n/s/Ci	neutron mrem/hr per Ci @ 30 cm
$Cf^{252}O$	4.5	8.73E6	3.23E8	3,600
$Cm^{244}Be$	4	1.0E5	3.7E6	41.1
$Cm^{244}O$	1.9	1.0E5	3.7E6	41.1
$Cm^{242}Be$	4	1.12E5	4.1E6	45.5
$Cm^{242}O$	1.9	1.12E5	4.1E6	45.5
$Am^{241}Be$	4.5	7.6E4	2.8E6	34.7
$Am^{241}B$	2.8	1.3E4	4.8E5	5.9
$Am^{241}F$	1.3	4.1E3	1.5E4	0.17
$Am^{241}Li$	0.7	1.4E3	5.2E4	0.29
$Am^{241}O$	1.9	250	9.23E3	0.1
$Pu^{242}O$	1.7	2.13E-4	7.88E-3	8.7E-8
$Pu^{240}O$	1.9	0.86	32	3.6E-4
$Pu^{239}Be$	4.5	6.1E4	2.3E6	28.5
$Pu^{239}O$	1.9	0.06	2.36	2.6E-5
$Pu^{238}Be$	4.5	7.9E4	2.9E6	32.2
$Pu^{238}O$	1.9	6.19E3	2.29E5	2.5
$Pu^{239}F$	1.4	5.4E3	2E5	2.2
$Pu^{238}Li$	0.6	38	1.4E3	0.008
$Pu^{238}C^{13}$	3.6	1.1E4	4.1E4	0.46
$Pu^{236}O$	2.0	54	2E3	0.02
$Np^{237}O$	1.2	54	2E3	0.02

$U^{238}O$, $U^{235}O$, $U^{234}O$, $U^{233}O$, and $U^{232}O$ have similar alpha particle energies, therefore the energy and yield of the neutrons from the uranium oxide alpha, n reactions are similar.

$U^{238}O$	1.2	54	2E3	0.02
$Th^{232}O$	1.2	54	2E3	0.02

Energy & Yield of neutrons from the alpha, n reaction

	η energy MeV	n/s/GBq	n/s/Ci	neutron mrem/hr per Ci @ 30 cm
Ac^{227}Be	av 5	7.02E5	2.6E7	289
Ra^{226}Be	av 4.5	5.02E5	1.9E7	211
Ra^{226}B	3.0	8.0E4	3.0E5	3.3
Po^{210}Be	4.2	7.1E4	2.6E6	28.9
Po^{210}Li	0.48	1.2E3	4.4E4	0.49
Po^{210}B	2.5	1.0E3	3.7E5	4.1
Po^{210}F	0.42	3E3	1.1E5	1.2

Ra-226 and Ac-227 include progeny effects

Energy & Yield for 5.2 MeV alpha particles for various elements

α, η sources	**η energy (MeV)**	**n/s/GBq**	**n/s/Ci**
Li	0.3	1.13E3	4.2E4
Be	4.2	6.5E4	2.4E6
B	2.9	1.75E4	6.5E5
C	4.4	7.8E1	2.9E3
O	1.9	5.9E1	2.2E3
F	1.2	5.9E3	2.2E5
Na	?	1.1E3	4.1E4
Mg	2.7	8.9E2	3.3E4
Al	1.0	4.1E2	1.5E4
Si	1.2	7.6E1	2.8E3

Isotopic Mix of Heat Source (RTG) Pu^{238}

	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
% Weight	90.0	9.10	0.60	0.30	<0.01
% Activity	97.99	0.036	0.009	1.972	3.6E-6
Curies for a 1 kilo-gram mixture of RTG Pu-238					
	1.54E4	5.65	1.36	309	6.48E-3
exposure rates in rem/hr at 30 cm					
γ	2.46	7.3E-4	1.6E-3	- - -	3.2E-5
η	- - -	- - -	- - -	- - -	6.4E-5

Total γ + η 2.46

Isotopic Mix of Reactor Grade Pu

	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
% Weight	1.50	58.1	24.1	11.4	4.90
% Activity	2.12	0.30	0.45	97.13	1.6E-3
Curies for a 1 kilo-gram mixture of reactor grade Pu	256.5	36.1	54.7	1.17E4	0.19
exposure rates in rem/hr at 30 cm					
γ	0.041	4.7E-3	0.063	- - -	9.5E-4
η	- - -	- - -	- - -	- - -	1.9E-3

Total γ + η 0.109

Heat Source (RTG) Pu238 15 years after fabrication

	Pu-238	U-234	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
% Wt	79.94	10.06	9.10	0.60	0.14	<0.01	0.16
% Act	99.00	1.2E-3	3.7E-5	9.1E-5	0.99	3.7E-8	3.7E-4
Curies for a 1 kilo-gram mixture of 15 years-old RTG Pu-238	1.37E4	0.626	5.65	1.36	144.2	6.5E-3	5.49
exposure rates in rem/hr at 30 cm							
γ	2.19	1.9E-4	7.3E-4	1.6E-3	- - -	3.3E-5	0.933
η	- - -	- - -	- - -	- - -	- - -	6.6E-5	- - -

Total γ + η 3.13

Reactor Grade Pu 15 years after fabrication

	Pu-238	U-234	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
% Wt	1.33	0.17	58.1	24.1	5.54	4.90	5.86
% Act	3.66	4.6E-5	0.58	0.88	91.83	3.1E-5	3.05
Curies for 1 kilo-gram mixture of 15 year-old reactor grade Pu	227.4	0.01	36.1	54.7	5.71E3	0.19	201
exposure rates in rem/hr at 30 cm							
γ	0.036	3E-6	4.7E-3	0.063	- - -	9.5E-3	34.2
η	- - -	- - -	- - -	- - -	- - -	1.9E-2	- - -

Total γ + η 34.3

Neutron exposure rates from the oxide form of radionuclides

mrem/hr per	Pu^{238}	U^{234}	Pu^{239}	Pu^{240}	Pu^{242}	Am^{241}
Ci at 30 cm	2.5	2E-2	2.6E-5	3.6E-4	8.7E-8	0.1

Neutron and gamma exposure rates from Spontaneous Fission (SF) for Pu and U Power Source Radionuclides

			γ mrem /hr	S. F. mrem/hr	Ci@30 cm	
	Half-life	Ci / g	Ci @ 30 cm	S. F. Half-life	γ	η
Pu-238	87.7y	17.1	0.16	4.9E10y	- - -	- - -
U-234	2.45E5y	6.22E-3	0.3	2E16y	- - -	- - -
Pu-239	2.41E4y	6.21E-2	0.13	5.5E15y	- - -	- - -
Pu-240	6.56E3y	0.227	0.16	1.39E11y	1	- - -
Pu-241	14.4y	103	- - -	- - -	- - -	- - -
Am-241	432.7y	3.43	170	2E14y	- - -	- - -
Pu-242	3.75E5y	3.94E-3	- - -	7E10y	5	10
U-238	4.47E9y	3.36E-7	0.4	7E15y	0.6	1.2
Th-234	24.1d	2.32E4	35.6	- - -	- - -	- - -
Pa-234m	1.17m	6.86E8	50	- - -	- - -	- - -
U-235	7.04E8y	2.16E-6	755	1.9E17y	- - -	- - -
Th-231	25.22h	5.32E5	48	- - -	- - -	- - -
U-234	2.46E5y	6.22E-3	0.3	2E16 y	- - -	- - -

Isotopic Mix of Natural U

	U-238	Th-234	Pa-234m	U-235	Th-231	U-234
% Wt	99.27	- - -	- - -	0.72	- - -	0.0057
% Act	24.39	24.39	24.39	1.16	1.16	24.51
Curies for a 1 kilo-gram mixture of natural uranium						
	3.3E-4	3.3E-4	3.3E-4	1.6E-5	1.6E-5	3.5E-4
gamma exposure rates in μrem/hr at 30 cm						
	0.13	11	17	12	0.77	0.11

Total gamma exposure rate 40 μrem/hr at 30 cm

Isotopic Mix of Commercial U

	U-238	Th-234	Pa-234m	U-235	Th-231	U-234
% Wt	97.01	- - -	- - -	2.96	- - -	0.03
% Act	11.23	11.23	11.23	2.27	2.27	61.76
Curies for a 1 kilo-gram mixture of commercial uranium						
	3.3E-4	3.3E-4	3.3E-4	6.4E-5	6.4E-5	1.9E-3
gamma exposure rates in μrem/hr at 30 cm						
	0.13	11	17	48	3.1	0.57

Total gamma exposure rate 79 μrem/hr at 30 cm

Isotopic Mix of 10% Enriched U

	U-238	Th-234	Pa-234m	U-235	Th-231	U-234
% Wt	89.87	- - -	- - -	10.0	- - -	0.13
% Act	3.25	3.25	3.25	2.32	2.32	85.59
Curies for a 1 kilo-gram mixture of 10% enriched uranium	3.0E-4	3.0E-4	3.0E-4	2.2E-4	2.2E-4	8.1E-3
gamma exposure rates in µrem/hr at 30 cm	0.12	11	15	170	11	2.4

Total gamma exposure rate 210 µrem/hr at 30 cm

Isotopic Mix of 20% Enriched U

	U-238	Th-234	Pa-234m	U-235	Th-231	U-234
% Wt	79.68	- - -	- - -	20.0	- - -	0.32
% Act	1.25	1.25	1.25	2.00	2.00	92.25
Curies for a 1 kilo-gram mixture of 20% enriched uranium	2.7E-4	2.7E-4	2.7E-4	4.3E-4	4.3E-4	2.0E-2
gamma exposure rates in µrem/hr at 30 cm	0.11	9.6	14	320	21	6.0

Total gamma exposure rate 370 µrem/hr at 30 cm

Isotopic Mix of Depleted U

	U-238	Th-234	Pa-234m	U-235	Th-231	U-234
% Wt	99.75	- - -	- - -	0.25	- - -	0.0005
% Act	32.01	32.01	32.01	0.53	0.53	2.90
Curies for a 1 kilo-gram mixture of depleted uranium	3.4E-4	3.4E-4	3.4E-4	5.4E-6	5.4E-6	3.1E-5
gamma exposure rates in µrem/hr at 30 cm	0.14	12	17	4.1	0.26	9.3E-3

Total gamma exposure rate 33 µrem/hr at 30 cm

Isotopic Mix of HEU

	U-238	Th-234	Pa-234m	U-235	Th-231	U-234
% Wt	6.7	- - -	- - -	93.2	- - -	0.01
% Act	0.5	0.5	0.5	42.6	42.6	13.3
Curies for a 1 kilo-gram mixture of HEU	2.3E-5	2.3E-5	2.3E-5	2.0E-3	2.0E-3	6.2E-4
gamma exposure rates in µrem/hr at 30 cm	9.2E-3	0.82	1.2	1500	96	0.19

Total gamma exposure rate **1.6 mrem/hr** at 30 cm

MISCELLANEOUS RULES OF THUMB

1. One watt of power in a reactor requires 3.1E10 fissions per second. In a reactor operating for more than 4 days, the total fission products are about 3 Ci / watt at 1.5 min after shutdown. At 2 years after shutdown, the fission products are approximately 75 Ci / MW-day.
2. The quantity of a short-lived fission product in a reactor which has been operated about four times as long as the half-life is given by; Ci ~ (FY)(PL) ,
   where FY is the fission yield (%/100) and PL is the power level in watts.
3. Correction factor for unsealed ion chambers to STP (0^0C and 760 mm of Hg) is $f = (t + 273)/(273) \times (760 / P)$ where t is the ambient temperature in degrees C and P is the ambient barometric pressure in mm of Hg.
4. The activity of an isotope (without radioactive daughter) is reduced to less than 1% after seven half-life.

NATURALLY OCCURRING RADIONUCLIDES

Primordial	**Cosmogonic**
K-40	Tritium
Rb-87	Be-7
Natural U and Th	C-14

Unified Time, Distance, and Shielding formula for reduction of external dose

Rem = Initial Rem/hr x T in hours x $(D_2)^2/(D_1)^2 \times 0.5^n$

Where: Rem is the dose after applying reduction methods
T is the exposure time in hours
D_1 is the initial distance to the source
D_2 is the new distance to the source
0.5^n is the Shielding for ‘n’ half-value layers

Characteristic X-Rays (KeV) of the Elements

These characteristic x-rays originate in the shell of the atom and can be used to identify specific elements but not a specific isotope. These characteristic x-rays are emitted from the shell of the atom after sufficient energy in the form of thermal heat, laser, micro-waves, or other type of energy is directed into the atom shell.

Z #		Kα	Kβ	Lα	Lβ
89	Ac	90.89	102.85	12.65	15.71
47	Ag	22.16	24.94	2.98	3.15
13	Al	1.49	1.55	X	X
95	Am	106.35	120.16	14.62	18.83
18	Ar	2.96	3.19	X	X
33	As	10.54	11.73	1.28	1.32
85	At	81.53	92.32	11.42	13.87
79	Au	68.79	77.97	9.71	11.44
5	B	0.185	X	X	X
56	Ba	32.19	36.38	4.47	4.83
4	Be	0.110	X	X	X
83	Bi	77.10	87.34	10.84	13.02
97	Bk	111.90	126.36	15.31	19.97
35	Br	11.92	13.29	1.48	1.53
6	C	0.282	X	X	X
20	Ca	3.69	4.01	0.34	X
48	Cd	23.17	26.09	3.13	3.32
58	Ce	34.72	39.26	4.84	5.26
98	Cf	114.75	129.54	15.66	20.56
17	Cl	2.62	2.82	X	X
96	Cm	109.10	123.24	14.96	19.39
27	Co	6.93	7.65	0.78	0.79
24	Cr	5.41	5.43	0.57	0.58
55	Cs	30.97	34.98	4.29	4.62
29	Cu	8.05	8.90	0.93	0.95
66	Dy	45.99	52.18	6.50	7.25
68	Er	49.10	55.69	6.95	7.81
99	Es	117.65	132.78	16.02	21.17
63	Eu	41.53	47.03	5.85	6.46
9	F	0.677	X	X	X
26	Fe	6.40	7.06	0.70	0.72
100	Fm	120.60	136.08	16.38	21.79

Z #		Kα	Kβ	Lα	Lβ
87	Fr	86.12	97.48	12.03	14.77
64	Gd	42.98	48.97	6.06	6.71
31	Ga	9.25	10.26	1.10	1.12
32	Ge	9.89	10.98	1.19	1.21
1	H				
105	Ha				
2	He				
72	Hf	55.76	63.21	7.90	9.02
80	Hg	70.82	80.26	9.99	11.82
67	Ho	47.53	53.93	6.72	7.53
53	I	28.61	32.29	3.94	4.22
49	In	24.21	27.27	3.29	3.49
77	Ir	64.89	73.55	9.19	10.71
19	K	3.31	3.59	X	X
36	Kr	12.65	14.11	1.59	1.64
57	La	33.44	37.80	4.65	5.04
3	Li	0.052	X	X	X
103	Lr				
71	Lu	54.06	61.28	7.65	8.71
101	Md				
12	Mg	1.25	1.30	X	X
25	Mn	5.90	6.49	0.64	0.65
42	Mo	17.48	19.61	2.29	2.40
7	N	0.392	X	X	X
11	Na	1.04	1.07	X	X
41	Nb	16.61	18.62	2.17	2.26
60	Nd	37.36	42.27	5.23	5.72
10	Ne	0.851	X	X	X
28	Ni	7.48	8.26	0.85	0.87
102	No				
93	Np	101.00	114.18	13.95	17.74
8	O	0.526	X	X	X
76	Os	62.99	71.40	8.91	10.36
15	P	2.02	2.14	X	X
91	Pa	95.85	108.41	13.29	19.70
82	Pb	74.96	84.92	10.55	12.61
46	Pd	21.18	23.82	2.84	2.99
61	Pm	38.65	43.96	5.43	5.96

Z #		Kα	Kβ	Lα	Lβ
84	Po	79.30	89.81	11.13	13.44
59	Pr	36.02	40.75	5.03	5.49
78	Pt	66.82	75.74	9.44	11.07
94	Pu	103.65	117.15	14.28	18.28
88	Ra	88.46	100.14	12.34	15.23
37	Rb	13.39	14.96	1.69	1.75
75	Re	61.13	69.30	8.65	10.01
104	Rf				
45	Rh	20.21	22.72	2.70	2.83
86	Rn	83.80	94.88	11.72	14.32
44	Ru	19.28	21.66	2.56	2.68
16	S	2.31	2.46	X	X
51	Sb	26.36	29.72	3.61	3.84
21	Sc	4.09	4.46	0.40	X
34	Se	11.22	12.50	1.38	1.42
106	Sg				
14	Si	1.74	1.83	X	X
62	Sm	40.12	45.40	5.64	6.21
50	Sn	25.27	28.48	3.44	3.66
38	Sr	14.16	15.83	1.81	1.87
73	Ta	57.52	65.21	8.15	9.34
65	Tb	44.47	50.39	6.28	6.98
43	Tc	18.41	19.61	2.42	2.54
52	Te	27.47	30.99	3.77	4.03
90	Th	93.33	105.59	12.97	16.20
22	Ti	4.51	4.93	0.45	0.46
81	Tl	72.86	82.56	10.27	12.21
69	Tm	50.73	57.58	7.18	8.10
74	W	59.31	67.23	8.40	9.67
92	U	98.43	111.29	13.61	17.22
23	V	4.95	5.43	0.51	0.52
54	Xe	29.80	33.64	4.11	4.42
39	Y	14.96	16.74	1.92	2.00
70	Yb	52.36	59.35	7.41	8.40
30	Zn	8.64	9.57	1.01	1.03
40	Zr	15.77	17.67	2.04	2.12

COUNTING STATISTICS

Minimum Detectable Activity (MDA)
$\text{MDA} = 2k\sqrt{}(R_B \times t_S + R_B \times t_B) / (t_S \times \text{Eff})$

Minimum Detectable Count Rate
$(\text{MDCR} = \text{LLD} = L_D) = 2k\sqrt{}(R_B \times t_S \times R_B \times t_B) / t_S$

$L_C = k\sqrt{}(R_B \times t_S + R_B \times t_B)$
k = sigma multiplier
t_S = sample count time
t_B = background count time
R_B = background count rate
Eff = efficiency of the detector (expressed as a decimal)
R_S = sample count rate
LLD is Lower Limit of Detection
L_D is the Decision Level
L_C is the Critical Level
MDA, MDCR, LLD, LD, and LC are generally expressed as signal level (or counts) above background

K	0.674	1.00	1.645	1.96	2.58	3.00	3.29	4.00
% C.L.	50.0	68.3	90.0	95.0	99.0	99.7	99.9	99.99

If R_B is in DPM it must be converted to CPM and then multiplied by the count time to get accumulated counts.
A 'k' of 1.645 is used as the 95% confidence level for a two-tailed distribution.
Gaussian statistics should be used for $\geq$ 30 counts and Poisson statistics for < 30 counts.

Gaussian Formula

When background and sample count times are one minute and k is 1.645.
$\text{MDA} = 2k\sqrt{}(R_B \times t_S + R_B \times t_B) / (t_S \times \text{Eff})$

When background count time is ten minutes and sample count time is one minute and k is 1.645.
$\text{MDA} = 2k\sqrt{}(R_B \times t_S + R_B \times t_S / t_B) / (t_S \times \text{Eff})$

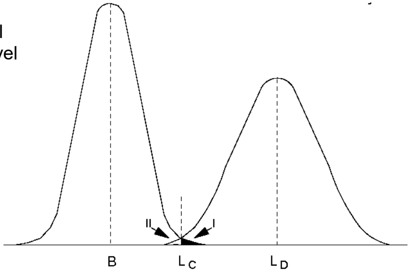
To determine an action level or an alarm setpoint consider how many false positives are acceptable in a time frame.

Example: 100 Area Radiation Monitors (ARMs) are operating in a work area. The annual false alarm rate is 2 alarms in one year for all of the ARMs combined. The ARMs update and check for an alarm every minute. The combined ARMs check for the alarm condition 52,560,000 times each year. More than 2 false alarms in 52,560,000 checks is unacceptable. A 'K' of 6 (99.9999998 % C. L.) is required.

POISSON STATISTICS

IF you have less than 30 counts then use Poisson statistics.
For Poisson distributions the following logic applies.
Pn is the probability of getting count "n"
Pn = $\mu^n e^{-\mu} / n!$
n = the hypothetical count
μ = true mean counts

If the true mean, μ, is 3, then there is a 5% probability that we will get a zero count and a 95% probability that we will get greater than zero counts. There is a 65% probability that we will get 3 or more counts.
I = Probability of Type I error (false positive)
II = Probability of Type II error (false negative)
B = Bkg
L_C = Critical level
L_D = Decision level



INTERFERENCE DUE TO ENVIRONMENTAL RADON

If you are sampling for radon particulate progeny and/or thoron particulate progeny or if those might interfere with your sampling for other airborne radioactive material you will need to take some repetitive measurements to quantify the radioactivity. Radon-222 is a gas in the U-238 decay chain while Radon-220 (known as thoron) is a gas in the Th-232 decay chain.

Refer to the radioactive decay chain for uranium-238 and thorium-232 starting with Po-218 in the U-238 chain and starting with Pb-212 in the Th-232 chain. These particulate progeny and their immediate progeny determine the overall half-life of the alpha emitters in those decay chains. The overall half-life of the particulate progeny alpha emitters in the radon chain is 30 minutes while the overall half-life of the particulate progeny alpha emitters in the thoron decay chain is 10.6 hours (636 minutes).

The following table indicates the decay rates you should observe if you measure the activity on your sample filter at specific times and for different conditions of radon and thoron concentrations.

The assumptions are; almost all radon, almost all thoron, radon and thoron particulate progeny of approximately equal levels of activity.

Measure the initial activity on the sample filter. Then perform the measurement again at 30 minutes, 120 minutes, 240 minutes, and finally 300 minutes after you removed the filter.

INTERFERENCE DUE TO ENVIRONMENTAL RADON

Time Minutes	Mostly Radon % Remaining	Mostly Thoron % Remaining	Equal Mixture % Remaining
30	50%	96.78%	73.4%
120	6.25%	87.74%	47.0%
240	0.49%	77.0%	38.7%
300	0.098%	72.1%	36.1%

Examples:
Assume your initial measurement right after removing the sample filter indicates a count rate of 10,000 cpm.

If you have ONLY radon the count rate will decrease by ½ every 30 minutes and the count rate after 300 minutes will be only 10 cpm.

If you have ONLY thoron the count rate will decrease by ½ every 10.6 hours and therefore the count rate rafter 300 minutes will be 7,200 cpm.

If you have an unknown mixture of radon and thoron then after 300 minutes there is no longer any radon so the measurements should follow the 10.6 hour half-life for thoron only after that initial 300 minute interval.

IF there is a potential for other airborne radioactivity and you have ONLY radon you may be able to determine the presence or absence of that other airborne radioactivity after waiting 7 to 10 half-lives of the radon particulate progeny.

IF there is thoron progeny present you will have a lot of difficulty in determining the presence or absence of that other airborne radioactivity. A portable alpha spectrometer is a useful instrument to have in this case.

UNITS AND TERMINOLOGY

	"Special Units"	**SI Units**
Exposure	Roentgen	Coulombs / kg
Dose	rad (0.01 Gy)	Gray (100 rad)
Dose Equiv	rem (0.01 Sv)	Sievert (100 rem)
Activity	Curie (2.22 E12 dpm)	Becquerel (1dps)

1 Roentgen = 2.58 E-4 coulomb / kg in air
= 1 esu / cm^3 in air
= 87.7 ergs / gm in air
= 98 ergs / gm in soft tissue

1 rad = 100 ergs / gm in any absorber
1 Gray = 10,000 ergs / gm in any absorber
1 rem = 1 rad x QF = 0.01 Sv
H = DQN (from ICRP 26)
H (Dose Equiv.) = D (absorbed dose) x Q (quality factor) x N (any other modifying factors)

DEFINITIONS

Acute	any dose in a short period of time
Chronic	any dose in a long period of time
Somatic	effects in the exposed individual
Genetic	effects in the offspring of the exposed individual
Teratogenic	effects in the exposed unborn embryo/fetus
Stochastic	effects for which a probability exists and increases with increasing dose
Non-Stochastic (deterministic)	effects for which a threshold exists - effects do not occur below the threshold
(examples;	cataracts, erythema, epilation, acute radiation syndrome)

PUBLIC RADIATION DOSES

Average per capita US Dose	200 mrem (2 mSv) / yr
Living in Los Alamos (7000' elev)	327 mrem (3.27 mSv)/yr
Flying from NY to LA	2.5 mrem (25 ìSv) / trip
Chest x-ray	10 mrem (0.1mSv)/exam
Full mouth dental x-ray	9 mrem (90 ìSv) / exam

The external dose rate for cosmic rays doubles for each mile increase in elevation.

BACKGROUND RADIATION

Cosmic = 28 mrem (0.28 mSv) / yr
Rocks = 28 mrem (0.28 mSv) / yr
Internal = 36 mrem (0.36 mSv) / yr
Medical x-rays = 20 to 30 mrem (0.2 to 0.3 mSv)/yr
Nuclear medicine = 2 mrem / yr
TOTAL US Ave ~ 120 mrem / yr
US Ave H_E from radon = 200 mrem / yr

Ave H_E from medical x-ray procedures:
Skull 20 mrem (0.2 mSv)
Upper GI 245 mrem (2.45 mSv)
Hip 65 mrem (0.65 mSv)
Chest 6 mrem (60 ìSv),
Kidney 55 mrem (0.55 mSv)
Dental 55 mrem (0.55 mSv)

Occupational Doses	**mrem /yr**	**mSv/yr**
airline flight crew	1,000	10
nuclear power plant	700	7
Grand Central Station workers	120	1.2
medical personnel	70	0.7
DOE employees	44	0.44

COMPARATIVE RISKS OF RADIATION EXPOSURE

	Estimated Days of Life Lost
Smoking 1 pack of cigarettes / day	2,370
20% overweight	985
Average US alcohol consumption	130
Home accidents	95
Occupational exposure	
• 5.0 rem (50 mSv) / year	32
• 0.5 rem (5 mSv) / year	3

OCCUPATIONAL RISKS **Occupation**	**Estimated Days of Life Lost**
demolition	1,500
mining	1,100
firefighting	800
police	750
railroad	500
farming	300
construction	200
transportation & public utilities	160
average of all occupations	**60**
government	55
radiation dose of 1 rem (10 mSv) per year	50
service	45
trade	30
single radiation dose of 1 rem (10 mSv)	1.5

Relative Risk

Your overall risk of dying is 1 in 1

Heart disease	1 in 5
Cancer	1 in 7
Stroke	1 in 24
Motor vehicle accident	1 in 84
Suicide	1 in 119
Falling	1 in 218
Firearm assault	1 in 314
Pedestrian accident	1 in 626
Drowning	1 in 1,008
Motorcycle accident	1 in 1,020
Fire or smoke	1 in 1,113
Bicycle accident	1 in 4,919
Air / space accident	1 in 5,051
Accidental firearm discharge	1 in 5,134
Accidental electrocution	1 in 9,968
Alcohol poisoning	1 in 10,048
Hot weather	1 in 13,729
Hornet, wasp, or bee sting	1 in 56,789
Legal execution	1 in 62,468
Lightning	1 in 79,746
Earthquake	1 in 117,127
Flood	1 in 144,156
Fireworks discharge	1 in 340,733

Author’s notes

Over my career in health physics starting with a US Army CBR unit at Dugway Proving Ground in 1965 I have needed to quickly find that elusive data point that I just couldn’t remember, even though I knew the information was in one of my several hundred reference books. I was a Spec 4 at DPG with the tasks of developing methods to generate liquid particles of specific sizes (around 10 micron diameter), disperse, collect, and analyze those particles. During my TDY to Fort Greely Alaska in 1966 I was in charge of the lab crew analyzing the samples of sarin collected during the field tests. After my service in the military I worked in the commercial nuclear power plants and fossil power plants as a Radiation Control Technician and Level II Startup Engineer before joining the DOE at WIPP as a Senior Health Physics Specialist then later at Los Alamos National Laboratory as a Certified Health Physicist.

So, here it is today, the product of my work to assemble useful field information from a wide range of sources. I must give credit to those individuals who put their efforts into creating the original data. Without their work, this document could not have been assembled.

My family has given me their unlimited support in my development of this reference book and in my projects all through my career. Sandy my wife of 44 years and our two daughters Susan and Sarah and their husbands, Bill Gilson and Ian Curtis, continue to provide me with a steady foundation that allows me to try out new concepts.

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Northern New Mexico, 2019
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