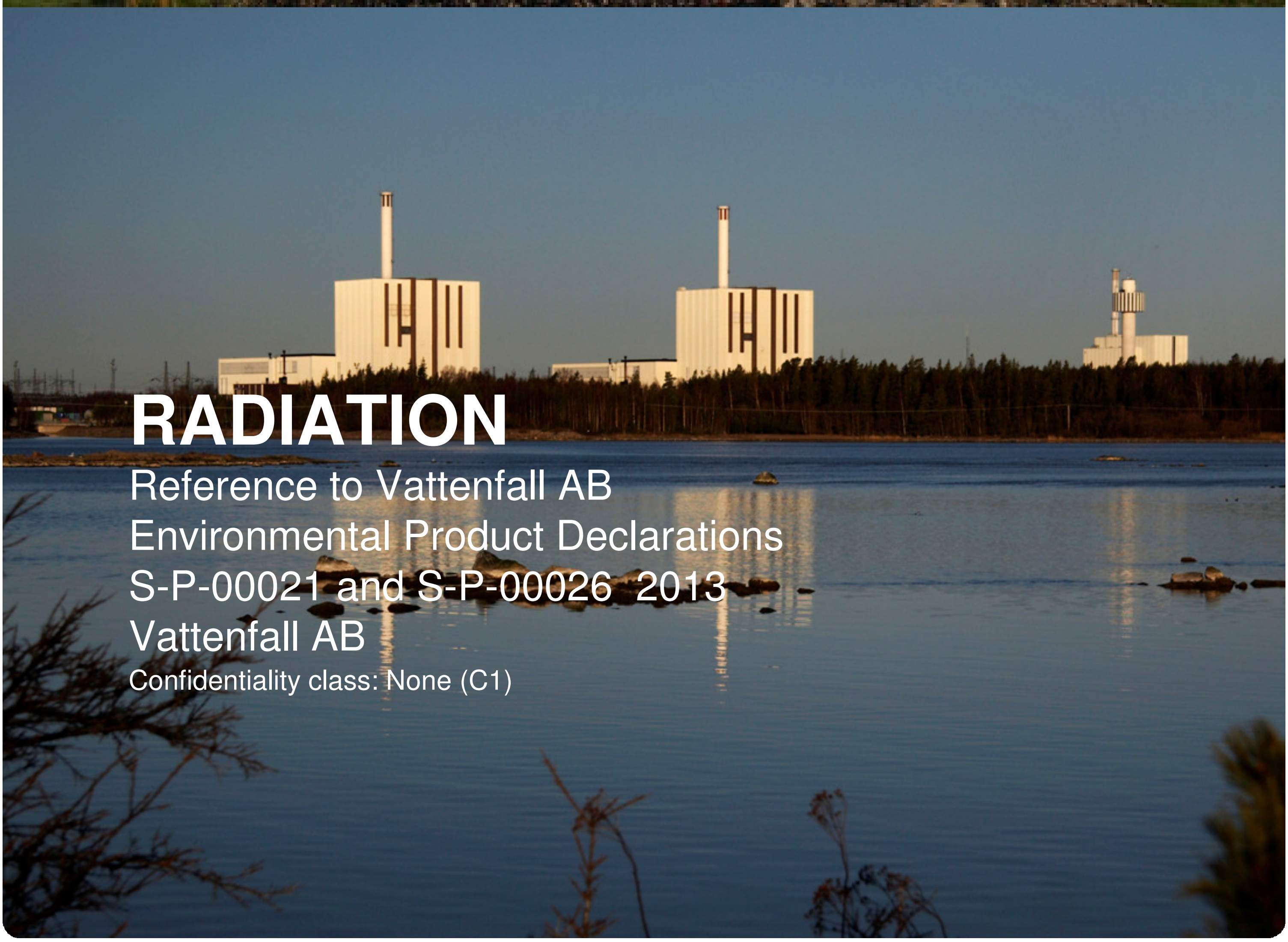

RADIATION

Reference to Vattenfall AB
Environmental Product Declarations
S-P-00021 and S-P-00026 2013
Vattenfall AB

Confidentiality class: None (C1)

VATTENFALL

Contents

1. RADIATION, GENERAL

When the Earth was formed, like the rest of the universe, many of its elements were radioactive. Man has therefore always been exposed to radiation from different sources in the environment. The largest proportion of human radiation exposure originates from the natural environment. Among these radiation sources a significant one is the radioactive radon gas that occurs in many Nordic homes and other buildings. In addition, exposure is caused by cosmic radiation, radioactivity in the ground and even in our own bodies, which contain small amounts of radioactive potassium and carbon. Radiation exposure also occurs due to diagnostic examinations and radiotherapy of tumors. The picture below shows how much radiation an average Swedish person annually is exposed to according to various sources.

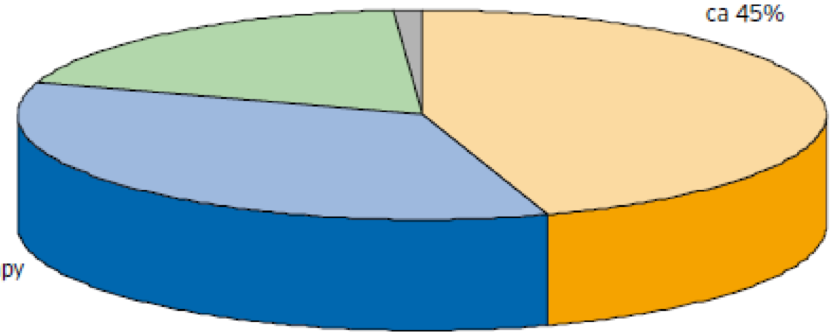

Figure 1.1. Annual radiation dose equivalent to the average Swede is about 4 milliSievert.

All kinds of radiation are carriers of energy. When radiation interacts with matter, e.g. living tissue, some of the energy is transferred to the atoms and molecules of that matter. If the radiation has enough energy, it may strip electrons from atoms. This is called ionization and we therefore refer to the phenomenon as ionizing radiation. Ionizing radiation is emitted when radioactive atomic nuclei decay. Ionizing radiation is also emitted in nuclear reactions such as those occurring in the sun. Ionizing radiation can also be produced in X-ray tubes or atomic particle accelerators. Due to their high energy content, radioactive substances are unstable, and therefore seek a lower energy level that is more stable. When a radioactive atom decays and emits its surplus energy, it is transformed into another isotope of the same or a different element that in turn also may be radioactive. This process continues until a stable isotope has been formed.

2. DIFFERENT KINDS OF RADIATION

Alpha radiation consists of relatively large heavy particles (helium nuclei composed of two neutrons and two protons). The alpha particles are usually emitted by heavy radioactive elements such as uranium, radium, radon and plutonium. The range of alpha particles is a few centimetres in air and it is easily stopped when it reaches any material such as a sheet of paper. It cannot penetrate the skin. Therefore alpha radiation is only dangerous to man if the particles enter the body by inhalation or by ingestion.

Beta radiation consists of electrons. These are much lighter than the alpha particles and therefore have a longer range – typically around 10 meters in air. Glasses and thick clothes are sufficient as protection against external beta radiation which otherwise may reach basal skin cells. Beta radiation may also cause damage if it enters the human body via inhalation or ingestion.

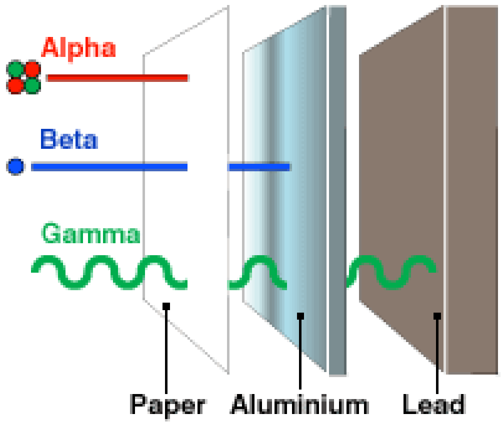

Figure 2.1. Penetration of different types of radiation

Gamma radiation and X-rays are electromagnetic waves (photons), related to radiofrequency waves and visible light but with much higher energy. Gamma radiation generally has higher energy than X-rays but there is no defined energy range. The difference lies in the origin of the radiation: while gamma radiation is created due to changes in the atomic nucleus, X-rays occur as a consequence of rearrangements of electron shells or by the retardation of free electrons. Gamma radiation may have a very long range and, as opposed to alpha and beta radiation, can easily penetrate living tissue. In order to stop most gamma radiation a protective shield of several centimetres of lead or tens of centimetres of concrete or water is usually necessary. The gamma radiation decreases exponentially with the thickness of the shield – a decrease that is dependent on the initial energy of the photons. For X-rays used in clinical applications a few millimetres of lead are usually sufficient for adequate protection.

Neutron radiation is only emitted through spontaneous fission decay of a few specific radionuclides as well as by fission induced by other small particles such as neutrons themselves or alpha particles. Neutrons are always emitted in fission processes such as those occurring in nuclear reactors during operation.

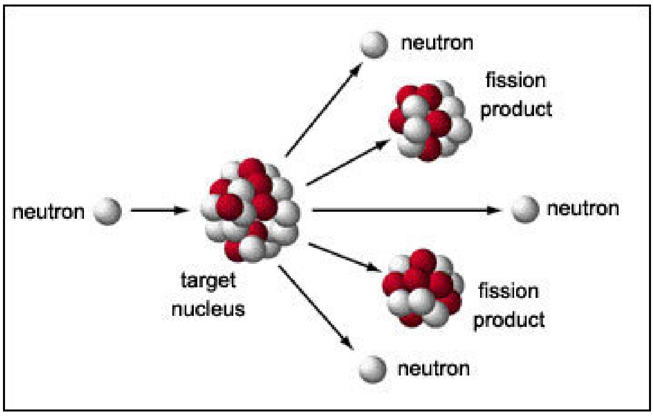

Figure 2.2. Neutrons emitted in the fission process.

The neutron radiation does not reach outside the nuclear reactor and essentially disappears when the nuclear fission processes are stopped. However, radiation exposure due to neutrons is ordinarily of concern in the operation of a nuclear reactor.– these neutrons essentially disappear when the reactor is shut down. The biological effects of neutrons are for a given absorbed dose (Gy) larger than the effects of gamma or X-rays.

3. MEASUREMENT OF RADIATION

Whereas ionizing radiation cannot be recognized by our natural senses, it may easily be detected by sensitive instruments such as Geiger-Müller counters (“GM tubes”) or scintillation counters. The intensity of the radiation can be read on a scale of the GM tube and the sound from the tube can also give the user some indication of the intensity.

Individuals who work with radiation wear dosimeters, which monitor the accumulated radiation dose over a specified time, which may span from hours to months or years.

Figure 3.2. Figur 3.2. Geiger-Müller tube.

Figure 3.1. Personnel working in an ionizing radiation environment wear dosimeters

4. UNITS AND CONCEPTS

A number of units and concepts are used for the measurement of radiation. A brief description of the most commonly used and their interpretation is given below.

4.1. Activity

The activity of a radioactive substance indicate the rate of which atomic nuclei decay per unit time. 1 Becquerel, (Bq), equals a decay rate of one atomic nucleus per second. This is a very small quantity. Consequently, the number of Bq describing the activity in a small amount of material is very large. As an example, naturally occurring radioactive Potassium 40 typically has a total activity of 4 000 Bq in an adult human.

4.2. Absorbed dose

The unit for absorbed dose is based on the energy that the radiation delivers per kilo. The unit is Gray, (1 Gy = 1 J/kg). Absorbed dose is, however, not a unit that adequately describes the corresponding damage in living tissue (see Effective dose below).

4.3. Effective dose

Equally large absorbed doses of for instance gamma radiation and alpha radiation result in different biological effects. One Gy of alpha radiation is considered to be 20 times more damaging than 1 Gy of beta or alpha radiation. We therefore say that the alpha radiation has the weighting factor 20. In order to avoid a separate consideration of each kind of radiation, the absorbed dose is often multiplied by the weighting factor and to calculate the “equivalent dose” = effective dose. The unit for effective dose is Sievert (Sv) and is what we usually use when we refer to a radiation dose to man. One Sv is a large dose and one therefore more commonly indicates the doses based on 1/1 000 Sv = 1 milliSievert (1 mSv).

4.4. Collective dose

Collective dose is the sum of the radiation doses for all individuals irradiated by a certain source or due to some habit or procedure. The collective dose is a calculated estimate of the societal risk that result from the circumstances. The unit used is Sv. In order to indicate that many individuals are involved, “manSievert” (manSv) is often used. As an example the annual natural background radiation gives rise to a global (collective) dose to all individuals on Earth of about 13 million manSv.

5. HOW ARE WE AFFECTED BY RADIATION?

Depending on the size of the radiation dose and the duration of exposure, the consequences may differ. A large statistical material has been analyzed from events such as the atomic bomb explosions in Japan and from clinical contexts as well as from laboratory experiments. Therefore much is known about the effects of radiation at high radiation doses (more than about 200 mSv). It has been observed that high doses given over a short time result in an enhanced cancer incidence. On the other hand it has not been possible to show convincingly that low doses of radiation result in enhanced cancer incidence. The reason for this is that the “normal” cancer incidence and its causes such as tobacco smoking or food habits result in a high statistical background. More information about radiation and its health risks can be found at SSM, the Swedish Radiation Safety Authority: http://www.ssm.se.

5.1. Acute radiation sickness

Acute radiation sickness occurs if one is exposed to a radiation dose exceeding about 2 Sv during a short time. At this dose it is primarily the blood-forming organ (red bone marrow) that is damaged. The first symptoms of acute radiation sickness are nausea and vomiting which usually disappear within a day or two. After a few weeks the level of white blood cells is so low that the capacity of the immune system has been severely weakened which may in turn result in serious infections. At higher doses (2–3 Sv or more), epithelial intestinal cells also are affected by serious damage, which results in problems maintaining salt and fluid balances in the body, in addition to enhancing the risk of self-infection from intestinal bacteria. At very high doses (10 Sv and above) nerve and brain cells are also damaged – no one has ever survived an acute effective dose exceeding about 7 Sv (whole body irradiation) – even with the most modern intensive medical care available.

5.2. Cancer

Cells, which are irradiated, may be damaged without dying. Such cells are to a large extent repaired or eliminated by different defense mechanisms but a few such cells may survive and transfer their damage (in particular DNA damage on a sequence level) to their progenitor cells. This may ultimately lead to cancer/tumors. There are many factors that must coincide or interplay for a tumor to develop. The probability of developing a tumor is assumed to be related to the magnitude of the radiation dose. An enhanced cancer risk has been demonstrated for groups or populations of individuals who have been exposed to 100 mSv. The effects at lower doses of radiation can however, as mentioned above, be difficult to distinguish from the effects of other carcinogenic factors in the environment including those from smoking. The general cancer risk increases exponentially with increasing age. A few notable exceptions from this rule of thumb include the acute lymphatic leukemias and brain tumors of children. The latency for different forms of radiation-induced cancer varies and may be 50 years or longer. The additional risk to the general risk of becoming diseased by cancer is so low, however, that it would not be possible to detect even if the individual has received that maximally permissible dose of 20 mSv/year throughout his/her working life (ICRP 60, 1991). Among the exceptions are leukemias, thyroid cancer among children as well as thyroid cancer related to a larger intake of radioactive iodine.

5.3. Teratogenic (fetal) damage

The fetus grows very rapidly and is therefore particularly sensitive to ionizing radiation. One type of fetal damage that has appeared following the atomic bombs in Japan is mental retardation. Their mothers who at the time where in their 8th to 17th week of pregnancy, which is the time when much of the brain is developed, and had received a radiation dose of 1,000 mSv had a 40% probability of having a mentally retarded child. At doses below a few hundred milliSievert it is questionable whether detectable fetal damage may occur.

5.4. Hereditary changes

The probability of hereditary changes following exposure to ionizing radiation is smaller than that of developing a tumor. A germ cell that has been hit by radiation can, in principle, via conception transfer the genetic damage to the next generation. Malforming inherited genetic damage induced by ionizing radiation has never been shown in man, including descendants of survivors of the atomic bombs in Japan. Chromosomal damage to DNA has, however, been shown in animal experiments down to a level of 2.7 mGy of gamma radiation per day. In order to be inherited, such damage must occur in germ cells. The majority of the DNA damages a cell experiences are repaired. For a relevant risk perspective of DNA damage in man it should be noted the naturally caused damages of various types, most of which are trivial for the cell to repair, which may amount to 100,000 per cell and 24 hours.

6. RADIATION DOSES AND REGULATORY LIMITS

In Sweden, the SSM (Swedish Radiation Safety Authority) sets the radiation dose limits through the radiation protection law, SFS/1988:220, and special regulations for different situations and activities. Corresponding authorities to SSM exist in most countries in the world. The SSM consults its own researchers as well as qualified scientists at universities throughout the country. Emphasis of the SSM is both on physics and medicine with the overall purpose of protecting humans, animals and the environment from harmful effects of radiation regardless of whether the source is the sun, cosmos, lasers, radon or other radioactive elements, X-ray apparatus or nuclear power.

The annual dose limit for radiation exposure from nuclear power to the public is 0,1 mSv per person. An individual who works professionally with radiation sources (in the nuclear power industry, health care or any other area) is permitted to be exposed to a maximum of 50 mSv during a single year, but in addition no more than 100 mSv for five consecutive years. Individuals working at a nuclear power plants in Sweden receive an average of about 2 mSv per year, typically a few individuals may rarely receive as much as 20 mSv during a single year. The dose limit for radon in air is established by the Swedish National Board of Health and Welfare. As an example, the concentration limit for radon gas has been set at 200 Bq/m3 in homes.

What is known about low radiation doses?

The present knowledge about the radiation risks for humans is to a large extent based on analysis of the surviving Japanese atomic bomb victims from Hiroshima and Nagasaki. In total 500 more cancer cases than expected have been found among these individuals. This finding is statistically significant and for all these individuals the radiation doses were 200 mSv or higher. There are no studies that convincingly show that radiation doses below 200 mSv increase the risk of prematurely dying from cancer. The relation, if it exists, between low doses and cancer cannot be detected among all other cancers in the society (about 20% of all deaths in Sweden are due to cancer). For carcinogenic chemicals, limits for occupational or public exposure are sometimes set at levels which have been considered acceptable with regard to health effects. For extremely hazardous substances the first principle, if possible, is to use an alternative substance. For radiation protection in the cancer risk context, no threshold limit has been assumed. The basis for this is that the ICRP (International Commission on Radiological Protection) uses a hypothetical risk model with a linear relation between radiation dose and cancer risk, i.e. that the damaging effects of radiation are proportional to the radiation dose. This means that the relationship can be described by a straight line, the higher the dose is, the higher the probability is for damage.

As an implicit consequence of this, ICRP assumes that all radiation doses, regardless of how small they are, are deleterious, in other words there is no experimental evidence of a threshold under which the radiation doses are harmless. The figure below illustrates the extrapolation from epidemiological cancer risk data to the low dose region. For high doses it has been shown that the risk of death is proportional to the dose.

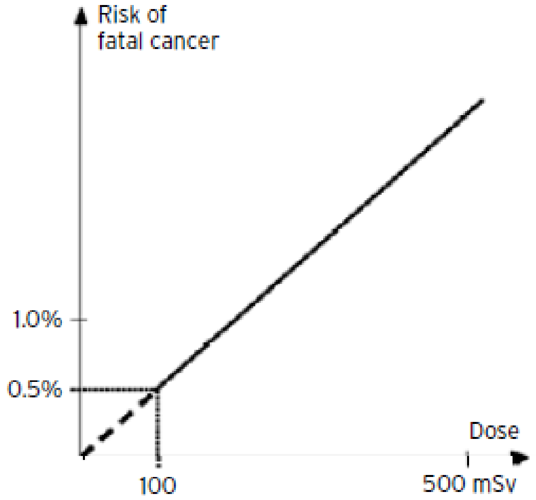

Figure 6.1. Risk for radiation induced cancer death as a function of dose according to ICRP. For high doses it has been shown that the risk is proportional to the dose. For low doses there is no experimental evidence for the slope of the graph but ICRP assumes a straight line for the low dose region as well.

In radiation exposure contexts the concept collective radiation dose is often used. Collective dose is the sum of the radiation doses to all individuals exposed by a specific source and is usually given in manSievert. One purpose of the use of collective dose is the comparison of doses from various sources and activities.

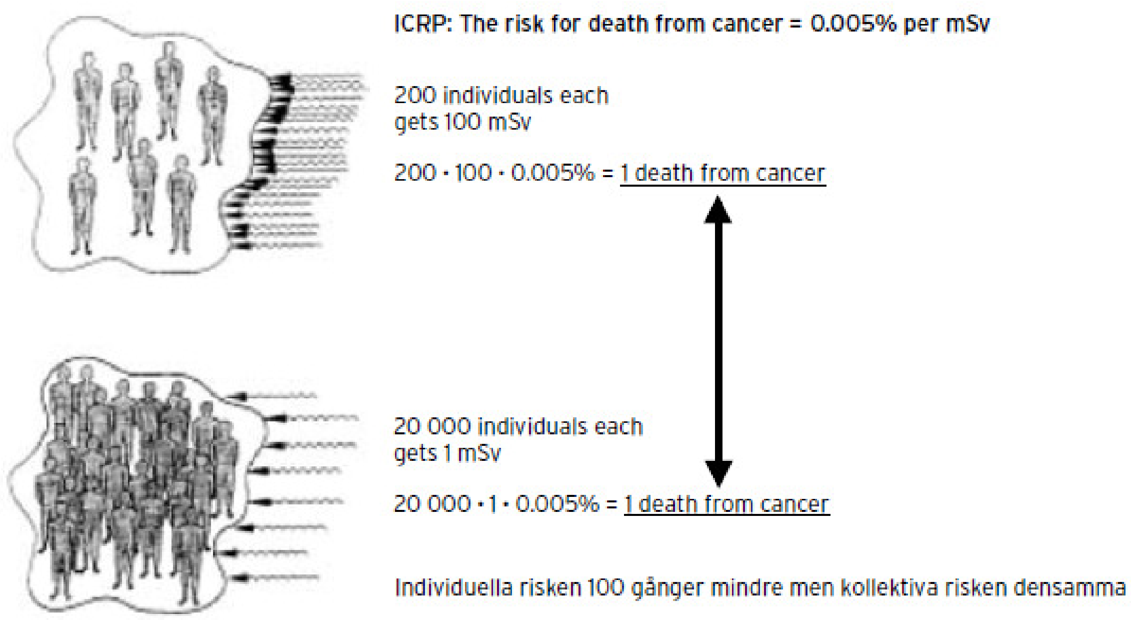

Figure 6.2. A relatively high dose of radiation to few individuals can give the same collective risk as a low dose to many individuals.

Even small radiation doses, which can be considered negligible for the individual, may result in a very high collective dose if the population is large and the dose is accumulated over a long time. A calculation of the global collective dose from cosmos gives 0,3 mSv * 6 billion = 1 800 000 manSv (per year). According to the ICRP model with a linear relation between radiation dose and radiation induced cancer, the increased risk of death from cancer is 0.005% per mSv. If the collective dose concept is used to calculate the cancer risk due to cosmic radiation among the global population this results in 60 000 extra annual cancer deaths. For the doses discussed here (1–100 mSv) the cellular damage is in terms of extent and accuracy repaired independently of the dose rate. It is not clear how the doses affect the actual cancer risk and therefore the linear model may be regarded as an administrative tool.

7. PERSPECTIVE ON RADIATION – A COMPARISON

The amount of radiation that a radioactive substance emits per unit time (i.e. the radioactivity) depends on how rapidly the radioactive element decays. Half-life is the time it takes for half of the unstable atoms of a radioactive substance to decay. In the table below, half-lives of some radionuclides are given as examples (d=days, y=years).

Radionuclide	Half-life
Carbon 14	5 700 years
Potassium 40	1 300 million years
Cobalt 60	5.3 years
Strontium 90	29 years
Iodine 131	8 days
Cesium 137	30 years
Radon 222	3.8 days
Radium 226	1 600 years
Plutonium 239	24 000 years
Uranium 238	4 500 million years

Numerical values relating to radiation and radioactivity can be given in several different ways. For radioactivity, besides the use of half-lives, the (radio) activity (becquerel, i.e. decays per second) is often used. A high activity means that the radionuclide decays relatively rapidly into its daughter products. The corresponding half-life will then be short. The opposite situation, i.e. for radionuclides with a long half-life, generally means that the corresponding activity is low. The radioactivity also depends on the quantity of the radionuclide.

The ultimate dose that an individual receives will partly depend on the composite effect of these factors as well as other factors relating to the exposure situation (pathway, distance from the source, shielding and biological considerations). In the table below are a few examples of half-lives and Becquerel levels from our daily life. As can be seen, the numbers vary and it is therefore not easy to directly determine questions of risk based on such data – tabulating them is more for the purpose of providing reference frames.

Examples of radioactivity levels (Bq):

Substance/source	Activity (Bq)
Earth/ground (1 kg)	Ca 400 (varies from 100 to 1000)
Brazilian nuts (1 kg)	Up to about 500 (alpha radiation)
Bananas (1 kg)	100 (from potassium 40)
Human body (1kg)	100 (carbon 14 and potassium 40)

The total natural radioactivity in a human adult is about 7 000 Bq, which corresponds to 150 billion decays per year. In other words, values for radioactivity often give very large numbers and in addition give little information about the associated risks for humans. Soil for example contains high levels of radioactivity in the sense “high Becquerel values” whereas the dose this gives rise to in the environment can be considered small. Therefore effective dose, which is measured in Sv, is used instead to describe the amount of radiation an individual has been exposed to. 1 Sv is a very high dose and therefore more often milliSievert, mSv, is used instead, which is one 1 000th of 1 Sv.

In order to give some idea about the size of doses the bar graph below shows the radiation doses an average Swedish person annually receives from various sources.

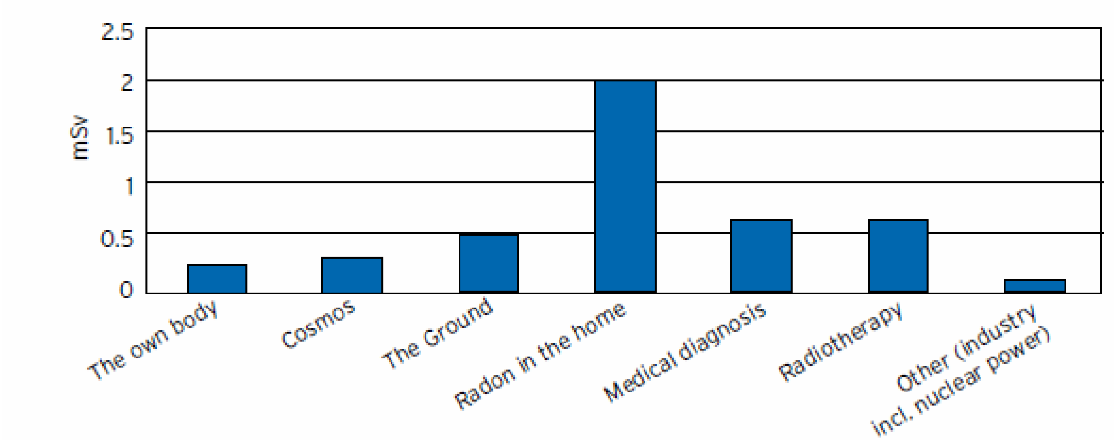

Figure 7.1. Average annual dose for a Swedish individual.

The total annual dose a Swedish person receives is about 4 mSv but this may vary significantly between individuals. The radiation from the ground varies a lot depending on where one is located. In Sweden the radiation from ground typically results in an individual annual dose of 0.5 mSv but in certain areas like for instance some bedrock cliff areas in south-western Sweden this dose may be three to four times higher. Other places in the world have much higher radioactivity levels in the ground. One example is the town Guarapari in Brazil where some individuals may receive annual doses of 50 mSv or more due to the natural background radiation from the ground.

0.1 milliSievert	• Dose for a transatlantic air flight (both directions). Or • Highest permissible additional annual dose to individuals living or working near a nuclear power plant. In reality, these doses have usually been at levels of 0,01 mSv or lower.
1 milliSievert	• Dose for a gastrointestinal X-ray diagnostic examination. Or • Annual dose from the body's own radioactivity (mainly potassium 40), cosmic and ground radiation put together.
1-3 milliSievert	• Annual dose for transatlantic aircraft personnel. Or • Average annual dose for a Swedish nuclear worker. Or • Annual dose from radon in homes (100 Bq/m3 gives about 2 mSv per year).
5 milliSievert	• Total dose received at a daily consumption of 300 grams of fish or meat, which contains 3000 Becquerel cesium 137 per kilo.
50 milliSievert	• Dose for a diagnostic radiography examination of the thyroid gland with radioactive iodine. Or • The maximum permissible annual dose for professionals working with radiation (with the added restriction that the total dose over a period of five years shall not exceed 100 mSv).
100 milliSievert	• Highest permissible dose to professionals working with radiation over a five-year period. This is also the dose at which enhanced cancer risks have been observed in epidemiological studies of individuals exposed to the radiation for a short time period (less than a day).
500 milliSievert	• Dose to individuals who lived within 10 km from the Chernobyl nuclear power plant in 1986 before evacuation.
5000 milliSievert	• This dose kills essentially anyone who does not receive special medical treatment.
50 000 milliSievert	• Approximate dose for radiotherapy treatments of many types of tumors. The radiation is focused on the tumor while other parts of the body are shielded against the radiation. A corresponding whole body radiation at this dose would kill the individual in less than 24 hours.

8. REFERENCES

http://www.ssm.se
http://www.analys.se