1

Assessment and Perception of Nuclear Risk

1.1. Introduction

Nuclear power, whether in the form of military applications, in particular atomic bombs, or civilian use in electricity generation, lacks a positive image. We might say that it has had a bad press, among the public, whatever the country. This is partly a result of the origin in war of the use of nuclear energy and the Hiroshima and Nagasaki bomb disasters. This has been reinforced by accidents, including the two major accidents at Chernobyl and Fukushima. It is certainly also a result, at least in France, of the technopolitical regime of the French nuclear power program and strong criticism of it by social movements. Chambru [CHA 15] traces the emergence and deployment of the anti-nuclear phenomenon within the public arena, with the aim of capturing this protest effervescence and reintroducing it political analysis. He notes that criticism by the anti-nuclear movement has never ceased since its inception more than four decades ago. Today, it is embodied particularly in the refusal of the anti-nuclear movement to participate in the consultation mechanisms set up by public authorities, such as the public debates organized under the aegis of the *Commission Nationale du Débat Public* (CNDP).

For three years, Colmellere [COL 14] conducted a pedagogical device for public debate on a project to install a nuclear reactor as part of a sociology course for second-year engineers at the Ecole Centrale Paris. It concerns a group of about 20 students and is inspired by a real situation, albeit an old one, which is the project to build an EPR nuclear reactor at Penly (Seine-Maritime). The system is based on a documentary film, "*Nucléaire en alerte*" [JOH 10]. This film is in turn based on an observation that French citizens, all of whom are concerned by the risk of a nuclear accident, lack information. Without partisan activism, based on the principle that "zero risk does not exist", this film raises the question of how to manage a nuclear crisis at health, technological, media, economic and political levels. To simulate public debate, students choose their roles. While places for residents and protesters, operators and industrialists were sought, it is difficult to find places for ASN or IRSN experts. This seems to be down to the fact that the students did not have a clear representation of the ASN's position on the nuclear issue. Students are convinced that the principled position is pro-nuclear. They also find it difficult to understand IRSN's role and position. It is clear from this exercise that the risks of nuclear accidents – and therefore safety – are not objective data. They do not reflect the calculation of the product of the severity of the consequences of the accident and its probability of occurrence. Students note that there are "differences in perceptions or representations" of risks and that they are legitimate, logical and well-founded. Some questions remained unanswered, such as life in low-dose contaminated areas where experts are divided. The students also realized that the ASN and IRSN experts had difficulty holding a firm and substantiated position towards citizens and operators because they were torn between their position as representatives of an institution (or at least what they thought it should be) and their position as citizens much closer to that of citizens or representatives of environmental associations. According to them, this difficulty showed that the same person can represent the same risk differently depending on the context in which he or she finds himself or herself, whether professional or personal.

Risk perception varies among populations. For example, when a dangerous industry, such as a nuclear power plant providing jobs, imposes a delicate compromise with fear in a region marked by unemployment. Residents and workers then minimize the risks of contamination and hold a different debate position from those who live elsewhere without being economically involved [LEB 12, ZON 89].

According to sociologist Le Breton [LEB 12], nuclear workers distinguish themselves into two categories: those that were “legalists”, concerned about protective measures and sometimes raising their prices, and “dare devils”, always ready to perform dangerous tasks, without much concern for safety. The “dare devils” want to show that they are men and are not afraid of death.

The point of view of engineers or scientists often differs from that of people living in the vicinity, because if the former see the potential dangers of a nuclear power plant in terms of probability and physical risks, for example, the latter assess them in terms of the disorders that affect their health or those that would affect them in the event of an accident.

Nuclear safety is essential because in the event of a major accident, the consequences are immense. Thus, huge areas were wiped off the map during the Cold War, particularly during nuclear weapons research. There are many “national sacrificed areas” in the United States (California, Nevada, Utah), Siberia, etc. [BRO 02].

In France, nuclear safety is implemented by two normally independent and transparent authorities, one for civil activities, the Autorité de Sûreté Nucléaire (ASN), and the other for military activities, the Autorité de Sûreté Nucléaire Défense (ASND). They act in a coherent and coordinated manner. They are independent of nuclear operators and also in the technical support they provide. The ASN relies technically, and mainly, on IRSN and the ASND is on the CEA. The Institut de Radioprotection et de Sûreté (IRSN), a French public institution created in 2001, has a mission of monitoring and research as well as expertise with public authorities. The CEA, a research organization, particularly in the nuclear field, also operates experimental reactors. In addition, the Agence Nationale pour la gestion des Déchets Radioactifs (ANDRA), a public institution created in 1991, is responsible for long-term management, specifically to find, implement and guarantee safe management solutions for all French radioactive waste.

In addition to these official bodies, the main actors in nuclear safety are the operators of nuclear installations, who are primarily responsible for the safety of their installations. The French operators are mainly EDF, ORANO (formerly AREVA) and Framatome.

The third pillar of French nuclear security is the public, represented by the *Haut-Comité pour la Transparence et l'Information pour la Sécurité Nucléaire* (HCTISN) and by the *Commissions Locales d'Information* (CLI). The HCTISN is in charge of organizing information and structuring consultation at the national level, while the CLIs do so at the local level.

This chapter will present methods for assessing the radioactive risk to non-human organisms and humans. These assessments will be detailed later in the fourth and fifth volumes of the *Radioactive Risk* series. The chapter will also provide some information on public opinion on nuclear energy and public perception of radioactive risk.

1.2. Danger, exposure, radiotoxicity and risk

Risk is the crossover between a hazard and an exposure. If the hazard is low, even with intense exposure, the risk will be low. If the hazard is high but the exposure low, the risk will also be low.

Risk assessment is carried out in four stages (Figure 1.1 based on [AMI 16]):

– hazard identification;

– hazard exposure assessment;

– hazard characterization or effect assessment (dose–response relationship);

– risk characterization.

The second step is carried out in three successive phases. The first phase is the quantification of radioactive contamination of the environment in the broad sense. The second phase is the identification of all routes of exposure likely to reach the individual. The third phase is the estimation of the doses suffered by the individual. This phase is much more precise for humans than for all other organisms.

The fourth step is to compare the no-effect levels recommended by official agencies with the estimated levels experienced.

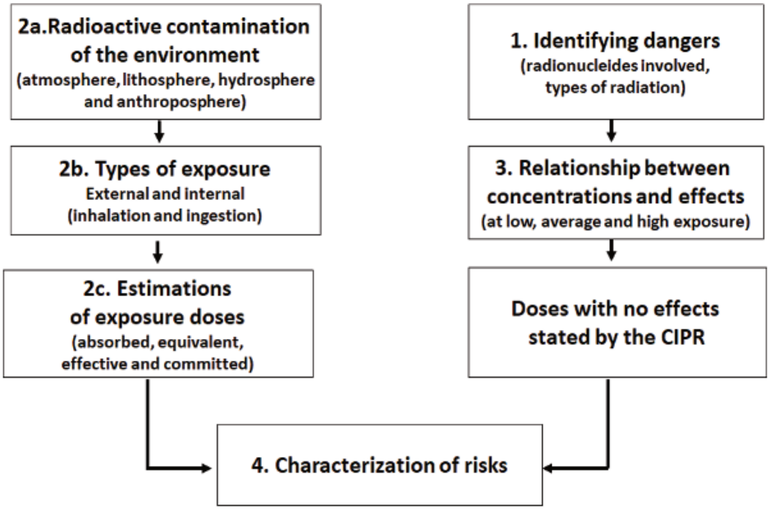

Figure 1.1. *The general principle of estimating radioactive risk for humans*

1.2.1. *Identification of radionuclide hazards*

By limiting the discussion to radionuclides and ionizing radiation, the first step, hazard identification, is obvious, because radioactivity is dangerous for all life forms.

1.2.1.1. *Chemical toxicity and radiotoxicity*

The danger of radionuclides may be related to their chemical toxicity and/or their radiotoxicity resulting from their radiation properties. For all radionuclides except uranium, radiotoxicity is significantly more dangerous than chemical toxicity. Radiotoxicity is highly variable depending on the radionuclide.

1.2.1.2. *Types of ionizing radiation*

Radioactivity corresponds to an unstable nucleus which spontaneously emits one or more particles to regain its stability. There are three main types of radiation:

– α radioactivity, where a helium nucleus is emitted;

– β radioactivity, where either an electron and an electronic antineutrino ($\beta-$) or a positron and an electronic neutrino (β^+) are emitted;

– γ radioactivity by which a nucleus loses its energy through high energy electromagnetic radiation.

To these must be added X-rays, of the same photonic nature as γ emitters, but produced by electronic transitions, and neutrons, present during chain reactions in nuclear reactors or during the explosion of atomic bombs.

The two main properties of radiation are the power of penetration into a material and the ionizing power.

1.2.1.3. *Half-life*

In a radioactive sample, the number of disintegrations per unit of time is proportional to the number of unstable nuclei of the radionuclide present in the sample. As a result, for a given sample, the number of unstable nuclei gradually decreases over time. The period during which half of the unstable nuclei disappear is called the half-life (Tp) or physical half-life. It is a characteristic and unchanging quantity of each radionuclide. Thus, radionuclides composed of highly unstable nuclei will have a half-life of a few fractions of a second, while those composed of very stable nuclei will have a half-life of thousands of years. Thus, after four half-lives, the radioactivity of a sample is reduced by a factor of sixteen (Figure 1.2). Table 1.1 provides some examples of half-lives for radionuclides frequently found in the environment in their natural state and/or as a result of human activities. Strontium 90 equilibrates with yttrium 90 (2.668 days) and cesium 137 rapidly equilibrates with barium 137m (2.554 min).

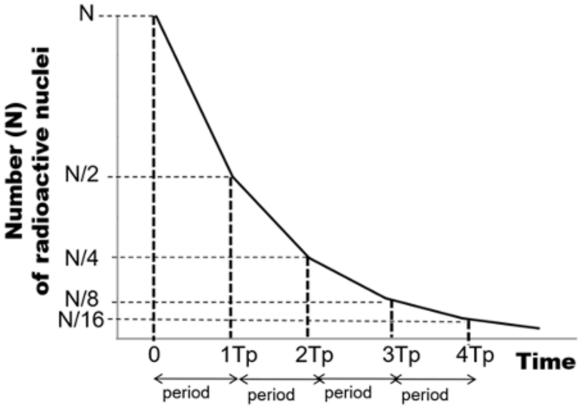

Figure 1.2. *The physical half-life of radionuclides*

Isotope	**Symbol**	**Physical half-life**	**Type of emission**	**Energy Eα, (Eβmax), Eγ in MeV**
Tritium	^{3}H	12.312 y	β	(0.018)
Carbon 14	^{14}C	5.700 y	β	(0.157)
Phosphorus 32	^{32}P	14.284 d	β	(1.710)
Cobalt 60	^{60}Co	5.271 y	β and γ	(0.317), 1.173 and 1.333
Strontium 90	^{90}Sr	28.80 y	β	(0.546)
Iodine 125	^{125}I	59.388 d	e, X, γ	0.035
Iodine 131	^{131}I	8.023 d	β, γ	(0.334 and 0.606) 0.284 0.364 0.637
Cesium 137	^{137}Cs	30.05 y	e, X, γ	(0.514 and 1.175) 0.662
Uranium 235	^{235}U	7.04×10^{8} y	e, X, γ	α 4.215 to 4.596 - γ 0.109 and 0.144
Uranium 238	^{238}U	4.468×10^{9} y	e, X, γ	α 4.151 and 4.198 - γ 0.050 and 0.114
Plutonium 239	^{239}Pu	24,100 y	e, X, α	α 5.106 to 5.157

Table 1.1. *Half-lives (Tp) or physical half-lives, types of radiation and energies of various radionuclides (y: year; d: day) (adapted from [CEA 14b, CEA 15])*

1.2.2. *Contamination of the environment, including the anthroposphere, by radionuclides*

1.2.2.1. *Natural contamination*

There are two categories of natural radionuclides that differ in their origin, either cosmic or telluric. Radiation of cosmic origin, that is, galactic or solar, gives rise either directly to radionuclides in the various compartments of the environment or to atmospheric radionuclides that will be introduced into terrestrial and aquatic environments by simple gas diffusion or with precipitation. Among the radionuclides formed by cosmic rays, those with a relatively long half-lives are ^{3}H (12.3 y), ^{10}Be (1.51×10^{6} y), ^{14}C (5.730 y), ^{32}Si (650 y) and ^{36}Cl (3.1×10^{5} y).

Originally, the earth was relatively radioactive. By decay, radionuclides with the shortest half-lives disappeared. Only a number of radionuclides remain in the lithosphere, from the four natural radioactive families (^{232}Th, ^{235}U, ^{237}Np and ^{238}U) and a few isolated radionuclides with very long half-lives. The term radioactive family refers to the fact that new nuclides resulting from the decay of a heavy radionuclide are also generally unstable. They disintegrate by releasing fewer and less heavy radionuclides until a stable and therefore non-radioactive nuclide appears following a series of transmutations. The last descendant is often an isotope of lead.

Apart from the four radioactive families, other long-lived natural radionuclides exist in the lithosphere, such as potassium 40.

Among the main natural radionuclides, radium 226, radon 222 and polonium 210 have a significant influence on the exposure of living organisms to radioactivity.

1.2.2.2. *Anthropogenic contamination*

The discovery of artificial radioactivity by Frédéric Joliot-Curie in 1934 led to the military and civilian use of nuclear energy. This use has led to the creation of various artificial radionuclides, fission products and activation products. Fission products result from the fracture of fissile radionuclides (uranium 235, uranium 233, plutonium 239) and activation products result from the bombardment by neutrons of stable elements present throughout the environment of neutron flows (sheaths, fluids, etc.).

Fission into two equal masses is not the most likely modality. In the case of the fission of uranium 235, the masses created have two peaks with a higher probability, one peak approximately 95 (6.545%) and the other at 138 (6.751%). The fission of about 100 uranium 235 atoms produces on average 5.835 ^{90}Sr atoms, 2.885 ^{131}I atoms and 6.236 ^{137}Cs atoms. The main characteristics of these radionuclides are given in Table 1.2.

Many other radionuclides are also fission products such as tritium, radioactive isotopes of transition metals (Se, Br, Kr, Kr, Rb, Sr, Y, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba) and lanthanides (La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb and Dy).

To these must be added the noble gas radionuclides, the main ones being ^{85}Kr (10.72 y) and ^{133}Xe (5.25 d) for most reactors and ^{41}Ar for gas-cooled reactors (GCR). Noble gases do not interact with living matter, so there will be no contamination. However, since their release is significant, radiation doses cannot be neglected for all terrestrial organisms, including humans.

	^{90}Sr	^{131}I	^{137}Cs	^{137}Cs/^{90}Sr
Radioactive period	28.64 y	8.02 d	30.17 y	
Decline (MeV)	0.546β-, 2.24β-. (^{90}Y)	0.606β-, 0.364β	0.514-, 0.662 (^{137m}Ba)	
Stable element	^{90}Zr	^{131}Xe	^{137}Ba	
Production rate during nuclear tests (per megaton)	3.9 PBq	4,200 PBq	5.9 PBq	1.51
Chernobyl production rate per gigawatt yr^{-1}	38 PBq	640 PBq	45 PBq	1.18

Table 1.2. *Characteristics of the three main fission-produced radionuclides [AMI 13]*

The elements of the actinide (or transuranic) series often have very long half-lives. This is the case for plutonium 239 (24,360 years), plutonium 240 (6.6×10^3 years), americium 243 (7.6×10^3 years), protactinium 231 (3.28×10^4 years) and technetium 99 (2.1×10^5 years). In addition, most of them are emitters causing intense internal radiation. Health hazards to living organisms are obviously significant for these transuranics.

Activation products are generated by neutron capture in the constituent materials of nuclear facilities that undergo prolonged neutron irradiation. The main activation products encountered result from elements present as trace elements, mainly in concrete or steel. The main activation products are iron 55, cobalt 60 and nickel 63 and, to a lesser extent, carbon 14, chlorine 36, manganese 54, cesium 134 and europium 152, 154 and 155, as well as some silver, zirconium and niobium isotopes (Table 1.3).

	^{51}Cr	**^{54}Mn**	**^{55}Fe**	**^{59}Fe**	**^{58}Co**	**^{60}Co**	**^{65}Zn**	**^{110m}Ag**
Protons	24	25	26	26	27	27	30	47
Radioactive half-life (d)	27.7	312.2	997.1	44.503	70.86	1925.5	244.3	249.9
(MeV)	0.315	0.829		0.475	0.474	0.314	0.327	
(keV)	320	835	X-rays	1.099, 1.292	511, 811	1.173, 1.332	511; 1.115	658; 885
Reaction producing the activation product	^{50}Cr (n, γ)	^{56}Fe (d, α)	^{54}Fe (n, γ)	^{58}Fe (n, γ)	^{55}Mn (α, n)	^{59}Co (n, γ)	^{64}Zn (n, γ)	^{109}Ag (n, γ)

Table 1.3. *Characteristics of the main radionuclides produced by neutron activation*

1.2.2.3. *Transfers from radionuclides to living organisms*

Radionuclides present in one compartment of the environment can, more or less easily and more or less quickly, leave it for another physical compartment or bioaccumulate in a living organism. This is reflected in the biogeochemical cycles of radionuclides. A schematic representation is proposed for the human species (Figure 1.3).

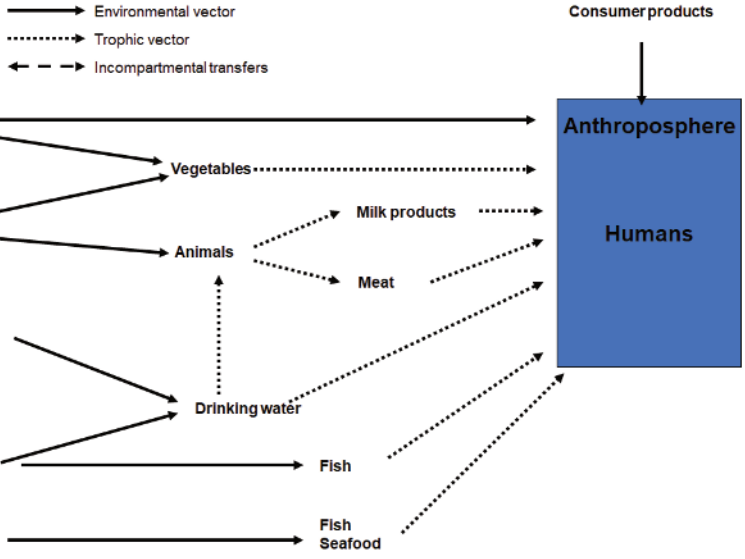

Figure 1.3. *Schematic representation of human exposure to radionuclides from the environment [AMI 13]*

Similarly, once incorporated by an organism, the radionuclide can move within that organism. An example of the various internal transfer pathways is presented for a mammal (Figure 1.4).

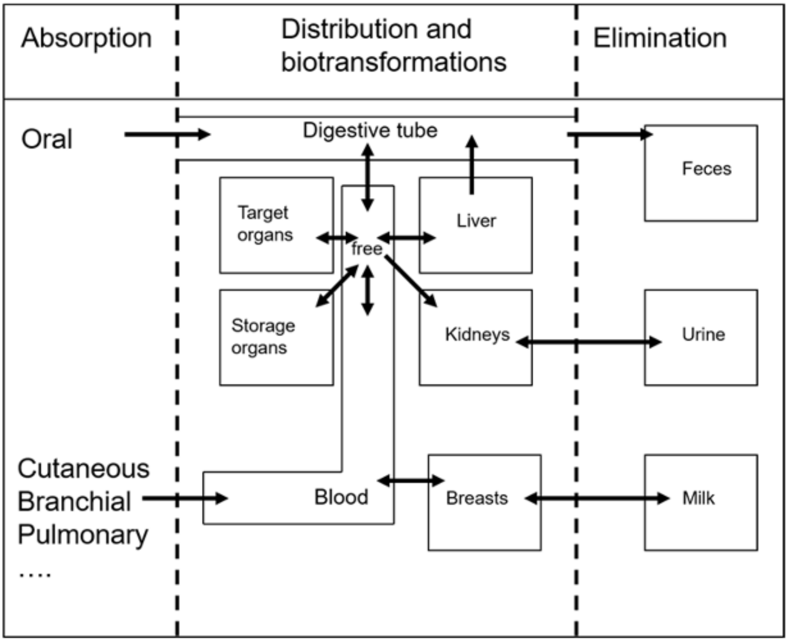

Figure 1.4. *General schema of the fate of radionuclides in a mammal [AMI 13]*

1.2.3. *Exposure to radiation*

1.2.3.1. *External and internal routes of exposure*

Living organisms, including our own species, are exposed to radionuclides through many pathways. When radionuclides are present in the various compartments of the environment (atmosphere, lithosphere, hydrosphere and anthroposphere), exposure is external. On the contrary, in the case of ingestion of contaminated food and inhalation of radioactive air, exposure becomes internal. As with radioactive contamination, it is possible to distinguish between natural and artificial exposures, both external and internal.

As it is impossible to limit natural exposures, it is therefore necessary to limit artificial external and internal exposures as much as possible.

A concrete example of the various pathways of contamination and exposure to radionuclides is shown in Figure 1.5. This is the case for the population of Beaumont-Hague (France), who suffered from atmospheric and liquid emissions from the La Hague spent fuel reprocessing plant as a result of the GRNC study [GRN 99].

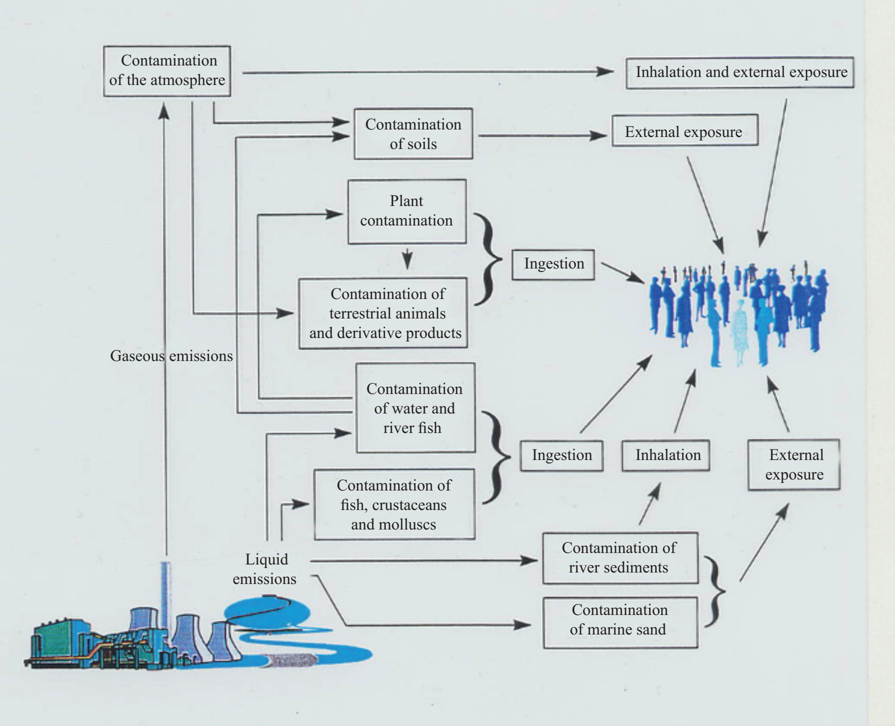

Figure 1.5. *The various exposure pathways of the population of Beaumont-Hague (adapted from [GRN 99]). For a color version of the figure, see www.iste.co.uk/amiard/nuclear.zip*

1.2.3.2. *The absorbed dose*

The dose absorbed by an organism from ionizing radiation is officially expressed in gray (Gy) which is the standard unit of the International System equivalent to one joule per kilogram (J kg^{-1}).

For the human species, estimation of the irradiation dose is not limited to the absorbed dose. It is refined to take into account two important factors, radiation energy and the type of biological tissue, which strongly influence radiosensitivity.

1.2.3.3. *The equivalent dose*

The quality factor or weighting factor (Q or W_R) is used to take into account the type of radiation and its energy; this factor varies from 1 to 20 (Table 1.4). For neutrons, the ICRP allows the use of a continuous relationship law instead of discrete values (values ranging from 2.5 to 20). The weighting factor is used to calculate the equivalent dose (H_T), the unit of which is also the joule per kilogram, but because of the weighting, its name becomes the sievert (Sv). Formerly, the unit was the rem, for Röntgen equivalent man (1 rem = 1 rad × Q), where 1 rad = 0.01 Sv. The "equivalent" terminology comes from the fact that a dose equivalent to the dose delivered by radiation and X (or $W_R = 1$), which serve as a reference, is calculated to produce the same stochastic biological effect.

Type of radiation	Weighting factor (W_R)
Alpha	20
Beta	1
Gamma and X-ray	1
Neutrons (various energies)	5–20
Protons (various energies)	1–5

Table 1.4. *Weighting factors (W_R) (adapted from [ICR 91])*

1.2.3.4. *The effective dose*

The relationship between the probability of stochastic effects and the equivalent dose is not the same from one organ or tissue irradiated to another. Rather, it depends on their radiosensitivity. A tissue weighting factor is therefore used. A limited number of dose conversion factors (FCD or W_T) are used for regulatory purposes to convert the energy transferred. This tissue weighting factor varies from 0.01 to 0.12 depending on the organ (Table 1.5).

Tissue	Weighting factor (W_T)
Colon	0.12
Stomach	0.12
Bone marrow	0.12
Spleen	0.12
Breast	0.12 (0.05)
Gonads	0.08 (0.20)
All other tissues	0.08
Bladder	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Surface bone	0.01
Skin	0.01 (0)
Salivary gland	0.01 (0)
Brain	0.01 (0)
Or for the whole body a total of:	1.00

Table 1.5. *Tissue weighting factor (W_T) adapted from [ICR 07a] (values from [ICR 91] in brackets)*

After this double weighting, we obtain the effective dose (E) that is also expressed in sieverts (formerly in rem, 1 Sv = 100 rem). The fact that the effective dose has the same unit (sievert) as the equivalent dose is confusing. In addition, the effective dose has its limits because the tissue weighting factors used to define it are not constant and vary more or less for each tissue depending on the absorbed dose, as well as with the dose rate:

$$\text{Effective dose} = W_R \times W_T \times \text{absorbed dose}$$

The summation of all effective doses for each organ provides the effective dose for the whole body (Figure 1.6).

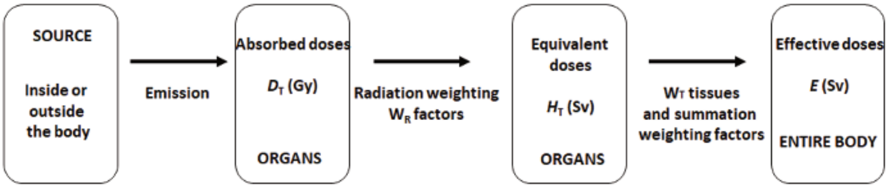

Figure 1.6. *The steps for calculating the effective dose (adapted from [AMI 13])*

1.2.3.5. *Linear energy transfer*

Linear energy transfer (LET) is a quantity that describes the energy transferred by an ionizing particle passing through a material, per unit distance. It varies according to the nature and energy of the ionizing radiation. Typically, the LET is used to quantify the effect of ionizing radiation on biological matrices. LET has an important relationship with stopping power (average energy loss of the particle per distance traveled). The smaller the distance traveled, the greater the energy transfer, and consequently the greater the adverse effects.

1.2.3.6. *Relative biological effectiveness*

Relative biological effectiveness (RBE) is a measure that compares the biological effect of two radiations. To characterize the relative biological effectiveness, the generally accepted reference is X-radiation (X-photon) for a linear energy transfer (LET) of 3 KeV μm^{-1}. The RBE varies with many factors, including the organ exposed and the age at which exposure occurs. The choice of the RBE factor chosen is a delicate one, particularly for alpha emitters and some beta emitters. There is currently no consensus on the subject, and this remains a delicate point of controversy for doses delivered by radionuclides with a short linear path such as tritium. In the literature, RBE values are very variable. These depend on the criteria taken into account (cell death, genetic damage, etc.), the tissue examined, the dose delivered (external or internal), the type of exposure (acute or chronic), and the energy of the alpha or beta particle.

Generally, it is recommended to use an RBE of 20 for stochastic effects in humans and an RBE of 5 for deterministic effects in non-human populations [UNS 96].

Some RBEs can be very high. Thus, for mouse sperm irradiated with ^{210}Po, an RBE of 245 was obtained by Rao *et al*. [RAO 91]. For hematopoietic tissue irradiated by ^{239}Pu, an RBE ranging from 150 to 360 is proposed by various authors [JIA 94; LOR 96]. In addition, alpha particles can trigger genomic instability transmissible to offspring [LIT 98, WRI 98, MOR 11].

Similarly, in the case of tritium, a low-energy beta emitter and until recently considered to be of low radiotoxicity, more and more scientists believe that the RBE of 1 is not appropriate and that an RBE of 2 or even 5 should be used [GAZ 10].

1.2.3.7. *The committed dose*

The committed dose for a single absorption of a given radionuclide is the total dose that the individual concerned will receive over his or her lifetime. It will therefore depend on the actual period. Thus, for iodines 131, 123 and 129, whose effective periods are 7.6 days, 13 hours and 16×10^6 years, respectively, the committed dose will be 13, 0.13 and 30 Gy.

In the case of internal radioactive contamination, assessment of the irradiation dose is more difficult than in the case of external contamination. Indeed, unlike external irradiation, where the dose is delivered in its entirety at the same time, the internal dose is constituted over time and will vary according to the organs and tissues irradiated. This dose is said to be the committed dose and can only be an estimated and calculated quantity. To estimate this committed dose, numerous studies have been initiated. Biokinetic and biophysical models are used to simulate radionuclide transfers through the individual. In addition, the weighting factors described above to account for the energy of different radiations and the different radiosensitivities of each biological tissue will be used to move from the committed dose to the effective dose.

1.2.3.8. *Limits to the estimation of effective doses*

The limitations of estimating effective doses are that this estimate must be modeled, that the microdistribution of radionuclides is not taken into account, that some radionuclides transmute, changing chemical nature, that interactions may exist between radiotoxicity and chemical toxicity, and that there is a high degree of individual variability. In addition, the fact that in human exposure assessment, the effective dose has the same unit (the sievert) as the equivalent dose is confusing.

1.2.3.9. *Dose rates*

The dose can be delivered to the body in a single dose, or in several doses, or it can be delivered continuously over a long period of time. As with other pollutants, the dose will be referred to as a chronic or acute dose. This will result in significantly different adverse effects. Thus, for an identical total dose, a high single dose generally causes more harmful effects than a summation of low doses. This results from an easier repair by the body of its affected organelles, cells and tissues, when the dose is delivered repeatedly but over a long period of time. It is also often useful to express doses as dose rates (Gy per time unit or Sv per time unit). The time unit is frequently an hour or a day.

1.2.4. Collective doses

All the quantities described above are individual doses and concern only one individual with his or her habits and life history. It may be interesting to know the exposure of a group or human population by calculating the collective equivalent dose and the collective effective dose. The calculation is simple and consists of multiplying the average (equivalent or effective) dose by the number of individuals in the group or population concerned. The unit of these collective quantities is the human-sievert, denoted by h Sv. These quantities are used in particular to manage groups of workers in order to reduce the collective dose. It should be noted that these collective doses do not take into account individual behaviors in lifestyle and eating habits.

In the case where the reasoning does not concern a single generation but several generations, the quantity used is then the dose commitment. This quantity is calculated as the integral over an infinite time of the dose rate per head. This quantity will be used, for example, in the estimation of the irradiation dose suffered in the case of long-term waste storage.

These two principles are essentially used for radioactive risk management. These are the only values that can be used to judge the implementation of the ALARA optimization principle ("as low as reasonably achievable"). The principle of optimization is a pragmatic approach to be able to act responsibly, consensually and fairly in a context of uncertainty about risk. Apart from the radioactive risk, this principle is also used for some chemical pollutants such as dioxins or biotoxins [AMI 16].

1.3. From dose to adverse effect in non-human organisms (flora and fauna)

For a long time, the protection of the environment from ionizing radiation has been completely ignored. Indeed, the principle was that humans are the most complex animal of all the organisms living on our planet and therefore also the most radiosensitive. Consequently, if humans were protected, *a fortiori* all other living organisms would be protected. Despite the weakness of this reasoning, and even its falsity, it was not until the 21st Century that international organizations became concerned about environmental protection.

In May 2000, the International Commission on Radiological Protection (ICRP) decided to set up a working group to make recommendations on the development of an environmental protection policy and to propose a framework (based on scientific, ethical and philosophical principles) for achieving such protection [ICR 03]. The ICRP recognizes that there is no single or simple definition of "environmental protection". The commission is currently developing the concept of a representative body, which can be identified from specific legal requirements or more general requirements to protect local habitats or ecosystems. This approach is addressed by Copplestone [COP 12].

To date, biota radiation protection has largely focused on limiting deterministic effects, such as reduced reproductive fitness. However, many other harmful effects are produced by ionizing radiation. Various studies show that the magnitude of a biological effect depends not only on the dose, as well as on other factors, including the rate at which the dose is delivered and the type and energy of the radiation delivering the dose [HIG 12].

The ICRP Publication 91, entitled "Cadre pour l'évaluation de l'impact des rayonnements ionisants sur les espèces non humaines", was published in 2003 [ICR 03]. The ICRP has chosen to address environmental protection on the basis of biology and to develop the same approach proposed for the human species in its publications 103 [ICR 07a], 108 and 114 [ICR 08, ICR 09a, LAR 12].

Given the intensification of the global debate on the environmental benefits of different forms of energy production, it would seem imperative that the different practices involved in the nuclear fuel cycle can demonstrate, in a clear and independent manner, their actual or potential impact on the environment [PEN 12].

1.3.1. *The harmful effects of ionizing radiation*

The harmful effects of ionizing radiation can occur at various levels of biological organization from the molecule to the ecosystem [AMI 13]. At the molecular level, all molecules can be affected (Figure 1.7). However, DNA damage will generally have a greater impact when any repair is not sufficiently effective. This will result in effects at the cellular, then the tissue level and ultimately in the development of cancer (Figure 1.8).

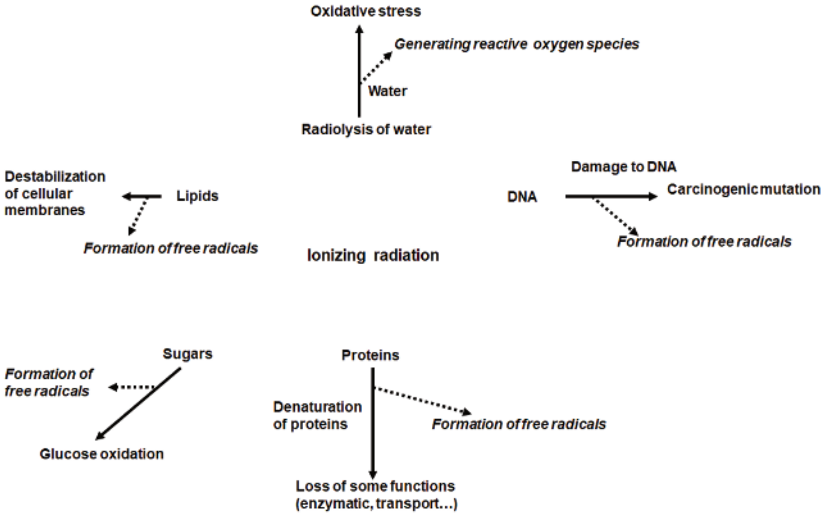

Figure 1.7. *The effects of ionizing radiation at the molecular level (adapted from [AMI 13])*

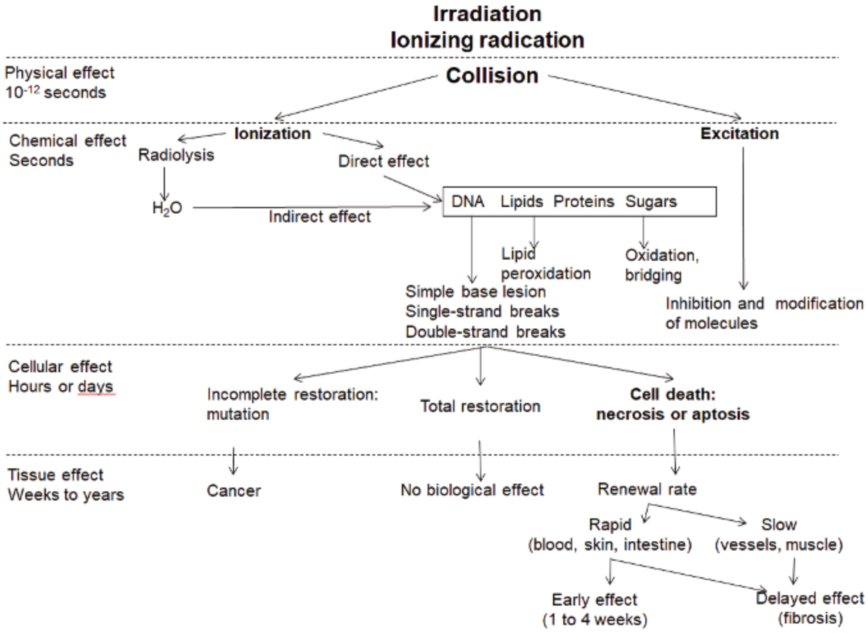

Figure 1.8. *Biological effects of ionizing radiation. Possible changes at the cellular level as a function of time (adapted from [HAT 05])*

1.3.2. *The dose–response relationship*

To estimate the radioactive risk, it is necessary to have a good assessment of the relationship between the dose received and the adverse effect. For all living organisms excluding humans, the dose estimate stops at the absorbed dose and is expressed in grays (Gy).

At high doses of radiation, individuals die. The lethal dose is highly variable depending on the systematic group or taxon to which the organism belongs. The first groups to appear on earth are apparently the most radioresistant, such as prokaryotes including bacteria. Conversely, vertebrate groups, and particularly mammals, are the most radiosensitive (Figure 1.9).

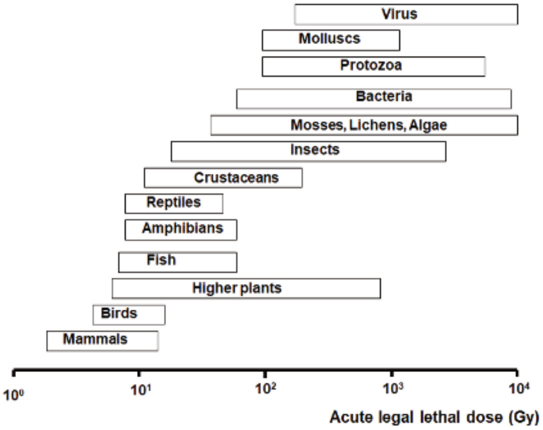

Figure 1.9. *Lethal dose (LD_{50}) and radioresistance in several taxonomic groups [UNS 96])*

Among vertebrates, fish, amphibians and reptiles are more resistant than other groups, and in each group, adults are more resistant than juveniles (Table 1.6 where the LD50 is the death of half the population.). It is generally accepted that for all living organisms, the adverse effect will be greater when the radiation dose is higher.

The sub-lethal effects of ionizing radiation generally occur at doses lower than those causing mortality. For example, acute and chronic doses resulting in sterility in invertebrates and vertebrates are provided in Table 1.7, and at Soviet sites, plants and animals chronically exposed to various doses have a wide range of adverse effects (Table 1.8).

Taxonomic group	**LD_{50} (Gy)**	**Taxonomic group**	**LD_{50} (Gy)**
Fish		**Reptiles**	3–17
Juveniles	0.16–5	**Birds**	5–23
Adults	3.75–100	**Mammals**	
Amphibians		Humans	3
Juveniles	10	Others	1.6–15
Adults	7–23		

Table 1.6. *Lethal dose ranges (Gy) in vertebrates (adapted from [HAR 01])*

Taxonomic group	**Acute exposure Dose (Gy)**	**Taxonomic group**	**Chronic exposure Dose (Gy)**
Invertebrates		Invertebrates	
Neanthes arenaceodentata (polychaete worm)	50	*Neanthes arenaceodentata*	20
Artemia salina (brine shrimp, crustacean)	21	*Daphnia magna* (water flea, crustacean)	1,400
Physa acuta (freshwater gastropod mollusk)	1,000		
Fish		Fish	
Oryzias latipes	80	*Oryzias latipes*	140
		Ameca splendens	>0.6
		Poecilia reticulata	13
		Reptiles	
		Crotaphytus wislizenii	0.46–0.57
		Cnemidophorus tigris	0.23–0.28
		Uta stansburiana	>0.46
Mammals		Mammals	
Mice	1	Dogs	0.17
Rats	8		
Monkeys	>20		
Humans (males)	2–6	Humans (males)	0.23
Females	3–10		

Table 1.7. *Induction of sterility in invertebrates and vertebrates after acute and chronic exposure (adapted from [HAR 01])*

Dose rate (µGy h^{-1})	**Biological effect on representative organisms**
< 0.04	No adverse effects
0.04–4	No data available
4–20	Minor cytogenetic effects in sensitive vertebrate species
20–80	Minor morbidity effect threshold for sensitive vertebrate species
80–200	Threshold of minor effect on reproductive organs in vertebrate species; decrease in embryo survival
200–400	Vertebrate lifetime threshold; invertebrate effect threshold; pine growth effect threshold
400–4,000	Chronic radiation diseases in vertebrates; considerable damage to pines
4,000–40,000	Diseases resulting from acute radiation in vertebrates; death of pines; considerable damage to invertebrate eggs and larvae
>40,000	Lethal dose to vertebrates if received over several days; increased mortality of eggs and invertebrate larvae; death of pines; damage to deciduous trees

Table 1.8. *Review of dose–response relationships for chronic exposure of wild flora and fauna to low-LET radiation observed in situ at Soviet sites (adapted from [SAZ 05])*

1.3.3. *Recommended threshold values*

The evolution of the concepts, doctrines and recommendations of the ICRP was analyzed and detailed by Clarke and Valentin [CLA 09].

UNSCEAR [UNS 08] recommends a dose rate limit of 400 µGy h^{-1} for terrestrial plants and aquatic organisms and 100 µGy h^{-1} for terrestrial animals (Table 1.9). As part of the ERICA project on radioactive risk assessment for terrestrial, limnic and marine fauna, Garnier-Laplace *et al.* [GAR 10] proposes a unique value of 10 µGy h^{-1} (87.6 mSv y^{-1}).

Groups	**ENEV (Gy y^{-1})**
Fishes	0.2
Benthic invertebrates	2
Algae	1
Macrophytes	1
Mammals	1
Terrestrial plants	1
Terrestrial invertebrates	2

Table 1.9. *Summary of estimated no-effect values (ENEV) by Health Canada (adapted from [UNS 08])*

ICRP Publication 108 ([ICR 08]) introduces the concept of reference animals and plants. It reviews current knowledge on the effects of radiation on these biotic types (or similar organisms for which more precise data are not available) with regard to the effects of mortality, morbidity, reduced reproductive success and chromosomal damage. This publication identifies preliminary reference levels for reference animals (deer, rat, duck, frog, trout, flatfish, bee, crab and earthworm), as well as for reference flora (pine, wild grasses and brown algae) ([ICR 08]). The threshold values are grouped in Table 1.10.

	Reference body	**Initial threshold (µGy h^{-1})**
Plants	Pine	4–40
	Wild grass	40–400
Animals	Bee	400–4,000
	Earthworm	400–4,000
	Duck	4–40
	Fallow deer	4–40
	Rat	4–40
Freshwater organisms	Frog	40–400
	Trout	400–4,000
Marine organisms	Crab	400–4,000
	Flatfish	40–400
	Brown algae	40–400

Table 1.10. *Effect threshold in µGy h^{-1} for chronic exposure situations (adapted from [ICR 08])*

To strengthen the international radiological protection system, the ICRP had to develop dosimetric models for a set of reference animals and plants, representative of flora and fauna in different environments (terrestrial, freshwater, marine), and had to define criteria based on the information on radiation effects [TEL 15].

Through several examples, Garnier-Laplace *et al.* [GAR 15a] consider it necessary to implement an approach combining laboratory models and field studies to obtain reference doses (or dose rates) based on reliable scientific data. The analysis should be based on a meta-analysis of dose–response relationships covering various scales of exposure time, several species and ecologically relevant endpoints.

1.4. From dose to adverse effect in humans

The effects of ionizing radiation on humans result from a transfer of energy to human tissue leading in several successive stages to pathological manifestations. These steps are physical interactions, physic chemical reactions, molecular damage, cellular damage, tissue damage and pathological effects [GAM 07].

1.4.1. *Deterministic and stochastic effects*

Exposure to ionizing radiation leads to two types of effect: deterministic and stochastic. Deterministic manifestations are generally related to radiation-induced cell death. Stochastic manifestations are generally attributed to mutations.

Stochastic effects are the long-term probabilistic consequences, in an individual or in his or her offspring, of the transformation of a cell. Stochastic effects are of two types: carcinogenic (somatic cells) or hereditary (germ cells). The harmful effects of ionizing radiation can occur at the molecular and cellular levels. If germ cells are affected, human fertility may decrease until sterility.

Deterministic effects are definitely occurring. They usually occur rapidly and increase in severity with dose. These are threshold effects and only appear above a threshold dose. In humans, the generally accepted threshold value is 0.5 Gray (Gy). The risk of death appears at 2 Gy. The LD_{50} (lethal dose for 50% of the exposed population) is 4.5 Gy.

Deterministic effects differ depending on whether the exposure is global (i.e. at the level of an individual) or partial (i.e. affecting only a part of the body). In the case of overall exposure, it is the radiosensitive organs (bone marrow, intestinal mucosa, respiratory system) that will determine the vital prognosis. The most serious disease is acute radiation syndrome (ARS), which includes all pathological manifestations occurring after significant overexposure to ionizing radiation. The ARS is traditionally described as appearing in three phases (see [AMI 13]).

1.4.2. *Dose–response relationships for average doses: epidemiological studies*

For high doses, the main data come from effects observed, particularly following accidents or explosions in Hiroshima and Nagasaki. This has been detailed in Volume 1 of this series [AMI 18a].

In the case of medium doses, the effects are stochastic and can only be understood by epidemiological studies. In epidemiology, there are mainly three types of studies, aggregate studies, case–control studies and cohort (or prospective) studies. The last two types are analytical studies. Aggregate studies are the most frequent but generally provide less information. Cohort studies are more powerful because the population studied is more homogeneous. More details are provided in [AMI 16].

The power (or resolution) of epidemiological studies depends on many parameters, the most important of which is the size of the populations studied. This is the reason for the appearance of multiple meta-analyses which consist of merging several epidemiological studies with each other. There are also many possible biases for epidemiological studies. One of the most common is the wrong choice of control group or unexposed population compared to the exposed population.

Confounding factors (or co-factors) are also numerous, especially if the study is long-term. For example, the effects of radiation and smoking are linked for a large number of diseases. It is therefore necessary to apply corrective factors to eliminate the influence of confounding factors.

The analysis of epidemiological studies uses a large number of statistical tools such as the relative risk (RR), the excess relative risk (ERR) or the odds ratio (OR), the standardized mortality ratio (SMR) or the standardized incidence ratio (SIR). The details are provided in Amiard [AMI 16].

The fact that a correlation is positive does not mean that there is a real causal relationship between these two parameters. This shortcut is too frequently noted, and as the sophism "*Cum hoc ergo propter hoc*" (Latin, meaning "with this, therefore because of this") says. It is common to claim that if two events are correlated, then there is a causal relationship between the two. This confusion between correlation and causality is absolutely forbidden.

In the nuclear field, the main epidemiological studies have focused on populations of nuclear workers, including uranium miners, populations living in the vicinity of nuclear power plants and other nuclear facilities, particularly children, the military and civil populations around atomic test sites, populations living on primary massifs, particularly granitic ones, which are rich in radon, and populations living in areas where natural radioactivity is high. The main results concerning epidemiological studies following military and civil nuclear accidents are provided by the Amiard volumes [AMI 18a, AMI 19]. All epidemiological studies will be detailed in the fifth volume of this series (*Radioactive Risk to Humans*).

1.4.3. *Responses to low doses*

In the case of low irradiation doses, epidemiological studies generally cannot provide any usable results because they are at the limit of the significance of excess damage resulting from irradiation compared to naturally occurring damage [ANC 12], particularly caused by the problem of co-factors.

The effects of low doses can be addressed using results from experimental disease models (animal studies and cell cultures) that provide information on the biological mechanisms concerned. While molecular biological techniques allow DNA damage to be detected, there are repair mechanisms (hormesis and apoptosis), even though there is no 100% guarantee of repair.

From the morbidity results recorded in populations generally irradiated at moderate to high doses (epidemiological studies), it is possible to extrapolate the dose–effect relationship to low doses according to four curves (Figure 1.10). The four scenarios are (1) linear without threshold, (2) infra-linear, (3) supra-linear or (4) linear with threshold. Scenario 2 involves hormesis and is optimistic. Scenario 3 involves the proximity effect and is pessimistic. Scenario 4 uses a threshold and is also optimistic. Moreover, as a precautionary measure, the agencies responsible (ICRP, WHO, etc.) have chosen to carry out a linear extrapolation of the dose–response relationship.

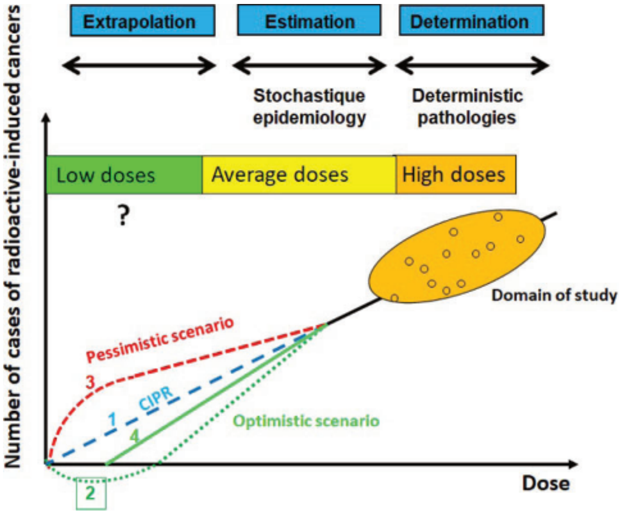

Figure 1.10. *Diagram showing the principle of extrapolating the dose–effect relationship from the data obtained for high doses (adapted from Amiard, 2013). 1. Linear without threshold; 2. Infra-linear (hormesis); 3. Supra-linear (proximity effect); 4. Linear with threshold. For a color version of the figure, see www.iste.co.uk/amiard/nuclear.zip*

The relationship between low doses of radiation and their consequences in terms of morbidity and mortality has been the subject of much controversy as many questions remained unanswered. What is the relationship between the adverse effect and low radiation? Is there a threshold or not? Is the dose versus effect relationship linear or nonlinear? Is the hormesis phenomenon generalizable? What are the consequences of proximity effects (bystander), that is, the stress of cells neighboring the one that has been irradiated, on the appearance of morbidity? These key questions will be discussed in the following sections.

1.4.3.1. *Responses with or without threshold, controversy*

Masse [MAS 00] believes that the choice of non-threshold linearity mainly derives from a weakness in dosimetric estimates and that once this poor quantification of doses is removed, another alternative will be possible. In 2002, Masse [MAS 02] pointed out that there is no known pathogenic effect induced in humans by low dose rates up to 100 mSv per year and that the effects attributed to low exposures are the result of extrapolations. In addition, many adverse effects are attributed to exposure to ionizing radiation, whereas they are likely to be due to real health effects in populations in distress and are attributable to social disorganization, deficiencies and possibly other environmental factors. The ICRP report [ICR 05b] concludes that while the existence of a threshold at a low dose of radiation does not seem unlikely for cancers of certain tissues, the evidence does not support the existence of a universal threshold. The linear no threshold (LNT) relationship hypothesis, associated with an uncertain DDREF (Dose and Dose-Rate Effectiveness Factor) for extrapolation from high doses, remains a conservative basis for radiation protection at low doses and low dose rates.

However, three reports on the effects of low radiation doses were published between December 2004 and July 2005 [TUB 06a, TUB 06b]. These are the ICRP report [ICR 05b], the joint report of the French Academies of Science and Medicine [TUB 05] and a report of the American Academies of Science [NRC 05]. Despite the fact that these reports are based on the same studies of the biological effects of low doses, their conclusions differ significantly. The French report concludes that recent biological data show that the effectiveness of defense systems is modulated by dose and dose rate and that the linear non-threshold relationship is implausible. On the contrary, the ICRP and BEIR VII (NRC) reports, while acknowledging that there are biological arguments against the linear no-threshold relationship (LNTR), consider that there is insufficient biological evidence to counter and change the risk assessment methodology and current regulatory policy based on the LNTR.

Tubiana *et al.* [TUB 07] believe that multicellular organisms are more effective in defending against ionizing radiation at low doses (oxidative stress, apoptosis, etc.) than at high doses. However, they acknowledge the lack of mechanistic explanations of phenomena such as hypermortality at low doses or adaptive response (i.e. better tolerance to radiation doses).

These authors believe that the epidemiological and experimental data challenge the validity of the LNTR hypothesis to assess the carcinogenic effect of low doses, but do not allow its exclusion. Therefore, the main criteria for selecting the most scientifically reliable dose–response relationship should be based on biological data. Their analysis should help an understanding of the current controversy.

However, the controversy is becoming increasingly vigorous. Thus, in February 2015, a request was submitted to the US Nuclear Regulatory Commission (NRC) to reject the linear no-threshold (LNT) assumption as the basis for regulating radiation protection and to promote the use of threshold and hormesis evidence [GLA 18]. There are many authors who refute the LNT (e.g. [CAR 18]). We should note that this controversy concerns only the occurrence of cancers. However, the effects of irradiation are not limited to this type of morbidity alone. This is particularly the case for cardiovascular diseases, where the relationship between low-dose ionizing radiation and this pathology is not fully understood [DIN 17]. These conflicts demonstrate that our knowledge of the effects of low ionizing radiation is far from complete [BAL 15].

1.4.3.2. *Linear or nonlinear responses? Non-monotonous responses*

For a long time, toxicology was based on a premise expressed during the Renaissance by Paracelsus: “All things are poison and nothing is without poison, only the dose makes the poison.” This meant that the adverse response was dose-dependent. There had to be a linear relationship. Toxicologists knew of a few exceptions where the toxicant acted at low doses and there were few effects at high doses such as arsenic. Since then, this certainty has been invalidated in several circumstances. This is particularly the case for endocrine disruptors that act at low doses and little at high doses [AMI 17]. Responses are then qualified as non-uniform. Is this non-monotonic relationship also applicable to low radiation doses? As shown in Figure 1.10, at low doses, the dose–response relationship can take four forms. The debate remains very lively on these various solutions [RHO 11].

1.4.3.3. *Hormesis or restorative power*

The term hormesis is used to describe a stimulation of biological defenses in organisms exposed to low doses of different physical or chemical stressors, which is obviously likely to impact the dose–response curve.

However, it has not been fully established whether hormesis is a common and important phenomenon. Indeed, the idea that the effects of low doses may be zero is otherwise accepted, but the concept that the effect of low doses is positive is doubtful for many authors. One of the areas where hormesis is best studied is the effects of radiation [AGA 18].

Hormesis is based on the concept that a low dose of radiation received previously can protect the victim. This phenomenon would correspond to an "adaptive" response. Radiation adaptation occurs when cells subjected to low prior irradiation and then undergo higher irradiation doses without developing any harmful effects. A low dose (a few tens of mSv), delivered a few hours before a higher dose irradiation, reduces the effect (especially mutagenic) of this second dose, and could therefore reduce the risk of cancer. Rodgers and Holmes [ROD 08] observed this phenomenon of radio-adaptation for mice subjected *in situ* to various doses of radiation in the Chernobyl exclusion zone. For their part, Møller and Mousseau [MØL 16], analyzing 17 studies, found that only one experimental study met the criteria for evolutionary adaptation. Finally, they concluded that they did not detect any evidence of hormesis. The lack of evidence of adaptation is mainly a result of the lack of replication and rigor in the experimental design. In particular, most studies were based on transplants with organisms from a limited number of sites.

The mechanisms responsible for radio-adaptation are complex and involve more intense activation of repair systems, the action of certain cytokines (e.g. interleukins I) and the slowing of the cell cycle. The interpretation would be that the initial low dose led to the initiation of repair processes, making it possible to limit the toxic effects of the high dose delivered at a later stage. To what extent can this phenomenon lead to "protection" in human clinical practice? To date, the answer is not known with any precision.

The literature on hormesis is abundant. However, the phenomenon is also controversial. Some authors consider this phenomenon to be important. Under certain conditions, according to Shibamoto and Nakamura [SHI 18], low-dose radiation can have beneficial effects and the LNT theory may be outdated. Kudryashevaa and Rozhkob [KUD 15], who studied the bioluminescent response of microorganisms to irradiation with americium 241 or tritium, observed three successive steps of this response: a first step with no effects (stress recognition); a second step with activation (adaptive response); and a third step with inhibition (suppression of physiological function, i.e. toxicity due to irradiation). If the second step can be assimilated to hormesis, it is canceled by the third step.

On the contrary, Sugie *et al.* [SUG 16] consider that they do not have enough data to confirm a hormesis phenomenon in human salivary cells. In addition, the concept of hormesis should be applied with caution, as hormetic stimuli can act without threshold on pre-damaged or atrophic tissues or in synergy with other harmful agents. Experimental evidence in favor of hormesis is considerable, but further studies are needed [JAR 17]. In a recent synthesis, Beyea [BEY 17] considers the linear relationship without threshold to be the most plausible hypothesis.

In their opinions, the National Research Council (NRC) of the United States (part of the National Academy of Sciences), the National Council on Radiation Protection and Measurements (NCRP), a body created by the United States Congress, and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) consider the assumption to be unjustified that any stimulation of the hormesis phenomenon at low doses of ionizing radiation has a significant health benefit for the population, exceeding the potential harmful effects of the irradiation [NRC 06] and this position remains valid to this day.

1.4.3.4. *Non-target effects, proximity effects, genomic and epigenetic instability*

Recently, studies have shown that living organisms respond to ionizing radiation not only through direct reactions at the DNA level, but also indirectly with non-targeted effects (NTE). Bright and Kadhim [BRI 18] review the different types of NTEs and their potential implications for radiobiology research and applications. The best known NTEs are genomic instability, neighborhood effects and epigenetic phenomena. Non-targeted effects must be considered, and modeling experimental and epidemiological approaches could all be used to determine the impact of non-targeted effects on the linear non-threshold model currently used in radiation protection [MOT 18].

The bystander effect corresponds to responses induced by ionizing radiation in directly irradiated cells and also in neighboring cells that have not been affected by ionizing radiation and the corresponding energy deposition. These neighboring cells therefore react to a soluble signal secreted by the irradiated cells [COA 04, MOR 07, ERM 11].

The proximity effect is well demonstrated and predominates at low doses (0.2 Gy). At higher doses, the response is overwhelming. This effect is of obvious interest for estimating the risk due to ionizing radiation [PRI 03]. Examples of neighborhood effects have recently been published. Thus, depleted uranium (DU) plays a role in both toxic and neoplastic "neighborhood effects" on human osteoblastic cells (HOS) [MIL 17]. The proximity effect is demonstrated in fish. Moreover, this effect is triggered even though only one parent is irradiated and it persists two generations after the irradiated generation [SMI 16].

The radiation-induced bystander effect (RIBE) presents potential risks for normal tissues in radiotherapy and confers a higher risk of low radiation doses than we previously thought [WAN 15].

The instability of the genome induced by irradiation is well documented for cells and organisms directly exposed [MOT 16]. This instability has also been observed in neighboring but non-irradiated cells. Enigmatically, increased instability is even observed in the offspring of pre-conceptionally exposed animals, as well as in humans [MOR 11]. Twenty years after the Chernobyl accident, the liquidators are highly unstable in genomics. The effects of irradiation are still clear at the cytogenetic and molecular levels [MEL 07].

In recent years, the discovery of epigenetic changes in chromatin, such as DNA methylation, following exposure to very low doses of radiation has been well documented [SCH 18].

Non-targeted effects represent a paradigm shift from the "DNA-centered" vision that ionizing radiation only produces biological effects and health consequences as a result of energy deposition in the cell nucleus [MOR 15].

1.5. Radiation protection and recommendations for human irradiation

Radiation protection or radiological protection is a discipline applied to protect humans from ionizing radiation. This science is based on three fundamental principles [MÉT 97, DEL 06, MÉT 06]. The simultaneous application of these three principles is necessary.

The first principle is the justification of practices. No practice can be adopted if it does not provide a sufficient benefit to exposed individuals or society.

The second principle is the optimization of protection. It led to the precautionary adoption of the linear dose–response relationship without threshold. In this context, since any irradiation is likely to have an effect, for any source associated with a practice, the level of individual doses, the number of persons exposed, and the probability of exposure should be kept as low as reasonably achievable, taking into account economic and social factors. This is the principle of ALARA (As Low As Reasonably Achievable) optimization [AMI 16].

The third principle is the limitation of exposure. No individual shall be exposed to a level of risk that is unacceptable under normal practices and circumstances.

In humans, a comparison of various natural and artificial exposures can be made (Figure 1.11).

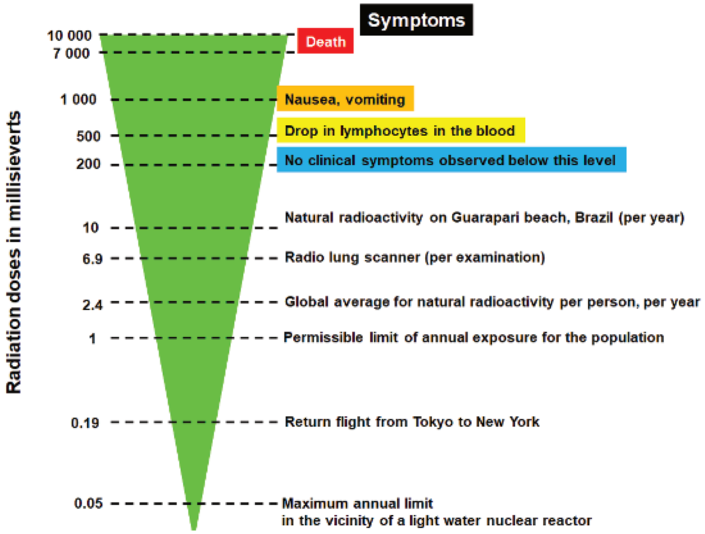

Figure 1.11. *Human exposure and health (adapted from [AMI 13]). For a color version of the figure, see www.iste.co.uk/amiard/nuclear.zip*

Following exposure to low-dose or low-dose rate ionizing radiation, the main radiation risk is cancer [WAK 12].

In the 2007 ICRP recommendations, a higher risk coefficient is assigned to the general population compared to the adult population because this group includes children, a sub-population with higher radiosensitivity and a longer lifespan. The argument was whether to set a lower reference level for children only [SAK 12].

Deterministic effects are often referred to as "tissue reactions". Threshold doses have been defined for practical reasons with an incidence of 1% [HEN 12].

The ICRP [ICR 91] proposed probability coefficients for irradiation of 10 mSV (Table 1.11), and in 2007 [ICR 07a], it proposed new exposure limits for two categories of humans, nuclear workers and the public (Table 1.12).

	Detriment (10^{-2} Sv^{-1})			
Exposed population	Fatal cancer	Non-fatal cancer	Severe hereditary effects	Total
Nuclear workers	4.0	0.8	0.8	5.6
General population	5.0	1.0	1.3	7.3

Table 1.11. *Nominal probability coefficients for stochastic effects (adapted from [ICR 91])*

Limit type	**Nuclear workers**	**Public**
Effective dose	20 mSv y^{-1}, averaged over 5 years	1 mSv y^{-1}
Annual equivalent dose		
The eye's crystalline lens	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	-

Table 1.12. *Recommended dose limits in planned exposure situations (adapted from [ICR 07a])*

The European Directive no. 96/29/Euratom adopted on May 13, 1996 sets out the basic standards for the protection of the health of the population and nuclear workers against the dangers arising from ionizing radiation (OJ C.E.O. no. 159 of June 29, 1996). The annual effective dose limits are 1 mSv for the public and 100 mSv for workers for five consecutive years and at most 50 mSv y^{-1}. The equivalent dose to the skin is 50 mSv for the public and 500 mSv for workers.

The Brochure of the Journal Officiel de la République Française (J.O.) no. 1420, *Protection contre les rayonnements ionisants*, gathers all the legislative and regulatory texts on radiation protection, in particular Decree No. 88-521 of April 18, 1988 amending the Decree of June 20, 1966 on the general principles of radiation protection and Decree No. 86-1103 of October 2, 1986, as amended, on the protection of workers against the dangers of ionizing radiation and its implementing regulations.

Revisions of standards

The standards are reviewed regularly and more generally in a more drastic way. Thus, the ICRP of April 21, 2011 called for a lowering of the threshold for the appearance of induced cataracts to 0.5 Gy, and the annual dose limit equivalent to 20 mSv for nuclear workers. This was recorded in December 2013 by Euratom.

For workers likely to be exposed, the Directive introduces an annual effective dose limit of 20 mSv, replacing the value of 100 mSv over five consecutive years. As early as 2003, this limit was included in the Labor Code (20 mSv over 12 consecutive months). However, the equivalent dose limit of 150 mSv over 12 consecutive months for the lens of the eye should be modified to 20 mSv per year [BEH 14].

1.6. Risk perception

The risk assessment results in a probability of an adverse effect such as death for a number X of individuals. The public has great difficulty grasping the meaning of probabilities that refer to an event whose occurrence is uncertain. It should be noted that substantial risks arising from addiction (to tobacco, alcohol, etc.) or common actions (driving, etc.) are greatly underestimated by the public, while on the contrary, low or unproven risks in unfamiliar areas (genetically modified organisms, electromagnetic waves from connected electricity meters, etc.) generate great concern.

The public is increasingly suspicious of the management of nuclear activities. However, public trust is a prerequisite for effective environmental management of hazardous sites and their rehabilitation. Without trust, it is unlikely that such institutions can effectively convince the public that a site is safe and can be reused. Public confidence depends on its proximity to the hazardous waste site, as well as on economic dependence, directly or indirectly, on the nuclear site.

1.6.1. *Probability of a future nuclear accident*

The probability of an accident follows a binomial probability law. The probability of a severe accident is calculated based on various findings. In 1986, the world total consisted of 450 reactors (143 of which were in Europe). These have undergone four core meltdowns followed by a massive release of radioactive elements (Chernobyl unit 4 and Fukushima Daiichi units 1, 2 and 3) over a cumulative operating life of 14,000 reactor years. The observed accident frequency is therefore 4/14,000 or about 0.0003. The probability that there will be no major accidents in 30 years' time in Europe is about 0.28 per year per reactor. The probability of an accident within 30 years in Europe is therefore 0.72 [LÉV 13b]. The same calculation of the probability of an accident in Europe for next year gives the result of 0.042, that is, almost four chances (or rather bad luck) per 1,000.

However, there are several biases in this calculation. First of all, the number of core meltdown accidents is not four, but varies according to the authors' more or less complete censuses. Amiard [AMI 19] lists 12 important core mergers. Cochran and McKenzie [COC 11] reported 25 core meltdown accidents, adding 13 additional accidents (Experimental Breeder Reactor-I, Stationary Low-Power Reactor No. 1, Enrico Fermi Reactor-1, Ågesta, Dresden-3, Hatch-1, Surry-1, Arkansas Nuclear One-1, Oyster Creek, Atucha-1, Limerick-1, Pickering A-1 and Hadden Neck), but excluding the Windscale accident in 1957.

Nuclear power plants containing several reactors (such as Fukushima) present multiple risks. In addition, the territory available per nuclear reactor is very small in Korea compared to Canada (Table 1.13) [SEO 18].

Country	**Number of reactors**	**National territory area per reactor (km^2)**
Korea	28	3,561
Japan	45	8,398
France	59	10,912
United States	104	94,487
China	55	174,490
Canada	19	525,509

Table 1.13. *National territory area for each nuclear reactor (adapted from [SEO 18])*

1.6.2. *Countries using or renouncing the use of nuclear energy*

The position of countries with regard to the use of nuclear energy is very variable. Some countries do not use nuclear energy and do not intend to do so in the medium term. Thus, in Africa, with the exception of South Africa, no country has nuclear reactors. In South America, only Argentina and Brazil have nuclear power plants. In the Middle East, only Iran and Israel have nuclear electricity, but other countries are considering developing this energy source (Iraq, Egypt, Turkey, etc.). Some countries have even included the non-use of nuclear energy in their national legislation. These are Australia, Denmark, Greece, Ireland and Norway.

Several countries have abandoned nuclear energy. Thus, the phaseout of civil nuclear power has been implemented in Austria (1978), Sweden (1980), Italy (1987), Belgium (1999), Germany (2000), Switzerland (2011) and the province of Quebec (2013). It is discussed in other countries such as Spain. However, situations change over time. For example, in February 2009, Sweden lifted its moratorium on the construction of nuclear power plants. It should also be noted that Austria imports about 5% of its nuclear electricity consumption.

To date, some countries such as France, Finland, Sweden, the United Kingdom, Russia, China, the United States, South Korea, India and Iran have maintained the use of nuclear energy for electricity generation.

In addition, various countries such as Abu Dhabi, Poland, Turkey and Saudi Arabia are expected to acquire nuclear reactors in the short term.

1.6.3. *Opinion polls on nuclear power*

Among the 10 potential disasters that could impact life on earth, respondents believe that the most likely are nuclear war in the second place and nuclear accidents in the third place [MÖR 15].

The societal impact is not limited to areas directly impacted by the nuclear accident. For example, Visschers and Siegrist [VIS 13] conducted two surveys in Switzerland, one conducted five months before the accident and the other conducted directly after the Fukushima accident, using a longitudinal study (790 people surveyed). They assessed the acceptance, perceived risks, perceived benefits and confidence associated with nuclear power plants. In their model, the perceived benefits and risks determined the acceptance of nuclear power plants before and after Fukushima. Trust has had a strong impact on both perceived benefits and risks. People's confidence before Fukushima strongly influenced their confidence after the accident. In addition, the benefits received before Fukushima were correlated with the benefits received after the accident. Thus, the nuclear accident did not appear to have changed the relationships between the determinants of acceptance. Even after a serious accident, the public can still consider the benefits to be relevant, and trust remains important in determining their perceptions of risks and benefits. A public debate on the benefits of nuclear energy seems to have an impact on public acceptance of nuclear energy, even after a nuclear accident.

The negative opinion of Nevada (United States) residents regarding a radioactive waste disposal site at Yucca Mountain depends on subjective risk factors, in particular the perceived severity of the risk for future generations. Perceived risks depend in part on the trust placed in the Department of Energy to manage the security of deposits. Opposition to this local waste disposal did not decrease significantly when the authorities proposed various compensations paid annually. This opposition did not change regardless of the value of the compensation offered to residents ($1,000, $3,000 or $5,500 per year for 20 years) [KUN 90].

The nuclear accidents at Three Mile Island and Lucens had no negative global impact on the construction of new nuclear reactors. On the contrary, the Chernobyl accident considerably slowed down the construction of new nuclear power plants. It appears that an accident is likely to have a negative and lasting impact in the country where it occurred, and perhaps in countries affected by the direct consequences, or when governments are under strong public pressure [CSE 13].

On the contrary, the Fukushima accident had a major impact on Japanese public opinion of nuclear energy. Negative feeling began in June 2011, just after the accident, and continued for at least one year (Figure 1.12).

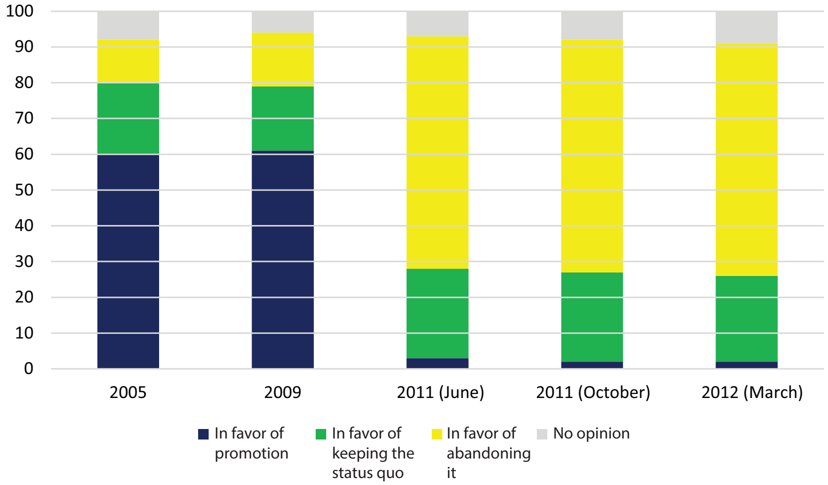

Figure 1.12. *Japanese public opinion trends on nuclear energy (adapted from [HAS 13]). For a color version of the figure, see www.iste.co.uk/amiard/nuclear.zip*

In the United States, in 1965, 60% of Americans surveyed were in favor of nuclear energy. After the Three Mile Island accident, the number of Americans in favor of nuclear reactors dropped to 30% in 1983. Many referendum votes were held between 1976 and 1982 in the United States at the state level. Several votes were against nuclear power plants. This was the case in Montana in 1978, Oregon in 1980, Washington in 1981, Idaho and Massachusetts in 1982. In addition, 11 states passed laws to ban new nuclear reactors between 1976 and 1982 [ANO 84].

More recently, substantial majorities of Americans oppose the location of coal, natural gas and nuclear power plants in their region, although a majority support locating wind farms in their vicinity. The first factor in the release of an energy source is related to the environmental damage it produces [ANS 09].

At the OECD level, in countries with nuclear programs, the risks are perceived by their populations to be lower than those of their counterparts in countries without nuclear energy. However, in only six countries, the majority of respondents consider that the benefits of nuclear energy outweigh the risks it poses. These are Sweden, Bulgaria, the Czech Republic, Estonia, Finland and Slovakia. Strangely enough, the score is highest in Sweden (61%), despite their government's policy of phasing out nuclear energy. Of these six countries, Estonia is the only one that does not have nuclear energy [NEA 10].

The data show that in countries where nuclear energy is already present, the population is generally much more favorable to its use. The temporal trend in public opinion is generally more and more favorable to nuclear energy in the energy mix (this was analyzed before the Fukushima accident). However, nuclear accidents can lead to a rapid reduction in public support for nuclear energy, which recovers only very slowly [NEA 10].

Since 2005 in France, the ASN has set up an opinion barometer to better understand the expectations of the general public, as well as those of an "informed" public made up of professionals. Analyzing this River and Delmestre barometer [RIV 12], they note that despite the fact that 2011 was marked by the Fukushima nuclear accident, public opinion is not changing in its assessments of nuclear power. Thus, 64% of the population is suspicious of nuclear power, 46% say they are powerless in the face of nuclear development and 45% are afraid of it. On the contrary, the Fukushima accident affected the way the French view nuclear safety control in France. At the end of 2010, nearly six out of ten French people (57%) considered the way in which the safety of nuclear power plants was controlled in France to be effective. A few days after the nuclear accident, this confidence dropped by ten points [RIV 12].

In 2010, cancer was the most feared disease by the French population. Behind the already well-identified behavioral risks (tobacco, alcohol, exposure to the sun and artificial UV rays), environmental concerns are increasing. Living near a nuclear facility is considered a risk by nearly 77% of the population. However, general practitioners are very rarely asked about the risks from radioactivity or specifically the radioactive gas radon [MÉN 14].

Among industrial or technological activities, nuclear power plants (22%) once again appear to the French as having the greatest catastrophic potential. In the IRSN 2018 Barometer, the perception of their potential to cause a serious accident deteriorated in this year and was similar to that observed in the 2012 edition, for which the survey was conducted a few months after the Fukushima accident [IRS 18a].

1.6.4. *Estimated risk and perceived risk*

The acceptance of nuclear risk by people living near the US Department of Energy's Savannah River Nuclear Weapons Site (SRS) is influenced by a variety of factors, including personal characteristics, experiences and economic needs. Public confidence is higher among respondents living upstream of the SRS and respondents whose county was economically dependent on the SRS. Similarly, respondents who were predisposed to accept additional hazardous waste or public health risks for economic gain also showed high levels of confidence [WIL 99].

The comparison (in %) of the probability of premature death increases with exposure duration, assuming an average life expectancy at birth of 80 years. Three causes of premature death are examined: tobacco consumption (one pack per day), fine particulate matter $PM_{2.5}$ for the average concentration currently measured in Paris and radioactivity levels of 20 and 100 mSv y^{-1} observed in Fukushima. Two calculations were used for the Paris case, one from the InVS [DEC 12] and the other from Beelen *et al.* [BEE 13]. For Fukushima, the radioactive decay (30 years) of ^{137}Cs has been taken into account (adapted from [NIF 15]). Premature mortality is significantly higher for tobacco and substantially similar for an irradiation dose of 100 mSv and the amount of fine particles in Paris (Figure 1.13).

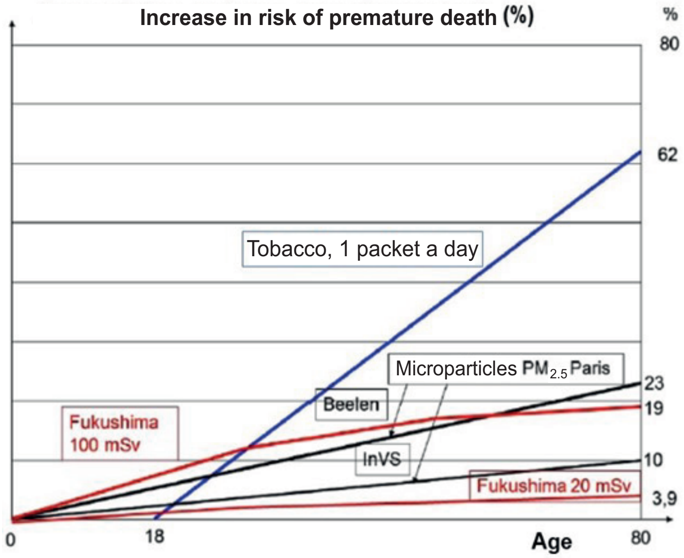

Figure 1.13. *Premature deaths (%) over an 80-year lifetime, based on tobacco consumption (one pack per day), the average concentration in Paris of fine particles PM2.5 and the exposure doses at 20 and 100 mSv y^{-1} observed at Fukushima (adapted from [NIF 15]). For a color version of the figure, see www.iste.co.uk/amiard/nuclear.zip*

1.7. Conclusion

Radioactive risk is estimated like all other risks in several steps beginning with the identification of radionuclide hazards, followed by the quantification of environmental contamination and the estimation of exposure to ionizing radiation. The relationship between dose and adverse effects then makes it possible to estimate the probability of the radioactive risk. Unlike non-human organisms, human exposure estimates are more advanced to take into account the different radiosensitivities of the various organs and the highly variable radiotoxicity of the various radiation types. Uncertainties and controversies exist about the real effects of low doses on the onset of cancers and other diseases. The main controversies concern the existence (or not) of a threshold for effects, whether the dose–response relationship is linear or not (depending on the importance given to the hormesis phenomenon) and non-target (or indirect) effects such as the proximity effect (bystander), genomic instability and epigenetic phenomena.

It should be recalled that radioactive risk management must necessarily follow certain principles. One of them is the principle of optimization (ALARA, as low as reasonably achievable), which is a responsible, consensual and equitable approach in a context of uncertainty about risk. Another important principle that must be applied in the case of a radioactive risk is the precautionary principle, which states that “when the occurrence of damage, although uncertain according to the state of scientific knowledge, could seriously and irreversibly affect the environment, public authorities shall ensure, by application of the precautionary principle, and within their fields of responsibility, that risk assessment procedures are carried out and that provisional and proportionate measures are adopted to prevent the occurrence of the damage.” Case law has even extended the precautionary principle to an area other than the environment, that of health. It is a principle of positive action and not a plea for inaction and abstention [AMI 16]. Other principles must be implemented in the case of a radioactive risk such as the principle of prevention, the principle of equity and proportionality, and the polluter pays principle.

With the exception of uranium, for all radionuclides, radiotoxicity is higher than chemical toxicity.

The effects of ionizing radiation are very varied with many pathologies. Some effects are deterministic and occur with certainty, often rapidly and highly dependent on the dose received. They are associated with a threshold of effect. Other effects are stochastic and only appear with a certain probability and in the long term (up to several decades). There are two types of stochastic effects: carcinogenic effects on somatic cells and hereditary effects involving germ cells.

The ICRP issues recommendations that are regularly updated. Since the 2000s, this organization has taken the same approach for all non-human organisms based on a certain number of reference species, supposedly representative of all biodiversity.

Risk is a concept that is not well understood by the public. It is a probabilistic relationship between a hazard and an exposure. The public's perception of radioactive risk is often far from the estimates made by scientists. This is by no means a privilege of radioactivity and this phenomenon is general for all risks. Perception is indeed dependent on many factors. Thus, a familiar risk (road traffic risk, risk from tobacco or alcohol, etc.) is always reduced in the eyes of the public. On the contrary, a little-known, mysterious or invisible risk will be overestimated. Phenomena such as neighborhood or direct or indirect dependence (employment, etc.) will lead to an underestimation of the risk. On the contrary, a recent event, such as an incident or accident, with significant media coverage, will lead to an overestimation of the risk.