

HEALTH PHYSICS II PHS 455

Introduction

The problems presented by such an operation as we have here are somewhat different from the problems of the hospital radiologist. Here we not only have alpha, beta, gamma, and X rays, **but** we also have fast neutrons and thermal neutrons. In addition to these particles, we have the recoil fission elements and the neutrinos. We also have epithermal neutrons. However, we do not have much knowledge of the biological damage associated with neutrinos or epithermal neutrons.

Principal Objectives of Health Physics

The principal objectives of the Health Physics students can be outlined as follows:

1. Make a Study of Various Radiation Problems. One of these problems is shielding. In order to protect personnel by shielding, it is necessary to know something about the nature of radiation and how to shield one from this radiation. If you are working in the pile building, you know that you have to put up a certain shield to stop the neutrons and would prefer to use light material such as paraffin to slow down or stop the neutrons. You might mix paraffin with iron (for fast neutrons) or boron (to capture thermal neutrons), but then, if you left it at that, you would run into trouble because fast neutrons react with iron and slow neutrons with hydrogen to produce gamma radiation. It would then be necessary, in addition, to surround the paraffin mixture with lead or heavy material to stop the gamma rays which are produced by slowing down and capture of neutrons. Shielding of radiation can be quite a complex problem.
2. Develop Methods of Preventing or Minimizing Radiation Exposures. Along with the idea of making the study of radiation, the next step is making a study of how to prevent radiation exposure. This is our primary objective. Shielding is not the only method of preventing radiation exposures. For example, using psychological means or "horse sense" in dealing with people may be an important element in obtaining cooperation and preventing overexposure to radiation. In preventing radiation exposures you will find quite a challenge. If you develop any new methods of minimizing radiation exposure, bring it to the attention of the supervisor so that he can pass it on to others.
3. Understand the Operation and Interpretation of Radiation-detection Instruments. I do not mean by this that each of you needs to become an expert in electronics. A few of you may go on in electronics or some other branch of physics. I hope that quite a few of you will take additional college work and advance in these fields. A large majority will certainly not become specialists in electronics, but I do hope that each of you will understand the fundamentals of instrument usage, how the instruments operate, their limitations, etc. Film meters, for example, have certain inherent limitations. Understand what they are good for and what they are not good for. Know why a film meter may give a different reading from a Cutie Pie; if a supervisor wishes to know why these two meters read differently, give the whole radiation story to the supervisor, and I am sure that you will gain the complete respect of the people with whom you work.
4. Understand the Rules and Procedures for Radiation Protection. There is no substitute for

this. I have to study the rules and procedures every day or so, but I suggest, to begin with, that you obtain a copy of the manual of rules and procedures for working with radioactive material and practically memorize the rules and procedures for the area in which you are working. As you acquire a knowledge of all operations relative to Health Physics, you become a senior man and take on more responsibility. I have had this question asked: Here is a fellow in Health Physics working side by side with someone else. Both are doing the same type of work, but one is making 30 per cent more than the other. Why is this? The answer is that the person who is receiving 30 per cent more not only knows how to do this particular job, but he knows how to carry out Health Physics functions on 10 other operations. He is a much more useful man, although he may be doing just the same type of work as a less experienced man on a particular job. Look forward to familiarizing yourself with all the varied Health Physics survey functions. If you have research interests, add to your education, and there is no reason why you cannot go on and become a research Health Physicist. If you wish to be a supervisor, make a study of that field. There is plenty of chance for advancement in Health Physics.

5. Maximum Permissible Levels of Exposure. You should know the maximum permissible level of exposure for every operation with which you are associated, or know how to find them in a hurry. It is not enough to know that the present level is 1/10 r/day and the new level is 3/10 r/week. You want to know the permissible contamination on the hands, when a person should wear gloves, and when he should wear complete protective clothing or just a lab coat. Never use the word "tolerance." Replace it with "maximum permissible exposure." No radiation is tolerable. We all take some radiation exposure and can never get away from the natural radiation of the earth, but we should not tolerate any unnecessary radiation exposure.

6. Become Thoroughly Familiar with Employee Relations and Supervisory Relations. This will be discussed further in later lectures. Later on you will be able to attend supervisory lectures. Health Physics occupies a rather delicate position as far as management is concerned. We tie into all operations at various levels. You are directing the radiation-protection procedure on a job, and yet on this job you probably find people working who are assigned to it from a number of divisions or departments. I am sure you have found out already that you do not go up to a plumber and tell him to get away from what he is doing before he has obtained a slight overexposure. In practically all cases we work with supervision and try to offer advice and recommendations to the supervisor in the area in which we work, and he passes these recommendations on down to the people under him. If damage may result to the plumber from what he is doing, then try to remove him from the area in which he is working as quickly and quietly as possible. Otherwise, go to the supervisor. If no cooperation is available, contact your own supervisor, and he will see that the case is taken care of.

Do not cut channels except in serious emergencies where life is endangered. Offer advice where and when it will do the most good and in a manner that will be accepted. This is a challenge to each individual. Some are born with a good personality and a knack of getting along with people, but others must develop it.

7. Have a General Knowledge of the Total Laboratory Operation, with a Working Knowledge of the Various Operating Techniques in Your Particular Assigned Area. This is also a matter of psychology, in that you must be able to create opportunities to learn of the operation without taking up someone's time or aggravating him. Previously I pointed out the fact that if you become a good Health Physicist here, you are not necessarily limited to ORNL or to

Oak Ridge. There is a great need for Health Physicists in many walks of life and in all countries of the world. Wherever you have people working with radioactive materials or Instruments that protect from radiation, you find a need for Health Physicists. The greatest need has been, up to now, on the AEC projects. Altogether, we have trained in our division roughly 150 persons in Health Physics, some for periods of one year or more, and others for months, weeks, or days. We have sent trained personnel to Mound, Hanford, Los Alamos, and general AEC operations. Many opportunities in the AEC operations still exist, and these operations are quite anxious to get additional personnel. Our division is conducting at this time a Health Physics training program for 10 persons from other laboratories.

As time goes on, the need for Health Physicists and/or Radiological Physicists in hospitals becomes more urgent. There is going to be a cancer research program at our local hospital, and a project is starting in Knoxville which will need Health Physicists on the staff. Various universities are taking this job seriously Purdue, Chicago, M. I. T., and others are sending men here for training, and they are going back to set up their own nuclei of organizations. The steel industry, using C * and radioactive iron, is anxious to get started in tracer work and to obtain Health Physicists.

The petroleum industry has indicated that it would like to send people here for training. The Army, Navy, and Air Force need senior and junior Health Physicists The Public Health Service will need quite a number of persons trained in the field of Health Physics. Some senior men from the Public Health Service are in training here now. TVA has a senior man here in training. The transportation industry will be anxious to get a few senior men trained in Health Physics because they are responsible for seeing that all shipments of radioactive material are made safely. Insurance companies are interested and have inquired about the possibility of organizing a school for insurance specialists.

An effort is already under way to give safety engineers some elementary but fundamental training in Health Physics. Many research organizations are interested in securing Health Physicists.

Radiation dosimetry is the branch of science that attempts to quantitatively relate specific measurements made in a radiation field to physical, chemical, and/or biological changes that the radiation would produce in a target. Dosimetry is essential for quantifying the incidence of various biological changes as a function of the amount of radiation received (dose-effect relationships), for comparing different experiments, for monitoring the radiation exposure of individuals, and for surveillance of the environment. In this lecture we describe the principal concepts upon which radiation dosimetry is based and present methods for their practical utilization.

When radiation interacts with a target it produces excited and ionized atoms and molecules as well as large numbers of secondary electrons. The secondary electrons can produce additional ionizations and excitations until, finally, the energies of all electrons fall below the threshold necessary for exciting the medium. The initial electronic transitions, which produce chemically active species, are completed in very short times ($\leq 10^{-15}$ s) in local regions within the path traversed by a charged particle. These changes, which require the direct absorption of energy from the incident radiation by the target, represent the initial physical perturbations from which subsequent radiation effects evolve. It is natural therefore to consider measurements of ionization and energy absorption as the basis for radiation dosimetry.

As experience and knowledge have been gained through the years, basic ideas, philosophy, and concepts behind radiation protection and dosimetry have continually evolved. This process continues today. On a world scale, the recommendations of the International Commission on Radiological Protection (ICRP) have played a major role in establishing protection criteria at many facilities that deal with radiation. In the first part of this lecture we will deal with radiation quantities and units that are of historical and current importance.

Quantities and Units

Exposure

Exposure is defined for gamma and X rays in terms of the amount of ionization they produce in air. The unit of exposure is called the roentgen (R) and was introduced at the Radiological Congress in Stockholm in 1928. It was originally defined as that amount of gamma or X radiation that produces in air 1 esu of charge of either sign per 0.001293 g of air. (This mass of air occupies 1 cm³ at standard temperature and pressure.) The charge involved in the definition of the roentgen includes both the ions produced directly by the incident photons as well as ions produced by all secondary electrons. Since 1962, exposure has been defined by the International Commission on Radiation Units and Measurements (ICRU) as the quotient $\Delta Q/\Delta m$, where ΔQ is the sum of all charges of one sign produced in air when all the electrons liberated by photons in a mass Δm of air are completely stopped in air. The unit roentgen is now defined as

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C kg}^{-1}. \quad (1)$$

The concept of exposure applies only to electromagnetic radiation; the charge and mass used in its definition, as well as in the definition of the roentgen, refer only to air.

Example

Show that 1 esu cm⁻³ in air at STP is equivalent to the definition (1) of 1 R of exposure.

Solution

Since the density of air at STP is 0.001293 g cm⁻³ and 1 esu = 3.34 × 10⁻¹⁰ C, we have
 $1 \text{ esu/cm}^3 = (3.34 \times 10^{-10} \text{ C}) / (0.001293 \text{ g} \times 10^{-3} \text{ kg g}^{-1}) = 2.58 \times 10^{-4} \text{ C kg}^{-1}$.

Absorbed Dose

The concept of exposure and the definition of the roentgen provide a practical, measurable standard for electromagnetic radiation in air. However, additional concepts are needed to apply to other kinds of radiation and to other materials, particularly tissue. The primary physical quantity used in dosimetry is the absorbed dose. It is defined as the energy absorbed per unit mass from any kind of ionizing radiation in any target. The unit of absorbed dose, J kg⁻¹, is called the gray (Gy). The older unit, the rad, is defined as 100 erg g⁻¹. It follows that

$$1 \text{ Gy} \equiv 1 \text{ J kg}^{-1} = 10^7 \text{ erg} / 10^3 \text{ g}^1 = 10^4 \text{ erg g}^{-1} = 100 \text{ rad}. \quad (2)$$

The absorbed dose is often referred to simply as the dose. It is treated as a point function, having a value at every position in an irradiated object. One can compute the absorbed dose in air when the exposure is 1 R. Photons produce secondary electrons in air, for which the average energy needed to make an ion pair is $W = 34 \text{ eV}$ per ion pair = 34 JC⁻¹. Using a more precise W value) one finds

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg} \times 33.97 \text{ J/C} = 8.76 \times 10^{-3} \text{ Jkg}^{-1}. \quad (3)$$

Thus, an exposure of 1 R gives a dose in air of $8.76 \times 10^{-3} \text{ Gy}$ (= 0.876 rad). Calculations also show that a radiation exposure of 1 R would produce a dose of $9.5 \times 10^{-3} \text{ Gy}$ (= 0.95 rad) in soft tissue. This unit is called the rep (“roentgen equivalent-physical”) and was used in early radiation-protection work as a measure of the change produced in living tissue by radiation. The rep is no longer employed.

Dose Equivalent

It has long been recognized that the absorbed dose needed to achieve a given level of biological damage (e.g., 50% cell killing) is often different for different kinds of radiation. Radiation with a high linear energy transfer (LET) is generally more damaging to a biological system per unit dose than radiation with a low LET.

To allow for the different biological effectiveness of different kinds of radiation, the International Commission on Radiological Protection (ICRP), introduced the concept of dose equivalent for radiation-protection purposes. The dose equivalent H is defined as the product of the absorbed dose D and a dimensionless quality factor Q , which depends on LET:

$$H = QD. \quad (4)$$

In principle, other multiplicative modifying factors can be included along with Q to allow for additional considerations (e.g., dose fractionation), but these are not ordinarily used. Until the 1990 recommendations made in ICRP Publication 60, the dependence of Q on LET was defined as given in Table 6.1. Since then, the ICRP has defined Q in accordance with Table 2. In the context of quality factor, LET is the unrestricted stopping power, L_∞ . For incident charged particles, it is the LET of the radiation in water, expressed in keV per μm of travel. For neutrons, photons, and other uncharged radiation, LET refers to that which the secondary charged particles they generate would have in water. Like absorbed dose, dose equivalent is a point function. When dose is expressed in Gy, the (SI) unit of dose equivalent is the sievert (Sv). With the dose in rad, the older unit of dose equivalent is the rem (“roentgen-equivalent man”). Since $1 \text{ Gy} = 100 \text{ rad}$, $1 \text{ Sv} = 100 \text{ rem}$.

Table 1 Dependence of Quality factor Q on LET of radiation as formerly recommended by ICRP (Turner, 2007)

LET (keV μm^{-1} in water)	Q
3.5 or less	1
3.5 – 7.0	1-2
7.0 – 23	2-5
23 – 53	5-10
53 -175	10-20
Gamma rays, X-rays, electrons, positrons of any LET	1

Table 2 Dependence of Quality factor Q on LET as currently recommended by ICRP (Turner, 2007)

LRT, L(keV μm^{-1} in water)	Q
<10	1
10-100	0.32L – 2.2
>100	300/ \sqrt{L}

Dose equivalent has been used extensively in protection programs as the quantity in terms of which radiation limits are specified for the exposure of individuals. Dose equivalents from different types of radiation are simply additive.

Example

A worker receives a whole-body dose of 0.10 mGy from 2-MeV neutrons. Estimate the dose equivalent, based on Table 1.

Solution

Most of the absorbed dose is due to the elastic scattering of the neutrons by the hydrogen in tissue. To make a rough estimate of the quality factor, we first find Q for a 1-MeV proton — the average recoil energy for 2-MeV neutrons. The stopping power for a 1-MeV proton in water is $270 \text{ MeVcm}^{-1} = 27 \text{ keV } \mu\text{m}^{-1}$. Under the current recommendations of the ICRP, Q is defined according to Table 2. However, the older recommendations, which include Table 6.1, are still in effect.

We see from Table 1 that an estimate of $Q \sim 6$ should be reasonable for the recoil protons. The recoil O, C, and N nuclei have considerably higher LET values, but do not contribute as much to the dose as H. (LET is proportional to the square of a particle’s charge.) Without going into more detail, we take the overall quality factor, $Q \sim 12$, to be twice that for the recoil protons alone. Therefore, the estimated dose equivalent is $H \sim 12 \times 0.10 = 1.2 \text{ mSv}$. [The value $Q = 10$ is obtained from detailed calculations] We note that Table 2 implies a comparable value, $Q = 6.4$, for the protons.

By the early 1990s, the ICRP had replaced the use of LET-dependent quality factors by *radiation weighting factors*, w , specified for radiation of a given type and energy. The quantity on the left-hand side of the new equation, $H = wD$, is then called the *equivalent dose*. In some regulations the older terminology, dose equivalent and quality factor, is still employed. However, the latter has come to be specified by radiation type and energy, rather than LET.

Equivalent Dose

The equivalent dose, $H_{T,R}$, in a tissue or organ T due to radiation R, is defined as the product of the average absorbed dose, $D_{T,R}$, in T from R and a dimensionless radiation weighting factor, w_R , for each radiation:

$$H_{T,R} = w_R D_{T,R}. \tag{4}$$

The values of w_R specified by the ICRP are shown in Table 3. When the radiation consists of components with different w_R , then the equivalent dose in T is given by summing all contributions:

$$H_T = \sum_R w_R D_{T,R} \quad (5)$$

With $D_{T,R}$ expressed in Gy ($1 \text{ Gy} = 1 \text{ Jkg}^{-1}$), $H_{T,R}$ and H_T are in Sv ($1 \text{ Sv} = 1 \text{ Jkg}^{-1}$).

NOTE

The equivalent dose replaces the dose equivalent for a tissue or organ, defined earlier. The two are conceptually different. Whereas dose equivalent in an organ is defined as a point function in terms of the absorbed dose weighted by a quality factor everywhere, equivalent dose in the organ is given simply by the *average* absorbed dose weighted by the factor w_R .

Table 3 Radiation weighting factors, w_R by ICRP

Radiation	w_R
- X and gamma rays, electrons, positrons, and muons	1
- Neutrons, energy <10 keV	5
10 keV to 100 keV	10
>100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
- Protons, other than recoil protons and energy > 2 MeV	5
- Alpha particles, fission fragments, and nonrelativistic heavy nuclei	20

For radiation types and energies not included in Table 3, the ICRP give a prescription for calculating an approximate value of w_R as an average quality factor, \bar{Q} . For this purpose, the quality factor Q is defined in terms of the linear energy transfer L by means of Table 2, given earlier in the text. One computes the dose-average value of Q at a depth of 10 mm in the standard tissue sphere of diameter 30 cm specified by the ICRU. Specifically, at the prescribed depth, one calculates

$$w_R \cong \bar{Q} = \frac{1}{D} \int_0^\infty Q(L)D(L)dL, \quad 5$$

where $D(L)dL$ is the absorbed dose at linear energy transfer (LET) between L and $L + dL$.

Effective Dose

Since different tissues of the body respond differently to radiation, the probability for stochastic effects that result from a given equivalent dose will generally depend upon the particular tissue or organ irradiated. To take such differences into account, the ICRP assigned dimensionless tissue weighting factors w_T , shown in Table 4, which add to unity when summed over all tissues T. The equivalent dose H_T in a given tissue, weighted by w_T , gives a quantity that is intended to correlate with the overall detriment to an individual, independently of T. The detriment includes the different mortality and morbidity risks for cancers, severe genetic effects, and the associated length of life lost. Table 4 implies, for

example, that an equivalent dose of 1 mSv to the lung entails the same overall detriment for stochastic effects as an equivalent dose to the thyroid of $(0.12/0.05) \times (1 \text{ mSv}) = 2.4 \text{ mSv}$.

Table 4 Tissue weighting factors, w_T

Tissue or Organ	w_T
Gonads	0.20
Bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder*	0.05

* Note: The data refer to a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effect dose, they apply to workers, to the whole population, and to either sex. The w_T are based on rounded values of the organ's contribution to the total detriment.

The risk for all stochastic effects for an irradiated individual is represented by the effective dose, E , defined as the sum of the weighted equivalent doses over all tissues:

$$E = \sum_T w_T H_T \quad 5$$

Like H_T , E is expressed in Sv. The risk for all stochastic effects is dependent only on the value of the effective dose, whether or not the body is irradiated uniformly. In the case of uniform, whole-body irradiation, H_T is the same throughout the body. Then, since the tissue weighting factors sum to unity,

$$E = \sum_T w_T H_T = H_T \sum_T w_T = H_T \quad 6$$

the value of the equivalent dose everywhere. The effective dose replaces the earlier effective dose equivalent. The latter quantity was defined the same way as E in Equation 5, with H_T being the organ or tissue dose equivalent.

It should be understood that the procedures embodied in Equation 5 have been set up for use in radiological protection. As the note to Table 4 specifies, the values of w_T are simplified and rounded for a reference population of equal numbers of males and females over a wide range of ages. They “should not be used to obtain specific estimates of potential health effects for a given individual.”

Committed Equivalent Dose

When a radionuclide is taken into the body, it can become distributed in various tissues and organs and irradiate them for some time. For the single intake of a radionuclide at time t_0 , the committed equivalent dose over a subsequent time τ in an organ or tissue T is defined as

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T dt \quad 7$$

where \dot{H}_T is the equivalent-dose rate in T at time t . Unless otherwise indicated, an integration time $\tau = 50$ y after intake is implied for occupational use and 70 y for members of the public.

Committed Effective Dose

By extension, the committed effective dose $E(\tau)$ following the intake of a radionuclide is the weighted sum of the committed equivalent doses in the various tissues T:

$$E(\tau) = \sum_T w_T H_T(\tau) \quad 8$$

The effective half-life of a radionuclide in a tissue is determined by its radiological half-life and its metabolic turnover rate. For radionuclides with effective half-lives of no more than a few months, the committed quantities, Eqs. (7) and (8), are practically realized within one year after intake. If a radionuclide is retained in the body for a long time, then the annual equivalent and effective doses it delivers will be considerably less than the committed quantities.

The committed effective dose replaces the earlier committed effective dose equivalent. The latter is defined like Eq. (8), with HT representing the committed dose equivalent in the organ or tissue T.

Collective Quantities

The quantities just defined relate to the exposure of an individual person. The ICRP has defined other dosimetric quantities that apply to the exposure of groups or populations to radiation. The *collective equivalent dose* and the *collective effective dose* are obtained by multiplying the average value of these quantities in a population or group by the number of persons therein. The collective quantities are then expressed in the unit, “person-sievert,” and can be associated with the total consequences of a given exposure of the population or group.

The Commission additionally defines collective dose commitments as the integrals over infinite time of the average individual \dot{H}_T and \dot{E} due to a specified event, either for a critical population group or for the world population.

Other Dosimetric Concepts and Quantities

Kerma

A quantity related to dose for indirectly ionizing radiation (photons and neutrons) is the initial kinetic energy of all charged particles liberated by the radiation per unit mass. This quantity, which has the dimensions of absorbed dose, is called the *kerma* (Kinetic Energy Released per unit mass). By definition, kerma includes energy that may subsequently appear as

bremstrahlung and it also includes Auger-electron energies. The absorbed dose generally builds up behind a surface irradiated by a beam of neutral particles to a depth comparable with the range of the secondary charged particles generated. The kerma, on the other hand, decreases steadily because of the attenuation of the primary radiation with increasing depth. The two are identical as long as all of the initial kinetic energy of the recoil charged particles can be considered as being absorbed locally at the interaction site. Specifically, kerma and absorbed dose at a point in an irradiated target are equal when charged-particle equilibrium exists there and bremsstrahlung losses are negligible. It is often of interest to consider kerma or kerma rate for a specific material at a point in free space or in another medium. The specific substance itself need not actually be present. Given the photon or neutron fluence and energy spectra at that point, one can calculate the kerma for an imagined small amount of the material placed there. It is thus convenient to describe a given radiation field in terms of the kerma in some relevant, or reference, material. For example, one can specify the air kerma at a point in a water phantom or the tissue kerma in air. Additional information on kerma can be found in the references listed at the end of the lecture.

Biological Effects

It is generally assumed that biological effects on the cell result from both direct and indirect action of radiation. Direct effects are produced by the initial action of the radiation itself and indirect effects are caused by the later chemical action of free radicals and other radiation products. An example of a direct effect is a strand break in DNA caused by an ionization in the molecule itself. An example of an indirect effect is a strand break that results when an OH radical attacks a DNA sugar at a later time (between about 10^{-12} s and about 10^{-9} s).

Depending on the dose, kind of radiation, and observed endpoint, the biological effects of radiation can differ widely. Some occur relatively rapidly while others may take years to become evident. Table 3 (13.1) includes a summary of the time scale for some important biological effects caused by ionizing radiation. Probably by about 10^{-3} s, radicals produced by a charged-particle track in a biological system have all reacted. Some biochemical processes are altered almost immediately, in less than about 1 s. Cell division can be affected in a matter of minutes. In higher organisms, the time at which cellular killing becomes expressed as a clinical syndrome is related to the rate of cell renewal. Following a large, acute, whole-body dose of radiation, hematopoietic death of an individual might occur in about a month. A higher dose could result in earlier death (1 to 2 wk) from damage to the gastrointestinal tract. At still higher doses, in the range of 100 Gy, damage to membranes and to blood vessels in the brain leads to the cerebrovascular syndrome and death within a day or two. Other kinds of damage, such as lung fibrosis, for example, may take several months to develop. Cataracts and cancer occur years after exposure to radiation. Genetic effects, by definition, are first seen in the next or subsequent generations of an exposed individual.

Table 5 Acute radiation syndrome for gamma radiation (Turner, 2007)

Dose (Gy)	Symptoms	Remarks
0–0.25	None	No clinically significant effects.
0.25–1	Mostly none. A few persons may exhibit mild prodromal symptoms, such as nausea and anorexia.	Bone marrow damaged; decrease in red and white blood-cell counts and platelet count. Lymph nodes and spleen injured; lymphocyte count decreases.
1–3	Mild to severe nausea, malaise, anorexia, infection.	Hematologic damage more severe. Recovery probable, though not assured.
3–6	Severe effects as above, plus hemorrhaging, infection, diarrhea, epilation, temporary sterility.	Fatalities will occur in the range 3.5 Gy without treatment.
More than 6	Above symptoms plus impairment of central nervous system; incapacitation at doses above ~10 Gy.	Death expected.

Types of Biological effects of radiation

The biological effects of radiation can be divided into two general categories, stochastic and deterministic, or nonstochastic.

Stochastic effects

As the name implies, stochastic effects are those that occur in a statistical manner. Cancer is one example. If a large population is exposed to a significant amount of a carcinogen, such as radiation, then an elevated incidence of cancer can be expected. Although we might be able to predict the magnitude of the increased incidence, we cannot say which particular individuals in the population will contract the disease and which will not. Also, since there is a certain natural incidence of cancer without specific exposure to radiation, we will not be completely certain whether a given case was induced by or would have occurred without the exposure. In addition, although the expected incidence of cancer increases with dose, the severity of the disease in a stricken individual is not a function of dose.

Stochastic effects of radiation have been demonstrated in man and in other organisms only at relatively high doses, where the observed incidence of an effect is not likely due to a statistical fluctuation in the normal level of occurrence. At low doses, one cannot say with certainty what the risk is to an individual. As a practical hypothesis, one usually assumes that any amount of radiation, no matter how small, entails some risk. However, there is no agreement among experts on just how risk varies as a function of dose at low doses.

Deterministic effects

In contrast, deterministic effects are those that show a clear causal relationship between dose and effect in a given individual. Usually there is a threshold below which no effect is observed, and the severity increases with dose. Skin reddening is an example of a deterministic effect of radiation.

Objective of Radiation Protection

Man benefits greatly from the use of X rays, radioisotopes, and fissionable materials in medicine, industry, research, and power generation. However, the realization of these gains entails the routine exposure of persons to radiation in the procurement and normal use of sources as well as exposures from accidents that might occur. Since any radiation exposure presumably involves some risk to the individuals involved, the levels of exposures allowed should be worth the result that is achieved.

In principle, therefore, the overall objective of radiation protection is to balance the risks and benefits from activities that involve radiation. If the standards are too lax, the risks may be unacceptably large; if the standards are too stringent, the activities may be prohibitively expensive or impractical, to the overall detriment to society.

The balancing of risks and benefits in radiation protection cannot be carried out in an exact manner. The risks from radiation are not precisely known, particularly at the low levels of allowed exposures, and the benefits are usually not easily measurable and often involve matters that are personal value judgments. Because of the existence of legal radiation-protection standards, in use everywhere, their acceptance rests with society as a whole rather than with particular individuals or groups. Even if the risks from low-level radiation were established quantitatively on a firm scientific basis, the setting of limits would still represent a social judgment in deciding how great a risk to allow. The setting of highway speed limits is an example of such a societal decision—one for which extensive quantitative data are available at the levels of risk actually permitted and accepted.

The specific objectives of radiation protection are:

- (1) to prevent the occurrence of clinically significant radiation-induced deterministic effects by adhering to dose limits that are below the apparent threshold levels and
- (2) to limit the risk of stochastic effects, cancer and genetic effects, to a reasonable level in relation to societal needs, values, benefits gained and economic factors.

The Council goes on to include the principle of ALARA in its philosophy. It states, further, that for radiation-protection purposes, the risk of stochastic effects is assumed to be proportional to dose without threshold throughout the dose range of relevance in routine radiation protection.

Elements of Radiation-Protection Programs

Different uses of ionizing radiation warrant the consideration of different exposure guidelines. Medical X rays, for example, are generally under the control of the physician, who makes a medical judgment as to their being warranted. Specific radiation-protection standards, such as those recommended by the International Commission on Radiological Protection (ICRP), have been traditionally applied to the “peaceful uses of atomic energy,”

the theory being that these activities justify the exposure limits being specified. In contrast, different exposure criteria might be appropriate for military or national-defense purposes or for space exploration, where the risks involved and the objectives are of an entirely different nature than those for other uses of radiation.

The maximum levels of exposure permitted are deemed acceptable in view of the benefits to mankind, as judged by various authorities and agencies who, in the end, have the legal responsibility for radiation safety. Since, in principle, the benefits justify the exposures, the limits apply to an individual worker or member of the public independently of any medical, dental, or background radiation exposure he or she might receive.

Different permissible exposure criteria are usually applied to different groups of persons. Certain levels are permitted for persons who work with radiation. These guidelines are referred to as “occupational” or “on-site” radiation-protection standards. Other levels, often one-tenth of the allowable occupational values, apply to members of the general public. These are referred to as “non-occupational” or “offsite” guides. Several philosophical distinctions can be drawn in setting occupational and nonoccupational standards. In routine operations, radiation workers are exposed in ways that they and their employers have some control over. The workers are also compensated for their jobs and are free to seek other employment. Members of the public, in contrast, are exposed involuntarily to the gaseous and liquid effluents that are permitted to escape from a site where radioactive materials are handled. In addition, off-site exposures usually involve a larger number of persons as well as individuals in special categories of concern, such as children and pregnant women. (Special provisions are also made for occupational radiation exposure of women of child-bearing age.)

On a worldwide scale, the potential genetic effects of radiation have been addressed in setting radiation standards. Exposure of a large fraction of the world’s population to even a small amount of radiation represents a genetic risk to mankind that can be passed on indefinitely to succeeding generations. In contrast, the somatic risks are confined to the persons actually exposed.

An essential facet of the application of maximum permissible exposure levels to radiation-protection practices is the ALARA (as low as reasonably achievable) philosophy. The ALARA concept gives primary importance to the principle that exposures should always be kept as low as practicable. The maximum permissible levels are not to be considered as “acceptable,” but, instead, they represent the levels that should not be exceeded.

Another consideration in setting radiation-protection standards is the degree of control or specificity that the criteria may require. The ICRP has generally made recommendations for the limits for individual workers or members of other groups in a certain length of time, for example, a year or three months. Without requiring the specific means to achieve this end, the recommendations allow maximum flexibility in their application. Many federal and international agencies, however, have very specific regulations that must be met in complying with the ICRP limits.

Occupational Limits

The ICRP recommends occupational annual effective-dose limit of 50 mSv. However, its cumulative limit is different, being simply 100 mSv in any consecutive 5-y period.

For preventing deterministic effects, the ICRP recommends the following annual occupational equivalent-dose limits: 150 mSv for the crystalline lens of the eye and 500 mSv for localized areas of the skin, the hands, and feet. The limits for deterministic effects apply irrespective of whether one or several areas or tissues are exposed.

Nonoccupational Limits

Historically, limits for nonoccupational exposures have been one-tenth those for occupational exposures. That practice continues. The following recommendations for the exposure of an individual to man-made sources (natural background and medical exposures are not to be included) apply:

For continuous (or frequent) exposure, it is recommended that the annual effective dose not exceed 1 mSv. Furthermore, a maximum annual effective dose limit of 5 mSv is recommended to provide for infrequent annual exposures.

For deterministic effects, the recommendations in ICRP Publication 60 are: An individual annual effective dose limit of 1 mSv is also set for nonoccupational exposures. There is a proviso that a higher annual limit may be applied, if the annual average over 5 y does not exceed 1 mSv.

Principle of External Radiation Protection

We now describe procedures for limiting the dose received from radiation sources outside the human body. There are other procedures for limiting dose received from radionuclides that can enter the body.

Distance, Time, and Shielding

In principle, one's dose in the vicinity of an external radiation source can be reduced by increasing the distance from the source, by minimizing the time of exposure, and by the use of shielding. Distance is often employed simply and effectively. For example, tongs are used to handle radioactive sources in order to minimize the dose to the hands as well as the rest of the body. Limiting the duration of an exposure significantly is not always feasible, because a certain amount of time is usually required to perform a given task. Sometimes, though, practice runs beforehand without the source can reduce exposure times when an actual job is carried out.

While distance and time factors can be employed advantageously in external radiation protection, shielding provides a more reliable way of limiting personnel exposure by limiting the dose rate. In principle, shielding alone can be used to reduce dose rates to desired levels. In practice, however, the amount of shielding employed will depend on a balancing of practical necessities such as cost and the benefit expected.

Radiation Interactions with Matter: Energy Deposition

Biological effects are the end product of a long series of phenomena, set in motion by the passage of radiation through the medium

Interactions of Heavy Charged Particles

Energy-Loss Mechanisms

- The basic mechanism for the slowing down of a moving charged particle is Coulombic interactions between the particle and electrons in the medium. This is common to all charged particles
- A heavy charged particle traversing matter loses energy primarily through the ionization and excitation of atoms.
- The moving charged particle exerts electromagnetic forces on atomic electrons and imparts energy to them. The energy transferred may be sufficient to knock an electron out of an atom and thus ionize it, or it may leave the atom in an excited, nonionized state.
- A heavy charged particle can transfer only a small fraction of its energy in a single electronic collision. Its deflection in the collision is negligible.
- All heavy charged particles travel essentially straight paths in matter.

Maximum Energy Transfer in a Single Collision

The maximum energy transfer occurs if the collision is head-on

Assumptions:

- The particle moves rapidly compared with the electron.
- For maximum energy transfer, the collision is head-on.
- The energy transferred is large compared with the binding energy of the electron in the atom.
- Under these conditions the electron is considered to be initially free and at rest, and the collision is elastic.

Conservation of kinetic energy:

$$\frac{1}{2}MV^2 = \frac{1}{2}MV_1^2 + \frac{1}{2}mv_1^2$$

Conservation of momentum:

$$MV = MV_1 + mv_1$$

$$Q_{\max} = \frac{1}{2}MV^2 - \frac{1}{2}MV_1^2 = \frac{4mME}{(M+m)^2}$$

Where $E = MV^2/2$ is the initial kinetic energy of the incident particle.

Q_{\max} values for a range of proton energies.

Except at extreme relativistic energies, the maximum fractional energy loss for a heavy charged particle is small.

Maximum Possible Energy Transfer, Q_{\max} , in Proton Collision with Electron

Proton Kinetic Energy E (MeV)	Q_{\max} (MeV)	Maximum Percentage Energy Transfer $100Q_{\max}/E$
0.1	0.00022	0.22
1	0.0022	0.22
10	0.0219	0.22
100	0.229	0.23
10^3	3.33	0.33
10^4	136	1.4
10^5	1.06×10^4	10.6
10^6	5.38×10^5	53.8
10^7	9.21×10^6	92.1

Stopping Power

- The average **linear rate of energy loss** of a heavy charged particle in a medium (MeV cm^{-1}) is of fundamental importance in radiation physics, dosimetry and radiation biology.
- This quantity, designated $-dE/dx$, is called the **stopping power** of the medium for the particle.
- It is also referred to as the **linear energy transfer (LET)** of the particle, usually expressed as $\text{keV } \mu\text{m}^{-1}$ in water.
- **Stopping power** and **LET** are closely associated with the dose and with the **biological effectiveness** of different kinds of radiation.

Calculations of Stopping Power

In 1913, Niels Bohr derived an explicit formula for the stopping power of heavy charged particles.

Bohr calculated the energy loss of a heavy charged particle in a collision with an electron, then averaged over all possible distances and energies.

The Bethe Formula for Stopping Power.

Using relativistic quantum mechanics, Bethe derived the following expression for the stopping power of a uniform medium for a heavy charged particle:

$$-\frac{dE}{dx} = \frac{4\pi k_0^2 z^2 e^4 n}{mc^2 \beta^2} \left[\ln \frac{2mc^2 \beta^2}{I(1-\beta^2)} - \beta^2 \right].$$

$k_0 = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$, (the Boltzman constant)

z = atomic number of the heavy particle,

e = magnitude of the electron charge,

n = number of electrons per unit volume in the medium,

m = electron rest mass,

c = speed of light in vacuum,

$\beta = V/c$ = speed of the particle relative to c ,

I = mean excitation energy of the medium.

- Only the **charge** ze and **velocity** V of the heavy charged particle enter the expression for stopping power.
- For the medium, only the **electron density** n is important.

Tables for Computation of Stopping Powers

If the constants in the Bethe equation for stopping power, dE/dX , are combined, the equation reduces to the following form:

$$-\frac{dE}{dx} = \frac{5.08 \times 10^{-31} z^2 n}{\beta^2} [F(\beta) - \ln I_{ev}] \text{ MeV cm}^{-1}$$

where, $F(\beta) = \ln \frac{1.02 \times 10^6 \beta^2}{1 - \beta^2} - \beta^2$

Table 7 showing data for computation of stopping power for heavy charged particles

Proton Kinetic Energy (MeV)	β^2	$F(\beta)$ Eq. (5.34)
0.01	0.000021	2.179
0.02	0.000043	3.775
0.04	0.000085	4.468
0.06	0.000128	4.873
0.08	0.000171	5.161
0.10	0.000213	5.384
0.20	0.000426	6.077
0.40	0.000852	6.771
0.60	0.001278	7.175
0.80	0.001703	7.462
1.00	0.002129	7.685
2.00	0.004252	8.376
4.00	0.008476	9.066
6.00	0.01267	9.469
8.00	0.01685	9.753
10.00	0.02099	9.972
20.00	0.04133	10.65
40.00	0.08014	11.32
60.00	0.1166	11.70
80.00	0.1510	11.96
100.0	0.1834	12.16
200.0	0.3205	12.77
400.0	0.5086	13.36
600.0	0.6281	13.73
800.0	0.7088	14.02
1000.	0.7658	14.26

For a given value of β , the kinetic energy of a particle is proportional to the rest mass, *Table 7 can also be used for other heavy particles.*

Example:

The ratio of kinetic energies of a deuteron and a proton **traveling at the same speed** is

$$\frac{\frac{1}{2}M_d V^2}{\frac{1}{2}M_p V^2} = \frac{M_d}{M_p} = 2$$

Therefore the value of $F(\beta)$ of 9.972 for a 10 MeV proton, also applies to a 20 MeV deuteron.

Mean Excitation Energies

Mean excitation energies, I , have been calculated using the quantum mechanical approach or measured in experiments. The following approximate empirical formulas can be used to estimate the I value in eV for an element with atomic number Z :

$$\begin{aligned} I &\approx 19.0 \text{ eV}; Z = 1 \text{ (hydrogen)} \\ I &\approx 11.2 \text{ eV} + (11.7)(Z) \text{ eV}; 2 \leq Z \leq 13 \\ I &\approx 52.8 \text{ eV} + (8.71)(Z) \text{ eV}; Z > 13 \end{aligned}$$

For compounds or mixtures, the contributions from the individual components must be added.

In this way a composite $\ln I$ value can be obtained that is weighted by the electron densities of the various elements.

The following example is for water (and is probably **sufficient for tissue**).

$$n \ln I = \sum_i N_i Z_i \ln I_i$$

Where n is the total number of electrons in the material ($n = \sum_i N_i Z_i$)

When the material is a pure compound, the electron densities can be replaced by the electron numbers in a single molecule.

Example:

Calculate the mean excitation energy of H_2O

Solution:

I values are obtained from the empirical relations above.

For H, $I_{\text{H}} = 19.0 \text{ eV}$, for O, $I_{\text{O}} = 11.2 + 11.7 \times 8 = 105 \text{ eV}$.

Only the ratios, $N_i Z_i / n$ are needed to calculate the composite I .

Since H_2O has 10 electrons, 2 from H and 8 from O, the equation becomes

$$\ln I = \frac{2 \times 1}{10} \ln 19.0 + \frac{1 \times 8}{10} \ln 105 = 4.312 \quad \text{giving } I = 74.6 \text{ eV}$$

Stopping power versus distance: the Bragg Peak

$$-\frac{dE}{dx} = \frac{5.08 \times 10^{-31} z^2 n}{\beta^2} [F(\beta) - \ln I_{ev}] \quad \text{MeV cm}^{-1}$$

- At low energies, the factor in front of the bracket increases as $\beta \rightarrow 0$, causing a peak (called the Bragg peak) to occur.
- The linear rate of energy loss is a maximum as the particle energy approaches 0.

- For most of the alpha particle track, the charge on the alpha is two electron charges, and the rate of energy loss increases roughly as $1/E$ as predicted by the equation for stopping power.
- Near the end of the track, the charge is reduced through electron pickup and the curve falls off.

Stopping Power of Water for Protons

$$-\frac{dE}{dx} = \frac{5.08 \times 10^{-31} z^2 n}{\beta^2} [F(\beta) - \ln I_{ev}] \text{ MeV cm}^{-1}$$

What is needed to calculate **stopping power**, $-dE/dX$?

n = the electron density

z = the atomic number

$\ln I$ = the mean excitation energy

For protons, $z = 1$,

The gram molecular weight of water is 18.0 g/mole and the number of electrons per molecule is 10.

One m^3 of water has a mass of 10^6 g.

The density of electrons, n , is: