Chapter 3

Radioactive Decay Laws

Half-life

The term half-life has been mentioned earlier. So far, this has referred to only the ***physical half-life.*** When considering health and the environment, we have to introduce also the ***biological half-life***. Furthermore with regard to environment and biology we sometimes use the ***ecological half-life.***

Definition

The half-life is defined as the time elapsed when the intensity of the radiation is reduced to one half of its original value.

The Physical Half-life

The radiation from a radioactive source will gradually be reduced. The rate of this decay is given by the half-life. It is usually denoted as $t_{1/2}$ – but sometimes as t_p for the physical half-life.

In an experiment in which the intensity of the radiation is measured versus time, a curve like that shown in Figure 3.1 is observed. The activity is given along the vertical axis (100 % when the experiment is started) and the time (in half-lives) is given along the horizontal axis.

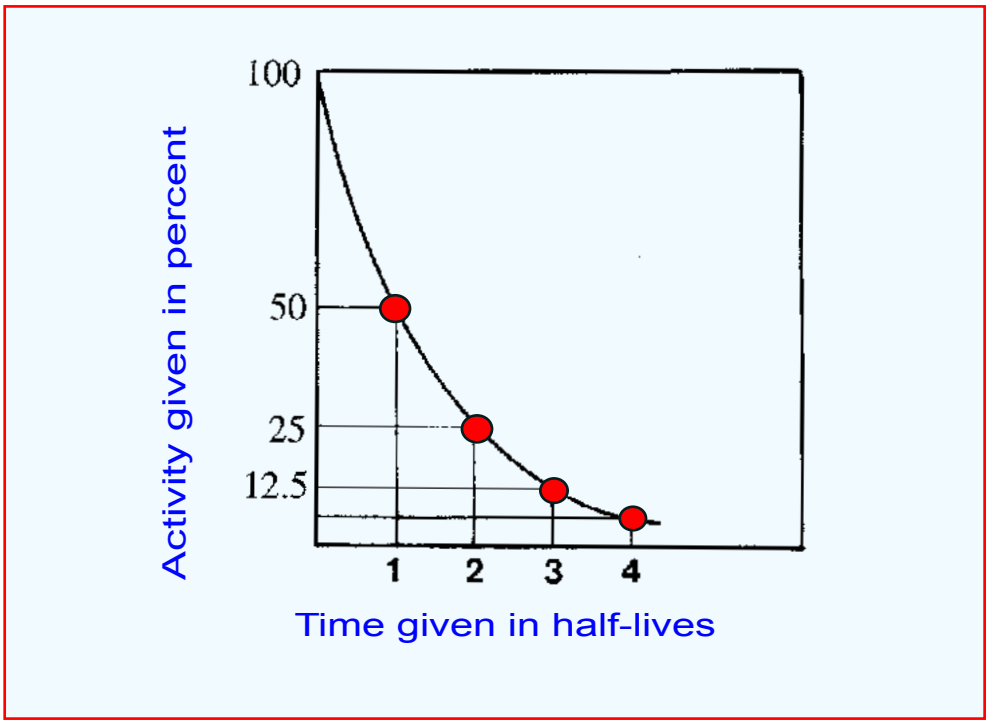


Figure 3.1. The radiation from a radioactive source decreases with time as shown. The curve can be described by an exponential formula. The figure demonstrates the meaning of the half-life.

After one half-life the intensity of the radiation has decreased to 50 %. After two half-lives only 25 % remains, and so on. Each half-life reduces the remaining amount by one half.

The Earth still contains large amounts of naturally occurring radioactive isotopes, such as U-238. For this to occur the half-lives must be very long. We saw in Figure 2.3 that U-238 has a half-life of 4.47 billion years.

The Laws of Radioactive Decay

The activity of a radioactive source (A), i.e. the number of disintegrations per second (becquerel), is given as:

$$A = -\frac{dN}{dt} = \lambda \cdot N$$

λ is the *disintegration constant* and it varies from one isotope to another. N is the number of atoms that, in time, will disintegrate and dN is the change in N during the time interval dt. The negative sign shows that the number remaining is decreasing.

Equation 3.1 shows that when N is larger, the radioactive source is stronger. The difference in activities from one isotope to another is due to the different half-lives which depend on different disintegration constants λ (see equation 3.3).

In order to determine how the the number of atoms (N) decrease with time, the change in N must be summed over time. This is done mathematically by integrating, giving:

$$N = N_0 \cdot e^{-\lambda t} \qquad (3.2)$$

N_o is the number of radioactive atoms at time zero (i.e., when the first measurement was made). By substituting a later time (day, year) for t in (3.2) we can solve the equation and determine the radioactivity at the new time.

The two equations (3.1) and (3.2) are very important in order to evaluate risks and radiation doses. These equations are used in the examples later in the book.

It was noted above that there is a relation between the half-life ($t_{1/2}$) and the disintegration constant λ. The relationship can be found from equation (3.2) by setting $N = ½ N_o$. This gives:

$$t_{1/2} = \frac{\ln 2}{\lambda} \qquad (3.3)$$

where ln 2 (the natural log of 2) equals 0.693.
If the disintegration constant (λ) is given, it is easy to arrive at the half-life, and vice-versa. In calculations using radioactive compounds one of these two constants must be known.

Biological Half-life

Radioactive isotopes that are ingested or taken in through other pathways will gradually be removed from the body via kidneys, bowels, respiration and perspiration. This means that a radioactive atom *can* be expelled before it has had the chance to decay. The time elapsed before half of a compound (whether radioactive or not) has been removed by biological means is called the *biological half-life* and is usually denoted t_b.

If a radioactive compound with physical half-life t_p ($t_{1/2}$) is cleared from the body with a biological half-life t_b, the ***"effective" half-life*** ($\mathbf{t_e}$) is given by the expression:

$$\frac{1}{t_{\text{effective}}} = \frac{1}{t_{\text{physical}}} + \frac{1}{t_{\text{biological}}} \qquad (3.4)$$

If t_p is large in comparison to t_b, the effective half-life is approximately the same as t_b (see example below).

The biological half-life is rather uncertain as compared to the exact value of the physical half-life. It is uncertain because the clearance from the body depends upon sex, age of the individual and the chemical form of the radioactive substance. The biological half-life will vary from one type of animal to another and from one type of plant to another.

Radio-ecological Half-life

Radio-ecological half-life is even less precise than the physical and biological half-life. Consider a region which has been polluted by a radioactive isotope (for example Cs-137). Part of the activity will gradually sink into the ground and some will leak into the water table. Each year, a fraction of the activity will be taken up by the plants and subsequently ingested by some of the animals in the area.

Radio-ecological half-life is defined as the radioactive half-life for the animals and plants living in the area. It varies for the different types of animals and plants.

Summing up

With regard to radioactive pollution we have the following:

1. The type of a radioactive isotope must be established. Each isotope has a well determined physical half-life.

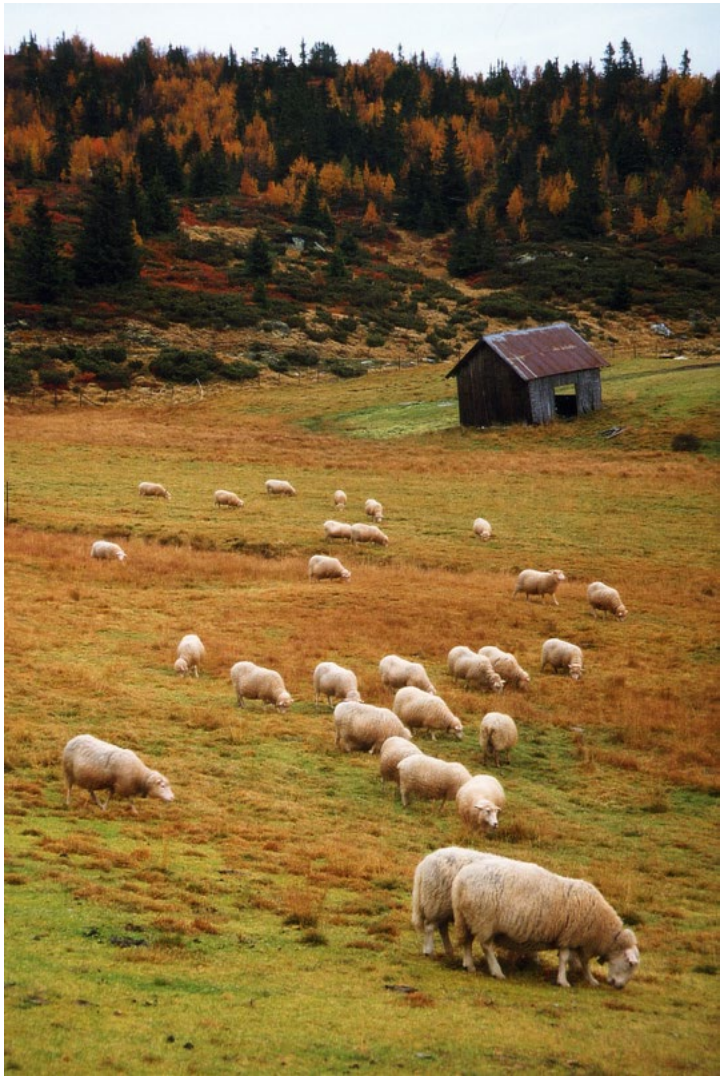
2. If the isotope enters a living biological system, it will be excreted with a biological half-life which is related to the living system itself. This implies that the ingested radioactivity may decrease more rapidly – and that an effective half-life has to be used when calculating doses and evaluating the health effects.

3. The fallout in an area will be more and more unavailable for uptake in a biological system with time. Knowledge about this is lacking.

Examples on how to use the knowledge

Cs-137 has a physical half-life of 30 years. This isotope was the most prominent of the radioactive isotopes in the fallout following the Chernobyl accident in the Ukraine in 1986 – a number of European countries had a fallout of up to 100 000 Bq per m^2 in certain areas.

The activity of Cs-137 can easily be measured because of the γ-radiation emitted. Thus, whether Cs-137 is on the ground or in plants, animals and humans it can be measured. Cesium gradually sink into the ground, some will leak into the water table, and some of it will find its way into the food system and into animals and humans.



One such way is for example illustrated in the picture. Cs-137 comes into the grass and then into the sheep. When we eat the meat the Cs-137 will enter our bodies.

Cesium is cleared rather rapidly from the body and the biological half-life for the sheep is 2 – 3 weeks. If we use equation 3.4 we will find that the effective half-life is almost exactly equal to the biological half-life. Now we can imagine two scenarios:

1. The sheep in the polluted area are slaughtered directly. The Cs-137 activity in the meat will then decay with a half-life equal to the physical one – 30 years.

2. The sheep are moved to an area with no activity – or fed on non-radioactive food. The activity in the sheep will then decay with the biological half-life. After approximately 4 weeks the activity has been reduced to about 25 percent in the living sheep.

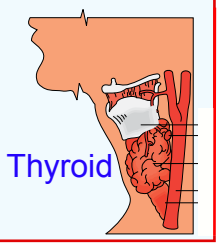
This may be a way to reduce the radioactivity in the meat. When you slaughter the animal it is the physical half-life that count – whereas in a living system the biological half-life may be very important.

Some other radioactive species like radium and strontium are bone seekers and the biological half-life is rather long. These isotopes are much more difficult to remove – and if radium is ingested, it is retained the rest of one's life.

Can uptake be prevented?

It may be possible to reduce the effects of a radioactive compound by simply preventing its uptake. This is a questionable issue that has been discussed after the Chernobyl accident. The isotope in question is I-131 (Iodine). This isotope is important, mainly during the first weeks after a pollution. In the Chernobyl accident considerable amounts of I-131 was released – which resulted in fallout to regions in Russia, Belarus and Ukraine.

I– 131 emits β-particles. The main fraction has a maximum energy of 0.606 MeV. The β-particle emission is followed by γ-rays with energy of 0.365 MeV (and others). The physical half-life is 8.04 days. The isotope is mainly taken up by the thyroid gland – and all β-particles give off their energy to the thyroid. The biological half-life in the thyroid is approximately 120 days. This reduces the effective half-life to 7.6 days.

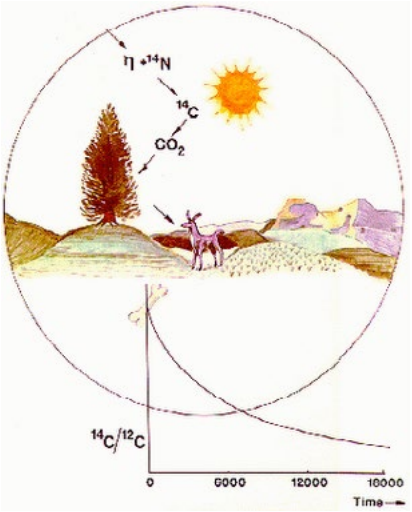


In this case the idea has been considered to add non-radioactive iodine to the food. All iodine isotopes are chemically identical and the body can not discriminate one isotope from the other. There will be a competition between the different isotopes. If the amount of non-radioactive iodine is far larger than the radioactive isotope the uptake of radioactivity may be hindered. This method seems however to be a risky one. Potassium iodide (with non-radioavtive I-127) was used in connection to the Chernobyl accident. Whether this reduced the thyroid dose is not known.

I can be mentioned that I-131 is used for treatment of different sicknesses to the thyroid

C-14 used as a biological clock

Radioactive carbon (C-14) has a half-life of 5730 years. In spite of this rather "short" half-life compared to the age of the earth, C-14 is a naturally occurring isotope! The reason for this is that C-14 is formed continuously in the atmosphere when neutrons (originating from the cosmic radiation) interact with nitrogen atoms. This reaction can be written:



$$^{14}_{7}N + ^{1}_{0}n \Rightarrow ^{14}_{6}C + ^{1}_{1}H$$

Carbon exists in the atmosphere as a component of carbon dioxide. Most of the carbon dioxide contains the ordinary C-12 isotope. However, a few molecules are made with the C-14 isotope. The C-14 isotope enters the biosphere when plants utilize carbon dioxide in photosynthesis. Consequently, all biological systems; plants, animals and humans contain a certain level of C-14. As long as the biological system is alive the level is constant. When the system die – the level of C-14 decay according to the physical half-life. This implies that with knowledge about the half-life and the C-14 level when living – it would be possible to calculate the time elapsed from the death; that is a "*biological clock*".

It was Willard Libby and coworkers in USA that explored the possibility to use C-14 for dating. During the 1940-ties and 1950-ties they worked on this method. Libby assumed that the cosmic radiation was constant with the result that the formation of C–14 would be constant (we shall return to this point). This implies that all living organisms would have a constant specific level of C–14. They made a lot of experiments and found that the C-14 level was on average 15.3 disintegrations per minute per gram carbon (this is 0.255 Bq per gram carbon or 255 Bq/kg).

They determined the physical half-life and found in 1948 the value 5568 years. This is shorter than the value we use today – and it is known as the "*Libby half-life*". With these two parameters in hand, they tested the method by comparing measured values with historical data. Samples with known age was obtained from Pompeii (Italy) and a number of samples from Egypt (from the First Dynasty about 5000 years ago). They had a remarkable good agreement – which showed that the method was useful.

Willard Frank Libby
(1908 – 1980)

Libby was born in Colorado and educated as a chemist. He was professor in chemistry at the Berkeley University. After the war he was professor at University of Chicago (now the Enrico Fermi Institute for Nuclear Studies).
Libby worked and developed the technique to use C-14 for dating and this earned him the Nobel prize in Chemistry in 1960.

Nobel Prize in Chemistry 1960
To Willard F. Libby
"for his method to use carbon-14 for age determination in archaeology, geology, geophysics, and other branches of science".

C-14 emits β-particles. The energy is rather small (max. 156 keV) and the half-life of 5730 years is relatively long, Consequently, the number of disintegrations is small, and the usual C-14 dating method requires rather large samples (many grams) in order to yield enough radiation to provide a high degree of certainty in the age determination.

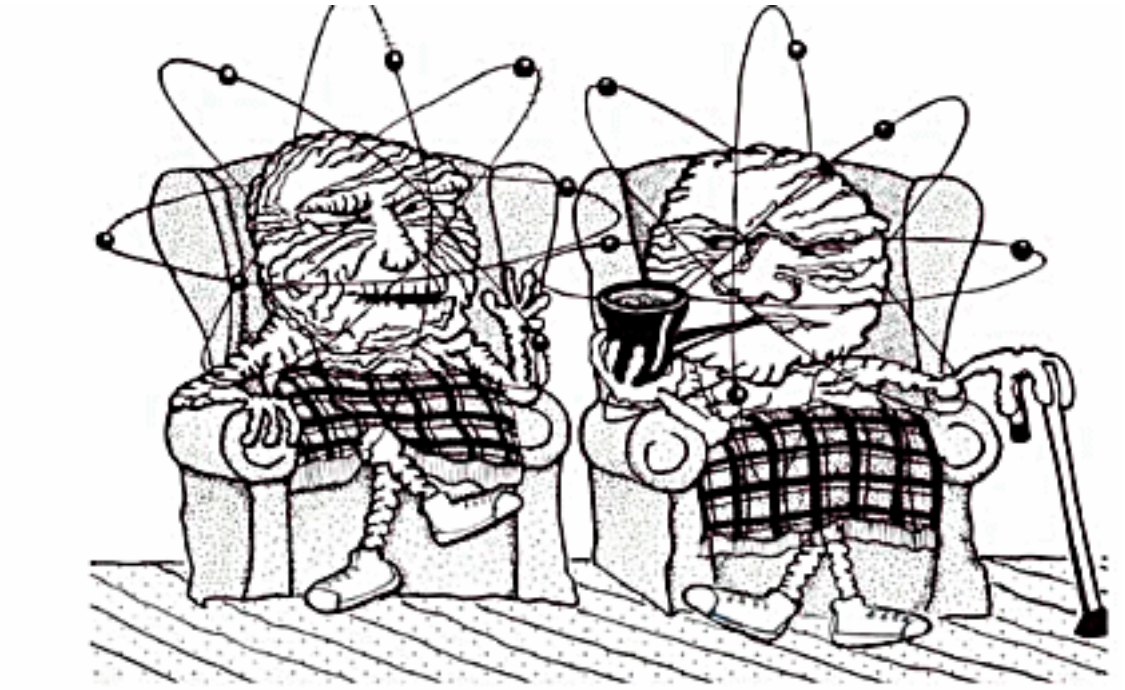
The major developments in the radiocarbon method up to the present day involve improvements in measurement techniques. The initial method has been replaced with the "gas counting method" and "liquid scintillation counting"

The ordinary carbon dating was based on the measurement of β-particles from the C-14 atoms that disintegrate during measurement. In order to yield an activity of 1 Bq the sample must contain 260 billion C-14 atoms (this can easily be calculated using the equations in this chapter). Consequently, if one could observe the **total amount of C-14 atoms** in a sample (not only those disintegrating per second), both the sensitivity and the age determination would be improved. This is the idea behind the AMS-method (Accelerator Mass Spectrometry) which was introduced in 1977. The method involves a mass spectrometer, that detects C-14 atoms based on their atomic mass.

Thus, the total number of C-14 atoms are observed, not only those that disintegrated during the observation period. With this technique, it is possible to date very small samples (a few milligrams).

Some problems

One important requirement was that the content of C-14 at the point of death was a constant. This relies on the assumption that the production of C-14 in the atmosphere is constant. Today we know that the rate of C-14 production exceeds the rate of decay. Several reasons have been proposed such as atmospheric nuclear testing. We assume that before the industrial revolution, the rates should have been at steady-state. It has therefore been important to find and use a sample from early in the 19th century as a reference sample.
Speculations such as variation of the earths magnetic field could affect the flux of cosmic rays and consequently the C-14 production.
The method with C-14 for dating is useful for about 10 half-lives – or about 60 000 years.



"When I was young I used to feel so alive, so dangerous! In fact, would you believe I started life as a Uranium-238? Then one day I accidentally ejected an alpha particle....now look at me, a spent old atom of Lead-206. Seems that all my life since then has been nothing but decay, decay, decay..."