Chapter 3. The Natural Radiation Background

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Abstract. The natural background radiation, to which the human race has always been subjected, has many components. Each component varies from place to place and also with time. Cosmic radiation is a major contributor to the external dose to the human body whilst naturally-occurring radionuclides of primordial and cosmogenic origin contribute to both the external and internal doses, with the primordial radionuclides being the major contributor in both cases. The components of the natural background radiation and their variations are described.

Man himself, by his practices, habits and technological innovations, has continually modified the radiation dose to which he has been subjected. Some of these modifications are described briefly.

The two traditional methods of measuring background radiation, viz. ionisation chamber measurements and scintillation counting, are looked at and the prospect of using thermoluminescent dosimetry is considered.

INTRODUCTION

Man has always been exposed to ionizing radiation from various natural sources. A distinguishing characteristic of this natural irradiation is that it involves the entire population of the world and it has been experienced at a relatively constant rate for a very long time. On the other hand, natural background radiation is not uniform throughout the world, and in fact, exposure to natural radiation sources varies substantially from place to place. In addition, exposure to some of its components can exhibit time variations though, in general, these are small. The description of natural radiation background, its components and its variations form the bulk of this chapter. More details of the radiation levels quoted below and other related information may be found in Annex B to the 1977 Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1977).

Man has in many ways altered the original pattern of natural sources of radiation and has introduced new sources of radiation into the environment. In most cases this has increased the radiation dose he receives and is often referred to as technologically enhanced radiation; this aspect of radiation received by man will be dealt with briefly in this chapter and in greater detail in other chapters.

The various natural radiation sources include:-

(a) External sources of extra-terrestrial origin (cosmic rays) and of terrestrial origin (radionuclides present in the earth's crust and the atmosphere). Both vary from place to place, the terrestrial radiation being the more variable.

(b) Internal sources, comprising naturally occurring radionuclides which are taken into the body. A few of these (carbon-14, potassium-40) have fairly constant concentrations in the body but, for the majority, the concentrations vary according to the concentrations in the environment.

A summary of typical absorbed dose-rates arising from the components of the natural radiation background is given in Table 1.

Table 1
Typical absorbed dose-rates arising from the components of the natural radiation background (UNSCEAR 1977) *

	nGy h^{-1}	nGy h^{-1}
External dose-rates		
Cosmic radiation		32
Hard component	22	
Soft component	9.6	
Neutron component	0.4	
Cosmogenic radionuclides		0.2
Primordial radionuclides (world-wide average)		45
Internal dose-rates		
Cosmogenic radionuclides		1.53
Tritium-3	0.001	
Beryllium-7	0.009	
Carbon-14	1.5	
Sodium-22	0.02	
Primordial radionuclides		19.5
Potassium-40	18	
Rubidium-87	0.5	
Uranium-238 series)		
Uranium-235 series)	1 **	
Thorium-232 series)		
	Total	98

* An absorbed dose rate of 1 nGy h^{-1} is the same as an absorbed dose rate of approximately 0.874 mrad per year.

** Lung tissue receives an additional absorbed dose-rate of 34 nGy h^{-1} from radon and its daughters, and bone-lining cells receive an additional absorbed dose-rate of 4 nGy h^{-1} from lead-210 and polonium-210.

EXTERNAL RADIATION

Cosmic Rays

The high energy radiations that enter the earth's atmosphere from outer space are known as primary cosmic rays. When they interact with atomic nuclei in the atmosphere, secondary particles and electromagnetic radiation are produced; these are called secondary cosmic rays.

The origin of primary cosmic rays is still not completely determined. However, it is known that most of the observed radiation originates within our galaxy. In addition to the galactic cosmic rays, the sun produces solar cosmic rays related to solar flares.

Primary galactic cosmic rays consist largely of high-energy protons, some helium-4 ions and very small proportions of heavier particles together with electrons, photons and neutrons. The energy spectrum covers the range 1 MeV to 10^{14} MeV with a peak around 300 MeV per particle. The galactic cosmic ray flux density remains fairly constant though there is a small 11-year variation, coinciding with the solar cycle of sunspot activity, with large bubbles of ionized gas of solar origin temporarily deflecting the primary cosmic rays. The earth's magnetic field also deflects low-energy protons in the primary cosmic rays towards the magnetic poles to produce a latitude variation.

Primary cosmic rays of solar origin have energies in the 1 MeV to 40 MeV range and are associated with solar flares which reach their maximum in about 10 minutes before slowly subsiding. Because of the relatively low energy of primary solar cosmic rays, only the largest flares produce an observable effect at the earth's surface and such effects are observed less than once per year on average.

The highest energy cosmic ray particles entering the atmosphere undergo nuclear reactions with atoms present in the air, producing neutrons, protons, pions and kaons. In a succession of reactions which can then follow (producing a 'cascade' effect), pions decay to muons or photons and cosmogenic nuclides including, among others, tritium, beryllium-7, beryllium-10, sodium-22 and sodium-24 are formed. One important reaction is the capture of thermalized neutrons by nitrogen-14 to form carbon-14.

The ionizing component of cosmic radiation can be regarded as having two components - 'soft' and 'hard'. The soft component, which is responsible for some 30 percent of the dose, consists mainly of electrons and is stopped by about 5 cm of lead whilst the hard component, being composed of heavier particles, can penetrate many metres of earth. The absorbed dose rate in air of unattenuated cosmic radiation at ground level is 32 nGy h^{-1}. The principal variation with time of unattenuated cosmic radiation is that due to barometric pressure and is about 3.5 percent per cm Hg pressure variation (the variation with pressure decreases as the radiation becomes harder through attenuation). A small variation with atmospheric temperature has also been reported. The variation of dose-rate with atmospheric pressure leads naturally to an increase of dose-rate with altitude. The dose-rate from the neutron component of cosmic radiation is comparatively small, being approximately 0.4 nGy h^{-1}, but rises above 1 nGy h^{-1} at 1000 metres altitude.

Terrestrial Radiation

Radioactive nuclides have always been present in the natural environment, their decay producing alpha particles, electrons and electromagnetic radiation. Because the human organs and tissues in which the doses are

usually calculated are shielded by at least a few millimetres of tissue, which absorbs practically all of the energy of alpha particles and electrons emitted by natural radionuclides, only the gamma contribution will be considered here. However, it should be borne in mind that the skin and, to a lesser extent, the lens of the eye, being at or near the surfaces of the body, receive higher doses than tissues and organs of primary interest.

The natural radionuclides in the environment can be divided into two classes, cosmogenic and primordial. The cosmogenic radionuclides have been listed above. Of these, beryllium-10 is a long-lived beta-emitter which does not therefore contribute to the dose rate. The contributions from beryllium-7, sodium-22 and sodium-24 are negligible when compared with those from the primordial radionuclides. However, beryllium-7 with a half-life of 53.3 days and emitting a γ-ray of 478 keV is easily measured in air filters and some other environmental samples using standard low-level gamma spectroscopy techniques. Among the primordial radionuclides, the main contributors to external exposure are potassium-40 and the two radioactive series headed by uranium-238 and thorium-232. All are long-lived radio-nuclides that have existed in the earth's crust throughout its history.

In igneous rocks, the concentration of radioactive nuclides is related to the quantity of silicates, being highest in acidic rocks and lowest in the ultrabasic rocks. Generally, sedimentary rocks have a lower radioactivity than igneous rocks, though some shales and phosphate rocks are highly radioactive. The concentration of radionuclides in soil is that of the rock from which it is derived, diminished by the leaching of moving water, diluted by increased porosity and by added water and organic matter and augmented by sorption and precipation of radionuclides from incoming water.

Taking a representative soil of density 1.6 cm^{-3} and consisting by weight of 67.5 percent SiO_2, 13.5 percent Al_2O_3, 4.5 percent Fe_2O_3, 4.5 percent CO_2 and 10 percent H_2O, it is possible to calculate the dose rate at a height of 1 metre above ground for any gamma-emitter homogeneously distributed in the soil. For a distribution of 37mBq potassium-40 per gram of soil, the dose-rate would be 1.6 nGy h^{-1}; the equivalent figures for the uranium-238 and thorium-232 series in which all constituents are in radioactive equilibrium are 15.8 and 24.5 nGy h^{-1}. The assumption of radioactive equilibrium is generally not strictly valid for soils because of differentiation resulting from

(1) the soil-forming process and biological reworking and
(2) the escape of some radon from the soil into the atmosphere.

The main contributions to the absorbed dose-rate are due to thallium-208 and actinium-228 in the thorium-232 series, while for the uranium-238 series, about 99 per cent of the dose-rate is due to lead-214 and bismuth-214. Gamma energies range up to 2.6 MeV and are partly attenuated by the soil with the result that, for a typical natural radiation field, the predominant contribution to external irradiation above the ground originates from the top 30 cm of soil.

Surveys of the radiation dose-rate from the natural background have been made in a number of countries by a variety of methods, some being more comprehensive and valid than others. A population-weighted average absorbed dose rate in air obtained from data submitted to UNSCEAR before 1977 gives a figure of 43 nGy h^{-1}. This involves 30 percent of the world population but only about 2 percent of the total land area, all in three separate regions of the Northern Hemisphere. Based on the world-wide average concentration of primordial radionuclides in soil, a figure of 46 nGy h^{-1} can be calculated.

Hence a value of 45 nGy h^{-1} can be considered a reasonable estimate of the outdoor average absorbed dose-rate in air, 1m above the ground, from terrestrial radiation.

The dose-rate from all cosmogenic radionuclides taken together can be calculated using a few approximations. The figure so calculated is of the order of 0.2 nGy h^{-1}, which is insignificant compared with the contribution from primordial radionuclides in the ground.

The absorbed dose-rate in air at a given location is not constant. The most significant variations are associated with snow cover, soil moisture content and the atmospheric concentration of radon-222 decay products. Snow cover acts as an attenuator of the radiation from the underlying soil and a 20cm blanket of snow reduces the exposure rate by about 50 per cent. Soil moisture similarly has an attenuating effect on radiation from the soil; however, it also prevents the emanation of radon-222 and the resultant accumulation of its decay products in the soil compensates to a variable extent for the attenuation effect of the moisture. The overall attenuation can average 20 percent during periods of wet weather. Strong inversion conditions prevent the mixing of radon-222 and its daughters in the whole atmosphere and by confining them to the layers near the ground can raise the local dose-rate by as much as 10 nGy h^{-1}. Increases of a similar amount can be produced by a heavy rainstorm scavenging the atmosphere of the daughters of radon-222 and depositing them on the ground; this however is only a temporary effect as the two predominant daughters decay with half lives of 26.8 and 19.7 min respectively and then the dose-rate from the ground is further lowered by the attenuation effect of the rainwater.

It should be noted that a comprehensive study of background radiation dose-rate has not been carried out in Australia to date, but that plans are being made for this Laboratory to make such a survey in the near future.

Overseas surveys have revealed areas, sometimes well-populated, where the background dose-rate is very high due to strong concentrations of radionuclides in the soil; the best known of these are in India and Brazil. In India, a narrow coastal strip 250 km long and averaging 0.5 km wide in the States of Kerala and Tamil Nadu is very rich in monazite mixed with ilmenite, rutile, sillimanite and zircon. In one part of the strip which is populated by about 70,000 persons, the thorium concentration ranges between 8.0 and 10.5 percent by weight in patches, with an average dose-rate in the region of about 1300 nGy h^{-1}. In Brazil, three coastal towns are built on monazite sands and in one of these with a resident population of 12000 and an additional 30000 holiday makers every summer, absorbed dose-rates of 1000-2000 nGy h^{-1} are measured in the streets and up to 20000 nGy h^{-1} over selected spots on the beach. Also in Brazil two volcanic regions exhibit high dose-rates. In one, a mineral called pyrochore containing 60 percent niobium oxide, 1.9 percent thorium oxide and 1.3 percent uranium oxide produces local dose-rates up to 4000 nGy h^{-1} whilst, in the other region, an uninhabited hill has a dose-rate of 28000 nGy h^{-1}.

In Ramsar, Iran, dose-rates of 2000-50000 nGy h^{-1} have been reported in a small area characterized by the presence of spring water rich in radium-226. In France, dose-rates of 2000 nGy h^{-1} are not uncommon and a very localised value of 100000 nGy h^{-1} has been discovered.

INTERNAL RADIATION

Cosmogenic Radionuclides

Very little of the dose from natural background is contributed by the cosmogenic radionuclides. Of the many nuclides produced by cosmic rays, only tritium, beryllium-7, carbon-14 and sodium-22 contribute appreciably to the dose. Practically all of the tritium participates in the normal water cycle as tritiated water. Its concentration in the oceans averages 110 mBq l^{-1} and in continental surface waters ranges from 220 to 880 mBq l^{-1}. Assuming that the specific activity in the body is similar to that in continental surface waters, the dose to whole body is of the order of 1×10^{-3} nGy h^{-1}.

Because of its comparatively short half-life (53.6 days) the bulk of the beryllium-7 remains in the surface air where it contributes about 2×10^{-3} nGy h^{-1} to the lung. However, some beryllium-7 enters the body through leafy vegetables and delivers a whole body dose of 9×10^{-3} nGy h^{-1}.

Carbon-14, though formed in smaller quantities than the other cosmogenic radionuclides named, has a long half-life and universal biological involvement. The natural specific activity of carbon-14 is 230 mBq g^{-1} and the dose to whole body calculated to be 1.5 nGy h^{-1}.

Sodium-22 also has a small production rate and atmospheric concentration but because of its 2.62 year half-life and its metabolic behaviour in the body, it delivers a whole body dose estimated to be 2×10^{-2} nGy h^{-1}.

Primordial Radionuclides

The primordial radionuclides which are significant sources of internal radiation are potassium-40, rubidium-87 and the members of the three radioactive series headed by uranium-238, thorium-232 and uranium-235 respectively.

The major naturally-occurring source of internal radiation dose is potassium-40. Being an essential element, potassium is under close homeostatic control in the body; that is, any excessive intake of the element is eliminated again by the body which retains only the quantity required for its healthy functions. The concentration of potassium contained in the whole body is a function of age, sex and physical fitness, and any radical departure from normal (especially a reduction) is generally a sign of ill-health.

A typical value for a healthy, male adult would be 2g of potassium per kilogram body weight. Potassium concentration is high in well-used muscles and low in bones and fat. Therefore, the average concentration of potassium in the body falls with advancing years (as a consequence of loss of muscle tone and less physical activity), obesity (due to excessive low-potassium fat) and some diseases. In the general population, females have a lower concentration of potassium in their bodies than males; athletes, on the other hand, tend to have high potassium concentrations. The highest concentration in the human body is in the red marrow where a value of 4.4 g kg^{-1} is typical.

The isotopic abundance of potassium-40 is 118 parts per million and the radionuclide is both a beta and gamma-emitter. Consequently, the average absorbed dose to the red marrow is 31 nGy h^{-1} and to other vital organs and the whole body is 17 to 19 nGy h^{-1}.

Very little is known about the behaviour of rubidium-87 in man's environment. From known mass concentrations of rubidium in body organs and its radiation characteristics, absorbed doses in the various organs range between 0.5 and 1 nGy h^{-1}, with 0.5 nGy h^{-1} being the dose to the whole body.

Of the three natural series of primordial radionuclides, the biological effects of the members of the series headed by uranium-235 can be ignored when compared with those of the far more abundant radionuclides in the uranium-238 and thorium-232 series. All members of the series can enter the body through ingestion whilst radon-222 and radon-220 with their short-lived daughters may also be inhaled. The natural distribution of members of the series in the human body combined with the variability of the concentration of these radionuclides in the various components of the environment makes the assessment of radiation dose from each radionuclide to the various body organs a very complicated problem.

However, it has been estimated that the dose to lung from the average concentration in the environment of radon-222 and its daughters is 34 nGy h^{-1} and from radon-220 and its daughters is 5 nGy h^{-1}. The dose to bone-lining cells from the long-lived lead-210 and its daughters has been estimated at 4 nGy h^{-1} and from ingested radium-228 and daughters to be 1 nGy h^{-1}. The contributions of each of the radionuclides in the two series to gonads, lung, bone-lining cells and red bone marrow, other than the ones specifically mentioned above, are less than 1 nGy h^{-1}.

MAN'S MODIFICATION TO HIS RADIATION ENVIRONMENT

Since man abandoned his primitive nomadic existence he has, through his practices, habits and technological innovations continually modified the radiation dose to which he has been subjected. Such modifications are numerous and they will be described briefly below.

Man's first modification to his radiation environment occurred when he started constructing buildings in which to live. The construction of a floor, walls and roof attenuates the background radiation reaching the inhabitant; however, this is counteracted by the dose from the radioactivity contained in the construction materials. The net result can be positive or negative. If the wall materials are rich in radium and thorium, an additional dose may arise from the accumulation of radon and thoron gas and daughter products in unventilated parts of the building, especially basements. In modern times, air-conditioning with a high proportion of re-cycled air can have a similar effect.

When man started burning coal, he unwittingly added to his radiation dose. Coal contains all members of the uranium-238 and thorium-232 series. When coal burns the radon and thoron are released to the atmosphere, and the other radionuclides are concentrated in the slag and fly ash. In large coal-burning power stations, the slag and the bulk of the fly ash are retained, but the finer particles of fly ash escape with the gaseous products and may be deposited in the surroundings. Sampling of the top layers of soil and of snow in the vicinity of coal-fired power stations has revealed enhanced quantities of the natural radionuclides and these, together with inhaled radioactive gases and particles contribute an additional radiation dose to the inhabitants of the area.

An increasing number of consumer products are being made with a radioactive content. Earlier this century, radium was the radionuclide used in most products, but the hazard from this radionuclide was recognised and now it has been replaced by one of several artificially-produced radionuclides selected for their lower hazard. Radionuclides are used in radioluminous products, electronic and electrical devices, antistatic devices, gas and smoke detectors, glazed ceramics, welding rods and other devices including scientific instruments. Although the contribution from any one product is very small, it could become appreciable if their use is unchecked by regulation.

During the past 85 years, x rays and radionuclides have found increasing use in medicine. Initially radium was used almost exclusively, though thorium also played a minor role. In more recent years, radon replaced radium for many medical applications and now these radionuclides have been replaced by short-lived artificial radionuclides. Whilst the benefits of x rays and radionuclides in medicine obviously greatly exceed any disadvantages, they nevertheless increase the radiation dose to the population and should not be used indiscriminately.

Phosphate deposits usually contain relatively high concentrations of the naturally-occurring radionuclides of the uranium-238 series. About half of marketable phosphate rock is converted to fertilizer, and the other half is used to produce other commodities such as phosphoric acid. The mining and processing of phosphate ore redistributes uranium-238 and its daughters among the various products, by-products and wastes of the industry. For example in the production of phosphoric acid, most of the uranium and thorium is transferred to the acid, whilst most of the radium remains with the gypsum by-product. Gypsum has been found to be useful in the building industry where it contributes to the radiation dose in buildings.

With the increasing popularity of air travel, there is a corresponding increase in the radiation dose to the population due to the enhanced dose-rate from cosmic radiation at high altitudes. Measurements show that at an altitude of 10,000 metres the absorbed dose-rate is 1500 nGy h^{-1} and at 13,000 metres it is 3000 nGy h^{-1}. Supersonic planes fly at higher altitudes and thus passengers in them are subject to higher dose-rates; however, for a given journey the total dose is less than for a subsonic flight at normal operational altitude because of the reduced time spent on the journey.

Some pockets of commercially used natural gas contain enhanced concentrations of radon. Some of this is removed by the processes used to extract methane, ethane, propane and heavier hydrocarbons for bottled gas and more of it decays in the time between extraction from the well and use by the domestic consumer. Nevertheless, the remainder adds a small fraction to the dose-rate received by some users of natural gas.

In the last 35 years a small additional dose-rate to the population has arisen from radioactive fallout from the detonation of nuclear devices in the atmosphere. This is sometimes estimated as the 'dose commitment', being the total dose received to date from fallout plus the dose to which a person is committed in the future as a result of (i) strontium-90 already in his bones and (ii) the very small quantity of radionuclides in the environment which is still to find its way into his body or subject him to future external radiation. As the majority of nuclear tests have been carried out in the Northern Hemisphere, the Australian adult population has a lower dose commitment than the world average. It has been estimated at 580 μGy to the whole body, 1110 μGy to the bone-lining cells and 950 μGy to the bone marrow; the additional dose commitment to the bone components arise from beta-emitting strontium-90 in the bones.

A small portion of the world population will have received an increased dose due to the nuclear industry which includes uranium mining and milling, fuel processing and the generation of nuclear power. This subject will be dealt with more fully in other chapters.

METHODS OF MEASUREMENT

The measurement of radon and its daughters in the atmosphere and the radiochemical analysis of radionuclides in environmental samples, with emphasis on enhanced levels, will be discussed in other chapters; the measurement of normal levels of background gamma radiation will be briefly discussed here.

Two methods have been traditionally used in the past - ionisation chamber measurements and scintillation counting. Ionisation chamber measurements, due to the fact that they use the same method by which dose is defined, are the more accurate and reliable, scintillation counting is generally more convenient because the equipment is lighter and more compact.

Because the dose-rate from normal background radiation is so small, it is not feasible to construct a workable ionisation chamber operating at atmospheric pressure to measure it accurately. By filling a 25cm diameter spherical ionisation chamber with argon to a pressure of 25 atmospheres, the output current for a typical background of 100 nGy h^{-1} would be 3×10^{-13} amps. Some years ago this could be measured using specially selected tetrode electrometer valves in rate-of-drift circuitry for portable instruments; for studies of background fluctuations using a static monitor, a vibrating reed electrometer was necessary. Before the advent of Teflon in the late 1950s natural amber or highest grade polythene were the only suitable insulator materials available for such instruments. Present day equipment can be manufactured using metal oxide-silicon field effect transistors (MOSFET) in the current measuring circuitry and alumina ceramic insulators to support the central electrode. With rechargeable batteries, the equipment can be made portable though still rather heavy. By suitable design of the chamber, the variation of response with incident gamma-ray energy can be minimised and an accuracy of better than 5 percent regardless of the composition of the background gamma-ray energy spectrum, is claimed by a commercial manufacturer. Because the detecting medium inside the chamber is unaffected by outside conditions and the current measuring circuitry is very simple, high stability under the full range of likely meteorological conditions can also be claimed.

Scintillation counting equipment is more compact and hence more portable, because the detecting medium is condensed as a solid. In the 1950s expensive sodium iodide crystals or anthracene crystals were the only detectors available. The development of plastic scintillators in the late 1950s provided a cheaper alternative which could be manufactured in larger volumes. The photomultiplier tubes, required to be coupled to the scintillators, have improved in their characteristics in recent years, but are still a source of instability in the circuitry. The presence of the photomultiplier tube attached to the scintillator introduces an inhomogeneity into the directional response of such an instrument. Though the equipment is easily made portable, the manufacturer of one such commercial instrument claims an accuracy of only 20 percent.

Recent developments in the field of thermoluminescent dosimetry indicate that theoretically this technique could be used to measure radiation doses at background levels with good accuracy over a period of months. This appears to have been borne out in practice by a series of exposures at this Laboratory but the validity of the data has not yet been confirmed. The technique suggests a convenient method of carrying out large scale population dose surveys.

Further reading

A precis of the latest available information on natural and technologically enhanced radiation is contained in some of the Reports of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to the U.N General Assembly. Reports containing such information were published in 1958, 1962, 1966, 1972 and 1977. A further report will be published in 1981 or 1982. Conferences on the Natural Radiation Environment were held in 1962, 1972 and 1978 and Reports have been published in book form as follows:

"The Natural Radiation Environment", ed. J.A.S. Adams and W.M. Lowder (1964). Uni. of Chicago Press.

"The Natural Radiation Environment II" (2 vols.) ed. J.A.S. Adams, W.M. Lowder and T.F. Gesell (1975). National Technical Information Service, Springfield, Virginia. (Also as CONF-72-0805 P1-2).

"The Natural Radiation Environment III" (2 vols.) ed. T.F. Gesell and W.M. Lowder (1980) National Technical Information Service, Springfield, Virginia (Published as CONF 780422).

All of these publications contain extensive bibliographies.

REFERENCE

UNSCEAR (1977) 'Sources and Effects of Ionizing Radiation'. United Nations Scientific Committee on the Effects of Atomic Radiation. 1977 Report to the General Assembly, with annexes.