Chapter 15 Radiation in the Environment[1]

Many forms of "radiation" are encountered in the natural environment and are produced by modern technology. Most of them have the potential for both beneficial and harmful effects. Even sunlight, the most essential radiation of all, can be harmful in excessive amounts. Most public attention is given to the category of radiation known as "ionizing radiation." This radiation can disrupt atoms, creating positive ions and negative electrons, and cause biological harm. Ionizing radiation includes x-rays, gamma rays, alpha particles, beta particles, neutrons, and the varieties of cosmic rays.

Radiation Damage and its Study

All ionizing radiations, at sufficiently large exposures, can cause cancer. Many, in carefully controlled exposures, are also used for cancer therapy. Whether harmful or beneficial, exposures to ionizing radiation have been an inevitable part of the environment throughout the Earth's history. The nucleosynthesis processes that produced the elements created both stable and unstable nuclides. The unstable nuclides with very long half-lives, together with their radioactive progeny, constitute the natural radioactivity on Earth today. In addition, violent processes in the sun and elsewhere lead to the bombardment of the Earth by cosmic rays. Thus, radiation is an old and familiar, if unrecognized, pollutant.

However, human awareness of radioactivity and ionizing radiation has only a 100-year history starting with the discovery of x-rays and radioactivity. The first evidence that ionizing radiation could do harm came within months after the discovery of x-rays, when an early x-ray worker developed injuries to his skin. Serious efforts[2] to understand and control radiation exposures started in the 1920s and greatly expanded during and after World War II.

Information on the effects of radiation comes from studies of exposed groups and individuals, from animal experiments, and from studies at the cellular and molecular level. It is now well established that ionizing radiation has both prompt and delayed effects. At very high radiation exposures, death will occur within several months or less. At moderate levels, radiation exposure increases the chance that an individual will develop cancer, with a time delay of ten or more years for most cancers. At low levels, the cancer risk decreases, but the relationship between cancer risk and the magnitude of the exposure is uncertain.

Other effects of radiation, in part inferred from animal experiments, include an increased risk of genetic defects and, for exposures of the fetus before birth, of mental retardation. In terms of frequency of occurrence and severity of effects, cancer is the most serious consequence and receives the greatest attention.

The importance of genetic effects has turned out to be much less than was originally expected. In the words of a 1993 NCRP report: "... the genetic risks have been found to be smaller and the cancer risks larger than were thought (in the 1950s)." Strikingly, no statistically significant genetic effects have been found among the extensively studied children of survivors of the Hiroshima-Nagasaki bombings. On the basis of animal experiments, however, one expects some genetic effects—even if so far not observable above the large background of "natural" defects. In addition, the Hiroshima-Nagasaki studies have shown an increased incidence of mental retardation among children who received large prenatal radiation doses, especially for exposures 8 to 15 weeks after conception.

Units of Radioactivity and Dose

The original unit for measuring the amount of radioactivity was the *curie* (Ci)—first defined to correspond to one gram of radium-226 and more recently defined as:

1 curie = 3.7×10^{10} *radioactive decays per second* [exactly].

In the International System of Units (SI) the becquerel (Bq) has replaced the curie, where
1 becquerel = 1 radioactive decay per second = 2.703×10^{-11} *Ci.*

The magnitude of radiation exposures is specified in terms of the *radiation dose*. There are two important categories of dose:

1. The *absorbed dose*, sometimes also known as the *physical dose*, defined by the amount of energy deposited in a unit mass in human tissue or other media. The original unit is the *rad* [100 erg/g]; it is now being widely replaced by the SI unit, the *gray* (Gy) [1 J/kg], where 1 gray = 100 rad.
2. The *biological* dose, sometimes also known as the *dose equivalent,* expressed in units of *rem* or, in the SI system, *sievert* (Sv). This dose reflects the fact that the biological damage caused by a particle depends not only on the total energy deposited but also on the rate of energy loss per unit distance traversed by the particle (or "linear energy transfer"). For example, alpha particles do much more damage per unit energy deposited than do electrons. This effect can be represented, in rough overall terms, by a *quality factor,* Q. Over a wide range of incident energies, Q is taken to be 1.0 for electrons (and for x-rays and gamma rays, both of which produce electrons) and 20 for alpha particles. For neutrons, the adopted quality factor varies from 5 to 20, depending on neutron energy.

The biological impact is specified by the *dose equivalent* H, which is the product of the absorbed dose D and the quality factor Q: $H = Q\,D$.

The unit for the dose equivalent is the rem if the absorbed dose is in rads and the sievert (Sv) if the absorbed dose is in grays. Thus, 1 Sv = 100 rem. As discussed below, 1 rem is roughly the average dose received in 3 years of exposure to natural radiation. 1 Sv is at the bottom of the range of doses that, if received over a short period of time, are likely to cause noticeable symptoms of radiation sickness.

The dose equivalent is still not the whole story. If only part of the body is irradiated, the dose must be discounted with an appropriate weighting factor if it is to reflect overall risk. The discounted dose is termed the *effective dose equivalent* or just the *effective dose*, expressed in rems or sieverts.

Radioactivity in the Natural Environment

The radioactive nuclei, or *radionuclides*, found naturally on Earth can be grouped into three series—headed by uranium-238, uranium-235, and thorium-232—plus several isolated beta-particle emitting nuclei, most prominently potassium-40 and rubidium-87. Average abundances of these nuclides are listed in Table 15-1.

Table 15-1. Half-lives and average abundances of natural radionuclides.

	^{40}K	^{87}Rb	^{232}Th	^{238}U
Half-life (billion years)	1.277	47.5	14.05	4.468
Upper continental crust				
Elemental abundance (ppm)	28000	112	10.7	2.8
Activity (Bq/kg)	870	102	43	35
Activity (nCi/kg)	23	2.7	1.2	0.9
Activity (kCi/km^3)	66	8	3.3	2.6
Oceans				
Elemental concentration (mg/liter)	399	0.12	1×10^{-7}	0.0032
Activity (Bq/liter)	12	0.11	4×10^{-7}	0.040
Activity (nCi/liter)	0.33	0.003	1×10^{-8}	0.0011
Ocean sediments				
Elemental abundance (ppm)	17000		5.0	1.0
Activity (Bq/kg)	500		20	12
Activity (nCi/kg)	14		0.5	0.3
Human body				
Total activity (Bq)	4000	600	0.08	0.4[a]
Total activity (nCi)	100	16	0.002	0.01

a. In the human body the activity of ^{210}Pb and ^{210}Po, both progeny of ^{238}U, is much greater than that of ^{238}U itself.

The most interesting of the series is the uranium-238 series which decays via a chain containing 8 alpha decays and 6 beta decays to lead-206. This chain includes the longest-lived isotopes of radium and radon: radium-226 and radon-222, respectively. In each of the three chains the parent nucleus has a much greater lifetime than does any of the progeny. Therefore, a steady-state is established in which, for a given sample of material, each member of the series has the same activity—aside from deviations due to differences in chemical properties, which cause different elements to be transferred at different rates into or out of a given sample of material.

Including all the succeeding decays, the total activity in the thorium-232 and uranium-238 series is, very roughly, ten times the activity indicated for thorium-232 and uranium-238 alone. Thus, for each of the series, the total activity in the Earth's crust averages roughly 30,000 Ci/km^3. For both series together and including the contributions of potassium-40 and rubidium-87, the total activity in the crust averages about 100,000 Ci/km^3. There is also a considerable amount of radioactivity in the oceans, with potassium-40 dominant in the ocean itself and thorium-232 relatively more important in the ocean sediments. For the oceans as a whole (1.4 × 10^{21} liters), the total activity is about 4 × 10^{11} Ci for potassium-40 and 1 × 10^9 Ci for uranium-238. Potassium-40 is also present in significant amounts in the human body, especially in muscle tissue.

In addition to these ancient radionuclides and their progeny, some radionuclides are being continually produced by cosmic rays. The most prominent of these is carbon-14, produced in the interaction of cosmic ray neutrons with nitrogen in the atmosphere.

Table 15-2. Average radiation doses in the United States, 1980-1982 (effective dose per year).*

		Effective dose	
Radiation source	**Comments**	**mSv/yr**	**mrem/yr**
Natural sources			
indoor radon	due to seepage of ^{222}Rn from ground	2.0	200
radionuclides in body	primarily ^{40}K and ^{238}U progeny	0.39	39
terrestrial radiation	due to gamma-ray emitters in ground	0.28	28
cosmic rays	roughly doubles for 2000 m gain in elevation	0.27	27
cosmogenic	especially ^{14}C	0.01	1
total (rounded)		3.0	300
Medical sources			
Diagnostic x-rays	excludes dental examinations	0.39	39
Medical treatments	radionuclides used in diagnosis (only)	0.14	14
total		0.53	53
Other			
consumer products	primarily drinking water, building materials	0.1	≈10
occupational	averaged over entire US population	0.01	1
nuclear fuel cycle	does not include potential reactor accidents	0.0005	0.05
TOTAL (rounded)		3.6	360

*From *Ionizing Radiation Exposure of the Population of the United States,* NCRP Report No. 93 (National Council on Radiation Protection and Measurements, Washington DC, 1987).

Typical Radiation Doses

The chief sources of radiation exposure in the United States, as tabulated by the NCRP, are indicated in Table 15-2. The largest single source of exposure is from radon, which is produced in the decay of radium-226 in the soil and enters a house through openings at the base. The "radon" dose arises mostly from the inhalation of the progeny of radon-222, and varies widely from house-to-house depending upon the radium content of the underlying soil, its porosity, and the house construction. The average effective dose of

2.0 mSv/yr (200 mrem/yr) corresponds to the average radon concentration, but there are more than one million homes with radon levels that are more than five times as great. Appendix D has more information on the average annual radiation exposure and its sources that are received by the U.S. population.

Effects of Low Doses

Most of the radiation doses that are received by members of the public and by radiation workers—both routinely and in accidents—are what are commonly referred to as "low doses." There is no precise definition of "low" but it would include doses below, for example, 10 mSv per year. As seen from Table 15-2, the average radiation doses received by people in the U.S. are in the "low dose" region. It is obviously important to determine the effects of low radiation doses—or, more precisely, the effects of small additions to the unavoidable natural background dose.

However, despite much study, these effects are not known, being too small to see unambiguously. The most prominent assumption, accepted by most official bodies, is the so-called *linearity hypothesis*, according to which the cancer risk is directly proportional to the magnitude of the dose, down to zero dose. In applying this assumption a consensus estimate is that the risk to a "typical" individual of an eventual fatal cancer is 0.00005 per mSv (or 0.05 per Sv). Thus, if 100,000 people each receive an added dose of 1 mSv, then 5 additional cancer deaths are to be expected. At the same time, while adopting the linearity hypothesis as a prudent working assumption, many of the leading studies have also indicated the possibility that small increases in radiation dose do not create any additional cancer risk. This reflects the considerable disagreement that exists within the scientific community as to the validity of the linearity hypothesis (see Appendix F).

Effects of Large Doses

Radiation doses above 3 Gy (300 rad) can be fatal and doses above 6 Gy (600 rad) are almost certain to be fatal, with death occurring within several months (in shorter times at higher doses). [Note: Very high doses are commonly expressed in grays, because the standard quality factor is not appropriate. For gamma rays and electrons, 1 Gy corresponds to 1 Sv.] Above 1 Gy, radiation causes a complex of symptoms, including nausea and blood changes, known as radiation sickness. For doses below 1 Sv (100 rem), there is little likelihood of radiation sickness, and the main danger is an increased cancer risk. The most important data base and analyses are from the RERF studies of the Hiroshima and Nagasaki survivors. In these studies, the exposure and medical histories are analyzed for an exposed group (50,113 people) and an unexposed, or minimally exposed, group (36,459 people). Through 1990, there have been 4,741 cancer fatalities in the exposed group, of which 454 are attributed to radiation exposure. There is a statistically significant excess for both solid cancer tumors and leukemia for doses above 0.2 Sv (20 rem). These data, in a succession of updated versions, have provided much of the information used in comprehensive studies of radiation effects.

Nuclear Reactor Accidents

The accidents at the Three Mile Island (TMI) and Chernobyl nuclear reactors have triggered particularly intense concern about radiation hazards. The TMI accident, in Pennsylvania in 1979, resulted from a combination of deficient equipment and operator errors. Even though there was severe damage to the nuclear fuel within the reactor, very little radioactivity escaped into the outside environment. The effectiveness of the large concrete containment building that surrounded the reactor contributed to this relatively small release. Subsequent studies concluded that the maximum dose received by any member of the public was less than 1 mSv (100 mrem). The collective off-site dose is estimated to have been about 20 person-Sv. Under the standard low-dose assumption, this corresponds to one eventual cancer fatality in the neighboring population of 2 million people. (This population receives an annual collective dose of about 6000 person-Sv from natural sources.)

The 1986 Chernobyl accident was far more serious. It occurred in a reactor with an unsafe reactor design unique to the Soviet Union. The reactor had no effective containment, and there was a very large release of radionuclides to the environment. The accident led to the death within several months of 31 reactor personnel and firefighters—28 from a combination of radiation effects and burns from fire, 2 from other injuries, and one from a heart attack. A total of 237 workers were hospitalized for symptoms of radiation sickness, including the 28 who died. A 1996 summary reported additional 14 deaths among the more severely exposed workers, but it is not clear that these deaths were all due to the prior exposure.

There is strong evidence of a substantial increase in thyroid cancers among children living in the vicinity. No other health effects from Chernobyl have been convincing established. However, it is too soon for them to have been fully manifested. Standard calculations of radiation effects predict that there will be a large number of excess cancer deaths among the so-called “liquidators,” who were engaged in cleanup operations after the accident, as well as in the neighboring population.

Considering impacts at greater distances, one early study estimated that the collective dose in the Northern Hemisphere over a 50-year period would be about 930,000 person-Sv. While there is substantial uncertainty in the dose estimate, there is even greater uncertainty as to the impact. If one accepts the linearity hypothesis and assumes 0.05 fatalities per Sv, this dose corresponds to 47,000 eventual cancer fatalities. About 29,000 of these fatalities would occur in Europe (outside the former Soviet Union) due to a cumulative collective dose of 580,000 Sv—an average individual *lifetime* dose of 1.2 mSv for 490 million people. Given these low average doses, any estimate of predicted deaths from Chernobyl is highly speculative. The deaths will not be identifiable, being masked by the 88,000,000 “normal” cancer fatalities expected in this region during the 50-year period.

Criteria for Radiation Protection

The responsibility in the United States for regulation of radiation exposures rests with the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC). There has been a gradual worldwide tightening of the standards for radiation protection. This principle is driven, in part, by the view that it is better to "err on the side of caution" and somewhat more formally by the ALARA principle. As expressed by the ICRP in 1977, the ALARA principle states that "all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account." Current EPA and NRC limits and other recommendations are summarized in Table 15-3.

Table 15-3. Dose standards for radiation exposure in the United States, expressed in terms of annual effective dose.

	Dose limit (mSv/yr)	**Dose limit (mrem /yr)**
Occupational limit	50	5000
General public		
limit for any licensed facility (excluding medical)	1	100
limit for nuclear power facility	0.25	25
limit for waste repository (excluding Yucca Mountain)	0.15	15
NAS recommendation for Yucca Mountain[a]	0.02 - 0.2	2 - 20
EPA recommended "action level" for indoor radon	≈ 8	≈ 800

[a] Converted from the recommendation on risk, assuming risk of 0.05 per Sv.

The NRC imposes a limit of 1 mSv/yr on the effective dose that can be received by any member of the public from a NRC-licensed facility (exempting medical treatments). EPA regulations impose a limit of 0.25 mSv/yr on the effective dose from nuclear power facilities, including nuclear reactors. They provide a still more stringent 0.15 mSv/yr for waste disposal sites under the EPA's authority.

Actual exposures to the public from nuclear power operations are lower than the regulatory limit of 0.25 mSv/yr, and the limit is not presently constraining. It is unlikely to be approached except in the case of an accident, in which case the existence of regulations might be moot. The regulatory limits may, however, provide a spur to careful operation.

Permitted occupational exposures, for nuclear workers and others, are considerably higher than those for the general public—the present US limit is 50 mSv/yr. However, the ALARA principle also applies, and the average dose for nuclear workers is much below this limit.

The EPA has taken only an advisory, but not regulatory, position on indoor radon exposures, because it has no authority over air in private residences. For radon, the EPA suggests that remedial action be taken if the indoor concentration exceeds a level of 4 pCi/liter, corresponding roughly to an effective dose of 8 mSv/yr.

Standards for the proposed Yucca Mountain nuclear waste repository have not yet been established. However, recommendations on the nature of these standards have been made by a congressionally mandated committee working under the auspices of the National Research Council, an agency of the National Academy of Sciences. This committee recommended a limiting risk factor of 10^{-5} to 10^{-6} per year. If one assumes the present conventional risk factor of 0.05 per Sv, this translates to effective doses of 0.2 mSv/yr to 0.02 mSv/yr. This limit is to be applied to the average member of a small "critical group" (probably numbering under 100 people) that is particularly dependent on water contaminated by radionuclide releases from the repository. In the NAS recommendation, this limit would apply for up to 1 million years. Some observers believe that it unreasonable to require this level of protection for a small group of people so far into an unpredictable future.

Perspectives on Radiation Risks

The recommended standards for Yucca Mountain are illustrative of the unusual attention and concern surrounding risks from man-made ionizing radiation. Many reasons have been advanced for this concern, including the connection between radiation and nuclear weapons and the fact that human senses cannot detect radiation.

Ironically, however, it has also been very difficult to detect adverse effects from low-level radiation. The search for radiation effects among populations exposed to moderately elevated radiation levels—inhabitants of regions with high natural levels of radiation, nuclear industry workers (excluding miners), and residents of houses with high radon levels—has not provided any conclusive evidence of excess cancer rates. In a push of the pendulum far to the skeptical side, this creates a temptation to dismiss entirely the hazards of low doses.

It is difficult to find a firmly based middle ground. The available information, taken as a whole, provides no conclusive evidence as to the nature of the consequences at low doses and low dose rates. However, proponents of the linearity hypothesis and of hormesis —as well as believers in a near-zero effect—can find support from individual studies (see Appendix F). Under these circumstances, adopting the linearity hypothesis for purposes of setting radiation limits may be a prudent regulatory expedient. However, it should be recognized that the scientific validity of the hypothesis is not well established.

The current uncertainties highlight the importance of continued studies of the effects of low-level radiation. A better scientific understanding of radiation risks is crucial to the formulation of appropriate protective standards and, more broadly, to the achievement of a responsible balance in assessing the use of nuclear technologies in industry, medicine, and energy production.

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[1] Parts of this chapter and of Appendix F draw upon: David Bodansky, *Nuclear Energy: Principles, Practices, and Prospects* (AIP/Springer-Verlag, New York, 1996).

[2] There are now a many official and semi-official bodies that are concerned with radiation protection. These bodies provide important summary reports and advice. These include the International Commission on Radiological Protection (ICRP), the (US) National Council on Radiation Protection and Measurements