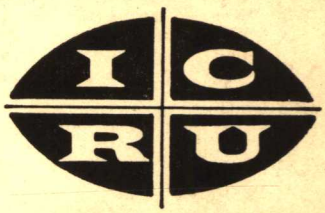
ICRU REPORT 20

Radiation Protection Instrumentation and Its Application



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Radiation Protection Instrumentation and Its Application

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INTERNATIONAL COMMISSION ON RADIATION
UNITS AND MEASUREMENTS
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see page 55)

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 and techniques 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

The Commission has divided its field of interest into eleven technical areas and has assigned one or more members of the Commission to serve as sponsor for each area. A body of consultants has been constituted for each technical area to advise the Commission on the need for ICRU recommendations relating to the technical area and on the means for meeting an identified need. Each area is reviewed periodically by its sponsors and consultants. Recommendations of such groups for new reports are then reviewed by the Commission and a priority assigned. The Technical areas are:

Radiation Therapy
Radiation Diagnosis
Nuclear Medicine
Radiobiology
Radioactivity
Radiation Physics—X Rays, Gamma Rays and Electrons
Radiation Physics—Neutrons and Heavy Particles
Radiation Protection
Values of Factors—$\overline{W}$, S, etc.
Theoretical Aspects
Quantities and Units

The actual preparation of ICRU reports is carried out by ICRU report committees working in each of these technical areas. The currently active report committees in the various technical areas are as follows:

Radiation Therapy	Methods of Arriving at the Absorbed Dose at any Point in the Patient (In Vivo Dosimetry)
	Methods of Compensating for Body Shape and Inhomogeneity and of Beam Modification for Special Purposes (Beam Modification)
	Dose Specification for Reporting
Radiation Diagnosis	Modulation Transfer Function, Its Definition and Measurement
Nuclear Medicine	Scanning of Internally Deposited Radionuclides
	Methods of Assessment of Dose in Tracer Investigations
Radioactivity	Measurement of Low Level Radioactivity

Radiation Physics—X Rays, Gamma Rays and Electrons	Radiation Dosimetry—Electrons with Initial Energies Between 1 and 50 MeV
Radiation Physics—Neutrons and Heavy Particles	High Energy and Space Radiation Dosimetry

In 1962, the Commission decided to abandon its past practice of holding a meeting together with all its subunits 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.

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 report is published by the ICRU pursuant to this policy. With the exception of ICRU Report 10a, the other reports of the "10" series have continuing validity and, since none of the reports now in preparation is designed specifically to supersede them, they 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 55.

ICRU's Relationships With Other Organizations

The ICRU has developed 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 Office
International Union of Pure and Applied Physics
United Nations Educational, Scientific and Cultural Organization

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

Operating Funds

In the early days of its existence, the ICRU 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.

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 period 1962–1965 the Society contributed $5,000. For each of the periods 1965–1969 and 1969–1973 the Society's contribution was $7,500. In 1960 the Rockefeller Foundation supplied an additional sum of some $4,000 making possible a meeting of the Quantities and Units Committee in 1960. The Council for International Organizations of Medical Sciences contributed $500 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, $6,000 in 1969, and $8,000 in 1970.

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 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, 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.

In 1970 and again in 1971 the Statens laegevidenskabelige Forskningsråd of Denmark contributed $1,000 in support of the Commission's work.

The Radiological Society of North America contributed $5,000 in support of the Commission's work in 1971. The Commission received a grant of $1,900 from the John och Augusta Persson stiftelse of Sweden in 1971. As a result of the efforts of Prof. Flemming Norgaard, Honorary Secretary/Treasurer Emeritus of the International Society of Radiology (ISR), the Commission, in 1971, received over $500 in contributions from individual members of the ISR. In 1971 also, the Japan Association of Radiation Apparatus approved a grant to the ICRU of $1,000 per year for a period of three 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 the organizations and individuals 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 91 persons drawn from 14 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 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

Initial work on this report was carried out by two task groups working under the direction of the Planning Board on Radiation Protection Instrumentation and Its Application. Serving on the task group concerned with instruments other than those used for neutrons were:

J. Zakovsky, *Chairman*
K. Becker
C. B. Braestrup
H. Y. Joffre
S. B. Osborn

Serving on the task group concerned with neutron instruments were:

F. P. Cowan, *Chairman*
J. A. Auxier
J. H. Martin
B. M. Wheatley
M. F. Yudin

J. Baarli and I. M. G. Thompson served as consultants to the task group on neutron instruments.

Serving on the Planning Board on Radiation Protection Instrumentation and Its Application during the preparation of this report were:

L. E. Larsson, *Chairman*
F. P. Cowan
S. B. Osborn
E. E. Smith
H. O. Wyckoff
J. Zakovsky

F. P. Cowan 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.
June 1, 1971

Contents

Radiation Protection Instrumentation and Its Application

Introduction

In the past, the International Commission on Radiation Units and Measurements (ICRU) has concerned itself primarily with the theoretical aspects of dose equivalent rather than with the practical problem of its measurement. Any user of ionizing radiations or of radioactive materials, or anyone having responsibilities for persons exposed to such radiations or radioactive materials, should attempt to comply with the recommendations of the International Commission on Radiological Protection (ICRP, 1966)[1] or with national safety requirements derived therefrom. Therefore, a means of assessing the pertinent compliance is necessary. Appropriate instrumentation is required as well as a knowledge of how to use the instrumentation and how to interpret correctly the results of measurements. The present report has been prepared to give practical guidance on these measurement and interpretation problems.

Organization of the Report

The report begins with a basic discussion of radiation quantities and units, of the interpretation of instrument readings in terms of such units, and of the accuracy usually required. Sections on various types of radiation detector follow. These are purposely brief and concentrate on instrument characteristics since descriptions of detectors and discussions of their operations are available elsewhere (ICRU, 1964; ICRU, 1969; Attix and Roesch, 1966; and Attix and Tochilin, 1969). The choice and use of instruments are then discussed in four sections dealing respectively with sealed gamma-ray sources and sources of x rays and electrons; unsealed radioactive sources; reactors and sealed neutron sources; and charged particle accelerators. Many features are common to all four types of application, but most of the material on gamma-ray and x-ray instruments will be found in the first section, that on alpha-ray and beta-ray instruments used for evaluating contamination in the second, and material on neutrons up to 20 MeV in the third section. Special considerations important for the higher energy ranges are taken up in the fourth section. There is a separate section on monitoring instruments for individuals. The report ends with a discussion of calibration procedures.

In considering various types of instrument, good and bad features are discussed but there are no detailed descriptions of particular commercially available instruments. Specific types of instruments can be chosen more intelligently on the basis of a knowledge of the features of each type and a consideration of specific applications.

Radiations to be Measured

Since the recommendations of ICRP apply to all types of ionizing radiations, including both electromagnetic and corpuscular radiations capable of producing ions either directly or indirectly, methods of measurement for all these radiations over the ranges of energy that occur in practice must be discussed. In general, the development of protection instrumentation has lagged behind the development of new sources of radiation, particularly as radiation energies have increased. One of the objectives of this report is to stimulate the development of reliable protection instrumentation as well as to encourage the effective utilization of existing instruments.

Some types and energies of radiation occur more frequently than others. With regard to radiations from external sources, those in most frequent use are x rays and gamma rays employed in medical and industrial work having energies up to a few MeV. Next are per-

[1] The references cited are not necessarily the first or most recent on a particular subject but have been chosen because of their usefulness to the reader.

haps beta rays from radioactive materials and electrons up to a few MeV. These are followed by neutrons of energies ranging from thermal to about 20 MeV. The frequencies of use or production of the remaining radiations are less obvious but may well be as follows: (1) alpha rays, (2) electromagnetic radiations and electrons of energies higher than a few MeV, (3) neutrons above 20 MeV and protons of all energies, and (4) pions, muons, and heavy particles.

With regard to internal radiations, the ICRP has published comprehensive recommendations on maximum permissible concentrations in air and in drinking water, as well as maximum permissible body burdens, for virtually all available nuclides (ICRP, 1960). Also given are examples of derived working limits for the radioactive contamination of surfaces (ICRP, 1964a). Instruments for determining such quantities will be discussed briefly in this report, although the determination of concentrations in water and foodstuffs is largely confined to specialized laboratories which tend to develop their own instruments. The same applies generally to the determination of body radioactivity.

Classification of Neutrons

Although a number of different classifications of neutrons according to energy have been suggested, it will be convenient in this report to use the following scheme:

(a) Thermal neutrons	0–0.5 eV
(b) Intermediate energy neutrons	0.5 eV–200 keV
(c) Fast neutrons	200 keV–20 MeV
(d) Relativistic neutrons	Above 20 MeV

The upper limit for the thermal group has been chosen as 0.5 eV to correspond to the high energy boundary of cadmium absorption (cadmium cut-off). For intermediate energy neutrons, 200 keV has been chosen as the upper limit because many fast neutron monitoring instruments become grossly inaccurate below this energy. The 20 MeV upper limit for fast neutrons has been chosen because a number of instruments have a useful response only above or below that value.

I. Basic Considerations

A. Radiation Quantities and Units

The radiation quantities and units of particular interest in this report are (a) absorbed dose with its special unit, the rad; (b) dose equivalent with its special unit, the rem; (c) particle fluence; (d) kerma; (e) exposure with its special unit, the roentgen; and (f) activity with its special unit, the curie. Fundamental definitions of these quantities and units are contained in ICRU Report 11 (ICRU, 1968).[2] For convenience, these definitions are summarized in somewhat less rigorous form below.

1a. Absorbed Dose (D). The energy absorbed per unit mass at a specific place in a material. The special unit of absorbed dose is the rad, equal to 0.01 joule per kilogram.

1b. Absorbed Dose Index (D_I). The absorbed dose index, D_I, at a point is the maximum absorbed dose within a 30 cm diameter sphere centered at this point and consisting of material equivalent to soft tissue with a density of 1 g/cm³. This is a new quantity not available for use in this report. See ICRU Report 19 (ICRU, 1971).

2a. Dose Equivalent (H)[3]. In general, the biological effectiveness of a given absorbed dose depends on the type of radiation and on the irradiation conditions. In current radiation protection procedures, an indication of the effect upon a given organ is inferred by weighting the absorbed dose in that organ by certain modifying factors. The product of these modifying factors and absorbed dose is called *dose equivalent*, H. The special unit of H is the rem. When D is expressed in rads, H is in rems.

One modifying factor of substantial importance is the quality factor, Q.[4] It is used to account for the dependence of biological effect on the linear energy transfer (L_∞) of charged particles within the irradiated medium. The relation between Q and L_∞ is shown in Table I (ICRP, 1966). In most instances when an organ is irradiated, there is a distribution of values of L_∞ and it is therefore necessary to derive an average quality factor, $\bar{Q}$. Table II lists suggested values of $\bar{Q}$ for monoenergetic neutrons of energies ranging from thermal to 2 GeV in a tissue-equivalent phantom at the region of maximum dose equivalent (ICRP, 1971). For x rays, gamma rays and electrons, $\bar{Q}$ may be assumed to have a value of 1.

A $\bar{Q}$ of 20 is normally used for heavy recoil nuclei and heavy particles (i.e., heavier than protons) from accelerators although it is permissible to use the $Q - L_\infty$ relationship where sufficient spectral information is available. Further discussions of the concepts of quality factor, dose equivalent and RBE can be found in the report of a joint ICRP/ICRU committee on RBE (ICRP, 1963).

The product of other modifying factors such as those allowing for distribution of absorbed dose in space and time are currently lumped into a single factor, N. This factor is presently assigned a value of 1 for external sources.

2b. Dose Equivalent Index (H_I). The dose equivalent index, H_I, at a point is the maximum dose equivalent within a 30 cm diameter sphere centered at this point and consisting of material equivalent to soft tissue with a density of 1 g/cm³. This is a new quantity not available for use in this report. See ICRU Report 19 (ICRU, 1971).

3. Particle Fluence or Fluence (Φ). The number of particles which enter a small sphere divided by the cross sectional area of this sphere.

4. Kerma (K). The sum of the initial kinetic energies of charged particles produced by the interaction of uncharged radiation (e.g., electromagnetic radiation or neutrons) per unit mass of the material in which the interaction takes place. Kerma is expressed in joules per kilogram or in rads. For electromagnetic radiation absorbed in air, the principal quantity in the relationship between kerma and exposure is the average energy required to produce an ion pair.

5. Exposure (X). A measure of the ability of x particu-

[2] A revision of ICRU Report 11 (ICRU, 1971) is in press. It will contain two new quantities useful for radiation protection, absorbed dose index and dose equivalent index. These terms became available too late for use in the body of this report but definitions have been included later in this section as items 1b and 2b.

[3] Formerly designated by DE.

[4] The quality factor, Q (formerly designated by QF) must not be confused with the Relative Biological Effectiveness, RBE, which is limited by definition to radiobiological applications in which the conditions are appropriately defined.

TABLE I—*Relationship between Q and L_∞ recommended by ICRP for radiation protection calculations*

L_∞ in water (keV per μm)	Q
3.5 or less	1
7	2
23	5
53	10
175	20

TABLE II—*Quality factor and fluence-MADE[a] conversion factors for monoenergetic neutrons*

[Monoenergetic neutrons incident normally on a 30 cm-thick tissue equivalent phantom (ICRP, 1971)]

Neutron Energy (MeV)	$\bar{Q}$	Fluence rate per unit MADE[a] rate ($cm^{-2}\ s^{-1}$ $mrem^{-1}$ h)	Fluence per unit MADE[a] (cm^{-2} rem^{-1} $\times 10^{-6}$)
2.5×10^{-8} (thermal)	2.3	260	9.5
1×10^{-7}	2	240	8.7
1×10^{-6}	2	220	8.0
1×10^{-5}	2	230	8.3
1×10^{-4}	2	240	8.6
1×10^{-3}	2	270	9.8
1×10^{-2}	2	280	10.2
1×10^{-1}	7.4	48	1.75
5×10^{-1}	11	14	0.52
1	10.6	8.5	0.31
2	9.3	7.0	0.25
5	7.8	6.8	0.24
10	6.8	6.8	0.24
20	6.0	6.5	0.23
50	5.0	6.1	0.22
1×10^{2}	4.4	5.6	0.20
2×10^{2}	3.8	5.1	0.18
5×10^{2}	3.2	3.6	0.13
1×10^{3}	2.8	2.2	0.079
2×10^{3}	2.6	1.6	0.058

[a] MADE is an abbreviation for "Maximum Dose Equivalent" occurring at any point in an irradiated body.

lar field of electromagnetic radiation, i.e., x rays or gamma rays, to ionize air. These radiations interact with the molecules in the air to produce electrons which in turn ionize the air. The special unit of exposure is the roentgen, symbol R, this being 2.58×10^{-4} coulombs per kilogram of air.

Exposure and kerma are both useful concepts because they are characteristics of the indirectly ionizing radiation field at the point of determination, and are relatively easy to calculate from the fluence at that point provided the spectrum is known. The procedures for the absolute determination of kerma and exposure will be found in ICRU Reports 10b and 13 (ICRU, 1964 and ICRU, 1969).

With further reference to the several definitions reviewed here, it is noteworthy that absorbed dose depends on both the radiation field and the secondary radiation reaching a given point and thus is dependent on the geometrical arrangement of absorbing materials from which secondaries can reach the point. The absorbed dose is important for two reasons. First, it is a basic physical quantity correlating with biological effect. For this reason, absorbed dose is incorporated into the definition of dose equivalent. Second, the absorbed dose prevailing at a specific point is a measure of the charged particle field at that point. When the charged particles are generated by indirectly ionizing radiation, the absorbed dose is not a measure of the indirectly ionizing radiation at the point of measurement, but at the position of charged particle generation. For a beam of radiation the average point of such charged particle generation is generally upstream from the point of measurement.

6. Activity (A). The time rate of disintegration of a radionuclide. The special unit of activity is the curie, symbol Ci, equal to 3.7×10^{10} disintegrations per second.

B. Assessment of Dose Equivalent

The assessment of the dose equivalent prevailing at a specified place in any organ or tissue requires knowledge of both the absorbed dose, D, and the average quality factor, $\bar{Q}$, at that point. For external radiation, the absorbed dose at a point of interest in tissue is the product of the absorbed dose measured at the surface of the body and a factor relating the absorbed dose at the depth of interest to that at the surface. This factor is a complex function of the area of the field irradiated, the depth of the point of interest, the type and energy of the radiation, and the direction of incidence of the radiation on the body.

If the measuring instrument is calibrated in units other than absorbed dose (e.g., exposure, particle fluence, kerma in tissue, etc.), conversion of values to absorbed dose will be necessary. Assessment of dose equivalent therefore may require four steps: (1) measurement of the radiation field at the body surface, (2) conversion of measured values to values expressed as absorbed dose, (3) determination of absorbed dose at a position of interest by use of an experimentally derived depth-to-surface dose relationship and (4) multiplication of the absorbed dose at the position of interest by a quality factor based on the dose average LET of the radiation at the point of interest.

In practice, many simplifications and approximations are permitted in the assessment of dose equivalent when the adequacy of radiation protection procedures is evaluated. Since the objective of such procedures is to ensure that the dose equivalent received by any part of the body does not exceed applicable maximum per-

missible values, one simplification that has been found useful is the determination of the highest value of H prevailing in a region of the body regardless of the tissue in which this value occurs. If this value is less than the maximum permissible dose equivalent of any tissue in the region, detailed mapping of dose equivalent values throughout the region is unnecessary.

The place at which the dose equivalent of a region reaches its maximum value is a function of the type and energy of the exposing radiation at the position of interest. As an approximation, calculations of the maximum dose equivalent (MADE) for complex radiations may be obtained by summing the values of MADE for each radiation component and assuming that all occurred at the same depth. Calculations of MADE performed in this way generally yield overestimates of the actual MADE.

In addition to the foregoing, a number of other conservative approximations may be made. For example, if, in the case of exposure to neutrons, the neutron spectrum is not known, it is permissible to assume that $\bar{Q}$ is 10. As the maximum $\bar{Q}$ for neutrons is 11 and as neutrons of most energies have values of $\bar{Q}$ less than 10, any errors resulting from this approximation will almost always result in an overestimate of the actual H.

Data relating neutron fluence to MADE, and neutron fluence rate to MADE rate are given in Table II. These data apply to normally incident monoenergetic neutrons without secondaries. Neutron radiation which is isotropic or otherwise not normal to the surface will almost always result in lower values. Hence Table II can be used safely for such cases.

Under most circumstances, the maximum value of dose equivalent occurs at very nearly the same depth in the body as the maximum absorbed dose. In cases when this is not so, the absorbed dose is seldom more than 5% different at the two depths. Therefore, it is usually acceptable to assume that the maximum absorbed dose occurs at the same place as the MADE. The maximum absorbed dose obtained with a tissue equivalent chamber as its wall thickness is increased, is often a good measure of the absorbed dose prevailing at the depth at which the MADE occurs.

In the case of electromagnetic radiations, measurements of the exposure or of the kerma in tissue may also be used to determine the MADE. In some circumstances, particularly with lower energy photons (less than about 300 keV), and when the exposure is measured in free air as in a radiation survey, the numerical value of the MADE (in rem) may exceed that of this exposure (in roentgens) by a factor of up to 2 due to scattered radiation (Jones, 1966). When the exposure is measured at the surface of the body, as in individual monitoring, this factor is considerably less. In these circumstances, if values of the MADE are comparable with the maximum permissible dose equivalent (MPD), an estimate of the energy of the radiation will be needed.

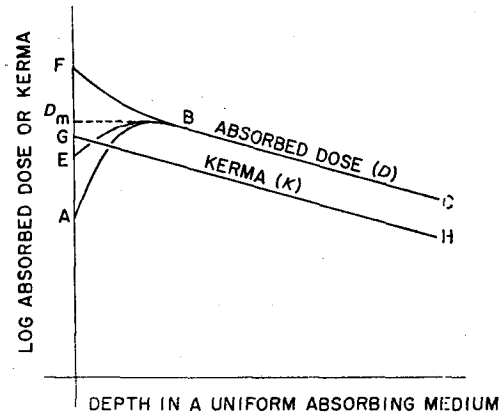

Fig. 1. Relationship between absorbed dose and kerma.

C. Protection Measurements

The response of a dosimeter[5] is, of course, due only to the energy absorbed in the detector itself. By a proper choice of the detector and the material surrounding it, the response of the detector can be made adequately proportional to any of the radiation quantities of interest here. The proportionality may change with the type and energy of the radiation; with the atomic number and geometry of the detector and the material immediately surrounding it; and with the orientation of the body and the position of a critical organ in that body. Proper instrument design attempts to minimize such changes for the particular conditions of interest. The calibration of a device indicates the adequacy of such attempts.

Before proceeding further it is necessary to discuss the relationship between absorbed dose and kerma (ICRU, 1969) at various depths in an absorbing medium such as the body. The meaning of instrument readings is to be found by a consideration of this relationship, the nature of the instrument itself, and the particular procedures used in calibrating it.

Figure 1 indicates the way in which absorbed dose and kerma vary with depth in a uniform absorbing medium for indirectly ionizing radiation, e.g., x rays or fast neutrons. If only primary radiation is incident, absorbed dose will, due to the generation of secondary charged particles, increase to a maximum (D_m) as indicated by the curve ABC. If charged particle sec-

[5] The words "dosimetry", "dosimeter", etc. are used in the broad generic sense to mean a radiation detector that might measure in terms of any of the radiation quantities: exposure, particle or energy fluence, kerma or absorbed dose in specific materials, or their rates.

TABLE III—*Approximate thickness of water required to establish complete equilibrium for neutrons of various energies*

Neutron Energy (MeV)	Thickness[a] (g cm^{-2})
5	0.034
10	0.12
20	0.42
50	2.2
100	7.6

[a] The thicknesses quoted are based on the range of protons in water. The values will be substantially correct for tissue-equivalent ionization chamber walls and also for air. Half of the above thickness will give an absorbed dose within a few percent of its equilibrium value.

ondaries are incident along with the primary radiation, absorbed dose will increase less as in curve EBC, or even show a decrease as in curve FBC. A quasi-equilibrium between uncharged primaries and charged particle secondaries exists from B to C, the decrease being due to absorption of the primaries. The variation of kerma with depth follows the relationship shown by GH. (The kerma is determined by the spectrum at the point of interest. It may be difficult to separate the primary radiation from the uncharged secondaries.) The plot of kerma in Fig. 1 is shown as a straight line, although a departure from linearity near the surface of the medium might occur under some circumstances. A more detailed discussion of these phenomena will be found in ICRU Report 13 (ICRU, 1969).

1. X or Gamma Radiation

The difference in the values of D and K at depths beyond the peak of the absorbed dose curve depends on the photon energy. In practice, the difference is only about 0.5% for cobalt-60 gamma rays and is not more than about 10% for 40 MV x rays. Thus, beyond the depths in tissue at which quasi-equilibrium is reached, the value of K can be regarded for protection purposes as approximately equal to D for primary x rays of up to at least 40 MV. The situation for photons of higher energy, is somewhat more complicated than that shown in Fig. 1. As the energy of the secondary electrons increases, the bremsstrahlung process competes increasingly with ionization and kerma may exceed absorbed dose at certain depths at very high energy levels. Quasi-charged-particle equilibrium then occurs at still greater depths. The relationship between absorbed dose and kerma for gamma radiation is discussed further by Attix (1968).

It may be shown (ICRU, 1964) that under conditions of electronic equilibrium or quasi-equilibrium, electromagnetic radiations in soft tissue yield a numerical value of absorbed dose in rads very close to that of exposure in roentgens (D up to about 8% less than X). Thus, under these conditions it may be assumed that, with an accuracy adequate for most radiation protection situations, the numerical value of the exposure may be used for the value of the absorbed dose at the point of interest.

2. Neutron Radiation

For fast neutron radiation, as for x and γ radiation, the separation of the D and K curves for quasi-equilibrium is small under most circumstances. In tissue or other hydrogenous materials, the secondaries are predominantly recoil protons and the maximum value of absorbed dose, D_m, is reached at a small depth in the medium (see Table III).

For neutrons of higher energy, the situation in tissue becomes increasingly complicated due to the occurrence of nuclear reactions. Non-ionizing secondaries such as neutrons and neutral mesons are produced, ionizing secondaries of greater range than those occurring at low energies are present and the build up in absorbed dose with depth depends increasingly on the direction of the neutrons relative to the surface of the body. For neutron beams having an energy of a few hundred MeV, uncontaminated by incident secondaries, absorbed dose may increase with depth by a factor of as much as five. However, the absence of secondaries seldom occurs in practice and the approximations used at lower energies may still be applicable. Obviously, simple measurements of absorbed dose or kerma in air, or at the surface of a phantom, will not suffice for energies of hundreds or thousands of MeV although, once their relation to D_m has been established by more complete studies, they may often be used for routine measurements.

3. Charged Particle Radiations

In tissues irradiated by beta particles, the absorbed dose decreases rapidly with depth and hence the absorbed dose at the surface is of primary importance to those concerned with radiation protection. In the case of electron beams from accelerators, the relationship between absorbed dose and depth of tissue is similar to that shown by EBC in Fig. 1 with D_m occurring at increasingly greater depths at higher energies. This effect is greater for tissues located within the beam of radiation; for tissues exposed to scattered radiation outside the beam, the effect will frequently be negligible. As in the case of neutrons, the relationships are more complex when primary energies are high (i.e., hundreds or thousands of MeV).

In tissues irradiated by heavy charged particles such as protons, deuterons and alpha particles having energies up to a few tens of MeV, most of the dose is delivered to the surface. However, at higher energies the primary particles become more penetrating and secondaries similar to those occurring in high energy neutron beams are produced. Hence the MADE may occur deep within the body and may rise to a level two or more times the dose equivalent at the surface. If the incident heavy particles are homogeneous in energy, there may be a sharp rise in the absorbed dose vs. depth curve near the end of the range of the primary particles (the Bragg peak). In practice this terminal rise is lessened if the orientation of the beam with respect to the body changes during exposure. In most situations, even for extremely high energies, the build-up of absorbed dose with depth due to secondaries is not great, although one should establish this by suitable depth-dose investigations before relying on simple measurements or approximations to determine the MADE.

4. Interpretation of Instrument Readings

Ideally, the radiation measuring instruments used in the field of radiation protection should be designed and calibrated to yield values of D_m. In practice, however, this goal is not reached although with some effort it can be closely approximated under many conditions. This is possible because, as previously pointed out, values of kerma approach those of D_m when determined at the same depth. Furthermore, values of kerma at the surface are closely similar to those of D_m. The value of absorbed dose at the surface may often be an acceptable approximation to D_m but under some circumstances it may be less by as much as a factor of two. It should be emphasized that where measurements indicate that a dose equivalent close to the MPD may prevail, it is necessary not only to make a careful assessment of radiation levels in terms of kerma, exposure or absorbed dose, but also to carry out an evaluation of radiation quality and depth-dose patterns in order to determine the dose equivalent levels existing at specified points of interest.

Since the meaning of readings obtained with each instrument must be established by consideration of various factors applicable to that particular instrument, further consideration of this important subject is postponed to later chapters and especially to the chapter on calibration.

5. Instrument Range Requirements

ICRP recommendations require the determination of dose equivalent rates over a wide range of values. Under some circumstances dose equivalent rates as high as 100 to 1000 rem h^{-1} require measurement. At the other extreme, dose equivalent rates as low as 0.01 mrem h^{-1} may prevail.

Similarly wide ranges of measurement are encountered when concentrations of radionuclides in air and water are to be evaluated.

6. Accuracy

Values of the absorbed dose received at points in a person's body from external or internal sources can rarely, if ever, be determined directly. It is, therefore, necessary to estimate these values from such measurements as can be made, including those from environmental or individual monitoring. Approximations and uncertainties are inevitably involved and these raise questions concerning the accuracy that must be achieved in protection measurements.

Because the dose limits recommended by ICRP have been conservatively derived, great accuracy in radiation protection measurements appears unwarranted. It is suggested that when the MADE is comparable to the maximum permissible dose, an accuracy of $\pm 30\%$ be achieved. When the MADE is considerably less than the MPD, less accuracy is acceptable (e.g., at a level equal to 0.1 of the MPD an uncertainty of as much as a factor of three seems acceptable).

When one investigates the accuracy that is obtainable in practice, one finds that individual monitoring for fast neutrons by the widely used nuclear track method is open to considerable inaccuracy, particularly at low levels, because of the care needed in scanning the emulsion. Because the number of tracks is small, the uncertainty may well approach $\pm 100\%$ at levels of the order of 0.1 MPD for a four-week period, and $\pm 30\%$ as the maximum permissible dose is reached. A somewhat higher accuracy is usually obtainable in careful determinations of absorbed dose for individuals from x and γ irradiation. However, very large errors have been shown to occur in single tests when proper care was not exercised.

When levels considerably greater than the MPD are encountered, major effort should be expended to increase the accuracy with which the radiation measurements are made. The care afforded an exposed individual may be markedly influenced by the dose received. Hence, accurate estimates of dose are of substantial importance. Such accuracy is also desirable as a basis for epidemiological studies of dose-effect relationships.

For higher exposures, such as whole-body exposures 1000 times the annual MPD delivered in a short time, the accuracy requirements may be relaxed again because the results will hardly influence treatment. How-

ever, there may be cases of high partial body exposure for which the treatment may depend on a detailed knowledge of the absorbed dose. Under these circumstances, as high an accuracy as possible is desirable.

The principles just enunciated for external exposures apply equally well to internal exposures, i.e., rather crude estimates will suffice when dosage levels are much less than maximum permissible values, while increased accuracy is appropriate for doses comparable to maximum permissible limits. The accuracy values suggested as desirable for external exposure determinations are also desirable for internal exposures but are frequently unattainable in practice. Achievable accuracies vary widely, depending on the method or isotope involved, and must be taken into account when the results of measurements are evaluated.

II. Instrument Characteristics

A. Ionization Chamber Instruments

General Characteristics

The ionization chamber (Boag, 1966) is among the oldest devices used in radiation measurement. Perhaps its principal advantage is that its absorbed dose, kerma or exposure sensitivity is computable provided that its design is optimized and there is a rudimentary knowledge of the spectrum of the radiation to which the chamber is exposed. Utilizing the Bragg-Gray relation one may construct, for virtually any ionizing radiation, either air equivalent chambers (Victoreen, 1944) for the determination of exposure, or tissue equivalent chambers (Rossi and Failla, 1956) for the determination of tissue kerma or of absorbed dose in tissue. If such chambers are homogeneous, i.e., have both wall and gas of the same composition, accuracies of the order of a few percent can be achieved under good laboratory conditions. The following summarizes some of the major factors which determine accuracy.

Construction. Unless the chamber is employed in the measurement of directly ionizing particles, the composition of the material surrounding the sensitive gas volume can be of critical importance, particularly for such radiation as x rays having energies below about 100 keV or thermal neutrons. If exposure is to be determined, it is essential that the wall be thick enough for electron equilibrium to be established (see Table IV). Similarly, if tissue equivalent (T.E.) chambers are utilized for the determination of kerma, the wall must be approximately as thick as the maximum range of any directly ionizing particles produced. The chamber must have a cross section that is less than that of the radiation beam. Parasitic volumes (i.e. regions where unwanted ions are collected) must be avoided and sufficient structural rigidity must be provided to eliminate variability of the collecting volume, changes in capacitance or motion of insulators or cables that cause the generation or redistribution of charges.

Ionization chambers used for the measurement of exposure are usually open to the atmosphere and require corrections for ambient temperature and pressure. Sealed chambers require no such corrections but the amount of ionizable gas may change because of leakage or absorption and adsorption on inside surfaces. This is particularly important in the case of chambers made of T.E. plastic which are likely to change in sensitivity by several percent in the course of a month if the volume is of the order of one liter, with even more rapid changes occurring for smaller volumes. The use of checking procedures is essential for accurate work in such cases. An alternative to frequent refilling is to operate the device with a steady gas flow, with the mixture venting to the atmosphere through a small aperture. However, both of these procedures are inconvenient.

Insulation. Since ionization currents are usually quite small—particularly in radiation protection measurements—it is essential that extraneous currents be minimized. There may be unintended electrical leakage between surfaces at different potentials caused by lint, dust, loose graphite particles, etc., and they must be guarded against. However, the principal source of leakage is deficient insulation. If the insulator material is intrinsically of high volume resistivity, the leakage is usually over the surface and is due to dirt, soap, mineral films or moisture remaining after insufficient or improper cleaning. Such insulators will commonly show increased leakage at high humidity. Ionization chamber cables should be kept out of beams to avoid conductivity in the cable insulation.

The sudden application of a collecting voltage results in polarization currents that persist for some time. A chamber that has one or more insulators that form an uninterrupted connection between the collecting and accelerating electrode may, after its first charging, show initial changes simulating leakage (dielectric after-effects). This difficulty may be overcome by operating the chambers with the collecting voltage applied for a sufficient period of time before use. Guard ring chambers are free from this defect and since the guard ring design minimizes not only polarization currents but also leakage currents, it should be used for optimum sensitivity and reliability.

Saturation. Except for devices in which recombination is specifically desired (see section III. A. 4) chambers must normally operate under saturation conditions. Attainment of this objective is facilitated by designs that minimize spatial variations of the electric

TABLE IV—*Thicknesses of ionization chamber walls required for establishment of electronic equilibrium (ICRU, 1964)*

Photon Energy (MeV)	Thickness[a] (g cm^{-2})
0.02	0.0008
0.05	0.0042
0.1	0.014
0.2	0.044
0.5	0.17
1	0.43
2	0.96
5	2.5
10	4.9

[a] The thicknesses quoted are based on the range of electrons in water. The values will be substantially correct for tissue-equivalent ionization chamber walls and also for air. Half of the above thickness will give an ionization current within a few percent of its equilibrium value.

field in the sensitive volume. These include use of parallel plate electrodes or, in the case of cylindrical geometry, hemispherical rather than planar ends and a large diameter of the central collecting electrode.

There are two types of recombination that must be overcome. In one of these, *general* or *intercolumnar* recombination, ions from several particle tracks recombine before they reach the collecting electrodes. This process is dose rate dependent and has been considered in detail (Boag, 1966). It is of importance in radiation protection measurements near generators having very short duty cycles in pulsed operation (klystrons, accelerators, etc.).

The other type of recombination, termed *columnar* recombination, occurs within particle tracks. A reasonably satisfactory theory was developed by Jaffe (1913) and a simplified procedure for its evaluation in practical situations has been devised (Zanstra, 1935). It is of principal importance when ionization due to high linear-energy-transfer secondaries (such as those produced by neutrons) is measured. Its effect should be negligible in properly designed chambers except for some uncertainties concerning its magnitude for exceptionally densely ionizing particles such as heavy nuclear recoils (e.g., carbon and oxygen ions) caused by neutrons of moderate energies.

Special Types

The ionization chamber responds to any ionization produced within its cavity and it is difficult to discriminate between radiation types and specifically between particles of different linear energy transfer. Special devices have been constructed to achieve discrimination in radiation protection measurements, particularly those involving fast neutrons. Examples of such devices will be discussed in the next two paragraphs.

Non-hydrogenous Chambers. Chambers having walls and gas of low atomic number but devoid of hydrogen have substantially the same response to gamma radiation of energy above 100 keV as dimensionally identical tissue equivalent chambers. However, they have a lower response to neutrons. The response to neutrons of a chamber made of Teflon or carbon and filled with CO_2 is reduced to a few percent of that obtained with tissue equivalent walls and filling if the neutron energy is below 100 keV, and ranges from about 10% at 500 keV to about 22% at 8 MeV. If the response of such a chamber is compared with that of a tissue equivalent chamber, it is possible to estimate the absorbed dose from neutrons within about 10% and the absorbed dose from gamma radiation with an error that depends on the relative fluences of the two radiations (NCRP, 1961). However the total maximum dose equivalent (MADE) can always be estimated with an accuracy of about ±15% for any neutron energy up to about 10 MeV (Goodman and Rossi, 1968).

Unsaturated Chambers. Since columnar recombination depends on LET, the shape of the saturation curve may be used as an indication of radiation quality. It has in fact been found possible to get useful estimates of the MADE on the basis of the combined response of two ionization chambers operated at widely differing collecting potentials (Sullivan and Baarli, 1963; Distenfeld and Markoe, 1965) which could also be inside a common envelope (Zielczynski, et al., 1964). This approach may well result in a particularly simple instrument having an accuracy that is sufficient for most radiation protection applications.

Current and Charge Determination

Ionization chamber currents are normally measured with electrometers using either the rate-of-drift method or the potential drop across a high resistance. For currents of 10^{-13} amperes or less the former is preferable since load resistors of 10^{12} ohms are approximately at the upper end of the practical range. However, for currents greater than about 10^{-13} amperes, the latter method is generally more practical as the need for precise timing is obviated. Currents in air equivalent ionization chambers with equilibrium walls amount to 0.93×10^{-13} A cm^{-3} at standard temperature and pressure for an exposure rate of one roentgen per hour if a correction is made for wall attenuation. The charge-sharing method of absorbed dose or exposure determination with condenser ionization chambers is commonly used for personnel monitoring. It can also be