ICRU REPORT 16

Linear Energy Transfer

ICRU

INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS

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see page 48)

Preface

Scope of ICRU Activities

The International Commission on Radiation Units and Measurements (ICRU), since its inception in 1925, has had as its principal objective the development of internationally acceptable recommendations regarding:

(1) Quantities and units of radiation and radioactivity,

(2) Procedures suitable for the measurement and application of these quantities in clinical radiology and radiobiology,

(3) Physical data needed in the application of these procedures, the use of which tends to assure uniformity in reporting.

The Commission also considers and makes recommendations in the field of radiation protection. In this connection, its work is carried out in close cooperation with the International Commission on Radiological Protection (ICRP).

Policy

The ICRU endeavors to collect and evaluate the latest data and information pertinent to the problems of radiation measurement and dosimetry and to recommend the most acceptable values for current use.

The Commission's recommendations are kept under continual review in order to keep abreast of the rapidly expanding uses of radiation.

The ICRU feels it is the responsibility of national organizations to introduce their own detailed technical procedures for the development and maintenance of standards. However, it urges that all countries adhere as closely as possible to the internationally recommended basic concepts of radiation quantities and units.

The Commission feels its responsibility lies in developing a system of quantities and units having the widest possible range of applicability. Situations may arise from time to time when an expedient solution of a current problem may seem advisable. Generally speaking, however, the Commission feels that action based on expediency is inadvisable from a long-term viewpoint; it endeavors to base its decisions on the long-range advantages to be expected.

The ICRU invites and welcomes constructive comments and suggestions regarding its recommendations and reports. These may be transmitted to the Chairman.

Current Program

In 1962 the Commission laid the basis for the development of the ICRU program over the next several years. At that time it defined three broad areas of concern to the Commission:

I. The Measurement of Radioactivity
II. The Measurement of Radiation
III. Problems of Joint Interest to the ICRU and the International Commission on Radiological Protection (ICRP)

The Commission divided these three areas into nine subareas with which it expected to be primarily concerned during the next decade. The division of work agreed upon is as follows:

I. Radioactivity
  A. Fundamental Physical Parameters and Measurement Techniques
  B. Medical and Biological Applications
II. Radiation
  A. Fundamental Physical Parameters
  B. X Rays, Gamma Rays and Electrons
  C. Heavy Particles
  D. Medical and Biological Applications (Therapy)
  E. Medical and Biological Applications (Diagnosis)
  F. Neutron Fluence and Kerma
III. Problems of Joint Interest to the ICRU and the ICRP
  A. Radiation Protection Instrumentation and its Application

The Commission established a separate planning board to guide ICRU activities in each of the subareas. The planning boards, after examining the needs of their respective technical areas with some care, recommended, and the Commission subsequently approved, the constitution of task groups to initiate the preparation of reports. The substructure which resulted from these actions is given below.

Planning Board I.A. Radioactivity—Fundamental Physical Parameters and Measurement Techniques
- Task Group 1. Measurement of Low-Level Radioactivity
- Task Group 2. Specification of Accuracy in Certificates of Activity of Sources for Calibration Purposes
- Task Group 3. Specification of High Activity Gamma-Ray Sources (Joint with P.B. II.B)

Planning Board I.B. Radioactivity—Medical and Biological Applications
- Task Group 1. In Vivo Measurements of Radioactivity
- Task Group 2. Scanning
- Task Group 3. Tracer Kinetics
- Task Group 4. Methods of Assessment of Dose in Tracer Investigations

Planning Board II.A. Radiation—Fundamental Physical Parameters

Planning Board II.B. Radiation—X Rays, Gamma Rays and Electrons
- Task Group 1. Radiation Dosimetry; X Rays from 5 to 150 kV
- Task Group 2. Radiation Dosimetry; X and Gamma Rays from 0.6 to 100 MV
- Task Group 3. Electron Beam Dosimetry

Planning Board II.C. Radiation—Heavy Particles
- Task Group 1. Dose as a Function of LET
- Task Group 2. High Energy and Space Radiation Dosimetry

Planning Board II.D. Radiation—Medical and Biological Applications (Therapy)
- Task Group 1. Measurement of Absorbed Dose at a Point in a Standard Phantom (Absorbed Dose Determination)
- Task Group 2. Methods of Arriving at the Absorbed Dose at any Point in a Patient (In Vivo Dosimetry)
- Task Group 3. Methods of Compensating for Body Shape and Inhomogeneity and of Beam Modification for Special Purposes (Beam Modification)
- Task Group 4. Statement of the Dose Achieved (Dosage Specification)

Planning Board II.E. Radiation—Medical and Biological Applications (Diagnosis)
- Task Group 1. Photographic Materials and Screens
- Task Group 2. Image Intensifier Radiography
- Task Group 3. TV Systems

Planning Board II.F. Radiation—Neutron Fluence and Kerma
- Task Group 1. Neutron Fluence, Energy Fluence, Neutron Spectra and Kerma

Planning Board III.A. Radiation Protection Instrumentation and its Application
- Task Group 1. Radiation Protection Instrumentation Handbook—Part I
- Task Group 2. Neutron Instrumentation and its Application to Radiation Protection

Because the Commission's basic recommendations on radiation quantities and units relate to the work of all of the planning boards, the Commission decided to establish a separate committee with membership drawn largely from the Commission itself to initiate the revision of ICRU Report 10a, *Radiation Quantities and Units*. Thus, the Committee on Fundamental Quantities and Units was added to the above substructure.

In 1962 the Commission decided to abandon its past practice of holding a meeting together with all of its sub-units every three years. Instead, it was decided that the Commission would receive reports from the subgroups at the time of their completion rather than at fixed deadlines. Meetings of the Commission and of the subgroups are held as needed.

The adoption of the above substructure and mode of operation was intended to alleviate some of the problems associated with the expanded program required in recent years. In the past, the Commission's attempt to administer and review the work of each of the working groups imposed a very considerable burden on the Commission itself. The need to concern itself with each detail, which was inherent in such a scheme of operation, when coupled with the procedure of completing all reports at one time, subjected the Commission members to an intolerable work load if rigorous standards were to be maintained. The above substructure and mode of operation have now produced results in the form of reports drafted by the task groups and reviewed by the planning boards. Present evidence indicates that the substructure and mode of operation, has to a substantial extent succeeded in alleviating the problems previously experienced. Recently, however, the Commission has begun the examination of further modification of the substructure.

ICRU Reports

In 1962 the ICRU, in recognition of the fact that its triennial reports were becoming too extensive and in some cases too specialized to justify single-volume publication, initiated the publication of a series of reports, each dealing with a limited range of topics. This series was initiated with the publication of six reports:

ICRU Report 10a, *Radiation Quantities and Units*
ICRU Report 10b, *Physical Aspects of Irradiation*
ICRU Report 10c, *Radioactivity*
ICRU Report 10d, *Clinical Dosimetry*
ICRU Report 10e, *Radiobiological Dosimetry*
ICRU Report 10f, *Methods of Evaluating Radiological Equipment and Materials*

These reports were published, as had been many of the previous reports of the Commission, by the United States Government Printing Office as Handbooks of the National Bureau of Standards.

In 1967 the Commission determined that in the future the recommendations formulated by the ICRU would be published by the Commission itself. This is the sixth report to be published under this new policy. With the exception of ICRU Report 10a, which was superseded by ICRU Report 11, the other reports of the "10" series have continuing validity and, since none of the reports now in preparation are designed to specifically supersede them, will remain available until the material is essentially obsolete. All future reports of the Commission, however, will be published under the ICRU's own auspices. Information about the availability of ICRU Reports is given on page 48.

ICRU Relationships With Other Organizations

One of the features of ICRU activity during the last few years has been the development of relationships with other organizations interested in the problems of radiation quantities, units, and measurements. In addition to its close relationship with the International Commission on Radiological Protection and its financial relationships with the International Society of Radiology, the World Health Organization, and the International Atomic Energy Agency, the ICRU has also developed relationships of varying intensity with several other organizations. Since 1955, the ICRU has had an official relationship with the World Health Organization (WHO) whereby the ICRU is looked to for primary guidance in matters of radiation units and measurements, and in turn, the WHO assists in the worldwide dissemination of the Commission's recommendations. In 1960 the ICRU entered into consultative status with the International Atomic Energy Agency. The Commission has a formal relationship with the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), whereby ICRU observers are invited to attend UNSCEAR meetings. The Commission and the International Organization for Standardization (ISO) informally exchange notifications of meetings and the ICRU is formally designated for liaison with two of the ISO Technical Committees. The ICRU also corresponds and exchanges final reports with the following organizations:

Bureau International des Poids et Mesures
Council for International Organizations of Medical Sciences
Food and Agriculture Organization
International Council of Scientific Unions
International Electrotechnical Commission
International Labor Organization
International Union of Pure and Applied Physics
United Nations Educational, Scientific and Cultural Organization

Relations with these other international bodies do not affect the basic affiliation of the ICRU with the International Society of Radiology. The Commission has found its relationship with all of these organizations fruitful and of substantial benefit to the ICRU program.

Operating Funds

Throughout most of its existence, the ICRU has operated essentially on a voluntary basis, with the travel and operating costs being borne by the parent organizations of the participants. (Only token assistance was originally available from the International Society of Radiology.) Recognizing the impracticability of continuing this mode of operation on an indefinite basis, operating funds were sought from various sources in addition to those supplied by the International Society of Radiology.

Prior to 1959, the principal financial assistance to the ICRU had been provided by the Rockefeller Foundation which supplied some $11,000 to make possible various meetings. In 1959 the International Society of Radiology increased its contribution to the Commission providing $3,000 for the period 1959–1962. For the periods 1962–1965 and 1965–1969 the Society's contributions were $5,000 and $7,500 respectively. In 1960 the Rockefeller Foundation supplied an additional sum of some $4,000 making possible a meeting of the Quantity and Units Committee in 1960.

In 1960 and 1961 the World Health Organization made available the sum of $3,000 each year. This was increased to $4,000 per year in 1962 and $6,000 per year in 1969. It is expected that this sum will be allocated annually, at least for the next several years.

In connection with the Commission's Joint Studies with the ICRP, the United Nations allocated the sum of $10,000 for the joint use of the two Commissions.

The most substantial contribution to the work of the ICRU has come from the Ford Foundation. In December 1960, the Ford Foundation made available to the Commission the sum of $37,000 per year for a period of five years. This grant was to provide for such items as travel expenses to meetings, for secretarial services and other operating expenses. In 1965 the Foundation agreed to a time extension of this grant making available for the period 1966–1970 the unused portion of the original grant. To a large extent, it is because of this grant that the Commission has been able to move forward actively with its program.

In 1963 the International Atomic Energy Agency allocated the sum of $6,000 per year for use by the ICRU. This was increased to $9,000 per year in 1967. It is expected that this sum will be allocated annually at least for the next several years.

From 1934 through 1964 valuable indirect contributions were made by the U.S. National Bureau of Standards where the Secretariat resided. The Bureau provided substantial secretarial services, publication services and travel costs in the amount of several thousands of dollars.

The Commission wishes to express its deep appreciation to all of these and other organizations that have contributed so importantly to its work.

Composition of the ICRU

It is of interest to note that the membership of the Commission and its subgroups totals 140 persons drawn from 16 countries. This gives some indication of the extent to which the ICRU has achieved international breadth of membership within its basic selection requirement of high technical competence of individual participants.

The membership of the Commission during the preparation of this report was as follows:

L. S. Taylor, *Chairman*
M. Tubiana, *Vice Chairman*
H. O. Wyckoff, *Secretary*
A. Allisy
J. W. Boag (1965–1966)
R. H. Chamberlain
F. P. Cowan
F. Ellis (1965)
J. F. Fowler
H. Fränz (1965)
F. Gauwerky
J. R. Greening
H. E. Johns (1965–1966)
K. Lidén
R. H. Morgan
V. A. Petrov (1965)
H. H. Rossi
A. Tsuya

The current membership of the Commission is as follows:

H. O. Wyckoff, *Chairman*
A. Allisy, *Vice Chairman*
K. Lidén, *Secretary*
F. P. Cowan
F. Gauwerky
J. R. Greening
A. M. Kellerer
R. H. Morgan
H. H. Rossi
W. K. Sinclair
F. W. Spiers
A. Tsuya
A. Wambersie

Composition of ICRU Subgroups Responsible for the Initial Drafting of this Report

Serving on the Task Group on Dose as a Function of LET during the preparation of this report were:

W. K. Sinclair, *Chairman*
P. R. J. Burch
A. Cole
D. V. Cormack
W. Gross
A. M. Kellerer

Serving on the Planning Board on Radiation—Heavy Particles during that time were:

W. K. Sinclair, *Chairman*
G. J. Neary
W. C. Roesch

H. H. Rossi served as Commission Sponsor for the Planning Board.

The Commission wishes to express its appreciation to the individuals involved in the preparation of this report for the time and effort they devoted to this task.

Harold O. Wyckoff
Chairman, ICRU

Washington, D. C.
January 15, 1970

Contents

Linear Energy Transfer

1. Introduction

1.1 Radiation-Induced Changes and Radiation Quality

Ionizing radiation can induce many physical, chemical and biological changes. The kind and the extent of change often depend on the physical conditions of irradiation. Foremost among such conditions is the energy dissipated per unit mass (absorbed dose) in the regions of interest. However, the quality of the radiation and the temporal distribution of the transferred energy sometimes exert a profound influence. Although factors such as absorbed dose rate and absorbed dose fractionation can be most important, especially in biological systems, these temporal aspects will not concern us here.

The subject of this report is radiation quality. The term *quality*[1] in this report refers to those features of the *spatial* distribution of energy transfers—along and within the tracks of particles—that influence the effectiveness of an irradiation in producing change, when other physical factors such as total energy dissipated, absorbed dose, absorbed dose rate and absorbed dose fractionation are kept constant. In this report particular emphasis is given to the description of quality in terms of *linear energy transfer* (LET). Many radiation-induced phenomena (such as intra-track ion combination, light emission from organic and inorganic scintillators, chemical yield, gene mutation and cell killing) depend on the spatial distribution of discrete energy transfers from the ionizing particle to the irradiated medium. In some systems a large number of energy transfers per unit length of track of a particle favors a high yield of one product but a low yield of another.

No single interpretation of the influence of LET on radiation-induced change has yet been given that is valid for all circumstances. In certain systems multiple energy transfers within a given small target region or regions may be needed to effect change. In others, the immediate physical or chemical products of an irradiation may interact with one another, along or close to the track of the ionizing particle. We may be concerned with the ultimate yield of products that either escape from, or are produced by, the intra-track interactions. We may also be interested in the physical, chemical, or biological effects produced by such intra-track products. A theory of radiation action in any given system must be able to explain the different effects produced by radiations of different quality.

In some circumstances, when the effect of a given absorbed dose of one type of radiation is known, we may wish to predict the effect of a similar absorbed dose of a different type of radiation. To do this, the quality aspects of both irradiations must first be described in quantitative terms. A complete description would list the spatial and temporal coordinates of every active product in the system, throughout the irradiation, and throughout the subsequent period during which change can be effected. However, the stochastic features of the interaction of radiation with matter alone prohibit any such exhaustive and unique description. The practical problem, therefore, is to find a convenient, but inevitably incomplete, characterization of radiation quality that will enable predictions to be made with sufficient accuracy for the purpose in question. A relatively crude account of radiation quality may be adequate for some purposes, for example in radiation protection, where often even absorbed dose need not be accurately assessed. In other applications, such as chemical dosimetry, a relatively detailed description becomes obligatory.

1.2 Specification of Radiation Quality: Historical

Lea (1946) calculated and tabulated the primary ionization densities, stopping powers and the spectra of

[1] Although strictly the term quality refers to the radiation only, independently of the medium irradiated, the distribution of events produced in a medium can also be used to describe radiation quality (as well as the irradiation circumstances). A precedent exists in the use of Half Value Layer in a given material for quality specification (ICRU, 1962b).

secondary or delta tracks produced in water by electrons (of energy 100 eV to 384 keV), protons (1 MeV to 10 MeV), and alpha particles (1 MeV to 10 MeV).

Gray (1947) introduced the parameter *mean linear ion density*, which, for x, γ, and β rays could be defined as follows:

Mean linear ion density

$$= \frac{\bar{E}_0}{R_{\bar{E}_0} \cdot \bar{W}}$$

where

$\bar{E}_0$ = average initial kinetic energy of primary electrons

$R_{\bar{E}_0}$ = range of electrons of energy $\bar{E}_0$

$\bar{W}$ = average energy expended per ion pair formed in a gas.

Cormack and Johns (1952) calculated complete distributions of electron fluence as a function of linear ion density, and used a more rigorous averaging procedure for mean linear ion density, in which the mean value is obtained by dividing the total number of ion pairs per cm^3 by the total length of the electron tracks per cm^3. The mean values obtained using this averaging procedure were about 30% lower for low LET radiations than those calculated by Gray (1947).

Ionization is difficult or impossible to measure or even to define in liquids and solids, and other types of energy transfer, notably excitation, can also lead to radiation-induced change. Zirkle et al. (1952) introduced the concept of *linear energy transfer* (LET), formerly called linear energy absorption by Zirkle (1940). This refers to the linear density of all forms of energy transfer including excitation and ionization.

Burch considered the problems raised by delta track formation, and by the variation in the linear density of energy transfers along the track of the decelerating ionizing particle. He determined the distribution of absorbed energy in LET (see Sec. 1.4) by calculating the fraction of total energy deposited within each LET interval and defined an energy-weighted mean LET for this distribution (Burch and Bird, 1956; Burch, 1957a, b). [Energy transfers to electrons in excess of 100 eV were regarded by Burch (and earlier by Lea, 1947) as constituting separate, independent (or delta) tracks.]

1.3 Current Definition of Linear Energy Transfer (LET)

LET has been defined in terms of *local* energy transfers. Unfortunately *local* has had various connotations and recent ICRU definitions (note modification from 1962 to 1968) have sought to avoid confusion. The matter is discussed in more detail in Section 3.4.

The following is the most recent definition given by ICRU (1968):

> The *linear energy transfer* or *restricted linear collision stopping power* (L_Δ) of charged particles in a medium is the quotient of dE by dl, where dl is the distance traversed by the particle and dE is the mean energy-loss due to collisions with energy transfers less than some specified value Δ.
>
> $$L_\Delta = \left(\frac{dE}{dl}\right)_\Delta$$
>
> NOTE: Although the definition specifies an energy cut-off and not a range cut-off, the energy losses are sometimes called "energy locally imparted".

By this definition, L_{100}, for example, designates the LET when $\Delta = 100$ eV. The symbol L_∞ is used when all possible energy transfers are included, in accordance with previous usage (RBE Committee, 1963). However, the subscript ∞ should not be taken to mean that infinitely large transfers of energy are possible. The maximum energy transfer (Q_{max}) is governed by the type and velocity of the incident particle and will be discussed in Appendix 1.

In this report, the symbol L will designate the LET without reference to any particular value of Δ.

1.4 LET Distributions and Averages

The "Report of the RBE Committee" (1963) discusses two types of LET distribution. In one type, i.e. $\boldsymbol{t}(L)$, $\boldsymbol{t}(L)dL$ represents the fraction of total track length, T, having values of LET between L and $L+dL$.[2] Thus, if $\boldsymbol{T}(L)$ is defined as the track length associated with LET up to L, divided by total track length, T, $\boldsymbol{t}(L) = d\boldsymbol{T}(L)/dL$. In the other, i.e. $\boldsymbol{d}(L)$, $\boldsymbol{d}(L)dL$ represents the fraction of the absorbed dose, D, delivered between L and $L+dL$. Thus if $\boldsymbol{D}(L)$ is that part of the absorbed dose with LET up to L, divided by the total absorbed dose, D, $\boldsymbol{d}(L) = d\boldsymbol{D}(L)/dL$. Thus $\boldsymbol{t}(L)$ and $\boldsymbol{d}(L)$ are the distributions of track length and absorbed dose in LET respectively.[3] Associated with the first distribution is a track average $\bar{L}_T$ and with the second, an

[2] The fraction of the track length with LET between L and $L + dL$ is equal to the probability that the particle is found with LET between L and $L + dL$. This alternate interpretation may be preferable in instances where the concept of a track is considered to be ill-defined.

[3] Strictly, absorbed dose distributions of LET should be described as absorbed energy distributions of LET as these

absorbed dose average, $\bar{L}_D$. Unless there is only a single value of L, these two averages have distinctly different values for the *same* circumstances because in the one equal weight is assigned to each unit of track length, while in the other equal weight is assigned to each unit of energy deposited along the track. The mean linear ion density of Gray (1947) and of Cormack and Johns (1952) corresponded to a track average LET, while Burch's calculations determined an absorbed dose average LET. The differences in values of $\bar{L}_D$ for different types of radiation are usually not as large as for $\bar{L}_T$. The relationship between these distributions, $\boldsymbol{t}(L)$ and $\boldsymbol{d}(L)$, their averages and the effect of an energy cut-off Δ will be discussed in Section 3.4.

Linear energy transfer distributions have been calculated by various authors for many radiations in common use (Boag, 1954; Burch, 1957a, b; Howard-Flanders, 1958; Danzker, Kessaris, and Laughlin, 1959; Haynes and Dolphin, 1959; Cormack, 1956; Bruce, Pearson and Freedhoff, 1963; Snyder, 1964; Lawson and Watt, 1967; Bewley, 1968a and 1968b). Examples of such distributions are shown in Section 4.

1.5 Other Methods of Specifying Radiation Quality

Although LET distributions can be calculated for many ionizing particles, it is difficult to measure LET distributions. Furthermore, the concept of LET has limitations; these are discussed in Section 7. Rossi (1959, 1964, 1966, 1967) introduced the concepts, local energy density (Z), incremental local energy density (ΔZ) and individual event size (Y) which overcome some of these difficulties and also make it possible to relate the energy deposition to the size of any structure which may be thought relevant.

The *local energy density*, Z, has been defined as the energy dissipated in a small sphere divided by its mass (Rossi, 1966, 1967). The probability distribution of the local energy density, $P(Z)$, can be determined for different radiations and the form of the distribution depends on the absorbed dose, D, to the irradiated medium and on the diameter of the test sphere. The mean value of Z is equal to D.

The energy dissipated by individual events divided by the mass of the content of the test sphere is called the *incremental local energy density* ΔZ. It can be shown (Rossi, 1966, 1967) that $\Delta Z = K\ Y/d^2$ where Y, the *individual event size*, is defined as the energy expended in the event divided by d, the diameter of the test sphere. K is a constant $= 6/\pi$ if the units used are coherent. However the units used for Y and ΔZ are often not coherent and then the value of K depends upon them. These concepts are discussed further in Section 8.

1.6 Scope of this Report

The progress that has been made in specifying radiation quality in terms of LET is described here, and some of the outstanding problems remaining are discussed. Descriptions are given of the physical and theoretical premises on which calculations of LET and LET distributions, are based. Examples of LET distributions are given. Examples of applications of average LET and LET distributions to practical and theoretical problems are described and the limitations of such procedures are discussed. Alternative methods of specifying radiation quality are briefly considered.

2. Interaction of Radiation with Matter

2.1 General

Energetic charged particles lose energy in traversing a medium mainly by processes of *electronic excitation* in which an orbital electron is raised to a higher energy level, and by *ionization* in which an orbital electron is ejected. Energy losses by other processes are less important, except for radiation losses from very energetic light particles, for nuclear interactions by very energetic heavy particles and, at very low speeds, for losses by elastic collisions.

Energetic photons such as x rays and gamma rays lose energy mainly by three mechanisms: (a) the photoelectric effect, in which the total energy of the photon is expended in the ejection of an orbital electron; (b) Compton scattering, in which a part of the photon energy is transferred to an orbital electron; and (c) pair production, in which the photon energy is converted to the mass and kinetic energy of an electron-

distributions are not necessarily related to mass. In accordance with past practice, however, the term absorbed dose distribution in LET will be used throughout.

positron pair. Thus the bulk of the incident photon energy is expended in the liberation of energetic electrons (and sometimes positrons) which then lose energy through mechanisms of atomic excitation and ionization.

Energetic neutrons lose energy mainly by elastic collision processes which impart energy to the atomic nuclei of the medium. In hydrogenous material the bulk of the energy of the fast neutron is given to hydrogen to produce proton recoils. Protons then lose energy by excitation and ionization processes. At energies below a few keV and above tens of MeV, neutrons interact with matter principally by inelastic nuclear reactions. These processes may give rise to both heavy particles and γ radiation.

All directly ionizing radiations transfer most of their energy to matter by collision processes involving ionization and excitation; these primary events occur randomly along the tracks of charged particles. The ratio of excitation to ionization energy losses and the relative frequency of ionization clusters of different size are considered to be nearly independent of the nature and energy of the primary particle. Hence differences in biological effectiveness of different ionizing radiations should be due mainly to differences in the *spatial distribution* of the primary events and not to differences in the *nature* of the events themselves. The factors relevant to quality are therefore the spacing of the primary collisions and the frequency of the more energetic delta rays along the track of the directly ionizing particle. These are discussed in more detail in Section 2.3.

Because energy losses are random in nature, the physical quantities pertaining to a specific irradiation should be described either in terms of mean values, or better, their probability distributions. Procedures for arriving at such descriptions are discussed in Section 4.

2.2 Absorbed Dose, Particle Fluence, and LET

The *absorbed dose, D*, is defined (ICRU, 1968) as follows:

> *The absorbed dose* (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of the matter in that volume element.

$$D = \frac{\Delta E_D}{\Delta m} \qquad 2.2.(1)$$

The *particle fluence*, $\boldsymbol{\Phi}$, in the region of interest is defined as the quotient of the number of particles ΔN which enter a sphere, by its cross-sectional area Δa.

$$\boldsymbol{\Phi} = \Delta N/\Delta a \qquad 2.2.(2)$$

The fluence spectrum in energy $\phi(E)$[4] is defined by

$$\phi(E) = \Delta n(E)/\Delta a \qquad 2.2.(3)$$

where $\Delta n(E)\mathrm{d}E$ is the number of incident particles with energies between E and $E + \mathrm{d}E$ entering Δa. One may further specify an angular distribution of fluence of a radiation field.

Directly ionizing particles of kinetic energy E will transfer energy locally to the medium according to $L = \overline{\Delta E}/\Delta l$ where $\overline{\Delta E}$ is the average energy transferred when the particle moves through the distance Δl.

L, the Linear Energy Transfer (LET), depends on the velocity, charge and mass of the particle. The particle fluence spectrum in LET is given by

$$\phi(L) = \Delta n(L)/\Delta a \qquad 2.2.(4)$$

where $\Delta n(L)\mathrm{d}L$ is the number of particles with LET between L and $L + \mathrm{d}L$ which enter Δa. Note that by normalizing the spectrum $\phi(L)$ one obtains the track length distribution in LET.

$$\frac{\phi(L)}{\int \phi(L)\,\mathrm{d}L} = \frac{\phi(L)}{\boldsymbol{\Phi}} = \frac{\Delta n(L)}{\Delta N} = \boldsymbol{t}(L)^5 \qquad 2.2.(5)$$

From 2.2.(3) and 2.2.(4) and the fact that $\Delta n(L)\mathrm{d}L = \Delta n(E)\mathrm{d}E$, the relation between $\phi\,(L)$ and $\phi(E)$ is

$$\phi(L) = \phi(E)\left(\frac{\mathrm{d}L}{\mathrm{d}E}\right)^{-1} \qquad 2.2.(6)$$

2.3 Delta Rays

The types of interaction (excitation-ionization) which occur along the tracks of individual ionizing particles are illustrated in Figure 1. Two main types may be distinguished, (a) a localized excitation or ionization in the track of the ionizing particle, (b) a larger energy transfer leading to the ejection of an atomic electron of sufficient energy to produce further ionizing events. In the latter case the energy transferred may be so

[4] Throughout this report the differential distribution of one quantity (A) with respect to another (B) will be written in the form $A\,(B)$ rather than in the form A_B to avoid complications in the use of additional suffixes. For example, the distribution of fluence with respect to LET when an energy limit Δ is imposed, is written $\phi_\Delta(L)$ in this report instead of ϕ_{L_Δ} which might have been chosen.

[5] See footnote 2, p. 2.

low that only an ion cluster of 2,3,4, etc. ion pairs is formed or it may be large enough to produce a separate track known as a delta ray. The distinction between clusters and delta rays, although largely arbitrary, has been used to construct models of track structure (e.g., Mozumder and Magee, 1966).

Tracks of heavy charged particles are essentially straight and except at higher energies they are densely ionizing, i.e. the mean spacing between successive primary collisions is very small. Single ions and ion clusters along the track constitute the track "core". Although the maximum delta-ray energy is only a small fraction of the energy of the primary particle, the more energetic delta rays generated by heavy charged particles may be clearly separated from the track core because their range greatly exceeds the mean spacing of the primary collisions in the track core.

The situation is different with fast electrons. Energetic delta rays can be formed with a range comparable to the range of the primary particle. The maximum energy that can be imparted to a delta ray is half that of the primary electron. On the other hand the distances between successive primary collisions are often larger than the range of the majority of the delta rays. Therefore, the notion of a track core distinct from the delta ray has little meaning for fast electrons. For slower electrons, including delta rays, the situation is also complicated by the fact that the tracks are devious (see Figure 1).

The probability per scattering center per unit area that a charged particle of energy E will undergo an interaction involving a given energy transfer, Q, is expressed by the collision cross section, $\sigma(Q)$. Classical collision theory indicates that the probability of an

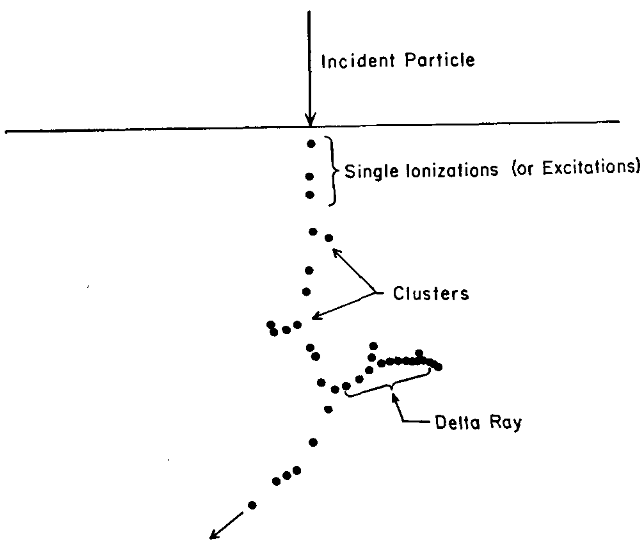

Fig. 1. Diagrammatic representation of the track of an ionizing particle in matter.

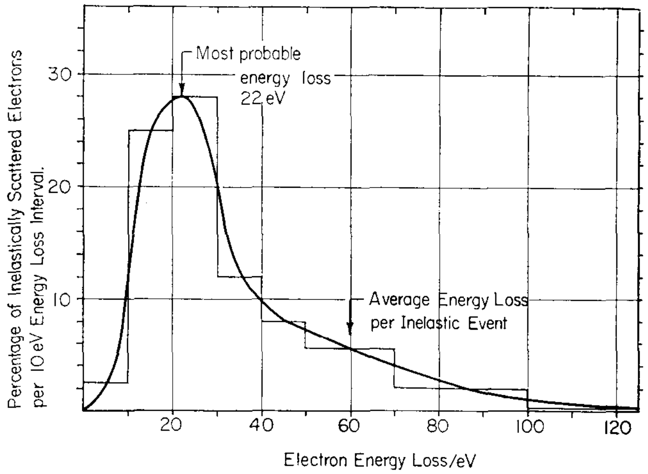

Fig. 2. The single collision energy loss distribution for 20 keV electrons passing through a layer of Formvar 13 nm thick. The percentage of the inelastically scattered electrons per 10-eV energy loss interval is plotted against the energy loss (Rauth and Simpson, 1964). [By courtesy of the authors and Radiation Research (copyright held by Academic Press).]

energy transfer Q is proportional to $1/Q^2$ and the recoil angle of the delta ray is

$$\cos^{-1}\left[\frac{Q}{E}\,\frac{(m_0 + M_0)^2}{4m_0M_0}\right]^{1/2} \qquad 2.3.(1)$$

where M_0 is the mass of the incident particle and m_0 is the mass of the struck particle. As the value of the cosine of the recoil angle ranges from 0 to 1, the recoil angle itself will range from 90° to 0°. The maximum delta ray energy is $[4m_0M_0/(m_0 + M_0)^2]\,E$, except for collisions involving identical particles, e.g. negative electrons, for which it is $E/2$.

These simple relationships hold only when the two particles are considered unbound and when no quantum mechanical, relativistic, or multi-body kinetics are involved.

Lea (1946) calculated the delta-ray energy distribution of different ionizing particles on the basis of the $1/Q^2$ dependence. Theoretical considerations and experimental evidence support this relationship for $Q \geq 200$ eV, in low atomic number media. However theoretical considerations imply that the relationship cannot hold for smaller values of Q and that the distribution is considerably steeper at energies below a few hundred eV. Thus the shape of the spectrum at low energies depends on the kinetic energy of the ionizing particle. Using Bethe's (1933) theory, Walske (1952, 1956) has derived theoretical relations for the collision spectra produced by energetic particles interacting with K- and L-shell electrons; numerical evaluations have been performed by Bichsel (1968). Choi and Merzbacher (1969) have treated the problem numerically for protons.

Experimental data on the shape of the energy-loss spectrum are scarce. Cloud chamber studies have been made by Alper (1932). Experiments have been conducted by Ruthemann (1948) and by Rauth and Simpson (1964) on the distribution of energy losses from low energy electrons in thin plastic foils. Ruthemann used 5 keV electrons and collodion foils and he found that collision losses of about 25 eV had the highest frequency. A similar peak was evident in early secondary electron emission work (e.g., Rudberg 1930, 1931) and has been observed in many other materials (for a review see Marton et al., 1955). An example from the work of Rauth and Simpson, who used 20 keV electrons and Formvar foils, is shown in Figure 2. The distribution maximum occurred at 22 eV and an average energy loss of about 60 eV was determined.

The simple classical relationships for angular distribution of delta rays are certainly not valid for moderate or small delta ray energies. In classical theory each recoil angle or related scattering angle has a unique value of ΔE associated with it. However, Rauth (1962) observed that a broad distribution of energy loss values was associated with all scattering angles between 0 and 50°. Details are available in Rauth (1962) and Rauth and Simpson (1964).

3. Definition and Concepts of LET

3.1 Current Definition of LET

The current definition of LET by ICRU (ICRU, 1968) is quoted on page 2, Section 1.3 of this report. This definition was modified from the previous definition (ICRU, 1962a) as a result of a recommendation developed by the Task Group responsible for this report. The background of the current definition is relevant to an understanding of the concept of LET.

3.2 1962 Definition of LET and Further Considerations

Report 10a of ICRU (ICRU, 1962a) defined LET as follows:

> The linear energy transfer (L) of charged particles in a medium is the quotient of dE_L by dl where dE_L is the average energy locally imparted to the medium by a charged particle of specified energy in traversing a distance dl.
>
> $$L = \frac{dE_L}{dl}$$
>
> The term "locally imparted" may refer either to a maximum distance from the (particle) track or to a maximum value of discrete energy loss by the particle beyond which losses are no longer considered as local. In either case, the limits chosen should be specified.

The report of the RBE Committee of the International Commissions on Radiological Protection and on Radiological Units and Measurements (1963) provided additional information.

"... Various cut-off levels of energy have been selected to separate delta ray tracks from clusters, and it is likely that different cut-off levels are appropriate for different reactions. It is, therefore, suggested that the cut-off level be indicated by a subscript, e.g. LET_{100} would be an LET obtained when tracks due to secondary particles with energy of 100 eV or more are counted as separate tracks. The simplest parameter to use is the LET_∞, defined as the energy loss per unit distance of the charged particles originally set in motion by electromagnetic radiation or neutrons, or of the charged particles which originate in radiation sources (α-rays, β-rays, etc.). LET_∞ is the same as "stopping power"...."

A discussion of the basic concepts and the limitations of these earlier definitions follows.

3.3 Concepts

Consider the possible types of energy loss by charged particles of specified energy, E, which are incident normally on an absorber of thickness Δl. It is assumed that Δl is sufficiently thin so that multiple scattering events can be neglected. A particle loses energy ΔE at a discrete site, is deflected at an angle θ, and passes out of the absorber with energy E'. As illustrated in Figure 3, the several types of energy loss may be characterized by the following:

- O represents a particle traversal with no energy inter-change
- U is the energy transferred to a localized interaction site

q is the energy transferred to a short range secondary particle for which $q \leq \Delta$ where

Δ is a selected energy cut-off level

Q' is the energy transferred to a long range secondary particle for which $Q' > \Delta$

γ is the energy transferred to photons (up to a maximum equal to E)

r is a geometric cut-off distance from the particle track

θ is the scattering angle of the incident particle

The interactions q, Q', and γ are further divided into three compartments: compartment 1 represents energy spent[6] within both Δl and a cylinder of radius r surrounding the particle track, compartment 3 represents energy spent outside Δl but within the cylinder surrounding the track, and compartment 2 represents energy spent outside the cylinder.

stopping power dl is replaced by ρdl, which is mass per unit area.

We now turn to the problem of defining LET with either energy or distance cut-off limits imposed. LET_Δ (or L_Δ) is defined as that part of the total stopping power, dE/dl, which is associated with excitation-ionization energy transfers up to a cut-off value Δ. From the classification of energy losses this can be seen to be

$$L_\Delta = \frac{\overline{\Delta E_\Delta}}{\Delta l} \quad \text{or} \quad \left(\frac{\mathrm{d}E}{\mathrm{d}l}\right)_\Delta \qquad 3.3.(2)$$

where $\overline{\Delta E_\Delta}$ represents the sum of the energies expended in categories in O, U, and q only divided by the total number of incident particles. L_Δ is the same as the "restricted stopping power" and can be readily calculated for a wide range of energies.

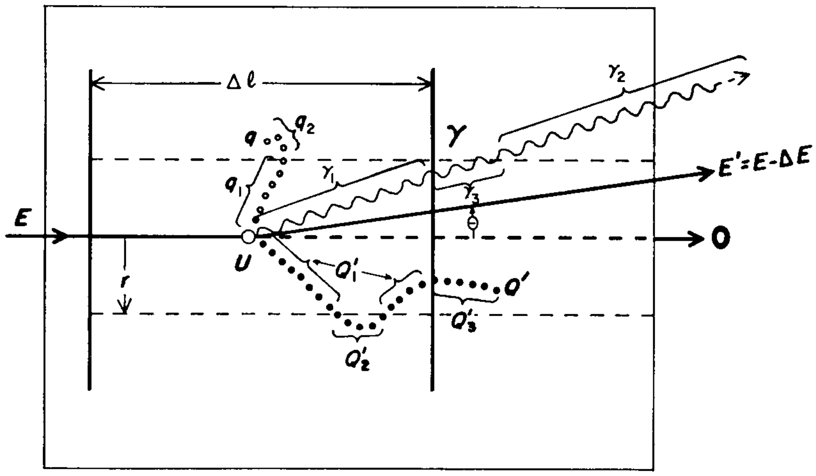

Fig. 3. Diagram of the passage of particles of energy E through a thickness Δl of material illustrating the several types of energy loss that may occur.

Distributions in the various energy compartments are generated as the result of many incident charged particles of energy E traversing the absorber. $\overline{\Delta E}$ represents the sum of the various energies expended in categories O, U, q_1, q_2, Q_1', Q_2', Q_3', γ_1, γ_2, and γ_3, divided by the total number of incident particles. The linear stopping power of the absorber is then defined as

$$\frac{\mathrm{d}E}{\mathrm{d}l} = \left(\frac{\overline{\Delta E}}{\Delta l}\right)_{\Delta l \to 0} \qquad 3.3.(1)$$

Hence dE/dl is an average rate of energy[7] loss and the distance travelled is dl. In the case of the mass

LET_r (or L_r) is defined as that part of the total energy loss dE/dl which is deposited within a cylinder of radius r and length Δl, centered along the particle track.

From figure 3, this is seen to be

$$L_r = \frac{\overline{\Delta E_r}}{\Delta l} \qquad 3.3.(3)$$

where $\overline{\Delta E_r}$ represents an average for the contributions in O, U, q_1, Q_1', and γ_1. However, on the average, compensation will occur and the energy portions, Q_3' and γ_3 which are expended outside Δl but within the cylinder will be compensated by similar tracks originating outside Δl; hence Q_3' and γ_3 should also be included in $\overline{\Delta E_r}$.

It is evident from the previous discussion that L_Δ is easy to evaluate analytically but difficult to measure

[6] Note that contributions from γ rays are not included in the definition of stopping power as explained in Appendix A1, page 21.

[7] The convention (ICRU, 1968) of treating energy losses as positive is adopted here.

directly; whereas L_r is difficult to evaluate analytically, but can be measured in principle by replacing the cylinder with a suitable measuring device such as a (micro) dosimeter.

3.4 LET Distributions and Their Averages

As a fast charged particle loses energy in its passage through an absorber, the value of L will also change. The resultant distribution in L can be expressed in two ways, the track length distribution, $\boldsymbol{t}(L)$ and the absorbed dose distribution, $\boldsymbol{d}(L)$, (see Section 1.4). The two distribution functions are related as follows

$$\boldsymbol{d}(L) = \frac{L\,\boldsymbol{t}(L)}{\bar{L}_T} \qquad 3.4.(1)$$

and are each normalized to unity. The integral forms of these distributions are denoted by

$$\boldsymbol{T}(L) = \int_0^L \boldsymbol{t}(L)\mathrm{d}L \quad \text{and} \quad \boldsymbol{D}(L) = \int_0^L \boldsymbol{d}(L)\mathrm{d}L$$

respectively. The mean LET associated with the track distribution is the track average LET, $\bar{L}_T$, where

$$\bar{L}_T = \int_0^\infty \boldsymbol{t}(L)L\mathrm{d}L \qquad 3.4.(2)$$

The mean LET associated with the absorbed dose distribution is the absorbed dose average LET, $\bar{L}_D$, where

$$\bar{L}_D = \int_0^\infty \boldsymbol{d}(L)L\mathrm{d}L \qquad 3.4.(3)$$

As discussed in Section 3.3, L_Δ represents the LET calculated when energy transfers above an energy Δ (in eV or keV) are considered to generate separate tracks. The track length and absorbed dose distributions corresponding to values of LET restricted in this way are $\boldsymbol{t}_\Delta(L)$ and $\boldsymbol{d}_\Delta(L)$, and in the integral form, $\boldsymbol{T}_\Delta(L)$ and $\boldsymbol{D}_\Delta(L)$. $\bar{L}_{\Delta,D}$ and $\bar{L}_{\Delta,T}$ represent the absorbed dose and track averages of these distributions. The distributions and averages when Δ is equal to the maximum delta ray energy are designated $\boldsymbol{t}_\infty(L)$ and $\boldsymbol{d}_\infty(L)$ and $\bar{L}_{\infty,T}$ and $\bar{L}_{\infty,D}$. Further discussion of these modified distributions of LET and their averages is presented in Section 4.

3.5 Recommendations

The use of the energy cut-off form of LET which can be evaluated in a straight-forward manner using restricted stopping power formulae, is recommended when a restricted form of LET is desired. Thus the linear energy transfer, L_Δ, is defined as that part of the total linear energy loss of a charged particle which is due to energy transfers up to a specified energy cut-off value, Δ. This definition corresponds to that for restricted stopping power.

L_∞ signifies the value of linear energy transfer which includes all energy losses up to the maximum allowed and is therefore numerically equal to the total mass stopping power. The subscript ∞ is used for convenience and to conform with recent usage but it should not be taken to mean that an arbitrarily high energy transfer could occur.

L_r is an interesting physical quantity of potential significance. However the question of whether L_r or L_Δ is of more significance or usefulness in the evaluation of radiation effects will not be discussed further here.

The most recent ICRU definition of LET, (ICRU, 1968), see page 2, is in accord with this discussion.

A special problem arises in the definition of the LET of low energy electrons where the total path or penetration length is comparable to the cut-off distance, r. This point is discussed in Section A4.2.2.

4. Calculation of Distribution of Absorbed Dose[8] in LET

4.1 Introduction

Equation 2.2.(3) defines the particle fluence spectrum in particle energy. However, what is usually of more interest in radiation biology is the distribution of the fluence, not in kinetic energy but in LET. Because LET is a unique function of kinetic energy for a given type of particle, the fluence distribution in kinetic energy may be converted directly to a distribution in LET. The absorbed dose delivered by particles with a given kinetic energy (or LET) may be found by multiplying the particle fluence by the corresponding LET.

A fluence spectrum may be calculated by means of

[8] See footnote 3, page 2.