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Acknowledgements

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1 Background Science of Radiation

1.1 What is ionizing radiation?

One often hears the terms radiation and radioactivity in the media. To a layperson, these terms may invoke a fear and avoidance reaction, as they imply some form of invisible substance or ray that may harm the body and even endanger life.

Scientifically speaking, radiation is simply a phenomenon that involves the travel of energy through a material or empty space. In this process, when radiation hits an object that falls within its path of travel, energy is transferred from the emitter of radiation to that object. A good example of radiation at work is when you are in front of an electric radiator in winter. The electric wire emits radiation (called infrared radiation) that travels from the radiator through the air, to your body, and your skin feels the radiation as heat.

However, the radiation that most people are afraid of is called ionizing radiation (the infrared radiation from the radiator is non-ionizing). Ionizing radiation is called as such because its energy levels are high enough to knock off electrons from the atoms or molecules that constitute matter, and produce 'ions' or charged particles. Ions are energetic and can react with cells and tissues, causing damage – this can result in the death of cells, or may change the DNA (deoxyribonucleic acid, a chemical inside our cells that makes up our genes) of a cell, which might lead to cancer or hereditary abnormality if a germ cell is affected (a germ cell is one involved with the transmission of genetic materials to offspring).

We are more familiar with different types of non-ionizing radiation such as radio waves, microwaves, visible light and ultraviolet rays. However, ionizing radiation is encountered more often nowadays, mainly in medical uses, such as X-rays and CT scans (CT stands for computerized tomography, a diagnostic method that produces cross-sectional images of the body by using a series of X-ray views) for diagnosis of diseases, gamma rays (for cancer treatment), and 'radioisotopes' or 'radionuclides' (both terms simply mean radioactive materials – substances with unstable nuclei in their atoms that tend to break apart spontaneously) used for diagnostic imaging or treatment of some cancers.

One may come across many terms, such as alpha particles, beta particles, gamma rays, neutrons, protons, etc. These particles or rays all have different properties and sources. Most occur naturally – cosmic rays originate from the sun and outer space; gamma rays are mostly from naturally occurring radioactive substances in rocks and soil. But X-rays can also be artificially produced, generated by a powerful beam of electrons hitting a 'target'. Both X-rays and gamma rays are at the 'higher end' (with the shortest wavelength) of a broad spectrum of electromagnetic waves of different wavelengths. In general, the shorter the wavelength of the electromagnetic wave, the more energy it possesses. The order of electromagnetic waves from longest (lowest energy) to shortest (highest energy) is: radio waves (used in radio and telecommunications), microwaves (used in radars, telecommunications and heating), infrared rays ('heat waves'), visible light, ultraviolet rays, X-rays and gamma rays. Only the latter two are classified as ionizing radiation because they possess sufficient energy to ionize atoms.

Table 1: Spectrum of electromagnetic radiation showing typical wavelength of various type of radiation

Radiation Type	Non-ionizing					Ionizing	
	Radiowave	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma
Wavelength (m)	10^{3}	10^{-2}	10^{-5}	$0.5\text{x}10^{-6}$	10^{-8}	10^{-10}	10^{-12}

Naturally occurring radioactive substances such as uranium, thorium and radium produce different types of ionizing radiation, such as alpha and beta particles and gamma rays, and are described as radioactive elements. Radioactivity refers to the phenomenon whereby the atoms of these substances, being unstable, break up by themselves (a process known as ‘spontaneous disintegration’ or ‘decay’) into different atoms (sometimes called ‘daughters’) through multiple steps, releasing energetic particles or rays during the process, and eventually become a stable element. A radioactive element[1] often exists in different forms (with different ‘atomic weights’), known as radioisotopes. Some radioactive substances are artificially made (e.g. technetium).

The ‘half-life’ of a radioactive substance is the time taken for half its atoms to disintegrate and change into another element. The half-life of a radioisotope gives an idea of how much of it will be found in the environment and for how long. Some radioisotopes have half-lives of hundreds, thousands, or even millions of years. That is why naturally occurring radioactive substances can still be found now, even though they were formed when the Earth was born. Some radioisotopes, typically intermediate ‘daughters’ from decay, exist for fractions of a second.

Radon, a radioactive gas formed from the natural breakdown (or ‘decay’) of uranium and thorium, emits an alpha particle when one atom breaks up. An alpha particle is the nucleus of the helium atom, with two protons (hence two positive charges) and two neutrons. It is relatively heavy and is low in penetrating power, being stopped by a piece of paper. However, when it comes into contact with tissues (e.g. when radon is inhaled into the lungs), it causes much damage because of its mass and doubly positive charge. A beta particle is an electron, with very small mass and a negative charge. It is more penetrating than an alpha particle, being stopped by a tin foil. Gamma rays, on the other hand, have no charge but are extremely penetrating, being stopped by a thick block of lead. X-rays are somewhat less penetrating, and lead aprons are worn by radiographers for protection during their work.

1.2 Units used in radiation

To a layperson, the different units of ionizing radiation may appear confusing. One reason is that these units have evolved over time. Nowadays, most countries adopt the standard SI unit, but the older system of units is still widely used in the United States (US). Conceptually, we can distinguish two types of units, the unit of radioactivity and the unit of radiation exposure (or radiation dose). The unit of radioactivity measures the frequency of the disintegration of an unstable substance (and therefore the amount of radiation emitted from a radioactive source). It reflects the instability of the radioactive substance. The SI unit[2] of radioactivity is the becquerel (Bq). This is the unit used to quantify radioactivity in the environment.

The amount of radiation (in terms of energy) absorbed by a material (such as tissue) is known as the radiation absorbed dose. The SI unit of radiation absorbed dose is the gray (Gy). Another SI unit that takes into account the type of radiation is the sievert (Sv). One sievert equals one gray times a ‘radiation weighting factor’. (See Box 1 for more details of the units.)

Box 1: Units used in radiation

One becquerel (Bq) is the activity of an amount of radioactive material in which one nucleus disintegrates (or decays) per second.

One gray (Gy) is the amount of radiation that causes one kilogram of matter to absorb one joule (the SI unit of energy).

The biological effect of an absorbed dose of radiation varies according to the type of radiation. This gives rise to the concept of ‘relative biological effectiveness’, the relative amount of damage to biological tissues caused by a fixed amount of a given type of radiation. The ‘equivalent’ dose is the absorbed dose multiplied by a ‘radiation weighting factor’ (a factor that denotes the relative biological effectiveness of a specific type of radiation). It is expressed in an SI unit called the sievert (Sv). Like the gray (Gy), the sievert is expressed as energy per unit mass and quantifies the biological effect of one joule of energy from gamma rays (which have a radiation weighting factor of one) absorbed by one kilogram of tissue.

Different tissues of the body have different sensitivity to ionizing radiation. This has implications in radiation protection, where another term – the ‘effective dose’ – is used to take overall account of the amounts of radiation received by different tissues of the body.

The table below summarizes the different units and their relationships, as well as the conversion factors to be used when converting older units to SI units.

Units used in ionizing radiation

	Activity	Absorbed dose	Radiation weighting factor	Equivalent dose
SI unit	bequerel (Bq)	gray (Gy)	(No unit)	sievert (Sv)
Old unit	Microcurie (µCi)	rad		rem
Conversion	1 µCi = 3.7 x 10^4 Bq	1 rad = 0.01 Gy		1 rem = 0.01 Sv
Uses	To express radioactivity in food, water, air, or contaminated soil	To express the amount of radiation absorbed by humans	To express in relative terms, the biological damage caused by the same amount of energy deposited by each type of radiation	A measure of the biological damage to living tissue resulting from radiation exposure

Absorbed dose x radiation weighting factor = equivalent dose

1.3 Radiation in our daily life

1.3.1 Background radiation

While the use of X-rays and radioisotopes in medicine is increasingly common and highly visible to the public, a more important, yet not so obvious source of radiation that a person receives is the background radiation naturally present in our environment. The following is a direct quotation from the Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in 2000 to the UN General Assembly:

> ‘*The exposure of human beings to ionizing radiation from natural sources is a continuing and inescapable feature of life on earth. For most individuals, this exposure exceeds that from all man-made sources combined. There are two main contributors to natural radiation exposures: high-energy cosmic ray particles incident on the earth's atmosphere and radioactive nuclides that originated in the earth's crust and are present everywhere in the environment, including the human body itself. Naturally occurring radionuclides of terrestrial origin (also called primordial radionuclides) are present in various degrees in all media in the environment, including the human body itself. Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in significant quantities in these materials.*’ [3]

The food we eat, the air we breathe and the water we drink, all contain radioactive substances found in nature. On average (worldwide), an annual dose of background radiation is 3 mSv, with 2.4 mSv (80%) from natural sources and 0.6 mSv from man-made sources. The most important source of external radiation is gamma rays from naturally occurring radioactive substances belonging to the uranium (^{238}U) and thorium (^{232}Th) series, and potassium (^{40}K).

In chemistry, U is the symbol for the element uranium. The number 238 in superscript is the “mass number”, which is the number of protons and neutrons inside the nucleus of an atom of uranium. Similarly, Th stands for thorium, another heavy metal, and K stands for potassium, a common “alkali metal” that combines with other chemicals to form compounds.

Radon (Rn) is a radioactive gas derived from the breakup (‘decay’ is the technical term) of radium, which exists in minute quantities in rocks, soil and building materials. Many different types of radioactive substances exist in nature. They find their way into our food and water, and even accumulate in our body, which is continuously bombarded by radiation produced by their decay. Burning fossil fuels such as coal and processing minerals increases our exposure to naturally occurring radionuclides. Apart from these terrestrial sources, cosmic rays are charged particles that originate from outer space and the sun. They travel to Earth at high speed. In the upper atmosphere, these charged particles initiate a cascade of reactions producing other charged and uncharged particles and electromagnetic radiation. They also produce radioactive materials in the atmosphere – tritium (hydrogen with two extra neutrons in the nucleus of its atom) and carbon-14 (^{14}C). Exposure to cosmic rays and their breakdown products increases with altitude. Airline crew or passengers who fly frequently will receive relatively higher doses of cosmic rays. Astronauts travelling in space are exposed to a much stronger dose compared to the rest of us who stay on the Earth's surface. The level of natural background radiation varies widely in different parts of the world. Table 2 shows the relative importance of different sources that contribute to natural background radiation.

Table 2: Average radiation effective dose from natural sources[4]

Source	Worldwide average annual effective dose (mSv)	Typical range (mSv)
External exposure		
Cosmic rays	0.4	0.3 – 1.0[a]
Terrestrial gamma rays	0.5	0.3 – 0.6[b]
Internal exposure		
Inhalation (mainly radon)	1.2	0.2 – 10[c]
Ingestion	0.3	0.2 – 0.8[d]
Total	2.4	1 – 10

[a] Range from sea level to high ground elevation.
[b] Depending on radionuclide composition of soil and building materials.
[c] Depending on indoor accumulation of radon gas.
[d] Depending on radionuclide composition of foods and drinking water

1.3.2 Radiation in medicine

Since their discovery in 1895 by Wilhelm Conrad Röntgen, a German physicist, X-rays have been widely used in medicine. Because of their ability to pass through most tissues, X-rays allow the doctor to 'see' our internal organs and tissues. An X-ray film makes use of differences in the ability of the X-rays to pass through different tissues. For example, lungs are quite transparent to them, while denser bones are 'radio-opaque'. As we shall see later, even though X-rays are useful in medicine, they do produce some tissue damage. Consequently, care has to be exercised to prevent unnecessary exposure to X-rays. X-rays of different parts of our body involve different doses of radiation. For example, when one takes X-ray pictures of the chest, a common diagnostic procedure in medical practice, a person typically receives a dose of 0.1 mSv. A higher dose (around 1 mSv) is usually required for X-rays of other parts of the body such as the abdomen and mammogram of the breast. This is because X-rays of different energy are used for creating images in different organs and tissues. Also, irradiation of different tissues produces different biological effects.

More complicated X-ray imaging, such as CT scans, involve an even higher dose of radiation (several mSv). Radioisotopes are also being used increasingly in imaging. They may be ingested or injected into the body, where they are distributed to different organs for diagnostic imaging purposes. Besides imaging techniques for diagnosis, radiation is used to treat cancers. The doctor may use high doses of X-rays or gamma rays to irradiate the cancer site. Cells that divide rapidly are more susceptible to radiation. Since cancer cells divide much more rapidly than cells of normal tissues, they are more easily killed by radiation than normal cells. In the process of ‘radiotherapy’, normal cells and tissues are also damaged, but the benefit of treating the cancer is thought to outweigh the radiation hazard. In the past, radioactive iodine has been used to irradiate (and kill) thyroid tissues to treat a disease called hyperthyroidism (caused by excessive thyroid hormone production).

The use of radiation in medicine has been increasing rapidly, and in developed countries, constitutes up to 50 per cent of the overall global average background level of radiation. With the advance of medicine, people in developing countries are expected to be exposed to higher doses of radiation from medical use in the future. Table 3 shows the relation between the level of health care in a country, the frequency of use of medical X-ray examinations, and the annual effective dose of radiation received.

Table 3: Radiation exposures from diagnostic medical X-ray examinations[5]

Health care level	Population per physician	Annual number of examinations per 1,000 population	Average annual effective dose to population (mSv)
I	<1,000	920	1.2
II	1,000 – 3,000	150	0.14
III	3,000 – 10,000	20	0.02
IV	>10,000	<20	<0.02
Worldwide average		330	0.4

Figure 1 gives a general idea of the radiation doses received by an individual undergoing different X-ray examinations (dark green bar), and its relation to background radiation (light green bar). The radiation doses for chest X-rays and skull X-rays are 0.02 mSv and 0.03 mSv respectively and are too little to be shown in Figure 1.

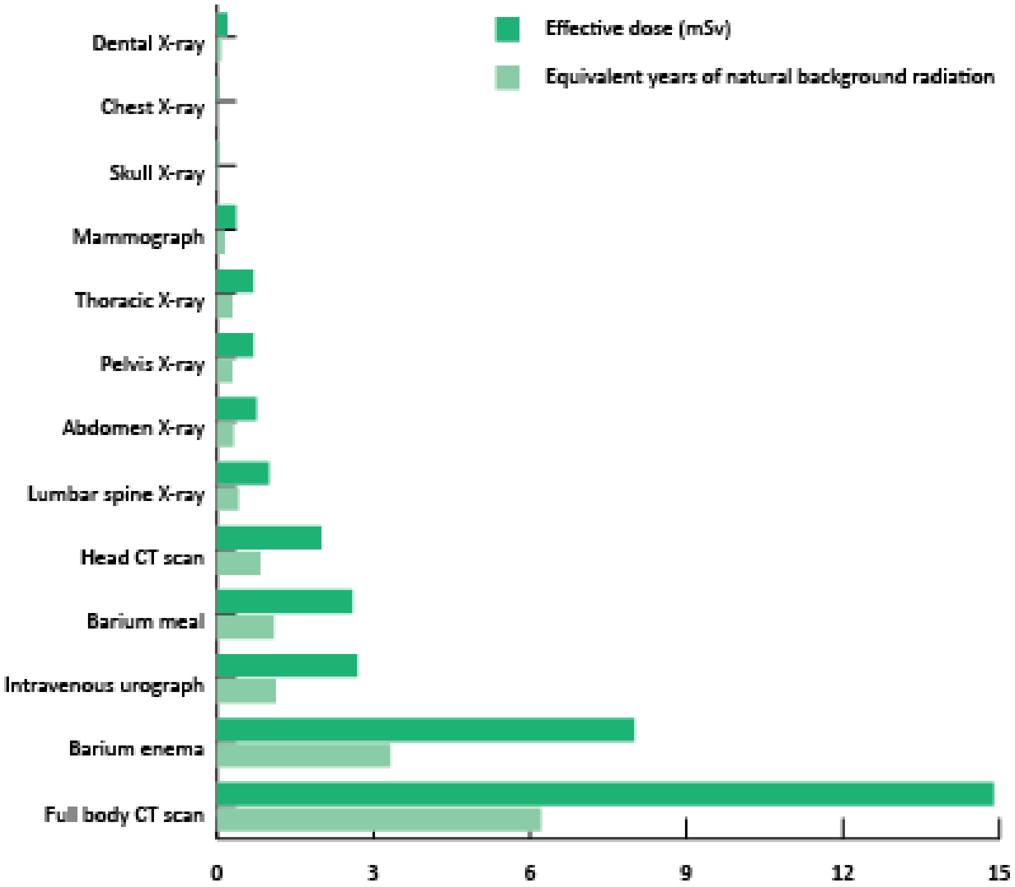

Figure 1: Radiation doses received in different medical radiographic examinations and equivalent background radiation exposure[6]

1.3.3 Other uses of ionizing radiation

Other man-made sources include the use of radiation in industry, consumer products that contain radioisotopes, nuclear plants and the testing and use of nuclear weapons. X-rays and gamma rays have been used in industry for various purposes. Metal pipes are X-rayed for detection of cracks. Radioisotopes have been used in the manufacture of smoke detectors, luminous displays on watches or fire exit signs, and lightning rods. Thorium dioxide has been used to impregnate incandescent gas mantles of portable gas lanterns, commonly used in developing countries in the last century. Gamma rays are very useful for the sterilization of food and medical equipment. Many different ocupational groups (e.g. underground miners, workers who come into contact with radioisotopes in their work, health workers involved in X-rays and radiotherapy, and air crews) are exposed to higher levels of radiation compared with the general public. Table 4 gives an idea of the effective dose among the different occupations. Table 5 shows the average doses of radiation from various sources.

Table 4: Doses of radiation in occupational radiation exposures[7]

Source / practice	Number of monitored workers (thousands)	Average annual effective dose (mSv)
Man-made sources		
Nuclear fuel cycle (including uranium mining)	800	1.8
Industrial uses of radiation	700	0.5
Defence activities	420	0.2
Medical uses of radiation	2,320	0.3
Education/veterinary	360	0.1
Total from man-made sources	4,600	0.6 (weighted average)
Enhanced natural sources		
Air travel (crew)	250	3.0
Mining (other than coal)	760	2.7
Coal mining	3,910	0.7
Mineral processing	300	1.0
Above ground workplaces (radon)	1,250	4.8
Total from natural sources	6,500	1.8 (weighted average)

Table 5: Annual per capita effective doses in year 2000 from natural and man-made sources[8]

Source	Worldwide annual per capita effective dose (mSv)	Range or trend in exposure
Natural background	2.4	Typically ranges from 1-10 mSv, depending on circumstances at particular locations, with sizeable population also at 10-20 mSv.
Diagnostic medical examinations	0.4	Ranges from 0.04-1.0 mSv at lowest and highest levels of health care; increasing trend of exposure because of widespread use of medical radiation services throughout the world.
Atmospheric nuclear testing	0.005	Has decreased from a maximum of 0.15 mSv in 1963. Higher in northern hemisphere
Chernobyl accident	0.002	Has decreased from a maximum of 0.04 mSv in 1986 (average in northern hemisphere). Higher at locations nearer accident site
Nuclear power production	0.0002	Overall, nuclear power production has increased.

Natural background radiation, which varies greatly by geographical location, is the major source of our radiation. Radiation in medicine is the second most important source, and is increasing rapidly with advances in medicine and better access to health care. Atmospheric nuclear testing in the 1950s and 60s is the single human activity that released the largest quantities of radioactive substances directly into the environment. Although its contribution to the overall background level is small (7 per cent of the annual background dose in 1963), radionuclides with long half-lives released from nuclear testing are still present in our environment.

1.4 Ionizing radiation from nuclear power plants

1.4.1 Nuclear power plant in normal operation

Nuclear power plants utilize uranium as fuel and capture the heat energy produced from a controlled process of nuclear fission. When a uranium atom is hit by a moving neutron, it splits into other smaller radioactive atoms, producing two or three neutrons during the fission process. These neutrons in turn will split other uranium atoms, causing a chain reaction. During the fission process, some matter is turned into energy. According to Einstein's well-known equation, Energy = Mass x Velocity of light^2, or $E=mc^2$, a large amount of heat is released. Different radionuclides ('fission products') are formed and various forms of ionizing radiation are emitted.

Nuclear fission takes place inside the core of the nuclear reactor, and the heat produced is transferred by circulating water under high pressure, which acts as coolant. This in turn heats up water in a heat exchanger to generate steam in a secondary circuit, which is fed to turbines to generate electricity. The steam is cooled down and recirculated to be heated up again by the water in the primary circuit, and the cycle is repeated (see Figure 2). The system operates under great pressure and small quantities of radioactive gaseous discharges (tritium, halogens, aerosols and noble gases) will be released into the environment. Some radioactive substances will be discharged as liquid effluents. Filtration of heavier radioisotopes will ensure minimal discharge of such radioactive substances. For environmental protection, annual, maximum weekly and daily regulatory limits have been set, and monitoring of the radioactive discharge is done to make sure the discharge of radioactivity does not exceed these limits.

In general, solid wastes are not discharged into the environment. Wastes of low and intermediate radioactivity are sealed, stored and transported to a repository for long-term storage. Highly radioactive 'spent' fuel will be stored and cooled inside the nuclear power plant and then reprocessed (when unused uranium, plutonium and fission products are chemically separated) or stored in a repository.

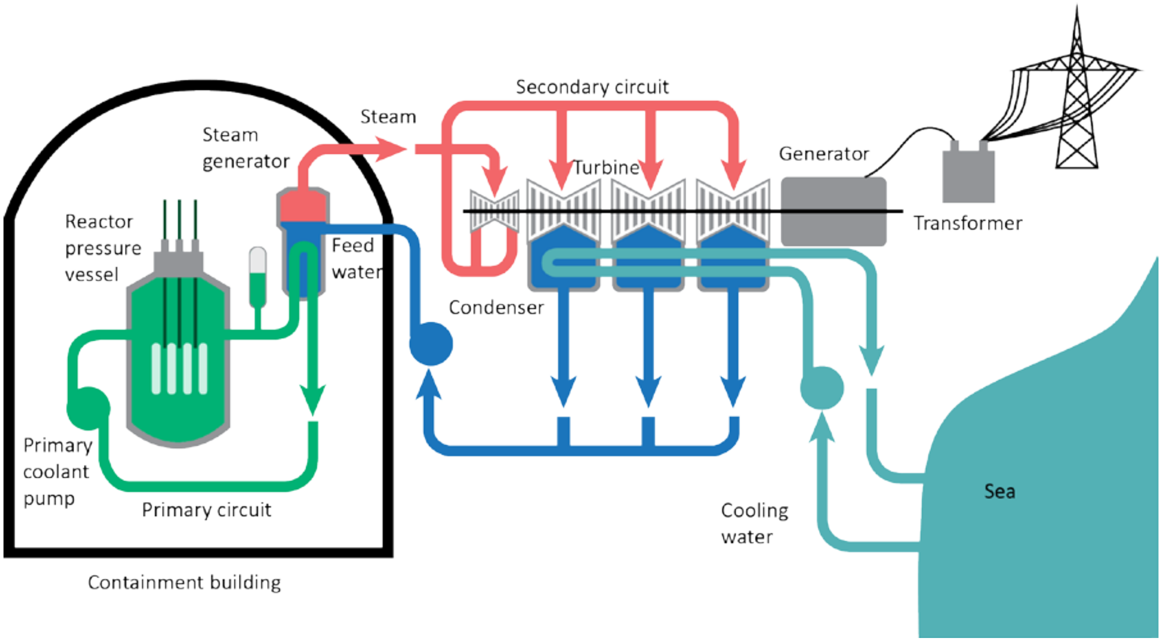

Figure 2: Nuclear power station using pressurized water reactor[9]

1.4.2 Release of radioactive substances during incidents

Before the Fukushima accident in 2011, there have been two major accidents in nuclear power plants that have resulted in environmental contamination and potentially significant population exposure to radiation.[10] The accident in the Three Mile Island nuclear power plant near Middletown, Pensylvania, in 1979 was the most serious accident in US commercial nuclear plant operating history. It was caused by a failure of the cooling system, resulting in the release of radioactive substances into the environment. No injuries or early deaths were reported. The average population exposure to radiation was less than one percent of the background level.[11]

The explosion of the nuclear power plant in Chernobyl of the former Soviet Union (USSR) in 1986 was the worst disaster recorded in the history of nuclear power plants. Human error, including inadequate design, unauthorized testing and violations of operating guidelines, was responsible for the disaster. An improper low power engineering test of the reactor led to an unstable fission reaction rate. A sudden surge of temperature then occurred and the cooling system failed. A violent explosion[12] then followed, damaging the reactor core and releasing large quantities of radioactive substances into the environment.

Radioactivity arising from the accident could be measured across most countries of the northern hemisphere.[13] Twenty-eight workers (including fire-fighters) died of acute radiation sickness, and many more workers suffered from radiation injuries. Hundreds of thousands of residents were evacuated because of the environmental contamination that ensued. Twenty years after the accident, several thousand extra cases of thyroid cancer in exposed children have been reported. However, most of the general population showed no measureable increase in the incidence of leukemia and other solid cancers.Many radionuclides, including radioactive iodine-131 (^{131}I), caesium-134 (^{134}Cs) and caesium-137 (^{137}Cs) were released into the environment. ^{131}I is selectively concentrated in the thyroid gland, thereby increasing the risk of thyroid cancer, and the Soviet authorities permitted children to continue to drink milk heavily contaminated with radioactive iodine, leading to high thyroid doses being received by many children. ^{134}Cs and ^{137}Cs have long half-lives (2 years and 30 years respectively), and stay in the environment and food for much longer than ^{131}I, which has a half-life of 8 days.

The Fukushima-Daiichi nuclear power plant accident, after the earthquake and tsunami in Japan in 2011, received worldwide attention. The potential effects on the health of residents from the accident are being assessed by the World Health Organisation (WHO) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). In a report, the WHO estimated that the effective doses for residents in Fukushima Prefecture range from 1-10 mSv, except in two locations (at 10-50 mSv). In prefectures neighbouring Fukushima, the estimated effective doses were from 0.1-10 mSv, while in all other prefectures, the estimated effective doses ranged from 0.1-1 mSv. In the rest of the world, the estimated effective doses were less than 0.01 mSv, and usually far less.[14] The WHO report stated that this level was comparable to the average population dose resulting from 1.5 days of exposure to natural background radiation sources. The estimated effective doses outside Fukushima and neighbouring prefectures were below the internationally accepted annual dose limit for public exposure (1 mSv). The estimated effective doses for residents in Fukushima Prefecture and in neighbouring prefectures are below the WHO reference level for public exposure due to radon in dwellings (annual effective dose of 10 mSv), except in two locations in the most affected part of Fukushima Prefecture, with an effective dose band of 10-50 mSv.[15] The Fukushima Nuclear Accident Independent Investigation Commission concluded that the accident was clearly “man-made, the result of collusion between the Japanese government, the regulators, the operator and the lack of governance of the said parties.”[16]

2 Health Impact of Ionizing Radiation

2.1 Radiation damage to living cells

Ionizing radiation is so energetic that when it comes into contact with biological cells, it ionizes their atoms and molecules and causes cell damage. Exposure to a large dose of radiation over a short time period may kill a substantial proportion of the cells of a tissue. If a cell dies, other cells may replace it. If a person is exposed to a radiation dose below a critical level (a 'threshold' dose), he/she will be able to repair the cellular and tissue damages to the extent that no clinical effects can be observed. Above the threshold doses, the ability of the human body to repair the damage fails and various tissue reactions begin to appear. The damage becomes more severe as the dose increases, and at high enough doses (several grays) death occurs. The harmful tissue reactions caused by radiation are known as 'deterministic effects'.

Even at low doses, radiation may damage and alter the DNA – genetic material in the nucleus of the cell which controls many different aspects of cell function. If the damage is beyond repair, the cell might turn cancerous. Damaged 'germ cells' – cells involved with the transmission of genetic materials into the offspring – might result in hereditary disorders. These effects – cancer and hereditary abnormalities – are known as 'stochastic effects', meaning that these effects are random. Even a change in a single cell or mutation at a single site of the DNA is of critical importance to the development of cancer after radiation exposure.[17] The probability of stochastic effects increases with dosage. The International Commission for Radiological Protection, an authority on ionizing radiation, recommends, for the protection of public health, that stochastic effects *do not have a threshold* (i.e. a level below which these effects will not occur). This viewpoint has been challenged by some scientists, as evidence of cancer risk at low doses is uncertain and controversial.

2.2 Acute effects of ionizing radiation on health

Evidence of acute effects of ionizing radiation on health is well established. When a person is exposed to a high dose of radiation, usually from an external source, he/she will suffer from a combination of symptoms called 'acute radiation sickness'. This occurs within hours or can take up to several days, and is due to tissue damage by the high-energy radiation. In general, the more rapidly the cells reproduce, the more susceptible they are to radiation damage. (This is also the underlying principle for the treatment of cancer by high-energy radiation.) When the skin is exposed to a large external dose of radiation, the skin will become inflamed. The skin will become red and swollen; there will be shedding of dead skin cells. The reaction is similar to damage to the skin caused by chemicals or heat. Hence, the condition is sometimes called 'radiation dermatitis', or 'radiation burns'. Hairs will drop off. The above reactions are side effects of patients being treated for cancer by external radiation.

Bone marrow is especially susceptible to radiation. Suppression of bone marrow cells, whose function is to produce various blood cells, will lead to bleeding (due to damage to cells forming blood platelets), susceptibility to infection (due to damage to white blood cells), and anaemia (decrease of red blood cell production). When a person is exposed to higher doses of radiation, he /she will exhibit gastrointestinal symptoms, such as vomiting and bloody diarrhoea. No tissue can escape injury. When the dose reaches even higher levels, the lungs, the kidneys, the liver, and even the most resistant tissues – the central nervous system and the heart – will be damaged. Death will occur. The dose threshold for acute radiation syndrome is about 1 Gy (1,000 mGy).[18] A dose of 4 Gy will kill about 50 per cent of healthy adults. Table 6 below illustrates the relationship between the radiation dose and the radiation-induced syndromes resulting in death.

Table 6: Range of doses associated with specific radiation-induced syndromes and death in healthy adult human beings exposed to acute low 'linear energy transfer'[19] (LET) uniform whole body radiation[20]

Whole body absorbed dose (Gy)	Principal effect contributing to death	Time of death after exposure (days)
3 – 5	Damage to bone marrow	30 – 60
5 – 15	Damage to the gastrointestinal tract	7 – 20
	Damage to the lungs and kidneys	60 – 150
>15	Damage to the nervous system	<5, dose-dependent

2.3 Chronic effects of ionizing radiation on health

Apart from early, acute effects on health from exposure to high doses of radiation, exposure to lower levels of radiation produces two types of damage – somatic and genetic damage. Somatic effects (effects on the body) include 'radiation cataract' (clouding of the lens of the eye). These effects may be present among workers occupationally exposed to radiation. An acute exposure or cumulative exposure of 0.5 Gy to the eye will result in vision-impairing cataracts.[21]

The most serious effect on health from radiation is the increased risk of cancer. As mentioned earlier, the probability of cancer increases with increasing exposure to radiation. Almost all tissues are susceptible, but the more often the cells divide, the greater is the risk of cancer. Hence, leukaemia (arising in the red bone marrow) is the most common and well-known cancer caused by radiation. The evidence is derived mainly from the follow-up of the Japanese atomic bomb survivors. Radon is a cause of lung cancer, owing to the damage to the cells of the lung or bronchus by the highly damaging alpha particles produced when radon disintegrates into its daughter nuclei. The main evidence is from epidemiological studies of miners. When a person ingests or inhales radioactive iodine, it is concentrated in the thyroid gland; this increases the risk of thyroid cancer, especially among those exposed as children.

Epidemiological studies of populations exposed to radiation (e.g. atomic bomb survivors, radiotherapy patients, occupationally exposed cohorts) have shown a significant increase of cancer risk at doses above 100 mSv. Children and adolescents are more susceptible to radiation as their cells and tissues are more actively dividing compared to adults. In addition, radionuclides absorbed by children are likely to stay longer inside the body due to their longer life expectancy than older individuals. Therefore, for radionuclides that remain in the body for a long time, the same amount of radionuclide intake can result in a higher internal dose in the young than in older people. Cancer usually manifests many years, or even decades, after exposure to radiation.

Data from animal studies show that irradiation of the embryo may lead to death or malformations, the damage being greatest during the early period of gestation, when major organs are formed. Such effects are dependent on the dose of radiation received as well as the gestational age. Prenatal exposure to ionizing radiation may induce brain damage in [human] foetuses following an acute dose exceeding 100 mSv between weeks 8 and 15 of pregnancy and 200 mSv between weeks 16 and 25 of pregnancy. Before week 8 or after week 25 of pregnancy, human studies have not shown radiation risk to foetal brain development. Foetal exposure to radiation can increase the risk of cancer in childhood. Studies have shown this effect with doses of above 100 mSv.[22]

The effects of different doses of radiation on health are shown in Figure 3.

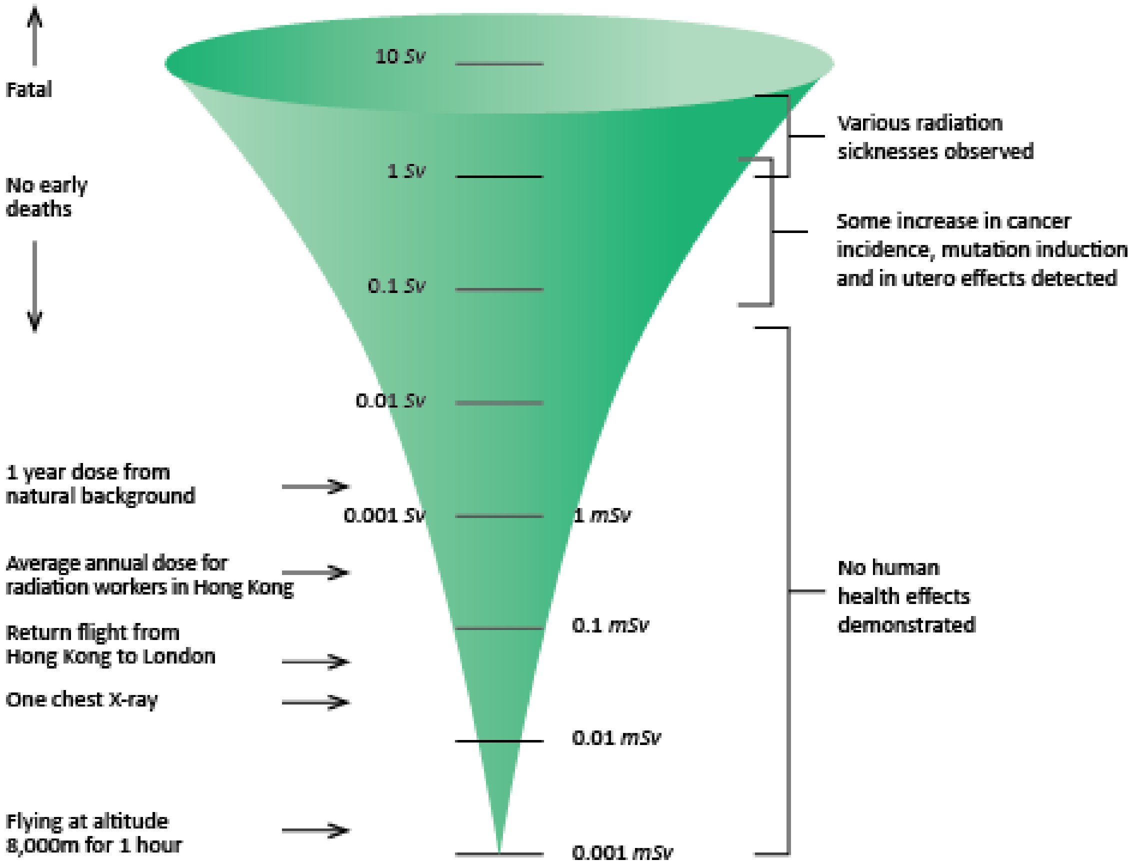

Figure 3: The effects of radiation on health[23]

3 The Hong Kong Context

3.1 Background radiation level in Hong Kong

Table 7 shows the external exposure rates from terrestrial gamma radiation in Hong Kong and selected countries. The range of exposure rates illustrates the wide geographical differences in the distribution of naturally occurring radionuclides in rocks and soil. The level of external gamma radiation in Hong Kong (87 nGy/hr) is at the high end of the global distribution. By comparison, external dose rates are even higher in places with high background radiation due to the presence of terrestrial sources (such as monazite sands): Yangjiang (Guangdong, China) at 370 nGy/hr, Kerala and Madras (India) at 200-4,000 nGy/hr, averaging 1,800 nGy/hr, and the Ganges Delta (India) at 260-440 nGy /hr.[24] Cosmic radiation varies with altitude and levels are high in several high-altitude provinces and cities, namely, Qinghai (95 nGy/hr) and Tibet (121 nGy/hr) in China, and Denver, Colorado (196 nGy/hr) in the US.

For Hong Kong, indoor radon dominates the total dose of background radiation Hong Kong people are exposed to. In a Hong Kong study, the arithmetic mean of the indoor dose rate of gamma (including cosmic) radiation is 0.22 ± 0.04 µGy per hour (1 µGy, or 1,000 nGy, for gamma radiation is equivalent to an absorbed dose of 1 µSv, or 0.001 mSv). The geometric means of the indoor radon concentrations are 48 ± 2 Bq m^{-3} and 90 ± 2 Bq m^{-3} for residential and non-residential buildings respectively. The geometric mean annual effective dose is 2.4 mSv, with a geometric standard deviation of 1.3 mSv.[25]

Table 7: External exposure rates from terrestrial gamma radiation in selected countries[26]

Country / region / city	Absorbed dose rate in air (nGy/hr)				Ratio (indoors to outdoors)
	Outdoors		Indoors		
	Average	Range	Average	Range	
Hong Kong[27]	87	51-120	200	140-270	2.3
China	62	2-340	99	11-420	1.6
Taiwan	57	17-87	-	-	-
Japan	53	21-77	53	21-77	1.0
South Korea	79	18-200	-	-	-
Malaysia	92	55-130	96	65-130	1.0
Thailand	77	2-100	48	2-22	0.6
Canada	63	43-101	-	-	-
US	47	14-118	38	12-160	0.8
Australia	93	-	103	-	1.1
United Kingdom	34	8-89	60	-	1.8
Germany	50	4-350	70	13-290	1.4
Median	57	18-93	75	20-200	1.3 (0.6-2.3)
Population weighted average	59		84		1.4

3.2 Impact of the Daya Bay nuclear power plant on radiation level

To many Hong Kong citizens, the Guangdong Nuclear Power Station at Daya Bay, about 50 km from Tsimshatsui in Kowloon, might be perceived to be a threat to their health and safety. Before the plant's operation in 1994, the Royal Observatory of Hong Kong (now Hong Kong Observatory) published a detailed report[28] on the impact on the environment and the radiation dose of the Hong Kong population from the release of radionuclides accumulated over a time frame of 30 years after its operation: there would be an increase of absorbed dose ranging from 24 nSv, or 2.4 x 10^{-5} mSv per year (for residents in Kat O and Tap Mun) to 5 nSv, or 5 x 10^{-6} mSv per year (for residents in Tai O, Lantau Island). For residents in Tai Po and Sha Tin, new towns in Hong Kong closest to the power plant, the increase in dose was estimated to be 16 nSv, or 1.6 x 10^{-5} mSv per year. This represented a 0.00067 per cent increase over the background radiation level of 2.4 mSv per year. The average additional dose for the entire population was estimated to be 6 nSv, or 6 x 10^{-6} mSv per year (an increase of 0.00025 per cent).

The two most important sources of the dose were external irradiation from radioactive gases in the atmosphere and ingested radionuclides from food. The report concluded that the routine atmospheric discharge of radioactive substances was unlikely to significantly increase the effective dose of the Hong Kong population. Presently, there are six reactors with the same design (but with a little higher power output) in Daya Bay. It is reasonable to assume that the previous estimate of radiation dose would be increased by a factor of three (six reactors at present compared to just two when the study was done), with residents in Tai Po and Sha Tin exposed to an increase of 48 nSv, or 4.8 x10^{-5} mSv per year, or a 0.002 per cent increase over the background level.

The radiation dose due to ingestion of marine fish affected by the discharge from the nuclear power plant has been estimated.[29] The predicted annual dose to an average local individual in Hong Kong, for a release rate of 10 GBq of ^{137}Cs per year from the power plant, is 0.032 nSv, or 3.2 x 10^{-8} mSv per year. This is dominated by the contribution from fish cultured in Hong Kong waters. The annual dose to members of the critical group of local fish farmers does not exceed 3 nSv, or 3.0 x 10^{-6} mSv per year. These doses are very small, compared to the dose of around 1.2 x 10^{-3} mSv (1200 nSv) per year arising from ingestion of naturally occurring radionuclides found in marine fish. In the normal operation of a nuclear power plant, highly radioactive spent fuel (rods of irradiated uranium embedded in zirconium alloy tube) need to be replaced.[30] Spent fuel rods are stored in the nuclear plant for about 10 years for the decay of short half-life radionuclides. They will then be reprocessed to be used again under the policy of the Chinese government. The reprocessing of the nuclear fuel will generate high level radioactive waste, which will have to be properly stored, because some radionuclides in the spent fuel have very long half-lives, and remain highly radioactive and very hazardous for generations to come. The choice of suitable storage sites, transportation links with the nuclear power plant, and security measures are important issues that need to be tackled with great attention to detail.

According to the reports by the Hong Kong Observatory in 2011 and 2012,[31,32] there were no significant changes in both the ambient radiation levels in Hong Kong and the activities of artificial radionuclides in the Hong Kong environment and foodstuffs consumed by Hong Kong people since the Guangdong Nuclear Power Station and Lingao Nuclear Power Station came into operation. This observation agrees with the estimated increase in radiation absorbed dose in the Hong Kong population in the report in 1992,[33] which was well below detection limit.

3.3 Risk of ionizing radiation compared to other non-consensual (involuntary) health risks

The lifetime risk (=chance or probability) of a fatal cancer from an absorbed effective dose of 1 mSv is low, at around 5.5×10^{-5}, or approximately one in 18,000 persons for the general public. For a radiation worker, the risk is even lower, at 4.1×10^{-5}, or about one in 24,000 persons.[34] This estimate takes into consideration that workers, unlike the general population, do not include children. In Hong Kong, the lifetime risk of having cancer is one in four for men and one in five for women. The lifetime risk of dying from cancer is one in eight for men and one in fourteen for women.[35] It is not easy to compare the health risk posed by ionizing radiation arising from man-made sources such as a nuclear power plant to other health risks, natural or man-made. In public health, the risk of developing a certain disease refers to the chance of getting that disease in a population exposed to an agent, such as ionizing radiation. The latter is commonly referred to as a 'risk factor'. While this risk factor is conventionally expressed as a probability, the severity of the risk depends on the outcome itself. Death is the most severe outcome. Fatal cancer is another example of a serious outcome. Hence, the concept of risk as perceived by the general public should include both the severity of the damage to health and the probability of an exposed person being affected. In Section 1.3.1, we have explained that ionizing radiation has always been part of our Earth long before the human species existed. Because of its propensity for inducing changes in the genetic materials of living organisms, ionizing radiation has long been considered to be an essential, and perhaps indispensable driver of the evolution of life on this planet, through mutation of genes that, if beneficial to the organism, will be passed on to successive generations. The logic behind the assumption that ionizing radiation is bad for humans (and other life forms) is that after millions of years of evolution that shaped humans to what we are today, any new mutation caused by exposure to radiation is more likely to be harmful than beneficial, from a probabilistic viewpoint.

Ionizing radiation is unavoidable in our life. Radiation from man-made activities such as the discharge of radioactive waste from the normal operation of nuclear power plants constitutes an insignificant dose to the Hong Kong community. It is not easy to compare the risk with that from other non-consensual risks to health. In the late 1980s, the UK Atomic Energy Authority (UKAEA) conducted a consultancy study for the Hong Kong Government. In this risk assessment report[36], risk is expressed in two dimensions – 'societal risk' and 'individual risk'. Societal risk refers to the probability of a specific number of individuals in a community being harmed in one year, while individual risk refers to the chance that an individual will experience some specific harm. Assuming the accidental release of radioactive materials into the air and water, the societal risk (= probability, p) of one or more early deaths (from acute effects of radiation) per year of operation of the power plant was about one in a million ($p = 1 \times 10^{-6}$). The societal risk of early injuries (from acute effects of radiation) was 2.3×10^{-6} (less than one in 400,000). The societal risk of one or more fatal cancers (from long-term effects of radiation that would occur up to 50 years later), in one year of operation was one in 50,000 ($p = 2 \times 10^{-5}$). The above risk estimates represent the upper bound (conservative or pessimistic) estimate of the societal risk. The risk to an individual is much lower. The estimated average risk of early death (from acute effects of radiation) to an individual, per year of operation, was one in 500 million ($p = 2 \times 10^{-9}$). The individual's average risk of early injuries (from acute effects of radiation) was one in 150 million (6.4×10^{-9}). The individual's average risk of fatal cancer (from long-term effects of radiation that would occur up to 50 years later), per year of operation, was estimated to be less than 1 in 10 million ($p = 8.4 \times 10^{-8}$). Likewise, these individual risks are also upper bound, conservative estimates. Risk (per year) of this order of magnitude was compared to an individual's annual risk of cancer death of 1 in 700 ($p = 1.4 \times 10^{-3}$), death from motor vehicle accidents of 1 in 20,000 ($p = 5 \times 10^{-5}$), homicide death of 1 in 60,000 ($p = 1.7 \times 10^{-5}$), and death from accidental poisoning of 1 in 100,000 ($p = 1 \times 10^{-5}$), based on health statistics in 1988.[37] More recent risks of fatal traffic accidents are 2.3, 2.0 and 1.7×10^{-5} respectively for the years 2008, 2009 and 2010. These risk levels are several orders of magnitude higher than the risk of fatal cancers and early deaths and injuries estimated from accidental release of radioactive materials from nuclear power plants.

3.4 Risk management measures

3.4.1 Radiological protection

According to the International Commission on Radiological Protection (ICRP), the aim of radiological protection is to protect human health against the harmful effects of ionizing radiation.[38] Its health objectives are 'to manage and control exposures to ionizing radiation so that harmful tissue reactions (the so-called 'deterministic effects') are prevented, and the risk of cancer or heritable effects ('stochastic effects') are reduced to the extent reasonably achievable'. Hence, the recommendations of the ICRP rely on scientific knowledge, based on data and on our understanding of the relationship between radiation and health, as well as expert judgement, with considerations of societal and economic aspects of radiation protection.[39] The ICRP assumes the 'linear no-threshold' hypothesis, i.e. at low doses below 100 mSv, any increase in dose proportionally increases the probability of cancer or heritable effects attributable to radiation.

Three categories of exposure to radiation are identified: workers who are exposed to radiation in the course of their work, the general public, and patients who are exposed to radiation in diagnostic, intervention or therapeutic procedures. Within the work environment where a source of radiation is present, the area may be designated as a 'controlled area', that requires specific safety provisions and protection measures to control normal exposure or prevent the spread of contaminated radioactive substances. Workers in controlled areas should be trained, monitored for exposure to radiation, and may require medical surveillance. A female worker who is pregnant should be further protected to the level of radiation exposure similar to the general public. This is for the protection of the foetus, not because females are more vulnerable to radiation.

For medical uses of radiation, the principle should be to do more good than harm to the patient. The responsibility for this decision should fall on the medical doctor who needs to have special training in radiation protection. For medical screening of healthy populations using radiological diagnostic tests, the potential harm of radiation must be weighed against the benefit of the screening test. This is a complex subject and the justification depends on many factors, such as the prevalence of the disease, the sensitivity and specificity of the test, the benefit of early detection, and the potential harm from exposure to radiation.

3.4.2 Dose limits and reference levels

The ICRP, after considering the health risks and benefits of individuals and the society, recommends dose limits for normal conditions and reference levels during an emergency. For the general public, other than medical needs and exposure to natural background radiation, the recommended dose limit is one mSv per year. Under special circumstances, a higher value could be allowed in a single year, provided that the average dose over five years is not more than one mSv per year.

For those occupationally exposed to radiation, the recommended effective dose limit is 20 mSv per year, or 100 mSv spread over a five-year period. However, the dose should not exceed 50 mSv in any one year. Pregnant workers should not receive a dose higher than that recommended for the general public.

The above dose limits do not apply to informed persons who volunteer to perform life-saving actions or prevent a catastrophic situation. However, they should be considered as occupationally exposed after the emergency operation, and should be protected accordingly.[40] During an emergency, the reference level is the dose level or risk that represents the upper limit of acceptable risk. Above this level, it is judged inappropriate to plan to allow exposure to occur, and protective actions should be planned and optimized. The reference level for members of the public ranges from 20 mSv to 100 mSv per year, and depends on the prevailing circumstances of the exposure situation. There will be no limit for informed volunteers if benefits to others outweigh the rescuers' risk. For urgent rescue, an exposure dose of less than 1,000 mSv or 500 mSv may be allowed. After the emergency, workers on recovery works may be allowed an exposure dose of less than 100 mSv. For the general public, an upper annual reference level of 20 mSv is recommended by ICRP.

These recommendations are based on data collected from long-term studies of people exposed to the radiation from the atomic bombs in Japan and from other exposure situations, such as the Chernobyl nuclear accident.

Workers who are occupationally exposed to radiation are required under the law to be registered and monitored for exposure to radiation to make sure they are not exposed to a dosage higher than the permitted limit of 20 mSv per year. Workers are also required to undergo annual medical examinations, including blood examinations, to detect any effect of radiation on their health by the Department of Health of the Hong Kong SAR Government.

3.4.3 Risk management of a nuclear power plant

The plan of constructing a modern nuclear power plant, including site selection, has to be approved by the Chinese government. The quality control in the construction and the operation are closely monitored by expert groups, such as the International Atomic Energy Agency (IAEA), government officials and interested parties. The operation including the authorization of the normal release of radioactive materials is transparent and is closely monitored by the Central People's Government of China and by the Hong Kong SAR Government.

Daya Bay was chosen with the consideration of a low probability of natural disasters such as earthquakes and tsunamis. Reactors in Daya Bay and Ling Ao are pressurized water types with redundant safety features and a containment construction to prevent the accidental release of radionuclides in disasters such as in Chernobyl.

The Central Government monitors the operation of the nuclear power plants. The environmental impact is monitored by the Central Government, the Hong Kong SAR Government, academics and interest groups.

In case of accident, the Central Government has an obligation to report the details of the accident to IAEA under the *Convention on Early Notification of a Nuclear Accident* when the accident has the potential for international transboundary release that could be of radiological safety significance for another state.[41]

As the last line of defence, the real time environmental radiation monitoring system by the Hong Kong Observatory will trigger the start of a contingency plan. The sensitivity of the monitoring system is high enough to detect 1/1,000,000 of the ^{131}I radioactivity at the intervention level (that will activate the contingency plan) (see Figure 4).

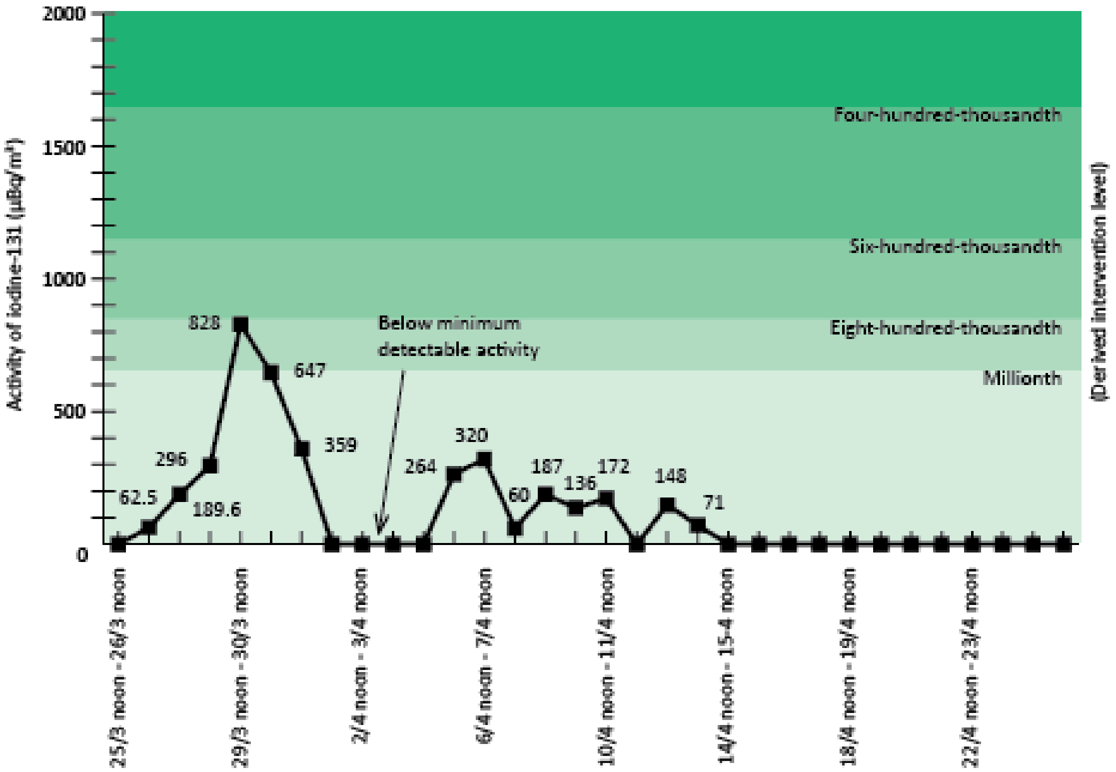

Figure 4: Radioactivity of Iodine 131 at the Hong Kong Observatory monitoring site in late March and April 2011 indicating the arrival of the radioactivity released in the Fukushima nuclear accident in March 2011[42]

The Hong Kong Observatory has been monitoring the background radiation levels in Hong Kong well before the operation of the nuclear power plant in Daya Bay. This includes radiation from the atmosphere, soil and water. In addition, radioactivity in food is monitored by the Hong Kong Observatory to ensure a safety level of radiation from ingested food.

3.4.4 Contingency plan

In most nuclear accidents, the radiation hazard is ‘on site’, which means that the radioactive materials are confined within the nuclear plant. Only when all the designed protections fail will radioactive materials escape into air in the form of a plume, which will then reach off-site areas.

A plume consists of a large amount of radioactive dust, gases (mainly noble gases such as xenon-133) and vapours (mainly volatile iodine and caesium). Some of the radioactive vapours and dusts will precipitate on to the ground as the plume moves, and this is enhanced by rain. The concentrations of radioactive substances in the plume will be reduced by dilution, precipitation and decay as the plume travels along its path.

In case the plume reaches Hong Kong, people in Hong Kong will be exposed to the radiation emitted by the radioactive plume. Furthermore, the precipitated radioactive dusts and vapours will contaminate the ground and water. In addition, radioactive substances will be inhaled as dusts or gases and ingested as contaminated food and water. The gamma dose rate will be highest when the plume arrives, but will decrease as the plume leaves, with the decay of the radionuclides of short half-lives.

The Hong Kong SAR Government has developed a contingency plan to protect the safety and health of members of the public from the health effects (both deterministic and stochastic) of radiation exposure due to the arrival of, and contamination by, a plume.

The IAEA recommends a radius of 3-5 km (away from the nuclear facility) as the Precaution Action Zone (PAZ). Within the PAZ, people may be exposed to the risk of severe deterministic effects if protection actions are not taken before or shortly after the release of radioactive materials begins. IAEA also defines an Urgent Protective Zone (UPZ), the radius of which may fall within a range from 5 to 30 km, to plan for evacuation, sheltering and distribution of stable iodine to the population, for reactors larger than 100 MW. The determination of the exact size of the zone is subject to site-specific analysis of the risk and consideration of practical circumstances, such as plant design, topography and other factors.[43] The European Commission recommends a radius of 25 km for the UPZ.[44] For the nuclear power plant in Tianwan in Jiangsu Province in China, the PAZ is 3-5 km, the UPZ is 7-10 km, and the ingestion exposure pathway zone is 20 km.[45]

Hong Kong is located outside of the PAZ. Ping Chau, Grass Island (Tap Mun) and Port Island are within the 25 km radius of the UPZ of the Daya Bay and Ling Ao nuclear power plant. Ping Chau is the only part of Hong Kong within 20 km of the power plants (see Figure 5). Therefore, when a radioactive plume is expected to approach Hong Kong, the planned evacuation of people from Ping Chau in the Hong Kong Daya Bay Contingency Plan has already fulfilled the international recommendations. For the people outside the UPZ, sheltering (staying indoors with windows closed) is an effective way to reduce the dose of any external source of radioactivity and reduces the inhalation of radioactive substances.

Under the Hong Kong Daya Bay Contingency Plan, Hong Kong has established two Emergency Planning Zones (EPZ): namely EPZ1 for protection against plume exposure and EPZ2 for protection against ingestion from contaminated food and water. EPZ1 is the area within the 20 km radius of the Daya Bay nuclear power plants. When there is a nuclear emergency in Daya Bay, regardless of the radiation level, evacuation of the people in this zone is taken as a precautionary measure. EPZ2 is the area within 85 km radius of the Daya Bay nuclear power plants. This zone covers the entire territory of Hong Kong. The food and water supplied in EPZ2 will be monitored and controlled.

Figure 5: Location of the Daya Bay nuclear power plants[46]

Besides Daya Bay and Ling Ao, the next closest nuclear power plant is in Taishan, Guangdong, more than 130 km away from Hong Kong, and is unlikely to pose any significant risk.[47] The Daya Bay Contingency Plan is in line with the IAEA Guideline[48] on the criteria for the protection against plume exposure (see Table 8).

Table 8: Countermeasures for the protection of exposed individuals[49]

Criteria	Countermeasures
Thyroid dose 50 mSv in 7 days	Iodine thyroid blocking
Whole body dose 100 mSv in 7 days Foetus dose 100 mSv in 7 days	Sheltering; evacuation; decontamination; restriction of consumption of food, milk and water; contamination control; public reassurance
Whole body dose 100 mSv in a year Foetus dose 100 mSv in whole development	Temporary relocation; decontamination; replacement of food, milk and water; public reassurance

In Hong Kong, food (including milk) and water are mainly imported. Therefore, people can be protected by the monitoring and control of radioactivity in food and water. Adults and infants are unlikely to have a fraction of 1 mSv from consuming food that can meet the requirement of CODEX[50] on radioactivity in food for a year.[51]

In the Chernobyl accident, milk was contaminated with ^{131}I. The delay of countermeasures (to stop the consumption of contaminated milk) led to large doses of radiation to the thyroids of members of the general public, especially children. Several thousand extra thyroid cancers (with 15 fatal cases by 2005) were observed among people who were children or adolescents at the time of accident.[52]

In the Fukushima accident, planned evacuation (or temporary relocation) from Iitate Village was implemented to protect residents who might otherwise have a cumulative dose of 20 mSv in a year after the accident.[53]

This planned evacuation was intended to reduce the risk of occurrence of stochastic illnesses (such as cancer) in the future and the psychological stress among these residents. However, evacuation will affect the social and economic conditions of the people in the affected area.

In the Daya Bay Contingency Plan, various government departments are involved. The Hong Kong Observatory has the expertise in monitoring weather and radiation and, in the unlikely event of an accidental release, predicting the movement of the plume. The Water Supply Department monitors and controls radioactivity in the drinking water supply. The Food and Environmental Hygiene Department and the Agriculture, Fisheries and Conservation Department monitor the food supply for radioactivity. The Fire Services Department and Police Department will assist with rescue and evacuation. The Department of Health advises on radiological protection. Hospitals will be prepared for medical support. Messages to the public will be broadcast by TV and radio.

The public should have some understanding of radiation risks and the Contingency Plan in order to prevent chaos when the plan is activated. For example, issuing the order to take shelter to residents in an area might trigger the opposite effect – spontaneous evacuation from the affected area that would result in traffic chaos and an increase of radiation exposures to these residents.

3.4.5 Risk management of the government to protect health and safety

The government has to justify its use of limited resources to protect the health and safety of members of the public. In Hong Kong, there are natural and man-made threats such as typhoons, heavy rain, landslides, fire, traffic accidents, collapse of buildings, electrical safety hazards, toxic chemicals in food and water, and infectious diseases. We should understand that a nuclear accident is only one of them.

During the normal operation of a nuclear power plant, its emissions have little impact on public health and safety, whereas other ways of generating electricity, such as using coal and natural gas, produce air pollutants that affect the health of the public, not to mention the release of greenhouse gases into the atmosphere and the potential for climate change.

The chance of a major nuclear accident is 30 in a million per year.[54] The adverse effects to health can be reduced to an acceptable level by an effective contingency plan if it ever occurs. However, it must be cautioned that a major nuclear accident can have lasting consequences to the environment and may affect human health.

4 Practical tips to minimize exposure to ionizing radiation

As inhalation of radon constitutes the major source of radiation for an individual not undergoing any medical radiation procedure, the most important thing to do is to reduce exposure to radon in the home and workplace:

1. Do not smoke. Radionuclides (^{210}Po and ^{210}Pb) are present in cigarette smoke. They cause lung cancer in addition to all the other cancer-causing chemicals in cigarette smoke. Moreover, the presence of radon in the environment enhances the risk of lung cancer from cigarette smoking;

2. Maintain good air quality in your living environment. Radon will accumulate when the windows are closed with no artificial ventilation. Also, cracks in the floor should be repaired as they will lead to the seepage of radon from the soil into the building;

3. Avoid unnecessary exposure to X-rays. This applies to some X-ray examinations for non-medical purposes (e.g., employment, legal, insurance), and one should ask if the risk of exposure to a radiation dose is worth the benefit, if any, of that examination. The harms and benefits of routine X-rays for screening purposes should be discussed with your doctor. The use of radiation in the treatment of cancer also produces harmful effects. However, the benefit of treating cancer generally outweighs the harm of radiation;

4. Beware of products that may use radioactive materials unnecessarily. Some of these items may even claim to have health benefits. All ionizing radiation produces some risk. Beware of the presence of radioactive materials added into food and other consumer products. To give some examples, radioactive thorium has been used as a long-lasting deodorant, in socks and underwear. Thorium has also been used in some water purifiers with unsubstantiated miraculous effects, and in pain-relief pads;[55] and

5. Use clean fuel. Coal burning is a potential source of inhalation of radioactive substances. Coal is being used in Hong Kong’s own power plants. Coal contains varying amounts of naturally occurring radionuclides and coal burning will result in the concentration of these radionuclides in the ashes (fly ash and furnace bottom ash).[56] Coal ash contains much higher concentrations of radionuclides than the source coal and is a potential source of radiation exposure to human.[57] To reduce the release of fly ash into the atmosphere, various filtration and dust suppression mechanisms are being used in power plants. The use of cleaner fuel such as natural gas in power generation will further reduce the amount of radioactive substances from this source.

Endnotes

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[1] An element is a pure chemical with a unique ‘atomic number’, the total number of protons in the nucleus of its atom. Its ‘atomic weight’ may vary depending on the number of neutrons present in the nucleus.

[2] SI unit refers to the International System of units (SI stands for *Système International*, in French), which was developed in 1960 based on the metric system of metre- kilogram-second. It is the most widely used system in science, except in the US, where the old system is still commonly used.

[3] UNSCEAR (2000), *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly*. New York: United Nations.

[4] UNSCEAR (2000), p. 5, Table 1.

[5] UNSCEAR (2000), p. 7, Table 2.

[6] UNSCEAR (2008), *Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly,* Annex A, Table B4, p. 70. New York, United Nations.

[7] UNSCEAR (2000), p. 8, Table 3.

[8] UNSCEAR (2000), p. 8, Table 4.

[9] Hong Kong Observatory (2012), “Basic operating principles of nuclear power station using pressurised water reactor”, http://www.hko.gov.hk/education/dbcp/pow_stat/eng/r4.htm (accessed May 2012).

[10] UNSCEAR (2008), Annex C.

[11] United States Nuclear Regulatory Commission, Office of Public Affairs (2009), “Three Mile Island Accident”. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.pdf (accessed October 2012).

[12] Note that this explosion is not a nuclear reaction, but is caused by the high pressure resulting from the formation of steam in the cooling system.

[13] UNSCEAR (2008), Annex D.

[14] World Health Organization (WHO) (2011), *Fact Sheet: Health effects of ionizing radiation. Ionizing radiation, health effects and protective measures*, http://www.who.or.jp/index_files/Fact%20sheet%20_%20Ionizing%20radiation_final.pdf (accessed May 2012).

[15] WHO (2011).

[16] The National Diet of Japan (2012), *The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission*.

[17] International Commission of Radiological Protection (ICRP) (2007) *Annals of the ICRP. Publication 103. The 2007 Recommendations of the International Commission of Radiological Protection*, Ch. 3, p50. Elsevier, Amsterdam, The Netherlands.

[18] WHO (2011).

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[19] A measure of radiation quality – low LET is sparsely ionizing radiation while high LET is densely ionizing radiation.

[20] International Commission of Radiological Protection (ICRP) (2007), *Annals of the ICRP. Publication 103. The 2007 Recommendations of the International Commission of Radiological Protection*, p. 164, Annex A, Elsevier, Amsterdam, The Netherlands.

[21] International Commission of Radiological Protection (ICRP) (2012). *Annals of the ICRP. Publication 118. ICRP Statement on Tissue Reactions and Early and Late Effects of Radiation in Normal Tissues and Organs-Threshold Doses for Tissue Reactions on a Radiation Protection Context*, Vol 41 (1/2), p. 304.

[22] WHO (2011).

[23] Adapted from http://www.hko.gov.hk/education/dbcp/rad_health/eng/r3_b.htm#.

[24] UNSCEAR (2000), Annex B, Table 11.

[25] Tso, M. Y. W. and J. K. C. Leung (2000), “Population dose due to natural radiations in Hong Kong”, in *Health Physics* 78(5): 555-558.

[26] UNSCEAR (2000), Annex B, Table 7.

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[34] ICRP (2007), Ch. 5, pp. 81-101, 143, 164 and 194, Annex A.

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[35] Hong Kong Cancer Registry, (2010), http://www3.ha.org.hk/cancereg/all_2010.pdf.

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[37] Cook *et al*. (1990).

[38] ICRP (2007), Ch. 2, p. 41.

[39] ICRP (2007).

[40] ICRP (2007), Ch. 6, p. 116, Table 8.

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[54] When comparing the risk of a nuclear accident with other accident rates in our daily life, the following statistics give a useful perspective:

- Fatality rate from traffic accidents = 200 in a million per licensed vehicle in 2009-2010 (http://www.roadsafety.gov.hk/eng/information/statistics_charts.html).
- Major release frequency from nuclear accidents = 30 in a million per year (Cook *et al*. (1990).

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