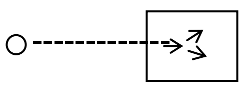
SECTION 17: Biological Effects of Radiation

In the previous discussion of the interaction of radiation with matter (Sec.5), the emphasis was on the effect of the medium on the radiation. In this section the focus will be upon the damage inflicted on the medium by the incident radiation, and in particular the biological effects of radiation. This subject has important implications for evaluating the risks of radiation from the many applications of nuclear processes that are now pervasive in our society.

The two basic concepts of the interactions of radiation with matter are relevant to these discussions:



$$dE/dx \propto AZ^2/E \quad \text{for charged particles}$$

$$dE/dx \propto \mu E_\gamma \quad \text{for photons}$$

Of particular importance to the question of biological effects is the nature of the chemical species that exist in materials subjected to energetic radiation.

Chemical Species Formed in the Medium

- **Cation-Electron Pairs –** In gases and liquids ionizing radiation produces mobile ions, which facilitates their detection,

  e.g., $CH_4 \longrightarrow CH_4^+ + e^-$

  In biological systems these species disturb the electrolyte balance in the affected area. In solids the cation-electron pairs become trapped and create lattice defects and modified conduction bands. These structural impurities can lead to modification of solid properties, for example causing bit upsets in silicon, a problem of concern in space where cosmic rays may alter chip function aboard satellites.
- **Free Radicals** – Bond cleavages induced by the passage of radiation through matter, especially organic molecules, can lead to highly reactive free radicals; e.g.

  $$CH_4 \xrightarrow{h\nu} \bullet CH_3 + \bullet H$$

  An important example is **radiolysis**, or the decomposition of compounds, especially water molecules, by radiation. This sequence of steps is illustrated below:

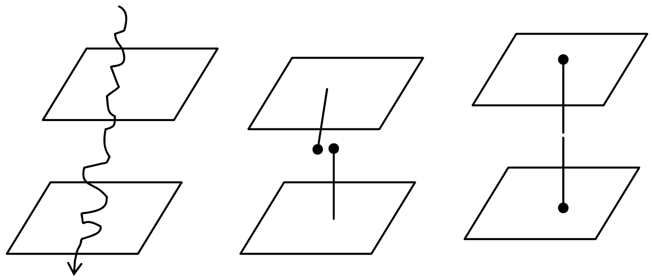
  $$H_2O \longrightarrow \bullet H + \bullet OH$$

  $$\bullet H + \bullet H \rightarrow H_2 \quad \text{(reducing agent)}$$

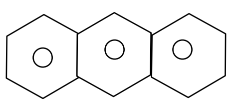
  $$\bullet OH + \bullet OH \rightarrow H_2O \quad \text{(oxidizing agent)}$$

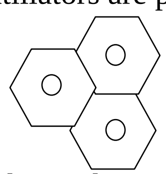
  Since the body is largely composed of water, radiolysis is a major concern in cases of high radiation exposure. The evolution of hydrogen gas was the major worry during the Three-Mile Island nuclear reactor accident in 1979. The danger was not that a nuclear explosion would occur, but rather that there would be a chemical explosion due to the ignition of hydrogen gas created by the radiolysis of the reactor's cooling water.

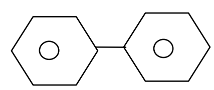
  In reactions with organic compounds the recombinants may alter the physical properties of the irradiated material, which may have either positive or negative effects. For example, biological alterations of hemoglobin may reduce the effectiveness of red blood cells. A positive result is used commercially to cross-link planar polymer and convert them to 3D polymers with improved qualities.



- **Excited Atoms and Molecules –** Radiation may also raise atoms and molecules to an excited state. Aromatic compounds are particularly susceptible to such excitations. The subsequent fluorescence radiation that is emitted as they de-excite proves useful as a **scintillation detection** technique that is widely used in biochemistry and medical sciences for detecting low-energy beta emitters such as ^{3}H, ^{14}C and ^{32}P that are used as tags for biomolecules. Among the common basic structures used for scintillators are polycyclic aromatics such as


Anthracene


Phenanthrene

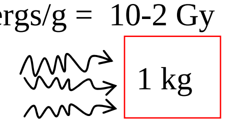

Stilbene

and their derivatives.

Radiation Dosimetry

The amount of radiation received during an exposure (or **dose**) may be quantified in terms of two units units, the rad or the Gray (Gy). The rad is an older unit that still finds frequent use and the Gray is the newer SI unit. These units are defined as the energy deposited per unit mass of absorbed material:

1 rad =10^{-2} J/kg = 100 ergs/g = 10-2 Gy = ΔE/mass



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To calculate ΔE for nuclear radiation (1 eV = 1.60 x 10^{-19} J), the following rules apply:

(1) For **charged particles**, use the energy **E** of the particle if it is stopped or **(dE/dx)(Δx)** if the particle is transmitted.
(2) For **photons**, which can only be attenuated, use $\mathbf{\Delta E = \mu E_{\gamma}/cm^{2}}$.

Example: A 2.0 g sample absorbs 1.0 μ Ci of 100 keV electrons in 10.0 min. What is the dose in rads?

$$\Delta E = \underbrace{(1.00 \times 10^{5} eV)(1.60 \times 10^{-19}\ J/eV)}_{\text{Energy/particle}}\underbrace{(3.70 \times 10^{4}\ dps)(600\ s)}_{\text{Number of particles}}$$

$\Delta E = 3.6 \times 10^{-7}$ J

Dose = $(3.6 \text{ x } 10^{-7}$ J)/(2.0 x 10^{-3} kg) x (1kg-rad/10^{-2} J) = 1.8 x 10^{-2} rads

= 18 mrad

= 1.8 x x 10^{-4} Gy

Biologically Permissible Doses

In order to evaluate the danger of a given dose to biological organisms, several factors come into play, strongly dependent on the ionization density created by the particle as it passes through matter. Charged particles have a high energy loss that depends on the AZ^2/E factor, whereas photons deposit their energy over a much more lengthy path. Beta particles are intermediate between the two. In order to account for these variations a **quality factor (QF) or rlelative biological effectiveness (RBE)** is defined in Table 17.1.

Table 17.1 QF/ RBE Factors for Various Types of Radiation

x-rays, γ-rays	= 1	protons	= 1-10 (depending on energy)
β±	= 1	α's	= 1-20 (depending on energy)
thermal neutrons	= 5	heavy ions (Z ≥ 3)	= 20
fast neutrons	= 10	or fission fragments	

As is evident, there is a degree of imprecision in defining the QF, which reflects variations in biological composition and susceptibility. With the QF factors in Table 17.1, a dose equivalent quantity, the **rem** or its SI equivalent the **Sievert (Sv)**, is defined as follows:

1 rem = 1 rad x QF and

1 Sv = 100 rems = Grays x RBE

If the result in the above negatron decay example is applied to other particles, we obtain

$$\left\{\begin{array}{lll} \text{dose}(e^-) & = 18\text{ mrads} \times 1 = & 18\text{ mrem} \\ \text{dose}(\gamma) & = 18\text{ mrads} \times 1 = & 18\text{ mrem} \\ \text{dose (slow n)} & = 18\text{ mrads} \times 5 = & 90\text{ mrem} \\ \text{dose (fast n)} & = 18\text{ mrads} \times 10 = & 180\text{ mrem} \\ \text{dose}(\alpha\text{'s}) & = 18\text{ mrads} \times 20 = & 360\text{ mrem} \end{array}\right\}$$

Radiation in the Environment

Any evaluation of radiation hazards must be taken in the context of the **natural background radiation** that permeates the environment – which has existed since the earth's formation and cannot be altered significantly. The natural background is easily measured and serves as the basis for setting standards for allowable radiation exposure. It has three primary sources:

- **Uranium and Thorium** – This component includes the radioactive decay products that exist in secular equilibrium with their parents, the most important of which is radon gas. The ambient concentration of these elements is **geology-dependent**. The western United States, Brazil and Sri Lanka have unusually high abundances of uranium and thorium in their soils.
- **^{40}K** – Since potassium is an alkali metal that is always found along with sodium, it is **ubiquitous** in the environment – in water, rocks, food, etc. ^{40}K is the most important source of radiation in the body and since it is an essential dietary element, cannot be avoided.
- **Cosmic Rays** – The earth is constantly being bombarded with energetic cosmic rays, mostly protons, from both solar and galactic sources. Cosmic ray exposure is **altitude dependent** and thus is greatest in mountainous regions and during air and space travel.

To the natural background radiation, numerous **anthropogenic sources** contribute to additional radiation exposure. Among these are:

- **Medical diagnostic and therapy procedures** – These include procedures such as x-rays, PET scans and radiation therapy with both particle beams and radioisotopes.
- **Jet Travel** – Above altitudes of 30,000 feet the earth's protective atmospheric shield is much thinner, enhancing cosmic ray exposure.
- **Coal-fired and Nuclear Power Plants** – Both coal-fired and nuclear power plants release nuclear radiation to the atmosphere. A coal-fired plant typically releases about 5-10 times more radiation than a nuclear power plant, largely due to the uranium and thorium content in coal.
- **Weapons Test Fallout** – Testing of thermonuclear weapons during the 1950s and 1960s injected radioactive nuclei into the stratosphere, the residues of which still mix with the atmosphere and contaminate our earth.

- **Nuclear Applications –** Many other sources of radiation are widespread in the environment, including smoke detectors (which have saved thousands of lives), tobacco smoke and TV. Two applications that are now banned due to their documented cancer-inducing effects are radium-dial wrist watches (once popular for showing the time in the dark) and shoe x-ray machines.

All concerns about the hazards of radiation must be taken in the above context. **Appendix 17.1 provides a dose-computation table** with which one can calculate his or her annual radiation exposure. The result should be compared with **the national average of ~360 mrem/year.**

Radiation Safety

Based on the values for the natural radiation background, exposure limits have been established. For the **general population** the limit is **500mr/year**. For **workers in radiation-related fields**, higher limits are permitted. These are:

(1) Weekly: 100 mr/week
(2) Annually: 5 r / year, and
(3) Lifetime: 5(N – 18) r, where N = age.

These guidelines restrict individuals under 18 from working in radiation-related fields.

Example: In the previous example a negatron source deposited 18 mrad in 10.0 minutes. How long can one work with this source before using up the weekly limit?

$$(\text{Time})(1.8\ \text{mr/min}) = 100\ \text{mr} \Leftarrow \text{LIMITING DOSE}$$

$$\text{time} = \boxed{55\ \text{minutes}}$$

In order to monitor the dose delivered by a radiation source, several approaches are employed. These include the **dosimeter**, a device for providing an **instantaneous** reading of the **total integrated dose** an individual receives when exposed to a radiation source. Dosimeters depend on calibrated, radiation-sensitive chemical redox reactions, for example,

$$\text{Radiation} + H_2O \longrightarrow H_2O_2$$

$$\text{Radiation} + Fe^{2+}(aq) \longrightarrow Fe^{+3}(aq).$$

For longer-term **integrated but not instantaneous** monitoring workers in the field are required to carry a **film badge**. Film badges are compact devices composed of x-ray-type film that can be boron-loaded for neutron sensitivity. In many cases one wants to know the **instantaneous radiation level** in a radiation area, while depending on a dosimeter film badge for an integrated reading. For this purpose, a **survey meter** (e.g. a Geiger counter), equipped with a meter and an audio output is used.

When working around a radiation source, two simple methods of dose reduction can be applied. The first is to attenuate the radiation with an appropriate **absorber**. A knowledge of stopping powers for various types of radiation (Section 5) is valuable in this regard. Absorbers are most effective for alpha and beta particles, less so for gammas and neutrons. The second method is to utilize the geometric **inverse-square law**; i.e. back away. This illustrated below for two distances from a source, R_1 and R_2.

Source • ⟶ 0 (R_1)

• ⟶ 0 (R_2)

$$\text{Dose (2)/Dose (1)} = [\text{Area (0)}/4\pi R_2^2]/[\text{Area (0)}/4\pi R_1^2 = R_1^2/R_2^2 \qquad \text{(Eq.17.1)}$$

That is, the dose decreases as the square of the separation distance.

Example: From the two earlier examples, if the dose rate at a distance of 1.8 mrem/min is measured at 20.0 cm, what will the dose rate be at a distance of 40.0 cm?

Dose (40.0 cm)/Dose(20.0 cm) = $(20.0)^{2}/(40.0)^{2}$ = 1/4

Dose (40.0 cm) = (1.8 mrem/min)/4 = 0.45 mrem/min

The most effective radiation-protection method, however, is often **common sense**.

Biological Exposures

The biological damage caused by exposure to radiation depends on several factors; e.g. the type of radiation, its energy, the dose received and the half-life if it is a radioactive species.

Radiation hazard also depends on the nature of the exposure. External exposures may cause burns, as in case of over-exposure to the sun's uv radiation, and induce skin cancer. The extremities are usually less sensitive than the torso. Alpha particles and spontaneous fission products are usually negligible, as they are easily stopped by a few centimeters of air. On the other hand, beta particles, gamma rays, neutrons and energetic accelerator beams are more dangerous since they penetrate the skin's outer layers, causing both external and internal damage.

Ingestion or inhalation of radioactive materials stimulate different biological effects. All types of radiation are hazardous when taken internally. This is especially true of alpha particles because of their high rate of energy loss and the fact that alpha particle ranges are roughly equivalent to the thickness of lung tissue. Radon gas, with its 3.8 day half-life, is a major component of nature's background radiation exposure. It is largely responsible for Black Lung disease suffered by workers in coal mines, where the radon concentrations can be quite high if the area is not properly ventilated.

The danger to an organism depends on both the rate of excretion and the biological distribution of the radionuclide in question. Rapid excretion rates and short half-lives minimize the hazard. On the other hand, if the radionuclide binds to some part of the organism, the problem may be more severe. Whether the radionuclide is concentrated in a given organ or distributed throughout the body is another factor. For example, ^{131}I concentrates in the thyroid gland, which is useful in treating thyroid tumors. ^{90}Sr is localized in the bones, while ^{40}K is distributed throughout the body fluids. An overriding factor in all of these considerations is that of biological susceptibility. Due to genetic differences, individuals differ in their physiological response to radiation. The familiar example is uv radiation from the Sun, which induces deep tans in some individuals and severe sunburns in others.

Clinical Effects

In examining the clinical effects associated with levels of radiation in excess of the natural background, it is important to distinguish between **somatic and genetic effects**. The data base for evaluating these effects is the result of an ongoing joint US-Japanese effort to trace the medical histories of the survivors of the Hiroshima and Nagasaki atomic bomb blasts during WW II. The results of an 18-year study anre shown in Table 17.2.

Table 17.2

Hiroshima-Nagasaki Survivor Leukemia Statistics

(18 year study)

Dose (rems)	No of Cases	Deaths	Person-Yrs ÷ 1000	Rate (per 10^5 p-yrs)
200 +	1460	22	26.7	81.6
100-199	1677	10	30.2	33.1
50-99	2665	7	48.3	14.5
10-49	10,707	17	195.4	8.7
0-9	43,830	34	795.6	4.3

Somatic effects refer to health problems induced in someone who has experienced high levels of radiation, including the fetus in cases of exposure during pregnancy. If the exposure very high, the dose may prove fatal in the short term. The immediate effect is leucopenia, a serious deficiency of the blood's leucocytes, which maintain the immune system. For a short exposure time ($\lesssim$1 day), the dose at which 50% of the exposed individuals will die within a few months is 450 rem. This is known as the lethal dose, or

$$\mathbf{LD_{50} = 450\ rem.}$$

Longer term, there is a well-documented correlation between radiation exposure and both leukemia and skin cancer. The clinical effects of high-level radiation are summarized in Table 17.3.

Genetic effects -- a popular subject of science-fiction writers – suggest an alteration of genetic material that is transferred to later generations. The studies of the Hiroshima-Nagasaki survivors indicate that there is no evidence to support this hypothesis, at least through the second and third generation.

While the dangers of high levels of radiation are now well-documented, those associated with low levels of exposure continue to be the subject of debate. Consider the effects of an additional 100 mrem of exposure (to be compared with the national average of 360 mrem).

Table 17.3

Clinical Effects of High-Level Radiation

Subclinical			Therapeutic		Lethal	
Dose (rems)	0-100	100 – 200	200 – 600	600 – 1000	1000 – 5000	> 5000
Symptoms	none		leukopenia hemorrhage infection		Diarrhea fever electrolyte imbalance	Convulsions
Critical Period	none	none	4-6 weeks		5-14 days	
Therapy	Reassurance surveillance		Blood transfusions; Bone marrow transplant		Balance electrolytes	Sedation
Prognosis	Excellent		Good	Guarded	Unfavorable	
Recovery Time	—	weeks	1-12 mo.	long	rare	
Death Rate	none	none	0 - 80%	80-100%	90 - 100%	
			2 mo.		2 wk	2 days

This additional dose is equivalent to a more than one-hundred-fold increase in nuclear power generation in the US or spending an entire year in Vail, Colorado. Computer-model estimates of the death rate that would be expected due to an additional 100 mrem/year for the entire US population range between ~1500/year using an absolute risk method and ~8300/year using a relative risk method. In addition, it has been suggested that small amounts of radiation may stimulate the immune system, leaving the body better prepared to deal with invading organisms. This theory, **radiation hormesis**, is difficult to validate because of the difficulties in performing a controlled experiment.

When considering the broader risk factors of low levels of radiation exposure in the broader national context, environmental factors must also be taken into account. For example, the average resident of Colorado, who lives at the highest overall altitude of any state in the US, receives an annual dose of ~500 mrem, well above the national average. Yet Colorado has one of the lowest cancer rates in the country. Pennsylvanians, on the other hand, receive the average dose of 360 mrem/year, yet they have one of the highest cancer rates. The synergistic effects due to air and water quality are essential factors in evaluating the total risk factors that are present in our environment.

Statistical Significance and the Press

In recent years, there have been a number of reports in the popular press suggesting that electromagnetic radiation from power lines, cell phones, etc. can cause cancer. These stories are based on cases involving a very small statistical sample in which a cluster of cancer cases had been observed. However, studies of tens of thousands of power-line workers in both the US and Europe have shown that there is no statistical evidence for a connection between electromagnetic radiation and cancer. The policy statement of the American Physical Society on this issue is presented in Appendix 17.2.

Similarly, some years ago headlines appeared that stated "studies show a 50% higher leukemia rates" in Utah, downstream from the thermonuclear tests conducted in Nevada during the mid-1960s. The actual numbers were 29 reported case versus 19 expected cases, numbers that are statistically equivalent at the 67% level. What was missing from the story was that the epidemiological study also showed that the incidence of other types of cancer was much lower among the sample group and that the total cancer rate was equal to the expected rate.

In reading of nuclear incidents in the popular press, two factors must be kept in mind: statistical significance and the radiation dose in mrem.

Relative Risks in Context

Excessive radiation is hazardous to one's health, with leukemia and skin cancer clearly documented maladies. The risk of lower levels of radiation are much less certain and must be taken in the broader context of all risks in our environment. Table 17.4 presents a table of risk factors and their annual death rate, as prepared by insurance actuarial, whose business it is to estimate death rates accurately in order to stay in business.

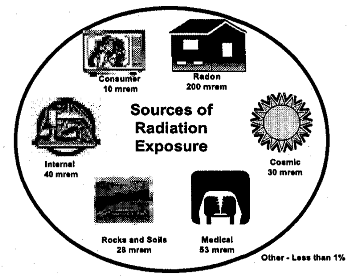
Table 17.4

RISK FACTOR	ANNUAL DEATHS
Smoking	434,000
Alcohol	105,000
Secondary Smoke	53,000
Motor Vehicles	49,000
AIDS	31,000
Homicides	22,000
Electric Power	14,000
Cocaine/Crack	3,300
Motorcycles	3,000
Swimming	3,000
Surgery	2,800
Heroin/Morphine	2,400
x-rays	2,300
Railroads	1,900
Aviation (not commercial)	1,400
Large Construction	1,000
Bicycles	1,000
Hunting	800
⋮ ⋮	
Nuclear Power	100
⋮	
Skiing	20

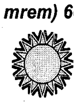
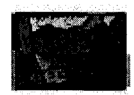
*Sources: US Center for Disease Control; National Safety Council, National Center for Health Statistics; Insurance Actuarial Tables

APPENDIX 17.1 Dose Computation Table

Radiation is in every part of our lives. It occurs naturally in the earth and can reach us through cosmic rays from outer space. Radiation may also occur naturally in the water we drink or the soils in our backyard. It even exists in food, building materials, and in our own human bodies. Fill out the chart below to see how much radiation you receive in a year.



Cosmic radiation at sea level (from outer space)	**26**
What is the elevation (in feet) of your town? ***Idaho Falls 4736 feet***	
Up to 1000 (add 2 mrem) 1000-2000 (add 5 mrem) 2000-3000 (add9 mrem) 3000-4000 (add 15 mrem) 4000-5000 (add 21 mrem) 5000-6000 (add 29 mrem) 6000-7000 (add 40 mrem) 7000-8000 (add 53 mrem) above 8000 (add 70 mrem)	________
Terrestrial (from the ground):	
What region of the US do you live in? ***Gulf Coast (23 mrem) Atlantic Coast (23 mrem) The Colorado Plateau (90 mrem) Elsewhere in the US (46 mrem)***	________
Internal radiation (in your body):	
From food and water, (e.g. potassium)	**40**
From air, (radon)	**200**
Do you wear a plutonium powered pacemaker? No (0 mrem) Yes (100 mrem)	________
Do you have porcelain crowns or false teeth? No (0 mrem) Yes (.07 mrem)	________
Travel Related Sources:	
Add 1 for each 1000 miles traveled by jet this year:	________
Are X-ray luggage inspection machines used at your airport? No (0 mrem) Yes (.002 mrem)	________
Do you use gas lantern mantles when camping? No (0 mrem) Yes (.003 mrem)	________
Miscellaneous Sources:	
Weapons test fallout	**1**
Do you live in a stone, brick, or concrete building? No (0 mrem) Yes (7 mrem)	________
Do you wear a luminous wristwatch (LCD)? No (0 mrem) Yes (.06 mrem)	________
Do you watch TV? No (0 mrem) Yes (1 mrem)	________
Do you use a computer monitor? No (0 mrem) Yes (.1 mrem)	________
Do you have a smoke detector in your home? No (0 mrem) Yes (.008 mrem)	________
How many medical x-rays do you receive per year? (40 mrem each)	________
How many nuclear medical procedures do you receive per year? (14 mrem each)	________
Do you live within 50 miles of a nuclear power plant? No (0 mrem) Yes (.009 mrem)	________
Do you live within 50 miles of a coal fired power plant? No (0 mrem) Yes (.03 mrem)	________
****TOTAL YEARLY DOSE (in mrem):**	________



Appendix 17.2

95.2 STATEMENT ON POWER LINE FIELDS AND PUBLIC HEALTH

(Adopted by Council 23 April 1995)

Physicists are frequently asked to comment on the potential dangers of cancer from electromagnetic fields that emanate from common power lines and electrical appliances. While recognizing that the connection between power line fields and cancer is an area of continuing study by research workers in many disciplines in the United States and abroad, we believe that it is possible to make serveral observations based on the scientific evidence at this time. We also believe that, in the interest of making the best use of the finite resources available for environmental research and mitigation, it is important for professional organizations to comment on this issue.

The scientific literature and the reports of reviews by other panels show no consistent, significant link between cancer and power line fields. This literature includes epidemiological studies, research on biological systems, and analyses of theoretical interaction mechanisms. No plausible biophysical mechanisms for the systematic initiation or promotion of cancer by these power line fields have been identified. Furthermore, the preponderance of the epidemiological and biophysical/biological research findings have failed to substantiate those studies which have reported specific adverse health effects from exposure to such fields. While it is impossible to prove that no deleterious health effects occur from exposure to any environmental factor, it is necessary to demonstrate a consistent, significant, and causal relationship before one can conclude that such effects do occur. From this standpoint, the conjectures relating cancer to power line fields have not been scientifically substantiated.

These unsubstantiated claims, however, have generated fears of power lines in some communities, leading to expensive mitigation efforts, and, in some cases, to lengthy and divisive court proceedings. The costs of mitigation and litigation relating to the power line cancer connection have risen into the billions of dollars and threaten to go much higher. The diversion of these resources to eliminate a threat which has no persuasive scientific basis is disturbing to us. More serious environmental problems are neglected for lack of funding and public attention, and the burden of cost placed on the American public is incommensurate with the risk, if any.