

IONIZING RADIATION UNITS AND STANDARDS

M. Ragheb
1/27/2006

INTRODUCTION

Radiation is a natural phenomenon that existed long before the advent of humans, and permeates the known Universe. Humans have used radiation in useful applications such as nuclear medicine, food preservation, weapons and power production, adding to the natural sources of radiation.

The term “radiation” is broad and encompasses photons in the electromagnetic spectrum (Fig. 1), such as visible light, microwaves, radio waves and x and gamma rays, as well as particles such as cosmic rays, electrons, and alpha particles. However the term is often used to mean ionizing radiation.

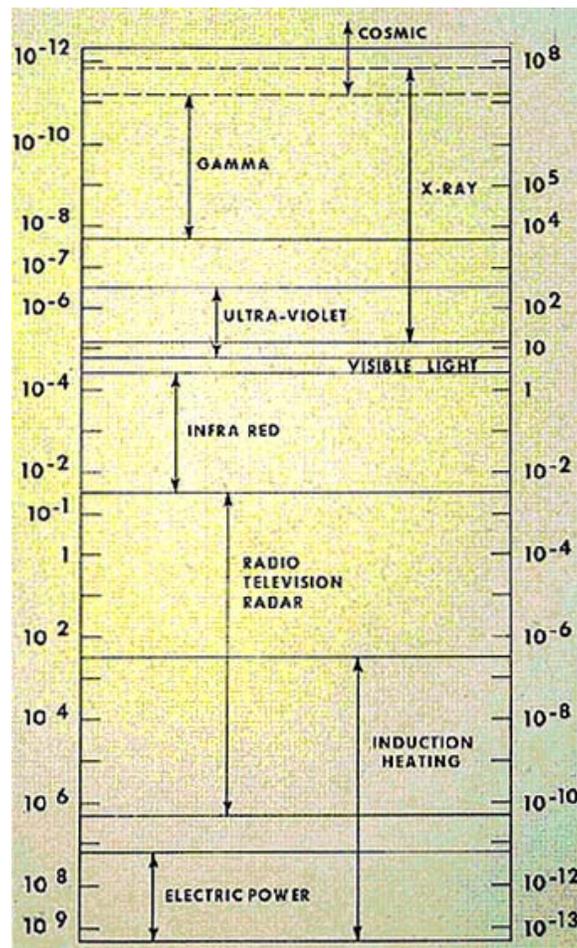


Fig. 1: The electromagnetic radiation spectrum. Left scale is wave length in cms, and right scale is energy in eV.

Ionizing radiation is radiation that has enough energy to remove electrons from atoms, consequently creating charged ions and radicals in the materials it interacts with. Ionizing radiation includes beta and alpha particles, neutrons, protons, as well as x and gamma radiation. Radio waves and microwaves used in communications do not possess enough energy to ionize matter. Microwaves used in cellular phones, for instance, are not considered as ionizing radiation even though they can cause damage by delivering energy to the adjacent tissue, in this case, the brain.

There are two types of ionizing radiation:

1. **Directly ionizing radiation:** Forms of radiation that can eject orbital electrons directly from atoms by interacting with the Coulomb force. These include charged particles such as electrons, protons and alpha particles.

2. **Indirectly ionizing radiation:** These are forms of radiation that indirectly transfer energy to charged particles of the absorber atom such as electrons or protons. These include gamma rays and neutrons (Fig. 2).

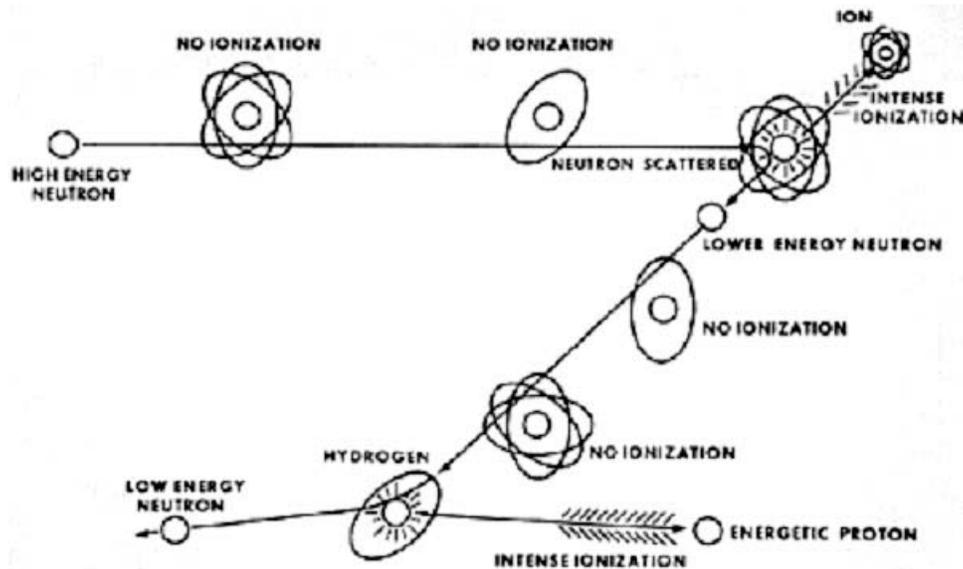


Fig. 2: Ionization created by a neutron as indirectly ionizing radiation.

Directly ionizing radiation tends to deposit its energy at a localized range in materials, whereas indirectly ionizing radiation deposits it along its whole path, as shown in Fig. 3.

Atoms or nuclei that emit ionizing radiation exhibit the process of radioactivity and can be naturally occurring or human made.

ACTIVITY

Activity refers to the rate of radioactive transformations of a radioactive isotope. The generally accepted is the number of transformations of decays per unit time.

The Système International (SI) unit is the Becquerel:

$$1 \text{ Becquerel} = 1 \text{ Bq} = 1 \text{ [Disintegration/sec]} \quad (1)$$

The conventional unit of activity is the Curie:

$$1 \text{ Curie} = 1 \text{ Ci} = 3.7 \times 10^{10} \text{ [Disintegrations/sec]}, \quad (2)$$

which corresponds to the activity of 1 gram of the Radium²²⁶ isotope. We can also write:

$$1 \text{ Bq} = 27 \times 10^{-12} \text{ Ci}. \quad (3)$$

Table 1 shows the activities in Bq of some materials and common objects.

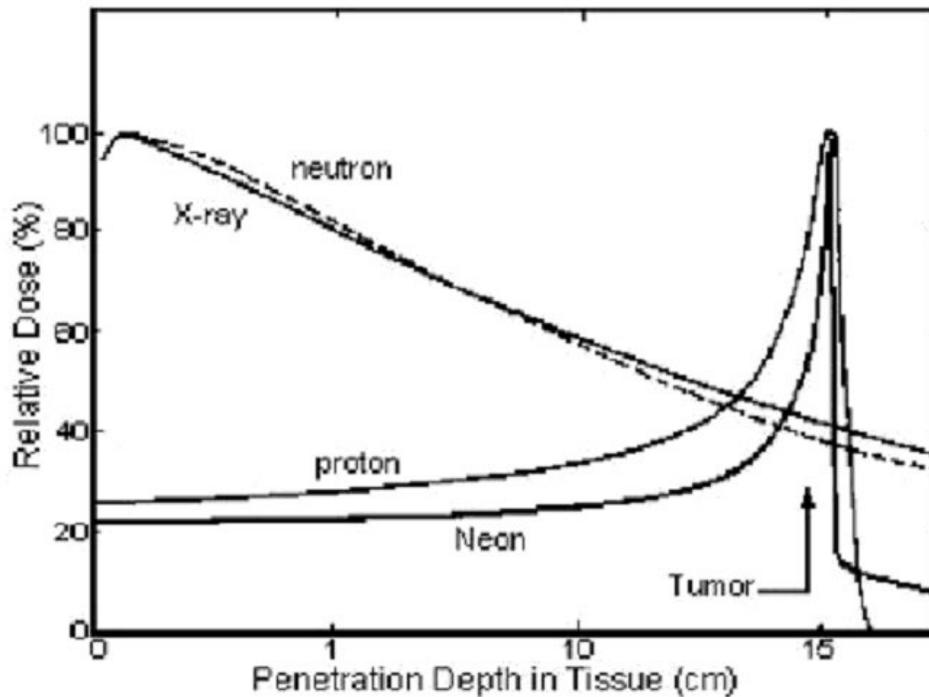


Fig. 3: Different patterns of energy deposition in tissue of directly and indirectly ionizing radiation.

RADIATION FIELD AND EXPOSURE

In the same way that one can define an electric, magnetic or gravitational field, a radiation field can be defined as a domain where ionization caused by radiation can be detected and its effects measured. Since electromagnetic radiation in the form of x rays or gamma rays can cause ionization in air, primarily through the processes of pair production, Compton scattering and the photoelectric effect, the presence of this ionization in air defines the presence of a radiation field.

Table 1: Activity in Becquerels of some materials and objects.

Material or Object	Activity, [Bq]
Adult human (100 Bq/kg)	7×10^3
One kg of coffee	1×10^3
One kg of super phosphate fertilizer	5×10^3
The air in a 100 m ² home from radon gas	$3 \times 10^3 - 3 \times 10^4$
Household smoke detector using radioactive americium	3×10^4
Radioisotope for medical diagnosis	7×10^7
Radioisotope source for medical therapy	1×10^{14}
One kg 50 year old vitrified high-level nuclear waste	1×10^{13}
One kg fresh separated uranium	2.5×10^7
One kg uranium 15 percent Canadian ore	2.5×10^7
One kg uranium of 0.3 percent Australian ore	5×10^5
One kg low level radioactive waste	1×10^6
One kg of coal ash	2×10^3
One kg of granite	1×10^3

This radiation field is considered as incident on a body immersed in the field at any point. The biological effects of radiation being a function of the ionization produced in air, it becomes important to measure the degree of “exposure” to the electromagnetic radiation field in terms of the number of ions or electrons produced in the adjacent atmosphere. Thus one can define the unit of exposure to a radiation field in air as:

$$\text{Exposure: } X = \frac{\Delta q}{\Delta m} \left[\frac{\text{Coulomb}}{\text{kg of air}} \right] \quad (4)$$

where: Δq is the sum of electrical charges on all the ions of one sign produced in air when all the electrons, negative and positive, liberated by photons in a volume of air after being completely stopped.

Δm is the mass of the volume of air under consideration. The electrons could be stopped outside the volume of interest.

In honor of the discoverer of x rays, the unit of exposure is the Röntgen defined as:

$$R: 1 \text{ Röntgen} = 2.58 \times 10^{-4} \left[\frac{\text{Cb}}{\text{kg}} \right], \quad (5)$$

which is equivalent to the production of 1 electrostatic unit (esu) of charge of one sign from the interaction of x rays or gamma rays in 0.001293 grams of air at standard temperature and pressure (STP) which is equivalent to 1 cm³ of air at atmospheric pressure and 0 degrees Celsius, where:

$$1 \text{ esu} = 3.33 \times 10^{-10} [\text{Cb}]$$

For a smaller magnitude, the milliRöntgen is defined as:

$$1 \text{ mR} = 10^{-3} R \quad (6)$$

The exposure rate is defined as:

$$\dot{X} = \frac{dX}{dt} \left[\frac{R}{\text{sec}} \right] \text{ or } \left[\frac{\text{mR}}{\text{hr}} \right] \quad (7)$$

It must be noticed that the concepts of exposure and exposure rates apply only to x rays and gamma rays not to other forms of radiation such as neutrons or charged particles, and that they are defined only in air and not in inert or biological materials.

The radiation field can be associated with a considerable amount of ionization in air.

EXAMPLE

For instance, by following a process of dimensional analysis, let us calculate the number of ions created per second per cubic centimeter, or ions rate density, associated with the exposure to a modest 1 [mR/hr] gamma ray field in air:

$$\begin{aligned}
& 1 \left[\frac{\text{mR}}{\text{hr}} \right] \\
&= 1 \frac{\text{mR}}{\text{hr}} \times 10^{-3} \frac{\text{R}}{\text{mR}} \times \frac{1}{60 \times 60} \frac{\text{hr}}{\text{sec}} \times 2.58 \times 10^{-4} \frac{\text{Cb/kg}}{\text{R}} \times \frac{1}{1.6 \times 10^{-19}} \frac{\text{ions}}{\text{Cb}} \times \frac{1}{10^3} \frac{\text{kg}}{\text{gm}} \times 0.001293 \frac{\text{gm}}{\text{cm}^3 \text{air}} \\
&= 1 \times 10^{-3} \times \frac{1}{60 \times 60} \times 2.58 \times 10^{-4} \times \frac{1}{1.6 \times 10^{-19}} \times \frac{1}{10^3} \times 0.001293 \frac{\text{ions}}{\text{cm}^3 \cdot \text{sec}} \\
&= 578 \left[\frac{\text{ions}}{\text{cm}^3 \cdot \text{sec}} \right]
\end{aligned}$$

This amounts to the creation of a considerable amount of about 580 ions per cubic centimeter of air per second.

ABSORBED DOSE UNIT

If we want to measure the effects of radiation on materials rather than air, we consider that the biological effects will depend on the amount of imparted energy that the radiation imparts to an arbitrary volume or control volume of material. The imparted energy must take into account the possibility of the occurrence of nuclear reactions within the volume of material of interest. Carrying out an energy balance over this control volume:

$$\text{Imparted energy: } \Delta E_D = E_{\text{in}} - E_{\text{out}} + Q_v \quad (8)$$

where: Q_v is the Q-values of the nuclear reactions taking place in the control volume,
 E_{in} is the input energy to the control volume,
 E_{out} is the output energy from the control volume.

This leads to the definition of the concept of the absorbed dose of radiation as:

$$\text{Absorbed dose: } D = \frac{\text{imparted energy}}{\text{mass}} = \frac{\Delta E_D}{\Delta m} \quad (9)$$

The absorbed dose at a point can be also defined as a limiting condition:

$$D_p = \lim_{\Delta m \rightarrow 0} \frac{\Delta E_D}{\Delta m} \quad (10)$$

A unit for the absorbed dose in the conventional system of units is the Rad standing for Radiation Absorbed Dose as:

$$1 \text{ Rad} = 0.01 \left[\frac{\text{Joule}}{\text{kg}} \right] = 100 \left[\frac{\text{ergs}}{\text{gm}} \right] \quad (11)$$

where 1 Joule = 10^7 ergs.
A smaller unit is:

$$1 \text{ mRad} = 10^{-3} \text{ Rad.} \quad (12)$$

In the Système International (SI) system of units, the unit for the absorbed dose is:

$$1 \text{ Gray} = 1 \text{ Gy} = 1 \left[\frac{\text{Joule}}{\text{kg}} \right] = 100 \text{ rads} \quad (13)$$

with smaller units:

$$\begin{aligned} 1 \text{ mGy} &= 10^{-3} \text{ Gy,} \\ 1 \text{ cGy} &= 10^{-2} \text{ Gy.} \end{aligned} \quad (14)$$

Similarly to the exposure rate, the absorbed dose rate is defined as:

$$\dot{D} = \frac{dD}{dt} \left[\frac{\text{Rad}}{\text{sec}} \right] \text{ or } \left[\frac{\text{Gy}}{\text{sec}} \right] \quad (15)$$

Only in situations when indirectly ionizing radiation; primarily fast neutrons, are under consideration, the Kerma (Kinetic Energy Released in Material) or Kerma Dose is defined as:

$K =$ [Sum of the initial energies of all the charged, ionizing particles released by indirectly ionizing radiation; mostly neutrons, per unit mass of the substance at hand]

The units of K are rads or Grays; the same as the absorbed dose units.

The human senses cannot detect radiation or discern whether a material is radioactive. However, a variety of instruments can detect and measure radiation reliably and accurately.

The amount of ionizing radiation, or dose, received by a person is measured in terms of the energy absorbed in the body tissue.

Since the Gray is also equal to 100 radiation absorbed doses (rads) in the conventional system of units. A commonly used unit is one hundredth of a Gray or centiGray, and is also equal to 1 rad of absorbed dose.

$$1 \text{ centiGray} = 1 \text{ cGy} = 1 \text{ rad} \quad (16)$$

THE RELATIVE BIOLOGICAL EFFECTIVENESS: RBE

To account for the biological effects of different types of radiation on biological matter an experimental approach is adopted where a tissue culture or organ is irradiated

with standard 100 keV x rays or gamma rays, then irradiated with the other type of radiation and the resulting effect such as cell survival is observed. The Relative Biological Effectiveness (RBE) of the considered type of radiation is defined as:

$$\text{RBE} = \frac{\text{Effect produced by other type of radiation}}{\text{Effect produced by 100 keV x or } \gamma \text{ rays}} \quad (17)$$

The RBE of 100 keV x or gamma rays is taken as a reference with an arbitrary assigned value of unity. Table 2 shows the values of the Quality Factor for different types of radiation.

Table 2: Assigned values of the Quality Factor for different types of radiation.

Radiation Type	Q_f
X rays or gamma rays	1
Alpha particles, protons, fast neutrons	10
Heavy recoil nuclei	20
Thermal neutrons	2
1 MeV neutrons	11
20 Mev neutrons	8
Beta particles above 30 keV	1
Beta particles below 30 KeV	1.7
Heavy ions	20

Being an experimental value, the value of the RBE is normally a fractional value. The round off of the RBE value is an assigned value designated as the Quality Factor:

$$\text{Quality Factor: } Q_f = \text{Round-off of RBE} \quad (18)$$

The Quality Factor is directly related to the degree of ionization that different types of radiation can create along their paths in materials. The higher the degree the ionization per unit length then the higher the resulting biological damage. This is expressed in terms of the Linear Energy Transfer (LET) for radiation:

$$\text{LET} = - \frac{dE}{dx} \left[\frac{\text{keV}}{\mu\text{m}} \right] \quad (19)$$

Alpha particles have a higher quality factor than x or gamma rays since they can cause a high degree of ionization in materials through collisions with the atomic nuclei. The ionization is notoriously high near the end of their tracks when the alpha particle has been slowed down, as shown in Fig. 4. This effect is known as the Bragg effect.

Beta particles tracks appear farther apart from those of alpha particles displaying a process of straggling as shown in Fig. 5. As the beta particle slows down, the path becomes more erratic and the ions are formed closer together, with the tracks at the very end behaving like the alpha particles tracks as shown in Fig. 4.

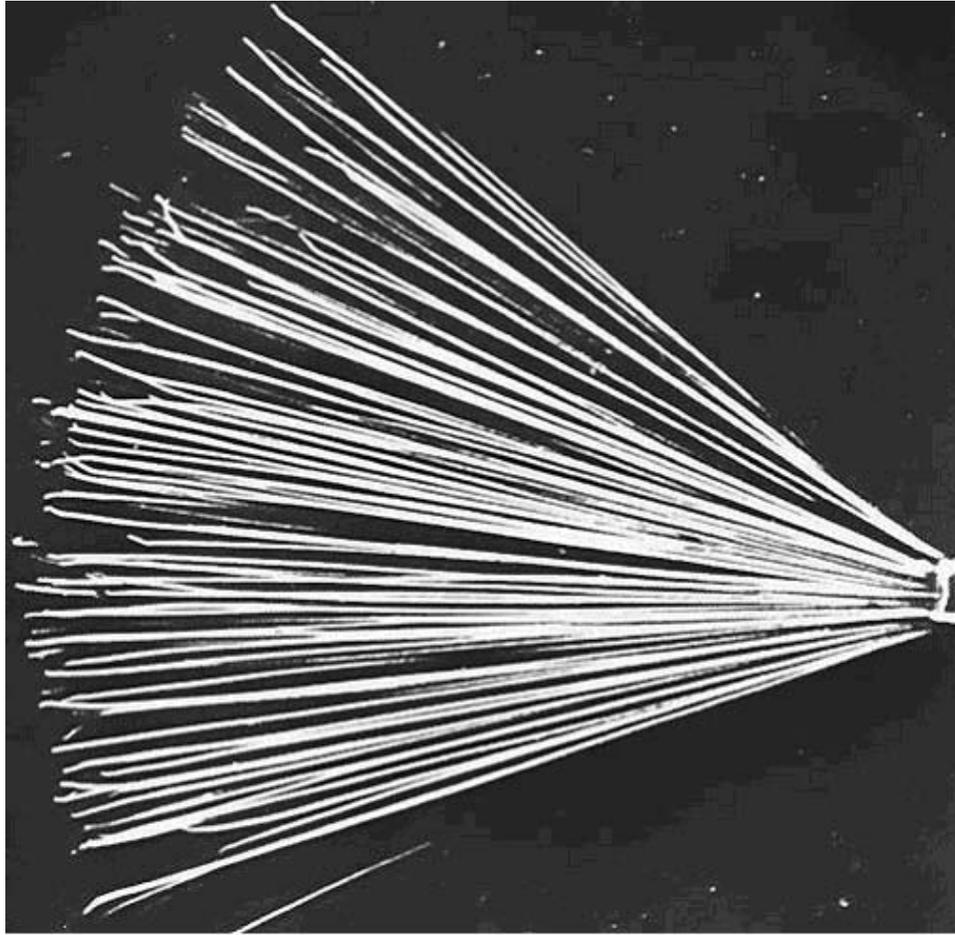


Fig. 4: Alpha particles tracks originating from a source on the right hand side in a cloud chamber.

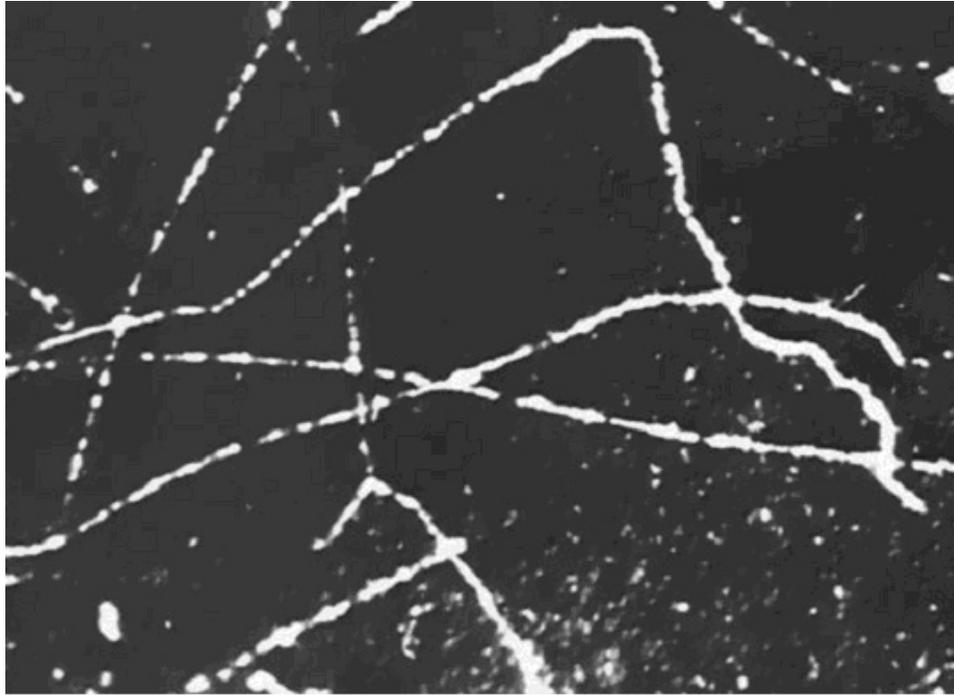


Fig. 5: Beta particles tracks in a cloud chamber.

Table 3 shows the relationship between the LET and the Quality Factor.

Table 3: Relationship between the LET and the Quality factor of radiation.

LET [keV/micron]	Q _f
3.5 or less	1
7	2
23	5
53	10
175 and above	20

EFFECTIVE DOSE, DOSE EQUIVALENT OR BIOLOGICAL DOSE

Equal exposure to different types of radiation expressed in Grays do not however necessarily produce equal biological effects. One gray of alpha radiation, for example, will have a greater effect than one gray of beta radiation.

Using the concept of the Radio Biological Effectiveness and the Quality Factor the Biological Dose or Dose Equivalent or Effective Dose is defined as the product of the absorbed dose and the quality factor as:

$$\begin{aligned} \text{Effective Dose} &= \text{Absorbed Dose} \times \text{Quality factor} \\ H &= D \cdot Q_f \end{aligned} \quad (20)$$

Similarly, an effective dose rate is defined as:

$$\dot{H} = \dot{D} \cdot Q_f \quad (21)$$

The conventional unit of the effective dose is the radiation equivalent man or rem, defined as:

$$1 \text{ rem} = 1 Q_f \cdot \text{rad} \quad (22)$$

with a smaller unit of:

$$1 \text{ mrem} = 10^{-3} \text{ rem} \quad (23)$$

In the Système International (SI) system of units it is defined as the Sievert:

$$1 \text{ Sievert} = 1 \text{ Sv} = 100 \text{ rem.} \quad (24)$$

For x rays and gamma rays where the quality factor is unity, 1 Rad of absorbed dose gives an effective dose of 1 Rem.

Now, regardless of the type of radiation, one Sievert of radiation produces the same biological effect.

Smaller dose equivalent quantities are expressed in centiSievert (cSv), milliSievert (mSv) or microSievert (μSv). The Sievert is equal to 100 radiation equivalent man (rem) in the conventional system of units:

$$1 \text{ centiSievert} = 1 \text{ cSv} = 1 \text{ rem} \quad (25)$$

NATURAL BACKGROUND RADIATION

The natural background radiation is low intensity radiation that is a part of our natural environment. Part of it is from constituents in the soil such as the heavy metals of thorium and uranium and their daughter nuclides such as radium and radon. These are continuously transforming through the process of radioactive decay giving up emissions of alpha, beta and gamma radiation. Although not very abundant, they are widely spread and minerals containing them are practically everywhere.

Cosmic rays from outer space also bombard the Earth with streams of highly energetic particles, and high energy particles from the solar wind continuously fall on the Earth and increase in intensity during solar flares and at the peaks of the 11 years solar cycle.

There are sources of radiation inevitably within the body itself such as carbon¹⁴ and potassium⁴⁰. The sources of radiation exposure in the USA estimated as an average exposure to the gonads is shown in Table 4.

Naturally occurring background radiation is the main source of radiation exposure for most people. Levels typically range from about 1.5 to 3.5 milliSieverts (mSv) per person per year but can be reach more than 50 [mSv/(person.yr)].

The highest known level of background radiation affecting a substantial population is in Kerala and Madras States in India where some 140,000 people receive doses which average over 15 milliSievert per year from gamma radiation in addition to a similar dose from radon gas. Comparable levels occur in Brazil and Sudan, with average exposures up to about 40 mSv/yr to many people. The source is environmental radiation from deposits of thorium and uranium, with radon as one of its decay daughter nuclides.

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

Radiation is all around us. It is naturally present in our environment and has been since the birth of Earth as a planet. Consequently, life has evolved in an environment which has significant levels of ionizing radiation. It comes from outer space as cosmic radiation, the ground as terrestrial radiation, and even from within our own bodies like carbon¹⁴ and potassium⁴⁰. It is present in the air we breathe, the food we eat, the water we drink, and in the construction materials used to build our homes. Certain foods such as bananas and Brazil nuts naturally contain higher levels of radiation than other foods. Brick and stone homes have higher natural radiation levels than homes made of other building materials such as wood. The USA's Capitol, and Central Station in New York which are largely constructed of granite, contain higher levels of natural radiation than most homes. Thunderstorms do generate measurable amounts of radiation.

Levels of natural or background radiation can vary greatly from one location to the next. For example, people residing in Colorado are exposed to more natural radiation than residents of the east or west coast because Colorado has more cosmic radiation at a high altitude of one mile above sea level and more terrestrial radiation from soils enriched in naturally occurring uranium and thorium. Furthermore, a lot of our natural exposure is due to radon, a gas from the earth's crust from the decay chain of thorium and uranium that is present in the air we breathe.

The average annual radiation dose equivalent from natural sources to an individual in the United States is about 126 millirem or 1.26 milliSieverts. Radon gas accounts for two-thirds of this exposure, while cosmic, terrestrial, and internal radiation account for the remainder. No adverse health effects have been discerned from doses arising from these levels of natural radiation exposure.

MAN-MADE RADIATION

In 1895 x rays were discovered by Röntgen in Germany and have become since then a useful source of medical diagnosis and therapy. In 1896 radioactivity was discovered by Henry Becquerel in France. In 1934 it was discovered that radioisotopes can be made and their usage spread in hospitals laboratories and industries. In 1945 atomic devices were developed and tested originally in the atmosphere, underground, and then their testing was banned. The fission fragments and resulting from the atomic testing in 1950s still exist in the stratosphere and are descending to the Earth's surface as radioactive fallout.

Man-made sources of radiation from medical, commercial, and industrial activities contribute another 672 mrem or 0.672 mSv to our annual radiation exposure. One of the largest of these sources of exposure is medical x-rays. Diagnostic medical procedures account for about 50 mrem or 0.5 mSv each year.

Other sources of technological radiation exposure include high flying airplanes, space travel, particle accelerators, and television and computer video screens. In addition, some consumer products such as tobacco, fertilizer, welding rods, gas mantles, luminous watch dials, and smoke detectors contribute another 6.2 mrem or 0.062 mSv to our annual radiation exposure.

Considering the data from Table 4 it appears that man-made radiation from all sources is being absorbed at nearly half the rate (0.672 mSv) of natural radiation (1.26 mSv). The additional dosage is primarily as a result of the use of x rays in the search for decayed teeth, broken bones, lung lesions, swallowed objects, instruments left inside the body in surgical procedures, and other useful or useless procedures.

Ionizing radiation is generated in a range of useful applications and medical, commercial and industrial activities. The most familiar and, in national terms, the largest of these sources of exposure is medical x-rays. A typical breakdown between natural background and artificial sources of radiation is shown in Table 4.

Natural radiation contributes about 65 percent of the annual dose to the population and medical procedures most of the remaining 35 percent. Natural and artificial radiations are not different in kind or effect.

Table 4: Sources and magnitude of radiation dose equivalent in the USA, estimated as an average exposure to the gonads.

Source	Yearly per capita dose equivalent [cSv/(person.year)] [rem/(person.year)]
<i>Natural sources</i>	
<u>External to body</u>	
Cosmic radiation	0.050
From Earth minerals	0.047
Building materials	0.003
<u>Internal sources</u>	
Air inhalation	0.005
Elements naturally occurring in tissue	0.021
Total, natural sources	0.126
<i>Man-made sources</i>	
<u>Medical procedures</u>	
Diagnostic x rays	0.050
Radiotherapy x rays, radioisotopes	0.010
Internal diagnosis, therapy	0.001
Subtotal	0.061

Atomic energy industry, laboratories	0.0002
Television tubes, computer screens, industrial waste	0.002
Radioactive weapons testing fallout	0.004
Subtotal	0.0062
Total, man-made sources	0.0672
Total, natural and man-made	0.1932

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) 2000 Report suggests that the average annual radiation dose from diagnostic x-rays in the U.S. has increased slightly so that the percentage of exposure from medical procedures may be higher than that represented in Table 4. Some Computed Tomography (CT) body scans can be of great benefit for the early detection of tumors, but delivers one thousand times the dose from a typical chest x-ray. A large number of dental x rays is also delivered to the head close to the vital organs of the brain and eyes.

RADIATION PROTECTION PRINCIPLES

Because exposure to high levels of ionizing radiation carries a risk, criteria for the safe handling of radiation have been established. Exposure to low level radiation is unavoidable. Radiation has always been present in the environment and in our bodies. The consensus is that we can and should minimize unnecessary exposure to significant levels of man-made radiation.

Radiation is easily detected. There is a range of simple, sensitive instruments capable of detecting minute amounts of radiation from natural and man-made sources. There are four ways in which people are protected from identified radiation sources:

1. **Limiting time:** For people who are exposed to radiation in addition to natural background radiation through their work, the dose is reduced and the risk of illness essentially eliminated by limiting exposure time.
2. **Distance:** In the same way that heat from a fire is less the further away one is the intensity of radiation decreases in an inverse square manner with distance from its source.
3. **Shielding:** Barriers of lead, concrete or water give good protection from penetrating radiation such as gamma rays. Radioactive materials are often stored or handled under water, or by remote control in rooms constructed of thick concrete or lined with lead.
4. **Containment:** Radioactive materials are confined and kept out of the environment. Radioactive isotopes for medical use, for example, are dispensed in closed handling

facilities, while nuclear reactors operate within closed systems with multiple barriers which keep the radioactive materials contained. Rooms have a reduced air pressure so that any leaks occur into the room and not out from the room.

SOURCES OF RADIATION EXPOSURE

The ionizing radiations of primary concern are alpha and beta particles, gamma rays, and x rays. Alpha and beta particles and gamma rays can come from natural sources or can be technologically produced. Most of the x-ray exposure people receive is technologically produced. Natural radiation comes from cosmic rays, naturally occurring radioactive elements found in the earth's crust such as uranium, thorium, C¹⁴ and K⁴⁰, and radioactive decay products such as radon and its subsequent decay products. The latter group represents the majority of the radiation exposure of the general public.

In addition to these natural sources, radiation can come from such wide-ranging sources as hospitals, research institutions, nuclear reactors and their support facilities, certain manufacturing processes, and Federal facilities involved in nuclear weapons production.

Any release of radioactive material is a potential source of radiation exposure to the population. In addition to exposure from external sources, radiation exposure can occur internally by ingesting, inhaling, injecting, or absorbing radioactive materials. Both external and internal sources may irradiate the whole body or a portion of the body. In the United States, the average person is exposed to an effective dose equivalent of approximately 0.360 cSv or rem of whole-body exposure per year from all sources. For comparison, the per capita yearly gonads exposure from Table 4 is 0.1932 cSv or rem.

CONSEQUENCES OF EXPOSURE

Ionizing radiation affects people by depositing energy in body tissue, which can cause cell damage or cell death. In some cases there may be no effect. In other cases, the cell may survive but become abnormal, either temporarily or permanently, or an abnormal cell may become malignant. Large doses of radiation can cause extensive cellular damage and result in death. With smaller doses, the person or particular irradiated organ may survive, but the cells are damaged, increasing the chance of cancer. The extent of the damage depends upon the total amount of energy absorbed, the time period and dose rate of exposure, and the particular organ exposed.

Evidence of injury from low or moderate doses of radiation may not show up for months or even years. For leukemia, the minimum time period between the radiation exposure and the appearance of disease or latency period is 2 years. For solid tumors, the latency period is more than 5 years. The types of effects and their probability of occurrence can depend on whether the exposure occurs chronically over a large part of a person's lifespan or acutely during a very short portion of the lifespan. It should be noted that all of the health effects of exposure to radiation can also occur in unexposed people due to other causes. Also, there is no detectable difference in appearance between radiation induced cancers and genetic effects and those due to other causes.

CHRONIC AND ACUTE RADIATION EXPOSURE

Chronic exposure to ionizing radiation is continuous or intermittent exposure to low levels of radiation over a long period of time. Chronic exposure is considered to produce only effects that can be observed some time following initial exposure. These include genetic effects and other effects such as cancer, precancerous lesions, benign tumors, cataracts, skin changes, and congenital defects.

Acute exposure is exposure to a large, single dose of radiation, or a series of doses, for a short period of time. Large acute doses can result from accidental or emergency exposures or from special medical procedures such as radiation therapy. In most cases, a large acute exposure to radiation can cause both immediate and delayed effects. For humans and other mammals, acute exposure, if large enough, can cause rapid development of radiation sickness, evidenced by gastrointestinal disorders, bacterial infections, hemorrhaging, anemia, loss of body fluids, and electrolyte imbalance. Delayed biological effects can include cataracts, temporary sterility, cancer, and genetic effects. Extremely high levels of acute radiation exposure can result in death within a few hours, days or weeks.

HEALTH EFFECTS RISKS

People are chronically exposed to background levels of radiation present in the environment. Many people also receive additional chronic exposures and/or relatively small acute exposures. For populations receiving such exposures, the primary concern is that radiation could increase the risk of cancers or harmful genetic effects.

The probability of a radiation-caused cancer or genetic effect is related to the total amount of radiation accumulated by an individual. Based on current scientific evidence, any exposure to radiation can be harmful or can increase the risk of cancer. However, at very low exposures, the estimated increases in risk are very small. For this reason, cancer rates in populations receiving very low doses of radiation may not show increases over the rates for unexposed populations.

For information on the effects at high levels of exposure, scientists largely depend on epidemiological data on survivors of the Japanese atomic bomb explosions and on people receiving large doses of radiation medically. These data demonstrate a higher incidence of cancer among exposed individuals and a greater probability of cancer as the level of exposure increases. In the absence of more direct information, that data is also used to estimate what the effects could be at lower exposures. Where questions arise, scientists try to extrapolate based on information obtained from laboratory experiments, but these extrapolations are acknowledged to be only estimates.

For radon, scientists largely depend on data collected on underground miners. Professionals in the radiation protection field prudently assume that the chance of a fatal cancer from radiation exposure increases in proportion to the magnitude of the exposure and that the risk is as high for chronic exposure as it is for acute exposure. In other words, it is assumed that no radiation exposure is completely risk free.

Table 5 gives an indication of the likely effects of a range of whole body radiation effective doses and dose rates to individuals. Table 6 lists the yearly allowable per capita effective dose rates.

Table 5: Observed effects from different effective doses.

Dose Equivalent cSv, rem	Observed Effect
1,000	10 Sieverts as a short-term and whole-body dose would cause immediate sickness, such as nausea and decreased white blood cell count, and subsequent death within a few weeks. Between 2 and 10 Sieverts in a short-term dose would cause severe radiation sickness with increasing the likelihood that this would be fatal.
100	1 Sievert in a short term dose is about the threshold for causing immediate radiation sickness in a person of average physical attributes, but would be unlikely to cause death. Above 100 cSv, severity of illness increases with dose. If doses greater than 100 cSv occur over a long period they are less likely to have early health effects but they create a definite risk that cancer will develop years later.
10	Above about 10 cSv, the probability of cancer, rather than the severity of illness, increases with dose. The estimated risk of fatal cancer is 5 of every 100 persons exposed to a dose of 100 cSv. If the normal incidence of fatal cancer were 25%, this dose would increase it to 30%.
5	5 cSv is, conservatively, the lowest dose at which there is any evidence of cancer being caused in adults. It is also the highest dose which is allowed by regulation in any one year of occupational exposure. Dose rates greater than 5 cSv/yr arise from natural background levels in several parts of the world but do not cause discernible harm to local populations.

Table 6: Allowable yearly per capita effective dose rates.

Effective Dose rate [cSv/yr], [rem/yr]	Allowable limits
2	Averaged over 5 years is the limit for radiological personnel such as employees in the nuclear industry, uranium or mineral sands miners and hospital workers, who are all closely monitored.
1	Is the maximum actual dose rate received by a uranium miner.
0.3-0.5	The typical dose rate above background received by uranium miners.

0.3	Is the typical background radiation from natural sources in North America, including an average of almost 0.2 cSv/yr from radon in air.
0.2	The typical background radiation from natural sources, including an average of 0.07 cSv/yr from radon in air. This is close to the minimum dose received by all humans anywhere on Earth.
0.03-0.06	Is a typical range of dose rates from artificial sources of radiation, mostly medical.
0.005	A small fraction of natural background radiation, is the design target for maximum radiation at the perimeter fence of a nuclear electricity generating station. In practice, the actual dose is less.

RADIATION PROTECTION STANDARDS

Most nations have their own systems of radiological protection which are often based on the recommendations of the International Commission on Radiological Protection (ICRP). The authority of the ICRP comes from the scientific standing of its members and the merit of its recommendations.

The three key considerations behind the ICRP's recommendations are:

1. **Justification:** No practice should be adopted unless its introduction produces a positive net benefit.
2. **Optimization:** All exposures should be kept as low as reasonably achievable, economic and social factors being taken into account.
3. **Limitation:** The exposure of individuals should not exceed the limits recommended for the appropriate circumstances.

National radiation protection standards are based on ICRP recommendations for both Occupational and Public exposure categories.

The ICRP recommends that the maximum permissible dose for occupational exposure should be 2 cSv or rem per year averaged over five years. This implies 10 cSv or rems in 5 years with a maximum of 5 cSv or rems in any one year.

For the public's exposure, 0.1 cSv or rem per year averaged over five years is the limit. In both categories, the figures are over and above background levels, and exclude medical exposure.

An array of international and national agencies promulgates the standards concerning the use of radiation:

ICRP:	International Commission on Radiological protection,
NCRP:	National Council on Radiation Protection and Measurement
FRC:	Federal Radiation Council
NRC:	Nuclear Regulatory Commission
EPA:	Environmental Protection Agency

The standards for the protection against radiation are enunciated in the Code of Federal Regulations (CFR), in Title 10, Part 20 or 10-CFR-20. To strictly abide by the rules and regulations pertaining to the safe use of radiation is a matter of utmost importance in professional ethics among scientists and engineers who are bound to follow and apply them for the protection of their subordinates, the public at large, and of themselves. Failure to follow these rules and regulations is not just unprofessional or unethical, but is a de facto crime that could lead to prosecution.

Some of the standards for maximum allowable radiation dose are shown in Table 7. Members of the public are allowed only one tenth the amount allowed to occupational workers.

Table 7: Standards for Limiting radiation effective doses.

Category	Maximum yearly per capita effective dose [cSv/(person.year)] [rem/(person.year)]
Occupational workers	5.0
Members of the public	0.5
Whole population average (all sources other than medical)	0.17
<u>Occupational Workers:</u>	
Gonads, total body, red bone marrow	0.005
Skin and bone	0.030
Other internal organs	0.015

The allowable effective dose is a cumulative figure that depends on age, thus over a lifetime the cumulative radiation effective dose to an occupational worker is:

$$\text{Effective Dose}_{\text{cumulative}} = 2(N-18) \left[\frac{\text{cSv}}{\text{person}} \right] \text{ or } \left[\frac{\text{rem}}{\text{person}} \right] \quad (26)$$

where N is the age of the exposed individual in years. Notice that the value of 2 is used for the averaging process, rather than the maximum value of 5.

This relationship suggests that occupational workers can only be exposed to radiation above the age of 18 years, after the body has nearly completed its growth and maturation stages. It also implies that should an individual be exposed to an amount exceeding the limit of 2 cSvs in a given year, for instance 5 cSv as a result of an emergency, then the exposure in the following year should be reduced to restore the average value.

Above background levels of radiation exposure, the NRC requires that its licensees limit maximum radiation exposure to individual members of the public to 100 mrem or 1mSv per year, and limit occupational radiation exposure to adults working with radioactive material to 5,000 mrem (50 mSv) per year. NRC regulations and radiation exposure limits contained in Title 10 of the Code of Federal Regulations under Part 20,

are consistent with recommendations of national and international scientific organizations and with practices in other developed nations.

At the boundary of a nuclear power plant the NRC maximum per capita dose equivalent is 5 [mrem/year], which amounts to 1 percent of the individual limit, 3 percent of the whole population limit as regulated by the ICRP and the FRC, and 1/20 of the natural background at about 102 [rem/year].

POPULATION EFFECTIVE DOSE

It can be noticed from Table 7 that the maximum allowable population effective dose or dose equivalent is lower than the maximum dose equivalent for an individual within the population. For a population of N individuals exposed to an effective dose H :

$$N = \int_0^{\infty} N(H)dH \quad (27)$$

The population effective dose is defined as:

$$H_{population} = \int_0^{\infty} H.N(H)dH \quad (28)$$

and its units are in [person.rem], or [person.cSv].

EXAMPLE

To calculate the population effective dose for a population of 2 million people half of them receiving 100 mrem and the other half receiving 200 mrem per year, the population effective dose is:

$$\begin{aligned} H_{population} &= (10^6 \times 100 \times 10^{-3}) + (10^6 \times 200 \times 10^{-3}) [\text{person.rem}] \\ &= 3 \times 10^5 [\text{person.rem}] \\ &= 3,000 [\text{person.Sievert}] \end{aligned}$$

Individual radiation doses vary from one individual to another, and depend on their different life styles, as shown in Table 8 which can be used to compute an individual's approximate yearly dose equivalent.

COMMITTED DOSE

The committed dose or dose commitment is a modified concept that considers the commitment to dose that occurs when a radionuclide is released to the environment or when it is taken into the body. For instance, if radioactive cesium is taken into the body, it is eliminated with an effective or biological half-life of about 100 days, even though its

physical half life is about 30 years. A dose commitment is considered to have taken place the moment radioactive cesium enters the body even though it will be one hundred days before that dose is actually accumulated. The concept is of more use for radionuclides such as plutonium that could become permanently fixed in human tissue. The committed dose is commonly calculated for a 50 year period.

Table 8: Computation of an individual's yearly effective dose.

Common Sources of Radiation		Your Annual Dose (mrem's)
WHERE YOU LIVE	Location: Cosmic radiation at <i>sea level</i>	<u>44</u>
	Elevation: Add 1 mrem for each 100 feet of elevation	
	Elevation of some U.S. cities (in feet): Atlanta 1050; Chicago 595; Dallas 435; Denver 5280; Las Vegas 2000; Minneapolis 815; Pittsburgh 1200; St. Louis 455; Salt Lake City 4400; Spokane 1890. (Coastal cities are assumed to be zero, or sea level.)	
	House Construction (based on 3/4 of time indoors)	
	Brick 45	
	Stone 50	
	Wood 35	
	Concrete 45	
	Ground: (based on 1/4 time outdoors); U.S. Average	<u>15</u>
WHAT YOU EAT, DRINK, AND BREATHE	Food	
	Water	
	Air	<u>25</u>
	Weapons test fallout	<u>4</u>
HOW YOU LIVE	X-ray diagnosis	
	Number of Chest X-rays _____ x 10	
	Number of lower Gastrointestinal tract X-rays _____ x 500	
	U.S. Average Dose: Whole Body _____ 100	
	Jet plane travel: For each 1500 miles add 1 mrem	
	TV viewing: For each hour per day _____ X .15	
HOW CLOSE YOU LIVE TO A NUCLEAR PLANT	At site boundary: average number of hours per day _____ x 0.2	
	One mile away: average number of hours per day _____ x 0.02	
	Five miles away: average number of hours per day _____ x 0.002	
	Over 5 miles away:	None
	My total annual mrem's dose _____	
Compare your annual dose to the U.S. annual average of 228 mrem's		

One mrem per year is equal to: Moving to an elevation 100 feet higher,
Increasing your diet by 4%,
Taking a 5-day vacation in the Sierra Nevada mountains.

LARGE ACUTE DOSES

The effects of large acute doses of radiation can be classified as early and late effects. The early effects are observed at less than 2 months after exposure and are normally expressed in terms of the LD₅₀/30 factor defined as:

$$\begin{aligned}
 LD_{50}/30 &= \text{Lethal Dose for 50\% of individuals within 30 days} \\
 &= 500 \text{ cSv or rems for humans} \\
 &= 10,000 \text{ cGy or rads for bacteria and adult insects}
 \end{aligned}
 \tag{29}$$

The larger lethal dose for insects and bacteria is the background for science fiction works suggesting a world where insects, bacteria, and dolphins (shielded by water), would become the dominant species in the case of a global nuclear conflict.

Table 9 shows the early effects of large acute doses of radiation.

Table 9: Early effects of large acute doses of radiation.

Large acute dose [cSv, rem]	Early clinical effect
0-50	No observable effect
50-100	Slight blood count changes
100-200	Vomiting, blood changes. Recovery within weeks.
200-600	Vomiting within 2 hours, severe blood changes, hemorrhage, and infection. Recovery of 20-100 percent of individuals within 1 month to a year.
600-1,000	Vomiting within 1 hour, blood changes, hemorrhage, infection, loss of hair. Death of 80-100 percent of exposed individuals within 2 months.

Table 10: Acute Radiation sickness statistics to workers and emergency response personnel in the Chernobyl accident.

Patient Classification	Effective Dose [cSv, rem]	Skin burns	Number of exposed individuals	Deaths	Death period
Fourth degree, extremely severe	600-1,600	all	22	21	4-50 days
Third degree, severe	400-600	6 out of 7	23	7	2-7 weeks
Second degree, moderate	200-400	few	53	1	-
First degree, slight	80-200	None	105	None	None
Total				29	

The most severe accident involving acute radiation exposure was at the Chernobyl reactor number 4 on April 26, 1986. The exposure was mainly to fire fighters who acted

heroically in their line of duty in containing the fire that resulted from the accident. Their exposure was associated with skin burns from the radioactive smoke particulates containing fission products beta emitters. Table 10 shows the acute radiation sickness statistics from the Chernobyl accident.

Information about the late effects of the large acute doses of radiation originate from 82,000 survivors from the Hiroshima and Nagasaki bombings. Below 100 Rems of dose equivalent no difference is observed in the leukemia incidence. In excess of 100 Rems, an excess incidence of 1 case of leukemia can be observed per million persons per year per Rem. The threshold for the occurrence of cataracts is 200 Rems. Brief infertility occurred below a dose of 1500 rads, and permanent infertility occurred at doses above 800 rads. The mutation rate doubled at dose equivalents between 20 and 200 rems. Life shortening and degenerative effects have also been observed among radiation practitioners such as radiologists.

LINEAR NO THRESHOLD HYPOTHESIS (LNTH)

Radiation protection standards are based on the conservative assumption that the risk is directly proportional to the dose, even at the lowest levels, though there is no evidence of risk at low levels. This assumption, called the linear no-threshold (LNT) hypothesis, is recommended for radiation protection purposes only such as setting allowable levels of radiation exposure of individuals. It cannot properly be used for predicting the consequences of an actual exposure to low levels of radiation. For example, it suggests that, if the dose is halved from a high level where effects have been observed, there will be half the effect, and so on. This could be very misleading if applied to a large group of people exposed to trivial levels of radiation and could lead to inappropriate actions to avert the doses.

Much of the evidence which has led to today's standards derives from the atomic bomb survivors in 1945, who were exposed to high doses incurred in a very short time. In setting occupational risk estimates, some allowance has been made for the body's ability to repair damage from small exposures, but for low-level radiation exposure the degree of protection may be unduly conservative.

CHRONIC LOW DOSES

Given a long period of time the body reconstructive processes are at work and are capable of repairing the damage resulting from low doses of radiation. It appears that damage from radiation could have a threshold below which this damage is repairable. The suggestion comes from experiments that observed that mutations in mice increased only above a dose of 300 cGy or rads, and not below it. Some other experiments even reported a longer life span in animals exposed to low chronic doses of radiation, the suggested explanation being that low doses of radiation may enhance the defense mechanisms of the immune system which can then protect the body against other forms of disease and injury.

In dealing with radiation a conservative assumption must be made which involves the linear extrapolation to low chronic doses of the observed effects from large doses of 100 cSv or rems or more.

The conservative assumption here is that the effects of radiation are directly proportional to the dose and independent of the rate at which the dose is received. This is not true in all cases since cataract incidence has indeed a threshold of 200 cSv or rems.

The extrapolated slope of the fatal cancer risk per person against the whole body dose from large doses to low doses is as shown in Fig. 6:

$$1.8 \times 10^{-4} \approx 2.0 \times 10^{-4} \left[\frac{\text{Fatal cancers}}{\text{person.cSv}} \right]$$

To place this in perspective 1 person out of 617 people dies of cancer in the USA, implying a random risk of death from cancer per year as:

$$\frac{1}{617} = 0.00162 .$$

Over a 30 years period this probability is:

$$30 \times \frac{1}{617} = 30 \times 0.00162 = 0.0486$$

For an individual at random receiving 1cSv or rem of whole body radiation over a 30 year period, the chances of acquiring a fatal cancer are:

$$2.0 \times 10^{-4} .$$

Thus the increase in the probability of acquiring a fatal cancer is just:

$$\frac{2.0 \times 10^{-4}}{0.0486} \approx 0.0041 = 0.41 \text{ percent.}$$

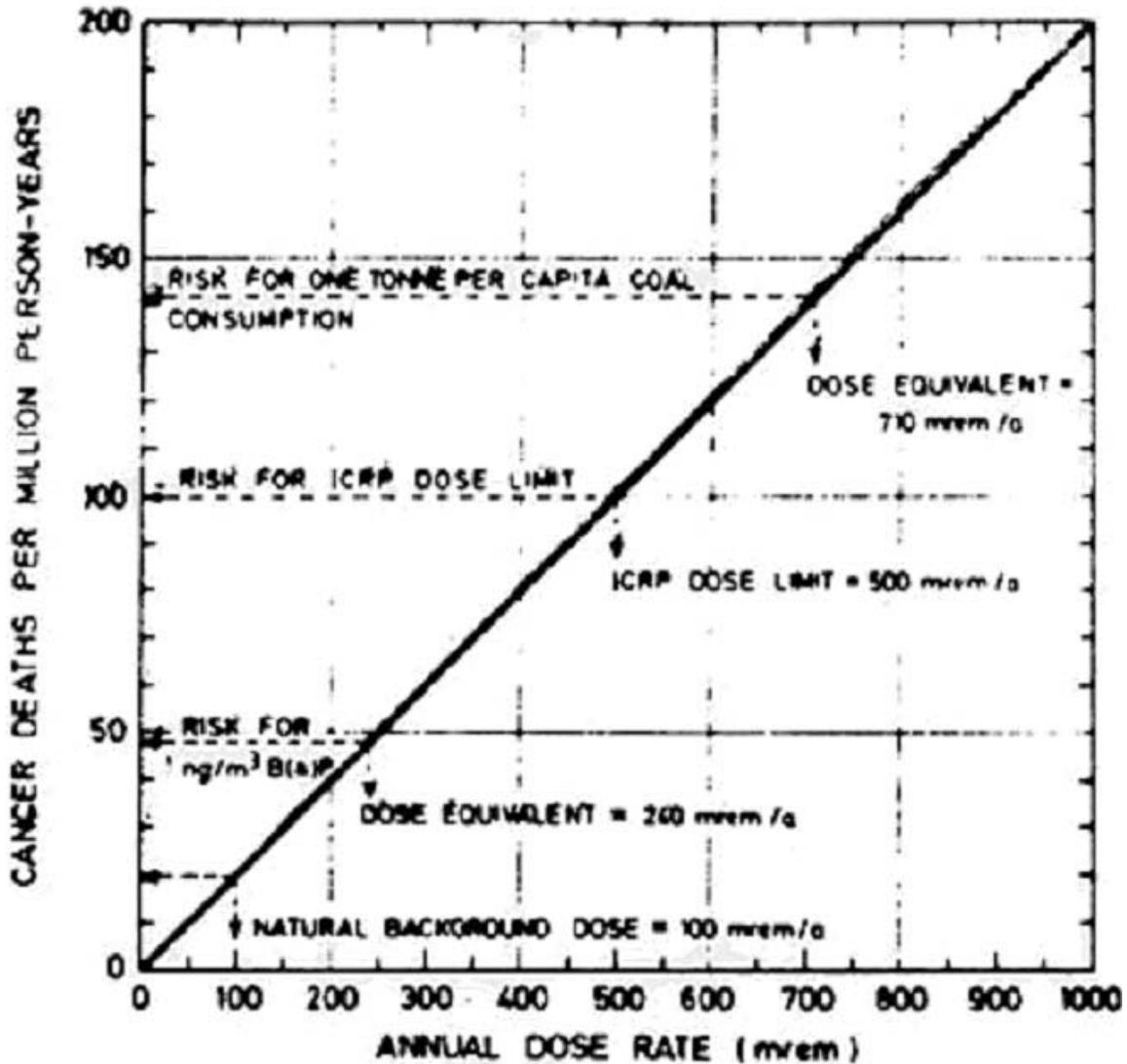


Fig. 6: Cancer Risk of radiation exposure, based on BEIR Committee Report.

Irrespective of the fact that it is impossible to ascertain the effects of low doses of radiation because their statistical error is masked by factors such as air pollution and the water supply which can cause more cancer deaths than radiation exposure to low doses of radiation, the professional and ethical application of two principles is generally accepted as the norm among users of radiation sources in terms of the levels of exposures and doses:

1. The As Low as practicable Principle (aslap),
2. The As Low as Reasonably Achievable principle (alara).

These principles simply state the ethical requirement that exposure to radiation should be limited to the levels that are conceived to lead to some beneficial output.

COMPARATIVE RISKS

Other sources of societal risks can cause cancer deaths, particularly chemical pollution. For instance, benzo(a)pyrene is a carcinogenic substance occurring in cigarette smoke, car exhaust and coal burning. The carcinogenicity of benzo(a)pyrene as well as radiation has been fully established partly from human experience and partly from human experiments out at high levels of exposure. Ionizing radiation is not likely to be any new type of harm since humans have been exposed to a fairly large dose of natural radiation background. A comparison of the risks from benzo(a)pyrene and radiation exposure is shown in Fig. 6.

The natural background dose at 100 cSv or rem per year per capita leads to a risk of about 20 cancer deaths per million persons per year. A concentration of 1 nanogram per cubic meter results in a dose equivalent of about 240 mrem per year per capita, and results in about 50 cancer deaths per million persons per year. However the risk from burning one metric tonne (1,000 kgs) of coal per person per year has a dose equivalent of 710 mrem per person per year will be exceeding the maximum allowable ICRP dose limit of 500 mrem per person per year.

Table 11: Fractional exposure to radiation sources.

Source of exposure	Fraction
Natural background	67.60
Medical irradiation	30.70
Fallout from weapons testing	0.60
Miscellaneous sources	0.50
Occupational exposure	0.45
Nuclear Energy	0.15
Total	100.0

DISCUSSION

Humans receive radiation from a number of sources both natural and human-made. Depending on the style of living one can receive more or less radiation from some of these sources. For instance, living in a brick house contributes a dose equivalent of 50-100 mrem per person per year, in a concrete house 70-100 mrem, and in a wooden house 30-50 mrem.

Cosmic rays contribute 45 mrems to the annual per capita dose equivalent, radioactive minerals in the soil 15 mrems, water food and air 25 mrems, air travel for a round trip from London to New York 4 mrems, diagnostics x-rays 20 mrems, and living in the vicinity of a nuclear power plant 1 mrem.

Most of human exposure to radiation comes from the natural radiation background and the medical applications of radiation as shown in Table 11. Exposure to radiation has been a fact of life since the beginning of life on Earth.

REFERENCES

1. W. E. Kisielewski and R. Baserga, "Radioisotopes and life Processes," USAEC, Division of Technical Information, 1967.
2. I. Asimov and T. Dobzhansky, "The Genetic Effects of Radiation," USAEC, Division of Technical Information, 1966.

EXERCISES

1. The radiation dose received by someone handling a kilogram of a 15 percent uranium ore will be about the same as the dose from a kilogram of fresh separated uranium. Explain why this statement is true or false.

2. Consider the isotope Ra^{226} . Using Avogadro's law, calculate its activity and discuss its relationship to the Curie unit of activity. You can obtain the half life of the radium²²⁶ isotope from the Table of the Nuclides.

3. Calculate the yearly dose accumulated by yourself according to your lifestyle, and compare it to the average natural background dose.

4. Calculate the energy in eV of photons of electromagnetic radiation of:

- a) X-rays,
- b) Gamma rays,
- c) Visible light,
- d) Ultra violet light,
- e) Infrared.

Start from an appropriate value of the wave length, and use:

$$E = h\nu,$$

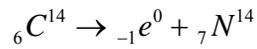
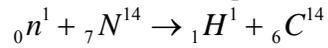
$$\nu = \frac{c}{\lambda}, c = \text{speed of light, } h = \text{Planck's constant, } \lambda = \text{radiation wave length}$$

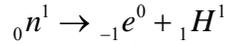
5. The naturally occurring isotope K^{40} is widely spread in the environment. In fact, the average concentration of potassium in the crustal rocks is 27 [g/kg] and in the oceans is 380 [mg/liter]. K^{40} occurs in plants and animals, has a half-life of 1.3 billion years and an abundance of 0.0119 atomic percent.

Potassium's concentration in humans is 1.7 [g/kg]. In urine, potassium's concentration is 1.5 [g/liter].

- a) Calculate the specific activity of K^{40} in Becquerels per gram and in Curies/gm of K^{40} .
- b) Calculate the specific activity of K^{40} in Becquerels per gram and in Curies per gm of overall potassium.
- c) Calculate the specific activity of K^{40} in urine in [Bq/liter].
- d. A beta activity above 200 transformations (disintegrations) per minute per liter of urine following accidental exposure to fission products is indicative of an internal deposition in the body, and requires intervention. How does this "body burden" criterion compare to the activity caused by the one due to the naturally occurring potassium?

6. The production of Carbon¹⁴ with a half life of 5730 years is an ongoing nuclear transformation from the neutrons originating from cosmic rays bombarding Nitrogen¹⁴ in the Earth's atmosphere:





Where Nitrogen¹⁴ and Carbon¹⁴ appear as catalysts in the overall reaction, leading to the disintegration of a neutron into a proton and an electron.

The atmospheric radiocarbon exists as C¹⁴O₂ and is inhaled by all fauna and flora.

Because only living plants continue to incorporate C¹⁴, and stop incorporating it after death, it is possible to determine the age of organic archaeological artifacts by measuring the activity of the carbon present.

Two grams of carbon from a piece of wood found in an ancient temple are analyzed and found to have an activity of 20 disintegrations per minute. Estimate the approximate age of the wood, if it is assumed that the current equilibrium specific activity of C¹⁴ in carbon has been constant at 13.56 disintegrations per minute per gram.