Radioactivity in Nature

Our world is radioactive and has been since it was created. Over 60 radionuclides can be found in nature, and they can be placed in three general categories:

1. Primordial - been around since the creation of the Earth
2. Cosmogenic - formed as a result of cosmic ray interactions
3. Human produced - enhanced or formed due to human actions

Radionuclides are found in air, water and soil, and additionally in us, being that we are products of our environment. Every day, we ingest/inhale nuclides in the air we breathe, in the food we eat and the water we drink. Radioactivity is common in the rocks and soil that makes up our planet, in the water and oceans, and even in our building materials and homes. It is just everywhere. There is no where on Earth that you can get away from Natural Radioactivity.

Note: Many of the units used in science are broken down into smaller units or expressed as multiples, using standard metric prefixes. As examples, a kilobecquerel (kBq) in 1000 becquerels, a millirad (mrad) is 10^{-3} rad, a microrem (μrem) is 10^{-6} rem, a nanogram is 10^{-9} grams, and a picocurie is a 10^{-12} curies. These are examples of units used frequently throughout this short paper. To find definitions of terms you're not familiar with, look on our glossary page.

Common abbreviations used on this page are: **m** - meter, **m^3** - cubic meter, **g** - gram, **kg** - kilogram, **Bq** - becquerel, **Sv** - sievert, **Gy** - gray, **Ci** - curie, **ppm** - parts per million, **yr**- year, **hr** - hour, **L** - liter

Radioactive elements are often called radioactive isotopes or radionuclides. There are over 1,500 different radioactive nuclides. They can be labeled based on the element and on the atomic weight, as in radioactive hydrogen (tritium) or Hydrogen 3. Radionuclide names are often abbreviated using the chemical symbol and the atomic weight, so that Uranium 235 would be shortened to U-235 or ^{235}U.

Much of the information and many of tables found here are adapted from information found in *Environmental Radioactivity from Natural, Industrial and Military Sources* by Merril Eisenbud and Tom Gesell, Academic Press, Inc. 4th Edition. Other tables are adapted from the National Council on Radiation Protection reports 94 and 95. References are listed at the bottom of this page. Several of the tables below were made from calculation based on available data.

This page is best viewed with a browser that is capable of using **tables and superscripts**.

In the United States, the annual estimated average effective dose equivalent is 360 mrem per adult. This is broken down as:

Annual estimated average effective dose equivalent received by a member of the population of the United States.

Source	Average annual effective dose equivalent

	(μSv)	(mrem)
Inhaled (Radon and Decay Products)	2000	200
Other Internally Deposited Radionuclides	390	39
Terrestrial Radiation	280	28
Cosmic Radiation	270	27
Cosmogenic Radioactivity	10	1
Rounded total from natural source	3000	300
Rounded total from artificial Sources	600	60
Total	3600	360

Shown in the table above, 82% of the total average annual effective dose is from natural sources of radiation, and of that, most is from radon. Of the other 18%, the majority is from medical diagnosis and treatments, with <1% from nuclear power and fallout.

This can perhaps be more easily seen with a graph (6K)

See Radiation and Us for more info on average U.S. doses of radiation.

United States Geological Survey map of estimated total gamma exposure for the U.S. (78 k)

Primordial radionuclides

Primordial radionuclides are left over from when the world and the universe were created. They are typically long lived, with half-lives often on the order of hundreds of millions of years. Radionuclides that exist for more than 30 half-lives are not measurable. The progeny or decay products of the long lived radionuclides are also in this heading. Here are few of what we are talking about:

Primordial nuclides

Nuclide	Symbol	Half-life	Natural Activity
Uranium 235	^{235}U	7.04×10^{8} yr	0.72% of all natural uranium
Uranium 238	^{238}U	4.47×10^{9} yr	99.2745% of all natural uranium; 0.5 to 4.7 ppm total uranium in the common rock types
Thorium 232	^{232}Th	1.41×10^{10} yr	1.6 to 20 ppm in the common rock types with a crustal average of 10.7 ppm

Radium 226	^{226}Ra	1.60 x 10^3 yr	0.42 pCi/g (16 Bq/kg) in limestone and 1.3 pCi/g (48 Bq/kg) in igneous rock
Radon 222	^{222}Rn	3.82 days	Noble Gas; annual average air concentrations range in the US from 0.016 pCi/L (0.6 Bq/m^3) to 0.75 pCi/L (28 Bq/m^3)
Potassium 40	^{40}K	1.28 x 10^9 yr	soil - 1-30 pCi/g (0.037-1.1 Bq/g)

Some nuclides, like ^{232}Th have several members in their decay chains. You can roughly follow the chain starting with ^{232}Th

^{232}Th --> ^{228}Ra --> ^{228}Ac --> ^{228}Th --> ^{224}Ra -->
^{220}Rn --> ^{216}Po --> ^{212}Pb --> ^{212}Bi --> ^{212}Po --> ^{208}Pb (stable)

Some other primordial radionuclides are: ^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, ^{123}Te, ^{138}La, ^{142}Ce, ^{144}Nd, ^{147}Sm, ^{152}Gd, ^{174}Hf, ^{176}Lu, ^{187}Re, ^{190}Pt, ^{192}Pt, ^{209}Bi.

United States Geological Survey Digital maps of estimated potassium, equivalent uranium-238, equivalent thorium-232 concentrations for the U.S.

Cosmogenic

Cosmic radiation permeates all of space, the source being primarily outside of our solar system. The radiation is in many forms, from high speed heavy particles to high energy photons and muons. The upper atmosphere interacts with many of the cosmic radiations, and produces radioactive nuclides. They can have long half-lives, but the majority have shorter half-lives than the primordial nuclides. Here is an table with some common cosmogenic nuclides:

Cosmogenic Nuclides

Nuclide	Symbol	Half-life	Source	Natural Activity
Carbon 14	^{14}C	5730 yr	Cosmic-ray interactions, $^{14}N(n,p)^{14}C$;	6 pCi/g (0.22 Bq/g)
Tritium 3	^{3}T	12.3 yr	Cosmic-ray interactions with N and O; spallation from cosmic-rays, $^{6}Li(n,alpha)^{3}H$	0.032 pCi/kg (1.2 x 10^{-3} Bq/kg)
Beryllium 7	^{7}Be	53.28 days	Cosmic-ray interactions with N and O;	0.27 pCi/kg (0.01 Bq/kg)

Some other cosmogenic radionuclides are ^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, ^{14}C, ^{32}Si, ^{39}Ar, ^{22}Na, ^{35}S, ^{37}Ar, ^{33}P, ^{32}P, ^{38}Mg, ^{24}Na, ^{38}S, ^{31}Si, ^{18}F, ^{39}Cl, ^{38}Cl, ^{34m}Cl.

Human Produced

Humans have used radioactivity for one hundred years, and through its use, added to the natural inventories. The amounts are small compared to the natural amounts discussed above, and due to the shorter half-lives of many of the nuclides, have seen a marked decrease since the halting of above ground testing of nuclear weapons. Here are a few nuclides:

Human Produced Nuclides

Nuclide	Symbol	Half-life	Source
Tritium	^{3}H	12.3 yr	Produced from weapons testing and fission reactors; reprocessing facilities, nuclear weapons manufacturing
Iodine 131	^{131}I	8.04 days	Fission product produced from weapons testing and fission reactors, used in medical treatment of thyroid problems
Iodine 129	^{129}I	1.57×10^{7} yr	Fission product produced from weapons testing and fission reactors
Cesium 137	^{137}Cs	30.17 yr	Fission product produced from weapons testing and fission reactors
Strontium 90	^{90}Sr	28.78 yr	Fission product produced from weapons testing and fission reactors
Technetium 99m	^{99m}Tc	6.03 hr	Decay product of ^{99}Mo, used in medical diagnosis
Technetium 99	^{99}Tc	2.11×10^{5} yr	Decay product of ^{99m}Tc
Plutonium 239	^{239}Pu	2.41×10^{4} yr	Produced by neutron bombardment of ^{238}U (^{238}U + n--> ^{239}U--> ^{239}Np +ß--> ^{239}Pu+ß)

Other Interesting Aspects of Natural Radioactivity

Natural Radioactivity in soil

How much natural radioactivity is found in an area 1 square mile, by 1 foot deep? The following table is calculated for this volume (total volume is 7.894 x 10^5 m^3) and the listed activities. Activity levels vary greatly depending on soil type, mineral make-up and density (~1.58 g/cm^3). This table represents calculations using typical numbers.

Natural Radioactivity by the Mile

Nuclide	Activity used in calculation	Mass of Nuclide	Activity
Uranium	0.7 pCi/gm (25 Bq/kg)	2,200 kg	0.8 curies (31 GBq)
Thorium	1.1 pCi/g (40 Bq/kg)	12,000 kg	1.4 curies (52 GBq)
Potassium 40	11 pCi/g (400 Bq/kg)	2000 kg	13 curies (500 GBq)
Radium	1.3 pCi/g (48 Bq/kg)	1.7 g	1.7 curies (63 GBq)
Radon	0.17 pCi/gm (10 kBq/m^3) soil	11 µg	0.2 curies (7.4 GBq)

Natural Radioactivity in the Ocean

How much natural radioactivity is found in the world's oceans?

All water on the Earth, including seawater, contains radionuclides in it. In the following table, the oceans' volumes were calculated from the *1990 World Almanac*:

- Pacific = 6.549 x 10^{17} m^3
- Atlantic = 3.095 x 10^{17} m^3
- Total = 1.3 x 10^{18} m^3

The activities used in the table below are from 1971 *Radioactivity in the Marine Environment*, National Academy of Sciences:

Natural Radioactivity by the Ocean

Nuclide	Activity used	Ocean

	in calculation	Pacific	Atlantic	All Oceans
Uranium	0.9 pCi/L (33 mBq/L)	6 x 10^{8} Ci (22 EBq)	3 x 10^{8} Ci (11 EBq)	1.1 x 10^{9} Ci (41 EBq)
Potassium 40	300 pCi/L (11 Bq/L)	2 x 10^{11} Ci (7400 EBq)	9 x 10^{10} Ci (3300 EBq)	3.8 x 10^{11} Ci (14000 EBq)
Tritium	0.016 pCi/L (0.6 mBq/L)	1 x 10^{7} Ci (370 PBq)	5 x 10^{6} Ci (190 PBq)	2 x 10^{7} Ci (740 PBq)
Carbon 14	0.135 pCi/L (5 mBq/L)	8 x 10^{7} Ci (3 EBq)	4 x 10^{7} Ci (1.5 EBq)	1.8 x 10^{8} Ci (6.7 EBq)
Rubidium 87	28 pCi/L (1.1 Bq/L)	1.9 x 10^{10} Ci (700 EBq)	9 x 10^{9} Ci (330 EBq)	3.6 x 10^{10} Ci (1300 EBq)

Human body

You are made up of chemicals, and it should be of no surprise that some of them are radionuclides, many of which you ingest daily in your water and food. Here are the estimated concentrations of radionuclides calculated for a 70,000 gram adult based ICRP 30 data:

Natural Radioactivity in your body

Nuclide	Total Mass of Nuclide Found in the Body	Total Activity of Nuclide Found in the Body	Daily Intake of Nuclides
Uranium	90 µg	30 pCi (1.1 Bq)	1.9 µg
Thorium	30 µg	3 pCi (0.11 Bq)	3 µg
Potassium 40	17 mg	120 nCi (4.4 kBq)	0.39 mg
Radium	31 pg	30 pCi (1.1 Bq)	2.3 pg
Carbon 14	95 µg	0.4 µCi (15 kBq)	1.8 µg
Tritium	0.06 pg	0.6 nCi (23 Bq)	0.003 pg
Polonium	0.2 pg	1 nCi (37 Bq)	~0.6 µg

It would be reasonable to assume that all of the radionuclides found in your environment would be in you in small amounts. The average annual dose equivalent from internally deposited radionuclides is given in the table at the top of this page.

Natural Radioactivity in Building Materials

As mentioned before, building materials have some radioactivity in them. Listed below are a few common building materials and their estimated levels of uranium, thorium and potassium.

Estimates of concentrations of uranium, thorium and potassium in building materials (NCRP 94, 1987, except where noted)

Material	Uranium		Thorium		Potassium	
	ppm	mBq/g (pCi/g)	ppm	mBq/g (pCi/g)	ppm	mBq/g (pCi/g)
Granite	4.7	63 (1.7)	2	8 (0.22)	4.0	1184 (32)
Sandstone	0.45	6 (0.2)	1.7	7 (0.19)	1.4	414 (11.2)
Cement	3.4	46 (1.2)	5.1	21 (0.57)	0.8	237 (6.4)
Limestone concrete	2.3	31 (0.8)	2.1	8.5 (0.23)	0.3	89 (2.4)
Sandstone concrete	0.8	11 (0.3)	2.1	8.5 (0.23)	1.3	385 (10.4)
Dry wallboard	1.0	14 (0.4)	3	12 (0.32)	0.3	89 (2.4)
By-product gypsum	13.7	186 (5.0)	16.1	66 (1.78)	0.02	5.9 (0.2)
Natural gypsum'	1.1	15 (0.4)	1.8	7.4 (0.2)	0.5	148 (4)
Wood'	-	-	-	-	11.3	3330 (90)
Clay Brick"	8.2	111 (3)	10.8	44 (1.2)	2.3	666 (18)

' Chang et al, 1974 " Hamilton, 1970

Oklo Natural Reactor

Adapted from August 1976 Scientific American article on Oklo by Cowan.

In 1972, natural nuclear reactor was found in a Western Africa in the Republic of Gabon, at Oklo. While the reactor was critical, approximately 1.7 billion years ago, it released 15,000 megawatt-years of energy by consuming six tons of uranium. It operated over several hundred thousand years at low power.

It was discovered by a French mining geologist while assaying samples for the Oklo Uranium mine. Today, the fissionable Uranium 235 has an natural abundance of 0.7202%, but the scientist noticed some samples from Oklo to be 0.7171%. While this difference was small, it led the scientists to take a look closer at the Oklo site. Later, samples were found that were even more depleted, down to 0.44%. This difference could only be explained if some of the fuel, the ^{235}U, had been used up in a fission reaction. Upon further investigation, abnormally high amounts of fission products were found in six separate reactor zones.

Like present day power reactors, a natural reactor would require several special conditions, namely fuel, a moderator, a reflector, lack of neutron absorbing poisons and some way to remove the heat generated. At Oklo, the area was naturally loaded with uranium by water transport and deposition. The concentration of Uranium 235 is artificially enriched for most modern reactors, but at the time of the Oklo reactor it was naturally enriched with an abundance of approximately 3%. This is because when the world was formed, there was a certain amount of ^{235}U, and it has been decaying ever since. So, because ^{235}U has a shorter half-life than ^{238}U, one billion years ago ,^{235}U made up a larger percentage of the natural uranium. The 3% ^{235}U was enough for a sustained nuclear reaction. Oklo site was saturated with groundwater, which served as a moderator, reflector and cooling for the fission reaction. There was a lack of poisons before the reaction began, and fission products like xenon and neodymium serve as neutron absorbing poisons, absorbing neutrons, acting to limit the power.

To confirm that there was a natural fission reactor, the scientists started looking for other evidence. First they wanted to look for some element that might have been produced in a reactor, but would have little natural occurrence else where. They looked at several, and neodymium gave strong indications that the reactor had indeed operated. Neodymium has seven stable isotopes, but only six are fission products. The abundance of the neodymium at Oklo sites was compared to other areas and to the neodymium found in modern reactors. Once the samples were compared, the abundance of neodymium was found to be almost exactly that found in present day reactors. All in all, the fission products studied matched what would have been the result of a sustained nuclear reaction. There is even evidence that the reactor bread its own fuel, bombarding the ^{238}U with neutrons, making the easily fissionable ^{239}Pu.

Some other interesting information has come out of this, over half of the thirty fission products found there were confined to the reactor zones, with all plutonium immobilized. The strontium was mainly confined to the local zones, with some release to environment estimated from krypton 85 and cesium 137

One of the greatest works of the 20th century was the building of the first atomic pile (nuclear reactor) in Chicago in 1941 by Enrico Fermi. It took some of the brightest minds in modern physics and great engineering efforts to duplicate what nature did two billion years earlier.

For more information on the Oklo Reactor, try:

The a-recoil effects of uranium in the Oklo reactor. Nature 312:535-6 Dec 6 '84

Gabon's natural reactors: nature shows how to contain radioactive waste. Nuclear-Engineering-International. vol.39, no.475; Feb. 1994; p.30-1

Organic matter and containment of uranium and fissiogenic isotopes at the Oklo natural reactors. Nature. vol.354, no.6353; 12 Dec. 1991; p.472-5

Estimation of burnup in the Oklo natural nuclear reactor from ruthenium isotopic composition. Journal of Radioanalytical and Nuclear Chemistry, Letters. vol.155, no.2; 16 Sept. 1991; p.107-13

The origin of the chemical elements and the Oklo phenomenon. Kuroda, P. K. Berlin ; New York :

Springer-Verlag, 1982.

High Background Radiation Areas

Background radiation levels result from a combination of terrestrial (from the ^{40}K, ^{232}Th, ^{226}Ra, etc.) and cosmic radiation (photons, muons, etc.). The level is fairly constant over the world, being 8-15 µrad/hr. Here is a radiation detector in Pittsburgh, Penn, USA showing background radiation levels.

Around the world though, there are some areas with sizable populations that have high background radiation levels. The highest are found primarily in Brazil, India and China. The higher radiation levels are due to high concentrations of radioactive minerals in soil. One such mineral, Monazite, is a highly insoluble rare earth mineral that occurs in beach sand together with the mineral ilmenite, which gives the sands a characteristic black color. The principal radionuclides in monazite are from the ^{232}Th series, but there is also some uranium its progeny, ^{226}Ra.

In Brazil, the monazite sand deposits are found along certain beaches. The external radiation levels on these black sands range up to 5 mrad/hr (50 µGy/hr), which is almost 400 times normal background in the US. Some of the major streets of the surrounding cites have radiation levels as high as 0.13 mrad/hr (1.3 µGy/hr), which is more than 10 times the normal background. Another high background area in Brazil is the result of large rare earth ore deposits that form a hill that rises about 250 meters above the surrounding area. An ore body near the top of the hill is very near the surface, and contains an estimated 30,000 tons of thorium and 100,000 tons of rare earth elements. The radiation levels near the top of the hill are 1 to 2 mrad/hr (0.01 to 0.02 mGy/hr) over an area of about 30,000 m^2. The plants found there have absorbed so much ^{228}Ra that they will produce a self "x-ray" if placed on a sheet of photographic paper (an autoradiograph).

On the Southwest coast of India, the monazite deposits are larger than those in Brazil. The dose from external radiation is, on average, similar to the doses reported in Brazil, 500-600 mrad/yr (5 - 6 mGy/yr), but individual doses up to 3260 mrad/yr (32.6 mGy/yr) have been reported.

An area in China has does rates that is about 300-400 mrad/yr (3-4 mGy/yr). This is also from monazite that contains thorium, uranium and radium.

From BEIR V, National Research Council report on Health Effects of Low Levels of Ionizing Radiation:

> In areas of high natural background radiation, an increased frequency of chromosome aberrations has been noted repeatedly. The increases are consistent with those seen in radiation workers and in persons exposed at high dose levels, although the magnitudes of the increases are somewhat higher than predicted. No increase in the frequency of cancer has documented in populations residing in areas of high natural background radiation.

Cosmic Radiation

Cosmic radiation (as discussed above) interacts with our atmosphere to produce cosmogenic radionuclides. It also is responsible for a whole body doses.

Cosmic radiation is really divided into two types, primary and secondary. Primary cosmic radiation is made up of extremely high energy particles (up to 10^{18} eV), and are mostly protons or sometimes larger particles. A large percentage of it comes from outside of our solar system and is found throughout space. Some of the primary cosmic radiation is from our sun, produced during solar flares.

Little of the primary cosmic radiation penetrates to the Earth's surface, the vast majority of it interacts with the atmosphere. When it does interact, it produces the secondary cosmic radiation, or what we actually see here on Earth. These reactions produce other lower energy radiations in the form of photons, electrons, neutrons and muons that make it to the surface.

The atmosphere and the Earth's magnetic fields also act as shields against cosmic radiation, reducing the amount that reaches the Earth's surface. With that in mind, it is easy to see that the annual dose you get from cosmic radiation depends on what altitude you are at. From cosmic radiation, the average person in the U.S. will receive a dose of 27 mrem per year and this roughly doubles every 6,000 foot increase in elevation.

Typical Cosmic Radiation Dose rates:

4 µR/hr in the Northeastern US

20 µR/hr at 15,000 feet

300 µR/hr at 55,000 feet

There is only about a 10% decrease at sea level in cosmic radiation rates when going from pole to the equator, but at 55,000 feet the decrease is 75%. This is on account of the effect of the earth's and the Sun's geomagnetic fields on the primary cosmic radiations.

Flying can add a few extra mrem to your annual dose, depending on how often you fly, how high the plane flies, and how long you are in the air.

Calculated cosmic ray doses to a person flying in subsonic and supersonic aircraft under normal solar conditions

Route	**Subsonic flight at 36,000 ft (11 km)**			**Supersonic flight at 62,000 (19 km)**		
	Flight duration (hrs)	**Dose per round trip**		**Flight duration (hrs)**	**Dose per round trip**	
		(mrad)	**(µGy)**		**(mrad)**	**(µGy)**
Los Angeles-Paris	11.1	4.8	48	3.8	3.7	37

Chicago-Paris	8.3	3.6	36	2.8	2.6	26
New York-Paris	7.4	3.1	31	2.6	2.4	24
New York-London	7.0	2.9	29	2.4	2.2	22
Los Angeles-New York	5.2	1.9	19	1.9	1.3	13
Sydney-Acapulco	17.4	4.4	44	6.2	2.1	21

Astronauts are exposed to cosmic radiation, but they are also exposed to radiation as they pass through the Van Allen radiation belts that circle the Earth.

References and Additional Information Sources

- Naturally occurring radioactive material (NORM I&S, Inc)
- *Environmental Radioactivity from Natural, Industrial and Military Sources* 4th Edition by Merril Eisenbud and Tom Gesell, Academic Press, Inc. (now out!)
- *Radioactivity in the Environment*, Ron Kathren
- *Radioactivity in the Marine Environment* , National Academy of Sciences
- NCRP reports 62, 94, 95, 103, 116
- *BEIR V* Report, National Research Council, NAS
- Chart of the Nuclides
- Radon Update , A.B. Brill
- Radioactivity from Coal (ORNL)
- Information on Sources of Radiation
- Environmental Radioactivity Specialty area
- Chornobyl and the surrounding area
- Radiation and Us (short essay)

Return to the top of this page