World Nuclear Association

Nuclear Radiation and Health Effects

(*Updated June 2010*)

- **Natural sources account for most of the radiation we all receive each year.**
- **The nuclear fuel cycle does not give rise to significant radiation exposure for members of the public.**
- **Radiation protection standards assume that any dose of radiation, no matter how small, involves a possible risk to human health. This deliberately conservative assumption is increasingly being questioned.**

Radiation is energy in the process of being transmitted, which may take such forms as light, or tiny particles much too small to see. Visible light, the ultra-violet light we receive from the sun and from sun-beds, and transmission signals for TV and radio communications are all forms of radiation that are common in our daily lives. These are all referred to as 'non-ionizing' radiation.

Radiation particularly associated with nuclear medicine and the use of nuclear energy, along with X-rays, is 'ionizing' radiation, which means that the radiation has sufficient energy to interact with matter, especially the human body, and produce ions, *i.e.* it can eject an electron from an atom.

X-rays from a high-voltage discharge were discovered in 1895, and radioactivity from the decay of particular isotopes was discovered in 1896. Many scientists then undertook study of these, and especially their medical applications. This led to the identification of different kinds of radiation from the decay of atomic nuclei, and understanding of the nature of the atom. Neutrons were identified in 1932, and in 1939 atomic fission was discovered by irradiating uranium with neutrons, and this led on to harnessing the energy released by fission.

Types of radiation

Nuclear radiation arises from hundreds of different kinds of unstable atoms. While many exist in nature, the majority are created in nuclear reactions[a]. Ionizing radiation which can damage living tissue is emitted as the unstable atoms (radionuclides) change ('decay') spontaneously to become different kinds of atoms.

The principal kinds of ionizing radiation are:

Alpha particles

These are helium nuclei consisting of two protons and two neutrons and are emitted from naturally-occurring heavy elements such as uranium and radium, as well as from some man-made transuranic elements. They are intensely ionizing but cannot penetrate the skin, so are dangerous only if emitted inside the body.

Beta particles

These are fast-moving electrons emitted by many radioactive elements. They are more penetrating than alpha particles, but easily shielded – they can be stopped by a few millimetres of wood or aluminium. They can penetrate a little way into human flesh but are generally less dangerous to people than gamma radiation. Exposure produces an effect like sunburn, but which is slower to heal. Beta-radioactive substances are also safe if kept in appropriate sealed containers.

Gamma rays

These are high-energy beams much the same as X-rays. They are emitted in many radioactive decays and are very penetrating, so require more substantial shielding. Gamma rays are the main hazard to people dealing with sealed radioactive materials used, for example, in industrial gauges and radiotherapy machines. Radiation dose badges are worn by workers in exposed situations to detect them and hence monitor exposure. All of us receive about 0.5-1 mSv per year of gamma radiation from cosmic rays and from rocks, and in some places, much more. Gamma activity in a substance (*e.g.* rock) can be measured with a scintillometer or Geiger counter.

X-rays are also ionizing radiation, virtually identical to gamma rays, but not nuclear in origin.

Cosmic radiation consists of very energetic particles, mostly protons, which bombard the Earth from outer space.

Neutrons are mostly released by nuclear fission (the splitting of atoms in a nuclear reactor), and and hence are seldom encountered outside the core of a nuclear reactor. Thus they are not normally a problem outside nuclear plants. Fast neutrons can be very destructive to human tissue.

Units of radiation and radioactivity

In order to quantify how much radiation we are exposed to in our daily lives and assess potential health impacts as a result, it is necessary to establish a unit of measurement. The basic unit of radiation dose absorbed in tissue is the gray (Gy), where one gray represents the deposition of one joule of energy per kilogram of tissue.

However, since neutrons and alpha particles cause more damage per gray than gamma or beta radiation, another unit, the sievert (Sv) is used in setting radiological protection standards. This unit of measurement takes into account biological effects of different types of radiation. One gray of beta or gamma radiation has one sievert of biological effect, one gray of alpha particles has 20 Sv effect and one gray of neutrons is equivalent to around 10 Sv (depending on their energy). Since the sievert is a relatively large value, dose to humans is normally measured in millisieverts (mSv), one-thousandth of a sievert.

The becquerel (Bq) is a unit or measure of actual radioactivity in material (as distinct from the radiation it emits, or the human dose from that), with reference to the number of nuclear disintegrations per second (1 Bq = 1 disintegration/sec). Quantities of radioactive material are commonly estimated by measuring the amount of intrinsic radioactivity in becquerels – one Bq of radioactive material is that amount which has an average of one disintegration per second, *i.e.* an activity of 1 Bq.

Older units of radiation measurement continue in use in some literature:
1 gray = 100 rads
1 sievert = 100 rem
1 becquerel = 27 picocuries or 2.7 x 10^{-11} curies
One curie was originally the activity of one gram of radium-226, and represents 3.7 x 10^{10} disintegrations per second (Bq).

The Working Level Month (WLM) has been used as a measure of dose for exposure to radon and in particular, radon decay products[b].

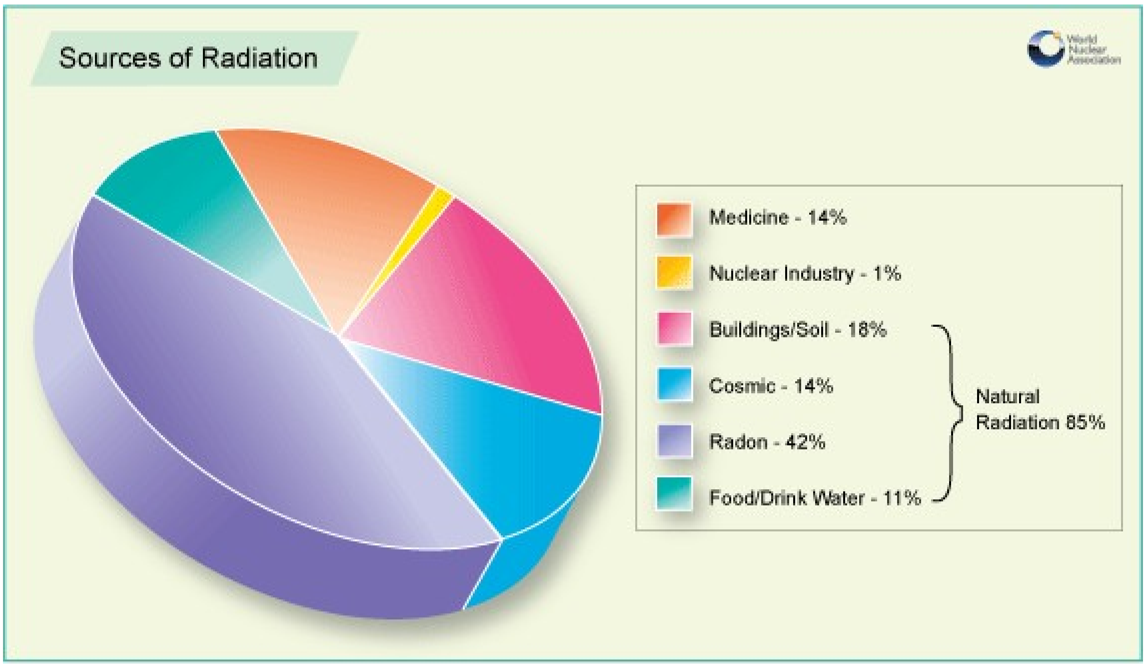
Sources of radiation

Radiation can arise from human activities or from natural sources. Most radiation exposure is from natural sources. These include: radioactivity in rocks and soil of the Earth's crust; radon, a radioactive gas given out by many volcanic rocks and uranium ore; and cosmic radiation. The human environment has always been radioactive and accounts for up to 85% of the annual human radiation dose.

Radiation arising from human activities typically accounts for up to 15% of the public's exposure every year. This radiation is no different from natural radiation except that it can be controlled. X-rays and other medical procedures account for most exposure from this quarter. Less than 1% of exposure is due to the fallout from past testing of nuclear weapons or the generation of electricity in nuclear, as well as coal and geothermal, power plants.

Backscatter X-ray scanners being introduced for airport security will gives exposure of up to 5 microsieverts (μSv), compared with 5 μSv on a short flight and 30 μSv on a long intercontinental flight across the equator, or more at higher latitudes – by a factor of 2 or 3. Aircrew can receive up to about 5 mSv/yr from their hours in the air, while frequent flyers can score a similar increment[c]. In the UK, the National Radiation Protection Board's 1999 survey showed that on average, nuclear power workers received a lower annual radiation dose than flight crew, and frequent flyers in 250 hours would receive 1 mSv.

The maximum annual dose allowed for radiation workers is 20 mSv/yr, though in practice, doses are usually kept well below this level. In comparison, the average dose received by the public from nuclear power is 0.0002 mSv/yr, which is of the order of 10,000 times smaller than the total yearly dose received by the public from background radiation.



Natural background radiation

Naturally occurring background radiation is the main source of exposure for most people, and provides some perspective on radiation exposure from nuclear energy. The average dose received by all of us from background radiation is around 2.4 mSv/yr, which can vary depending on the geology and altitude where people live – ranging between 1 and 10 mSv/yr, but can be more than 50 mSv/yr. The highest known level of background radiation affecting a substantial population is in Kerala and Madras states in India where some 140,000 people receive doses which average over 15 millisievert per year from gamma radiation, in addition to a similar dose from radon. Comparable levels occur in Brazil and Sudan, with average exposures up to about 40 mSv/yr to many people.

Several places are known in Iran, India and Europe where natural background radiation gives an annual dose of more than 50 mSv and up to 260 mSv (at Ramsar in Iran). Lifetime doses from natural radiation range up to several thousand millisievert. However, there is no evidence of increased cancers or other health problems arising from these high natural levels.

Radon gas has decay products that are alpha emitters. People everywhere are typically exposed to around 0.2 mSv/yr, and often up to 3 mSv/yr, from inhaled radon without apparent ill-effect[d]. However, in industrial situations its control is a high priority.

Public exposure to natural radiation[e]

Source of exposure		Annual effective dose (mSv)	
		Average	Typical range
Cosmic radiation	Directly ionizing and photon component	0.28	
	Neutron component	0.10	
	Cosmogenic radionuclides	0.01	
Total cosmic and cosmogenic		*0.39*	*0.3–1.0*[e]
External terrestrial radiation	Outdoors	0.07	
	Indoors	0.41	
Total external terrestrial radiation		*0.48*	*0.3-1.0*[e]
Inhalation	Uranium and thorium series	0.006	
	Radon (Rn-222)	1.15	
	Thoron (Rn-220)	0.1	
Total inhalation exposure		*1.26*	*0.2-10*[e]
Ingestion	K-40	0.17	
	Uranium and thorium series	0.12	
Total ingestion exposure		*0.29*	*0.2-1.0*[e]
Total		**2.4**	**1.0-13**

Limiting exposure

Public dose limits for exposure from uranium mining or nuclear plants are usually set at 1 mSv/yr above background.

In most countries the current maximum permissible dose to radiation workers is 20 mSv per year averaged over five years, with a maximum of 50 mSv in any one year. This is over and above background exposure, and excludes medical exposure. The value originates from the International

Commission on Radiological Protection (ICRP), and is coupled with the requirement to keep exposure as low as reasonably achievable (ALARA) – taking into account social and economic factors.

Radiation protection at uranium mining operations and in the rest of the nuclear fuel cycle is tightly regulated, and levels of exposure are monitored.

There are four ways in which people are protected from identified radiation sources:

- Limiting time. In occupational situations, dose is reduced by limiting exposure time.
- Distance. The intensity of radiation decreases with distance from its source.
- Shielding. Barriers of lead, concrete or water give good protection from high levels of penetrating radiation such as gamma rays. Intensely radioactive materials are therefore often stored or handled under water, or by remote control in rooms constructed of thick concrete or lined with lead.
- Containment. Highly radioactive materials are confined and kept out of the workplace and environment. Nuclear reactors operate within closed systems with multiple barriers which keep the radioactive materials contained.

Nuclear fuel cycle

The average annual radiation dose to employees at uranium mines (in addition to natural background) is around 2 mSv (ranging up to 10 mSv). Natural background radiation is about 2 mSv. In most mines, keeping doses to such low levels is achieved with straightforward ventilation techniques coupled with rigorously enforced procedures for hygiene. In some Canadian mines, with very high-grade ore, sophisticated means are employed to limit exposure. (See also information page on Occupational Safety in Uranium Mining.) Occupational doses in the US nuclear energy industry – conversion, enrichment, fuel fabrication and reactor operation – average less than 3 mSv/yr.

Reprocessing plants in Europe and Russia treat used fuel to recover useable uranium and plutonium and separate the highly radioactive wastes. These facilities employ massive shielding to screen gamma radiation in particular. Manual operations are carried by operators behind lead glass using remote handling equipment.

In mixed oxide (MOX) fuel fabrication, little shielding is required, but the whole process is enclosed with access via gloveboxes to eliminate the possibility of alpha contamination from the plutonium. Where people are likely to be working alongside the production line, a 25mm layer of perspex shields neutron radiation from the Pu-240. (In uranium oxide fuel fabrication, no shielding is required.)

Interestingly, due to the substantial amounts of granite in their construction, many public buildings including Australia's Parliament House and New York Grand Central Station, would have some difficulty in getting a licence to operate if they were nuclear power stations.

Nuclear accidents

The March 1979 accident at Three Mile Island in the USA caused some people near the plant to receive very minor doses of radiation, well under the internationally recommended level. Subsequent scientific studies found no evidence of any harm resulting from that exposure. In 1996, some 2,100 lawsuits claiming adverse health effects from the accident were dismissed for lack of evidence.

Immediately after the Chernobyl disaster in 1986, much larger doses were experienced. Apart from the residents of nearby Pripyat, who were evacuated within two days, some 24,000 people living within 15 km of the plant received an average of 450 mSv before they were evacuated.

In June 1989, a group of experts from the World Health Organization agreed that an incremental long-term dose of 350 mSv should be the criterion for relocating people affected by the 1986 Chernobyl accident. This was considered a "conservative value which ensured that the risk to health from this exposure was very small compared with other risks over a lifetime". (For comparison, background radiation averages about 100-200 mSv over a lifetime in most places.)

Out of the 134 severely exposed workers and firemen, 28 of the most heavily exposed died as a result of acute radiation syndrome (ARS) within three months of the accident. Of these, 20 were from the group of 21 that had received over 6.5 Gy, seven (out of 22) had received between 4.2 and 6.4 Gy, and one (out of 50) from the group that had received 2.2-4.1 Gy.[1] A further 19 died in 1987-2004 from different causes (see information page on Chernobyl Accident Appendix 2: Health Impacts).

Regarding the emergency workers with doses lower than those causing ARS symptoms, a 2006 World Health Organization report[2] referred to studies carried out on 61,000 emergency Russian workers where a total of 4995 deaths from this group were recorded during 1991-1998. "The number of deaths in Russian emergency workers attributable to radiation caused by solid neoplasms and circulatory system diseases can be estimated to be about 116 and 100 cases respectively." Furthermore, although no increase in leukaemia is discernable yet, "the number of leukaemia cases attributable to radiation in this cohort can be estimated to be about 30." Thus, 4.6% of the number of deaths in this group are attributable to radiation-induced diseases. (The estimated average external dose for this group was 107 mSv.)

The report also links the accident to an increase in thyroid cancer in children: "During 1992-2000, in Belarus, Russia and Ukraine, about 4000 cases of thyroid cancer were diagnosed in children and adolescents (0–18 years), of which about 3000 occurred in the age group of 0-14 years. For 1152 thyroid cancer patient cases diagnosed among Chernobyl children in Belarus during 1986-2002, the survival rate is 98.8%. Eight patients died due to progression of their thyroid cancer and six children died from other causes. One patient with thyroid cancer died in Russia."

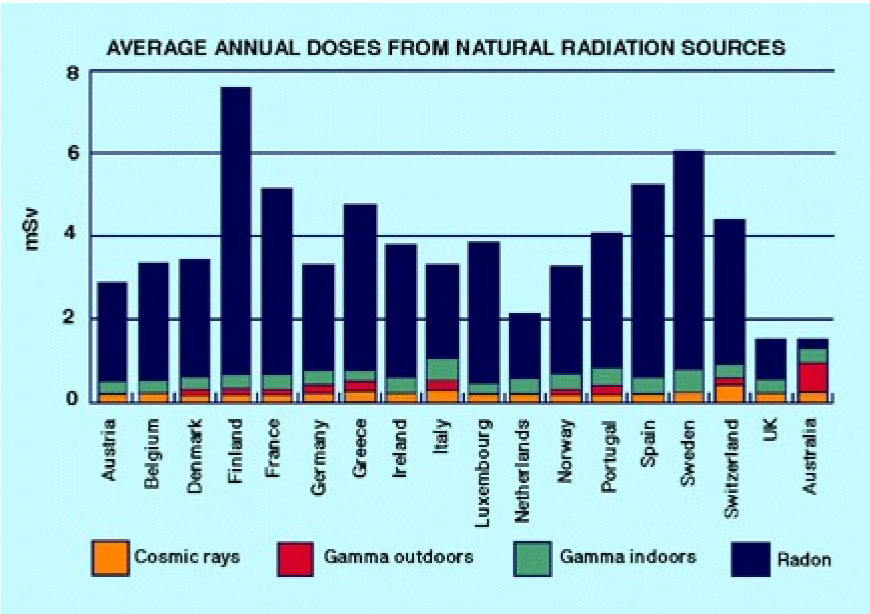
There has been no increase attributable to Chernobyl in congenital abnormalities, adverse pregnancy outcomes or any other radiation-induced disease in the general population either in the contaminated areas or further afield.

After the shelter[f] was built over the destroyed reactor at Chernobyl, a team of about 15 engineers and scientists was set up to investigate the situation inside it. Over several years they repeatedly entered the ruin, accumulating individual doses of up to 15,000 mSv. Daily dose was mostly restricted to 50 mSv, though occasionally it was many times this. None of the men developed any symptoms of radiation sickness, but they must be considered to have a considerably increased cancer risk.

Effects of radiation

Our knowledge of radiation effects derives primarily from groups of people who have received high doses. The risk associated with large radiation doses is relatively well established. However, the risks associated with doses under about 200 mSv are less obvious because of the large underlying incidence of cancer caused by other factors. Radiation protection standards assume that any dose of radiation, no matter how small, involves a possible risk to human health. However, available scientific evidence does not indicate any cancer risk or immediate effects at doses below 100 mSv a year. At low levels of exposure, the body's natural repair mechanisms seem to be adequate to repair radiation damage to cells soon after it occurs.

Some comparative radiation doses and their effects	
2 mSv/yr	Typical background radiation experienced by everyone (average 1.5 mSv in Australia, 3 mSv in North America).
1.5 to 2.0 mSv/yr	Average dose to Australian uranium miners, above background and medical.
2.4 mSv/yr	Average dose to US nuclear industry employees.
Up to 5 mSv/yr	Typical incremental dose for aircrew in middle latitudes.
9 mSv/yr	Exposure by airline crew flying the New York – Tokyo polar route.
10 mSv/yr	Maximum actual dose to Australian uranium miners.
20 mSv/yr	Current limit (averaged) for nuclear industry employees and uranium miners.
50 mSv/yr	Former routine limit for nuclear industry employees. It is also the dose rate which arises from natural background levels in several places in Iran, India and Europe.
100 mSv/yr	Lowest level at which any increase in cancer is clearly evident. Above this, the probability of cancer occurrence (rather than the severity) increases with dose.
350 mSv/lifetime	Criterion for relocating people after Chernobyl accident.
1,000 mSv cumulative	Would probably cause a fatal cancer many years later in 5 of every 100 persons exposed to it (*i.e.* if the normal incidence of fatal cancer were 25%, this dose would increase it to 30%).
1,000 mSv single dose	Causes (temporary) radiation sickness such as nausea and decreased white blood cell count, but not death. Above this, severity of illness increases with dose.
5,000 mSv single dose	Would kill about half those receiving it within a month.
10,000 mSv single dose	Fatal within a few weeks.



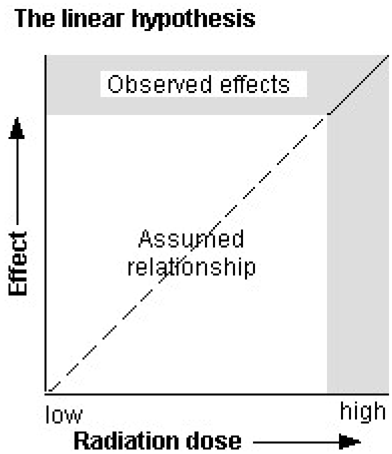
Epidemiological studies continue on the survivors of the atomic bombing of Hiroshima and Nagasaki, involving some 76,000 people exposed at levels ranging up to more than 5,000 mSv.

These have shown that radiation is the likely cause of several hundred deaths from cancer, in addition to the normal incidence found in any population[g]. From this data the International Commission on Radiological Protection (ICRP) and others estimate the fatal cancer risk as 5% per sievert exposure for a population of all ages – so one person in 20 exposed to 1,000 mSv could be expected to develop a fatal cancer some years later. In Western countries, about a quarter of people die from cancers, with smoking, dietary factors, genetic factors and strong sunlight being among the main causes. Radiation is a weak carcinogen, but undue exposure can certainly increase health risks.

In 1990, the US National Cancer Institute (NCI) found no evidence of any increase in cancer mortality among people living near to 62 major nuclear facilities. The NCI study was the broadest of its kind ever conducted and supported similar studies conducted elsewhere in the USA as well as in Canada and Europe.

In the UK there are significantly elevated childhood leukaemia levels near Sellafield as well as elsewhere in the country. The reasons for these increases, or clusters, are unclear, but a major study of those near Sellafield has ruled out any contribution from nuclear sources. Apart from anything else, the levels of radiation at these sites are orders of magnitude too low to account for the excess incidences reported. However, studies are continuing in order to provide more conclusive answers.

Low-level radiation risks



A lot of research has been undertaken on the effects of low-level radiation. Many of the findings have failed to support the so-called linear no-threshold hypothesis. This theory assumes that the demonstrated relationships between radiation dose and adverse effects at high levels of exposure also applies to low levels and provides the (deliberately conservative) basis of occupational health and other radiation protection standards.

Some evidence suggests that there may be a threshold below which no harmful effects of radiation occur. However, this is not yet accepted by national or international radiation protection bodies as sufficiently well-proven to be taken into official standards.

A November 2009 technical report from the Electric Power Research Institute in USA drew upon more than 200 peer-reviewed publications on effects of low-level radiation and concluded that the effects of low dose-rate radiation are different and that "the risks due to [those effects] may be over-estimated" by the linear hypothesis[4]. "From an epidemiological perspective, individual radiation doses of less than 100 mSv in a single exposure are too small to allow detection of any statistically significant excess cancers in the presence of naturally occurring cancers. The doses received by nuclear power plant workers fall into this category because exposure is accumulated over many years, with an average annual dose about 100 times less than 100 mSv". It quoted the US Nuclear Regulatory Commission that "since 1983, the US nuclear industry has monitored more than 100,000 radiation workers each year, and no workers have been exposed to more than 50 mSv in a year since 1989."

In addition, there is increasing evidence of beneficial effect from low-level radiation (up to about 10 mSv/yr). This 'radiation hormesis' may be due to an adaptive response by the body's cells, the same as that with other toxins at low doses. In the case of carcinogens such as ionizing radiation, the beneficial effect is seen both in lower incidence of cancer and in resistance to the effects of higher doses. However, until possible mechanisms are confirmed, uncertainty will remain. Further research is under way and the debate continues. Meanwhile standards for radiation exposure continue to be deliberately conservative.

Further Information

Notes

a. Three of the main radioactive decay series relevant to nuclear energy are those of uranium and thorium. These series are shown in the Figure at www.world-nuclear.org/uploadedImages/org/info/radioactive_decay_series.png [Back]

b. One 'Working Level' (WL) is approximately equivalent to 3700 Bq/m^3 of Rn-222 in equilibrium with its decay products. Exposure to 0.4 WL was the maximum permissible for workers. Continuous exposure during working hours to 0.4 WL would result in a dose of 5 WLM over a full year, corresponding to about 50 mSv/yr whole body dose for a 40-hour week. In mines, individual workers' doses are kept below 1 WLM/yr (10 mSv/yr), and typically average half this. [Back]

c. At an altitude of 30,000 feet, the dose rate is 3-4 µSv per hour at the latitudes of North America and Western Europe. At 40,000 feet, the dose rates are about 6.5-8 µSv per hour. Other measured rates were 6.6 µSv per hour during a Paris-Tokyo (polar?) flight and 9.7 µSv per hour on the Concorde, while a study on Danish flight crew showed that they received up to 9 mSv/yr. [Back]

d. A background radon level of 40 Bq/m^3 indoors and 6 Bq/m^3 outdoors, assuming an indoor occupancy of 80%, is equivalent to a dose rate of 1 mSv/yr and is the average for most of the world's inhabitants. [Back]

e.
Range for cosmic and cosmogenic dose for sea level to high ground elevation.
Range for external terrestrial radiation depends on radionuclide composition of soil and building material.
Range for inhalation exposure depends on indoor accumulation of radon gas.
Range for ingestion exposure depends on radionuclide composition of foods and drinking water.
Source: Table 12 from Exposures of the Public and Workers from Various Sources of Radiation, Annex B to Volume I of the 2008 United Nations Scientific Committee on the Effects of Atomic Radiation Report to the General Assembly, *Sources and Effects of Ionizing Radiation*, available on the UNSCEAR 2008 Report Vol. I webpage (www.unscear.org/unscear/en/publications/2008_1.html) [Back]

f. A reinforced concrete casing was built around the ruined reactor building over the seven months following the accident. This shelter – often referred to as the sarcophagus – was intended to contain the remaining fuel and act as a radiation shield. As it was designed for a lifetime of around 20 to 30 years, as well as being hastily constructed, a second shelter – known as the New Safe Confinement – with a 100-year design lifetime is planned to be placed over the existing structure. [Back]

g. The actual doses received by atomic bomb survivors are uncertain. Also much of the radiation then was from neutrons, though gamma radiation is the prime concern for radiation protection. Some 65 years after the acute exposure it can be seen that cancer rate in the irradiated survivors is lower than the controls, and lower than in the Japanese population as a whole[3]. [Back]

References

1. Table 11 from Exposures and effects of the Chernobyl accident, Annex J to Volume II of the 2000 United Nations Scientific Committee on the Effects of Atomic Radiation Report to the General Assembly, available on the UNSCEAR 2000 Report Vol. II webpage (www.unscear.org/unscear/en/publications/2000_2.html) [Back]

2. Health Effects of the Chernobyl Accident and Special Health Care Programmes, Report of the UN Chernobyl Forum, Expert Group "Health", World Health Organization, 2006 (ISBN: 9789241594172). [Back]

3. T. D. Luckey, *Nuclear law stands on thin ice*, International Journal of Nuclear Law, Vol 2, No 1, P 33-65 (2008) [Back]

4. Program on Technology Innovation: Evaluation of Updated Research on the Health Effects and Risks Associated with Low-Dose Ionizing Radiation, Electric Power Research Institute (EPRI), Palo Alto, California, USA, 1019227 (November 2009) [Back]

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Prof Zbigniew Jaworowski, Radiation Risk and Ethics, Physics Today, 52(9), p24-29 (September 1999)

Position Statements webpage and the Policy Papers webpage of the Health Physics Society (www.hps.org)

Health Physics Web Site of the University of Michigan (www.umich.edu)