4. Ionizing radiation

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4.1. Areas of protection and environmental mechanisms covered

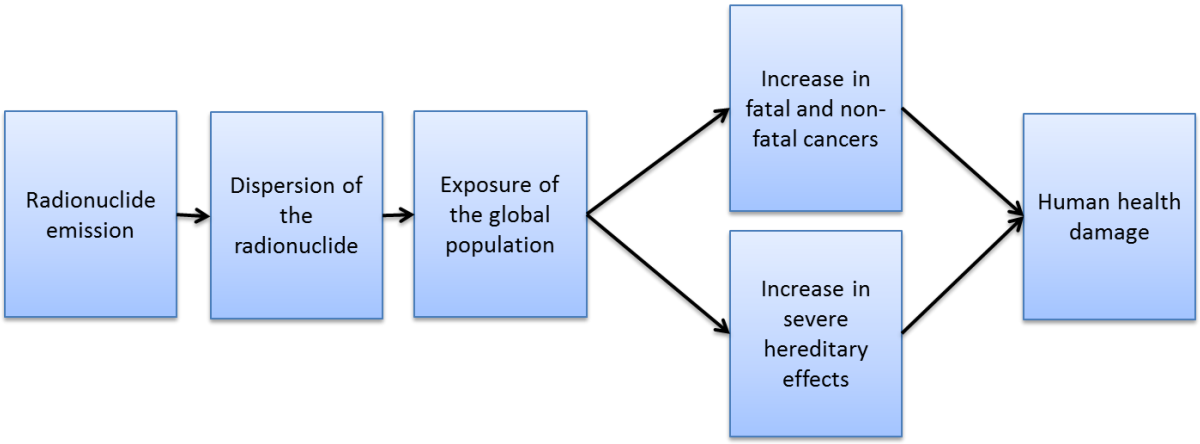

Figure 4.1: Cause-and-effect chain from an airborne or waterborne emission of a radionuclide to human health damage (from: Huijbregts et al., 2014)

Radionuclides can be released during a number of human activities. These can be related to the nuclear fuel cycle (mining, processing, use or treatment of the nuclear fuel) or during more conventional energy generation such as the burning of coal. Airborne radionuclides can be inhaled by humans, while radionuclides that end up in freshwater can be ingested during swimming in open water, via drinking water produced from surface water or can enter the food cycle via crops.

When the radionuclides decay, they release ionizing radiation. Human exposure to ionizing radiation causes alterations in the DNA, which in turn can lead to different types of cancer and birth defects. Similar effects must be expected in other living organisms, but damage to ecosystems is not quantified at the moment. Thus, the only area of protection covered is human health (Figure 4.1).

The effect factors are based on disease statistics resulting from relatively high work-related or accident-related exposure. An average approach is used to calculate the amount of additional cancer-incidences resulting from this exposure. In LCA however the exposure doses are generally very low. Therefore, the value based on relatively high exposure was corrected for the difference in cancer incidences per exposure dose, thereby approximating a marginal approach.

4.2. Calculation of the characterization factors at endpoint level

The calculation procedure here is equal to that of the latest ReCiPe update (Huijbregts et al. 2014), which in turn is based mostly on the works from De Schryver et al. (2011) and Frischknecht et al. (2000). The division of the value choices (see below) is different, meaning that the CFs with good robustness are not the same as the factors provided in ReCiPe. However, the total CFs are equal to the endpoint CFs of the Egalitarian perspective in ReCiPe, because in both methodologies these reflect all potential

impacts. The endpoint CF is calculated as shown in equation 4.1, where CD stands for collective dose of radionuclide x, and EF for effect factor for radionuclide *x,* environmental compartment *i* (air, freshwater or marine water) and time horizon *TH*

$$CF_{end,x,i,TH} = CD_{x,i,TH} \cdot EF$$

Equation 4.1

Unlike most other CFs the damage is not expressed per kg of emission but rather per kBq. The unit Becquerel (Bq) is the number of atom nuclei that decay per second. Even though the CF for every radionuclide is based on the same activity level (1kBq = a decay of 1000 nuclei per second), there are differences due to the type of radiation, the half-live of the radionuclide and the environmental fate of the radionuclide. For emissions to air a Gaussian plume model is used to describe the dispersion around the emission location for all but four radionuclides. Tritium (H-3), carbon-14, krypton-85 and iodine-129 are assumed to disperse globally. Models that cover the global water cycle, the carbon cycle, a two compartment dynamic model and a nine compartment dynamic model were used for these radionuclides respectively. Emissions to river water are modelled via a box-model with several different river compartments. By taking into account the fraction that is taken up by the human population one can calculate the collective dose (CD). As shown in equation 4.2, the collective dose (unit: man.Sv) is a measure for the total amount of exposure to a radionuclide for the entire, global population.

$$CD_{TH} = \int_{t=0}^{TH} Exposure_t \; Population_t$$

Equation 4.2

Exposure is the average exposure in Sievert (Sv=J/kg body weight) and Population represents the number of people at time *t*, integrated over time horizon TH. For the longest time horizon (100 000 years) the total human population was assumed to be stable at 10 billion people (Dreicer et al., 1995; Frischknecht et al., 2000).

The effect factor, shown in equation 4.3, combines the damages of the different disease types that can be caused by ionizing radiation.

$$EF = \sum_i Incidence_i \; Severity_i$$

Equation 4.3

Where Incidence is the extra incidence of disease type *i* (incidences/man.Sv) and Severity represents the human health damage caused by these diseases (DALY/incidence).

The incidence rates of the different cancer types and hereditary disease were taken from Frischknecht et al. (2000) while the corresponding human health damage (in DALY) per disease type was taken from De Schryver et al. (2011). This yields a robust damage factor of 0.617 DALY/man.Sv and a less robust factor of 1.239 DALY/man.Sv. Multiplied by the collective dose in man.Sv (taken from De Schryver et

al. 2011 for almost all radionuclides, Frischknecht (2000) for the others) for emissions to the different compartments this yields the final CFs (Table 4.2).

4.3. Uncertainties

The CFs for this impact category are based on reported data from existing literature. Assessing the sensitivity of the CFs to uncertainties in the individual parameters is therefore only possible to a limited extent and is dependent on the reported data in the original reports. The uncertainties in this impact category are a combination of the uncertainty in the environmental fate and the damage factors of the different radionuclides. Because of the extremely long lifetimes of most radionuclides it is likely that the uncertainty in the first part (fate) is larger than the uncertainty in the second part (damage). Quantitative assessments are unavailable, but it is not difficult to identify potential sources of uncertainty in the fate modelling. Firstly, quite simple fate models with a limited number of compartments are used for modelling the environmental fate of the radionuclides. In contrast to other long-term effects, an important distinction for the radionuclides is that the uncertainty of the decay intensity and the type and intensity of the released radiation is negligible. The uncertainty concerns the extent to which humans will be exposed to the released radiation, which depends on the compartments where the radionuclides end up and perhaps more importantly, on the future population levels and distributions. The accuracy is highly questionable because the human exposure was modelled in quite a simplistic way. The collective dose is determined based on the assumptions that the population is evenly spread throughout the world and will remain stable at a level of 10 billion people for the next 100’000 years. Both predictions are likely to be very inaccurate. The number of 10 billion people will overestimate impacts in the short run, but potentially underestimate the future impact if the population grows beyond that number in the (distant) future.

On top of the uncertain collective dose there is also uncertainty related to the amount and types of cancer caused by exposure to radiation. Some of this uncertainty relates to whether or not different types of cancer can be caused by radiation, this is covered in the next section on value choices. Another part that is uncertain is how to adjust the factors derived from high exposure to radiation to the low exposure levels that are assessed in LCA. Partly this is a subjective choice as well, this is therefore also considered in the next section. In addition to these sources of uncertainty there is also uncertainty in the amount of DALYs caused by each cancer type. It is important to keep in mind that the values used here are representative of the current situation, if advances in medical development continue to progress it is likely that the burden of (some) types of disease decreases substantially. The longer the time horizon, the more likely it is that this will happen.

4.4. Value choices

Radioactive half-lives of radionuclides can vary from less than a second to millions of years. The harmful ionizing radiation is released during the radioactive decay. The decay is described by an exponential function, and radionuclides that decay very slowly (half-lives > 100 years) therefore release the majority of their radiation in the far future, while shorter-lived radionuclides (half-lives <100 years) will release the majority of their radiation during the first couple of years after release. It is therefore important to know over which time horizon the impact of the different radionuclides is considered. The impacts over a 100 year time horizon are considered to be robust, while the impacts occurring in a 100 000 year period after that are considered uncertain and less robust (Table 4.1).

It should be noted that even the 100.000 year time horizon is still relatively short compared to the half-life of Uranium-235 of 7.10 * 10^8 years. However, the models that were used to derive these factors only calculated results for a time period up to 100.000 years.

While it is certain that ionizing radiation can cause hereditary disease and thyroid, bone marrow, lung and breast cancer it is less clear whether other types (bladder, colon, ovary, skin, liver, oesophagus, stomach, bone surface and remaining types) of cancer can also be caused by exposure to ionizing radiation. Therefore in the core CF only the first four types of cancer and hereditary disease are included, while for extended CF all cancer types are assumed to be caused by ionizing radiation. The incidence rate of cancer caused by ionizing radiation was determined by statistics based on accidental medium to high exposure (for example from workers in nuclear power plants). It is uncertain by how much the high to medium exposure doses should be corrected to get a CF that accurately reflects the very low exposure situations considered relevant in life cycle assessment. A factor called the Dose and dose rate effectiveness factor (DDREF) is used to correct for the fact that at higher exposures less dose is needed to result in the same effect. A factor of 10 is considered an optimistic estimate (based on animal studies), i.e. meaning that for the same cancer incidence rate caused by medium to high exposure one would need to get a dose that is 10 times higher as a result of (prolonged) low exposure (used for core CFs). A more conservative estimate is that this factor is only about 2 (used for the cancer types that are added to the extended CFs). For hereditary diseases no correction factor is applied.

Table 4.1: Value choices in the modelling for core and extended CFs. The right column shows what is added to the core values to reach the extended values.

Choice category	Core	Addition in extended
Time horizon	100 yr	100 - 100,000 years
Dose and dose rate effectiveness factor (DDREF)	10	2
Included effects	-Thyroid, bone marrow, lung and breast cancer -Hereditary disease	- bladder, colon, ovary, skin, liver, oesophagus, stomach, bone surface and remaining types of cancer

Table 4.2: Characterization factors (CF) for the core and extended values for human health damage DALY (DALY/kBq = y/kBq) for emissions to air, freshwater or the marine environment. HH stands for human health.

Emission to air	HH, core [DALY/kBq]	HH, extended [DALY/kBq]
Am-241	3.7E-07	7.6E-07
C-14	7.8E-09	1.8E-07
Co-58	1.7E-10	3.5E-10
Co-60	6.8E-09	1.4E-08
Cs-134	4.9E-09	9.8E-09
Cs-137	1.1E-08	2.2E-08
H-3	5.8E-12	1.2E-11
I-129	7.1E-08	2.8E-06
I-131	6.2E-11	1.2E-10
I-133	3.8E-12	7.7E-12
Kr-85	5.8E-14	1.2E-13
Pb-210	6.2E-10	1.2E-09
Po-210	6.2E-10	1.2E-09
Pu alpha		6.8E-08
Pu-238		5.5E-08
Pu-239	2.2E-07	4.3E-07
Ra-226		7.4E-10
Rn-222	9.9E-12	2.0E-11
Ru-106	6.8E-10	1.4E-09
Sr-90	1.7E-08	3.3E-08
Tc-99	8.0E-09	1.6E-08
Th-230		3.7E-08
U-234		7.9E-08
U-235		1.7E-08
U-238		6.7E-09
Xe-133	5.8E-14	1.2E-13
Emission to river and lakes		
Ag-110m	2.0E-10	4.1E-10
Am-241	2.3E-11	5.0E-11
C-14	4.1E-11	1.7E-10
Co-58	1.7E-11	3.3E-11
Co-60	1.8E-08	3.6E-08
Cs-134	5.9E-08	1.2E-07
Cs-137	6.8E-08	1.4E-07
H-3	2.8E-13	5.6E-13
I-129	1.9E-09	2.1E-06
I-131	2.0E-10	4.1E-10
Mn-54	1.3E-10	2.6E-10
Pu-239	2.5E-12	5.7E-12
Ra-226		1.1E-10
Ru-106	1.6E-12	3.2E-12
Sb-124	3.3E-10	6.7E-10
Sr-90	1.7E-10	3.8E-10
Tc-99	2.1E-10	4.2E-10
U-234		2.0E-09
U-235		1.9E-09
U-238		1.9E-09
Emission to ocean		
Am-241	3.3E-10	6.6E-10
C-14	1.9E-10	3.7E-10
Cm alpha		4.7E-08
Co-60	1.6E-10	3.2E-10

Cs-134	3.2E-11	6.4E-11
Cs-137	3.9E-11	7.9E-11
H-3	2.8E-14	5.5E-14
I-129	2.0E-10	2.1E-06
Pu alpha		6.1E-08
Pu-239	3.6E-11	7.8E-11
Ru-106	7.4E-12	1.5E-11
Sb-125	6.0E-12	1.2E-11
Sr-90	3.1E-12	6.2E-12
Tc-99	5.4E-13	1.5E-12
U-234		1.9E-11
U-235		2.0E-11
U-238		1.9E-11

4.5. References

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