CHAPTER 2 PRINCIPLES OF RADIATION SAFETY

1.0 UNITS OF RADIATION DOSE

1.1 Historical Units

In 1896, x-rays were discovered by Wilhelm Roentgen. The Roentgen is unit of measurement for the exposure of x-rays and gamma rays. It is defined as the electric charge freed by such radiation in a specified volume of air divided by the mass of that air.
Radioactivity was discovered by Henri Becquerel. Radioactivity refers to the amount of radiation released when an element spontaneously emits energy as a result of the decay of its unstable atoms. The Becquerel is a unit used to measure radioactivity, and stands for 1 disintegration per second. The Curie is a unit of radioactivity equal to 3.7×10^{10} disintegrations per second and was first used, but being such a large unit was replaced by the Becquerel. The Curie is named for Pierre Curie, Marie Curie's husband and co-discoverer of radium. After his accidental death, she continued their work.

For some time, no one realized that radiation could cause harmful effects. It was recognized very soon that x-rays could be used in medical diagnosis, and early radiologists received large doses of radiation. Many of these radiologists later suffered severe injuries due to overexposure (radiation effects may appear years after exposure). The first unit of dose was the erythema dose. This was the amount of x-radiation which would barely cause reddening of the skin. It was not a very satisfactory unit of dose, but indicates the early recognition by some scientists that radiation exposure can be harmful and should be limited. One erythema dose consisted of about 270 to 1,000 Roentgens, depending upon the energy of the x-rays. The recommended limit was 1/1000 of an erythema dose per day (about 0.27 to 1.0 Roentgen per day).

Madame Curie, in her work with radium, received radiation exposure which eventually proved fatal. It should be noted that Madame Curie received what would now be considered extremely high doses of radiation exposure and that she lived to be 67, a long lifetime for the period. Radium-containing "tonics" were sold by unscrupulous persons as health aids and some of the persons taking large amounts of these "tonics" died of radiation poisoning. Probably the most widely known example of radiation poisoning is the case of the watch dial painters who used radium to paint luminous dials. These workers ingested radium by using their lips to make a pointed tip on their brushes. Many of them died later of bone cancer. It should be emphasized that the persons noted above who suffered radiation damage received very large doses of radiation and followed no standards of exposure limitation.

In 1928, the International Commission on Radiation Protection (ICRP) was established. This group defined the Roentgen as the unit of radiation dose. In 1934, a "tolerance dose" of 0.2 Roentgens per day (60 Roentgens per year) was agreed upon as the recommended limit for radiation exposure.

In 1936, the recommended limit was reduced to 0.1 Roentgen per day (30 Roentgens per year). In 1950, the National Council on Radiation Protection and Measurement (NCRP) and the ICRP introduced the concept of "permissible dose" and set the permissible exposure at 0.3 Roentgen per week (15 Roentgens per year). In 1956, the permissible dose was reduced to 0.1 Roentgen per week (5 Roentgens per year). This was not due to any observed ill effects at previous limits, but was based on the desire to be conservative and reduce the possibility of any long-range effects. At the present time, the limit for occupational exposure remains 5 Roentgens per year or the equivalent. No ill effects have been noted at this exposure level.

1.2 Rad

The Roentgen was not an ideal unit of radiation dose. It was defined as the amount of x or gamma radiation which produces ions carrying one electrostatic unit of charge of either sign in one cubic centimeter of dry air at standard temperature and pressure. Thus, the Roentgen was defined as a given amount of ionization in air and applied only to x and gamma radiation. It did not indicate directly the damage within a biological system. It was soon realized that a given amount of ionization in air could result in different amounts of damage in an object being irradiated. Results of experiments using low energy x-rays could not be compared with those using high energy x-rays or gamma rays. This led to much confusion in the literature on radiation effects.

This resulted in establishment of the rad. A rad is 100 ergs of energy per gram, absorbed by any material from any type of ionizing radiation.

1.3 Rem

By this time, it had also been established that radiation effects depended not only upon the number of ions being formed, but also upon their distribution within living tissue. Dense trails of ions cause more damage than the same number of ions spread widely apart. Thus, the specific ionization (ions per unit distance) must be taken into consideration. X and gamma radiation and beta particles tend to produce ions spread relatively far apart, while alpha particles and neutrons tend to cause dense trails of ions. The x-ray, beta, and gamma radiation is referred to as low Linear Energy Transfer (low LET) radiation, while alpha particles and neutrons are called high LET radiation. One explanation for the difference in effect between high and low LET radiation is that the cells within a living organism can repair small amounts of damage caused by radiation. However, if there is too much damage within one cell, the repair mechanism may be overwhelmed and the cell may die or be irreparably damaged.

To correct for differences in LET the Quality Factor (QF) was invented. Radiation with higher LET is given a higher Quality Factor. The rad (unit of absorbed dose) is multiplied by the Quality Factor to obtain the rem.

The rem is a unit of damage to a biological system. It is equivalent to the damage done by exposure to one Roentgen of 250 keV x-radiation and is called the equivalent dose. Effects from any type of ionizing radiation may be compared using the rem.

We now have the:

- Roentgen - **exposure dose** based on ionization in air
- rad - **absorbed dose** based on absorption of energy
- rem - **equivalent dose** based on biological effects

1.4 Quality Factors

For x-rays of 250 KeV, the Roentgen, rad and rem are approximately equal. For practical purposes it is usually assumed that all x and gamma radiation from about 100 KeV to 3 MeV have a quality factor of 1 and that the Roentgen, rad, and rem are equivalent in this range. Below are some examples of Quality Factors for different types of radiation.

Radiation	Q. F.
x-ray	1
gamma ray	1
beta particle	1
alpha particle	20
slow neutron	2.5
fast neutron	20
heavy ions	20

1.5 International Units

It should be mentioned here that there are also international (SI) units of dose. Applied health physicists in general feel that these new units are unnecessary and will cause much confusion, especially in record keeping. The new units have not, at this time, been widely accepted for use in the United States. While we will continue to use the Roentgen, the rad, and the rem, the following conversions can be made if desired:

Gray = 100 rad
Sievert = 100 rem

2.0 EFFECTS OF RADIATION EXPOSURE

2.1 Acute Exposure Effects

Radiation in large doses causes observable damage. The following list gives some typical effects of radiation exposure by X or gamma rays given to the total body at a high dose rate over a short period of time.

0 - 25 rem - No observable effects on the health of the individual. At 25 rem, a physician could probably see some changes in blood cells.

50-100 rem - Possible nausea and blood count depression. Recovery within days to weeks with no lasting ill effects.

500 rem - Nausea, weakness, anemia, internal bleeding, temporary sterility, susceptibility to infection, loss of hair. This is the LD^{50-30}. Half of the persons so exposed die within 30 days (without medical treatment). The other 50% recover with few lasting ill effects. Recovery takes months to years. Death is usually due to damage to the blood-forming stem cells in bone marrow.

1000 rem - Death within days to weeks, usually from damage to the gastrointestinal system.

10,000 rem - Death within hours to days from damage to the nervous system.

100,000 rem - Essentially instantaneous death from damage to the nervous system.

The above effects are observable within a short time after the exposure. They have been observed in persons exposed before the harmful effects of radiation were known, in persons exposed for medical treatment, in the watch dial painters, the atomic bomb survivors and a few persons suffering accidental occupational overexposures.

In addition to the effects listed above, persons who are exposed to large amounts of radiation and recover have an increased incidence of some types of cancer, leukemia being the most readily observed. For the atomic bomb survivors who received 200 rem or more of gamma radiation, the incidence of those types of cancer was approximately doubled over the following 25 years.

2.2 Genetic Effects

There is also the possibility of increased genetic damage in persons who recover from high doses. This is theoretically possible and has been observed in lower animals. However, there has been no observable increase in genetic defects among the atomic bomb survivors. Genetic effects have not been observed in humans.

2.3 Chronic Exposure Effects

The effects from radiation exposure decrease as the dose rate is lowered. Spreading the dose over a longer period reduces the effects. Much of the controversy over radiation exposure centers on the question of how much damage is done by radiation delivered at low doses or low dose rates. It has been assumed that one could predict the maximum amount of damage that might be expected from low doses of radiation by extrapolating from the effects at high doses. Some persons have claimed that there is no damage at very low doses. This is called the threshold model. Since cancers caused by radiation do not generally appear until years after the exposure and are of the same types as naturally occurring cancers, it has been impossible to show any effects for exposure below about 100 rem. While there may be some increase in cancer from exposures below 100 rem, the number is too small to measure statistically.

It has been popular to assume that the straight line model is fact and that the number of cancers depends strictly upon the number of person-rem of exposure to the population. If 10,000 persons are exposed to 100 rem each:

persons x rem = person-rem
10,000 x 100 = 1,000,000

Using this formula and data from persons exposed to high doses (such as the atomic bomb survivors) the report of the National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR Report) predicts that there will be approximately 200-400 fatal cancers for each 1,000,000 person-rem of exposure. This estimate has varied from 100 to 400 over the years, as new estimates were made based on revised data. The estimate is probably reasonably accurate for exposures above 50 rem. The value may even be zero for individual exposures much below 50 rem. One may take the straight-line model and apply it to low-level radiation exposure. For instance:

persons x rem = person-rem
1,000,000,000 x 0.001 = 1,000,000

This implies that one billion persons exposed to one-thousandth of a rem each (one millirem) would develop 200-400 fatal cancers. Since 400 cancers among one billion persons would be impossible to detect among the millions of cancers naturally occurring, it has been impossible to prove or disprove the straight-line model for low-level radiation. However, some persons have pointed out that if the straight-line model were correct for low-level radiation, background radiation would cause more cancers than those which are actually observed. A few persons have claimed that low-level radiation causes up to 10 times the number of cancers predicted by the straight-line model. However, in view of the above observation concerning background radiation, little credence is given to these claims by most scientists.

In Report No. 64 issued in April 1980, the NCRP set forth evidence indicating that the straight-line model overestimates the effects of low-level radiation. According to this report, the response to radiation exposure by biological systems follows a curve composed of at least two parts: a linear component due to low-level radiation and a quadratic component due to high dose and high dose rate. The curve is described by the formula:

$$I = \forall D + ßD^2$$

I is the effectiveness per unit dose.

D is the total dose given.

∀ and ß are constants which depend upon the particular effect being studied and experimental conditions.

The NCRP estimated that the straight-line model overestimates the effects of low-dose radiation by a factor of 2 to 10. This is called the Dose Rate Effectiveness Factor (DREF). The DREF may vary somewhat with the particular effect being studied. The most accurate data were obtained from plants and lower animals, but the same type of curves are presumed to apply to human beings. The above applies to low LET radiations. High LET radiations appear to follow the straight-line curve. Most occupational exposure is low LET radiation.

There also have been many studies performed, showing *beneficial* effects of irradiation – this is called "hormesis". At this time, the United States government has commissioned further studies about hormesis, but no changes have yet been made in government regulations concerning exposure/dose limits.

3.0 ESTABLISHED DOSE LIMITS

3.1 Occupational Exposure

Exposure to ionizing radiation through occupational exposure is limited by law to 5 rem per year. In accordance with the observation that the effects are less if the dose is spread over a longer period, the dose should be spread out as much as possible.

3.2 Medical Exposure

There is no limit to medical exposure. The medical doctor should ensure that no patient is exposed to more radiation than is necessary to achieve the required medical diagnosis or treatment. Medical x-rays may be considered as part of the background exposure and cause an average of about 50 to 100 millirem each year to persons in the U.S.

3.3 Background Exposure

Natural background gives one good reference which can be used in setting radiation limits. Human beings have been exposed to background radiation since the origins of mankind and it can probably be assumed that this amount is not very harmful. It may even be beneficial. Increased average lifespans have been observed in rats exposed to 100 millirads per day of x-radiation. In fact, some minimum level of background radiation may be essential to life on earth.

A typical background exposure might be as follows:

Radiation	Millirem/Year
Cosmic	40
Terrestrial	60
Potassium-40	20
Other	5
Total	**125**

Background radiation varies with location. Cosmic radiation increases with altitude, and terrestrial radiation varies with the types and quantities of minerals in the soil. Background in the United States may vary from approximately 90 millirem per year to more than 250 millirem per year. In some areas of Brazil and India, background may reach 3,000 millirem (3 rem) per year because of radioactive minerals in the soil. It has been impossible to show any ill effects, such as increase in cancer rate, among persons who live in these areas of high natural radioactivity. Therefore, it is believed that the exposure of a few people to occupational exposures of 5 rem per year is unlikely to cause any significant effects. The limit set for the general population is 100 millirem per year in addition to background.

3.4 As Low As Reasonably Achievable

In addition to the specific limits set above, U.S. law requires that no one be unnecessarily exposed to ionizing radiation. Exposure must be kept **A**s **L**ow **A**s **R**easonably **A**chievable (ALARA) in order to minimize any possible ill effects.

4.0 RISKS OF IONIZING RADIATION

4.1 Risk Comparison

Since many persons are particularly fearful of radiation, it may be helpful to compare the risk from radiation exposure to some other risks encountered in everyday life. Based on the straight-line model, a worker exposed to 1,000 millirem (one rem) per year for 30 years would lose about 30 days of life expectancy due to increased risk of cancer. This is comparable to other "safe" jobs. For comparison, the loss of life expectancy for some other risks is given below.

Job or Other Risk	Days of Life Expectancy Lost
Manufacturing	43
Agriculture	277
Construction	302
Coal Mining	1100
Being 30% overweight	1300
Being President of the U.S.	1861
Being an average male smoker	2153

To put it another way, statistically the risk from one millirem of exposure is approximately equal to the risk from taking one puff on a cigarette or driving a car 0.15 miles on the highway. Many persons do not approach radiation risk rationally. Some tend to ignore the risk because they cannot see any immediate ill effects. Others have an irrational fear of radiation entirely out of proportion to the actual risk (radiophobia).

It should be noted that no ill effects have ever been observed in persons whose exposure remained within the limits recommended by the NCRP, and incorporated into current government regulations and University policy.

4.2 What levels of Radiation are dangerous?

1000 rem

- Fatal to all exposed persons if received as total body exposure over a short period.
- Terminal case of radiation syndrome.

500 rem

- Fatal to approximately one-half the exposed persons if received as total-body exposure over a short period.
- Severe case of radiation syndrome.
- Increased risk of cancer in survivors.

100 rem

- Smallest dose that can definitely be shown to cause ill effects to adults.
- May cause mild symptoms of radiation syndrome.
- Slightly increased risk of cancer.

25 rem

- Smallest dose that will cause effects that can be detected by a physician.
- No readily detectable signs of illness.
- No long-range ill effects can be demonstrated.

5 rem (5000 mrem)

- Limit for one year of occupational exposure.
- Not expected to cause any ill effects over a lifetime.
- Epidemiological studies cannot detect any harmful effects at this level.

3 rem (3000 mrem)

- Maximum received in one year by the general population from natural radiation in the most radioactive areas of earth.
- No demonstrated ill effects.

1 rem (1000 mrem)

- Effective dose equivalent from living for one year in a house with 4 picocuries per liter of radon in the air (the EPA limit).
- This value may vary considerably depending upon assumptions made in the calculations.

- No demonstrated ill effects.

0.3 rem (300 mrem)

- Approximate effective dose equivalent from living in a house with 1 picocurie per liter of radon in the air.
- May be near the average for U.S. homes.
- No demonstrated ill effects.

0.125 rem (125 mrem)

- Average dose received in one year from background radiation (not including radon) in Athens, Ga.
- No demonstrated ill effects.

0.1 rem (100 mrem)

- Annual limit for non-occupational exposure (general public).
- Dose received each year by the average person from medical x-rays.
- Approximate dose received from background (excluding radon).

No demonstrated ill effects.

4.3 Additional Information

For additional information on the risks associated with radiation exposure you should read the U.S. Nuclear Regulatory Commission (NRC) document entitled *Regulatory Guide 8.29, Instruction Concerning Risks from Occupational Radiation Exposure*. A copy of this document is available from Radiation Safety.