REPORT OF THE
INTERNATIONAL COMMISSION ON
RADIOLOGICAL UNITS AND MEASUREMENTS (ICRU)
1956

Handbook 62

United States Department of Commerce
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UNITED STATES DEPARTMENT OF COMMERCE • Sinclair Weeks, *Secretary*
NATIONAL BUREAU OF STANDARDS • A. V. Astin, *Director*

Report of the International Commission on Radiological Units and Measurements (ICRU)
1956

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Preface

This Handbook gives the recommendations agreed upon by the International Commission on Radiological Units and Measurements (ICRU) of the International Congress of Radiology at its meetings in Geneva in April 1956.

The International Congress of Radiology was organized in 1925 under the auspices of radiological and medical groups from most countries of the world. Official delegates to the Congress are named from the radiological societies and national standardization laboratories of each country.

The International Commission on Radiological Units and Measurements is one of two permanent commissions operating under the auspices of the International Congress of Radiology. This Commission was first organized in 1925 and has been continuously active ever since. General meetings have been held during each Congress in which recommendations concerning radiological units and standards have been established.

Because of the rapid development of the high-energy radiation field it has been necessary to make frequent revisions of our ideas concerning radiological units and standards. At the outset, the basic unit of radiation dosage was built largely around the technique employed for its measurement. Because of the rapid advances in the art, this has necessitated a number of revisions in the last 30 years. In 1950, the first steps were taken towards the use of basic energy units for the measurement of radiation dose. In 1953, the rad, a unit of absorbed dose equal to 100 ergs per gram, was adopted. However, the data necessary to use this unit in practical situations were lacking; the present report supplies these. It is now possible to direct our attention toward basic physical units rather than to perpetuate the difficulties that have been encountered in the use of the old units, which have been in use since 1928.

A. V. Astin, *Director*

Contents

Report of the International Commission on Radiological Units and Measurements (ICRU)
1956

This report of the ICRU supersedes the material previously published in National Bureau of Standards Handbook 47, and was prepared as a result of the Commission's meetings in Geneva in April 1956. In addition to new recommendations regarding radiological units, the report includes an extensive description of the physical background and factors that enter into the problems of the measurement of absorbed dose of all kinds of radiation. It also includes reports of two Subcommittees of the ICRU; namely, Subcommittee on X-ray Standards and Subcommittee on Standards of Radioactivity. Five members of NBS are presently members of the ICRU or its Committees, and this report was prepared in the main through the efforts of four of the Bureau's staff members.

Introduction

A. Scope

The International Commission on Radiological Units and Measurements (ICRU), since its inception in 1925, has had the responsibility for developing (1) the basic principles of units, standards, and measurements needed in radiation dosimetry, and (2) the specification of radiation treatment. It has based its activities on a recognition of the need for worldwide uniformity in those fields.

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

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.

Recognizing the confusion that exists in the evaluation of different radiological equipment and materials, the ICRU will study standard methods of determination of characteristic data of the equipment and materials used in diagnostic and therapeutic radiology. This activity will be confined to methods of measurement and will not include the standardization of radiological equipment or parts thereof.

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

B. Policy

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 units and concepts.

The Commission feels its responsibility lies in developing a system of 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 feels that it is desirable to orient the thinking of radiologists to a more general use of the rad and the term "absorbed dose". Since the introduction in 1953 of energy units (rad) and the term "absorbed dose", it has become necessary to avoid possible confusion between the term "absorbed dose" and the more generic term "dose" as measured in roentgens. In 1953, the Commission considered the term "dose" to be a rather general and sometimes vaguely used medical and pharmaceutical concept that could not very well be defined and the decision as to its definition was left open. The Commission is still of this opinion and feels that the term for the quantity expressed in roentgens should be more restrictive; "exposure dose" is therefore recommended.

Hitherto the definitions and recommendations of the ICRU have been made with little explanation of the philosophy on which they were based. The Commission recognizes that this neglect has given rise to confusion in the past, and in the present report has made an attempt to facilitate the interpretation and clinical application of the recommendations. To this end, discussions have been included on distinguishing between absorbed dose and exposure dose (section 4) and on some methods and procedures for calculating the absorbed dose (section 5).

The aim of much of the work of the ICRU is to improve the accuracy of the evaluation of absorbed dose in all places of interest in a patient or other objects. For comparisons of biological effects, the absorbed dose should be known as accurately as possible and the limits of accuracy should be estimated. The objectives of this program and factors involved in achieving the requisite accuracy have been outlined in section 6.

The Commission has entered into an official relationship with the World Health Organization (WHO). In this relationship, the ICRU will be looked to for primary guidance in matters of radiation units and measurement, and in turn WHO will undertake the worldwide dissemination of the Commission's recommendations. This relationship does not affect the affiliation of the Commission with the International Congress of Radiology.

Informal relations have been developed with the International Standardization Organization (ISO).

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

C. Current Program

A two-day informal meeting of the ICRU was held in Geneva in August 1955, during the International Conference on the Peaceful Uses of Atomic Energy. Tentative agreements reached on several items substantially facilitated the Commission's work at its formal meetings held in Geneva in April 1956.* However, as will be made clear in this text, there still remain several essential items upon which firm recommendations cannot be made either for lack of adequate technical information or because of uncertainty of the wisdom of certain decisions.

Many and serious technical problems have arisen as new uses of radiations have developed and as the quantum energies of radiation have been pushed to higher and higher levels. These rapidly changing events have necessitated frequent modification of our ideas and principles regarding radiation measurements. It is appreciated that this changing situation has caused some degree of confusion in the radiological field. Yet at the same time, the use of older concepts has not led us too far astray. In an endeavor to provide a unit of dose derived from first principles, and at the same time more closely associated with radiological requirements, it was agreed in Copenhagen, in 1953, to express the absorbed dose of radiation in basic energy units (rad).

In the process of introducing this concept, insufficient attention was given to the proper explanation of the basic philosophy involved. Much of the present report is directed towards clarifying this situation.

During the preparation of these revised recommendations, the Commission was confronted with two facts: on the one hand, there has been a rapid development of new medical uses of (a) X-rays with high quantum energies, and (b) corpuscular radiations; on the other hand, most radiation treatments are still carried out with conventional X- and gamma radiations with moderate quantum energies.

In reviewing this situation, the Commission did not feel the need for new basic concepts for dosimetric quantities or units but decided to continue along the line started in 1950, when it recommended

> that the dose is expressed in terms of the quantity of energy absorbed per unit mass (ergs per gram) of irradiated material at the place of interest

but also stated

> that the roentgen in view of its long established usefulness, should continue to be recognized as the unit of X- and gamma-ray quantity or dose.

The roentgen is a unit having certain limitations, but at the same time a wide range of usefulness. In the measurement of output of X- and gamma rays at moderate quantum energies—the purpose for which the roentgen was intended—these limitations have not been serious. A measurement in roentgens is a determination of the ionization produced in air under certain conditions; it is not a direct measurement of the intensity of the X- or gamma radiation, of the energy absorbed in air, or of the biological effect, although their quantities may be calculated from the results of such measurements if the pertinent factors are known. Thus it may be difficult to compare directly the biological effects of X- and gamma rays of different energies measured in roentgens. It is even more difficult to compare the biological effects of X- or gamma rays measured in roentgens with the effects of other radiations (or particles) measured in different units. Arguments such as these were important contributing factors leading in 1953 to the concept of an "absorbed dose" expressed in rads. A dose determined in rads must also have certain factors applied to it in order to properly relate it to the biological effect. However, these factors require biological investigation; the dose in rads is as far as we can go with physical measurements at the present time. A determination in roentgens serves either as a first step in the computation of absorbed dose or as a measurement of the output of a radiation source. In this connection, the roentgen is a convenient and accepted unit of measurement for X- and gamma rays.

With the introduction of the "absorbed dose" concept, it was considered desirable to distinguish clearly between the dose to which an object is exposed (a measure of the radiation field) and the absorbed dose (a measure of the energy imparted to matter at a point). In its attempt to select a term to replace "dose" when referring to roentgen measurements, the Commission deemed it essential to introduce one that could not so easily be confused with "absorbed dose" through the careless use of either term. The term "exposure" seemed to satisfy this need, and it was felt that this choice of terms would be of substantial aid to the radiotherapist and the protection monitor in distinguishing between the absorbed dose concept and measurements made in roentgens. On the other hand, an expression embodying the term "dose" was preferred by some members of the International Commission on Radiological Protection to avoid the necessity of changing

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*The Commission is very grateful for the hospitality extended by WHO when the Commission met in Geneva, April 3 to 11, 1956.

existing laws and regulations in which the term "dose" has already been used.

As a solution to the problem, the term "exposure dose" is recommended for future use (section 1.7). This recommendation is either preferred or regarded as acceptable by a substantial majority of the members of both Commissions. The recommendation is put forward at this time in order that it may be considered seriously by the radiological profession, and to direct attention to the fact that there is a clear distinction between an absorbed dose measured in rads and a quantity in roentgens that measures a radiation field at a place.

The presently proposed unit of exposure dose for X- and gamma radiation is the roentgen, and the roentgen is then defined as an exposure dose of X- or gamma radiation that produces a measurable effect, namely, ionization, (section 1.8). With exposure dose defined as a measure of the radiation that is based upon its ability to ionize air, the modified definition of the roentgen would appear to remove the earlier difficulties. It can be argued that by using the roentgen as a unit of exposure dose, rather than a unit of dose, as in the 1953 recommendations, a new unit has been introduced. Actually, if the roentgen as modified is used in the manner discussed at length in this report, nothing will be changed insofar as radiation measurements and standards are concerned. Roentgen measurements will be made in the same way and reported in the same way; it is hoped that by naming the quantity being measured "exposure dose," sufficient attention will have been directed to the significance of the measurement being made. No change in the legitimate use of the roentgen is implied; the change only emphasizes that measurements made in roentgens are not the final answer in all problems of dosimetry of X- and gamma radiation.

If the use of modifying terms will better describe the kind of dose we mean, an important step forward will have been made. To allow the loose use of the term "dose" for measurements in either rads or roentgens would be an act of expediency, but from a long-range viewpoint probably would complicate rather than improve the situation. For convenience in writing, there is no objection to the use of the general term "dose", *provided* the kind of dose referred to is made clear through mention of the unit. For example, there can be no misunderstanding in the statement "the organ received a dose of 16 rads." On the other hand, the expression "maximum permissible dose" by itself, does not tell if you are speaking of roentgens, rads, or rems.

An additional factor leading to the proposed change in the definition of the roentgen centers about the use of the word "quantity" as contained in the 1953 definition. The use of the term "quantity" in the definition has long been a source of confusion. For that reason, there was a strong desire on the part of the Commission to avoid its use.

This whole situation directs attention to the need for a strong educational effort to insure proper understanding of the terms used in radiation dosimetry.

> NOTE.—A suggestion was put forward in 1950 (British) and again in 1956 (German) for a new unit to express the ion charge per unit mass of gas. No action was taken on these proposals, but comments are invited by the ICRU. These should be sent to the Secretary prior to January 1, 1958.

D. Rules Governing the Selection and Work of the International Commission on Radiological Units and Measurements

The International Commission on Radiological Units and Measurements (ICRU) functions under the auspices of the International Congress of Radiology. The Commission was established in 1925 by the First International Congress to define the physical units required in the field of radiology and to make recommendations on the standards required to realize proper measurements in terms of the units defined.

The following rules, amended in 1956, govern the selection and work of the ICRU.

1. (a) The International Commission on Radiological Units and Measurements (ICRU) shall be composed of a chairman and not more than 12 other members. The selection of the members shall be made by the ICRU from nominations submitted to it by the National Delegations to the International Congress of Radiology and by the ICRU itself. The selections shall be subject to approval by the International Executive Committee (IEC) of the Congress. Members of the ICRU shall be chosen on the basis of their recognized activity in the field of radiological units, standards, and measurements, without regard to nationality.

(b) The ICRU shall include at least three medical radiologists and three physicists.

(c) The members of the ICRU shall be approved during each International Congress to serve through the succeeding Congress. Not less than 2 but not more than 4 membership changes shall be made for any one Congress. In the intervening period a vacancy may be filled by the ICRU.

(d) In the event of a member of the ICRU being unable to attend the ICRU meetings, a substitute may be selected by the ICRU as a temporary replacement. Such a substitute member shall not have voting privileges at the meetings unless specifically authorized by the ICRU.

(e) The ICRU shall be permitted to invite individuals to attend its meetings to give special technical advice. Such persons shall not have voting privileges, but may ask permission to have their opinions recorded in the minutes.

2. The Chairman shall be elected by the ICRU from among its regular members to serve for a term corresponding to the interval between Congresses. The choice shall not be limited to

the country in which it is proposed to hold the succeeding Congress. The Chairman shall be responsible for reporting the proceedings and recommendations of the ICRU at the next Congress.

3. The ICRU may elect from among its members a Vice-chairman who will serve in the capacity of Chairman in the event that the Chairman is unable to perform his duties.

4. Minutes of meetings and records of the ICRU shall be made by a technical secretary selected by the Chairman of the ICRU subject to the approval of its regular members. The technical secretary need not be a regular member of the ICRU. The records of the ICRU shall be passed on to the succeeding secretary.

5. The Chairman, in consultation with the Vice-chairman, shall prepare a program to be submitted to the Commission for discussion at its meetings. Proposals to be considered shall be submitted to the Chairman and circularized to all members of the ICRU and other specially qualified individuals at least 2 months before any meeting of the ICRU.

6. Decisions of the ICRU shall be made by a majority vote of the members. A minority opinion may be appended to the minutes of a meeting if so desired by any member and upon his submission of same in writing to the secretary.

7. The ICRU may establish such committees as it may deem necessary to perform its functions.

E. Organization of ICRU Subcommittees

In 1953 the Commission established two subcommittees for the purpose of providing more concentrated study in special technical areas. These were (1) Subcommittee on X-ray Standards, and (2) Subcommittee on Standards of Radioactivity.

The success of the operation of these subcommittees, together with the expanding needs regarding radiological units, standards, and measurements, has led the Commission to rearrange its internal structure. The new committees[1] and their general scope of interest are as follows:

Committee I.

Standards and Measurement of Radioactivity for Radiological Use.

Chairman	W. E. Perry (National Physical Laboratory, Teddington, Middlesex, England).
Vice-chairman	W. B. Mann (National Bureau of Standards, Washington, D. C., U. S. A.).

This Committee will deal with topics such as:

1. Methods and accuracies of measurement.
2. Chemistry of standards (pharmaceutical aspects not included).
3. Review of existing standards.
    Gamma-ray (Ra, Co, etc.).
    Beta-ray (Ra(D+E), Sr).
    Alpha-ray.
    Simulated standards.
4. Intercomparison of standards.
5. Secondary or production standards.
6. Calibration techniques.

Committee II.

Standards and Measurement of Radiological Exposure Dose.

Chairman	H. O. Wyckoff (National Bureau of Standards, Washington, D. C., U. S. A.).
Vice-chairman	A. Allisy (École Normale Supérieure, Paris, France).

This Committee will deal with topics such as:

1. Concept of exposure dose.
2. Measurement of source output of all types of ionizing radiations including X-rays, gamma rays, beta rays and electron beams, alpha rays, neutrons, mixed radiations.
3. X-ray standard free-air chambers.
4. Extrapolation chambers.
5. Secondary chambers.
6. Scintillation counters (luminescence meters).
7. Calorimeters.
8. Meters based on chemical methods.
9. Radiation quality (spectra, HVL, effective energy).
10. Calibration techniques.

Committee III.

Measurement of Absorbed Dose and Clinical Dosimetry.

Chairman	L. H. Gray (British Empire Cancer Campaign Research Unit in Radiobiology, Mt. Vernon Hospital, Northwood, Middlesex, England).
Chairman, Subcommittee on Absorbed Dose.	J. W. Boag (British Empire Cancer Campaign Research Unit in Radiobiology, Mt. Vernon Hospital, Northwood, Middlesex, England).
Chairman, Subcommittee on Clinical Dosimetry.	R. H. Chamberlain (University of Pennsylvania Hospital, Philadelphia, Pennsylvania, U. S. A.).

This Committee will deal with topics such as:

1. Concept of absorbed dose.
2. Measurement of absorbed dose of all types of ionizing radiation including X-rays, gamma rays, beta rays and electron beams, alpha rays, neutrons, mixed radiations.
3. Determination of constants needed for the calculation of absorbed dose from ionization measurements.
4. Practical uses of specifications of radiological exposure dose.
5. Absorbed dose estimations in the human body and the specification of dose in rads.
6. Backscatter, isodose, and depth dose curves in homogeneous material.

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[1] As the main body is called a Commission, it is logical that the next subgroup be called a Committee; at the same time enabling the Committees to form subcommittees if needed.

7. Determinations of LET.
8. Factors which influence biological effects.

Committee IV.

Methods of Evaluating Radiological Equipment and Materials.

Chairman	B. Combée (Philips Physico-Technical X-ray Laboratory, Eindhoven, Netherlands).
Vice-chairman	E. D. Trout (General Electric Company, Milwaukee, Wisconsin, U. S. A.).

This Committee will deal with topics such as:

1. Focal spots.
2. Output of sources of radiation.
3. Sensitivity, gradation, and fog of photographic materials (film and paper).
4. Sensitivity and intrinsic blurring of fluoroscopic and intensifying screens and of image intensifiers.
5. Effectiveness of grids against scattered radiation.
6. Radioactive isotope equipment and instrumentation.
7. Body-section apparatus.
8. Cine-radiography apparatus.

F. Composition of the ICRU

a. Membership of Main Commission during preparation of this report.

Lauriston S. Taylor, Chairman	United States.
W. J. Oosterkamp, Secretary	Netherlands.
A. Allisy	France.
R. H. Chamberlain	United States.
F. Ellis	Great Britain.
G. Failla	United States.
L. H. Gray	Great Britain.
H. Holthusen	Germany.
H. E. Johns	Canada.
B. Rajewsky	Germany.
R. Sievert	Sweden.

b. Membership of Main Commission confirmed during Eighth International Congress of Radiology, Mexico City, 1956.

Lauriston S. Taylor, Chairman.	United States (National Bureau of Standards, Washington, D. C.).
L. H. Gray, Vice-chairman.	Great Britain (British Empire Cancer Campaign Research Unit in Radiobiology, Mt. Vernon Hospital, Northwood, Middlesex).
H. O. Wyckoff, Secretary	United States (National Bureau of Standards, Washington, D. C.).
A. Allisy	France (Ecole Normale Supérieure, Paris).
R. H. Chamberlain	United States (University of Pennsylvania Hospital, Philadelphia, Pennsylvania).
F. Ellis	Great Britain (Churchill Hospital, Headington, Oxford).
G. Failla	United States (Columbia University, New York, New York).
H. Holthusen	Germany (St. Georg Hospital, Hamburg).
H. E. Johns	Canada (Ontario Cancer Institute, Toronto).
F. E. Leborgne	Uruguay (Hospital Pereira Rossell, Montevideo).
W. J. Oosterkamp	Netherlands (Philips Research Laboratory, Eindhoven).
B. Rajewsky	Germany (Max Planck Institüt für Biophysik, Frankfurt).
R. Sievert	Sweden (Institute of Radiophysics, Stockholm).

I. Quantities, Units, and Symbols

1. Definitions of Quantities and Units [2]

1.1.[3] **Absorbed dose** of any ionizing radiation is the energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest.

1.2. The unit of absorbed dose is the **rad**. 1 rad is 100 ergs/g.

1.3. **Integral absorbed dose** in a certain region is the energy imparted to matter by ionizing particles in that region.

1.4. The unit of integral absorbed dose is the **gram rad**. 1 gram rad is 100 ergs.

1.5.[3] **Absorbed dose rate** is the absorbed dose per unit time.

1.6. The unit of absorbed dose rate is the **rad per unit time.**

1.7.[4] **Exposure dose of X- or gamma radiation** at a certain place is a measure of the radiation that is based upon its ability to produce ionization.

1.8.[4] The unit of exposure dose of X- or gamma radiation is the **roentgen**(r). One roentgen is an exposure dose of X- or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign.

1.9.[3] **Exposure dose rate** is the exposure dose per unit time.

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[2] Symbols and nomenclature. There are numerous national and international bodies that have reached varying degrees of acceptance of the use of symbols and units for physical quantities. However, there is no universal acceptance of any one set of recommendations. It is suggested that each country modify the symbols used herein, in accordance with its own practices. Thus one may write: kev, keV, or Kev; ^{14}C or C^{14}; rad per unit time, rad per time, or rad divided by time; rad/sec, rad/s, or rad·s^{-1}; etc. The most generally accepted system of symbols and units may be that contained in Document UIP 6 (1955) prepared by the International Union of Pure and Applied Physics. These are in fairly close agreement with the recommendations of the International Standardization Organization project ISO/TC 12, the Conférence Géuérale de Poids et Mesures, Union Internationale de Chimie Pure et Appliquée, and the International Electrotechnical Committee. No effort is being made in the present report to conform to the standards recommended by the above organizations.

[3] See notes following these definitions.

[4] See discussion in section C of the Introduction to this report and notes following these definitions.

1.10. The unit of exposure dose rate is the **roentgen per unit time.**

1.11. **Intensity of radiation** (radiant energy flux density) at a given place is the energy per unit time entering a small sphere of unit cross-sectional area centered at that place.

1.12. The unit of intensity of radiation may be **erg per square centimeter second,** or **watt per square centimeter.**

1.13. The unit of quantity of radioactive material, evaluated according to its radioactivity, is the **curie** (c). One curie is a quantity of a radioactive nuclide in which the number of disintegrations per second is 3.700×10^{10}.

1.14. **Specific gamma-ray emission** (specific gamma-ray output) of a radioactive nuclide is the exposure dose rate produced by the unfiltered gamma rays from a point source of a defined quantity of that nuclide at a defined distance.

1.15. The unit of specific gamma-ray emission is the **roentgen per millicurie hour** (r/mch) **at 1 cm.**

1.16 **Linear energy transfer** (LET) is the linear-rate of loss of energy (locally absorbed) by an ionizing particle traversing a material medium.

1.17. Linear energy transfer may be conveniently expressed in **kilo electron volts per micron** (kev/μ).

1.18. **Mass stopping power** is the loss of energy per unit mass per unit area by an ionizing particle traversing a material medium.

1.19. Mass stopping power may be conveniently expressed in **kilo electron volts per milligram per square centimeter** (kev cm^2/mg).

Notes on the foregoing definitions:

The numbering corresponds to the paragraphs above.

1.1. **Absorbed dose.**

(a) In the definition of absorbed dose "energy imparted to matter" means energy retained by matter and made locally available at the place of interest. The absorbed dose includes all energy absorbed per gram of any material under consideration. Thus it includes the energy of nuclear collisions as well as that of electronic collisions.

(b) Because the rad does not specify the medium, the medium should be stated unless it is clearly implied. For example, it is convenient to use the term "tissue rad", which corresponds to a rad at the point of interest in soft human tissue.

(c) Absorbed dose may be estimated by application of the cavity relation whereby the energy imparted to a solid per unit mass, $(\Delta E/\Delta m) = E_m$, is related to the ionization per unit mass of gas, $(\Delta J/\Delta m) = J_m$, by the equation

$$E_m = J_m W s_m, \tag{1}$$

where s_m is the ratio of the mass stopping power of the material to that of the gas.

(d) Whenever ionization methods are used for the estimation of absorbed dose, the observed ionization must be multiplied by a quantity W equal to the average energy expended by ionizing particles in the production of an ion pair in the gas.

The value of W for X- and gamma radiation probably lies between 33 and 35 ev for air. It is recommended that the value of $W = 34$ ev be used for calculations involving X- and gamma radiation of quantum energy greater than 20 kev. Section 5 contains the currently recommended values of W and s_m as needed in X- and gamma radiation and neutron dosimetry.

1.5. **Absorbed dose rate.**

It should be pointed out that there are special situations when the absorbed dose rate should be expressed more explicitly. For example: when the absorbed dose rate is not constant during the time of irradiation, it may be desirable to specify also the instantaneous absorbed dose rate. It is recognized that the term "instantaneous" may not always be sufficiently explicit and that perhaps a statement should be added referring specifically to an absorbed dose rate of pulsed radiation averaged over a single pulse.

1.7 **Exposure dose of X- or gamma radiation.**

(a) The translation of "exposure dose" into German is "Bestrahlungsdosis", into French "dose d'exposition", and into Spanish "dosis de exposición."

(b) Although the definition of exposure dose was purposely stated in loose terms, a more physically specific definition might be as follows: "the exposure dose is measured by the ion charge, ΔQ, of either sign, produced in air by the secondary electrons, which are produced by X- or gamma radiation in a small mass, Δm, of air divided by Δm." Note that according to the above definition, ΔQ is *not* the charge measured in Δm. However, under electronic equilibrium conditions, the charge produced in Δm is numerically equal to ΔQ (see sections 1.8 (a), 4.2.a, and 5.2).

(c) The wording of this definition leaves open the possibility of later defining exposure dose for radiations other than X- or gamma rays.

1.8. **The roentgen.**

(a) According to the definition, a dose of one roentgen is obtained at a point if the high-speed electrons generated in 0.001293 g of dry air at that point produce along their track 1 esu of ions of either sign. Accurate measurements in roentgens are not obtained by actually measuring these ions. Instead the concept of electronic equilibrium is used so that one can measure the ionization per 0.001293 g of air. According to this concept the ionization produced outside of a small mass, m, by high-speed electrons generated inside of m is compensated by ionization produced inside m by electrons generated outside of m (Fano, 1954).

(b) The corpuscular emission shall not include contributions due to secondary X- or gamma radiation produced in the quantity of air in which the corpuscular (electron) emission referred to is generated. This follows from a consideration of the actual definition of the roentgen and the concept of electronic equilibrium.

(c) It becomes increasingly difficult (because of electronic equilibrium limitations) to determine the exposure dose in roentgens as the quantum energy of the X- or gamma radiation approaches very high values. For practical purposes, 3 Mev is arbitrarily regarded as the useful upper limit of the energy range over which the roentgen should be used.

1.9. **Exposure dose rate.**

(a) Exposure dose rate can be used to specify a field of irradiation or the output from an X- or gamma-radiation source up to 3 Mev.

(b) For quantum energies above 3 Mev, the ICRU at present is not in a position to make a firm recommendation on the specification of output from a radiation source. One may use either intensity, or the absorbed dose rate at the peak of the buildup curve in a phantom under specified conditions; the latter may be derived from ionization measurements.

(c) It should be pointed out that there are special situations when the exposure dose rate should be expressed more explicitly. For example, when the exposure dose rate is not constant during the time of irradiation, it may be desirable to specify also the instantaneous exposure dose rate. It is recognized that the term "instantaneous" may not always be sufficiently explicit and that perhaps a statement should be added referring specifically to an exposure dose rate of pulsed radiation averaged over a single pulse.

2. Recognized Symbols

2.1. **RBE** (relative biological effectiveness). RBE is used to compare the effectiveness of absorbed dose of radiation delivered in different ways. It has been commonly represented by the symbol η. It signifies that m rads delivered by a particular irradiation procedure produces a biological response identical with that produced by $m\eta$ rads delivered by a different procedure.

The statement that "the RBE of α radiation relative to γ radiation is 10" signifies that m rads of α radiation produces a particular biological response in the same degree as $10m$ rads of γ radiation. This statement may be further summarized as $\eta_\gamma^\alpha=10$.

The concept of RBE has a limited usefulness because the biological effectiveness of any radiation depends on many factors. Thus the RBE of two radiations cannot in general be expressed by a single factor but varies with many subsidiary factors, such as the type and degree of biological damage (and hence with the absorbed dose), the absorbed dose rate, the fractionation, the oxygen tension, the pH, and the temperature.

2.2. **RBE dose** is equal numerically to the product of the dose in rads and an agreed conventional value of the RBE with respect to a particular form of radiation effect. The standard of comparison is X- or gamma radiation having a LET in water of 3 kev/μ delivered at a rate of about 10 rad/min.

2.3. The unit of RBE dose is the **rem.** It has the same inherent looseness as the RBE and in addition assumes conventional and not necessarily measured values of RBE. It is therefore recommended that its use be restricted to statements relating to radiation protection. For example, the statement might be made:

> The permissible weekly whole body RBE dose is 0.3 rem regardless of the type of radiation to which a person is exposed.

Should occasion arise when results have been evaluated with other than agreed conventional values of RBE, the values used should be clearly stated.

In the case of mixed radiations the RBE dose is assumed to be equal to the sum of the products of the absorbed dose of each radiation and its RBE:

$$\text{RBE dose in rems} = \Sigma[(\text{absorbed dose in rads}) \times \text{RBE}].$$

II. Guidance for Clinical Application

3. Specification of Radiation Treatment

A specification of radiation treatment should provide sufficient information to make possible subsequent analysis and publication.

The specification of the conditions of radiation treatment shall be such as to make it possible to reproduce the treatment in all its essential physical features. The completeness of specifications will vary in practice but they should be as detailed as necessary.

3.1. *Beam therapy.*

a. The nature of the beam may be conveniently characterized by stating the following factors:

(1) The type of radiation and source used: X-rays; gamma rays of cobalt-60, radium, etc.; neutrons; electrons; or other radiations.

(2) The type of energizing machine; the peak energy of X-rays; the peak energy of electron beams; the mean energy of a neutron beam; and the gamma-ray energies of radioactive sources.

(3) The inherent and added filter.

(4) For X-rays the half-value layer in some such material as

Aluminum	10 to 120 kv
Copper	120 to 400 kv
Tin or lead	400 kv to 1 Mv
Lead	above 1 Mv

b. In recording the technique the following data should be included:

(1) The number, dimensions, shape, and location of the ports of entry.

Or

In moving-beam therapy, the shape and dimension of the cross section of the beam taken at the axis of rotation of the radiation relative to the patient, the angle of inclination of the beam relative to the axis of rotation, and the arc traversed.

(2) The location of the source with respect to each port (surface-source distance and angle).

Or

In moving-beam therapy, the distance from the source to the center of rotation.

(3) The nature and method of use of "bolus" material.

(4) The total number of sessions. (A session is a treatment or group of treatments in one visit.)

(5) The total time over which the sessions are spread.

(6) The time distribution of the treatment sessions.

(7) The duration of each treatment, and either the exposure dose rate in roentgens per minute, or the source output rate, or the absorbed dose rate in rads per minute, at some suitable point.

c. In recording the irradiation, the following data should be included whenever possible:

(1) The exposure dose in roentgens at a specified place.[5]

(2) The surface absorbed dose in rads (daily increments and total).

(3) The absorbed dose to the region of interest in rads (daily increments and total maximum and minimum).

(4) Maximum absorbed dose in rads to any other significantly irradiated tissue (daily increments and total).

(5) All calculations, made as complete as possible, including a description of the dimensions and location of the tumor or region of interest and pertinent depth dose data. (Calculations for patients based purely on phantom measurements may be grossly in error because of air spaces and bone.)

(6) Other factors as may be required in moving-beam and particle-beam therapy with X- and gamma radiation.

3.2. *Surface, intracavitary, and interstitial use of radioactive substances.*

The following should be recorded:

a. The description of the treatment in sufficient detail to permit duplication of the technique.

b. The physical characteristics of the nuclide including half-life and types and energies of the radiations emitted.

c. The nature and thickness of material (including filtration) traversed by the radiation before reaching the tissues.

d. The initial activity of the nuclide used expressed in millicuries, its spatial distribution, and the total time per application.

e. The number and date of applications.

f. The total duration of the treatment.

g. A description of the dimensions and location of the area or volume of interest.

h. The absorbed dose in rads (increment per treatment and total) to the region of interest and any other significantly exposed tissue.

3.3. *Systemic treatment by radioactive substances.*

The following should be recorded:

a. The description of the treatment in sufficient detail to permit duplication of the technique.

b. The physical and chemical nature of the nuclide, including half-life and type and energy of radiations emitted.

c. The activity of the nuclide, in millicuries, at the time of administration.

d. The nature and if possible the volume (or weight) of the tissue of interest and the tissue with the maximum concentration of the nuclide.

e. The effective half-life and the pattern of distribution in tissues of interest, given as completely as possible.

3.4. *Treatment summary form.*

Although it would be desirable to agree on a form of prescription and recording of treatment given, there does not seem to be much likelihood of such a form being internationally accepted or used. On the other hand, there does seem to be willingness to accept a uniform presentation for summary of treatment. The use of such a form would be educative and would help to facilitate the interchange of information.

A suggested treatment summary form is given in appendix I.

4. Considerations Regarding Absorbed Dose and Exposure Dose of X- or Gamma Radiation

The definitions in section 1 are given as critically as possible but it is hoped that the explanation in this section may make their meaning clearer and facilitate their clinical use.

4.1. *The concepts of absorbed dose and exposure dose.*

It seems desirable to make a clear distinction between the X- or gamma radiation to which a patient or object may be *exposed* and the energy *absorbed* from radiation as this energy is made locally available in a patient or object. The former, which is a measure of the radiation field, is called *exposure dose* and is to be measured in *roentgens*. The latter, which is determined by the radiation field and by the composition of the object irradiated, is called *absorbed dose* and is expressed in *rads*. *Absorbed dose* can be calculated from the exposure dose, from other measurements of ionization, from luminescence, or from chemical effects; or measured directly calorimetrically. Because a biological effect of ionizing radiations presumably can result only from energy imparted to matter, it is evident that biological effect should be correlated more closely with the absorbed dose than with the exposure dose. The

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[5] To insure that the specification of a treatment is sufficiently complete when the absorbed dose in rads is calculated from exposure dose in roentgens, it is necessary to state the exposure dose as (1) surface exposure dose in air, or (2) surface exposure dose with backscatter, or (3) exposure dose at some other position in the patient, or (4) in rotation therapy, the exposure dose in air at the axis of rotation.

term "absorbed dose" is used to distinguish it from the various "doses" hitherto often expressed in roentgens. The term "exposure dose" replaces the term "dose" used in the 1953 recommendations to distinguish it more clearly from "absorbed dose"; in view of long-standing clinical practice and use in ICRP recommendations and national codes for radiation protection, it was considered expedient to retain the word "dose" in this expression.

That the absorbed dose gives a truer picture of the actual situation may be illustrated by the example that though bone adjacent to soft tissue may be exposed to the same exposure dose (expressed in roentgens) as the soft tissue, its absorbed dose expressed in rads may be more than three times as great for the average composition of bone.[6]

4.2. *The concept of the roentgen.*

In many instances the absorbed dose can be easily calculated from the measured value of exposure dose. Thus the roentgen used as a practical unit of X- or gamma-ray exposure will remain as a basis for practical dosimetry.

Certain features of the concept of the roentgen may be more clearly understood from the following:

a. According to the definition of the roentgen, the air ionization in esu produced by the high-speed electrons released by the photon beam per 0.001293 g of dry air (1 cm^3 at NTP) is equal to the number of roentgens. Actually the high-speed electrons generated in a given volume of air usually produce part of their ionization outside of that volume. However, some of the high-speed electrons formed outside of that volume also contribute to the ionization inside of the given volume. Thus the loss of ionization in the given volume may be partially or wholly compensated by the gain of ionization. A measurement in roentgens requires complete compensation. This compensation is obtained in a free-air ionization chamber by providing sufficient air in front of (upstream in the photon beam) and behind (downstream) the measuring volume for such compensation, and sufficient collection space to the sides for complete utilization of the energy of the high-speed electrons. In a cavity chamber, the compensation is provided by surrounding the measuring volume with a layer of solid (ideally air-equivalent) material. However, the surrounding material also produces secondary (annihilation, characteristic, or scattered) photons which may themselves produce high-speed electrons that contribute to the ionization in the measuring volume. In addition, the surrounding material attenuates the photon beam. If the measuring instrument is used as an absolute device, a correction must be made for the secondary photon contributions and the attenuation; but if it is calibrated by an instrument of known sensitivity, such corrections are not required.

b. It becomes increasingly difficult (because of electronic equilibrium limitations) to determine the exposure dose in roentgens as the quantum energy of the X- or gamma radiation approaches very high values. For practical purposes, 3 Mev is arbitrarily regarded as the useful upper limit of the energy range over which the roentgen should be used.

c. It is to be noted in the definition of the roentgen (section 1.8) that the *roentgen* is an *exposure dose* of X- or gamma radiation based upon ionization in air but that it *does not* express a quantity of ionization; it is *not* a unit of ionization, nor is it an absorbed dose in air.

4.3. *The quantitative relationship between absorbed dose and exposure dose.*

This subject will be more fully dealt with in section 5. Included here are some of the conclusions of that section for X- or gamma radiation.

Under conditions of electronic equilibrium, the absorbed dose, D, is proportional to the exposure dose, R, according to the relation $D=fR$. When the absorbing medium is air and W is 34 ev, f has the value 0.87_7 rad per roentgen for all radiation qualities. For other materials, f varies with the atomic composition of the tissue and with the radiation quality as more fully explained in section 5.

Some typical f-values in rads per roentgen are given in table 2 and figure 8, section 5.

In *transition zones* where electronic equilibrium conditions are not satisfied (i. e., between different tissues and on skin-, bone-, and cavity-surfaces), the absorbed dose may vary appreciably over distances comparable with the range of the secondary electrons. This effect is important within a few tenths of a millimeter from bone-tissue boundaries for low- and medium-voltage X-rays, and within a few centimeters for radiations of 20 Mev and above. It is also important within a few millimeters or centimeters of an air-skin boundary for megavolt therapy.

Two examples illustrating the difference between exposure dose and absorbed dose are given below.

Example 1.

Tube potential 250 kv.
HVL 1.0 mm Cu.
Field area 100 cm^2.
Conversion factor (f) roentgens to rads, 0.95 in soft tissue, 1.76 in bone. (See table 2, section 5.)
Backscatter factor 1.36 (Glasser et al., 1952).
Exposure dose at position of skin surface (without backscatter). $=1000$ roentgens.
Absorbed dose in soft tissue at position of skin surface. $=1000\times0.95\times1.36$ rads.
Absorbed dose at 80% isodose level in soft tissues not near bone. $=0.80\times1000\times0.95\times1.36$ rads.

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[6] The ratio of rads to roentgens is largest for low-energy photons where the electron ranges are short. Sharp fluctuations in the atomic composition over small distances may account for the experimentally small ratios obtained (Woodard and Spiers, 1953).

Absorbed dose in cells in or near bone at 80% isodose level. $=0.80\times1000\times f\times1.36$ rads.

Here f will vary from 1.76 in bone (or in tissue immediately adjacent to bone) to 0.95 in tissue at points more distant than the electron range from bone. A 250-kev electron has a range of about 0.7 mm in tissue (see fig. 9, section 5).

Example 2.

In the case of very energetic radiation (e. g., cobalt-60), the corpuscular radiation produced by primary interactions is overwhelmingly in a forward direction so that at the surface of the body or of a phantom the situation is as represented in figure 1.

4.4 *Routine measurement of the output of X- or gamma-ray sources*

The output of the source or equipment that emits radiation with quantum energies up to at least 3 Mev may conveniently be specified by the *exposure dose rate* in roentgens per minute or per second at a fixed position, preferably measured in free air.

For quantum energies above 3 Mev the ICRU at present is not in a position to make a firm recommendation. One may use either a calorimetric measurement of *intensity* in *watts per square centimeter* or the absorbed dose rate in a phantom under specified conditions. The more practical procedure may be to measure absorbed dose directly in a phantom of low atomic-number material at such a depth that the measured ionization is at its maximum value, i. e., at the peak of the buildup curve. Usually, the ionization chamber is placed in a lucite block. The size of this block cannot be specified in general but should be determined by experiment. It should have a front wall sufficiently thick to give the maximum ionization reading and a large enough cross-sectional area to cover the whole beam of radiation.

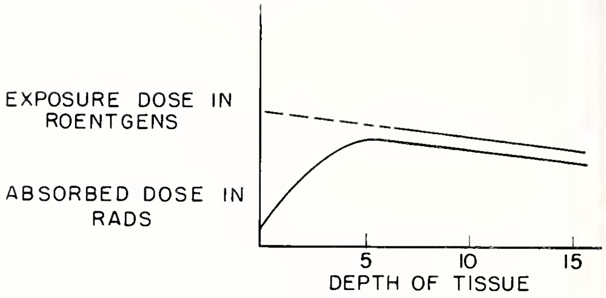

Figure 1. *Example to illustrate the difference between exposure dose and absorbed dose for cobalt-60 gamma radiation.*

The measurements were made near a cobalt-60 point source (at a distance short compared with the range of secondary electrons from cobalt-60 γ's). The dotted portion of the exposure dose curve indicates that measurements are not possible here but the values may be obtained by extrapolation.

III. Physical Aspects of Absorbed Dose Determination

5. Methods of Calculating the Absorbed Dose from Measured Ionization

5.1. *General principles.*

Although it is clearly recognized that the measurement of ionization is not the only approach by which the absorbed dose in rads can be determined, it nevertheless is the most common method now in use. This section is an attempt to summarize the usual techniques employed in such measurements, and to tabulate some of the data needed in carrying out the related calculations. These are selections from the current literature. It is anticipated that future experimental work will improve the accuracy with which some of these data are known. The ICRU plans to publish revised figures from time to time.

In general, absorbed dose may be estimated by application of the relation between the ionization produced in a gas filled cavity at the place of interest in the material irradiated and the energy imparted to unit mass of the material (Gray, 1936). When the cavity is sufficiently small the gas will be subjected to the same flow of ionizing particles as the material under consideration. Then the energy E_m in ergs absorbed per gram of the material, is related to the ionization per gram of the gas J_m by the equation

$$E_m = J_m W s_m \tag{1}$$

where

W=the average energy in ergs expended by the ionizing particles crossing the cavity per ion pair formed, and

s_m=the ratio of the mass stopping power of the medium to that of the cavity gas for these ionizing particles.

Furthermore, the absorbed dose, D, can be written as

$$D = 0.01\ E_m \text{ rad.} \tag{2}$$

The value of W in air for X- and gamma radiation probably lies between 33 and 35 electron volts. It is recommended that the value of $W=34$ electron volts ($5.4_4\times10^{-11}$ erg) be used for calculations concerning X- and gamma radiation of quantum energy greater than 20 kev.

The following paragraphs suggest convenient ways of applying the cavity relation to the measurement of absorbed dose. However, before proceeding further it will be worthwhile to define what is meant by the term "electronic equilibrium" and to describe the conditions necessary for its achievement.

5.2. *Electronic equilibrium conditions.*

Electronic equilibrium would exist at a point within a medium under irradiation if

(a) the intensity and spectrum of the X- or gamma radiation is constant throughout a region extending in all directions from the point a distance at least as great as the maximum range of the electrons generated by the radiation, and

(b) the energy absorption coefficient (see section 5.4) and stopping power are constant in the medium throughout the same region as in (a).

If these two conditions could be fulfilled then for each electron leaving an infinitesimal volume surrounding the point, another electron of practically the same energy enters. Thus the energy dissipated within the volume will be equal to that which would have been dissipated if all the electrons originating there had spent their entire energy within that volume. This is, therefore, an alternative definition of strict electronic equilibrium.

The presence of a small amount of foreign material at or near the point of interest (such as the air within a cavity ionization chamber) will not significantly upset the fulfillment of electronic equilibrium conditions provided that the quantity of material is small enough so that only a negligible part of the energy absorbed within it results from direct interactions of the X- or gamma rays with that material.

Some typical situations where electronic equilibrium will not be present are:

(a) Near a source of radiation where the intensity is rapidly changing.

(b) At high radiation energies where X- or gamma rays are appreciably attenuated in the medium over a distance equal to the mean range of the electrons generated.

(c) Near boundaries between different materials, such as bone-tissue or air-tissue boundaries.

5.3. *Absorbed dose in air exposed to X- or gamma radiation.*

The absorbed dose at a point in air (at NTP) or "air-equivalent" material that is surrounded on all sides by such material to a thickness at least equal to the range of the secondary electrons and uniformly exposed to 1 roentgen of X- or gamma radiation is equal to

$$\left(\frac{1\text{ esu}}{0.001293\text{ g air}}\right)\times\left(2.082\times10^{9}\frac{\text{electrons}}{\text{esu}}\right)\times\left(34\frac{\text{ev}}{\underset{\text{(or ion pair)}}{\text{electron}}}\right)\times\left(1.602\times10^{-12}\frac{\text{erg}}{\text{ev}}\right)\times\left(\frac{1\text{ rad}}{100\text{ ergs/g}}\right)=0.87_7\text{ rad}\tag{3}$$

for all qualities of X- or gamma radiation with quantum energies greater than 20 kev, the energy range over which W is assumed constant.

D_{air} will be referred to as the absorbed dose at a point in an extended mass of air under equilibrium conditions.

It follows that if any ionization chamber or other measuring instrument that has been calibrated in roentgens against a standard free air chamber, or in any other way, records under conditions of electronic equilibrium in the wall of the chamber an exposure dose of R roentgens in any situation, then in the same situation:

$$D_{\text{air}}=0.87_7\ R\text{ rad.}\tag{4}$$

5.4. *Absorbed dose in tissue or other material exposed to X- or gamma radiation.*

The estimation of absorbed dose presents two somewhat different problems dependent upon whether or not electronic equilibrium may be assumed. These will be treated separately.

Case I. Electronic equilibrium.

(a) In case an ionization chamber is available which has been calibrated in roentgens for the quality of X-rays present, then the exposure dose in roentgens at the place of interest should be measured. Dimensions of the ionization chamber should be sufficiently small, so that the radiation field at the place of interest is not appreciably changed by the insertion of the ionization chamber. The material of which the chamber is made affects the ionization within it, but this is taken into account in its calibration.

If the exposure dose at any point in the irradiated medium is R roentgens, then the absorbed dose in the medium at the same point is given by

$$D_{\text{medium}}=D_{\text{air}}\times\frac{({}_{\text{m}}\mu_{\text{en}})_{\text{medium}}}{({}_{\text{m}}\mu_{\text{en}})_{\text{air}}}\tag{5}$$

$$=0.87_7\ R\times\frac{({}_{\text{m}}\mu_{\text{en}})_{\text{medium}}}{({}_{\text{m}}\mu_{\text{en}})_{\text{air}}}=fR\text{ rad,}\tag{6}$$

where $({}_m\mu_{en})$, equal to $({}_m\tau + {}_m\sigma_a + {}_m K)$, is defined as the energy absorption coefficient[7] (in cm^2/g) of the medium or of air, to be evaluated for the total spectrum of X- or gamma radiation arriving at the point of interest, and f is the absorbed dose in rads per roentgen of exposure dose.

Table 1 gives values of the mass energy absorption coefficient for a number of elements and for water, air, bone, and muscle. Table 1 also contains values of f in water, muscle, and bone for monochromatic photon energies.[8] Mean values, $\bar{f}$, of f integrated over several typical primary X-ray spectra (some measured and some calculated by Kramers' rule (1923)), are given in table 2 and in figure 8.

(b) In the event that no calibrated ionization chamber is available, a cavity chamber with near-air-equivalent wall material such as carbon can be employed as an absolute device.[9] In this case, calculation of absorbed dose employs the general form of the cavity relation involving the relative stopping power of the wall material and air:

$$D_{\text{wall}} = 0.87_7 Q (s_m)^{\text{wall}}_{\text{air}} \text{ rads}, \qquad (7)$$

where Q is the charge in esu carried by the ions of either sign produced per centimeter cubed of air at 0° and 760 mm Hg (NTP). Hence

$$D_{\text{medium}} = 0.87_7 (s_m)^{\text{wall}}_{\text{air}} \times Q \times \frac{({}_m\mu_{en})_{\text{medium}}}{({}_m\mu_{en})_{\text{wall}}} \text{ rads}. \qquad (8)$$

The values of s_m are given in table 3[10] for H, C, N, O, P, Ca, and water relative to air (Nelms, 1956), not including density effect corrections. For C, water, and a "tissue" composed of 13 percent of C and 87 percent of water, the s_m values are also given in table 3 with density effect corrections[11] (Sternheimer, 1956).

In table 4, the mean stopping power ratios are given for C, water, and "tissue", relative to air. These were obtained by integrating the s_m ratios over the electron energy from nearly zero to the initial (monochromatic) energy of the electrons.[12]

Tables 3 and 4 can be used approximately for protons also, by entering the tables at an energy 1/1836 that of the proton. For example, an 18.36-Mev proton has the same velocity (and hence is subject to nearly the same stopping power) as a 10-kev electron.

In table 5a, the mean stopping power ratios for C, water, and "tissue" relative to air, are given for the Compton electron spectra generated by the γ-rays of Co^{60} and Cs ^{137}, including density effect. These were obtained by the following calculation:

$$\frac{\int_0^{T_m} A(T_o) \times T_o \times \bar{s}_m(T_o) dT_o}{\int_0^{T_m} A(T_o) \times T_o dT_o}, \qquad (9)$$

where $A(T_o)$ is the numerical spectrum of Compton electrons having energies T_o at production, for Co^{60} (γ-rays 1,250 kev) or Cs^{137} (670 kev). (Similar spectra for other γ-ray energies are shown in figures 4a to f.) T_m is the maximum value of T_o in the spectrum, and $\bar{s}_m(T_o)$ is the mean mass stopping power ratio for each value of T_o, taken from table 4. Table 5b lists values of rad/(esu/cm^3), the ratio of absorbed dose in the wall material to the ionization in an air cavity at NTP, which were obtained from table 5a by multiplying the corresponding figures by 0.87_7.

All the calculations of stopping power were carried out with the usual assumption that the electrons slow down at a continuous rate, ignoring the production of delta rays. The effect of these delta rays (Spencer and Fano, 1954; Spencer and Attix, 1955; Burch, 1955) can be neglected for cavity chambers with nearly air-equivalent walls, particularly in view of the present uncertainty in s_m (Caldwell, 1955; Bakker and Segre, 1951; Mather and Segre, 1951), which is of the order of 1 percent.

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[7] ${}_m\tau$, ${}_m\sigma_a$, and ${}_m K$ are the mass absorption coefficients for photoelectric effect, Compton effect, and pair production, respectively. For present purposes these coefficients should include corrections for energy losses through fluorescence, annihilation radiation, and bremsstrahlung produced by the electrons as they slow down. Such corrections are described by Fano (1953), and are small for the energy range considered here. The data in table 1, provided by G. White (1956) include these corrections.

[8] The following percentage compositions by weight were assumed for muscle and bone (from data of Joyet et al. (1953), except for the omission of the small amount of Cl):

Element	Muscle (striated)	Bone (femur)
H	10.2	6.4
C	12.3	27.8
N	3.5	2.7
O	72.9	41.0
Na	0.08	--------
Mg	.02	0.2
P	.2	7.0
S	.5	0.2
K	.3	--------
Ca	.007	14.7

Air was taken to be 75.5 percent N$_2$, 23.2 percent O$_2$, and 1.3 percent A, by weight.

The values given in the literature for the calcium content of various bones vary greatly. For example, D'Ans and Lax (1949) give 20.2 percent Ca for the skull, 14.5 percent for femur, and 15.2 percent for ribs. Geygy (1955) gives 11 percent Ca for long bones and ribs. The data of Joyet (1953) were arbitrarily chosen as roughly representative of bones in general. The errors resulting from this assumption are probably no greater than those resulting from (a) neglecting the scattered radiation in calculating $\bar{f}_{\text{bone}}$ (see table 2), and (b) ignoring the nonhomogeneous structure of bone.

[9] It will be assumed throughout this report, unless otherwise stated, that the cavity walls are thick enough to exclude any externally-produced electrons and that the cavity is small in comparison with the ranges of most of the electrons present. In the low-energy X-ray region, this latter requirement is difficult to fulfill, and the calibrated chamber method is preferable to the use of the cavity as an absolute device.

[10] The mean excitation potentials. $I = 13Z$, were used in Bethe's stopping power formula for electrons (Segre, 1953). (Atomic binding corrections were not included.) This choice of I is based upon a recent survey of existing stopping power measurements (Caldwell, 1955; Sternheimer, 1956). However, it must be emphasized that an uncertainty of the order of 1 percent exists in s_m at the present time.

[11] Density effect calculations were not available for the other materials but the magnitude of this effect can be seen for C and H$_2$O in table 3. Density corrections are taken from Sternheimer (1956).

[12] s_m in eq (7) and (8) may be evaluated at a mean energy for the spectrum of electrons crossing the cavity. Alternatively, s_m can be integrated as in table 4 to obtain the mean value $\bar{s}_m$. Strictly speaking, a further integration must be made over the initial spectrum of electrons produced by X- or gamma rays as has been done in table 5. However, it will suffice in many cases to take the mean initial electron energy from figure 2.

(c) Additional information which may be found useful for the evaluation of absorbed dose from X- and gamma radiation are given in figures 2 to 5 and in table 7. Figures 6a to c provide some information on LET.

For many purposes it will be sufficient to make the following approximations:

(1) The mean photon energy $h\bar{\nu}$ is numerically equal to 40 to 45 percent of the kilovoltage applied to the tube in the case of moderate filtration.

(2) The initial energy of the photoelectron $\approx h\bar{\nu}$. The mean initial energy of the recoil electrons is $(\sigma_a/\sigma)h\bar{\nu}$, where σ_a and σ are the "true" Compton absorption coefficient and the total Compton coefficient, respectively, of radiation of quantum energy $h\bar{\nu}$. A graph of $(\sigma_a/\sigma)h\bar{\nu}$ is given in figure 2.

The mean energy of the electrons and positrons resulting from pair production can be taken as $\approx(h\bar{\nu}/2-0.511)$ Mev.

(3) The mean instantaneous electron energy (for purposes of calculating stopping power ratios $\bar{s}_m$) is approximately 40 percent of the initial electron energy.

Case II. Electronic equilibrium conditions not satisfied (e. g., near tissue-air or bone-tissue boundaries).[13]

The ionization in this case is measured at the place of interest in an air-filled ionization chamber having walls that are very thin compared with the range of the secondary electrons at the place of interest. If the walls are so thin that they make a negligible contribution to the total secondary electron emission that ionizes the air in the chamber, the material of which the walls are composed is not important, but because this condition is difficult to fulfill, it may be found to be advantageous to make the walls of a material that fairly closely matches in composition the immediately surrounding medium. The depth of the ionization chamber should be small in the direction of the gradient of the absorbed dose.

If a charge Q esu is carried by the ions of either sign generated per unit volume of air at 0°C and 760 mm Hg, then applying the general cavity relation

$$D_{\text{medium}}=[0.87_7(s_m)_{\text{air}}^{\text{medium}}\times Q] \text{ rads.} \tag{10}$$

5.5. *Absorbed dose of fast neutron radiation in tissue.*

Only the case where corpuscular equilibrium conditions for the recoil protons exist will be considered here because the proton ranges are generally very small, and hence equilibrium will exist in most cases. (See section 5.2 for similar electronic equilibrium conditions.)

Because, on the one hand, the absorbed dose rate in tissue exposed to a given flux of fast neutrons is not at all simply related to the absorbed dose rate in air exposed to the same neutron flux, and, on the other hand, roughly 90 percent of the absorbed dose in tissue is due to recoil protons set in motion by collisions between fast neutrons and hydrogen atoms, it is most convenient to use ionization chambers made of hydrogen-rich materials. A rigid envelope may be lined with a suitable thickness of a gelatin mixture rather accurately reproducing the composition of wet tissue (Rossi and Failla, 1950). Such chambers can be entirely satisfactory if either polytetrafluoroethylene, or amber coated with cerasin, is used for insulation, despite the fact that the water vapor pressure in the chamber is high. It is, however, generally more convenient to use a conducting plastic,[14] rather than gelatin, and the choice in practice lies between the use of air as the gas that is ionized and a gas that matches the walls in composition, e. g., ethylene in polyethylene. In the former case, it is customary to assume $W'_{\text{air}}=35 \text{ ev}=5.6\times10^{-11}$ erg, where the prime by W indicates that the ionizing particles are protons. Application of the cavity relation requires a knowledge of s_m. The mean distance that the protons have to travel in crossing the cavity must be small compared to their total length of path (2 mm for 2-Mev neutrons) to satisfy the cavity condition. On the one hand, air contains no hydrogen, and on the other, it has a large excess of nitrogen compared with tissue. The nitrogen contributes protons through the reaction N^{14} $(n,p)C^{14}$. If the gas filling matches the walls, $s_m=1$. There is no N^{14} $(n,p)C^{14}$ reaction in the gas, but it is necessary to know W' for the gas in question.[15]

(a) Air-filled chamber made of conducting plastic.

Measure the ionization when the chamber is exposed to the neutron beam within the issue of interest or a phantom representing this tissue. Let the ions of either sign which are produced in the chamber (at NTP) carry a charge Q esu/cm^3.

The absorbed dose in the wall material can be calculated from the relation

$$D_{\text{wall}}=Q\times0.90(s'_m)_{\text{air}}^{\text{wall}} \text{ rad,}^{16} \tag{11}$$

where s'_m is the stopping power per unit mass for the protons generated by the neutron flux, or strictly, the weighted average stopping power for all recoils. The absorbed dose in tissue then becomes:

$$D_{\text{tissue}}=D_{\text{wall}}\times\frac{\Sigma\sigma_i k_i N_{i \text{ tissue}}}{\Sigma\sigma_i k_i N_{i \text{ wall}}}, \tag{12}$$

---

[13] It should be pointed out that in such a region the spectral distribution of the electrons is not in equilibrium, and hence is not given by the reciprocal of the stopping power in the medium (neglecting secondary electrons), as is usually assumed (Spencer and Attix, 1955). However, because s_m for near-air-equivalent materials does not vary rapidly with energy, it can be evaluated approximately hy assuming that the equilibrium conditions apply (see section 5.2).

[14] Such plastics having an atomic composition of approximately 10.1 percent of hydrogen, 3.5 percent of nitrogen, and the remainder carbon, are available commercially and may be molded into a variety of shapes.

[15] s_m may need adjustment to allow for density effect correction (Sternheimer, 1956).

[16] Note that the numerical factor is 0.90 instead of 0.87_7 because W is assumed 35 ev for protons instead of 34 ev as was used for electrons.

where σ_i is the scattering cross section of the ith kind of atom, k_i is the average fractional loss of energy with the ith kind of atom, and N_i is the number per unit mass of the ith kind of atom.

Table 6 gives values of $(\sigma\times k)$ for H, C, N, O, S, and P for neutron energies between 1/10 and 10 Mev (Hughes and Harvey, 1955).

(b) Gas and walls of matched composition.

Measure the ionization when the chamber is exposed to the neutron beam within the tissue of interest or in a phantom representing this tissue. Let the ions of either sign that are produced in the chamber (at NTP) carry a charge Q esu/cm³.

The absorbed dose in the wall material (according to eq (1)) is equal to

$$D_{\text{wall}}=\frac{J_{\text{m}}}{100}\times W'_{\text{gas}}\text{ rads,}\qquad(13)$$

where W'_{gas} is the energy in ergs for a proton to produce an ion pair in the gas. When W'_{gas} is expressed in electron volts and ${}_{\text{e}}d_{\text{gas}}$ is the gas density in electrons/cm³, then

$$D_{\text{wall}}=0.87_7Q\left(\frac{W'_{\text{gas}}}{34}\right)\times\frac{3.89\times10^{20}}{{}_{\text{e}}d_{\text{gas}}}.\qquad(14)$$

${}_{\text{e}}d_{\text{gas}}$ is given by $6.025\times10^{23}\ Zd/A$, where Z is the atomic number, A the atomic weight, and d the density (g/cm³) of the gas at the time of the measurement. 3.89×10^{20} is the electron density of air at NTP. The absorbed dose in tissue is then given by eq (12).

5.6. *The measurement of absorbed dose in a medium exposed to both neutron and X- or gamma radiation.*

The measurement of the total absorbed dose due to mixed neutron and X- or γ-ray beams at a point in a medium where equilibrium with the secondaries of both types of radiation exists presents no special difficulty. The ionization chamber should be of the thick-walled type, having the same composition as for the measurement of neutron radiation. The absorbed dose may be calculated with fair accuracy from the ionization produced in this chamber by the application of the cavity relation as already described. Slight ambiguity arises, however, regarding the appropriate values of W and s_{m} because these are not the same for the two radiations. If the relative contributions to the absorbed dose from neutron and γ radiation are approximately known, weighted mean values of W and s_{m} may be used. If the wall material accurately matches the medium of interest, $D_{\text{medium}}=D_{\text{wall}}$ and no further calculation is required. If the match is not exact, an additional step is given in eq (11) for the neutrons, and a step as in eq (8) for the γ-rays will be required to obtain the absorbed dose in the medium. An approximate knowledge of the relative neutron and γ-ray contributions is needed to make this latter transformation.

In radiobiology, as well as in health physics, it is generally necessary to know the magnitude of the contribution of each radiation separately to the total absorbed dose. The following procedures have been used:

(a) The ionization is measured at the place of interest with two thick-walled ionization chambers, (1) having walls of a hydrogen-rich material and (2) having walls of a material that contains no hydrogen, e. g., graphite, aluminum, or polytetrafluoroethylene.

The method of calculating separately the absorbed dose in tissue due to each radiation has been described by Ebert et al. (1955). There are two difficulties with this method. The first is that the gamma-ray chamber will also respond to neutrons. In the case of a carbon-CO_2 chamber, the neutron response (rads) is probably on the order of 10 to 20 percent of the gamma-ray response (rads) depending upon the neutron energy (Hurst et al., 1956). The second difficulty is that the gamma-ray response of the two chambers are in general different, especially for gamma rays of low energy, thus rendering the subtraction technique difficult unless the gamma-ray spectrum and gamma-ray response are known. The first difficulty makes it hard to measure gamma-ray absorbed dose in the presence of many neutrons and the second difficulty hinders the measurement of neutron absorbed dose in the presence of strong gamma radiation.

Neutron and gamma-ray contributions to absorbed dose may be distinguished in a proportional counter by separation of large pulses due to neutron recoils from the small pulses due to secondary electrons from gamma radiation. In the neutron dosimeter (Hurst, 1954), the total ionization due to the recoil protons is measured separately in a proportional counter of polyethylene filled with ethylene and the product of count and pulse height is registered. The small pulses due to secondary electrons from gamma rays are discarded. At the same time one cannot avoid losing the small neutron pulses. In the gamma-ray dosimeter (Caswell, 1957), large pulses due to neutron recoils are discarded electronically and secondary electron pulses due to gamma rays are recorded and the product of count and pulse height (analogous to a carbon-CO_2 ionization chamber) again registered. This dosimeter is a graphite-walled, He-CO_2-filled proportional counter, the helium being added as CO_2 is not a suitable counting gas.

From the total ionization associated with either radiation, the corresponding absorbed dose may be calculated by application of the cavity relation. In some cases it may be most convenient to combine one method of (a) with one method of (b).

A variation of this method (Rossi and Rosenzweig, 1955) allows measurement of the absorbed dose as a function of linear energy transfer (LET).

(b) The neutron contribution to the absorbed dose may be calculated from measurements of the number and length of the recoil proton tracks produced in photographic emulsion under controlled conditions.

(c) The neutron absorbed dose rate in any medium may be calculated from a knowledge of the flux and energy spectrum of the neutron beam at the place of interest. These two quantities may be inferred from the induced activity of a series of "threshold detectors" of Pu^{239} surrounded by B^{10}, Np^{237}, U^{238}, and S^{32} (Hurst et al., 1956).

5.7 *The determination of the volume of an ionization chamber by exposure to gamma radiation.*

Sometimes the volume of an ionization chamber cannot be calculated from its dimensions as these are not accurately known. The volume, V, then can be determined by measuring the total ionization, (QV) esu, produced by exposing the chamber to an exposure dose, R roentgens, of gamma radiation. The wall of the ionization chamber should be sufficiently thick to ensure electronic equilibrium at its inner surface. The dimensions of the chamber should be such that the range of the secondary electrons associated with the gamma radiation is great compared with the depth of the ionization chamber, e. g., 1 cm for Co^{60} radiation.

Then V can be calculated by the relation

$$V=\frac{(QV)}{R}\times\frac{({}_{\mathrm{m}}\mu_{\mathrm{en}})_{\mathrm{air}}}{({}_{\mathrm{m}}\mu_{\mathrm{en}})_{\mathrm{wall}}}\times(s_{\mathrm{m}})_{\mathrm{gas}}^{\mathrm{wall}}\times\frac{W_{\mathrm{gas}}}{W_{\mathrm{air}}}\times\frac{3.89\times10^{20}}{{}_{e}d_{\mathrm{gas}}}\times(1+\alpha), \tag{15}$$

where $({}_{\mathrm{m}}\mu_{\mathrm{en}})$ signifies the energy absorption coefficient (see footnote 7) for the gamma radiation used, whereas s_{m} and W are the mass stopping power ratio and the energy per ion pair for the associated secondary electrons. Alpha is a correction for the attenuation of the gamma radiation by the wall of the ionization chamber.

The relation can be simplified in case the ionization chamber is filled with air and/or when the wall material and the gas are matched for the gamma radiation.

5.8. *Other graphs and tables characterizing X-, gamma-, and neutron radiation and their associated secondary particles.*

(a) Typical primary X-ray spectra. Figures 3a to 3m present some measured typical primary X-ray spectra. They are by no means complete in their coverage of usual X-ray kilovoltage-filtration combinations, partially because of the limited number of spectral measurements now available. However, they do show that theoretical calculations can in some cases give a fairly useful estimate of an unknown spectrum. A brief bibliography of some of the literature of X-ray spectra is included in the references.

Very few data are now available on spectra of X-rays that have been degraded in energy by scattering in a phantom. A discussion of this problem together with some results are given by Cormack et al. (ref. 63). As a first approximation, this energy degradation is usually ignored in computing energy absorption in tissue, but considerable underestimation can result from this procedure, particularly in the case of bone for X-ray energies where the photoelectric effect is important. Figure 3m indicates the change in the total spectrum resulting from scattered radiation at a depth of 10 cm in a water phantom, for 400-kvp X-rays. $\bar{f}_{\mathrm{bone}}$ is 1.39 for the total spectrum with a 400-cm^2 field, compared to 1.11 for the primary spectrum, a difference of 25 percent. $\bar{f}_{\mathrm{muscle}}$ is the same within 0.5 percent for these two spectra. It would be desirable for further experiments of this type to provide tables of correction factors for various field sizes, depths, and primary X-ray qualities. These could then be applied to $\bar{f}_{\mathrm{bone}}$ as given in table 2 and figure 8 (calculated for the primary spectra), yielding $\bar{f}_{\mathrm{bone}}$ within a scattering medium much more accurately.

(b) Typical distribution functions for initial Compton recoil electron energy. The curves shown in figures 4a to 4f represent the recoil electron spectral distributions produced by a number of monochromatic γ-ray energies. They can be combined with pair and photoelectron spectra (at energies where these are important) to give the total initial electron spectral distributions.

(c) Typical "slowing-down" electron distribution functions. The spectrum of primary electrons produced in a medium, under equilibrium conditions, by the continuous slowing down of initially monoenergetic electrons, is given approximately by the reciprocal of the stopping power of the medium. The production of secondary electrons by collisions has been calculated approximately for a few initial energies. The resulting electron spectral distributions with and without secondaries are given in table 7 for tissue, assuming the production of secondaries to be the same as in graphite (Spencer and Fano, 1954; Spencer and Attix, 1955).

(d) Typical neutron energy spectra. The neutron energy spectra from the D-Be reaction with 15-Mev deuterons incident on a thick Be target is given in figure 5.

(e) Typical LET spectra. Figure 6a gives the LET spectra for several typical forms of radiation. Figures 6b and 6c represent the LET distributions for recoil protons produced in water by monoenergetic neutrons. Additional LET distribution curves for mixed-energy neutron beams and for total absorption of the neutrons in multiple collisions are given by Boag (1954).

5.9. *Saturation in ionization measurements.*

Failure to collect all the ions produced in an ionization chamber may be due to either initial or general recombination. The amount of initial recombination depends upon the LET of the ionizing particle and upon the strength of the collecting field and its direction in relation to the particle track. The best treatment of initial recombination is that by Jaffe (1929) with modifications by Zanstra (1935), and that by Kara-Michailova and Lea (1940). Initial recombination does not depend upon dose rate and is usually only troublesome for slow particles or high gas pressures.

General recombination can be treated theoretically in simple cases but it must be stressed that difficulty in achieving saturation is often due principally to inappropriate design of the ionization chamber. If there are regions in the chamber where the field strength is much lower than the maximum, it will be difficult to achieve saturation in these regions without exceeding the permissible field strength at the point where the maximum occurs.

For plane parallel ionization chambers uniformly irradiated at constant dose rate, a saturation curve can be drawn (Boag, 1956) as a function of the dimensionless variable $\xi=m(d^2\sqrt{q}/V,)$ where d is the spacing (cm), V the collecting voltage (volts), q the ionization intensity (esu/cm^3-sec), and m is a constant depending upon the type and density of the gas. This curve is illustrated in figure 7a, where $F\ (\xi)$=collection efficiency, and it can be represented with adequate accuracy by the formula $F(\xi)=2/(1+\sqrt{1+\xi^2})$. For air at 760 mm and 20° C, the constant m has the value 15.9.

For cylindrical or spherical geometry in the ionization chamber the foregoing saturation curve still applies, but instead of d, one must insert $K(a-b)$, where $(a-b)$ is the radial spacing of the electrodes, and K is a shape factor whose value are given in figure 7b.

The foregoing curve and formula for $F(\xi)$ apply to continuous radiation. In the case of instantaneous pulses of radiation (Boag, 1956) whose duration is short compared with the time required to collect the ions, the appropriate dimensionless variable is $u=\mu(d^2r/V)$, where r is the charge density per pulse (esu/cm^3). In this case the collection efficiency, $F(u),=(1/u)\ \log\ (1+u)$. For air at 760 mm and 20° C, $\mu=1000$. F(u) is given graphically in figure 7c for plane geometry. The extension to cylindrical and spherical geometry again involves the shape factors K_c and K_s from figure 7b.

Chambers that include regions of plane, cylindrical, and spherical geometry can be dealt with by considering the collection efficiency in each of the regions separately and adding together the currents from all regions. An experimental check is, of course, desirable whenever possible.

TABLE 1. *Values of the mass energy-absorption coefficients and the factor f*

Photon energy	Mass energy-absorption coefficient, $(_m\mu_{en})$ cm^2/g															$f=0.87_7\left[\frac{(_m\mu_{en})_{medium}}{(_m\mu_{en})_{air}}\right]$		
	H	C	N	O	Na	Mg	P	S	A	K	Ca	Water	Air	Bone	Muscle	Water/Air	Bone/Air	Muscle/Air
Mev																		
0.010	0.00992	1.94	3.42	5.50	15.4	20.9	40.1	49.7	62.0	77.0	89.8	4.89	4.66	19.0	4.96	0.92_0	3.58	0.93_3
.015	.0110	0.517	0.916	1.49	4.43	6.09	11.9	15.2	19.4	24.6	28.9	1.32	1.29	5.89	1.36	$.89_7$	4.00	$.92_5$
.020	.0133	.203	.360	0.587	1.77	2.47	5.00	6.41	8.31	10.5	12.5	0.523	0.516	2.51	0.544	$.88_7$	4.27	$.92_5$
.030	.0186	.0592	.102	.163	0.482	0.684	1.45	1.85	2.46	3.12	3.75	.147	.147	0.743	.154	$.87_7$	4.43	$.91_9$
.040	.0230	.0306	.0465	.0700	.194	.274	0.570	0.731	0.974	1.25	1.52	.0647	.0640	.305	.0677	$.88_7$	4.18	$.92_8$
.050	.0270	.0226	.0299	.0410	.0996	.140	.282	.361	.484	0.626	0.764	.0394	.0384	.158	.0409	$.90_0$	3.61	$.93_4$
.060	.0305	.0203	.0244	.0304	.0637	.0845	.166	.214	.284	.367	.443	.0304	.0292	.0979	.0312	$.91_3$	2.94	$.93_7$
.080	.0362	.0201	.0218	.0239	.0369	.0456	.0780	.0971	.124	.158	.191	.0253	.0236	.0520	.0255	$.94_0$	1.93	$.94_8$
.10	.0406	.0213	.0222	.0232	.0288	.0334	.0500	.0599	.0725	.0909	.111	.0252	.0231	.0386	.0252	$.95_7$	1.47	$.95_7$
.15	.0485	.0246	.0249	.0252	.0258	.0275	.0315	.0351	.0368	.0433	.0488	.0278	.0251	.0304	.0276	$.97_1$	1.06	$.96_4$
.20	.0530	.0267	.0267	.0271	.0265	.0277	.0292	.0310	.0302	.0339	.0367	.0300	.0268	.0302	.0297	$.98_2$	0.98_8	$.97_2$
.30	.0573	.0288	.0289	.0289	.0278	.0290	.0290	.0301	.0278	.0304	.0319	.0320	.0288	.0311	.0317	$.97_7$	$.94_7$	$.96_5$
.40	.0587	.0295	.0296	.0296	.0283	.0295	.0290	.0301	.0274	.0299	.0308	.0329	.0296	.0316	.0325	$.97_5$	$.93_6$	$.96_3$
.50	.0589	.0297	.0297	.0297	.0284	.0293	.0288	.0300	.0271	.0294	.0304	.0330	.0297	.0316	.0327	$.97_4$	$.93_3$	$.96_6$
.60	.0588	.0296	.0296	.0296	.0283	.0292	.0287	.0297	.0270	.0291	.0301	.0329	.0296	.0315	.0326	$.97_5$	$.93_3$	$.96_6$
.80	.0573	.0288	.0289	.0289	.0276	.0285	.0280	.0287	.0261	.0282	.0290	.0321	.0289	.0306	.0318	$.97_4$	$.92_9$	$.96_5$
1.0	.0555	.0279	.0280	.0280	.0267	.0275	.0270	.0280	.0252	.0272	.0279	.0311	.0280	.0297	.0308	$.97_4$	$.92_7$	$.96_5$
1.5	.0507	.0255	.0255	.0255	.0243	.0250	.0245	.0254	.0228	.0247	.0253	.0283	.0255	.0270	.0281	$.97_3$	$.92_9$	$.96_6$
2.0	.0464	.0234	.0234	.0234	.0225	.0232	.0228	.0235	.0212	.0228	.0234	.0260	.0234	.0248	.0257	$.97_4$	$.92_9$	$.96_3$
3.0	.0398	.0204	.0205	.0206	.0199	.0206	.0204	.0210	.0193	.0208	.0213	.0227	.0205	.0219	.0225	$.97_1$	$.93_7$	$.96_3$
4.0	.0351	.0184	.0186	.0187	.0184	.0191	.0192	.0199	.0182	.0199	.0204	.0205	.0186	.0199	.0203			
5.0	.0316	.0170	.0172	.0174	.0173	.0181	.0184	.0192	.0176	.0193	.0200	.0190	.0173	.0186	.0188			
6.0	.0288	.0160	.0162	.0166	.0166	.0175	.0179	.0187	.0175	.0190	.0198	.0180	.0163	.0178	.0178			
8.0	.0249	.0145	.0148	.0154	.0158	.0167	.0175	.0184	.0172	.0190	.0197	.0165	.0150	.0165	.0163			
10.0	.0222	.0137	.0142	.0147	.0154	.0163	.0174	.0183	.0173	.0191	.0201	.0155	.0144	.0159	.0154			

Table 2. *Average absorbed dose per roentgen of exposure dose in water, muscle, and bone, for various primary X-ray spectra*

Tube potential	Filter	HVL	Spectrum	$\bar{f} = (\overline{\text{rad/r}})$		
				Water	Muscle	Bone
kv	*mm*	*mm*				
100	0.18 Cu	0.25 Cu or 5.5 Al.	measured (fig. 3e).	0.91	0.94	3.10
100	.18 Cu	0.25 Cu or 5.5 Al.	Kramers' (fig. 3c).	.91	.94	3.13
150	.075 Cu	0.2 Cu	Kramers'	.92	.94	2.69
200	.20 Cu	.5 Cu	Kramers'	.94	.95	2.05
250	.17 Cu +3.0 Al.	1.0 Cu	Kramers'	.95	.95	1.76
250	.9 Cu +3.0 Al.	2.0 Cu	Kramers'	.96	.96	1.42
280	--------	1.7 Cu	measured (fig. 3f).	.96	.96	1.44
280	--------	2.5 Cu	measured (fig. 3g).	.97	.96	1.22
280	--------	3.1 Cu	measured (fig. 3h).	.97	.96$_5$	1.13
400	--------	4.16 Cu	measured (fig. 3m) (primary).	.97	.97	1.11

Table 3. *Mass stopping power ratios relative to air,* (s_m)[a]

Electron kinetic energy, *T*	Without density effect							Including density effect		
	H	C	N	O	P	Ca	Water	C	Water	"Tissue"
Mev										
0.001	3.564	1.079	1.018	0.965	0.692	0.598	1.254	1.079	1.254	1.231
.002	3.223	1.062	1.014	.973	.752	.685	1.223	1.062	1.223	1.202
.003	3.084	1.055	1.013	.976	.776	.720	1.211	1.055	1.211	1.190
.004	3.004	1.051	1.012	.978	.791	.741	1.203	1.051	1.203	1.184
.005	2.949	1.049	1.011	.979	.800	.755	1.198	1.049	1.198	1.179
.006	2.904	1.045	1.010	.979	.806	.764	1.193	1.045	1.193	1.174
.007	2.877	1.045	1.011	.981	.813	.773	1.192	1.045	1.192	1.173
.008	2.851	1.044	1.010	.982	.818	.780	1.189	1.044	1.189	1.171
.009	2.830	1.043	1.010	.982	.821	.785	1.188	1.043	1.188	1.169
.01	2.811	1.042	1.010	.983	.825	.790	1.186	1.042	1.186	1.167
.02	2.709	1.037	1.009	.985	.843	.816	1.177	1.037	1.177	1.158
.03	2.661	1.034	1.008	.986	.851	.828	1.172	1.034	1.172	1.154
.04	2.630	1.033	1.008	.987	.857	.836	1.169	1.033	1.169	1.152
.05	2.609	1.032	1.008	.987	.860	.841	1.168	1.032	1.168	1.150
.06	2.592	1.031	1.008	.988	.863	.846	1.166	1.031	1.166	1.148
.07	2.579	1.030	1.008	.988	.866	.849	1.165	1.030	1.165	1.147
.08	2.568	1.030	1.007	.988	.868	.852	1.164	1.030	1.164	1.146
.09	2.559	1.029	1.007	.988	.869	.854	1.163	1.029	1.163	1.146
1	2.550	1.029	1.007	.989	.871	.856	1.162	1.029	1.162	1.144
.2	2.502	1.027	1.007	.990	.879	.869	1.158	1.023	1.158	1.140
.3	2.476	1.025	1.006	.990	.884	.875	1.155	1.019	1.155	1.138
.4	2.458	1.024	1.006	.991	.887	.880	1.154	1.014	1.154	1.136
.5	2.444	1.024	1.006	.991	.889	.883	1.153	1.010	1.152	1.134
.6	2.433	1.023	1.006	.991	.891	.886	1.152	1.007	1.148	1.130
.7	2.424	1.023	1.006	.992	.893	.888	1.151	1.003	1.144	1.126
.8	2.417	1.022	1.006	.992	.894	.890	1.150	1.000	1.140	1.122
.9	2.410	1.022	1.006	.992	.896	.892	1.150	0.997	1.134	1.116
1.0	2.404	1.022	1.006	.992	.897	.894	1.149	.994	1.133	1.115
2	2.366	1.020	1.005	.993	.903	.903	1.146	.971	1.105	1.088
3	2.347	1.019	1.005	.993	.907	.908	1.144	.954	1.086	1.069
4	2.333	1.018	1.005	.994	.909	.912	1.143	.942	1.071	1.054
5	2.324	1.018	1.005	.994	.911	.914	1.142	.932	1.059	1.042
6	2.316	1.017	1.005	.994	.912	.916	1.141	.923	1.049	1.032
8	2.305	1.017	1.005	.994	.914	.919	1.140	.909	1.032	1.016
10	2.297	1.016	1.004	.995	.916	.921	1.139	.898	1.019	1.003

[a] Mean excitation potentials, *I*, assumed equal to 13*Z* (see footnote 10). Courtesy of A. Nelms (1956).

TABLE 4. *Mean mass stopping power ratios relative to air,* $\bar{s}_m$ [a]

Initial electron kinetic energy, T_o	Including density effect		
	C	Water	"Tissue"
Mev			
0. 002	1. 070	1. 238	1. 216
. 003	1. 064	1. 226	1. 205
. 004	1. 060	1. 220	1. 199
. 005	1. 058	1. 215	1. 195
. 006	1. 055	1. 212	1. 191
. 007	1. 054	1. 208	1. 188
. 008	1. 052	1. 206	1. 186
. 009	1. 051	1. 203	1. 183
. 01	1. 050	1. 202	1. 182
. 02	1. 044	1. 191	1. 172
. 03	1. 041	1. 185	1. 166
. 04	1. 039	1. 181	1. 163
. 05	1. 038	1. 179	1. 160
. 06	1. 037	1. 177	1. 159
. 07	1. 036	1. 175	1. 157
. 08	1. 035	1. 174	1. 156
. 09	1. 034	1. 173	1. 155
. 1	1. 034	1. 172	1. 154
. 2	1. 030	1. 166	1. 148
. 3	1. 027	1. 163	1. 145
. 4	1. 024	1. 161	1. 143
. 5	1. 022	1. 159	1. 141
. 6	1. 020	1. 158	1. 140
. 7	1. 017	1. 156	1. 138
. 8	1. 016	1. 154	1. 136
. 9	1. 014	1. 152	1. 134
1. 0	1. 012	1. 150	1. 132
2	1. 001	1. 139	1. 121
3	0. 985	1. 121	1. 103
4	. 976	1. 110	1. 093
5	. 968	1. 108	1. 084
6	. 961	1. 093	1. 076
8	. 950	1. 080	1. 063
10	. 940	1. 069	1. 052

[a] Mean excitation potentials, I, assumed equal to $13Z$ (see footnote 10).

$\bar{s}_m = \frac{1}{T_o}\int_0^{T_o} s_m dT$. Courtesy of A. Nelms (1956).

TABLE 5a. *Mean mass stopping power ratios relative to air, integrated over the initial Compton electron spectra produced by* Co^{60} *and* Cs^{137} *γ-rays*

γ-ray source	Graphite	Water	"Tissue"
Co^{60} ------------	1.01_6	1.15_5	1.13_7
Cs^{137} ------------	1.02_6	1.16_2	1.14_5

TABLE 5b. *Absorbed dose versus cavity ionization* [a]

(Rad in wall medium per esu/cm³ in air cavity (NTP))

γ-ray source	Graphite	Water	"Tissue"
Co^{60} ------------	0.89_1	1.01_3	0.99_7
Cs^{137} ------------	0.90_0	1.01_9	1.00_4

[a] These figures are equal to the corresponding figures in table 5a multiplied by 0.87_7 rad/r. Courtesy of A. Nelms (1956).

TABLE 6. *Product of scattering cross section and average fractional loss of energy, $\sigma \times k$ (barns)*[a], *for neutrons traversing various elements*

Energy	Element	H	C	N	O	P	S
	k^{b}=	0. 500	0.1431	0.1254	0.1116	0.0611	0.0592
Mev							
0. 1		6. 3	0. 66	(~. 6)	0. 39	0. 21	0. 42
. 15		5. 4	. 63	0. 51	. 39	. 15	. 24
. 2		4. 8	. 60	. 46	. 40	. 13	. 41
. 3		3. 95	. 56	. 40	. 44	. 15	. 13
. 4		3. 45	. 52	. 36	. 67	. 13	. 18
. 5		3. 1	. 49	. 30	. 65	. 17	. 12
. 6		2. 8	. 46	. 20	. 36	. 14	. 11
. 8		2. 4	. 41	. 23	. 33	. 15	. 14
1. 0		2. 12	. 39	. 25	. 89	(~. 18)	. 17
1. 5		1. 70	. 30	. 23	. 25	(~. 18)	. 14
2		1. 44	. 24	. 20	. 18	. 23	. 17
3		1. 14	. 17	. 21	. 13	. 23	. 19
4		0. 95	. 27	. 23	. 21	. 16	. 17
5		. 83	. 19	. 18	. 13	. 15	. 15
6		. 72	. 14	. 18	. 16	. 14	. 15
8		. 59	. 21	. 18	. 13	. 12	. 12
10		. 47	. 16	. 16	. 13	. 12	. 11

[a] σ is the scattering cross section. The $\sigma \times k$ values in parenthesis are rough estimates, the cross sections not having been measured. See eq (12) for application.

[b] k is the average fractional energy loss of the neutron. These values assume the total cross section is all elastic scattering, isotropic in the center-of-mass system. The errors introduced by this assumption (which is strictly true only for hydrogen) should be small in this energy range.

TABLE 7. *Approximate electron slowing-down spectral distributions in tissue*

Electron kinetic energy, T^{a}	Electron spectral distribution, neglecting secondaries	Electron spectral distribution, including secondaries (g/cm²)/Mev		
		$^{b}T_0$= 1.308 Mev	T_0= 0.654 Mev	T_0= 0.327 Mev
Mev	*(g/cm²)/Mev*			
0. 001	0. 00825			
. 002	. 01323			
. 003	. 01770	0. 474	0. 257	1. 138
. 004	. 0219	. 439	. 237	. 129
. 005	. 0260	. 410	. 225	. 124
. 006	. 0298	. 394	. 218	. 121
. 007	. 0336	. 383	. 212	. 119
. 008	. 0372	. 371	. 206	. 118
. 009	. 0408	. 361	. 202	. 117
. 01	. 0443	. 355	. 198	. 116
. 02	. 0760	. 315	. 187	. 127
. 03	. 1038	. 303	. 197	. 144
. 04	. 1289	. 305	. 209	. 160
. 05	. 1518	. 310	. 223	. 176
. 06	. 1730	. 317	. 235	. 194
. 07	. 1926	. 324	. 247	. 208
. 08	. 211	. 331	. 259	. 224
. 09	. 228	. 337	. 270	. 237
Mev	*(g/cm²)/Mev*			
. 1	. 244	. 346	. 283	. 251
. 2	. 360	. 410	. 371	. 360
. 3	. 427	. 453	. 427	. 427
. 2	. 469	. 480	. 469	
. 5	. 495	. 498	. 495	
. 6	. 514	. 514	. 514	
. 7	. 527	. 527		
. 8	. 535	. 535		
. 9	. 542	. 542		
1	. 546	. 546		
2	. 551			
3	. 543			
4	. 535			
5	. 528			
6	. 522			
8	. 514			
10	. 507			

[a] For any value of T in column 1 taken for the starting energy T_0, the second column gives the relative electron spectral distribution (without secondary electrons) at lower values of T, the degraded energy of the electrons. Columns 3, 4, and 5 give the relative spectral distributions for starting energies of 1,308, 0.654, and 0.327 Mev, respectively, including secondary electrons.

[b] T_0 is the initial energy of the primary electrons.

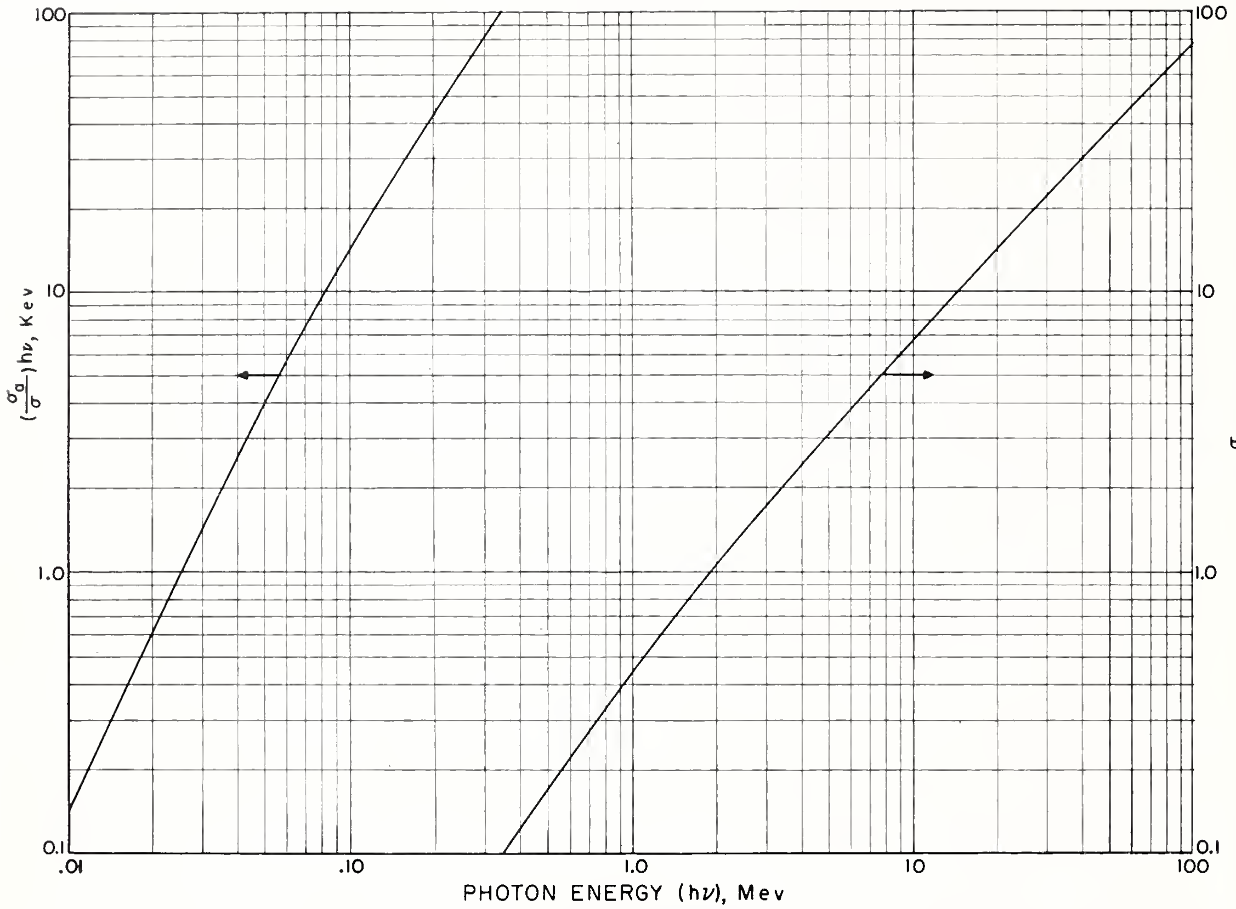


Figure 2. *Graph of* $\left(\frac{\sigma_a}{\sigma}h\nu\right)$, *the mean initial energy of the Compton recoil electrons produced by monochromatic* γ*-rays of quantum energy* $h\nu$.

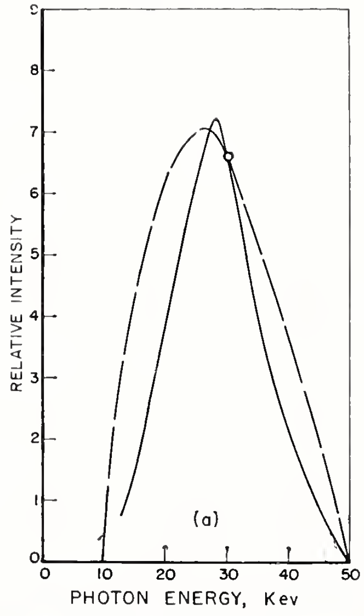


Figure 3a. *X-ray spectrum obtained with 50-kv tube potential, 0.5-mm* Al *inherent filtration.*

Solid curve: measured by scintillation spectrometer (the ordinate is photon energy multiplied by number of photons of that energy) (Ehrlich, 1955, 1956). Dashed curve: spectrum calculated by Kramers' method (1923).

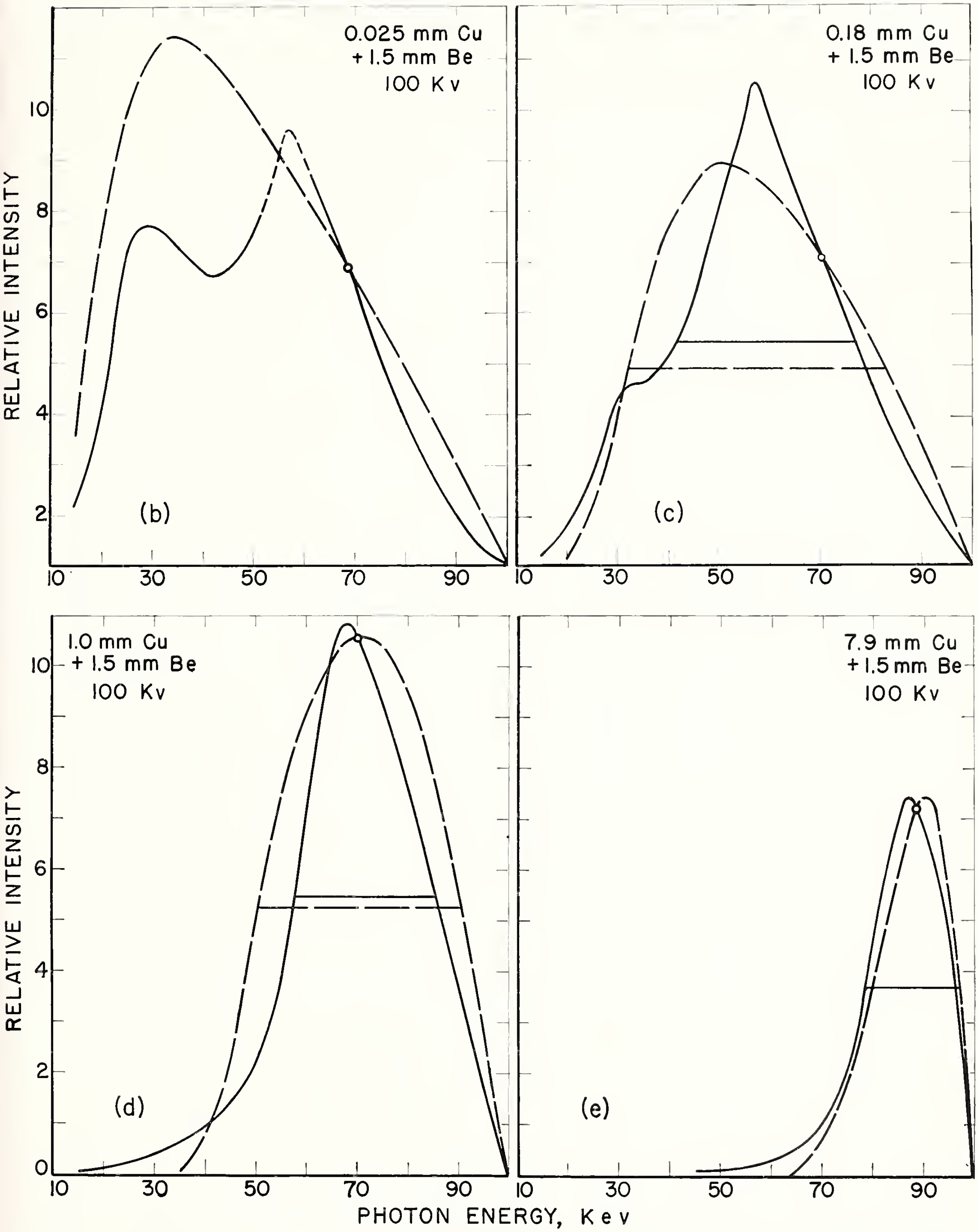
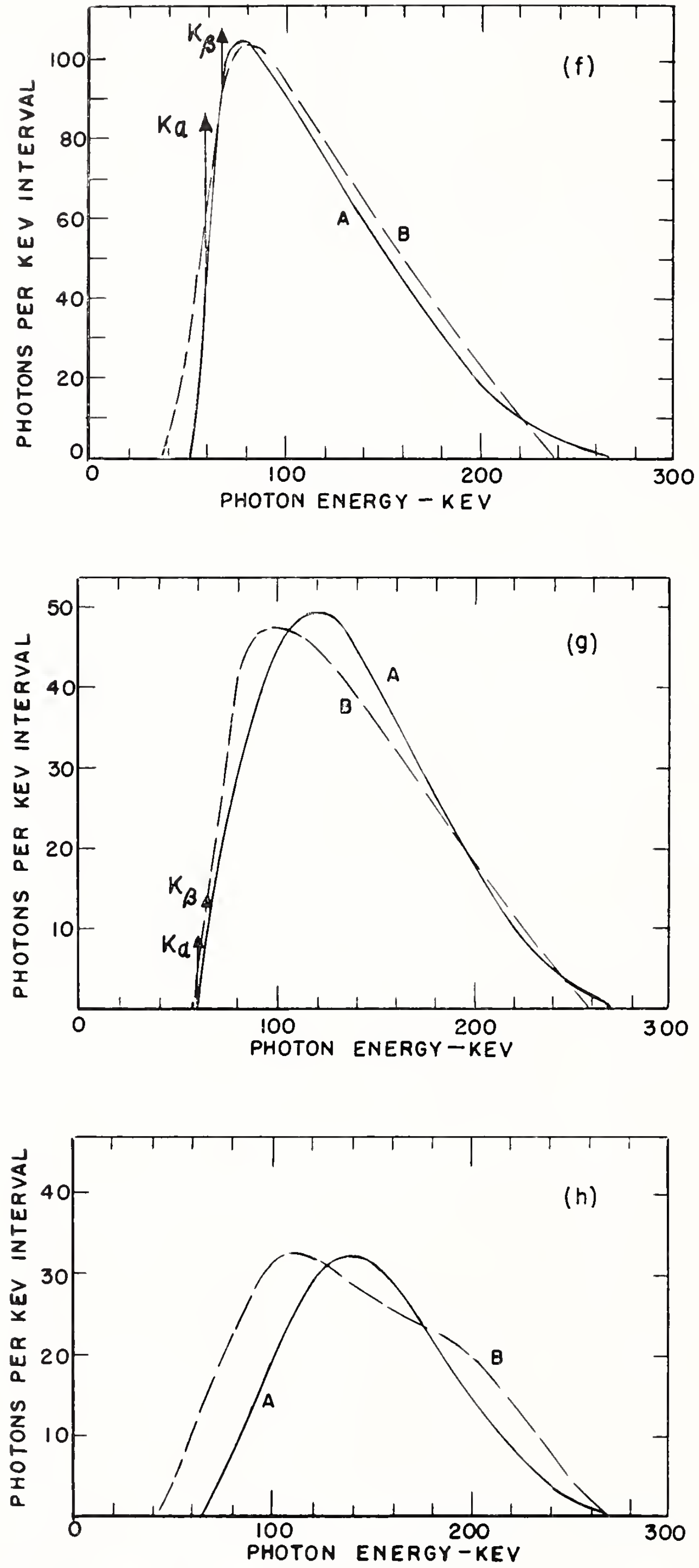


FIGURE 3b to e. *X-ray spectra obtained with 100-kv tube potential, 1.5-mm* Be *inherent filtration plus various thicknesses of* Cu.

Solid curves: measured by scintillation spectrometer (the ordinate is photon energy multiplied by number of photons of that energy) (Ehrlich, 1955, 1956). Dashed curves: spectra calculated by Kramers' method (1923).



FIGURES 3f to h. *X-ray spectra (in photons/kev interval) obtained with 280-kvp tube potential, with filtration to give copper HVL of 1.7 mm, 2.5 mm, and 3.1 mm, respectively.*

Solid curves: measured by scintillation spectrometer (Cormack, 1955). Dashed curves: spectra obtained from analysis of absorption data using Greening's method (1947).

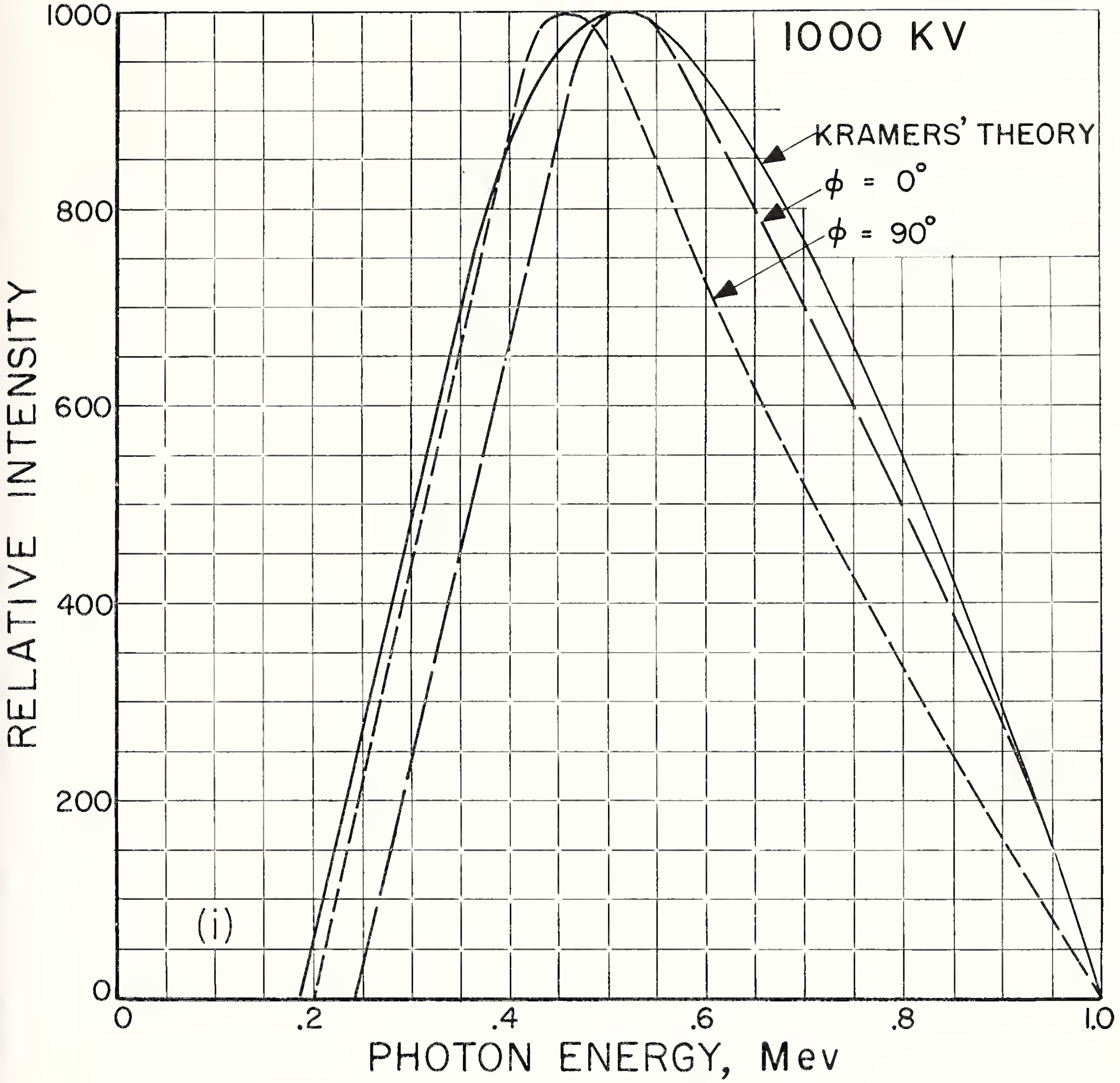


FIGURE 3i. *X-ray spectrum obtained at 1000-kv tube potential.*

Filtration: 2.8-mm W+2.8-mm Cu+18.7-mm water+2.1-mm brass. Dashed curves: spectra measured by Compton spectrometer (the ordinate is photon energy multiplied by number of photons of that energy) (Miller et al., 1954). Angles refer to direction of X-rays relative to initial electron direction. Solid curve: spectrum calculated by Kramers' method (1923).

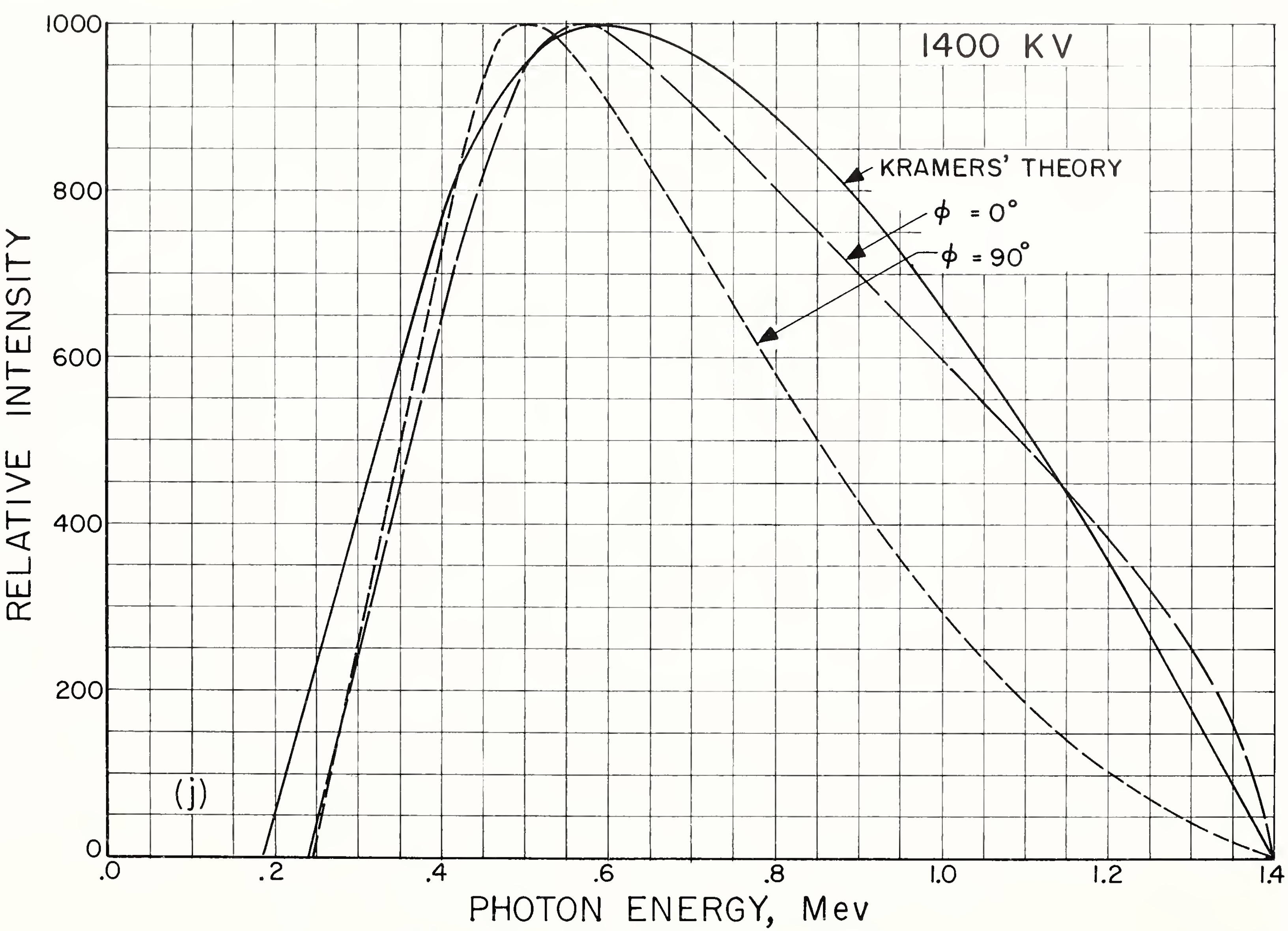


FIGURE 3j. *X-ray spectrum obtained at 1000-kv tube potential.*

Filtration: 2.8-mm W+2.8-mm Cu+18.7-mm water+2.1-mm brass. Dashed curves: spectra measured by Compton spectrometer (the ordinate is photon energy multiplied by number of photons of that energy) (Miller et al, 1954). Angles refer to direction of X-rays relative to initial electron direction. Solid curve: spectrum calculated by Kramers' method (1923).

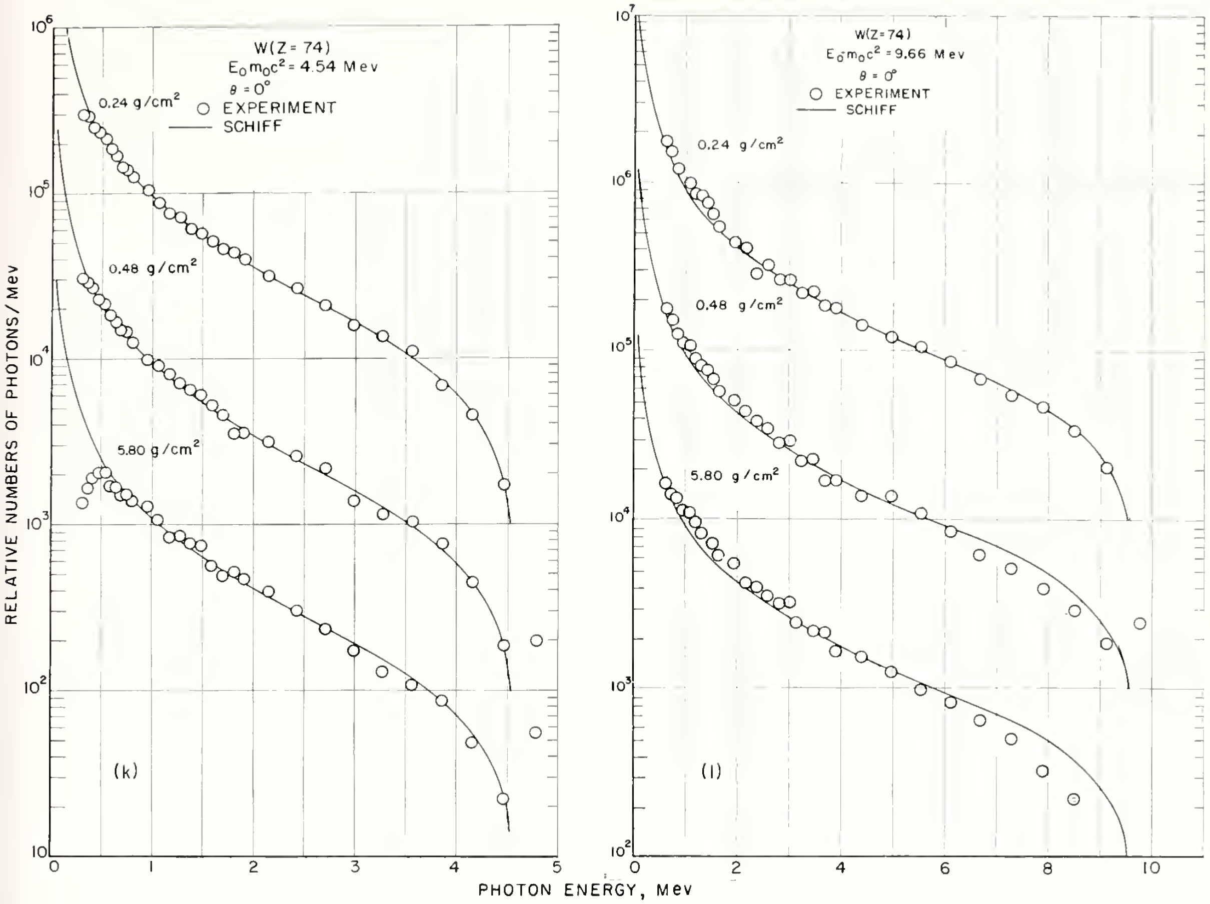


FIGURE 3k to l. *Relative X-ray spectra (in photon/Mev interval) produced by 9.66-Mev and 4.54-Mev electrons from a betatron (Starfelt and Koch, 1956).*

Curves are given for three tungsten target thicknesses: 0.24 g/cm², 0.48 g/cm², and 5.80 g/cm². Only the curve shapes, not their relative positions, are significant. The points were obtained with a scintillation spectrometer. The solid curves were calculated from the thin target formula of Schiff (1951), and normalized to the experimental data.

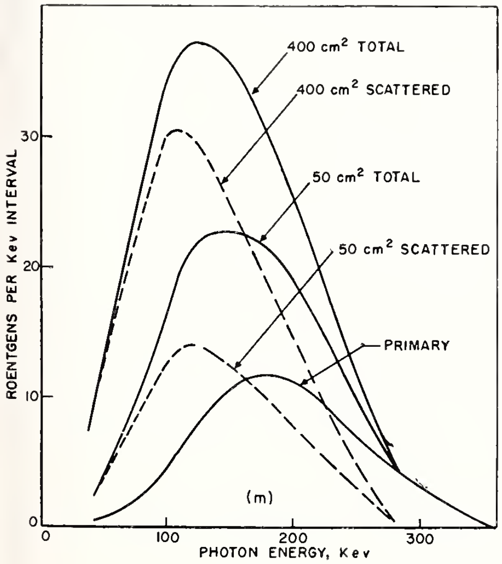


FIGURE 3m. *Spectral distribution of the exposure dose at a depth of 10 cm in a water phantom (Cormack, et. al.), X-rays generated at 400 kvp (HVL=3.8-mm Cu in absence of phantom).*

The dashed curves apply to the scattered radiation only for field areas of 50 cm² and 400 cm². The solid curves show the primary distribution and the total distribution combining both primary and secondary radiation. All curves are normalized to a primary surface exposure dose of 1000 r.

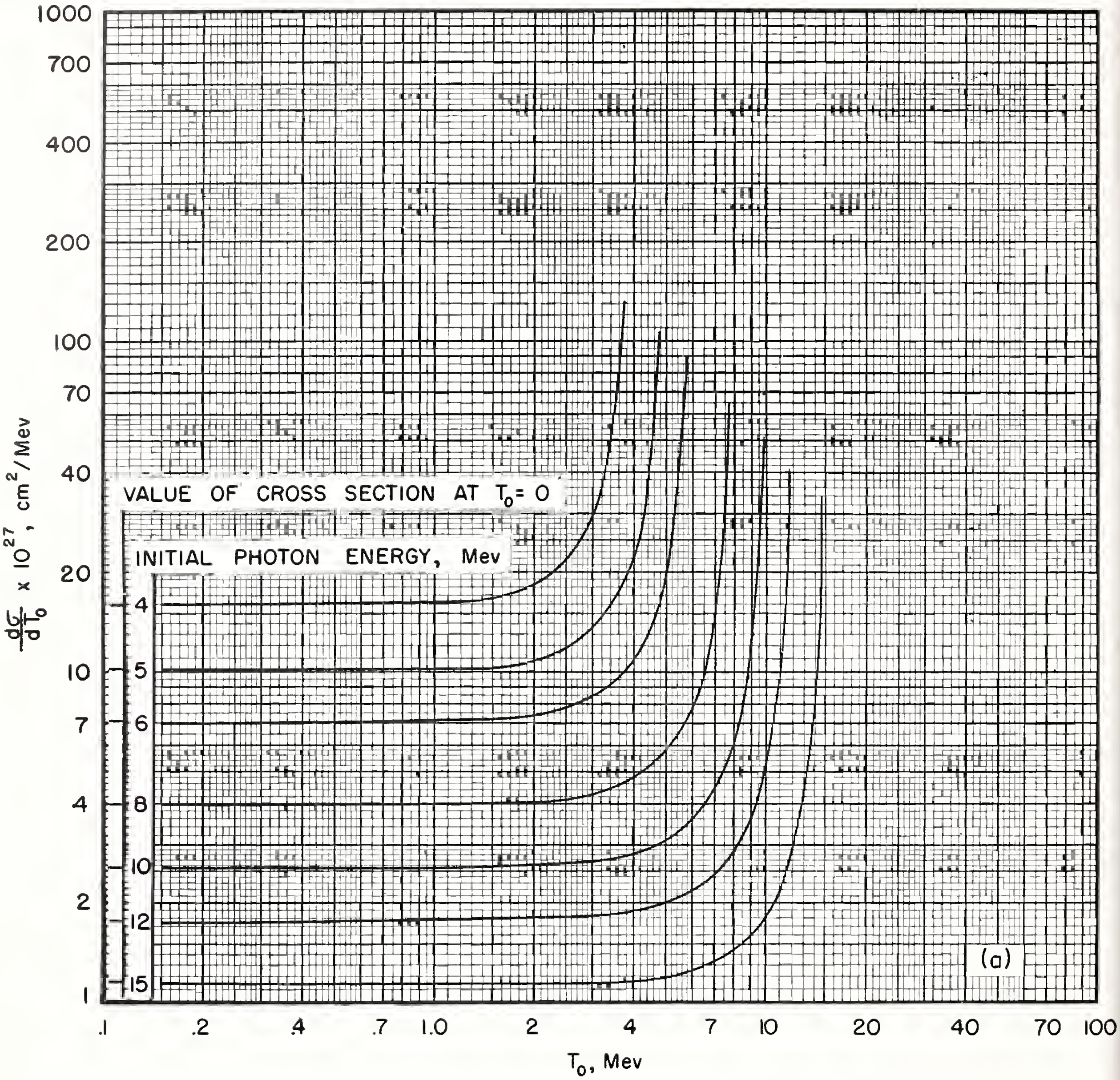


Figure 4a. *Starting-energy distribution for Compton-recoil electrons produced by photons with initial energies of 4 Mev to 15 Mev (Nelms, 1953).*

The ordinate is the absolute differential cross section for giving a free electron a recoil energy in the interval from T_0 to T_0+dT_0.

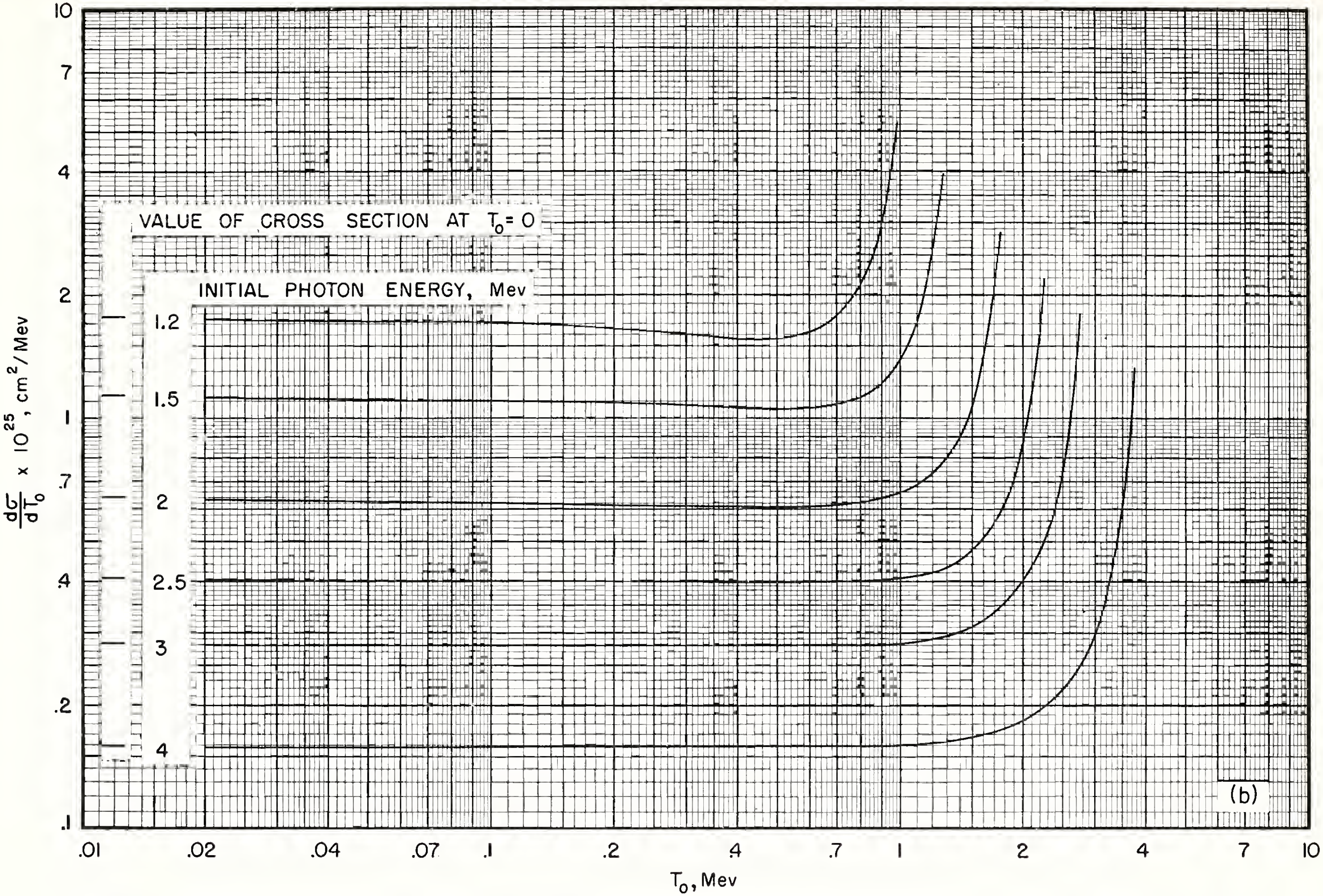


FIGURE 4b. *Starting-energy distributions for Compton-recoil electrons produced by photons with initial energies of 1.2 Mev to 4 Mev (Nelms, 1953).* The ordinate is the absolute differential cross section for giving a free electron a recoil energy in the interval from T_0 to T_0+dT_0.

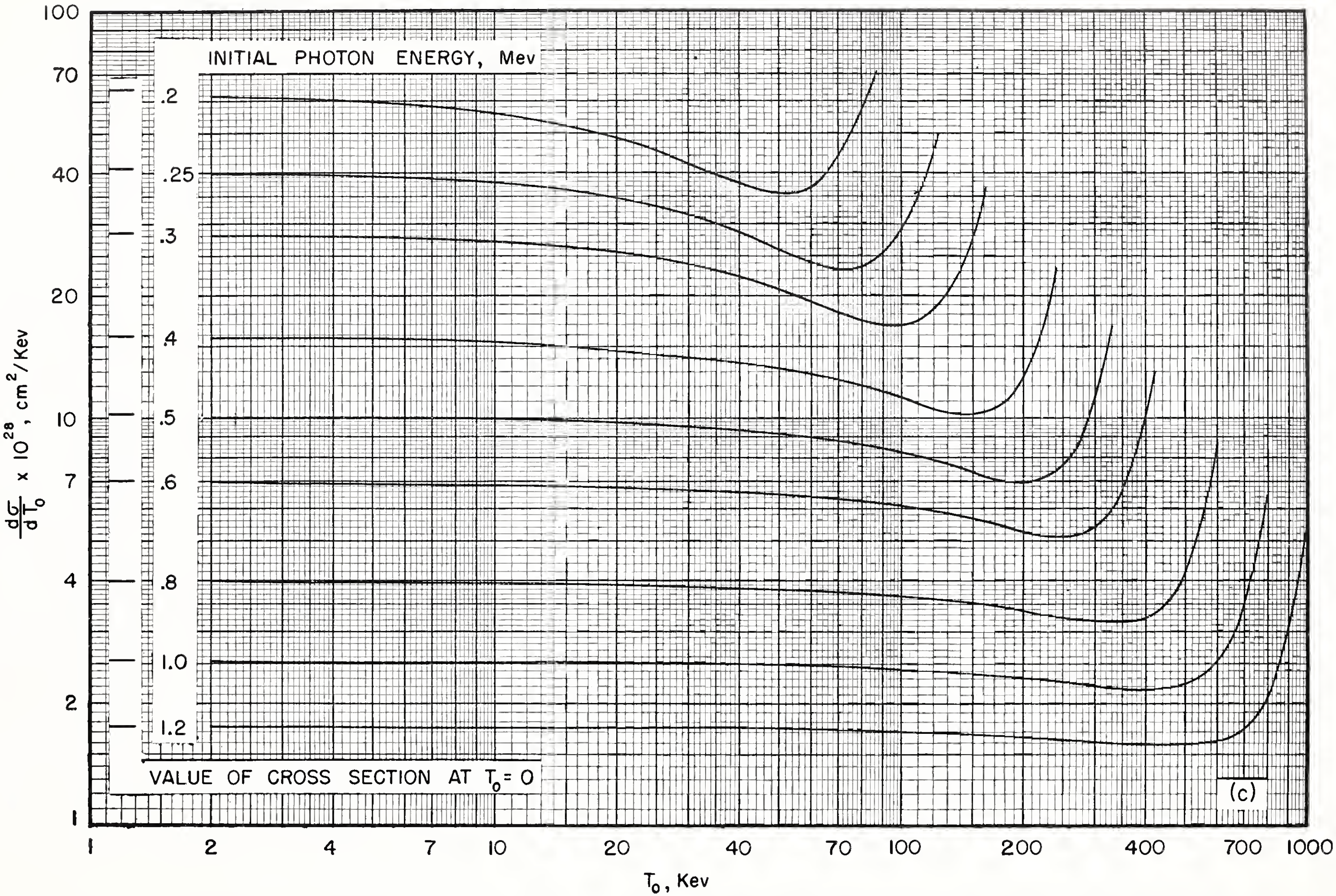


FIGURE 4c. *Starting-energy distributions for Compton-recoil electrons produced by photons with initial energies of 0.2 Mev to 1.2 Mev (Nelms, 1953).* The ordinate is the absolute differential cross section for giving a free electron a recoil energy in the interval from T_0 to T_0+dT_0.

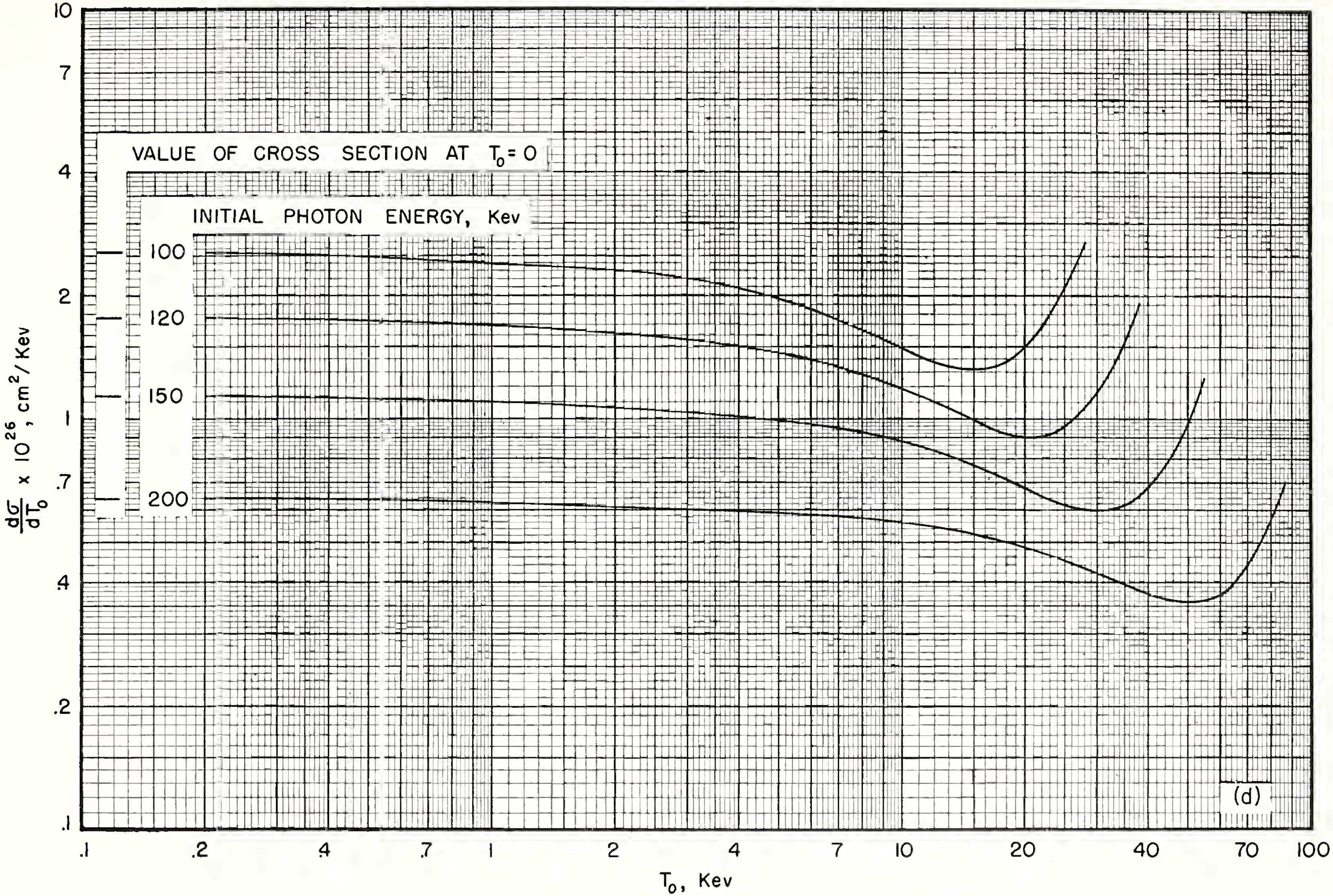


FIGURE 4d. *Starting-energy distributions for Compton-recoil electrons produced by photons with initial energies of 100 kev to 200 kev (Nelms, 1953).* The ordinate is the absolute differential cross section for giving free electron a recoil energy in the interval from T_0 to T_0+dT_0.

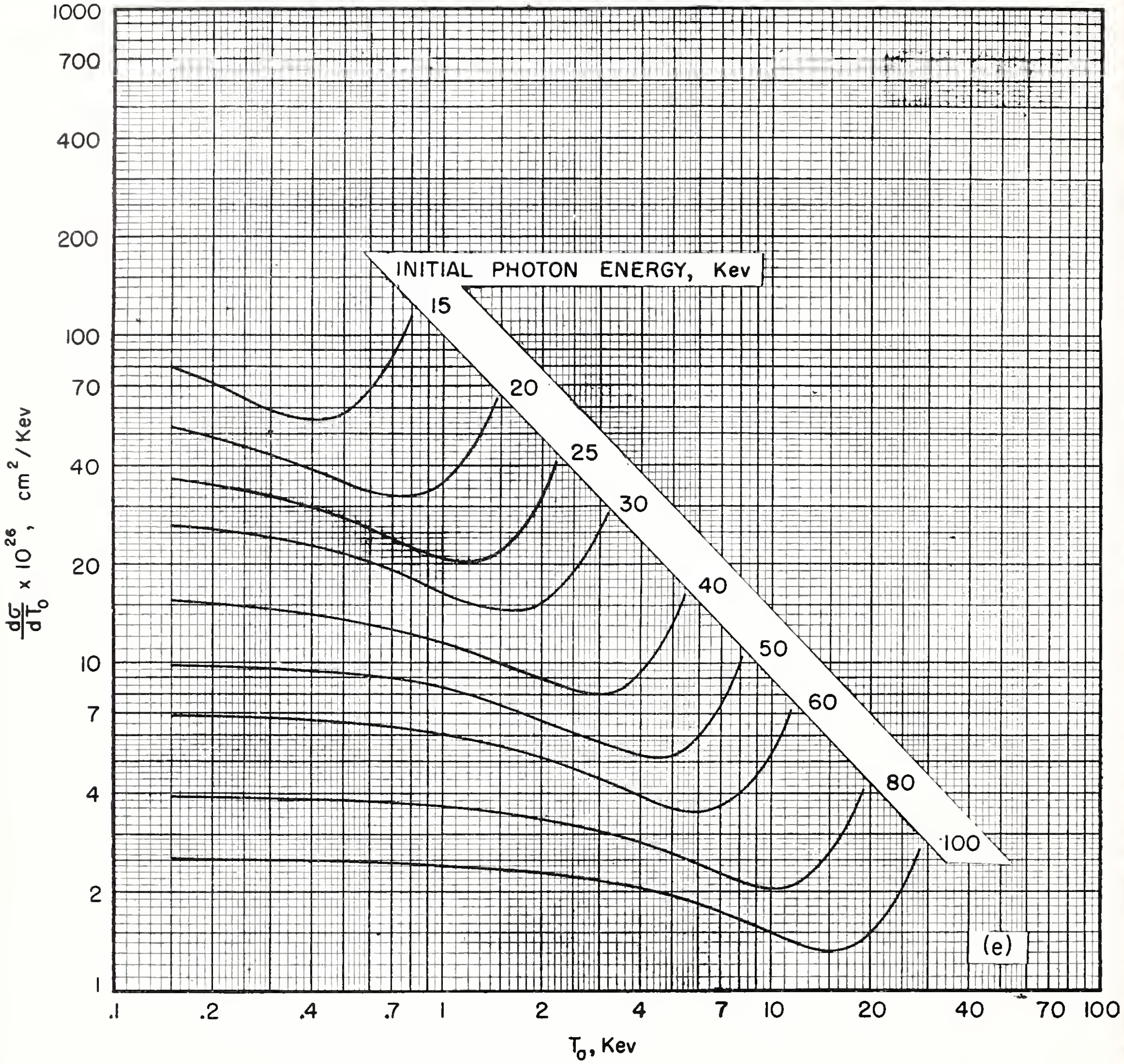


FIGURE 4e. *Starting-energy distributions for Compton-recoil electrons produced by photons with initial energies of 15 kev to 100 kev (Nelms, 1953).*

The ordinate is the absolute differential cross section for giving a free electron a recoil energy in the interval from T_0 to T_0+dT_0.

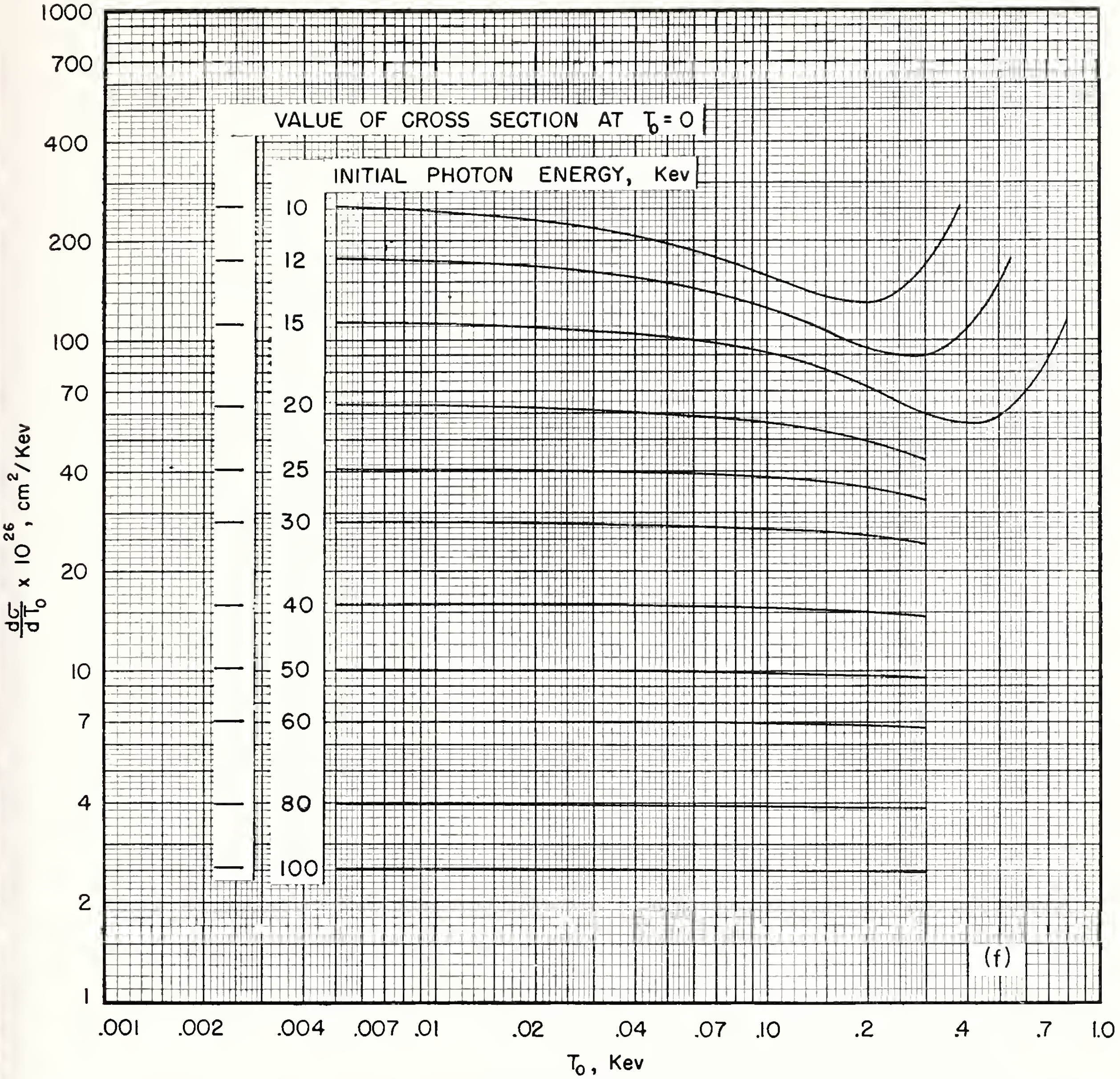


Figure 4f. *Starting-energy distributions for Compton-recoil electrons produced by photons with initial energies of 10 kev to 100 kev (Nelms, 1953).*

The ordinate is the absolute differential cross section for giving a free electron a recoil energy in the interval from T_0 to T_0+dT_0.

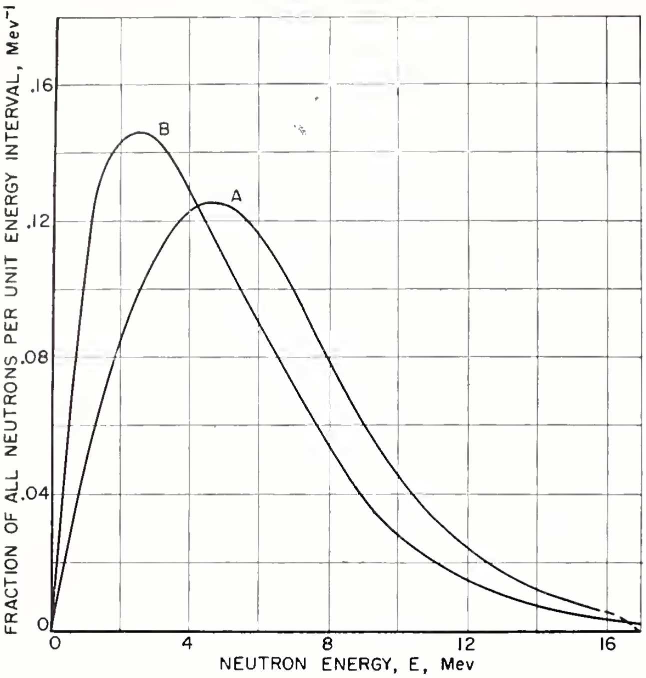


FIGURE 5. *Neutron energy spectra from the D–Be reaction 15-Mev deuterons incident on a thick target (Cohen and Falk, 1951).*

Curve A is for the forward neutrons and curve B for those emitted at 90° to the incident deuterons.

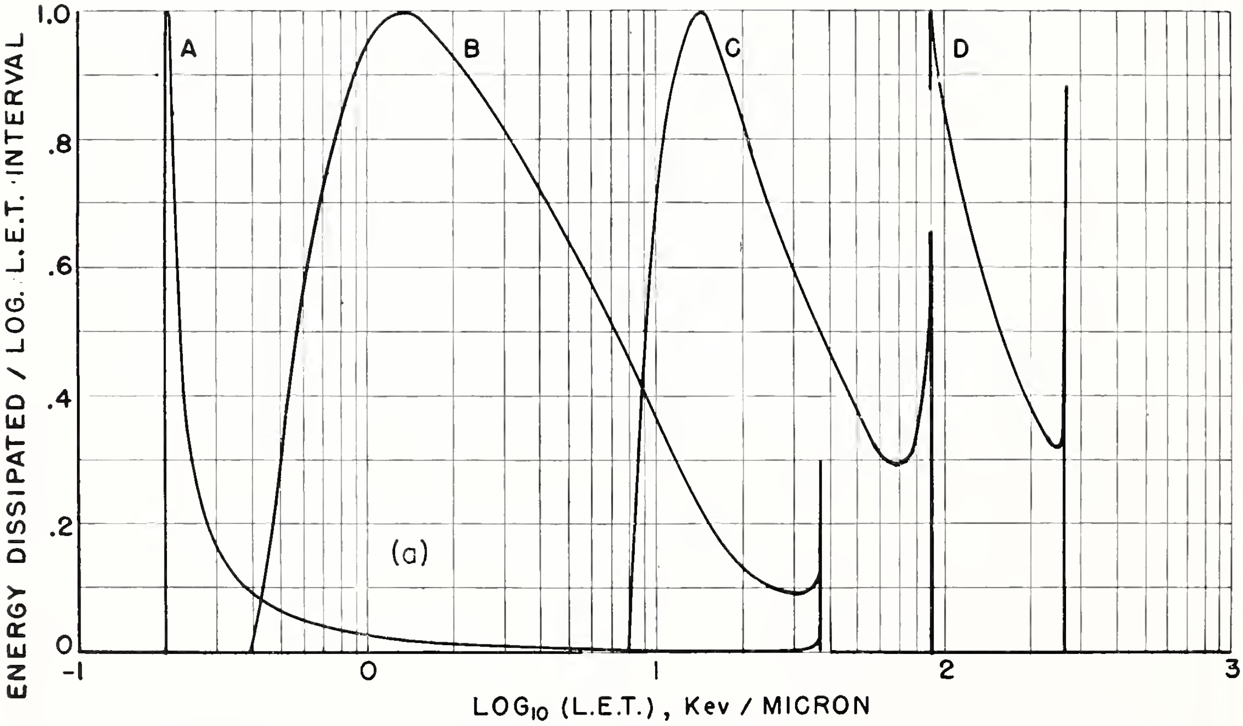


FIGURE 6a. *Linear energy transfer (LET) distribution of several ionizing radiations in water (Gray, 1955; Howard-Flanders, 1956).*

Energy transfers of all magnitudes (including δ-rays) have been attributed to the primary particle when calculating LET. The ordinate is proportional to the fraction of the total energy deposition per unit interval of $\log_{10}$ (LET). The proportionality factor is not the same for all radiations. Curve A is for Co^{60} γ-rays (Cormack and Johns, 1952); curve B for 200-kvp X-rays (referred to as radiation "b" by Cormack and Johns (1952)); curve C for 5-Mev neutrons (Boag, 1954); and curve D for 5.5-Mev α-rays (Gray, 1955; Howard-Flanders, 1956).

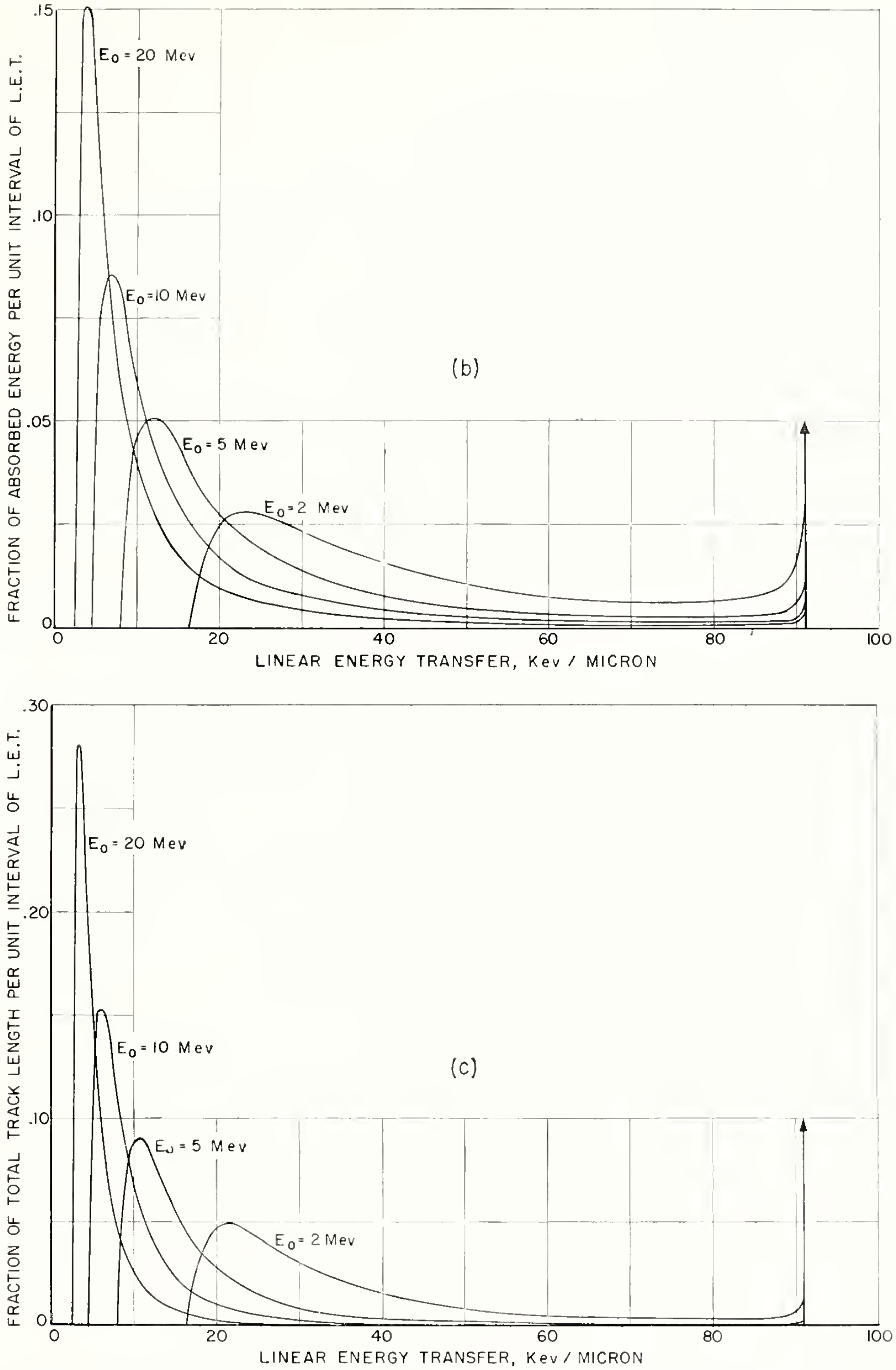


FIGURE 6b to c. *LET distribution for recoil protons produced in water by monoenergetic neutrons, when first collisions only are considered; i. e., when the irradiated object is thin compared with the mean free path of the neutrons in it.*

In figure 6b the ordinate gives the fraction of the total energy deposited per unit interval of LET and in figure 6c, the fraction of the total track length traversed per unit interval of LET. Additional LET distribution curves for mixed energy neutron beams and for total absorption of the neutrons in multiple collisions are given by Boag (1954).

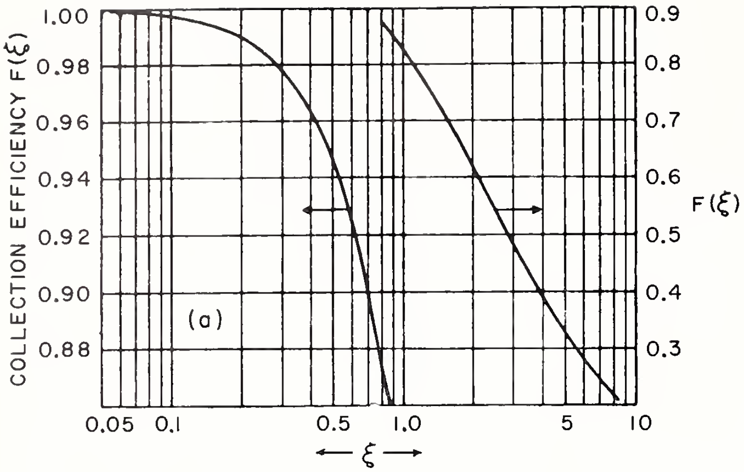


FIGURE 7a. *Collection efficiency in an ionization chamber exposed to continuous radiation.*

The curve is broken into two parts for greater accuracy in reading. The left-hand ordinate scale applies to the left-hand portion of the curve, and the right-hand ordinate scale to the remainder of the curve. (Boag, 1956)

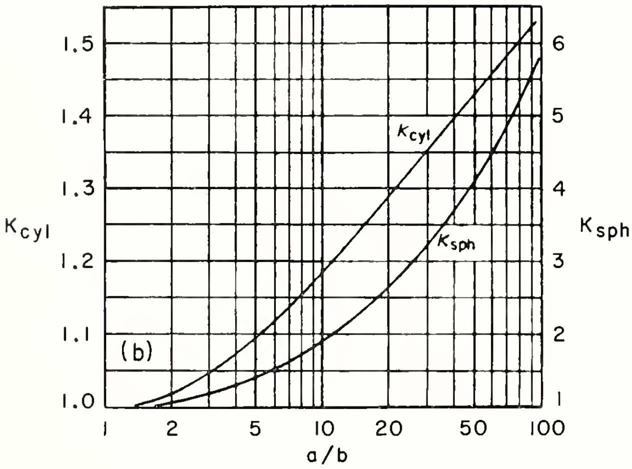


FIGURE 7b. *Factors for calculating the equivalent gap length in cylindrical and spherical ionization chambers.*

a and *b* are external and internal radii of the chamber, respectively. Equivalent gap length $=k_{cyl}(a-b)$ for cylindrical geometry. Equivalent gap length $=k_{sph}(a-b)$ for spherical geometry. (Boag, 1956).

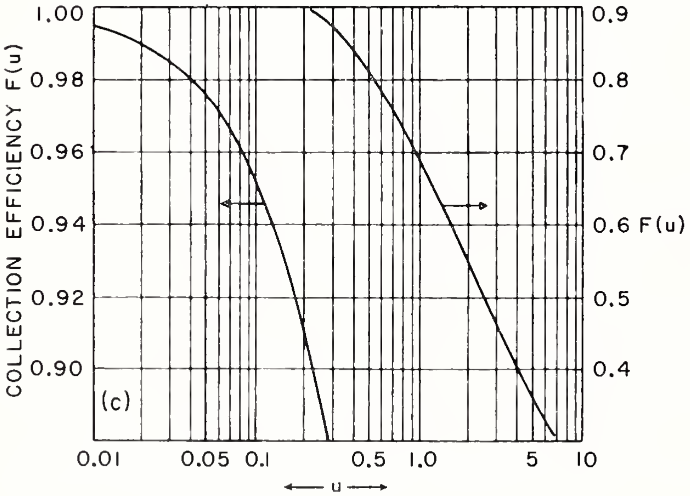


FIGURE 7c. *Collection efficiency of an ionization chamber exposed to pulsed radiation.*

The curve has been broken into two parts for accuracy in reading. Examples: For $u=0.2$, $F(u)=0.91$; for $u=2$, $F(u)=0.55$. (Boag, 1956).

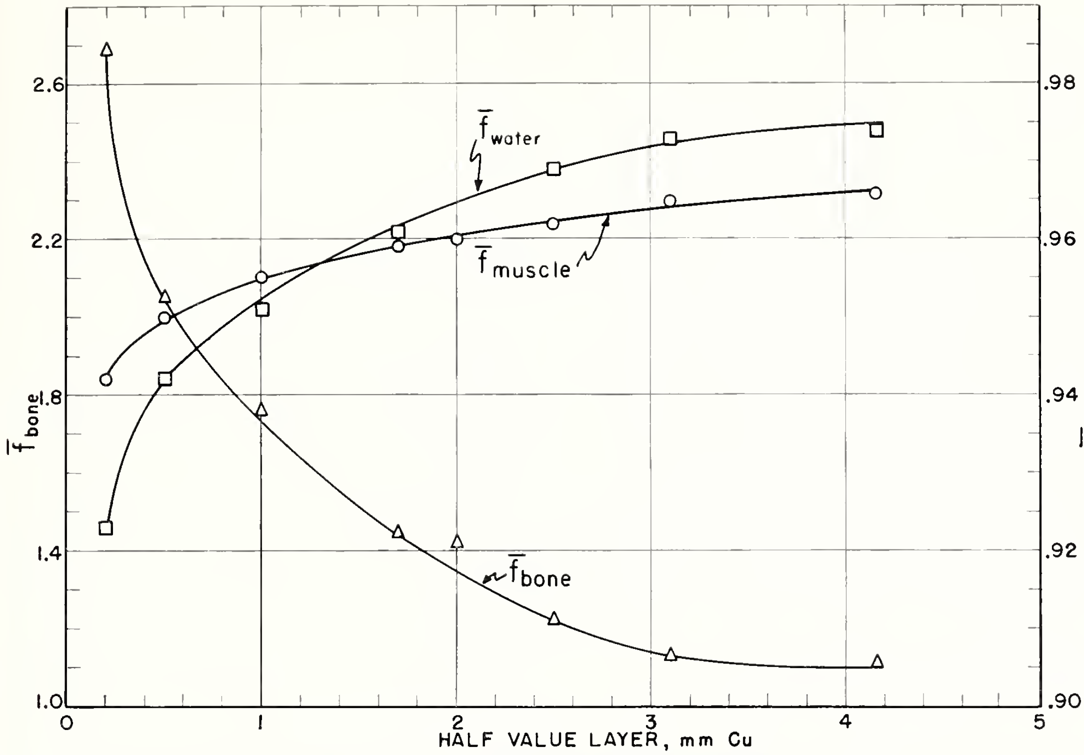


FIGURE 8. *Plot of the values of $\overline{f}$, the mean value of rad/r integrated over the primary X-ray spectrum, as given in table 2, as a function of the copper HVL.*

Tube potentials of 150 kv and higher are included in the figure. The 100-kv data given in table 2 do not fall upon the curve.

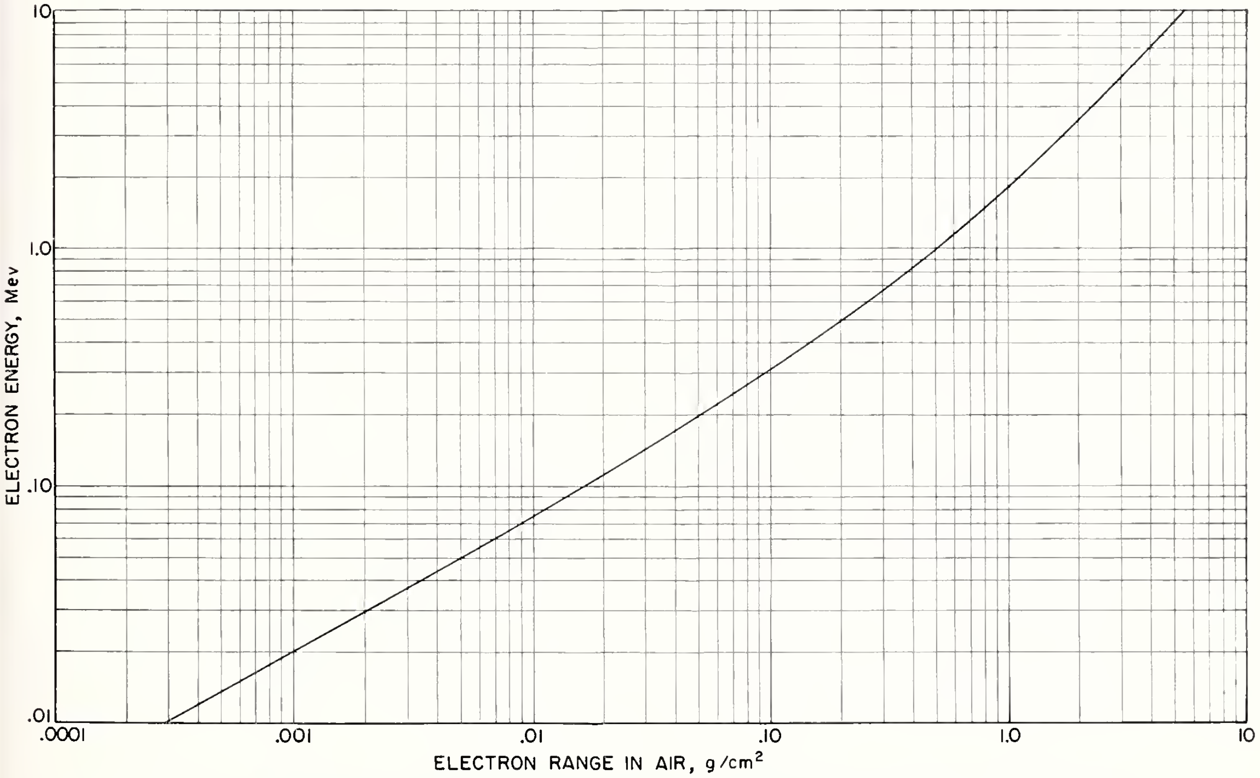


FIGURE 9. *Approximate range-versus-energy curve for electrons in air, calculated by Spencer (1954).*

6. Dosimetry Accuracy in X- and Gamma-ray Beam Therapy up to 3 Mev

6.1. *General considerations.*

The aim of much of the work of the ICRU is to improve the accuracy of knowledge of the absorbed dose in all places of interest in a patient or other object.

The units defined must be realized practically. For comparison of biological effects the absorbed dose should be known as accurately as possible and the limits of accuracy should be estimated. At present the thimble type of ionization chamber is considered the most practical instrument for measuring exposure dose rate.

The necessary steps are as follows:

A. Precise physical definition of units.

B. National standards of known accuracy.

C. Calibration of clinical dosimeters to a known accuracy over a known range of half-value layers.

D. Determination of exposure dose rate in air to a known accuracy under varying conditions.

E. Administration of known exposure dose of radiation at the place of interest.

F. Calculation of the absorbed dose in rads at the place of interest.

At each of these steps certain inaccuracies can occur which make difficult the correlation of the biological effects with absorbed dose. In addition, there are:

G. Estimations of the influence of volume treated and of the time factors in treatment on the biological effects.

H. Estimation of radiosensitivity of different biological materials.

Item A is the responsibility of the ICRU. B and C are the functions of the standardizing laboratories. D and E are measurements carried out in clinical departments and laboratories. F, the final process in arriving at the statement of absorbed dose in rads, is discussed in section 5 of this report. The elucidation of items G and H is the ultimate objective of biological and clinical work.

It would facilitate the correlation of biological effects with absorbed dose if the accuracy of all steps in the measurement were known and if a figure indicating limits of accuracy could be put on the final statement of absorbed dose. Such figures could be adduced for items B and C by the national standardizing laboratories or other authorized institutions. In hospitals or laboratories where a physicist is available, it should be possible to assess the accuracies of procedures D, E, and F. Statement of absorbed dose to a patient or a biological object in such terms that the limits of accuracy and probable error are known is not impossible. It would be both educative and in the interests of scientific progress if such statements could be made.

6.2. *Clinical dosimetry.*

An instrument should be available that fulfills specified conditions and carries instructions for its accurate employment.

The conditions of measurement should be so arranged as to make it possible to estimate the errors. The actual measurements with ionization chambers to be carried out in connection with clinical and laboratory work involve (a) measurements of exposure dose rate, (b) measurements of half-value layer, and (c) calculations of absorbed dose at the surface and at various depths. It is clear that much investigation is necessary before standard codes of practice for these procedures can be approved. The factors influencing these measurements should be reviewed, and before final recommendations are made by the ICRU, "standard" procedures should be tested at several qualified centers.

At many large centers throughout the world the sources of error of these measurements have been given full attention. On the other hand there are many centers where procedures are less precise than they could be in the light of present knowledge. It is possible that interim recommendations from appropriate sources of codes of practice for exposure-dose and HVL measurements would give direction where it is needed and improve the uniformity of the administration of radiation. It is expected that ICRU Committee II will do this.

Absorbed-dose calculations for patients based purely on phantom measurements may be grossly in error because of air spaces and bone. Effort should be devoted to estimating the absorbed dose at various points in different sized cadavers so that a series of correction factors related to body weight and dimensions could be produced and applied. Exit-radiation measurements are also of value in this connection.

An exposure dose of radiation should be given with great care. A suitable monitor of beam output is desirable and high standards of care, training, and experience in planning and administering the treatment are essential.

A method for the estimation of the absorbed dose is discussed in section 5 of this report.

Although development of direct measurements of absorbed dose is proceeding at various centers, there seems little likelihood of such measurements taking the place of ionization measurements for several years.

6.3. *Dose related to clinical effect of radiation.*

It has been found necessary in protection work (ICRP, 1954) to use a biological unit, the rem, which takes into account the variation in biological effectiveness of different types of radiation. In estimating the actual biological effect of irradiation, however, it fails to take into account the time element and other factors. Therefore this unit should not be used in the treatment of patients.

To improve the correlation of clinical and laboratory observations, it seems desirable to collect information on (1) the effects of dose, time, type, and energy of radiation, (2) the area or volume treated, and (3) the condition of the tissues treated, with the aim of obtaining uniform clinical effects on local tissues under varying conditions of treatment. These are all factors influencing the value of RBE.

It is expected that many of these items will be considered by the ICRU Committees during the interval before the next report.

IV. Reports of Subcommittees

7. Report of Subcommittee on X-ray Standards

7.1. *Standard free-air chamber design criteria.* Two reports on these criteria have been written:

(a) "Darstellung, Wahrung und Übertragung der Einheit der Dosis für Röntgen- und Gammastrahlen mit Quantenenergien zwischen 3 keV und 500 KeV", by B. Rajewsky et al., Max Planck Institut für Biophysik, Frankfurt a. M., and R. Jaeger et al., Physikalisch Technische Bundesanstalt, Braunschweig, 1955.

(b) "Design of Free-Air Ionization Chambers for X-rays of 50 to 500 kv" by H. O. Wyckoff and F. H. Attix, National Bureau of Standards, Washington, D. C., to be published.

The two reports are essentially in agreement, and contain the data necessary for designing adequate standard free-air chambers. A proposal to designate one preferred design for installation in all interested laboratories was rejected, as such a course might limit future investigations.

7.2. *Estimate of accuracy for an absolute determination in roentgens with the free-air chamber.*

A number of experimental factors are involved in the determination of exposure dose from a free-air chamber measurement. For each of these factors, one may ascribe an estimated maximum error beyond which it is not expected that the true value of the factor would lie (table 8). The data for these factors is given in the two references listed in section 7.1.

In the worst possible situation, the maximum error therefore is not likely to be greater than the sum of the estimated individual errors, namely 1.1 percent.

7.3. *Free-air chamber installations.*

A list of the standards laboratories that maintain free-air chambers, and the energy ranges covered by these chambers is given in appendix II.

7.4. *Recent intercomparisons of standard free-air chambers in the 50-* to *250-kv energy region, medium filtration.*

(a) National Bureau of Standards (NBS), Washington, D. C., U. S. A., and National Physical Laboratory (NPL), Teddington, Great Britain, at NBS, 1955. Here were compared the primary standard free-air chambers of the United States and the United Kingdom. The intercomparison has been described by G. H. Aston and F. H. Attix (1956).

After application of corrections for all known sources of error, the ratios are as given in table 9.

(b) National Bureau of Standards, Washington, D. C., U. S. A., and Institute of Radiophysics, Stockholm, Sweden, at NBS, 1956. The chamber provided by Dr. Thoraeus was a portable free-air chamber previously compared by him with the primary free-air chamber at Stockholm, with good agreement (Thoraeus, 1954). The work carried out at NBS has been analyzed and the same type of corrections applied as in the NPL–NBS intercomparison. The resulting ratios are also given in table 9. Detailed results have been described by R. Thoraeus and H. O. Wyckoff (1956).

7.5. *Estimate of the agreement to be expected in free-air chamber intercomparisons in the range of tube voltages from 50- to 250-kv constant potential.*

Such an intercomparison should include a separate intercomparison of charge-measuring systems to a precision of ±0.1 percent. The error in the ionized air volume remains ±0.3 percent in each chamber. The errors in correcting

TABLE 8. *Experimental maximum error for quality range of 50 to 500 kv (constant potential), and filtrations of 2-mm* Al *and 3-mm* Cu, *respectively*

Experimental factor	Estimated maximum error
Charge:	%
(assumed measured by accurate potentiometer and capacitor, using electrometer as a null-detector)	±0. 1
Air volume:	
(includes errors in diaphragm area, collecting plate alinement, and field distortion resulting from other causes)	±. 3
Air density:	
(includes pressure and temperature measurements)	±. 1
Humidity of the air:	
(includes measurement of the humidity and the effect of a slightly different value of the average energy per ion pair (W) for water vapor)	±. 1
Saturation of ion collection	±. 1
Scattering of X-rays by air in the chamber	±. 1
Inadequacy of plate separation for electron path length	±. 1
Air attenuation between diaphragm and collector	±. 2

Table 9. *Results of intercomparisons*

Radiation quality			Ratio of exposure dose rates	
Tube constant potential	Added filter	HVL	NPL/NBS	Swedish/NBS
kv	*mm*	*mm* Cu		
60	None	0. 077	1. 005	0. 995
75	None	0. 99	1. 005	. 992
100	1 Al	. 176	--------	. 995
110	0.097 Cu + 1.02 Al	. 34	1. 004	--------
150	0.228 Cu + 1.02 Al	. 60	1. 003	. 994
200	0.52 Cu + 1.02 Al	1. 23	1. 003	. 996
250	1.02 Cu + 1.02 Al	2. 14	1. 005	. 997
		Mean	1. 004	0. 995

for air density and humidity will nearly cancel out, as will the saturation losses if the gradients are equal in the two chambers. Errors in the corrections for scattering, air attenuation, and inadequacy of plate separation tend to cancel also, if the chambers are not too dissimilar in size.

Slight errors in alining the chamber diaphragms and variations in the X-ray tube output (or alternatively, errors in the monitor chamber measurements, if one is employed) could account for another 0.2 percent, taken together. Errors in timing the exposure doses can be reduced to a negligible amount by proper techniques.

Thus when two standard free-air chambers are compared under carefully controlled conditions, and all the known corrections applied, the exposure doses indicated by the two chambers should certainly agree within $(0.1\%+2\times0.3\%+0.2\%)$, or ±0.9 percent, taking the volume error twice because it may be in opposite directions in the two chambers.

If two standard chambers are intercompared through an intermediary free-air chamber, e. g., NPL-Sweden portable through NBS as intermediary, the 0.2 percent error due to alinement and tube output variations comes in twice, as does the 0.1 percent error for the intercomparison of charge measuring systems. Thus the corrected sensitivities of the two chambers might differ by as much as $2\times(0.1\%+0.3\%+0.2\%)=1.2$ percent without exceeding the maximum estimated error. The observed difference of 0.4 percent + 0.5 percent between NPL and the portable Swedish chamber therefore does not exceed the estimated maximum, based on known sources of error.

7.6 *Exposure dose standards in the energy region 0.5 to 3 Mev.*

The subcommittee decided against designating any particular type of instrument as a standard for measuring the exposure dose in roentgens at energies between 0.5 and 3 Mev. It is recognized that, in fact, the present procedure employed by many laboratories for exposure dose measurements in roentgens in this energy region makes use of cavity chambers, as for example with cobalt-60 gamma rays. This is done either directly, by using nearly air-equivalent cavity chambers of known volume with suitable stopping power corrections, or indirectly by calibrating a cavity chamber against a known radium source and making use of a value of the gamma-ray emission of radium to determine the sensitivity of the cavity chamber to gamma rays in this energy region.

Experience has shown that thimble chambers having plastic walls loaded with high atomic-number materials or having conducting coatings containing high atomic-number materials give a different sensitivity for cobalt-60 or other high-energy radiations than for conventional therapy X-rays. Therefore these chambers should not be used without a proper calibration.

Both free-air chamber and cavity chamber methods are being investigated to explore their relative merits. At present, the investigations are not sufficiently complete to draw final conclusions as to which should be designated the primary standard.

7.7. *Exposure dose standards in the 3- to 50-kv X-ray region.*

Additional design studies and subsequent intercomparisons in the 3- to 50-kv X-ray region are needed and should be encouraged in the various laboratories.

7.8. *Accuracy of instruments for clinical measurements of exposure dose.*

The required accuracy of clinical exposure dose meters is important. The manufacturers need guidance in the types and accuracies of instruments that should be developed. Any reasonable accuracy can be obtained but the higher the accuracy the greater the cost. At the same time, instruments requiring calibration at higher accuracies necessitate the development of more accurate standards, and consequently more costly calibrations. This problem will be studied in an endeavor to obtain the necessary information and to provide suitable accuracy recommendations.

7.9. *Facilities for future indirect intercomparisons of free-air chambers.*

Because of the great expense of time and effort necessary in carrying out a direct intercomparison between two free-air chambers, such intercomparisons are attempted only at infrequent intervals. It would be desirable, therefore, if a simpler, yet reasonably accurate method could be devised for more frequent intercomparisons. A properly designed secondary standard cavity chamber, sturdy enough to be easily transportable between laboratories, could probably fill this need.

The NBS has offered to design and build such a chamber, to have a volume of a few cubic centimeters and to have a response nearly independent of X-ray energy over the range 50 to 250 kv, medium filtration. This chamber would be of the guarded type, to avoid insulator leakage problems. It would be used in each laboratory with the same null-type charge measuring system as is employed with the standard free-air chamber, thus avoiding the error due to the shifts in electrometer sensitivity usually characteristic of secondary instruments.

NBS also proposes to construct an X-ray beam defining diaphragm and a charge-compensating capacitor (of about 1000 micromicrofarads) which would be calibrated and shipped to various national laboratories for comparison with their own corresponding equipment.

NBS plans to have this equipment available for circulation in 1957. It is believed that these steps will contribute to closer agreement in free-air chamber measurements of exposure dose in the various countries. They will be particularly advantageous to those laboratories that have not yet been able to arrange for direct intercomparisons.

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8. Report of Subcommittee on Standards of Radioactivity

8.1. It has been recognized that in the preparation and use of standards of artificially produced radioactive substances, countries fall into three groups:

Group I. Those countries having facilities for primary standardization and that are able and willing to supply primary or secondary standards to other countries.

Group II. Those countries having facilities for primary standardization.

Group III. Those countries that depend entirely on primary or secondary radioactivity standards from countries in group I.

The composition of groups I and II seems to be somewhat as follows:

Group I

United Kingdom	National Physical Laboratory, Teddington, Middlesex. Atomic Energy Research Establishment, Harwell, Berkshire.
United States	National Bureau of Standards, Washington, D. C.

Group II

Canada	Atomic Energy of Canada, Ltd., Chalk River. McGill University, Montreal, P. Q.
France	Commissariat à l'Energie Atomique, Chatillon.
Germany	Physikalisch-Technische Bundesanstalt, Braunschweig. Max-Planck Gesellschaft, Göttingen und Frankfurt a. M.
Japan	Electrotechnical Laboratory, Tokyo.
United Kingdom	National Physical Laboratory, Teddington, Middlesex. Atomic Energy Research Establishment, Harwell, Berkshire. Royal Marsden Hospital (formerly Royal Cancer Hospital), London. Medical Research Council, London.
United States	National Bureau of Standards, Washington, D. C. Oak Ridge National Laboratory, Oak Ridge, Tennessee.

8.2. It is recommended that one laboratory in any country should coordinate radioactivity standardization in that country. Where there is a recognized national laboratory this would generally be the focal spot for such coordination, but in the absence of any such laboratory this coordination should be carried out by a university laboratory or research institute.

8.3. Suitably designed beta and gamma ionization and counting equipment may eliminate the need for secondary standards where extreme accuracy is not required. A combined beta and gamma ionization chamber is at present under experimental development at the National Physical Laboratory (U. K.) and it is hoped that it will be possible to produce this chamber with appropriate calibrations for different beta- and gamma-emitting nuclides. The possession of such equipment would, it is suggested, reduce the demand for absolute standards and lead to a simplification of maintenance of standards of the short-lived nuclides. Similar combined ionization chambers are also being developed by the Commissariat à l'Energie Atomique (France) and the Max-Planck Institute (Germany). Ionization equipment (such as the above or the Chalk River, Canada, beta and gamma quartz-fibre electroscopes) and counting equipment can be used to maintain calibrations in terms of suitable reference sources such as Ra(D+E) for beta emitters, and radium in equilibrium with its products for gamma emitters. In the case of Ra(D+E) care must be taken to insure that the polonium-210 (Ra F) alpha particles do not enter the detector.

8.4. The accuracy to be aimed at for primary radioactivity standards should be 1 percent. An accuracy of 2 percent is probably at present obtainable in some cases. To attain this objective, frequent intercomparisons between standardizing laboratories are desirable.

The desirable accuracy for secondary standards is 3 percent, but for most medical purposes an accuracy of 5 percent is sufficient.

8.5. Consideration must be given to the effect on half-life values of isotopic impurity such as the presence of phosphorus-33 in phosphorus-32.

8.6. It may be desirable to consider a recommendation for the construction of uniform cobalt-60, tantalum-182, and gold-198 sources in the form of wires of definite diameter for standardization purposes in the millicurie range. In this event, the National Physical Laboratory (U. K.) and National Bureau of Standards (U. S.) would be the institutes to put forward proposals.

8.7. It is recommended that commercial suppliers of radioactive substances should control the amounts supplied within their specified limits of accuracy, but it is recognized that responsibility for the application of such materials will remain with the user.

8.8. Radioactivity standards available from the United States and United Kingdom are listed in appendix III.

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Appendixes

Appendix I. Treatment Summary Form

Dates of Treatment: from ________ to ________

Region under treatment ____________________

I. PREVIOUS TREATMENT

1. To this region ☐ To other region ☐
2. Beam therapy ☐ Radioactive substance ☐
3. Dates of treatment: from ____________ to ____________
4. Type of treatment ____________________
5. Absorbed dose (rad):
   - a. Lesion ________________
   - b. Skin ________________
   - c. Bone ________________
6. Number of sessions ________________
7. Volume treated ________________

II. PRESENT TREATMENT - BEAM THERAPY

1. Beam specification
   - a. Pulsed ☐ Continuous ☐
   - b. Filter: Inherent ________ Added ________
   - c. HVL ________
   - d. Peak energy (kev) ________

2. Type of treatment
   - a. Conventional ☐
   - b. Grid ☐
     - (1) Aperture diameter (cm) ________
     - (2) Proportion protected ________
   - c. Wedge ☐

   For a, b, and c:

	Fields	1	2	3	4	5	6	7	8
(1)	Region								
(2)	Area								
(3)	Source-surface distance								
(4)	Interval								
(5)	Abs. dose per treatment (rad)								
(6)	No. of treatments								
(7)	Total time								
(8)	Tissue thickness								

   - d. Moving beam ☐
   - e. Paraxial ☐
   - f. Circumaxial ☐

   For d, e, and f:

   - (1) Patient erect ☐ Patient lying ☐
   - (2) Depth of lesion (cm) ________
   - (3) Number of sessions ________
   - (4) Interval between sessions ________
   - (5) Total treatment time (min) ________
   - (6) Distance, source to focus (cm) ________
   - (7) Distance, skin to focus (cm) ________
   - (8) Arc (°) ________

3. Absorbed dose
   - a. Volume treated ________
   - b. Total time ________
   - c. Absorbed dose (rad) to:
     - (1) Lesion: Max. ________ Av. ________ Min. ________
     - (2) Other tissues (maximum):
       Skin ________ Bone ________ Other ________

III. PRESENT TREATMENT - LOCAL RADIOACTIVE SUBSTANCE

1. Radiation source
   - a. Nuclide ____________
   - b. Specific gamma-ray emission: ____________ r/mch at 1 m
   - c. Form (chemical composition) ____________
   - d. Half life ____________
2. Type of treatment
   - a. Surface ☐
     - (1) Distance, source to skin (cm) ____________
     - (2) Shape ____________
     - (3) Area (cm^2) ____________
   - b. Intracavitary ☐
     - Filter around source: Material ____________
     - Thickness (mm) ____________
   - c. Interstitial ☐
     - (1) Area treated (cm^2) ____________
       or
       Volume treated (cm^3) ____________
     - (2) Sources:
       Type ____________ Number ____________ Strength (mc) ____________
3. Absorbed dose - time calculations
   - a. Total mc ____________
   - b. Number of applications ____________
   - c. Interval between sessions ____________
   - d. Treatment time (hr) ____________
   - e. Total time (b • d) (hr) ____________
   - f. Total millicurie hours (a • e) ____________
   - g. For intracavitary and surface applications combined:
     - (1) Surface absorbed dose (rad) ____________
     - (2) Minimum absorbed dose to lesion (rad) ____________
   - h. For interstitial application:
     - (1) Maximum absorbed dose in volume treated (rad) ____________
     - (2) Average absorbed dose in volume treated (rad) ____________
     - (3) Minimum absorbed dose in volume treated (rad) ____________

IV. PRESENT TREATMENT - SYSTEMIC RADIOISOTOPES

1. Radiation source

a. Isotope ____________________

b. Chemical composition ________________________________

c. Carrier ____________________

d. Buffer ____________________

e. pH ____________________

f. Half life ____________________

g. Radiation emitted

(1) Type: α ☐ β ☐ γ ☐

(2) Amount (Mev) ____________________

2. Treatment

a. Method of administration ______________________________

b. Distribution pattern in body

	Proportion	Effective half life
(1) Whole body	__________	__________
(2) Liver	__________	__________
(3) Gonads	__________	__________
(4) Bone	__________	__________
(5) Thyroid	__________	__________
(6) Other (state) ________________	__________	__________
(7) Excreted	__________	__________

3. Absorbed dose (rad) in 3 half lives to:

a. Average whole body	__________
b. Liver	__________
c. Gonads	__________
d. Bone	__________
e. Thyroid	__________
f. Other (state) ______________	__________

Appendix II. Survey of Primary X-ray Standards

Standard No.	Country	Institute and custodian	Radiation range *kv*	Type	Compared with standard	Literature reference
1a	Australia	Commonwealth X-ray and Radium Lab., Melbourne (Mr. Stevens).	10 to 50	Free air, parallel plate (in construction).	---	---
1b	do	do	50 to 250	Free air, parallel plate (measuring system modified since publication).	---	14
2a	Canada	National Research Council, Ottawa (C. Garrett).	50 to 250	Free air, parallel plate	---	---
2b	do	do	50 to 250	Free air, parallel plate (in construction).	---	---
2c	do	do	10 to 50	do	---	---
3a	Deutsche Bundes-Republik.	Physikalisch-Technische Bundesanstalt, Braunschweig (R. Jaeger).	50 to 400	Free air, cylindrical	4a, 10a	37, 54
3b	do	do	3 to 120	Free air, parallel plate	---	37, 54
4a	do	Max Planck Institute, Frankfurt (B. Rajewsky).	30 to 400	Free air, cylindrical	3a, 13a	37, 54
4b	do	do	3 to 60	Free air, parallel plate	11, 13b	6
4c	do	do	3 to 10	Total absorption "Wilhelmy chamber."	---	5
5	France	École Normale Supérieure, Paris (A. Allisy).	50 to 200	Parallel plate	---	---
6	do	Laboratoire Central des Industries Electriques, Paris (M. Demanche).	50 to 200	---	---	---
7a	Great Britain	National Physical Lab., Teddington (G. H. Aston).	30 to 100	Free air, parallel plate	10a, 13a, 14a	45, 59
7b	do	do	100 to 300	do	14a	43, 1
8	Italy	Istituto Superiore di Sanita, Roma (G. C. Trabacchi).	50 to 250	do	---	56
9a	Japan	Electrotechnical Lab., Tokyo (G. Ito).	40 to 250	do	---	29
9b	do	do	5 to 40	Free air, guard wire	---	---
10a	Netherlands	Radio Therapeutic Inst , Rotterdam (A. Somerwil).	50 to 200	Free air, cylindrical	3a, 7a, 7b	45
10b	do	do	10 to 50	Free air, nylon mesh	11	44, 35
11	do	Philips Research Lab., Eindhoven (W. J. Oosterkamp).	10 to 50	Free air, parallel plate	4b, 10b	54, 35, 36
12	New Zealand	Dominion X-ray and Radium Lab., Christchurch (G. E. Roth).	50 to 300	do	---	---
13a	Sweden	Inst. of Radiophysics, Stockholm (R. Thoraeus).	50 to 250	Free air, cylindrical	4a, 7a, 14a	54, 53, 51, 52, 55
13b	do	do	8 to 50	do	4b	54, 53, 51
14a	United States	National Bureau of Standards, Washington (H. O. Wyckoff).	60 to 250	Free air, parallel plate	7a, 7b, 13a	59, 1, 55
14b	do	do	5 to 50	do	---	50
14c	do	do	---	10 atm. parallel plate (under investigation).	---	---

Appendix III. Radioactivity Standards Available From the United States and the United Kingdom

a. National Bureau of Standards (United States).

Alpha, beta, gamma standards

Sample No.	Radiation	Nuclide	Nominal activity [a]	Volume
4900	α	Polonium-210 [b]	200 dps	(c)
4901	α	Polonium-210 [b]	500 dps	(c)
4902	α	Polonium-210 [b]	1000 dps	(c)
4903	α	U_3O_8 [d]	15 dps	(e)
4910	β (α)	Ra(D+E) [f]	200 dps	(c)
4911	β (α)	Ra(D+E) [f]	500 dps	(c)
4912	β (α)	Ra(D+E) [f]	1000 dps	(c)
4913	β (γ)	Cobalt-60	10^4 dps/ml [g]	~3.0 ml [i]
4914	γ (β)	Cobalt-60	10^5 dps	5.0 ml
4915	γ (β)	Cobalt-60	10^6 dps [h]	5.0 ml
4916	β	Phosphorus 32 [j]	10^5 dps/ml [g]	~3.0 ml [i]
4917	β (γ)	Iodine-131 [j]	10^5 dps/ml [g]	~3.0 ml [i]
4918	β (γ)	Gold-198 [j]	10^5 dps/ml [g]	~3.0 ml [i]
4919	β	Strontium-90 Yttrium-90	10^4 dps/ml [g]	~3.0 ml [i]
4920	β	Thallium-204	10^4 dps/ml [g]	~3.0 ml [i]
4921	β (γ)	Sodium-22	10^4 dps/ml [g]	~3.0 ml [i]
4922	γ (β)	Sodium-22	10^6 dps [h]	5.0 ml
4923	β (γ)	Sodium-24 [j]	10^5 dps/ml [g]	~3.0 ml [i]
4924	β	Carbon-14	10^3 dps/ml [g]	25.0 ml
4925 [m]	β	Carbon-14 [k]	10^4 dps/g	----------
4926	β	Hydrogen-3	10^4 dps/ml [h]	25.0 ml
4927	β	Hydrogen-3	10^6 dps/ml [h]	~3.0 ml [i]
4928 [m]	β	Sulphur-35	10^4 dps/ml [g]	~3.0 ml [i]
4929 [m]	K	Iron-55	10^5 dps/ml [h]	~3.0 ml [i]
4930 [m]	K (γ)	Zinc-65	10^5 dps/ml [h]	~3.0 ml [i]
4931 [m]	γ (β)	Cesium-137	10^6 dps/ml [h]	5.0 ml
4932 [m]	γ (β)	Mercury-203	10^6 dps/ml [h]	5.0 ml

[a] The disintegration rate as of the reference date is given on a certificate accompanying the standard.

[b] Samples consist of polonium-210, deposited on a silver disk 1 in. in diameter, 1/16 in. thick and faced with 0.002 in. of palladium.

[c] Deposited source.

[d] Samples consist of U_3O_8 deposited on a 0.1-mm platinum foil and mounted on an aluminum disk, 1¼ in. in diameter and 1/32 in. thick. The alpha-ray disintegration rate as of the date of calibration is indicated on the certificate accompanying the standard.

[e] Evaporated source.

[f] Standards consist of Pb-210-Bi-210 in equilibrium, deposited on the 0.002-in.-thick palladium face of a silver-palladium disk.

[g] Total activity has been adjusted so that AEC authorization is not required for one standard.

[h] AEC authorization is required.

[i] Approximately 3 ml of low-solids carrier solution containing the active nuclide in a flame-sealed ampoule.

[j] Distributed periodically at announced intervals.

[k] Benzoic acid for use in liquid scintillation counters.

[m] In preparation.

Radium standards (for radon analysis) [a]

Sample No.	Radium content	Volume
	g	*ml*
4950	10^{-9}	100
4951	10^{-11}	100
4952	Blank solution	------

[a] Samples are sealed in glass containers.

Radium gamma-ray standards [a]

Sample No.	Radium content	Volume
	g	*ml*
4955	0.1×10^{-6}	5
4956	.2	5
4957	.5	5
4958	1.0	5
4959	2.0	5
4960	5.0	5
4961	10	5
4962	20	5
4963	50	5
4964	100	5

[a] Samples are contained in flame-sealed glass ampoules.

Rock and ore standards, radium rock samples [a]

Sample No.	Rock	Average radium content (gram of radium per gram of rock)
4975	Dunite	$(0.009 \pm 0.004) \times 10^{-12}$
4976	Carthage limestone	.15 ± .03
4977	Berea sandstone	.24 ± .02
4978	Columbia River basalt	.33 ± .03
4979	Chelmsford granite	2.96 ± .08
4980	Quartzite	0.06 ± .01
4981	Graniteville granite	3.3 ± .2
4982	Babbro-diorite	0.18 ± .02
4983	Milford granite	.23 ± .02
4984	Triassic diabase	.18 ± .03
4985	Deccan trap	.21 ± .04
4986	Kimberlite	.59 ± .04

[a] Each sample consists of 100 g of pulverized rock taken from bulk material analyzed for radium content. Petrographic data and approximate chemical analysis of a representative sample of each rock are also given in a certificate accompanying each sample.

b. Atomic Energy Research Establishment (United Kingdom).

The Atomic Energy Research Establishment, Harwell, provides a standardization service for a wide range of radioactive nuclides. Particulars of this service may be obtained from the Isotope Division, Atomic Energy Research Establishment, Harwell, Didcot, Berkshire, England.

c. National Physical Laboratory (United Kingdom).

Radioactivity standards

Nuclide	Radiation	Half-life	Radioactive concentration	Mass of solution	Particulars of solution	Months when issued[a]
Sodium-24	$\beta(\gamma)$	15.0 h	2.5 μc/g	*g* 4	Na_2CO_3 in H_2O	March, September.
Phosphorus-32	β	14.3 d	25 μc/g	4	NaH_2PO_4 in H_2O (0.1 g/liter) 0.1% Formalin.	June, December.
			1 mc/g	1		
Iodine-131	$\beta(\gamma)$	8.04 d	25 μc/g	4	KI in H_2O (50 mg/liter), also containing $Na_2S_2O_3$ (50 mg/liter) and 0.1% Formalin.	April, October.
			1 mc/g	1		
Gold-198	$\beta(\gamma)$	2.70 d	25 μc/g	4	$HAuCl_4$ in H_2O, stabilized with 10%-KCN solution.	May, November.

[a] Applications for standards should be made to the Director, National Physical Laboratory, Teddington, Middlesex, England, early in the month preceding that in which the standards are scheduled to be issued.

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