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Protection Against Ionizing Radiation from External Sources Used in Medicine

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ICRP PUBLICATION 33

Protection Against Ionizing Radiation from External Sources Used in Medicine

A report of Committee 3 of the
International Commission on Radiological Protection

ADOPTED BY THE COMMISSION IN MARCH 1981

This report supersedes the medical sections of ICRP Publication 15/21

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PREFACE

At its meeting in Stockholm in 1978 the International Commission on Radiological Protection established a task group to revise *ICRP Publication 15/21* in conformity with the 1977 Recommendation of the Commission, and to provide recommendations covering all fields in which external sources of ionizing radiation are used in medicine.

The membership of the task group was as follows:

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D. K. Bewley
J. H. E. Carmichael
J. Jankowski
C. Lagergren
P. A. J. Pellerin
J. Villforth

The Commission and Committee 3 are particularly grateful to L.-E. Larsson and J. H. E. Carmichael for undertaking the preparation and revision of the draft versions of the report.

Membership of Committee 3 1977–1981

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INTRODUCTION

(1) In 1977 the Commission issued new recommendations on radiation protection (*ICRP Publication 26*). The report now being introduced has been prepared in the light of those recommendations and replaces *ICRP Publications 15* and *21*.

(2) To fulfil the Commission's responsibilities in medical radiology, for the protection of staff, patients and the public, this publication gives recommendations and guidance for competent authorities regarding the safe use of ionizing radiation from external sources used in medicine. Guidance for individual practitioners will be given in the forthcoming ICRP publication Protection of the Patient in X-ray Diagnosis. The use of unsealed radionuclides is covered in *ICRP Publication 25*.

(3) *ICRP Publication 26* introduced new quantities and units in the field of radiation protection and the rationale of those that are applicable to this publication is discussed in a separate section.

(4) The recommendations in this report are based on the system of dose limitation laid down by the Commission. It should be the responsibility of international and national regulatory bodies to encourage the setting of standards and specifications to implement these recommendations. In particular, the design of apparatus should be governed by the principle of optimization.

(5) For details of the Commission's system of dose limitation, the reader is referred to *ICRP Publication 26*, and to the subsequent statements issued by the Commission.

(6) This report emphasizes protection relative to the technical aspects of the sources themselves. In addition, appropriate training of staff, optimization of working practices and administrative requirements are discussed as essential factors in radiation protection.

(7) In the recommendations given in this report, the words *shall* and *should* have the following meaning:

Shall—Necessary or essential for protection against radiation;

Should—to apply, whenever reasonable, in the interests of improving radiation protection.

(8) The Commission is aware that compliance with some of the new recommendations may entail structural changes in existing installations, and/or changes in operative procedures. It is desirable that such changes be made as soon as practicable, but not in such a way as to deprive patients of necessary medical attention.

A. QUANTITIES AND UNITS

(9) This section gives a brief review of the basic quantities used in radiation protection and the units in which these quantities are expressed. The purpose is to provide sufficient information for an adequate understanding of this report without reference to other material. Emphasis is given to quantities that are of prime importance in radiation protection. Readers who wish to pursue the subject in greater depth are referred to more detailed ICRP and ICRU reports.

(10) In radiation protection, the quantities and concepts of primary interest are the *absorbed dose, D*, and quantities and concepts related to various expressions of *dose equivalent, H*. The dosimetric quantities of prime importance may be derived from the absorbed dose as the following sequence indicates:

Absorbed dose (D)
Dose equivalent at a point in tissue (H)
Mean organ dose equivalent (H_T)
Effective dose equivalent (H_E)

In the ICRP system of dose limitation, it is the mean dose equivalent in the various body organs and tissues and the effective dose equivalent that are subject to assessments and limitation. The emphasis in this introductory material is therefore on these two quantities.

(11) The *absorbed dose*, D, is the energy imparted by ionizing radiation per unit mass of the irradiated material. The SI unit for absorbed dose is *joule per kilogram* J (J kg^{-1}) and its special name is *gray* (Gy). The previous special unit of absorbed dose was 1 rad = 0.01 J kg^{-1}. If the energy imparted is determined in a small mass, random fluctuations of energy deposition can play a role. The rigorous definition of absorbed dose (*ICRU Report 33*) is therefore given in terms of a statistical expectation value. The important role of the statistical fluctuations of energy deposition in cellular or subcellular structures has led to the introduction of microdosimetric quantities; these are not considered in the present report.

(12) Equal absorbed doses of radiations of different qualities may produce effects which differ in severity or differ in the probability of the occurrence of effect. The Commission has attempted to account for this inequality by introducing the *dose equivalent*, H, which is the absorbed dose modified by weighting factors. The dose equivalent at a point in tissue is given by the equation:

$$H = DQN$$

where D is the dose absorbed dose at the point and Q is the *quality factor* (see para. 13). N is a modifying factor that is presently assigned the value unity by the Commission, but is inserted in order to permit the possible future introduction of other modifying factors which might be needed to account for the influence of, for example, absorbed dose rate or dose fractionation. Since the weighting factors Q and N are dimensionless, the SI unit of dose equivalent is the same as the unit of absorbed dose, i.e. *joule per kilogram*, but to avoid confusion with absorbed dose it is given the special name *sievert* (Sv). The previous special unit was 1 rem = 0.01 J kg^{-1}.

(13) The *quality factor*, Q, is intended to allow for the difference in effectiveness of different types of ionizing radiation in producing deleterious effects. This effectiveness is linked to the differing microscopic or submicroscopic distribution of absorbed energy and Q is therefore defined as a function of the *collision stopping power* (L_∞) in water at the point of interest. Table A

Table A. $L_\infty - Q$ relationship

L_∞ in water (keV μ^{-1})	Q
3.5 (and less)	1
7	2
23	5
53	10
175 (and above)	20

lists the values of Q specified by the Commission for various values of L_∞. Interpolated values of Q as a function of L can be obtained from Fig. A.

(14) In the usual case where D is delivered by particles having a range of values of L_∞, an effective value $\bar{Q}$ of Q at the point of interest can be calculated (see *ICRU Report 33*). When the

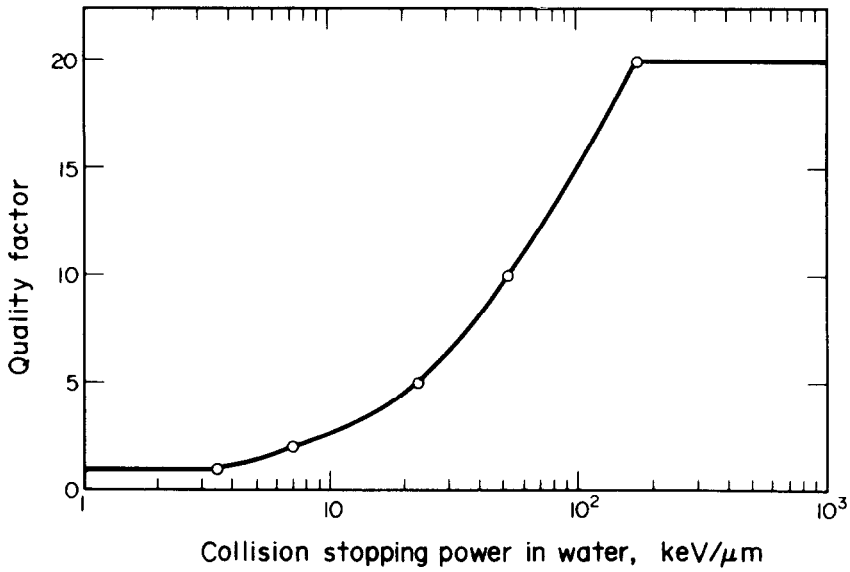

Fig. A. Quality factor as a function of collision stopping power in water.

distribution of L_∞ is not known at the point of interest, it is permissible to use approximate values for $\bar{Q}$, related to the type of radiation. Approximate values of $\bar{Q}$ recommended by the Commission for this purpose, both for external and internal exposures, are listed in Table B.

(15) The quality factors are chosen to represent the effectiveness of different types of ionizing radiation in producing harmful effects at low doses. It is therefore important that dose equivalent should not be used to assess the likely consequence of severe accidental exposures in man. For that purpose, absorbed dose is the appropriate quantity after weighting for the *relative biological effectiveness* (RBE) of each type of radiation for the effects at the high doses, if information is available.

(16) The next quantity of interest in radiation protection is the mean dose equivalent, $\bar{H}_T$, in each organ or tissue (T). This is the quantity to which the Commission's dose limits for non-stochastic effects basically apply. For workers, these limits are 500 mSv in a year for all organs

Table B. Recommended permissible approximations of $\bar{Q}$ for various types of radiation

Type of radiation	Approximate value of $\bar{Q}$
X rays, γ rays and electrons	1
Thermal neutrons	2.3
Neutrons, protons and singly-charged particles of rest mass greater than one atomic mass unit of unknown energy	10
α particles and multiply-charged particles (and particles of unknown charge) of unknown energy	20

except the lens of the eye, and 150 mSv in a year for the lens. For individual members of the public, the limit is 50 mSv in a year for all organs (see *ICRP Publication 26*).

(17) In addition to the dose limits recommended by the Commission to prevent non-stochastic effects, the Commission recommends a dose limit based on the total risk of stochastic effects from exposure of all organs and tissues. This is basically a dose-equivalent limit for uniform irradiation of the whole body. The limit is 50 mSv in a year for workers and 5 mSv in a year for individual members of the public, with the additional recommendation that, for members of the public, the lifetime average should not exceed 1 mSv per year if the dose is realistically assessed without maximizing assumptions (see *ICRP Publication 26*).

(18) In the case of non-uniform irradiation, the dose limitation for stochastic effects is based on the principle that the risk at the limit should be equal whether the whole body is irradiated uniformly or non-uniformly. This condition is met if:

$$\sum_T w_T H_T \leq H_{wb,L},$$

where $H_{wb,L}$ is the recommended annual dose-equivalent limit for uniform irradiation of the whole body and w_T is a weighting factor which is the ratio of the stochastic risk resulting from irradiation of tissue T to the total stochastic risk when the whole body is irradiated uniformly.

(19) The sum of the weighted mean organ dose equivalents is called the *effective dose equivalent*, H_E, when the weighting factors, w_T, are those recommended by the Commission (Table C). The Commission's dose limit for stochastic effects, $H_{wb,L}$, therefore applies to the

Table C. Recommended values of the weighting factors w_T for deriving effective dose equivalent

Organ or tissue (T)	w_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder[a]	0.30

[a] $w_T = 0.06$ for each of the five organs or tissues receiving the highest dose equivalent of the remainder.

effective dose equivalent, irrespective of whether the irradiation is uniform or not. The effective dose equivalent is measured in the same units as the dose equivalent, i.e. in sievert.

(20) In practice it is permissible to use secondary standards instead of actually assessing the effective dose equivalent in all circumstances. For internal exposure (not treated in this document) the secondary standard is the annual limit of intake, ALI (see *ICRP Publication 30*). For external exposure, the secondary standard is the dose-equivalent index, H_I (see para. 21). In the case of both internal and external exposure, the Commission's recommended dose limitation for stochastic effects will not be exceeded if both the following conditions are met:

$$\frac{H_{I,d}}{H_{E,L}} + \sum_j \frac{I_j}{\mathrm{ALI}_j} \leq 1$$

and

$$\frac{H_{I,s}}{H_{sk,L}} \leq 1$$

where $H_{I,d}$ is the annual deep dose-equivalent index, $H_{I,s}$ is the annual shallow dose-equivalent index, $H_{E,L} = H_{wb,L}$ is the annual limit of effective dose equivalent (see para. 17), $H_{sk,L}$ is the annual limit of dose equivalent in the skin (500 mSv for workers, 50 mSv for members of the public), I_j is the annual limit of intake for radionuclide j (see *ICRP Publication* 30).

(21) The *dose-equivalent index*, H_I, at a point is defined as the maximum dose equivalent within a 30 cm diameter sphere centred at that point and consisting of material equivalent to soft tissue with a density of 1000 kg m^{-3}. This quantity is referred to as the "unrestricted" dose-equivalent index. An important consequence of this definition is that H_I is not defined at distances closer than 15 cm from a surface or source. The centre of the sphere is almost always at a different point than that at which the maximum dose equivalent occurs.

(22) The definition of the dose-equivalent index may be modified to make provisions for radiation of low penetrating power. It is then convenient to consider separately the maximum dose equivalent in an inner core with a radius of 14 cm and the maximum dose equivalent in a surrounding shell of 1 cm thickness. These two maxima are termed the *deep* and *shallow* dose-equivalent indices, respectively, and their symbols are $H_{I,s}$. They are referred to as "restricted dose-equivalent indices". The larger of the two is the same as the unrestricted dose-equivalent index. It is recommended that the shallow dose-equivalent index shall not include the dose equivalent in the outer 0.07 mm of the 1 cm shell, since this is representative of the depth of the basal layer of the epidermis in areas where the skin is thin; any radiation effects in the outer 0.07 mm are assumed to be negligible.

(23) For a number of purposes, e.g. in optimization assessments of radiation protection measures, the *collective effective dose equivalent*, S_E, may be used. This is the product of the number of exposed individuals and their average effective dose equivalent (see paras. 22–24 of *ICRP Publication 26*). The unit of collective dose equivalent is *mansievert* (or *manrem* with the previous special unit of dose equivalent).

(24) *Kerma*, K (kinetic energy released per unit mass) is the kinetic energy of charged ionizing particles liberated per unit mass of the specified material by uncharged ionizing particles. Kerma is measured in the same units as absorbed dose. The SI unit of kerma is *joule per kilogram* (J kg^{-1}) and its special name is *gray* (Gy). Kerma can be quoted for any specified material at a point in free space or in an absorbing medium. Expressions such as "tissue kerma in air" and "tissue kerma in bone" are acceptable. Over a wide range of photon energies, air kerma and tissue kerma differ by less than 10% and may be considered equal in magnitude for radiation protection purposes. In this respect, air kerma means air kerma in air. Kerma is independent of the complexities of the geometry of the irradiated mass element and permits specification for photons or neutrons in free space or in an absorbing medium. For these reasons, kerma has a wider applicability than exposure (see para. 26).

(25) When kerma is determined with a radiation-measuring instrument designed to approximate charged particle equilibrium conditions, the value of the kerma is the same as that of the absorbed dose when both are expressed in the same units. However, significant differences between kerma and absorbed dose occur close to interfaces between two media, for example in the skin or in cells lying close to the bone surface. For very high energy radiations, the dose build-up due to charged particle energy transport can be substantial, and the kerma at a point may then exceed, or be less than, the absorbed dose in a small mass element at the point. Under such conditions, tissue or air kerma multiplied by the appropriate quality factor will be a

suitable approximation of the dose-equivalent index; absorbed dose in a small tissue element, multiplied by the appropriate quality factor, may underestimate the maximum dose equivalent that would occur in the human body.

(26) *Exposure*, X, is a dosimetric quantity for ionizing electromagnetic radiation, based on the ability of the radiation to produce ionization in air. The exposure is the absolute value of the total charge of the ions of one sign produced in air when all the electrons liberated by photons per unit mass of air are completely stopped in air. The SI unit of exposure is *coulomb per kilogram* ($C\,kg^{-1}$). The former special unit of exposure was *roentgen* (R), with $1\ R = 2.58 \times 10^{-4}\ C\,kg^{-1}$ (exactly).

(27) Exposure can be specified in free space or in an absorbing medium. By suitable conversion factors, exposure can be linked to air kerma and to the dose-equivalent index. For example, 100 kV x rays that produce an exposure of 1 roentgen at a point will also give an air kerma of about 8.7 mGy (0.87 rad) and a tissue kerma of about 9.5 mGy (0.95 rad) at that point. The magnitude of the kerma in any medium other than air depends upon the energy of the x rays and the atomic composition of the medium.

(28) *Fluence*, Φ, provides a characterization of a radiation field without regard to its interaction with the irradiated material. By means of suitable interaction factors one can, for any material of interest, derive various dosimetric quantities, e.g. dose equivalent. The fluence, Φ, of particles is the number of particles traversing a sphere of unit cross section. The SI unit of fluence is m^{-2}. For a unidirectional field, the fluence is equal to the number of particles incident per unit area of a surface perpendicular to the field. The *energy fluence*, Ψ, of a radiation is the kinetic energy of ionizing particles traversing a sphere of unit cross section. The SI unit of energy fluence is $J\,m^{-2}$.

(29) More precise information and precise definitions are found in *ICRU Report 33* (Radiation Quantities and Units). The concept of dose equivalent is discussed in *ICRU Report 25* (Conceptual Basis for the Determination of Dose Equivalent). Quantities and units are also discussed in Chapter C (Basic Concepts) of *ICRP Publication 26*, in the Statement from the 1978 Stockholm meeting of the ICRP (*Annals of the ICRP*, **23** (1), 1978), and in the Statement and Recommendations of the 1980 Brighton meeting of the ICRP (*Annals of the ICRP*, **4** (3/4), 1980).

B. THE SYSTEM OF DOSE LIMITATION

Introduction

(30) The ICRP recommends a system of dose limitation, the main purposes of which are to ensure that every exposure to ionizing radiation is justified in relation to its benefits or those of any available alternative, that any necessary exposures are kept as low as reasonably achievable, and that the dose equivalents received do not exceed certain specified limits. The system of dose limitation has the following main features:

(a) No practice shall be adopted unless its introduction produces positive net benefit—*justification.*

(b) All exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account—*Optimization of Protection.*

(c) The dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission—*Dose Limits.*

The principles of justification and optimization are essentially source-related, i.e. they are concerned with the adequacy of protection as applied to each radiation source. Dose limits are concerned with the individual worker, member of the public and patient participating in research studies.

Justification

(31) Ideally, the acceptability of a proposed operation or practice involving exposure to radiation should be determined by cost-benefit analysis, the purpose of which is to ensure that the total detriment should be appropriately small in relation to the benefit resulting from the introduction of the proposed activity. The choice between practices will depend on many factors, only some of which will be associated with radiation protection.

(32) The professional judgment of the referring physician and radiologist, singly or jointly, that a proposed medical radiological procedure may be of net benefit to the recipient patient will normally constitute "justification" *vis-à-vis* the individual patient's exposure. Retrospective analysis of the correctness of these decisions (efficacy) will refine the indications and non-indications for future patients for whom a given procedure may be considered as useful. This is discussed in detail in the forthcoming ICRP publication Protection of the Patient in X-Ray Diagnosis.

(33) Radiological examination shall be carried out only if it is likely that the information obtained will be useful for the management of the patient or for improving the health status of the population (but see also para. 209).

(34) The choice, and in some cases the order, of radiological examinations and the alternative choices of non-radiological examinations or of foregoing any examinations other than simple clinical examinations should be based on a judgment of the relative benefits, risks and costs of the available choices. In this context, the benefits are influenced by the diagnostic efficacy of the various procedures and on the desirability of employing invasive rather than non-invasive procedures, and it should be remembered that both positive and negative findings may be of benefit to the patient.

(35) When the physician or dentist performs his own radiological procedures, the balance between the radiologist and referring physician or dentist is absent; this could result in unnecessary examinations being performed.

(36) The possibility of inappropriate or too frequent self-referral by individual members of the public (e.g. in mass-miniature chest radiography) must also be considered.

(37) Even when the decision has been made that a radiological procedure is justified, the decision to perform a particular examination is a balance of cost, relative influence on patient-management, information yield, availability of specific equipment and radiation detriment.

(38) The justification of the use of radiation for treatment of malignant neoplasms will take into account the relative merits of treatment by radiation as compared with other methods, e.g. surgery, chemotherapy (see *ICRP Publication 26*, paras. 198, 199).

(39) It is particularly important to establish the justification for treatment of non-malignant conditions in view of the risks of the induction of malignant disease and the risks of alternative procedures. The severity of the condition being treated and its possible life-shortening effect must be balanced against the expectation of stochastic and non-stochastic effects resulting from the treatment.

(40) The justification of the use of ionizing radiation in medical research is more difficult as the person irradiated may receive no direct benefit from the examination. The benefit may be only to future patients whose clinical management may be improved as a result of that research (see para. 207).

Optimization of Radiation Protection

(41) One of the basic components of the system of dose limitation recommended by the Commission is the requirement that all exposures should be kept "as low as reasonably achievable", taking into account the relevant social and economical considerations. This requirement consists of increasing the level of protection to a point such that further improvements achieve exposure reductions which are less significant than the additional efforts required. This requirement is usually called *optimization of radiation protection.*

(42) The efforts involved in protection are taken to be quantifiable in terms of cost. If the radiation detriment (representing all exposures from the source, given the protection under consideration) can also be expressed as a cost, optimization can be expressed as

$$X(w)+Y(w)=\text{minimum}$$

where X is the cost of protection, and Y is the cost of the radiation detriment, both at a level of protection represented by w (e.g. shielding thickness, alternative options of protective equipment, etc.). It should be noted that w, and $X(w)$ and $Y(w)$, can in some cases be continuous, while in other cases they take only discrete values.

(43) When the level of protection, quantified by w, can be varied to any desired level, the minimum for the above expression can be obtained by differentiation

$$\frac{dX}{dw}=-\frac{dY}{dw}.$$

As X, Y and w are related to the collective dose S, the optimized situation can also be expressed (see *ICRP Publication 26*) as

$$\frac{dX}{dS}=-\frac{dY}{ds}$$

In many practical assessments of optimization, the changes in protection levels are achieved in finite increments, corresponding to successively more ambitious options. In these cases, the decision of going from a level of protection A to a more expensive level B would be taken if

$$\frac{X_B-X_A}{W_B-W_A}\leq\frac{Y_B-Y_A}{W_B-W_A}$$

For example, rare-earth screens of medium speed may be substituted for standard tungstate screens in some fraction of examinations. If the cost of detriment is taken to be $Y=\alpha S$, where α is the monetary value assigned to the unit of collective dose, an optimization assessment can be carried out as follows. Assuming a certain life of the screen, and knowing the collective dose reduction (number of examinations × dose-reduction per examination), then the cost of saving 1 mansievert can be determined. If this figure is below the assigned value α, then the step of using rare-earth screens is acceptable.

(44) Optimization should be exercised in planning new installations both with regard to the protective barriers and the design of protective devices in equipment. However, the case-by-case optimization of widely-used equipment is not appropriate because it would nullify the advantages of standardization and would cause a net social loss. Optimization should, however, play a part in the setting of such standards and specifications on their subsequent application.

For the practical application of this, the reader is referred to the forthcoming ICRP publication Optimization of Radiation Protection.

(45) Quality assurance programmes are, in part, means by which a level of radiation protection can be maintained or even improved (e.g. reduction of the number of rejected films). However, the cost incurred by such a programme has to be balanced against the gain of collective dose reduction and of the longer life of the equipment. Analysis of the reasons for rejection of films may show faults both in radiographic technique and in apparatus. Identifying the most prevalent faults should improve radiographic technique. Apparatus deficiencies will require the services of engineers but, if regularly adjusted, the number of rejected films due to faulty apparatus should fall and often the life of the equipment is increased. On cost-effectiveness analysis, it can be shown that dose-reduction of these means is worthwhile.

(46) The radiation dose delivered during a radiological examination is influenced by the knowledge and skill of both the radiologist and radiographer. In principle, money spent on training the staff can be related to a concomitant reduction in collective dose to the patients. At the present time, improved performance cannot be accurately cost-related nor is reduction in dose the only objective. (The collective dose for a given procedure might increase as a result of training and still be entirely justified on the basis of greater information content.) In spite of these difficulties, the general concept of optimization does have application in assessing the need to improve the performance of the staff.

(47) A simple example of this in fluoroscopy is to introduce a meter giving a reading of the product of radiation dose and area of tissue irradiated. If used to compare individual performance, particularly in a training department, it will encourage good protection practice. Recommendations in the following chapters indicate in more detail means by which the performance of the staff can be improved.

Dose Limits

(48) Although the application of the concepts described in the preceding paragraphs provides sufficient protection for the patient in medical radiology, it does not always provide such protection for staff, visitors, and individual members of the public. Regardless of the result of cost-effectiveness analysis and other measures, individual dose-equivalent limits must be respected (see *ICRP Publication 26*, paras. 92, 93, 103–108).

(49) In practice, risks and benefits are not equally distributed. Those who benefit from a given practice may not be the only ones who are exposed to the risks. Boundary limits are needed in order to ensure that justified and optimized practices do not result in unacceptably high risks to some individuals for the benefits received by others.

(50) The dose-equivalent limits for workers are to be considered as boundary conditions and not as permissible levels in the absence of optimization and other procedures, such as the setting of authorized limits.

(51) Since they form only part of the system of dose limitation, the dose-equivalent limits can no longer be used as the primary basis for planning and design. Operational or design limits should be established by appropriate international or local national authorities on the basis of optimization. For a discussion of authorized limits see *ICRP Publication 26*, paras. 147 and 148. These limits are often the result of optimization and other procedures. The limits that appear in the following paragraphs are based on experience and represent the practical application of the optimization of protection (see also Appendix, paras. 253–256).

C. RECOMMENDATIONS ON DESIGN AND OPERATION

(52) The following recommendations on general principles for operational radiation protection are quoted from *ICRP Publication 26* and are relevant to this section of this report.

> "(139) Responsibilities for achieving appropriate radiation protection fall on the employers, the statutory competent authorities, the manufacturers, and the users of products giving rise to radiation exposure and, in some cases, the exposed persons. The management of an institution must provide all the necessary facilities for the safe conduct of the operations under its control. In particular, it should designate persons with special duties for protection, such as members of radiation protection teams."
>
> "(140) All proposed installations and new operations, all changes in existing installations and operations, and all new or modified products containing radioactive materials or emitting ionizing radiation, should be examined at the design stage from the point of view of restricting the resulting occupational and general exposure. Such examinations can often be carried out by comparison with detailed technical standards prepared, taking into account the recommendations of the Commission."
>
> "(141) Before commissioning an installation, starting an operation or distributing a product, it should be established that the installation, operation or product conforms with the approved proposals and that the appropriate radiation protection requirements have been met. In the case of installations and operations, there should be continuing checks on the effectiveness of the organizational arrangements made to achieve protection, and on the availability and application of appropriate working instructions."
>
> "(160) The main responsibility for the protection of workers rests with the normal chain of management in an institution possessing any radiation source that causes exposure of workers. It is necessary to identify technically competent persons to provide advice on all relevant aspects of radiation protection, both inside and outside the institution, and to provide such technical services as are needed in the application of the appropriate recommendations for radiation protection."
>
> "(161) For the purposes of this report, occupational exposure comprises all the dose equivalents and intakes incurred by a worker during periods of work (excluding those due to medical and natural radiation). The scale and form of the problems of radiation protection of workers vary over very wide ranges, and there are practical advantages in introducing a system of classification of conditions of work. Conditions of work can be divided into two classes:
>
> Working Condition A: this describes conditions where the annual exposures might exceed three-tenths of the dose-equivalent limits;
>
> Working Condition B: this describes conditions where it is most unlikely that the annual exposures will exceed three-tenths of the dose-equivalent limits.
>
> The value of three-tenths of the basic limits for occupational exposure is thus a reference level used in the organization of protection. It is not a limit. Where the exposure is unconnected with the work, and where the work is in premises not containing the radiation sources giving rise to the exposure, the working condition should be such that the limits applicable to members of the public are observed.
>
> "(163) The practical application of this system of classification of working conditions is greatly simplified by the introduction of a corresponding system of classification of workplaces. The minimum requirement is to define controlled areas where continued operation would give rise to Working Condition A and to which access is limited. The demarcation of controlled areas will depend on the operational situation and it will often be convenient to use existing structural boundaries. The controlled area should in any case be large enough to make it most unlikely that the annual dose equivalents to workers outside the controlled area will exceed three-tenths of the limits."
>
> "(164) It is sometimes convenient to specify a further class of work place. It is called a "supervised area", and has a boundary chosen so as to make it most unlikely that the annual dose equivalents outside the supervised area will exceed one-tenth of the limits."
>
> "(168) Access to controlled areas should be restricted, at least by the use of warning signs. Inside controlled areas, it may sometimes be necessary to define regions where compliance with the relevant limits can be achieved only by limiting the time spent in the region or by using special protective equipment. The access of workers to controlled areas should be limited to those who are assigned to the area and to others who have been authorized to have access. The access of workers to supervised areas should be the subject of local operating instructions. Visitors, either workers or members of the public, should be admitted to workplaces only with the approval of an appropriate level of the management responsible for the workplace."

(53) The final plans for new installations or for modifications of existing installations involving structural shielding should be reviewed by a qualified expert and should, if required, be approved by the competent authority before building is commenced. Copies of the plans of the installation as built, including the shielding specifications, should be retained and be readily available at the site. Later modifications should be similarly recorded.

(54) Before any equipment or installation is put into use, surveys shall be carried out in order to establish that the approved plans have been followed and that the shielding and operating conditions are such as to provide protection for all persons in accordance with national and local requirements and/or the recommendations of the Commission. For details on surveys and monitoring, see paras. 211–223. Subsequent surveys shall be made after every change in the equipment, installation or conditions of use that might affect the protection, and at such intervals as may be necessary to check that satisfactory conditions still obtain.

(55) Protection can be achieved by distance, by shielding and by reduction of the duration of exposure. Proper siting of the installation and limitations of the possible directions of the useful beam are examples of means by which the cost of the shielding can be reduced.

(56) In *ICRP Publication 26*, para. 148, the Commission introduced the concept of authorized limits as limits laid down by a competent authority or by the management of an institution. The process of optimization (see Section B System of Dose Limitation) may be used in the establishment of authorized limits and they apply only in restricted circumstances. It is important that any such restrictions should be clearly stated.

(57) The shielding of the radiation source and the dimensions and the siting of the installation in which the source is situated, shall be such that work can be carried out in compliance with authorized limits and with due account being taken of optimization (see paras. 41–44).

(58) In the planning of a radiation installation, account should be taken of the maximum workload and of the number of radiation workers employed. In the absence of precise information on the workload and the number of radiation workers, it is prudent that they be overestimated.

(59) The shielding requirements depend on the nature of the occupancy of surrounding areas, that is whether (either as controlled or supervised areas) they are accessible to workers or to members of the public, including patients. There is no simple parallel between the classification of areas and the classification of working conditions because the classification of areas takes no account of the time spent by workers in the area during the course of the year and because conditions are rarely uniform throughout an area (see para. 71).

(60) For some areas it may be possible to employ "occupancy factors" and "use factors" in order to reduce the shielding requirements. Since these factors may differ considerably between installations, no recommendations regarding their magnitude are given in this report. Where such factors are employed, relaxations of the shielding requirements always need careful consideration and shall be in conformity with the requirements of the relevant national or local authority. If occupancy or use alter from that assumed in the design, then shielding requirements need to be re-assessed, but later changes in shielding may be difficult to make.

(61) In calculating the shielding required against the primary radiation beam, removable objects (e.g. phantoms) and patients, by which the beam may be partly absorbed, should not normally be taken into account.

(62) Stray radiation is radiation other than the useful beam and includes leakage and secondary radiation. In calculating the shielding required against stray radiation, the anticipated conditions of use which give rise to the maximum leakage and secondary radiation should be assumed.

(63) Where the primary beam strikes material, secondary radiation will be generated. Attention should be given to the choice of absorbing material and the arrangement of absorbers to minimize the secondary radiation, which will include x rays when electrons or beta particles are absorbed.

(64) Windows and doors of radiation rooms shall be subject to the same protection requirements as the adjacent parts of the walls in which they are located.

(65) Shielding materials such as lead shall be mounted in such a manner that they will not creep under their own weight. They shall also be protected against mechanical damage. When materials such as concrete are intended to provide radiation shielding, care must be exercised to ensure that they are sufficiently homogeneous and have the specified composition and density.

(66) In designing and building a radiation installation, care should be taken to ensure that the shielding is not impaired at joints, nails, bolts, etc., or where pipes, conduits and louvres, etc., are present or at the edges of doors and windows. At a joint between two different shielding materials, the overlap shall not be less than the required thickness of the material of the lower protective capability.

(67) Where operationally necessary, the attenuation equivalent provided by walls and protective barriers which form part of the shielding of an installation should be marked upon them. This should also include information concerning the radiation quality for which the attenuation has been specified.

(68) Equipment that complies with a published technical specification should be labelled accordingly. Auxiliary equipment such as filters and treatment cones should be marked with the appropriate characteristics (filtration, area covered at a given distance, etc.) in a manner that will prevent unintentional substitution and misuse.

(69) Equipment that does not and cannot be made to meet current standards should not be retained against the advice of qualified experts. No equipment should be used for purposes other than those for which it has been designed unless it has been surveyed and tested, and found to be satisfactory for the new purpose. No equipment shall be handed over to other users unless it will be subject to surveillance and testing for safe functioning.

(70) In assessing compliance with the leakage requirements for tube and source housings it is adequate, where other conditions are not specified, for measurements to be averaged over an area not larger than 100 cm^2 at a source distance of 1 m, or 10 cm^2 at a distance of 5 cm from the tube or source housing.

(71) Paragraph 52 quotes the Commission's system of classification of working conditions A and B and of working areas (e.g. controlled areas and supervised areas). Experience has shown that in medical radiation practice, where rudimentary optimization procedures have been used, the radiation doses to the workers do not exceed one-tenth of the effective dose-equivalent limit. In these cases, there is no practical need to introduce a supervised area.

(72) Access to controlled areas shall be limited. In order to avoid uncertainties in the determination of the extent of controlled or supervised areas, the boundaries should, when possible, be walls, doors, etc. Inside controlled areas it may sometimes be necessary to define regions where compliance with the relevant limits can be achieved only by limiting the time spent in the region or by using special protective equipment.

(73) The information and training of workers should particularly emphasize the importance of distance, time, shielding and technique. Training should be aimed at intelligent use of these factors, with particular attention being paid to the importance of avoiding exposure of any part of the body to primary beams.

(74) In order to maintain good radiation protection, quality assurance programmes shall be carried out. These programmes shall include both main equipment and accessories, recording and processing systems as appropriate. Quality assurance programmes include acceptance tests of new radiological equipment to ensure that such equipment meets applicable performance specifications as may have been determined by national or local authorities, or by the manufacturer. Thereafter, periodic performance tests should be carried out in order to check that conditions are unchanged (see paras. 90 and 133).

(75) Attention is drawn to the possible existence of non-radiological hazards such as electrical, mechanical and toxic hazards.

D. X-RAY DIAGNOSIS

This section provides detailed recommendations on equipment and procedures applicable to diagnostic radiology.

General Recommendations

(76) The levels recommended below for equipment and accessories are given for normal use, but special types of work,extreme work load, etc., may make it necessary to increase the level of protection. The recommended levels are expressed in air kerma and air-kerma rates (see para. 24).

(77) Every x-ray tube used for diagnostic purposes shall be enclosed in a housing such that the kerma in air from the leakage radiation measured at a distance of 1 m from the focus does not exceed 1 mGy in 1 h at every rating specified by the manufacturer for that tube in that housing. For the area over which these measurements shall be made (see para. 70).

(78) Beam-limiting devices (e.g. light beam diaphragms, cones or collimators) shall be used to limit the useful beam to the area of clinical interest. Wherever practicable, preference should be given to the use of light beam diaphragms. The beam-limiting devices in combination with the tube housing shall comply with the kerma requirements for leakage radiation given in para. 77. Cones and non-adjustable collimators shall be marked with the appropriate field size and other relevant data.

(79) The total filtration in the useful beam for normal diagnostic work shall be equivalent to not less than 2.5 mm Al, of which 1.5 mm shall be permanent. Exceptions are made for conventional dental units with a maximum voltage not exceeding 70 kV (see para. 120), and for special radiographic procedures detailed in the next paragraph.

(80) Some special radiographic procedures (e.g. mammography) may require very soft radiation. Such procedures should be carried out on special equipment and not on standard x-ray equipment intended for higher potentials. Under no circumstances shall be the total permanent filtration be equivalent to less than 0.5 mm Al or 0.03 mm Mo.

(81) Various types of timers are required for fluoroscopic and radiographic work (see paras. 99, 110, 111). The proper functions of timers to maintain appropriate levels of reproducibility and accuracy is of particular importance. The timer (x-ray exposure switch) shall be so arranged that accidental exposure is unlikely. It is of particular importance to check the time used for mobile and conventional dental radiographic equipment as these are more prone to error.

(82) An indication shall be provided at the control panel to show whether or not radiation is being generated. If there is more than one tube capable of being selected from a single location, then warning lights should also be displayed on or near each tube to indicate which tube or tubes have been selected.

(83) The patient shall be observable from the control position. Means should be provided for communication with the patient.

(84) The simultaneous examination of more than one patient in the same room may introduce unnecessary and not easily controllable hazards for both personnel and patients.

(85) The radiation level, outside equipment, equipment parts, or sub-assemblies not intended to emit radiation, e.g. high voltage generators, depends on local conditions and optimization procedures, but under no conditions shall it exceed 0.2 mGy air kerma in 1 h at a distance of 5 cm from the surface.

(86) No person shall remain in an unshielded position (i.e. outside a fixed barrier) in an x-ray diagnostic room when radiological procedures are being carried out, unless his presence is

essential to the conduct of the examination or is necessary for training purposes. All such persons shall wear protective clothing having a lead equivalent of at least 0.25 mm.

(87) No person should normally hold patients during diagnostic examinations. Motion-restricting devices shall be used as much as practicable, and cassettes should not be hand-held during exposure. When patients must be held during an examination, the individual holding should be chosen so that his cumulative doses will be held within local, authorized limits. No pregnant women nor persons under the age of 18 years should be permitted to hold patients. Those holding the patients shall wear protective aprons and gloves and should ensure, as far as practicable, that no part of their body, even if covered by protective clothing, is in the path of the useful beam.

(88) Attention is drawn to the special problems associated with the use of diagnostic x-ray equipment in surgery and in procedures such as cardiac catheterization devices. The x-ray equipment and protective devices used should be such that they are not unnecessarily obstructive to the work of the surgeon or members of his staff; however, adequate protection shall be provided. Image intensifiers should be used for all surgical procedures requiring fluoroscopy.

(89) Mobile equipment (i.e. transportable equipment intended to be moved from one location to another in the same establishment between periods of use) should only be employed when it is unwise to move the patient to a fixed installation.

(90) Equipment, including accessories and recording systems recommended in para. 74, shall be tested regularly at appropriate intervals.

Fluoroscopy with Fluorescent Screens or Image Intensifiers

(91) Whenever practicable, fluoroscopy should be performed with image intensifiers. Fluoroscopy shall not be performed with mobile equipment unless an image intensifier is employed. The equipment shall be so constructed that the radiation beam is fully intercepted by the image receptor area of the image intensifier. The use of image storage devices is recommended.

(92) To achieve a sufficiently low dose-rate to patients, measures must be taken to ensure that the apparatus is maintained in a satisfactory electronic condition.

(93) An adjustable collimator or diaphragm shall be provided to define the useful beam.

(94) The x-ray tube, adjustable beam-limiting device and fluoroscopic screen or image intensifer shall be linked together in such a way that the beam will not fall outside the screen, irrespective of the source–screen distance. In case of failure, an indication shall warn the operator.

(95) Image intensifiers, and adjacent fittings which may be exposed to the useful beam, shall provide the same protection as that required for a conventional fluoroscopic screen assembly.

(96) The fluorescent screen shall be covered with a protective glass sheet having a lead equivalent of not less than:

1.5 mm for apparatus having a maximum tube voltage up to and including 70 kV;
2.0 mm for apparatus having a maximum tube voltage above 70 kV up to and including 100 kV;
an additional 0.01 mm per kV above 100 kV.

(97) If the radiographic equipment permits spotfilms to be taken in connection with the

fluoroscopic examination, the beam should be intercepted by a barrier having a lead equivalent as specified in the preceding paragraph designed for the highest x-ray tube voltage at which radiographic exposure can be made.

(98) When fixed fluoroscopic equipment is used, the focus–skin distance should not be less than 45 cm and shall not be less than 30 cm. With regard to the distance between the focus and the patient, fluoroscopy and radiography should be performed in such a way that optimal conditions exist to minimize the radiation doses to the patient, without impairing the diagnostic information.

(99) A device shall be provided which will automatically terminate the fluoroscopy after a preset time, with a maximum setting of 10 min. To allow resetting, if clinically essential, it shall be supplemented with an audible signal giving warning of the impending cessation of fluoroscopy. The setting of the signal shall be adjustable within the overall time. It is recommended that the elapsed fluoroscopy time be clearly visible to the fluoroscopist.

(100) The fluoroscopy exposure switch shall be of the "dead-man" type, i.e. a switch so constructed that the circuit-closing contact is maintained only by continuous pressure on the switch.

(101) Means (control settings or meters) shall be provided to indicate the x-ray tube potential and current. These means should be located so that the values of voltage and current can be observed by the operator during photofluorography and by the fluoroscopist during fluoroscopy. Observation of these values is particularly important when using image intensifiers with "automatic brightness control" (automatic variation of either voltage or current, not under the direct control of the fluoroscopist, in order to maintain constant brightness (see para. 92).

(102) All tables and stands for fluoroscopy shall be provided with adequate means for protecting the fluoroscopist and his assistants against scattered radiation from the patient and from scattering materials between the source and the patient. A shield equivalent of not less than 0.5 mm lead shall be provided to cover openings such as the "Bucky slot". The fluoroscopist shall be protected by an "apron" or "drape" which may consist of overlapping parts to facilitate palpation. The apron shall have a lead equivalent of not less than 0.5 mm and shall have sufficient dimensions to protect the operator. It should be attached to the lower edge of the screenholder when the latter is vertical and to the edge nearest to the operator when the screen is horizontal.

(103) Whenever possible members of the staff shall remain behind protective screens or shields during all types of fluoroscopic examinations. If this cannot be done, protective aprons having a lead equivalent of at least 0.25 mm shall be worn.

(104) Protective gloves or sleeves having a lead equivalent of not less than 0.25 mm should be worn when any fluoroscopic examination may involve placing the hands in or near the useful beam. When gloves or sleeves are worn they shall cover the whole hand including back, palm, fingers, and wrist. Even when wearing protective gloves, the hands should not be placed in the beam unless it has been attentuated by the patient. Where fluoroscopy is performed with undercouch intensifier and overcouch tube, palpation shall be made only with mechanical devices.

(105) The air-kerma rate for fluoroscopy as measured at the patient entrance surface should be as low as practicable and should not exceed 50 mGy per min. If for special reasons a rate higher than 50 mGy per min is used, there should be clear indication to the fluoroscopist of this higher rate.

(106) It should be noted that the attenuation of the useful beam by the table top influences the dose to the patient. Attention should be paid to the material used in the table top. The use of carbon fibre in table tops (as well as in cassette fronts, grid fronts and grid interleaving) will

allow significant dose reduction and optimization or a cost-effectiveness study will show if the cost of this dose reduction is justified (see also para. 11).

(107) Before fluoroscopy without image intensification, the eyes shall be sufficiently dark-adapted. In order to enable work with an acceptably low exposure rate, the adaptation should be at least 10 min. When image intensifiers are used, ambient light should be of such a level that visual acuity is not impaired.

Radiography

(108) Generally, the beam-defining system mentioned in para. 78 should be adjustable. Non-adjustable systems may be used in certain conditions such as mass screening of the chest. In both these situations, the field should be limited to the area of clinical interest and shall not exceed the size of the film. Preference should be given to apparatus which gives a visual indication of the radiation field. Means should be provided to verify that the film is aligned with the beam.

(109) Recommended values for minimum distances between source and patient are the same as those given for fluoroscopy in para. 98, and for dental radiography in para. 124. An exception is extreme magnification radiography where shorter distances may be used. All radiographic equipment should be equipped with auxiliary devices in order to facilitate the measurement of focus–skin and/or focus–film distance.

(110) A device shall be provided to terminate the exposure after a pre-set time or exposure (see para. 81). If a recycling timer is used, it shall not be possible to make repeat exposures without release of the exposure switch to reset the timer except in the case of special techniques where repeated exposures are required.

(111) Means (control setting of meters) shall be provided on the control panel to indicate the x-ray tube potential and current, and the exposure time (or to indicate whether timing is automatic). A meter to indicate the product of current and time (mAs-meter) may be used in place of current and/or exposure-time indicators.

(112) With fixed equipment, the adequate protection of the operator during irradiation of the patient shall be provided by a fixed screen within the x-ray room or by locating the control panel outside the x-ray room.

(113) The minimum distance of the operator from the tube and patient during radiographic procedures with mobile equipment shall be 2 m. High workloads may require that the operator be shielded. The operator shall ensure that the only person exposed to the useful beam will be the patient.

(114) If an anti-scatter grid is used, the following data should be marked upon it: (a) focused or non-focused, (b) if focused, the radius, (c) tube-side. When an anti-scatter grid is used, particular attention should be paid to the importance of proper alignment between the central axis of the grid and the reference axis and, in addition, if a focused grid is used that the focus/grid distance is close to the radius of the grid.

(115) The aluminium equivalent of the table top or the aluminium equivalent of the front panel of the vertical cassette holder shall not be more than 1 mm at 100 kV.

Photofluorography

(116) The relevant parts of paras. 94, 98, 101, 108, 111 and 115, should be applied in photofluorography.

(117) Mass survey photofluorographic equipment, utilizing a camera with miniature film to

photograph the image produced on a fluorescent screen has, in the past, been widely used in chest surveys. The dose to the patient from this technique was many times that from full-size radiography. Where this system is still used, it is important to achieve maximum sensitivity by using a camera having a wide-aperture optical system, and the correct film for the type of fluorescent screen. It should be possible to achieve a satisfactory image with an entrance air kerma not exceeding 1 mGy.

(118) A wider application of photofluorography is its use in association with image intensification. Such systems give the possibility of dose reduction, but in all systems both the optical and electronic linkage must be maintained at high efficiency. The film selected for recording shall have a colour response corresponding to the colour of the light emitted from the fluorescent screen.

(119) Mass-survey photofluorographic equipment shall be so arranged and shielded that all personnel associated with the procedure, and waiting patients, are adequately protected during routine use, without the necessity for protective clothing.

Dental Radiography

(120) The total permanent filtration in the useful beam for conventional dental x-ray equipment with a maximum tube voltage not exceeding 70 kV shall be equivalent to not less than 1.5 mm Al. At higher tube voltages, the recommendations of para. 79 shall apply.

(121) Equipment used for special dental radiography, e.g. the so-called panoramic equipment and equipment for cephalometric (profile) procedures, shall comply with the applicable recommendations in the section on radiography.

(122) When using panoramic equipment, the alignment of tube (with its slit beam-limiting device) and film shield (again with its slit) is critical, and this shall be checked at suitable intervals.

(123) Some modern intra-oral tubes have been reduced in size to ease insertion. This reduction in size has resulted in potential for higher local exposures to the tissues of the mouth. Experience has shown that the use of the tubes can lead to an air kerma of 0.5–1.0 Gy per exposure at the surface of the tube. However, if used with the appropriate filtration and extra-sensitive films, doses no higher than 0.05–0.1 Gy may be delivered to limited parts of the tongue. With these precautions, the intra-oral tubes may even have certain advantages from the point of view of radiation protection; they may cause lower integral doses than regular dental tubes, and the exposure of the staff is much reduced since the entire dental examination can be accomplished with one exposure. Extra shielding in the applicator can easily limit the radiation field to that which is needed for the examination, thus further reducing the integral dose.

(124) For conventional dental radiography (use of intra-oral films) a field-defining spacer cone shall be employed, which provides a minimum focus–skin distance of 20 cm for equipment operating above 60 kV, and 10 cm for equipment operating at 60 kV or below. Open-ended cylinders or divergent cones conforming with para. 78 are preferable to pointer cones. The field diameter at the cone end should not exceed 6 cm and shall not exceed 7.5 cm. To comply with this field-size restriction, pointer cones shall be fitted with a suitable lead annulus in the base.

(125) For conventional dental radiography, the maximum range of the exposure timer should not exceed 5 s. The timer shall be capable of consistently reproducing the short exposure times needed for high-speed film. The exposure switch shall have a circuit-closing contact which can be maintained only by continuous pressure. It shall not be possible to make repeat exposures without release of the exposure switch (see para. 81).

(126) Dental installations should be so arranged that the operator remains outside the radiation beam at least 2 m from the tube and from the patient, or is adequately shielded.

(127) Whenever possible, the film shall be fixed in position or be held by the patient. Neither the film nor any film holder, should be held by the dentist or any member of his staff.

E. RADIOTHERAPY

This section provides detailed recommendations on equipment and procedures applicable to radiotherapy.

Beam Therapy

General recommendations

(128) All appropriate provisions given in paras. 76 and 83 shall apply.

(129) Reliable indicators shall be provided at the control panel and within the treatment room in a readily visible position in order to show whether or not the equipment is in operation. Corresponding indicators shall also be mounted immediately outside treatment rooms with apparatus capable of operating at x-ray tube voltages above 50 kV.

(130) With apparatus capable of operating at x-ray tube voltages above 50 kV, interlocks shall be provided which preclude entry to the treatment room while the equipment is in operation. The interlocks shall be of a fail-safe type which interrupt the radiation treatment when the door to the treatment room is opened. After such an interruption, it shall be possible finally to restore the apparatus to full operation only from the control panel. The functioning of interlocks shall be tested and maintained at regular intervals. Measures should be taken to prevent inadvertent entry to the treatment room, with the subsequent automatic interruption of patient treatment.

(131) A device shall be provided which will automatically terminate the exposure after the pre-set time or exposure has elapsed (see also para. 143). The proper functioning of these devices is of particular importance and special attention should be given to those components which may fail and cause malfunctioning of the device.

(132) No person other than the patient shall be in the treatment room during treatment except for x-ray therapy, at tube voltages below 50 kV (see para. 138). Special efforts shall be made to ensure that personnel cannot accidentally be left in during therapy. It shall be possible to open the treatment room door from the inside. Provision should be made so that staff in the treatment room become aware of the start of treatment.

(133) All beam-therapy equipment shall be tested for performance and calibrated by a qualified expert before it is first put into use for treatment, and at regular intervals thereafter. The minimum requirements in respect of the extent and frequency of repeat calibrations should be determined by the competent authority. It is of the utmost importance to establish quality control programmes for radiotherapy units (see para. 74) to be performed at intervals determined by national or local authorities.

(134) Therapy apparatus shall only be operated by persons trained for this purpose.

X-ray therapy apparatus operating at tube voltage below 150 kV

(135) The housing of tubes designed for superficial x-ray therapy shall conform to the requirements given in para. 140 except for tubes intended to operate at voltages within the range 5–50 kV which shall be provided with a special tube housing such that, at every specified

rating of the tube in that housing, the air-kerma rate from the leakage radiation does not exceed 1 mGy h^{-1} at any position 5 cm from the tube housing or its accessory equipment. For the area over which these measurements shall be made, see para. 70.

(136) Superficial x-ray therapy equipment shall be so designed as to prevent unintentional combinations of tube voltage and filtration. Means (control settings or meters) at the control panel shall be provided to indicate tube voltage and current when these can be varied, and for easy recognition of the filtration being used.

(137) The tube shall not be held by hand and it shall be fixed in correct position through mechanical devices.

(138) For treatment at tube voltages of not more than 50 kV, it is permissible for the operator and other essential persons to remain in the room. All these persons shall wear protective aprons having a lead equivalent of not less than 0.25 mm. The frequent presence of these persons due to a heavy workload, or for other reasons, may necessitate the use of aprons having a lead equivalent of 0.5 mm.

(139) Due to the low inherent filtration and short focus–window distance, the kerma rate close to the window of a low-voltage tube used for superficial therapy is very high, and even brief exposure to the radiation beam may cause serious injury. In the case of apparatus with x-ray tubes having beryllium windows, kerma rates as high as 10 Gy s^{-1} may occur. For this reason, special care is necessary to avoid accidental exposure. An audible signal or warning light prominently mounted on the housing shall be provided for any such tube, in order to indicate when the tube is energized.

X-ray therapy apparatus operating at tube voltages between 150–500 *kV*

(140) Each x-ray tube shall be enclosed in a housing such that, at every specified rating of that tube in that housing, the air-kerma rate from the leakage radiation measured at a distance of 1 m from the focus does not exceed 10 mGy h^{-1}, nor 300 mGy h^{-1} at any position accessible to the patient at a distance of 5 cm from the surface of the housing or its accessory equipment. For the areas over which these measurements shall be made see para. 70.

(141) At the control panel, means (control settings or meters) shall be provided to indicate tube voltage and current when these can be varied, and for easy recognition of the filtration being used. Whenever practicable, equipment which provides pre-set combinations of tube voltage, current and filter should be employed.

(142) Permanent diaphragms or cones, in combination with the tube housing, shall comply with the exposure requirements for leakage radiation as given in para. 140. Additional cones or adjustable diaphragms should be constructed so as to reduce the integral dose to the patient as much as practicable. They shall not transmit more than 2% of the useful beam. Where cones are not used, the diaphragm system shall include a light beam localizer.

(143) The equipment shall be provided with an automatic timer which will terminate the exposure after the pre-set time has elapsed. In order to ensure that the correct dose has been delivered, a transmission chamber or other device which monitors the constancy of the radiation output should be provided. These devices shall be checked by an independent measuring device.

Megavolt x-ray and electron beam therapy

(144) This section deals with particle accelerators that are used in medicine and which provide x-ray and/or electron beams.

(145) In the high energy range of radiation, the choice of absorbing material and the arrangement of absorbers are of special importance to minimize the secondary radiation, which will include x-rays when electrons or beta particles are absorbed.

(146) The equipment shall be provided with radiation shielding which shall be designed so that the following conditions are fulfilled outside the useful beam. The kerma rate due to leakage radiation (excluding neutrons) at any point outside the maximum useful beam, but inside a plane circular area of radius 2 m centred around, and perpendicular to, the central axis of the beam at the normal distance of treatment, shall not exceed 0.2% of the air-kerma rate on the axis at the same distance. The leakage radiation should be measured with the useful beam blocked by a thick absorbing plug. Except in the area defined above, the kerma rate of leakage radiation (excluding neutrons) at 1 m from the path of the electrons between their origin and the target or the electron window shall not exceed 0.5% of the air-kerma rate on the central axis of the beam at the normal treatment distance.

(147) The contribution of neutrons to the dose inside and outside the treated area should be kept as low as practicable. Inside the field the neutron-tissue kerma should be kept well below 1% of the x-ray kerma. Measurements made in the primary beam from electron accelerators have indicated that the dose-equivalent rate of neutrons does not exceed 1% of the dose equivalent of photons (*NBS Special Publication 554*). This implies that the neutron absorbed dose rate is never greater than about 0.1% of the photon dose rate and makes only a small addition to the therapeutic effect. Neutrons outside the primary x-ray beam make only a marginal contribution to the integral dose received by the patient. Outside the treated area the neutron kerma shall be reduced as far as practicable. Further discussion of inadvertently generated neutrons appears in paras. 153–156.

(148) The adjustable beam-limiting devices (adjustable diaphragms, cones, etc.) shall be so constructed that the leakage radiation imparts less energy to the patient than is imparted by a treatment field of 10 cm^2. This implies that for a field size of 10×10 cm^2 the leakage radiation shall contribute less than 10% of the energy imparted by the useful beam. Similarly if the maximum field size is 35×40 cm^2 the transmission of radiation through the diaphragms shall not exceed 0.8%.

(149) For the safety of the patient the accelerator shall be provided with two independent dose monitoring systems. The separation shall be such that any failure or malfunction in one system does not influence the function of the other system. The detectors of the two systems shall be provided inside the radiation head. Both systems shall be so constructed that they are able independently to terminate irradiation. The design of the systems shall be such that, in case the so-called "master system" fails to terminate the radiation, the other system will terminate after an additional 0.4 Gy.

(150) The indicator showing the preselected number of monitor units and the indicator showing the accumulating number of monitor units shall both be displayed at the control panel.

(151) Due to the complexity of accelerators and the possibility of changing the parameters, all efforts should be made by systems of interlocks to prevent mistakes being made in the selection of types and energy of radiation wedgefilters, scattering foils, etc.

(152) Parameters essential for the correct performance of a radiation treatment shall be displayed at the control panel.

Hazards from inadvertently generated neutrons from electron accelerators

(153) X-ray and electron generators working above 10 MeV may produce a significant photo-disintegration of the nucleus. For most elements the excitation function for neutron

production occurs in the region 10–20 MeV. A variety of methods can be used to measure the contribution of neutrons to the dose in the therapeutic beam and to the dose-equivalent rate outside the treatment room, but there is no fully satisfactory method for all situations. The perfect technique would have enough sensitivity to neutrons but zero (or negligible) response to the photons produced by the accelerator. It should have no energy threshold for the detection of neutrons. With pulsed accelerators there should be no response to an accumulation during the pulse (pulse pile-up effects). A variety of methods has been used, including activation, track registration in organic foils, BF_3 and other counters in moderating hydrogenous spheres, and a pair of ionization chambers of which one contains hydrogen and the other does not. All methods suffer from difficulties, so that more than one should be used to ensure a reliable result.

(154) Measurements made in the primary beam from electron accelerators have indicated that the dose-equivalent rate of neutrons does not exceed 1% of the dose equivalent of photons (*NBS Special Publication 554*). This implies that the neutron absorbed dose rate is never greater than about 0.1% of the photon rate and makes only a small addition to the therapeutic effect. Neutrons outside the primary x-ray beam make only a marginal contribution to the integral dose received by the patient.

(155) Measurements outside the treatment room have in some instances shown a significant dose-equivalent rate of neutrons outside the door to the labyrinth. Care should therefore be taken both at the design stage and during protection surveys to ensure that there is no significant hazard from neutrons outside the treatment room.

(156) The presence of neutrons may also result in significant radioactivity in components close to the target. Adequate precautions should be taken if these need to be handled during maintenance.

Sealed source beam therapy

(157) Every sealed γ-ray source used for beam therapy shall be enclosed in a housing such that, with the beam control mechanism in the OFF position, the air-kerma rate from the leakage radiation measured at a distance one 1 m from the source does not exceed 10 μGy h^{-1}. At any readily accessible position 5 cm from the surface of the housing, the air-kerma rate from the leakage radiation shall not exceed 200 μGy h^{-1}.

(158) With the beam control mechanism in the ON position, the air-kerma rate from the leakage radiation measured at a distance of 1 m from the source shall not exceed either 10 mGy h^{-1} or 0.1% of the useful beam air-kerma rate at 1 m from the source, whichever is the greater.

(159) Conditions for the measurement of leakage radiation are given in para. 70.

(160) Permanent diaphragms and cones shall afford the same degree of protection as the source housing. See paras. 157 and 158.

(161) Adjustable or interchangeable beam-limiting devices should be so constructed as to conform with para. 148. Under no circumstance shall leakage radiation through these devices exceed 2% of the useful beam.

(162) The beam control mechanism shall be such that it will automatically return to the OFF position at the end of an exposure or in the event of any breakdown or interruption of the force holding the beam control mechanism in the ON position. The OFF position shall be maintained until the mechanism is operated from the control panel. Additionally, the apparatus shall be so constructed that, in case of failure of the automatic return system, the exposure can be interrupted by other means, e.g. manually, in order to protect the patient.

(163) It must be possible to unload or repair the treatment head without exceeding the dose

limits for occupational exposure recommended by the Commission (see *ICRP Publication 26*, paras. 113 and 114).

(164) Source housings should, so far as practicable, be fire resistant. Consideration should be given to means whereby the integrity of the source housing is preserved in the event of fire.

(165) A reliable indication shall be provided at the control panel and, when practicable, also at the source housing, in order to show when the source is in the ON position. It is often advisable also to have an indication capable of showing when the source is in the OFF position. When appropriate, signals should also be displayed at the entrance to the treatment room.

(166) The requirements of paras. 130 and 132 apply equally here.

(167) The surface of the housing of the source capsule, particularly the beam aperture, together with any other locations likely to be contaminated in the event of a leakage, shall be tested for leakage of radioactive material at least every year. Should the presence of free activity of more than 2 kBq be indicated, the source shall be considered as leaking, the equipment withdrawn from use and arrangements made immediately for source repair and decontamination of equipment.

(168) Information on the location of major radioactive sources should be readily available to the appropriate fire authorities.

Non-collimated Sealed Source Therapy

(169) A sealed source is considered to be any radioactive substance sealed in an inactive container or capsule, or bonded wholly within inactive material, so as to prevent dispersion of the radioactive substance during routine use. It should be noted that some sources are fragile and may easily be damaged with consequent release of the radioactive material.

(170) A separate room or designated area with adequate ventilation and filtration of the exhaust air shall be provided for the preparation of sources and applicators. During such preparation only those persons engaged in the work shall be allowed in the area; eating, smoking and drinking and the application of cosmetics shall be prohibited.

(171) Sealed radioactive sources will need to be recognizable as such. The user will need an easy way of identifying the nature and the activity of the radioactive material. Hence, wherever practicable, the source container, capsule or bonding shall be labelled in such a way that the source can be identified. If practicable, the nature and the activity of the radioactive material should be marked directly on the label. The identification of needles and capsules of the same appearance but containing a different activity or nuclide should be facilitated during treatment by such means as coloured beads or threads.

(172) A register shall be kept of all sealed sources. The register should include: the serial number or other identification of each sealed source; the physical or chemical form of the radioactive substance, the date of receipt and its activity on that date; the date and manner of ultimate disposal from the establishment.

(173) Records shall be kept of the movement of all sealed sources both inside and outside an establishment in order to minimize the possibility of their loss. Actual or suspected loss of, or damage to, a sealed source shall be reported immediately to the person responsible for radiation protection. An audit of all sealed sources shall be carried out at appropriate intervals and at least once a year.

(174) The storage, use, issue and receipt of sealed sources shall be the responsibility of authorized persons only.

(175) Local rules shall be prepared detailing the manner of the use and ultimate disposal of sealed sources and the procedures to be adopted in the event of loss of, damage to, or accidents

involving a sealed source and the design of such sources. In preparing such rules, consideration should be given, as appropriate, to factors such as possible causes of loss, spread of contamination, effects of fire, and identification and treatment of casualties.

(176) When not in use, sealed sources shall be stored under conditions which provide adequate protection for those who enter the store and for those who may be adjacent to it; security against unauthorized removal; and minimal risk due to fire and flood. Where sources are liable to release a radioactive gas or vapour, the store shall, if necessary, be mechanically ventilated to the outside air.

(177) Sealed sources shall be tested for integrity at appropriate intervals and at least every year. See also para. 167.

(178) Whenever there are reasonable grounds for believing that the integrity of a sealed source is, or is liable to be, breached, it shall be hermetically sealed in a suitable container pending repair by the manufacturer or by a competent establishment. In such circumstances the area in which the source has been used, and any person who might have been contaminated, shall be surveyed.

(179) Appropriate handling tools or implant instruments shall be used in order to restrict the irradiation of personnel engaged in the preparation, application, sterilization, dismantling and cleaning of sources. These tools shall be constructed so as to provide the maximum handling distance compatible with effective manipulation. All operators shall have adequate training, e.g. with dummy sources, in these manipulative procedures. Whenever practicable, remote means of manipulation, which ensure adequate protection of the staff, shall be used. Sources shall never be picked up with the fingers.

(180) The use of after-loading techniques is strongly recommended, since these techniques have led to considerable reduction in doses to personnel.

(181) Since the decay products of radium (radon) are gaseous, radium sources are particularly liable to leak. Radium and its decay products constitute perhaps the greatest potential hazard among sealed sources used in medicine. It is strongly recommended that radium sources be properly disposed of and replaced as soon as practicable by sources containing other radionuclides such as ^{60}Co, ^{137}Cs, ^{192}Ir.

(182) The transport of sources within the institution shall be carried out in such a manner that all individuals are adequately protected. Where the total activity is low, sources may be transported by hand in a long-handled container. While being used for the transport of sources, containers shall be marked with the maximum allowable activities of the actual nuclides for which they are intended.

(183) In hospitals, both ambulatory and bed patients containing sealed radioactive sources should be segregated into rooms or wards where properly trained personnel are available. The beds and the rooms or wards shall be suitably identified when occupied by such patients.

(184) The number and position of removable sealed sources in or on the patient shall be checked during treatment. Dressings from patients receiving treatment with sealed sources shall not be destroyed until it has been ascertained that they do not contain any sources. After removal of the sources from the patient, all sources shall be accounted for and the patient and his dressings shall be monitored as an additional precaution.

F. NEUTRON GENERATORS AND SOURCES

(185) Medical uses of neutrons include both diagnostic and therapeutic applications. Diagnostic use of activation analysis *in vivo* can be performed with neutron generators or sealed sources containing ^{252}Cf or (α, n) sources such as Pu–Be. Neutrons should not be used for

routine radiography of patients in preference to x radiation because of the larger dose equivalent delivered to the patient.

(186) There are many physical factors associated with neutrons which complicate their use in diagnosis and therapy compared with the applications of x or gamma radiation. In the first place the measurement of neutrons, either in the working environment or for individual dosimetry, is more complicated than for low-LET radiations. The interactions of neutrons and matter are such that the shielding is more difficult than for low-LET radiations and the variation in the value of the quality factor complicates the assessment of shielding factors. It is also more difficult to provide sharp collimation of the effective beam. This makes the problems of patient protection more difficult than in the case for photons. Finally, there is the additional complication that the neutrons induce radioactivity in air and materials in the vicinity of the source or generator. For these reasons any use of neutrons in diagnosis or radiotherapy should be restricted to those specially trained in these fields.

(187) There are several practical problems to which special attention should be given if neutrons are used in diagnosis or therapy. Most of the these problems are similar to those which apply to the use of x or gamma radiation and many of the paragraphs concerned with these radiations apply equally to neutron diagnosis or therapy. Because of the wide range of systems used for neutron therapy it is convenient to express the leakage radiation in terms of a percentage of the useful beam. Wherever practicable the tissue kerma in air due to leakage radiation should be less than 1% of that in the primary beam at the same distance. Another practical problem is the activation by neutrons of objects in the treatment room, particularly those close to the target. Such objects should be properly stored and shielded and for those items in frequent use it may be preferable to keep them in the treatment room. The choice of materials in the treatment room should take into account the importance of activation and there are advantages in avoiding the use of metals, particularly aluminium and steel containing manganese, and other materials such as glass (which contains sodium). Following therapy the patient will also be measurably radioactive but most of the radionuclides are very short-lived and even the longer lived sodium-24 is at an activity level which will not call for special precautions.

G. PROTECTION OF THE PATIENT

Clinical Procedures

(188) The term "medical exposure" is applied to all types of radiation exposure of patients for the purpose of diagnosis, treatment and research.

(189) A number of the recommendations in the previous sections are also aimed at reduction of the radiation dose to the patient. The following paragraphs mainly deal with protection aspects which are less directly related to equipment. Although no guidance is given in this report with regard to the best methods of diagnosis or treatment, recommendations are given on various aspects of the operational procedures. It is important that those who use radiation on patients keep abreast of technological and clinical developments in respect to the methods.

(109) The forthcoming ICRP publication Protection of the Patient in X-ray Diagnosis presents guides to good practice for the protection of the patient in x-ray diagnosis.

(191) In *ICRP Publication 26*, para. 205, the Commission re-emphasized that:

> "Careful attention to techniques would, in many cases, result in a considerable reduction of the dose due to medical procedures, without impairment of their value. In general, the techniques and equipment used should allow: the reduction of the doses received by tissues in the region of the body under examination to the minimum

compatible with obtaining the necessary information in the particular patient; the delivery to the treated region of the body of a therapeutic dose, the magnitude of which is most likely to ensure the required response; the limitation as far as practicable of the exposure of other parts of the body."

(192) In Section B "System of Dose Limitation", the complex problem of the application of optimization in the medical radiation field was discussed and the reader is referred to that section.

(193) Good clinical judgment implies that no patient is exposed unnecessarily. It is therefore important that all relevant clinical information, including previous radiological data, be studied and that alternative techniques be considered before examinations or treatments with radiation are requested or initiated. It is, however, equally important that necessary examinations or treatments are not withheld because of radiation risks.

(194) Once a technique of radiological examination has been chosen, it shall be applied with the minimum patient exposure likely to secure the desired diagnostic information.

(195) No person shall operate radiological equipment without adequate technical competence or perform radiological procedures without adequate knowledge of the physical properties and harmful effects of ionizing radiation.

(196) Since most physicians are likely to become involved in some decisions implying irradiation of patients, extensive training in radiation fundamentals would be valuable for all medical students. Therefore a curriculum for medical students should include at least the foundation that is necessary for an understanding of the basic aspects of radiation risk and efficacy of various radiological procedures, particularly with regard to the elements necessary in the exercise of good clinical judgment.

(197) The interpretation of recommendations on protection of the patient has, on occasions, caused unwarranted alarm and has therefore led some patients to hesitate in seeking necessary medical attention. Every effort should be made to give referring physicians and the public an indication of the radiation risks and of the general benefit from, and need for, various types of diagnostic and therapeutic irradiations.

(198) The basic protective requirement is that the radiation dose to the patient, especially the dose to radiosensitive organs such as gonads, active bone marrow, female breast, foetus etc., shall not be greater than that likely to be needed to obtain the relevant diagnostic information or to produce the desired therapeutic result.

X-ray Diagnosis

(199) The dose to the patient is influenced by factors such as radiation quality (voltage, filtration), beam direction, source–skin distance, field size, sensitivity of the recording system as well as by the number of exposures. An assessment of the influence of these factors in diagnostic radiology is given in the forthcoming ICRP publication Protection of the Patient in X-Ray Diagnosis.

(200) Fluoroscopy shall be restricted to the situation where radiography alone is not expected to provide the required information.

(201) Care should be exercised when the gonads of a patient, particularly if young, are within or near the useful beam, or when a foetus may be irradiated. If the patient's gonads must be within the limits of the beam, but do not actually need to be exposed, they should be shielded, to the extent practicable.

(202) In *ICRP Publication 26*, para. 206, the following statement is given:

"Because of the risk of radiation injury to any embryo or fetus, the possibility of pregnancy is one of the factors to be considered in deciding whether to make a radiological examination involving

the lower abdomen in a woman of reproductive capacity. Although such an examination is least likely to pose any hazard to a developing embryo if carried out during the 10 day interval following the onset of menstruation, attention should always be paid to details of radiological technique that would ensure minimization of exposure to any embryo or fetus that may be present, whether or not the woman is known to be pregnant."

(203) Ultrasound should be preferred over ionizing radiation wherever possible in obstetric radiology.

(204) Patients awaiting radiological procedures shall wait outside the rooms where such procedures are performed. They are subject to the limitations that apply to non-medical exposure.

(205) The fastest film–screen combination should be used that yields the necessary diagnostic information. Screen-type film should not be used for non-screen techniques.

(206) Care should be taken to prevent fogging of the film. To maintain proper exposure, availability of exposure tables based on patient size are strongly recommended. Alternatively, automatic exposure control may be of value. Care must be taken that the correct type of film or film–screen combination is being used for the technique chosen. The type of film and screen in the cassette should be clearly marked so that it is evident to the technologist. Also, if different films are used in a department and loaded in the same darkroom, it is useful to make the cassettes have some palpable identification so that they can be identified in the darkroom and loaded with appropriate film. It is also important that detection chambers are properly chosen and positioned for a specific examination. Fogging may be caused by an unsatisfactory darkroom safe-light (e.g. incorrect filter; bulb power too high), by scattered radiation in the x-ray room or by x rays from unexpected souces such as rectifying valves in a high tension generator cabinet, or by heat and excess humidity. Fogging is also caused by the natural radiation background, but this may be reduced if particularly radioactive building material is avoided and if film stores are shielded or storage time is limited.

(207) Where there is a sufficient throughput of films, automatic processing machines should be used as they increase reliability and reproducibility.

(208) For manual development, it is usual to keep the developing and fixing solutions at a temperature in the range of 18–21°C (65–70°F), but where the ambient temperature often exceeds this and cooling systems are not available, other appropriate processing chemicals should be used. Developer temperature should always be checked using an accurate thermometer. The developer must be replenished as necessary and replaced at regular intervals.

(209) In *ICRP Publication 26*, para. 202, the following statement is made:

"Examinations carried out to assess the fitness of an individual for work, to provide information for medico-legal purposes, or to assess the health of a subscriber to, or beneficiary of, an insurance may carry some direct or indirect advantages for the individual examined, but they also carry advantages for the employer, third parties and the insurer. All these aspects should be considered in assessing the justification of such examinations."

Medical Research

(210) In *ICRP Publication 26*, the Commission gives the following statements and recommendations on medical research:

"(203) Examinations or treatment forming part of a medical research program sometimes involve direct benefits for the exposed individual and sometimes do not. When new and experimental methods of diagnosis or treatment are capable of benefitting the patients on whom they are tested, the justification for the procedures can be judged in the same way as for other medical exposures. Nevertheless, because of the experimental character of the procedures they should be subject to thorough review."

"(204) The deliberate irradiation of persons for the purposes of those research and other studies in which no

direct benefit to the persons irradiated is intended, in circumstances when the exposure is unrelated to any illness they may have, should only be undertaken by properly qualified and trained persons. Such irradiation should only be given with the consent of the authorities in charge of the institution where the irradiation is to take place, as advised by an appropriate expert body and subject to local and national regulations. The estimated risks of the irradiation should be explained to those involved, who should be volunteers fully able to exercise their free will. The higher the dose, the more rigorous should be the requirements on the conditions of securing true volunteers and on their capability of understanding the risk. It follows that the irradiation, for the purposes of such studies, of children and other persons regarded as being incapable of giving their true consent, should only be undertaken if the expected radiation dose is low (e.g. of the order of one-tenth of the dose-equivalent limits applicable to individual members of the public) and if valid approval has been given by those legally responsible for such persons. The individuals exposed under these conditions obtain no direct benefit from their exposure and it is therefore necessary to ensure that their detriment remains acceptable, and thus to set authorized limits. However, the magnitude of the detriment associated with the exposure depends on the age and the state of health of the exposed individual and it is not possible to fix limits of general applicability. Appropriate limits should therefore be authorized for each research program."

H. MONITORING

Introduction

(211) In *ICRP Publication 12** the Commission has given the general principles of monitoring for radiation protection of workers.

(212) The general term *monitoring* is used for measurements related to the assessment or control of exposure to radiation and radioactive materials.

(213) A programme of monitoring should be designed before an installation becomes operational or new radiological procedures are introduced.

(214) These measurements can be performed as monitoring of the workplace and as individual monitoring of the workers. It is convenient to sub-divide monitoring into three distinct types: routine monitoring, operational monitoring, and special monitoring. Routine monitoring is associated with continuing operations; operational monitoring is performed to provide information about a particular operation; and special monitoring is applied to an actual or suspected abnormal situation.

(215) No single instrument or procedure exists which will accurately measure all possible types of external radiation. It is therefore essential that a competent person shall determine which radiations can conceivably be produced in a given installation, and that he shall specify measuring instruments or procedures accordingly.

(216) All radiation measuring devices shall be calibrated, and some simple method of checking constancy should be employed. The calibration should be either specific to the conditions encountered in practice, or should be in the form of response curves from which the calibration factor appropriate to a specific condition may be derived.

(217) Records of monitoring of workplaces and individual monitoring of workers shall be kept. The purpose of record keeping, the nature and scope of the records, and the extent of record keeping systems, are influenced by national requirements, the evaluation of trends in exposure, the evaluation of collective or average dose equivalents, and the use of records for medical and legal purposes.

Individual Monitoring

(218) The Commission's recommendations provide for two classes of working conditions. Working Condition A describes conditions where the annual dose equivalents might exceed

* A revised version of this report is in preparation.

three-tenths of the related annual limits. Working Condition B describes conditions where it is most unlikely that the annual dose equivalents will exceed three-tenths of the relevant limits. In Working Condition B, individual monitoring generally is not necessary. Experience has shown that the majority of those who work in the medical field can be categorized as working in Condition B; although individual monitoring is not necessary, it may sometimes be carried out as a method of confirmation that conditions are satisfactory. (See *ICRP Publication 26*, para. 162.)

(219) Personal dosimeters should be designed for adequate reliability, sensitivity, and accuracy for the measurement of the types of radiation that occur.

(220) When it is desirable to increase the accuracy of the assessment of the effective dose equivalent, consideration shall be given to the position of the dosimeter and to the use of shielding devices such as protective aprons. When a lead apron is worn, it may be desirable to make an estimate of the effective dose equivalent in place of the procedure used in para. 108 of *ICRP Publication 26*. In that case it may be desirable to wear more than one dosimeter, at least for some period of time until experience has indicated the dose distribution pattern. It should be the responsibility of qualified experts to advise on these matters.

Monitoring of the Workplace

(221) Routine monitoring of the workplace is intended to show that the working environment is satisfactory for continued operations and that no change has taken place calling for a reassessment of operating procedures.

(222) Operational monitoring is intended to provide a check on a particular operation and to give, if necessary, a basis for immediate decisions on the conduct of the operation. Special monitoring may cover either a situation in the working environment where insufficient information is available to achieve adequate control, or an operation which is being carried out in abnormal circumstances which may include accidents.

Assessment of Monitoring Results

(223) The assessment of the readings of the detectors and instruments used for monitoring purposes has to be done in such a way that the results can be interpreted in terms of the recommendations given by the Commission or by national or local authorities. This assessment and interpretation shall be undertaken by a competent person.

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APPENDIX

Introduction

(224) The design of shields against x rays and gamma rays, and the estimation of radiation doses to staff and to patients undergoing radiological procedures is a common radiation protection task. This Appendix contains a substantial amount of output data, data on scattered radiation and of transmission data in graphical and tabulated form. It also contains some guidelines on design procedures in order to fulfil the criteria based on optimization considerations including cost-effectiveness analysis. Some new material, particularly from *NCRP Publications 49* and *51* is included, which was not available at the time of the publication of *ICRP Publication 15*.

Outputs of x-ray generators

(229) The outputs of x-ray generators, at a certain distance from the target, can be predicted with reasonable accuracy for a given potential, tube current, and beam filtration. The output is, however, a function of the type of generator and of the target material and configuration. When possible, therefore, the output of the generator of interest should be measured.

(225) Typical outputs on the axes of the x-ray beams are shown in Figs. 1–4. When calculating outputs for distances other than the ones shown, one may find it necessary to take air attenuation into account, especially at low potentials.

(226) The reference for Figs. 1–4 are as follows: Fig. 1 O'Riordan and Catt (1968); Fig. 2 Glasser *et al.* (1959); Fig. 3 upper curve Kaye and Binks (1940); lower curve Miller and Kennedy (1955). More recent measurements have confirmed the accuracy of Figs. 1 and 2; Birch, Marshall and Ardran (1979), HPA report series No. 7. Figure 4 is also taken from Birch, Marshall and Ardran (1979).

Outputs of gamma-ray sources

(227) The outputs of gamma-ray sources, for which transmission data are provided in this appendix, are given in Table 1.

Table 1. Outputs of gamma-ray sources

Nuclide	Half-life	Principal radiations (MeV)	Air kerma rate (approx.) μGy h^{-1} GBq^{-1} at 1 m[a]
^{60}Co	5.26 y	1.17, 1.33	310
^{125}I	60.25 d	0.027, 0.031, 0.035	30
^{137}Cs	30.0 y	0.66	80
^{182}Ta	115.0 d	0.0427–1.453	185
^{192}Ir	74.2 d	0.30–0.61	95
^{198}Au	2.7 d	0.412	55
^{226}Ra with daughters	1 604.0 y	0.18–2.2	195[b]

[a] Self-absorption in the source and absorption by air are not taken into account. Bremsstrahlung generated in the source also ignored. These remarks do not apply to ^{226}Ra; see note [b].

[b] Measured value assuming point source in 0.5 mm thick platinum capsule.

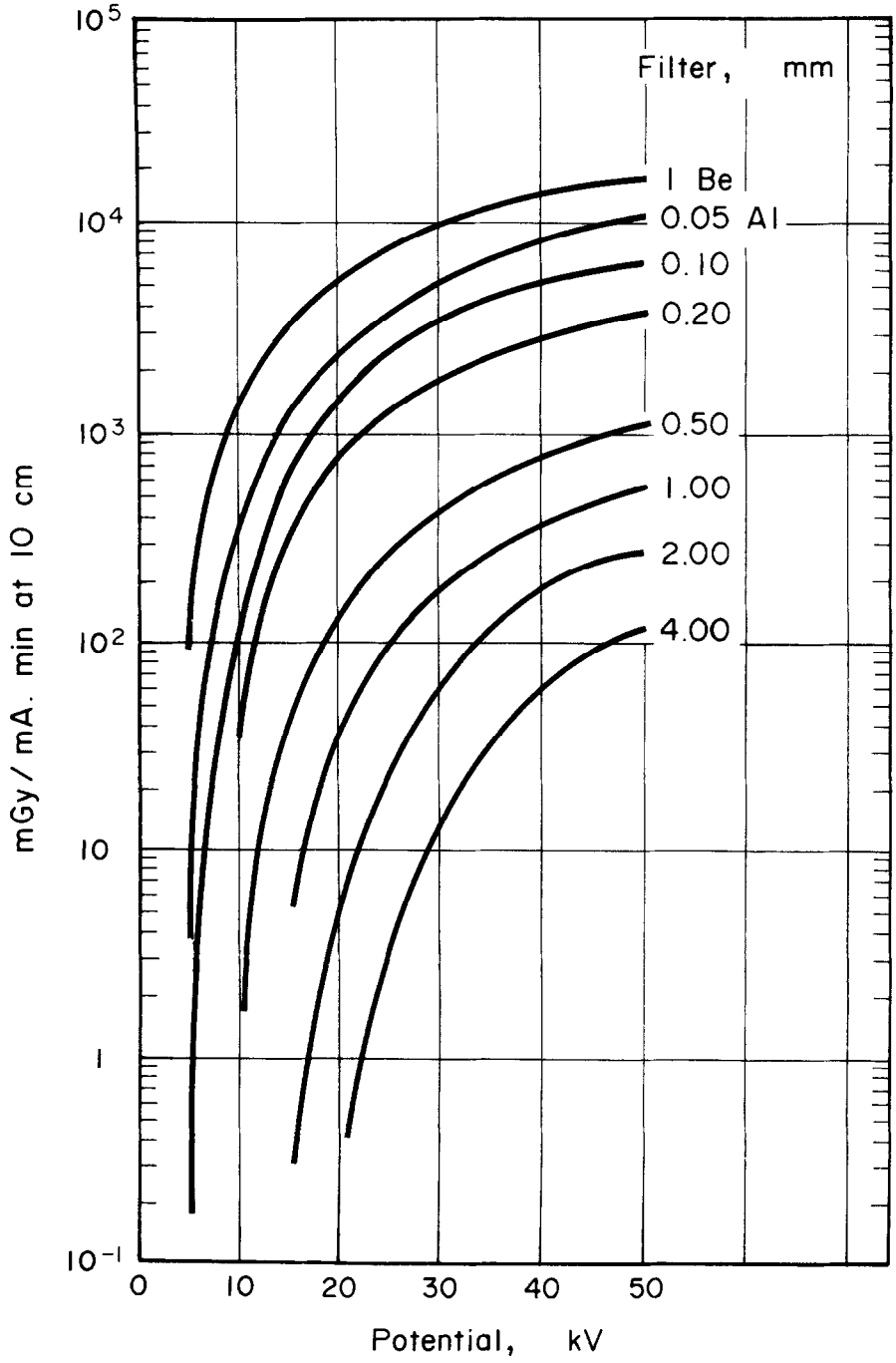

Fig. 1. Output of constant potential x-ray generator at 10 cm target distance for various beam filtrations and a tungsten reflection target. The 1 mm beryllium is the tube window.

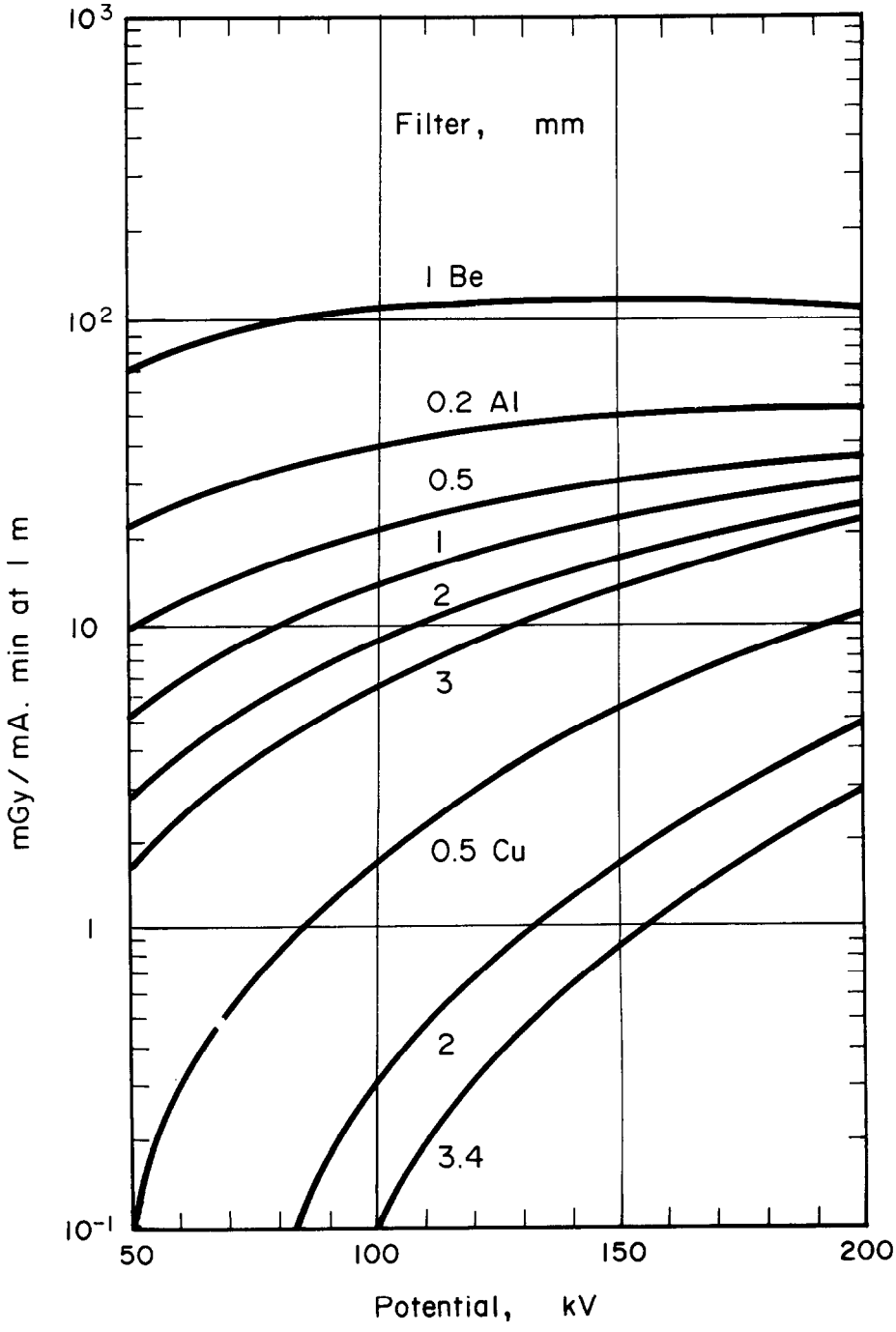

Fig. 2. Output of constant potential x-ray generator at 1 m target distance for various beam filtrations and a tungsten reflection target. The 1 mm beryllium is the tube window.

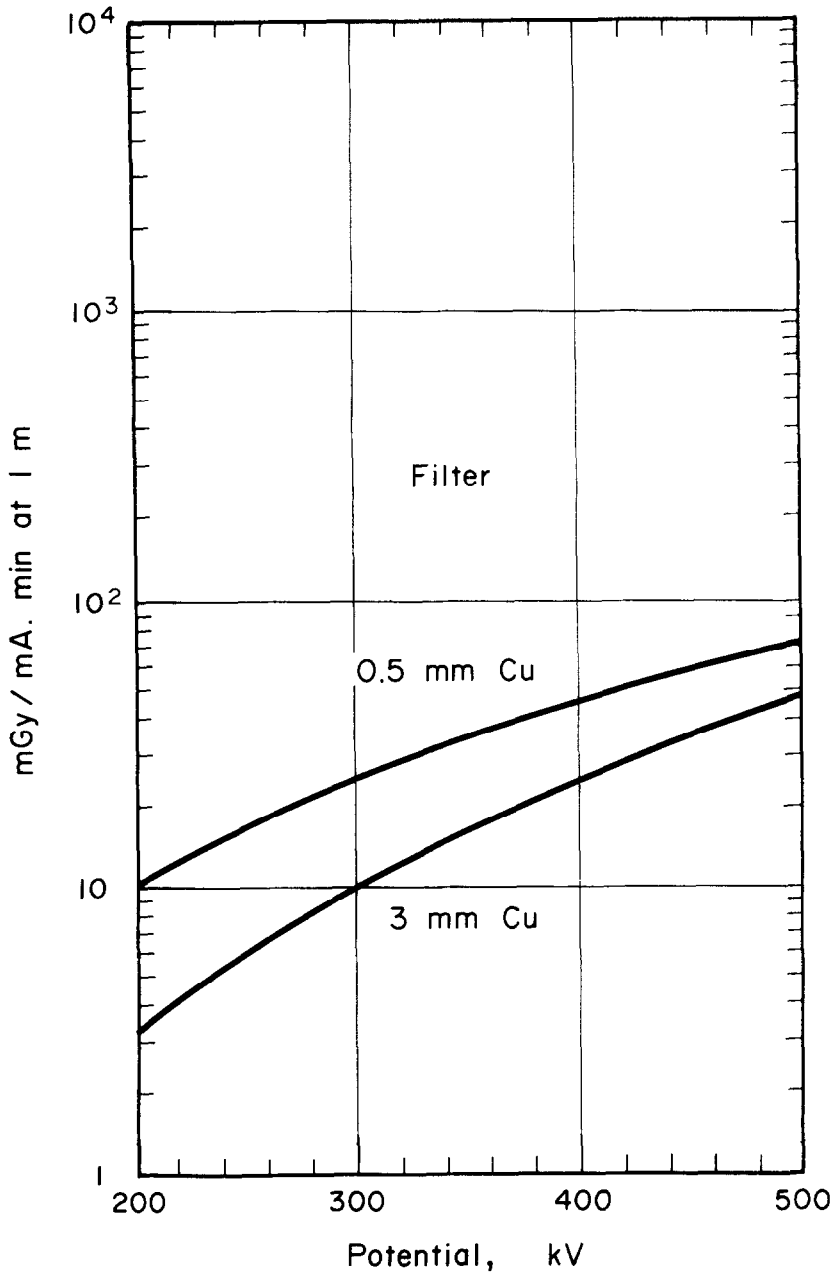

Fig. 3. Output of constant potential x-ray generators at 1 m target distance for various beam filtrations. The curves are for tungsten reflection targets, with 0.5 mm and 3 mm copper total filtration.

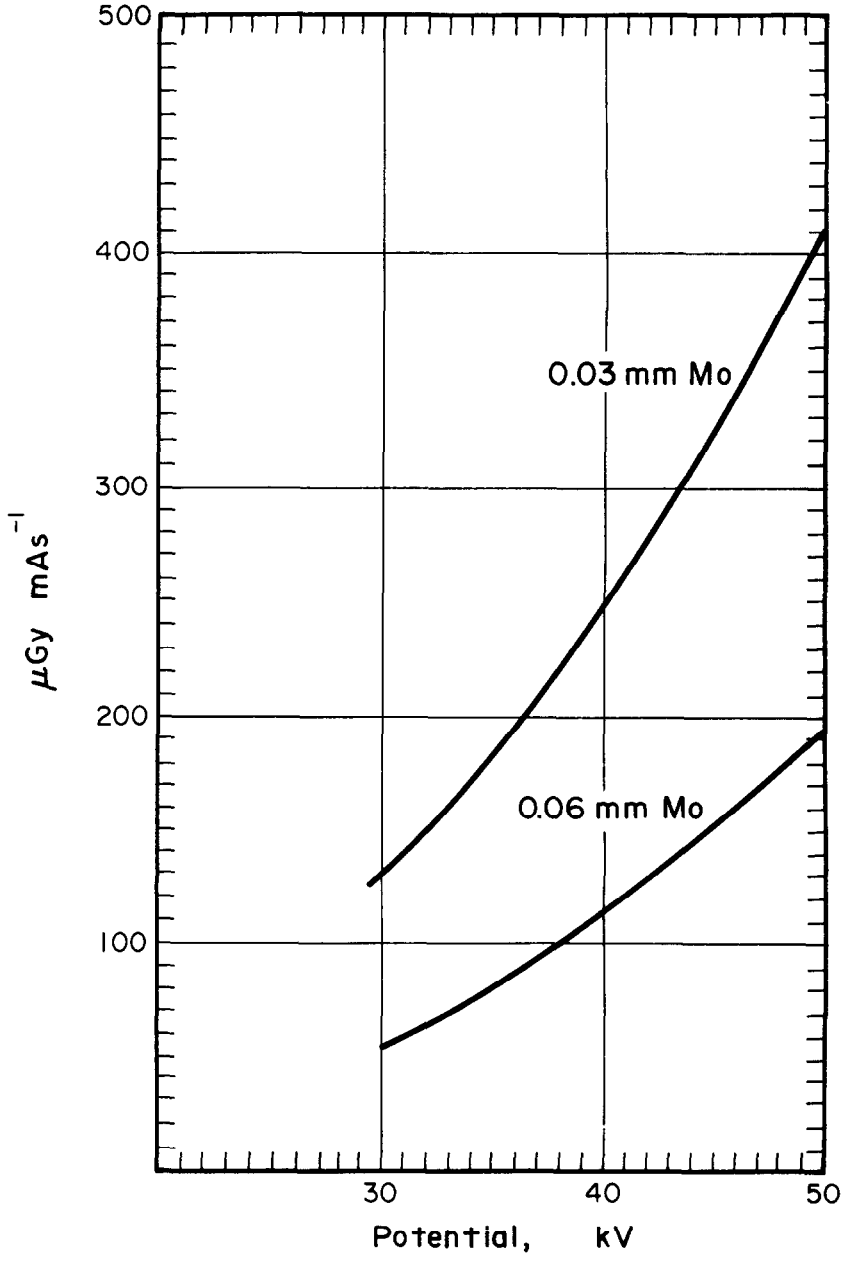

Fig. 4. Output of constant potential generators, air kerma, no phantom at 75 cm, molybdenum anode tube, 17° angle, molybdenum filtration (0.03 mm and 0.06 mm) plus 1 mm beryllium window plus molybdenum filtration.

Transmission of Primary X Rays and Gamma Rays through Shields

(228) Broad-beam transmission data for primary x rays and gamma rays are presented in Figs. 5–20; the reference and the irradiation geometries are given in Table 2. Transmission is in terms of kerma rates in air.

(229) The x-ray transmission charts are mostly for constant potential generators, but the data can be used for all types of generator without introducing serious discrepancies. Furthermore, most of the x-ray curves are for beam filtration which is negligibly small; thus they are, in effect, dependent only on peak operating potential. If it becomes necessary to make allowance for beam filtration, Figs. 1–3 will be useful.

(230) With regard to the gamma-ray transmission data, cognizance should be taken of the irradiation geometry for each nuclide and shield, since the geometry affects the transmission. For nuclides other than the ones presented here, reference may be made to the manual prepared by Steigelmann (1963).

(231) The concrete considered is made from natural aggregate and has a density of 2350 kg m^{-3}. Local variations from this value can usually be allowed for by applying a

Table 2. References and irradiation geometries for x-ray and gamma-ray transmission data

Radiations	Shields	Fig. no.	Geometries[a,b]	Authors
10–50 kV	Perspex[c], steel	5, 6	Diverging broad beam	O'Riordan and Catt (1969)
50–300 kV	Concrete	11	Diverging broad beam	Trout *et al.* (1959)
400 kV	Concrete	11	Unidirectional broad beam	Miller and Kennedy (1955)
50–200 kV	Lead	7	Diverging broad beam	Binks (1943)
250 kV	Lead	8	Diverging broad beam	Binks (1955)
300–400 kV	Lead	8	Unidirectional broad beam	Miller and Kennedy (1955)
0.5–1 MV	Lead, concrete	9, 12	Diverging broad beam	Wyckoff *et al.* (1948)
2 MV	Lead, concrete	9, 12	Narrow beam	Evans *et al.* (1952)
—	—	12	Diverging broad beam	*ICRP Publication 21*
3 MV	Concrete	12	Narrow beam	Goldie *et al.* (1954)
—	—		Unidirectional broad beam	*ICRP Publication 21*
4 MV	Concrete	13	Diverging broad beam	Greene and Massey (1961)
6–38 MV	Concrete	13	Diverging broad beam	Kirn and Kennedy (1954)
>38 MV	Concrete	13	Diverging broad beam	Miller and Kennedy (1956)
4–30 MV	Lead	10	Diverging broad beam	Maruyama *et al.* (1971)
4–10 MV	Iron	14	Unidirectional broad beam	NCRP Report No. 49
^{60}Co	Steel, concrete	15, 18	Diverging broad beam	Kennedy *et al.* (1950)
—	Lead	16	Unidirectional broad beam	Kirn *et al.* (1954)
—	Uranium	20	Cylindrical shield	Wright (1971)
^{137}Cs	Lead, concrete	16, 18	Unidirectional broad beam	Kirn *et al.* (1954)
—	Steel	15	Unidirectional broad beam	*ICRP Publication 21*
—	Uranium	20	Cylindrical shield	Wright (1971)
^{182}Ta	Lead	17	Cylindrical shield	Price *et al.* (1957)
^{192}Ir	Steel, lead, concrete	15, 17, 19	Diverging broad beam	Ritz (1958)
—	Uranium	20	Cylindrical shield	Wright (1971)
^{198}Au	Lead, concrete	17, 19	Unidirectional broad beam	Kirn *et al.* (1954)
^{226}Ra	Steel, lead, concrete	15, 17, 19	Diverging broad beam	Wyckoff and Kennedy (1949)

[a] For diverging broad beams, axes are normal to slab shields.
[b] Unidirectional broad beams are normally incident on slab shields.
[c] Polymethyl methacrylate $(C_5H_8O_2)_n$. Other trade names: Lucite, Plexiglass.

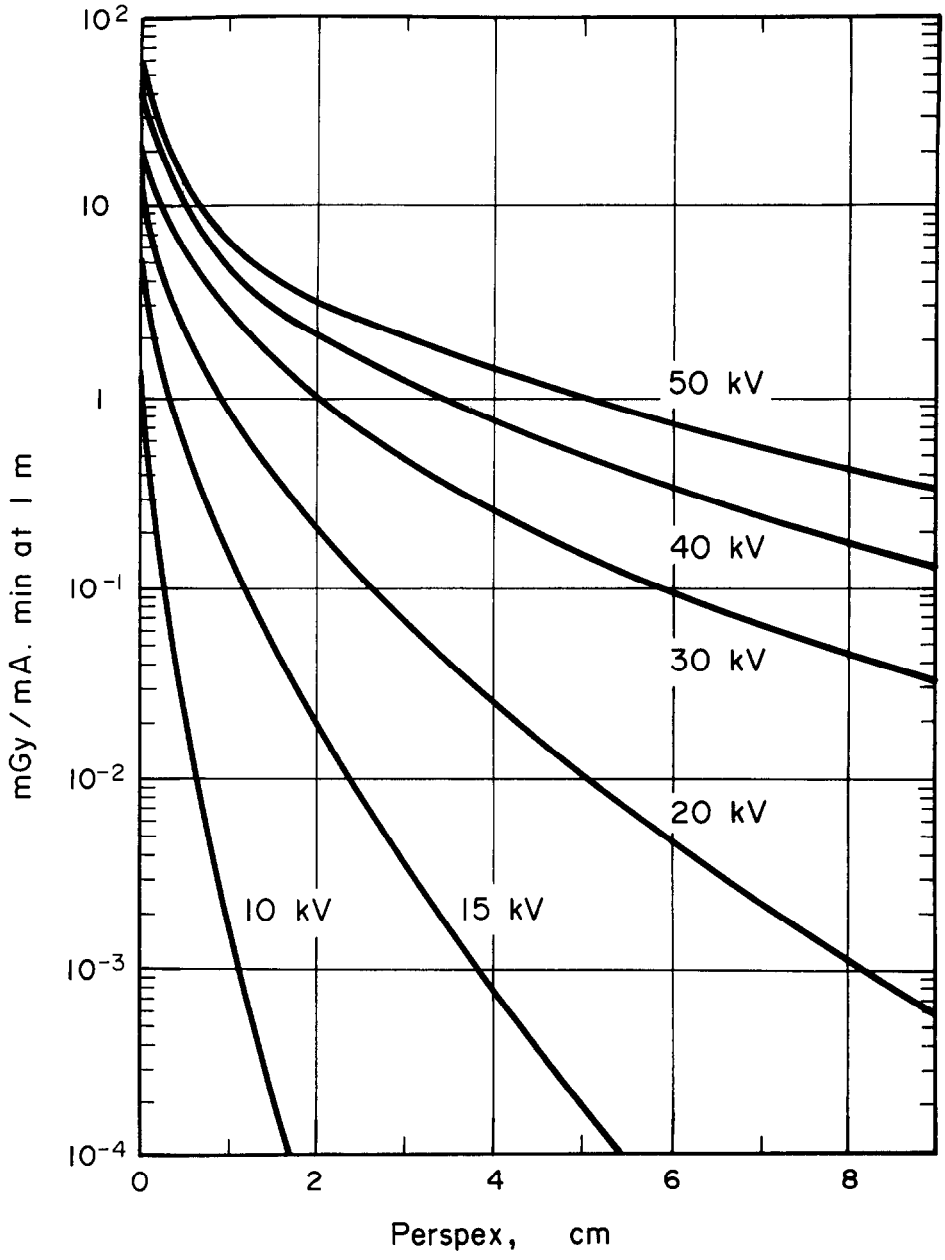

Fig. 5. Broad-beam transmission of x rays through Perspex, density 1 200 kg m^{-3}. Constant potential generator, tungsten reflection target; 1 mm beryllium total beam filtration. Ordinate intercepts are 72.91 at 50 kV; 57.24 at 40; 39.06 at 30.

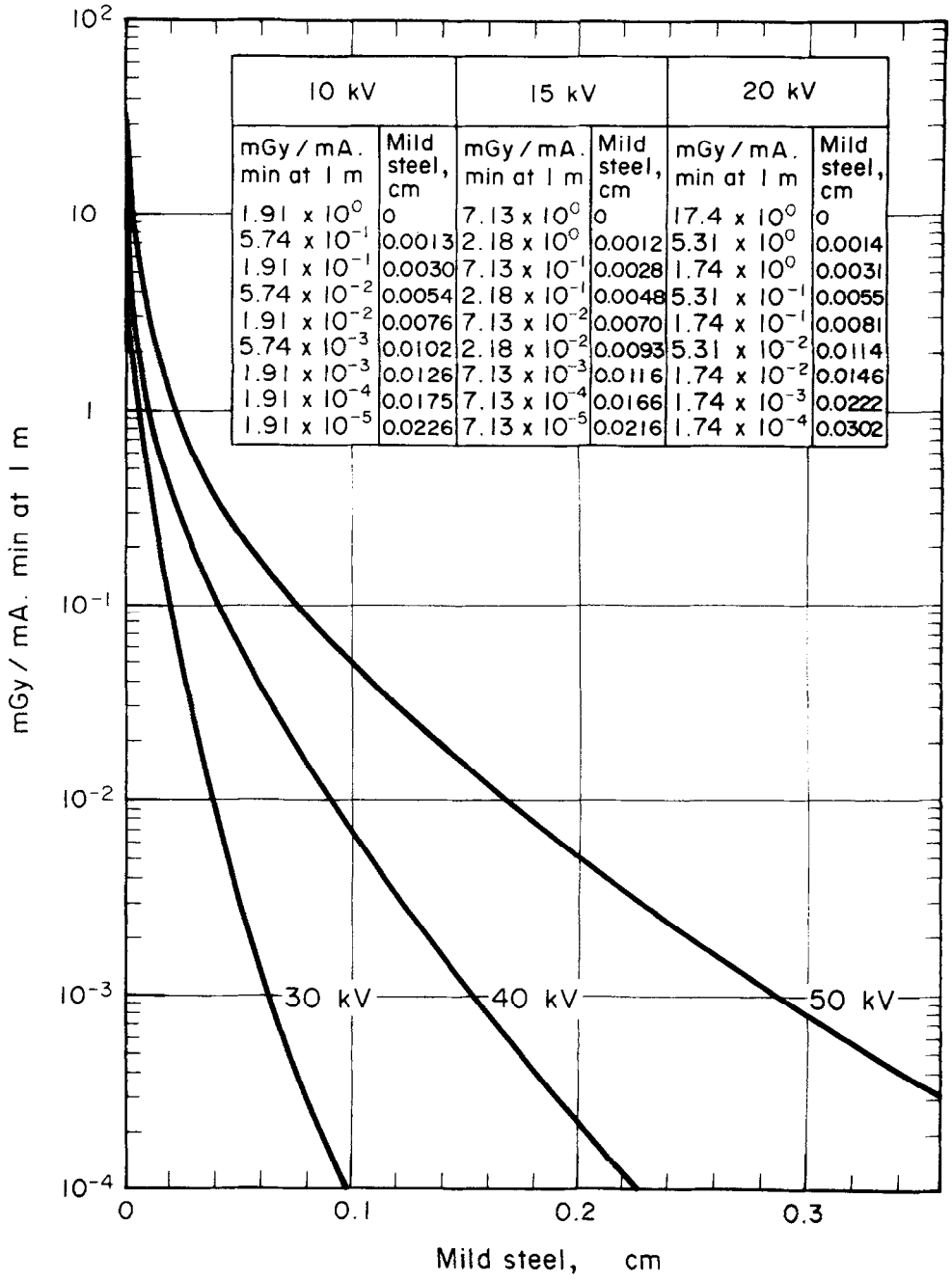

Fig. 6. Broad-beam transmission of x rays through mild steel, density 7 800 kg m^{-3}. Constant potential generator; tungsten reflection target; 1 mm beryllium total beam filtration. Ordinate intercepts are 72.91 at 50 kV; 57.24 at 40; 39.06 at 30.

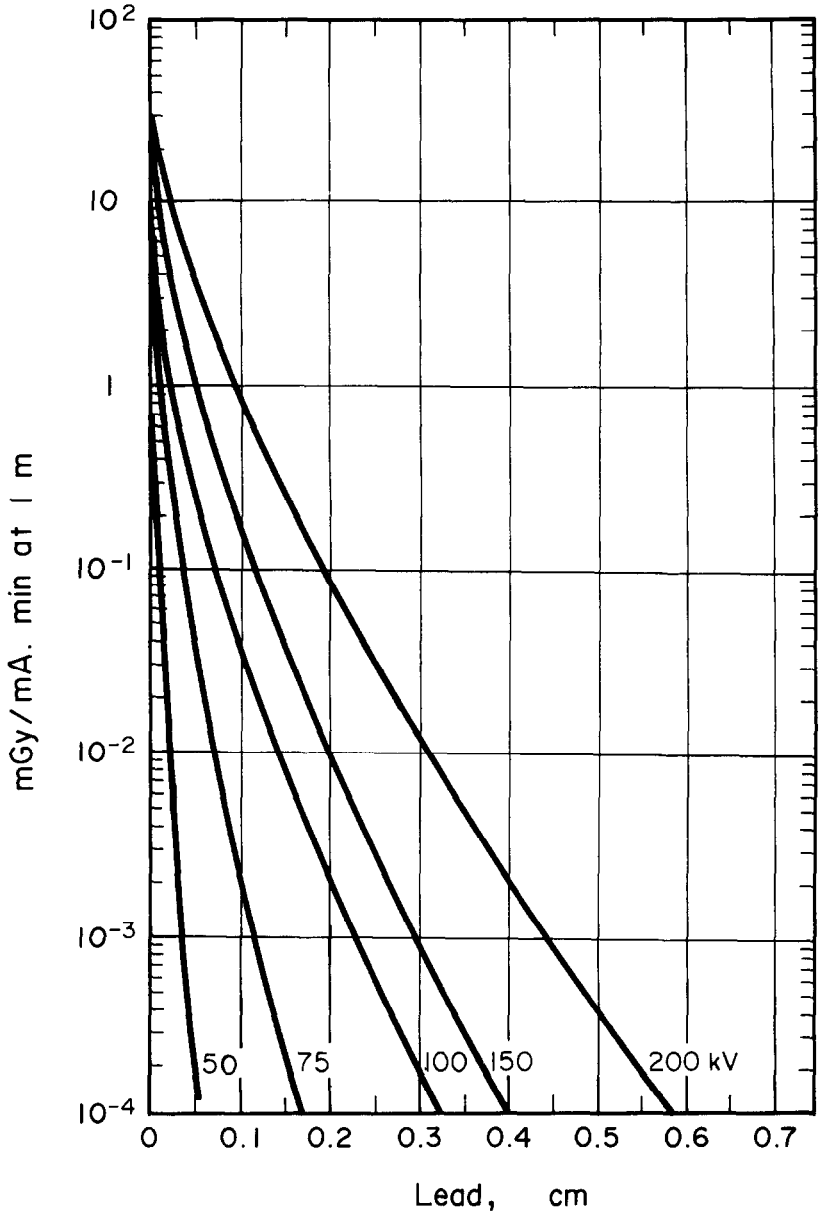

Fig. 7. Broad-beam transmission of x rays through lead, density 11 350 kg m^{-3}. Constant potential generator; tungsten reflection target; 2 mm aluminium total beam filtration. Ordinate intercepts are 28.7 at 200 kV, 18.3 at 150, 9.6 at 100, 6.1 at 75, 2.6 at 50.

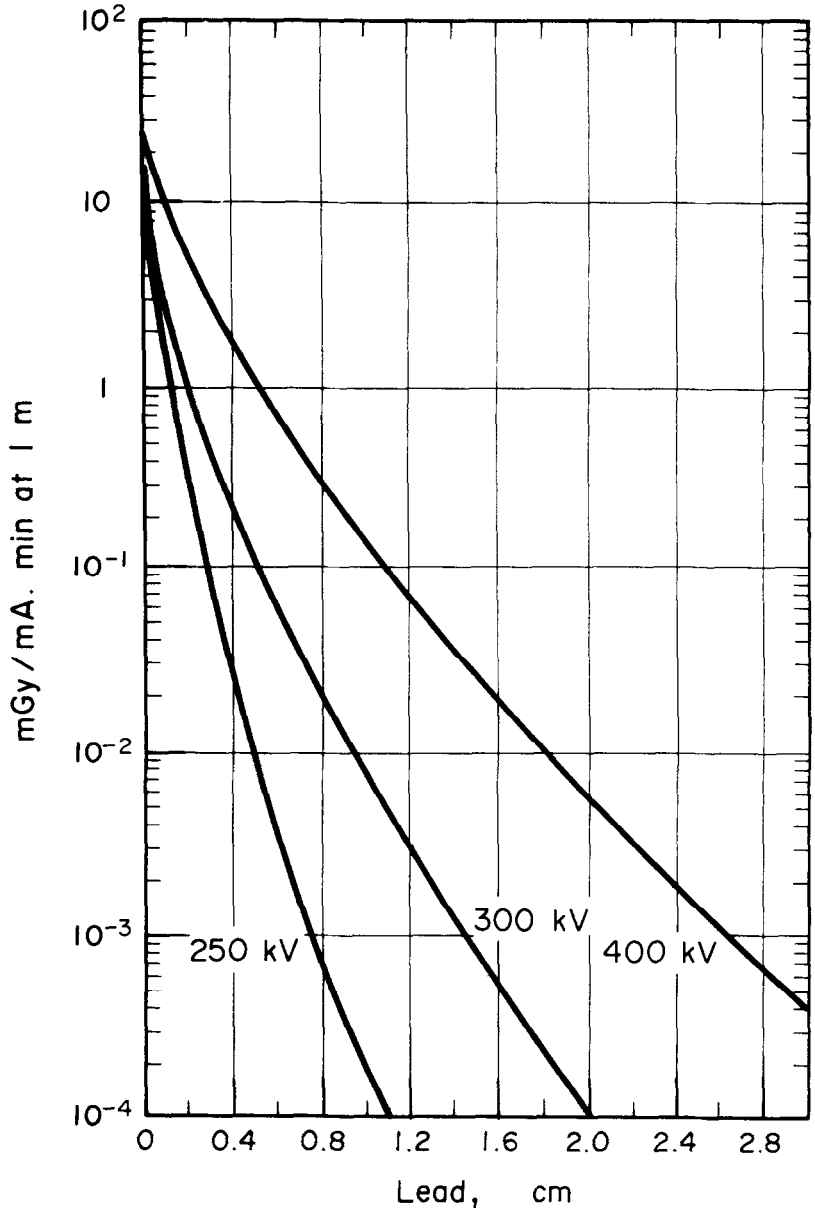

Fig. 8. Broad-beam transmission of x rays through lead, density 11 350 kg m^{-3}. 250 kV; constant potential generator; tungsten reflection target; 0.5 mm copper total beam filtration. 300 and 400 kV: constant potential generator; gold reflection target; 3 mm copper total beam filtration. Ordinate intercepts are 23.5 at 400 kV, 11.3 at 300, 16.5 at 250.

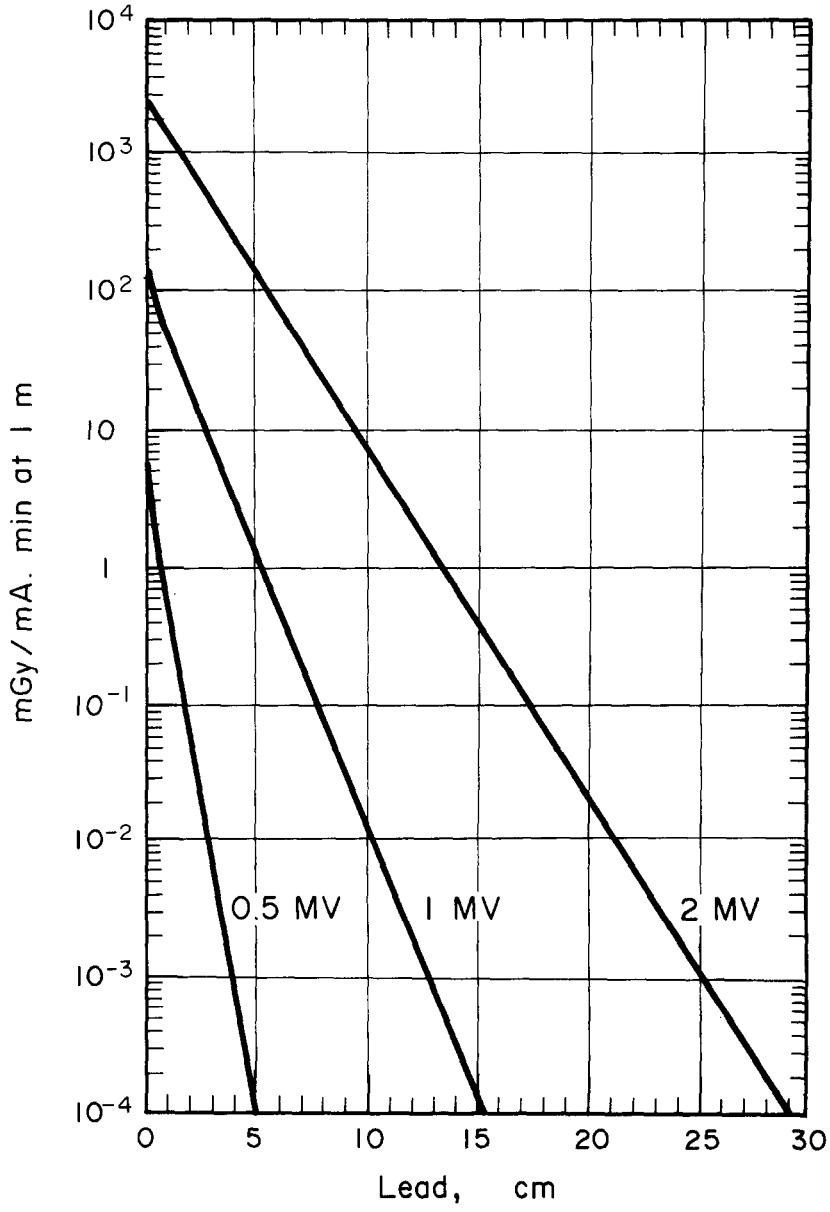

Fig. 9. Broad-beam transmission of x rays through lead, density 11 350 kg m^{-3}. Constant potential generators. 0.5 and 1.0 MV: 2.8 mm tungsten transmission target followed by 2.8 mm copper, 18.7 mm water, and 2.1 mm brass beam filtration. 2 MV: high atomic number transmission target; 6.8 mm lead equivalent total beam filtration. Ordinate intercepts are 2610 at 2 MV, 174 at 1, 9 at 0.5.

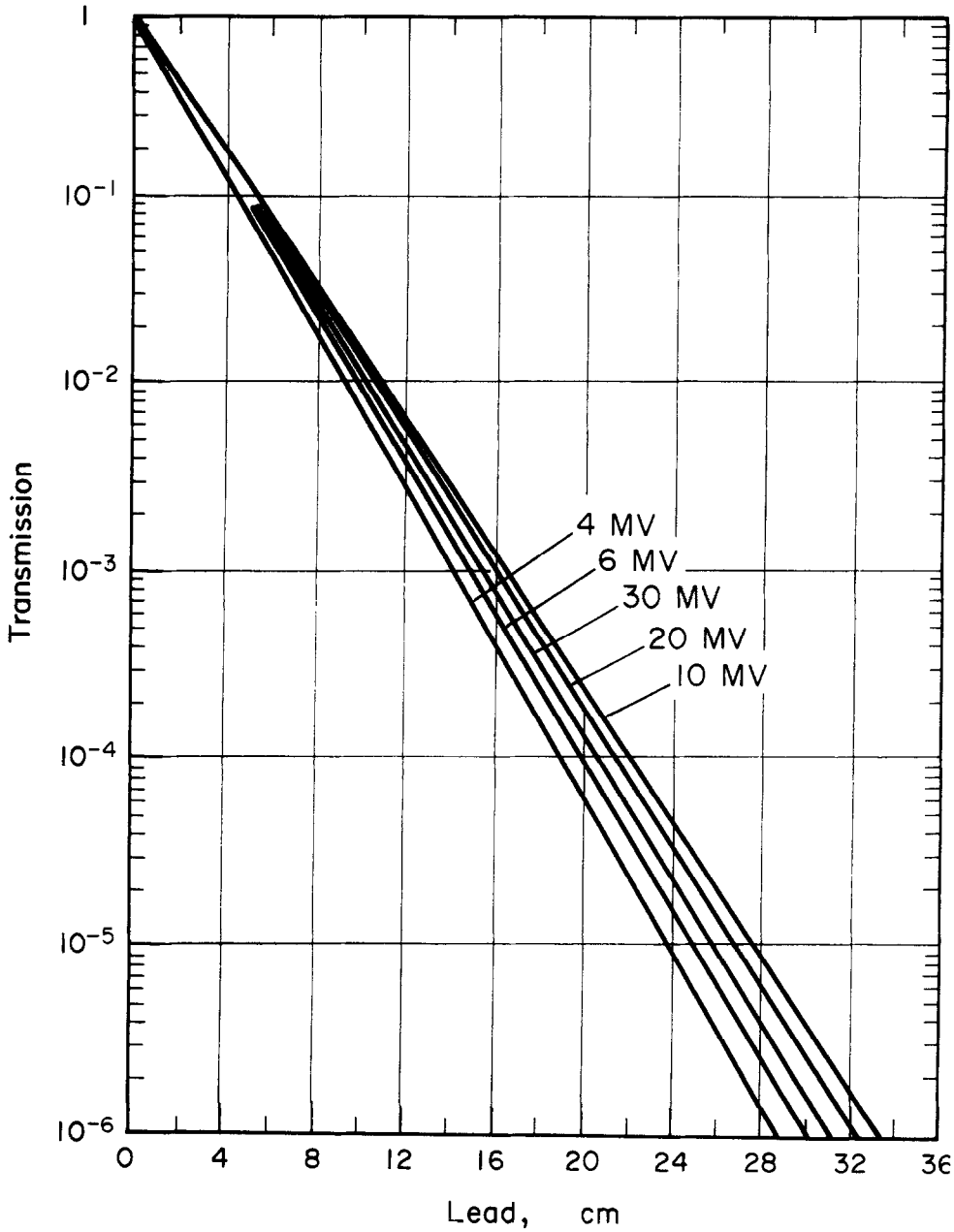

Fig. 10. Broad-beam transmission of x rays through lead, density 11 350 kg m^{-3}. Betatron; platinum wire target 2 × 8 mm; no beam filtration. For higher potential, see Miller and Kennedy (1956).

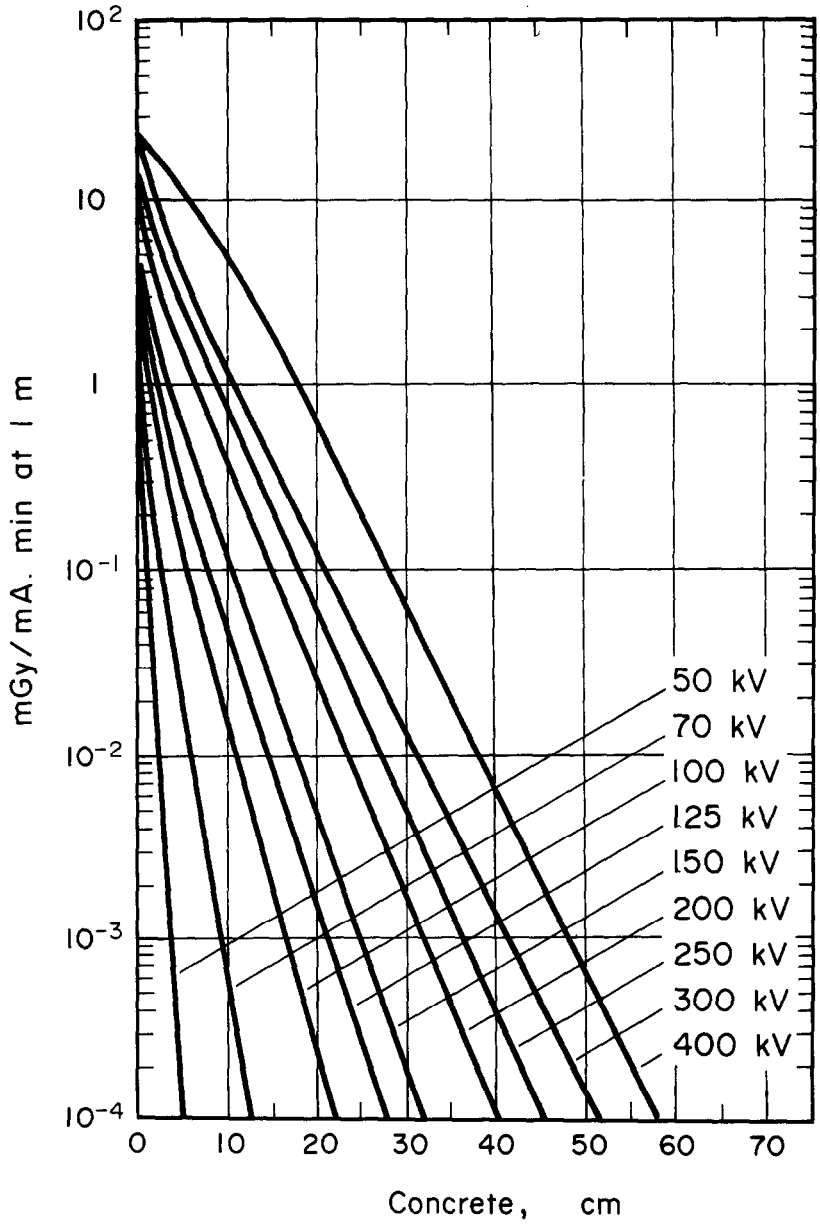

Fig. 11. Broad-beam transmission of x rays through concrete, density 2 350 kg m^{-3}. 50–300 kV: half-wave generator; tungsten reflection target; total beam filtration 1 mm aluminium at 50 kV, 1.5 at 70, 2 at 100, and 3 at 125–300. 400 kV: constant potential generator; gold reflection target; 3 mm copper total beam filtration. Ordinate intercepts are 23.5 at 400 kV, 20.9 at 300, 13.9 at 250, 8.9 at 200, 5.2 at 150, 3.9 at 125, 2.8 at 100, 2.1 at 70, 1.7 at 50.

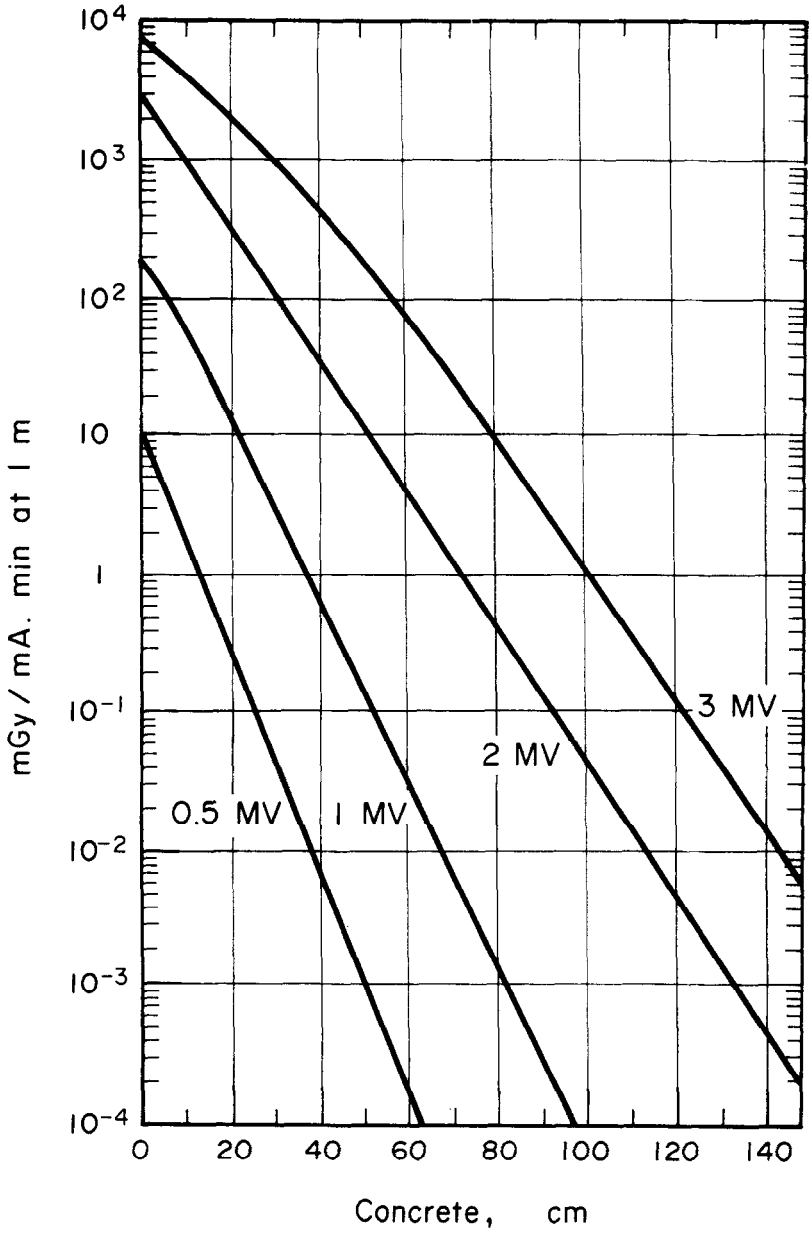

Fig. 12. Broad-beam transmission of x rays through concrete, density 2 350 kg m^{-3}. Constant potential generators 0.5 and 1.0 MV: 2.8 mm tungsten transmission target followed by 2.8 mm copper, 18.7 mm water, and 2.1 mm brass beam filtration. 2 MV: high atomic number transmission target; 6.8 mm lead equivalent total beam filtration. 3 MV: gold transmission target; 11 mm lead equivalent total beam filtration. Ordinate intercepts are 7 400 at 3 MV, 2 600 at 2, 170 at 1, 9 at 0.5

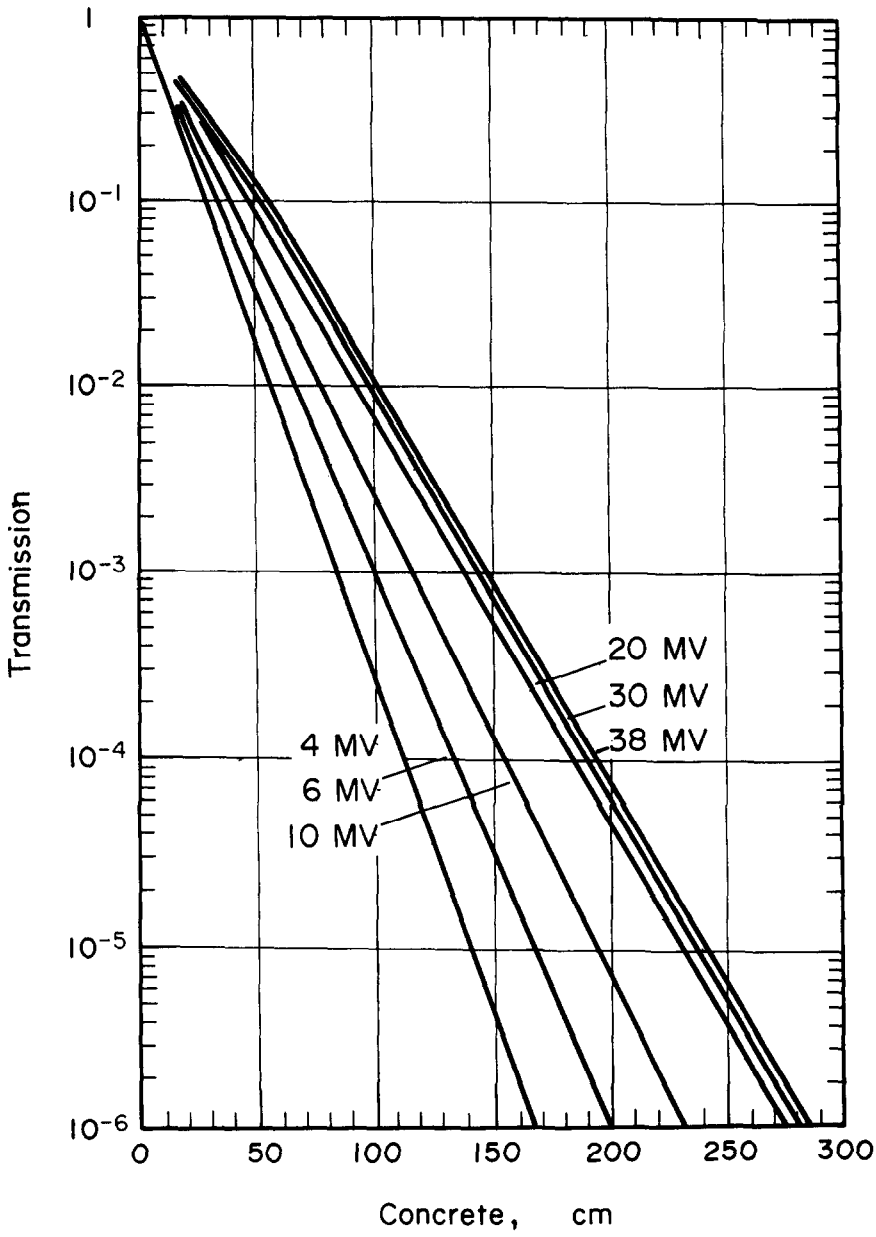

Fig. 13. Broad-beam transmission of x rays through concrete, density 2 350 kg m^{-3}. 4 MV: linear accelerator; 1 mm gold target followed by 20 mm aluminium beam flattener. 6–38 MV: Betatron; target and filtration not stated. The 38 MV curve may be used up to 200 MV (Miller and Kennedy, 1956).

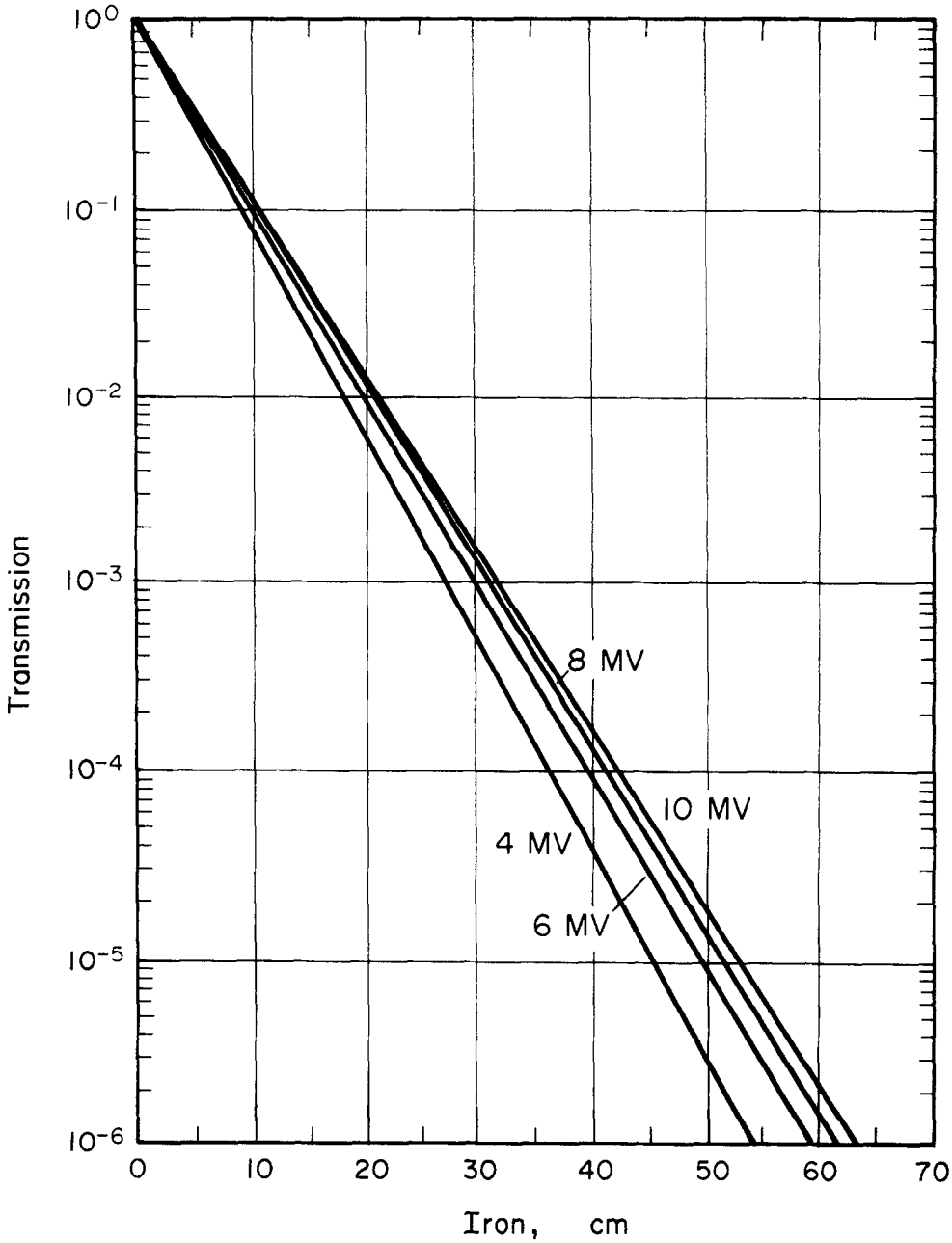

Fig. 14. Transmission of x rays, produced at 4–10 MV, through iron, density 7 800 kg m^{-3} (from NCRP Report No. 49 and Maruyama).

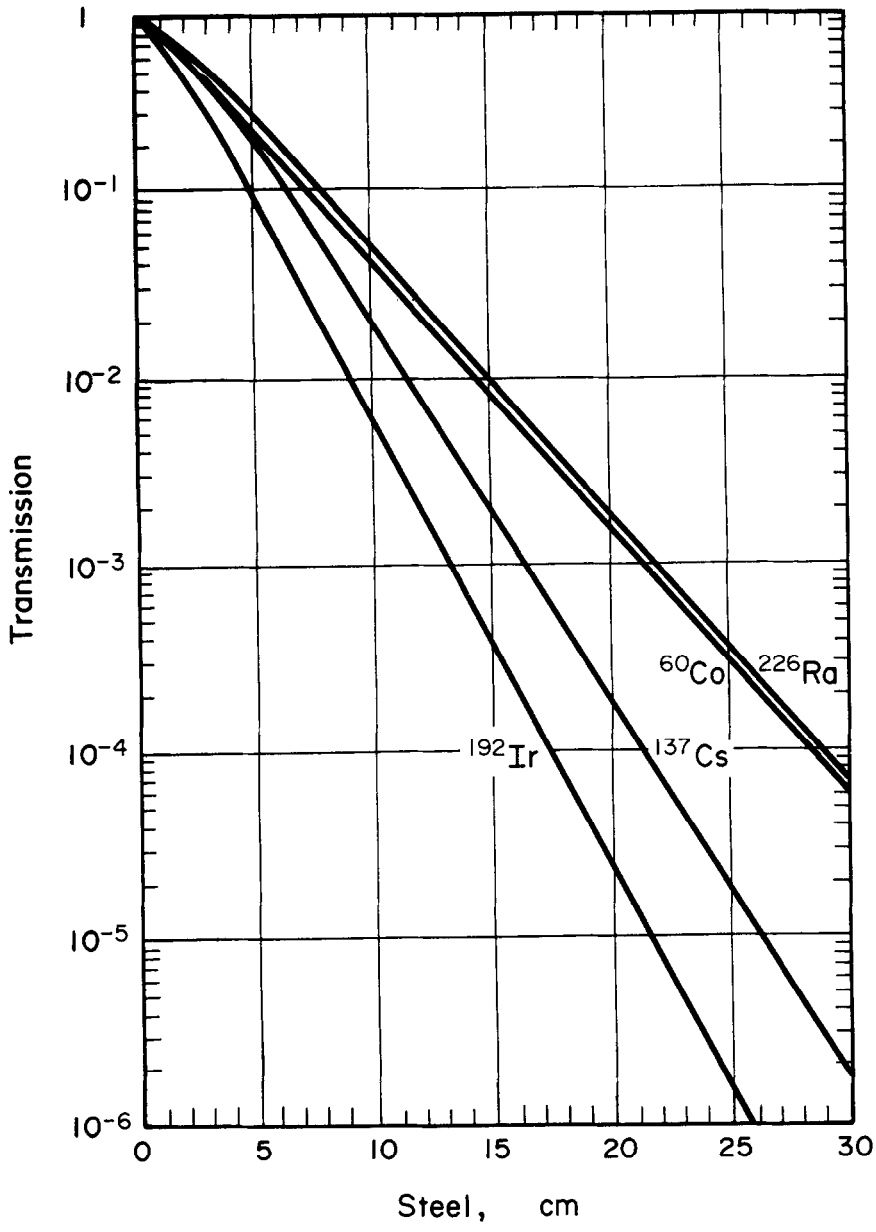

Fig. 15. Broad-beam transmission of gamma rays from various radionuclides through steel, density 7 800 kg m^{-3}

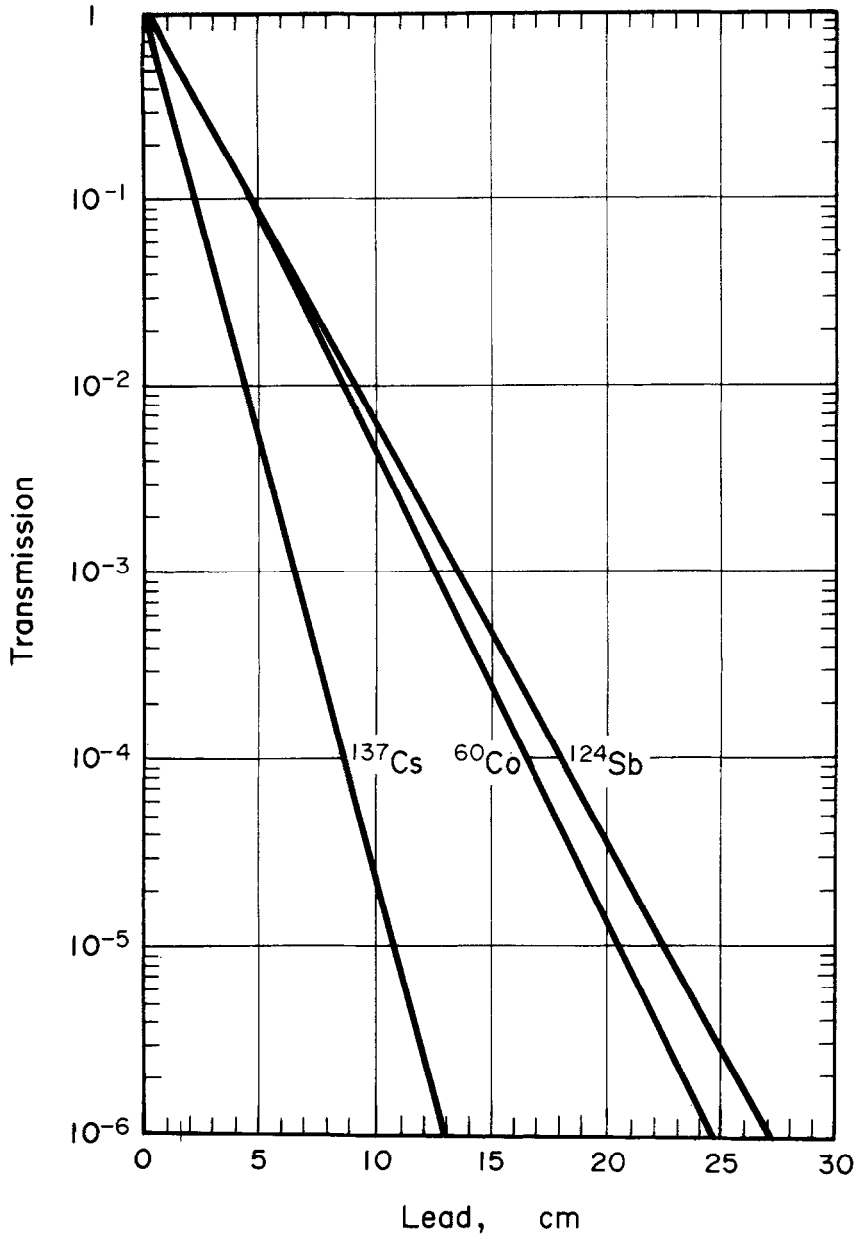

Fig. 16. Broad-beam transmission of gamma rays from various radionuclides through lead, density 11 350 kg m^{-3}.

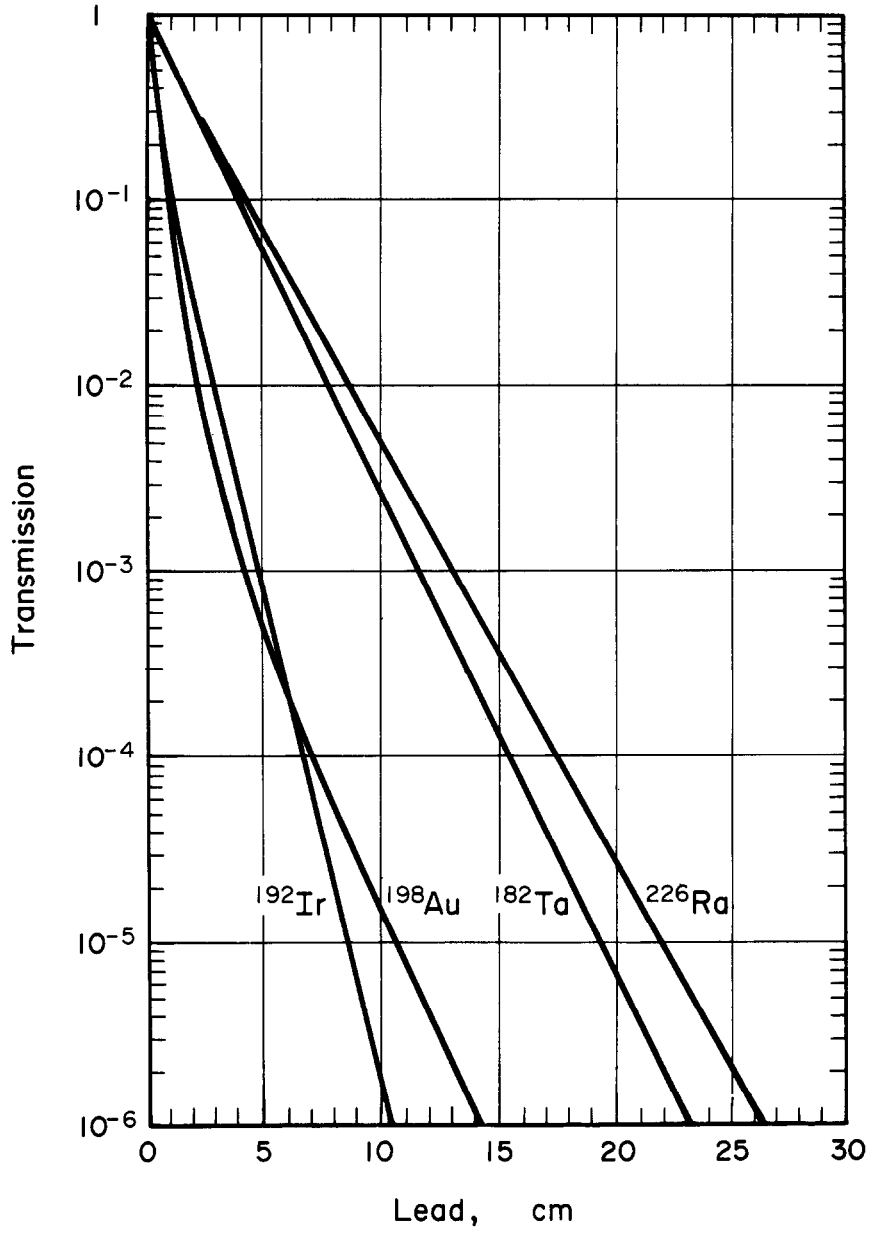

Fig. 17. Broad-beam transmission of gamma rays from various radionuclides through lead, density 11 350 kg m^{-3}

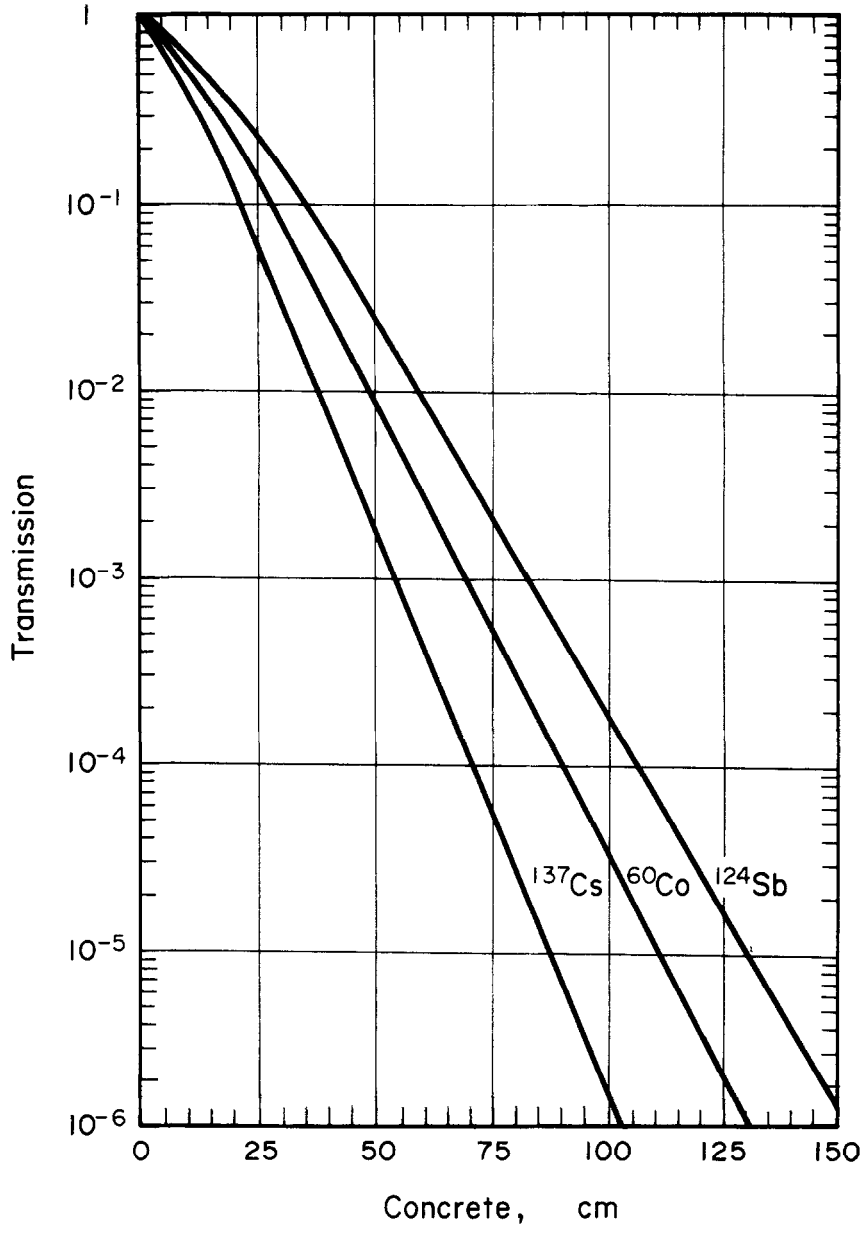

Fig. 18. Broad-beam transmission of gamma rays from various radionuclides through concrete, density 2 350 kg m^{-3}.

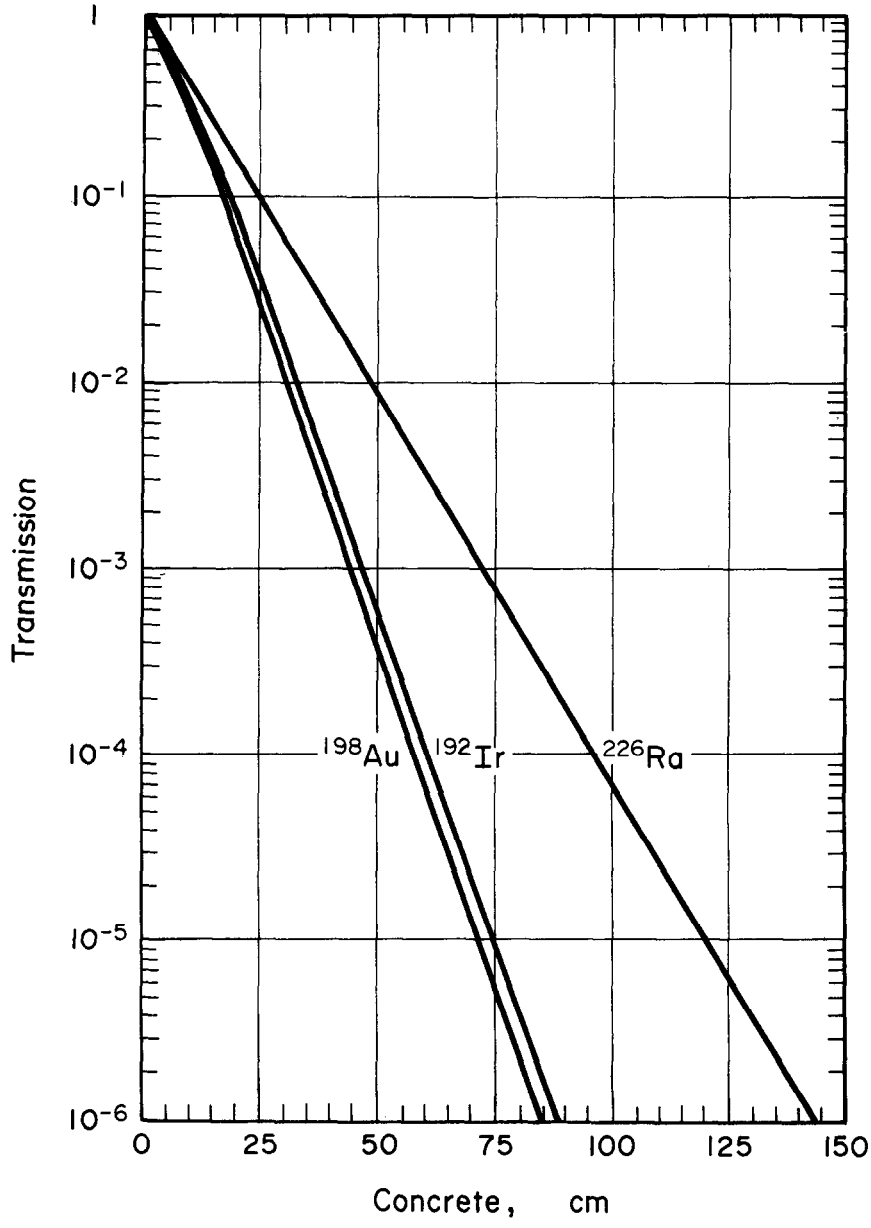

Fig. 19. Broad-beam transmission of gamma rays from various radionuclides through concrete, density 2 350 kg m^{-3}.

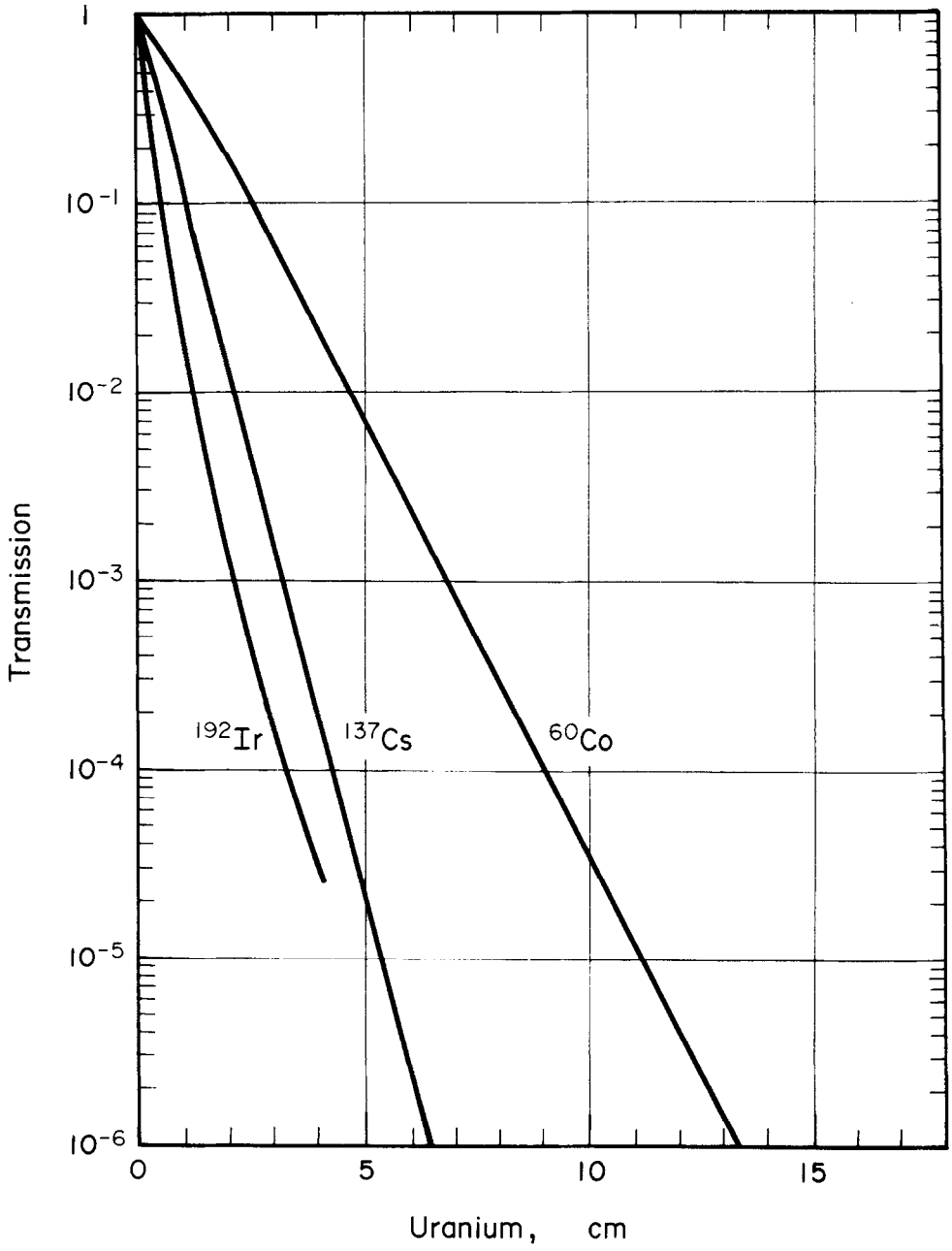

Fig. 20. Broad-beam transmission of gamma rays from various radionuclides through uranium, density 18 900 kg m^{-3}.

correction factor equal to the ratio of the densities. This procedure should not, however, be extended to markedly different aggregates, especially at low photon energies. (See the section below on the shielding values of selected materials for low energy x rays.)

(232) It is advisable to use low radioactivity building materials for shielding certain areas such as long-term stores for x-ray film, and whole-body counting laboratories (Lindell and Reizenstein, 1964; Hamilton, 1971).

Transmission of Obliquely Incident Beams

(233) Attention is drawn to the problem created by the oblique incidence of beams on slab shields (Kirn *et al.*, 1954). Shielding estimated on the basis of slant thickness using normal incidence data must be increased to allow for the accentuated transmission of scattered photons. For example, if the required transmission is 10^{-3} and the angle of incidence 45°, the increase required in concrete thickness is about 20% at low energies and 10% at high energies; the increase for lead, in similar circumstances, is negligible. (See British Standard 4094 (1966) and NCRP Report No. 34 (1970).)

Half-value thicknesses and tenth-value thicknesses

(234) Half value thicknesses (HVT) and tenth-value thicknesses (TVT) for heavily attenuated broad beams of x rays and gamma rays are presented in Tables 3 and 4, the values being obtained from the lowest decades of the transmission curves in Figs. 5–20. Because of the shapes of many of the transmission curves, HVT and TVT cannot be used to calculate primary shielding requirements; they may be used, however, to calculate the shielding required for leakage radiation.

Table 3. Approximate half-value thicknesses and tenth-value thicknesses for heavily attenuated broad beams of x rays

X-ray source	Half-value thicknesses, cm		Tenth-value thicknesses, cm	
	Lead	Concrete	Lead	Concrete
50 kV	0.005	0.4	0.018	1.3
70	—	1.0	—	3.6
75	0.015	—	0.050	—
100	0.025	1.6	0.084	5.5
125	—	1.9	—	6.4
150	0.029	2.2	0.096	7.0
200	0.042	2.6	0.14	8.6
250	0.086	2.8	0.29	9.0
300	0.17	3.0	0.57	10.0
400	0.25	3.0	0.82	10.0
0.5 MV	0.31	3.6	1.03	11.9
1	0.76	4.6	2.52	15.0
2	1.15	6.1	3.90	20.1
3	—	6.9	—	22.6
4	1.48	8.4	4.9	27.4
6	1.54	10.2	5.1	33.8
10	1.69	11.7	5.6	38.6
20	1.63	13.7	5.4	45.7
30	1.57	13.7	5.2	45.7
38	—	13.7	—	45.7

Table 4. Approximate half-value thicknesses and tenth-value thicknesses for heavily attenuated broad beams of gamma rays

	Material							
	Uranium, cm		Lead, cm		Steel, cm		Concrete, cm	
Nuclide	HVT	TVT	HVT	TVT	HVT	TVT	HVT	TVT
^{60}Co	0.7	2.2	1.2	4.0	2.0	6.7	6.1	20.3
^{137}Cs	0.3	1.1	0.7	2.2	1.5	5.0	4.9	16.3
^{182}Ta	—	—	1.2	4.0	—	—	—	—
^{192}Ir	0.4	1.2	0.6	1.9	1.3	4.3	4.1	13.5
^{198}Au	—	—	1.1	3.6	—	—	4.1	13.5
^{226}Ra	—	—	1.3	4.4	2.1	7.1	7.0	23.3

Shielding Values of Selected Materials for Low Energy X Rays

(235) Because transmission depends sharply, at low photon energies, on the composition of the shield, it is necessary to know the shielding values of materials commonly used in x-ray installations. The traditional way of expressing these shielding values is to tabulate the lead equivalence of the materials as a function of thickness and x-ray generating potential, and this is done, in Table 5, for clay brick, barytes aggregate concrete, and steel. The data relate to beam

Table 5. Lead equivalence of various materials for low energy x rays[a]

	Material density	Material thickness	cm lead equivalent at applied kilovoltages of							
Material	(kg m^{-3})	(cm)	50	75	100	150	200	250	300	400
Clay brick[b]	1 600	10	0.06	0.08	0.09	0.08	0.08	0.10	0.11	0.13
		20	0.14	0.17	0.19	0.17	0.17	0.23	0.30	0.45
		30	0.22	0.27	0.31	0.26	0.26	0.40	0.55	0.85
		40	—	0.38	0.45	0.37	0.37	0.60	0.83	1.27
		50	—	—	—	0.48	0.48	0.81	1.13	1.71
Barytes plaster or concrete[b]	3 200	1.0	0.09	0.15	0.18	0.09	0.07	0.06	0.06	0.08
		2.0	0.18	0.27	0.33	0.18	0.14	0.13	0.14	0.16
		2.5	0.23	0.33	0.40	0.22	0.17	0.17	0.18	0.20
		5.0	—	—	—	0.43	0.34	0.36	0.39	0.43
		7.5	—	—	—	0.59	0.50	0.56	0.61	0.68
		10.0	—	—	—	—	0.68	0.77	0.84	0.95
		12.5	—	—	—	—	—	—	1.08	1.21
Steel[c,d]	7 800	0.1	—	0.01	0.02	0.01	0.01	—	—	—
		0.2	—	0.03	0.03	0.02	0.02	—	—	—
		0.3	—	0.05	0.05	0.03	0.03	—	—	—
		0.4	—	0.07	0.07	0.04	0.04	—	—	—
		0.5	—	0.09	0.09	0.05	0.04	0.03	0.03	0.04
		1.0	—	—	—	0.09	0.08	0.08	0.08	0.09
		2.0	—	—	—	0.17	0.16	0.17	0.19	0.24
		3.0	—	—	—	0.25	0.23	0.28	0.33	0.43
		4.0	—	—	—	0.33	0.30	0.38	0.47	0.65
		5.0	—	—	—	0.40	0.37	0.49	0.63	0.88

[a] See text regarding geometry.
[b] Binks (1955).
[c] Kaye *et al.* (1938).
[d] Trout and Gager (1950).

geometries between narrow and broad; consequently the shielding values are over-estimated. Although determined with pulsating potential generators, the tabulated data may also be used in the constant potential case.

Scattering of X Rays and Gamma Rays

(236) It is convenient here to refer to all photons emitted by an irradiated object as scattered radiation, although some of them are not due to Compton interactions.

(237) There are two steps in designing a shield against scattered x rays and gamma rays: firstly, it is necessary to determine the absorbed dose rate resulting from the scattered radiation; secondly, it is necessary to estimate the shield thickness required to reduce this scattered radiation to the acceptable level.

(238) Figures 21 and 22, and Table 6, indicate the absorbed dose rate (kerma rate) measured in air due to scatter in typical situations. Figure 21 shows the variation with accelerating potential of x rays scattered at 90° from various thick scatterers (Wachsmann *et al.*, 1964). The beam is filtered so that its effective energy is about half the maximum photon energy; thus the figure may be used for gamma rays by reading from the curves the percentage scatter at the point corresponding to twice the gamma-ray energy. Note the dominating influence of the characteristic radiation from lead at low potentials (Lindell, 1954). The scattering patterns of diverging x-ray and gamma-ray beams, normally incident on a thick concrete shield, are shown in Fig. 22. The references are: 100–300 kV *ICRP Publication 21*; ^{60}Co, Dixon *et al.* (1952); Mooney and Braestrup (1957); 6 MV, Karzmark and Capone (1968). Table 6 indicates the amount of radiation scattered at various angles by patient-simulating phantoms for ^{60}Co gamma rays and for x rays generated at various potentials.

Table 6. Per cent of absorbed dose (kerma) rate due to incident radiation scattered to 1 m by a tissue-like phantom for 400 cm^2 irradiated area[a]

Angle of scatter	100 kV[b]	200 kV[b]	300 kV[b]	^{60}Co[c,e]	6 MV[d,e]
15°	—	—	—	— (0.48)	0.65 (0.48)
30°	0.02	0.24	0.34	— (0.27)	0.30 (0.24)
45°	0.03	0.23	0.26	0.18 (0.14)	0.14 (0.12)
60°	0.04	0.19	0.22	0.14 (0.08)	0.08 (0.07)
90°	0.05	0.14	0.19	0.07 (0.04)	0.04 (0.03)
120°	0.12	0.23	0.26	0.05 (0.03)	0.03 (0.02)
135°	0.17	0.30	0.33	0.04 (0.02)	0.03 (0.02)
150°	0.21	0.37	0.48	— (0.02)	— (0.02)

[a] Per cent scattered radiation is related to primary beam measurements in air at the point of reference, that is, at the same position as the phantom surface or phantom centre.

[b] Bomford and Burlin (1963). Cuboid phantom 30 cm wide × 22 cm deep. Field area and angle of scattered radiation referred to phantom surface.

[c] Dixon *et al.* (1952). Elliptic cylinder phantom 36 cm major axis, 20 cm minor axis. Field area and angle of scattered radiation referred to phantom centre. Beam along major axis.

[d] Karzmark and Capone (1968). Cylinder phantom 27 cm diameter. Field area and angle of scattered radiation referred to phantom centre.

[e] Figures in brackets are from Nilsson (1975): spherical tissue irradiated; equivalent phantoms with masses in the range 0.9–30 kg. Sources located in a separate room with a collimator in the intervening wall, which largely eliminated problems of scattered radiation from the walls.

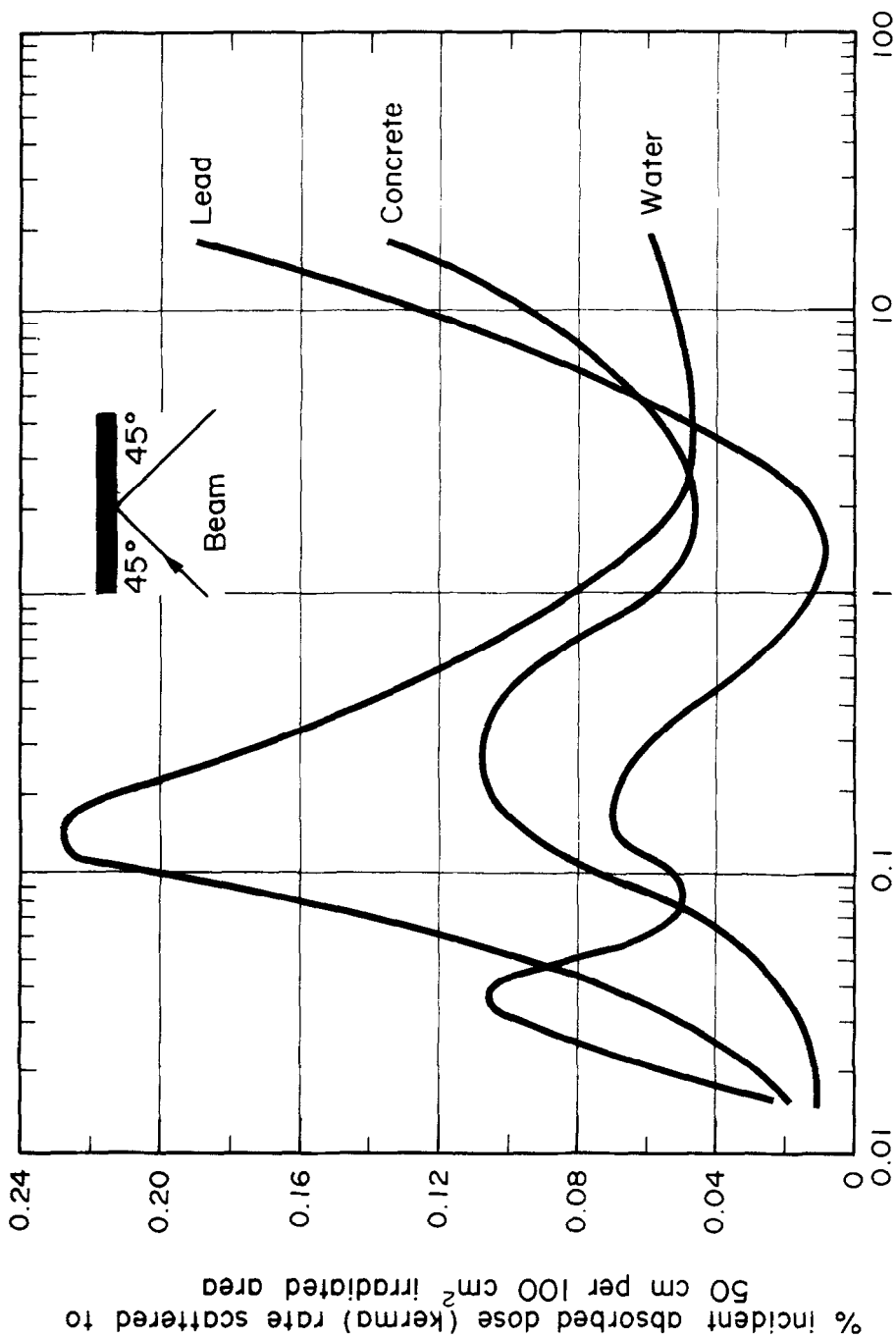

Fig. 21. Variation with potential of the absorbed dose (kerma) rate measured in air due to x rays scattered at 90° from various materials. The beam is obliquely incident on the thick scatterer. Per cent scatter is related to primary beam measurements in free air at the point of incidence.

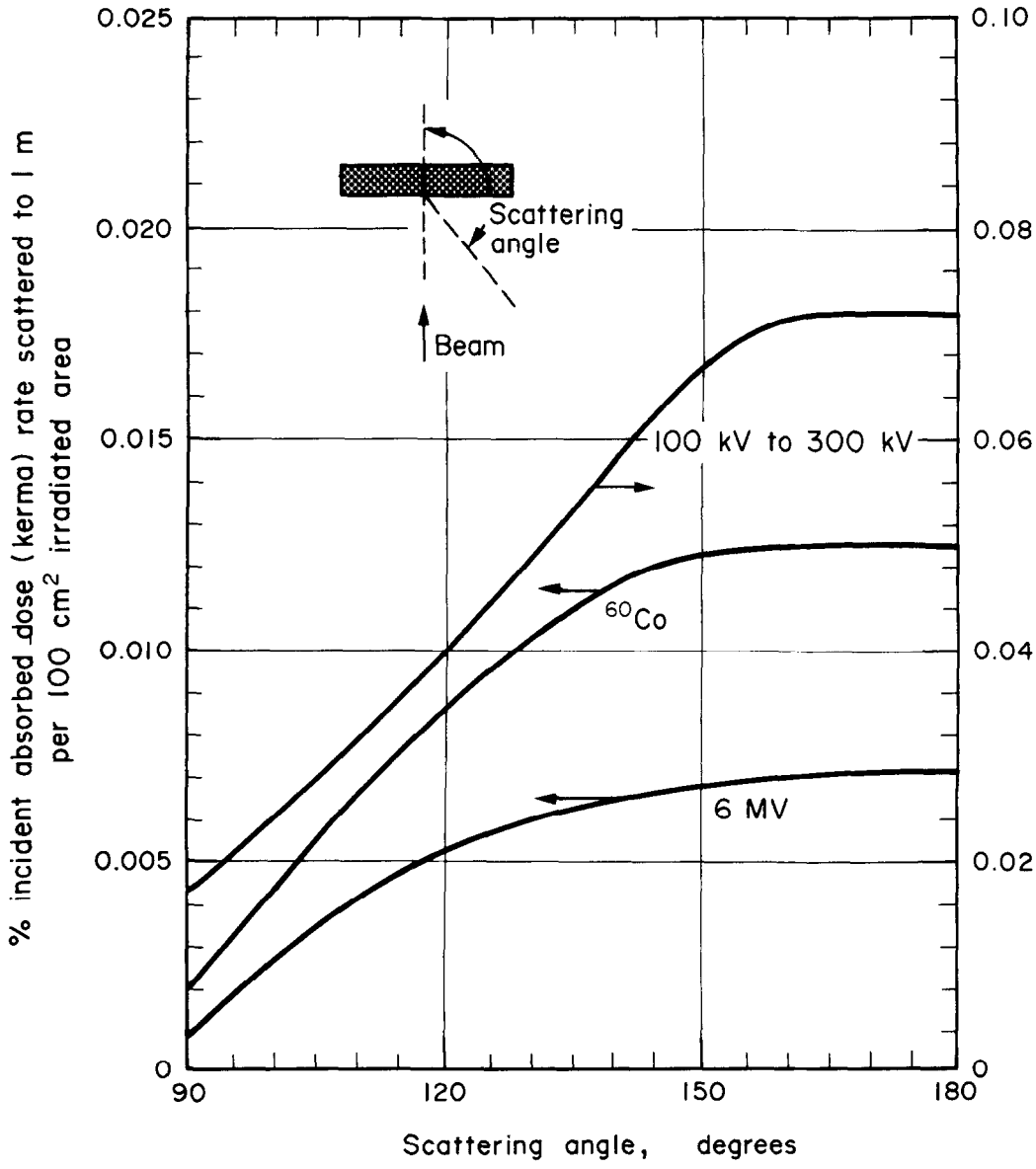

Fig. 22. Scattering patterns of diverging x-ray and gamma-ray beams normally incident on a concrete shield. Per cent scatter is related to primary beam measurements in free air at the point of incidence.

(239) The percentage scattered radiation varies with the irradiated area; there is an approximately linear relationship between these two parameters for the field areas normally encountered in medical radiology. The relationship may, however, lead to an overestimate of scattered radiation for very large fields (British Standard, 4094, 1971).

(240) A situation in which scattered radiation may present special difficulties should be noted (British Standard 4094, 1966). Large amounts of scatter may be encountered in maze entrances to radiation rooms. Detailed information about radiation scattered down mazes, and about

shielding doors at the end of a maze, is given in NCRP Report 51 (1977) and in Toy and Hoecker (1973). An example is given in the following paragraph.

(241) If the corner of a personnel maze is completely irradiated, the exposure rate 1 m down the sheltered leg is about 10% of the exposure rate at the centre of the corner, and it decreases approximately as the inverse square of the distance from the corner centre.

Transmission of Scattered Radiation through Shields

(242) Figures 23 and 24 show the transmission through concrete and lead of ^{137}Cs gamma rays scattered from an oblique concrete wall (Frantz and Wyckoff, 1959). Figures 25 and 26 show the transmission through concrete and lead of ^{60}Co gamma rays scattered from a patient-simulating phantom (Dixon *et al.*, 1952). Figure 27 shows the transmission through concrete of 6 MV x rays scattered at various angles from a phantom (Karzmark and Capone, 1968). All the above refer to broad beams.

(243) Where specific x-ray scattered radiation data are not available, an approximate method, suggested by Braestrup and Wyckoff (1958), may be used. 90° scatter is identified as the principal component of scattered radiation in typical shielding situations, and its attenuation characteristics in three bands, below 0.5 MV, 0.5–3 MV, and above 3 MV are considered. Below 0.5 MV, 90° scattered radiation may be assumed to have the same attenuation characteristics as the primary beam; consequently, the transmission data for the primary beam may be used to estimate the shielding required for scattered radiation. Trout and Kelley (1972) indicate the over-estimation inherent in this method at potentials up to 0.3 MV for lead shields: the overestimation is less for concrete. From 0.5 to 3 MV, the attenuation characteristics of 90° scatter are similar to those of a 0.5 MV primary beam (*ICRP Publication 21*) so that the transmission data for 0.5 MV x rays may be used. Above 3 MV, 90° scattered photons may be considered to have an energy of about 0.5 MeV, so that the 1 MV primary beam transmission data may be used in calculating shielding against scattered radiation.

(244) The method may be extended to gamma-ray sources by assuming that the generating potentials, in MV, are numerically twice the photon energies in MeV.

Transmission of Leakage Radiation through Shields

(245) It may be necessary to provide shielding against leakage radiation from a tube or source housing. Since this radiation is appreciably attenuated in passing through the housing, further attenuation is virtually exponential. Shielding against leakage radiation may therefore be estimated in terms of the requisite number of half-value thicknesses (HVT) or tenth-value thicknesses (TVT) using the values set down in Tables 3 and 4.

Shielding for Combined Scattered and Leakage Radiation

(246) It is usually necessary to determine the shielding required for scattered and leakage radiation combined. When calculations yield shield thicknesses for scatter and leakage radiation which differ by 1 TVT or more, the thicker shield should be adopted: if they differ by less than 1 TVT, however, the thicker shield should be adopted and 1 HVT added.

Formulae for Designing X-Ray and Gamma-ray Shields

(247) The boundary conditions for work (categories A and B, see para. 52) and for members of

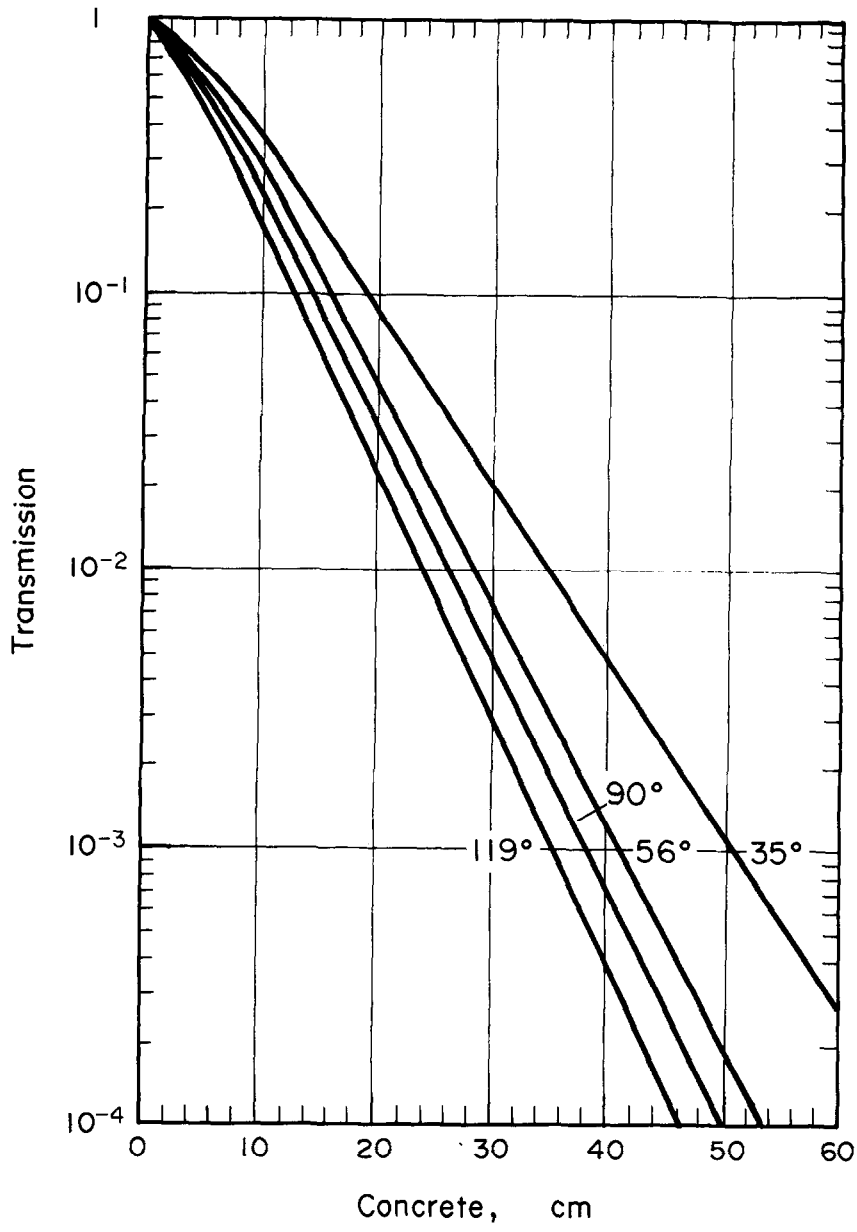

Fig. 23. Broad-beam transmission of ^{137}Cs gamma rays scattered at various angles from an oblique concrete wall through concrete, density 2 350 kg m^{-3}.

the general public set by the Commission shall not be used for design of radiation protection shielding. It may be helpful, however to calculate the shielding which would be required to assure that the boundary conditions are met. The following formula should be used as a starting point for calculating the boundary constraint, in respect of the primary beam:

$$B = \frac{Pd^2}{WUT}$$

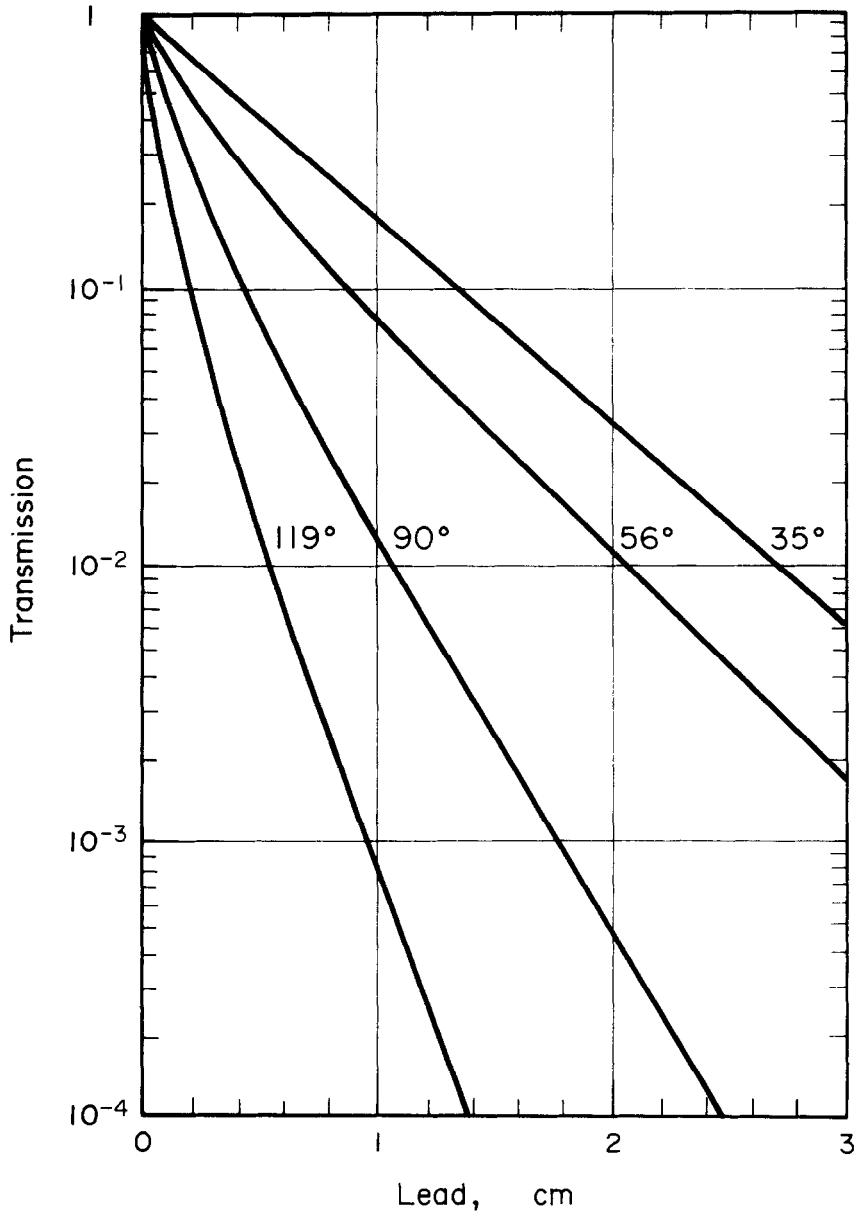

Fig. 24. Broad-beam transmission of ^{137}Cs gamma rays scattered at various angles from an oblique concrete wall through lead, density 11 350 kg m^{-3}.

where B is the transmission, d is the distance in metres from the source to the location of interest, W is the weekly workload (e.g. mA min per week or absorbed dose at 1 m), U is the use factor (fraction of the workload directed towards the location of interest), T is the occupancy factor and P is the boundary condition in terms of weekly dose equivalent, or collective dose equivalent. The shield thickness corresponding to the calculated value of B is read from the appropriate transmission curve.

(248) The calculation can be repeated with progressively lower values of P until the

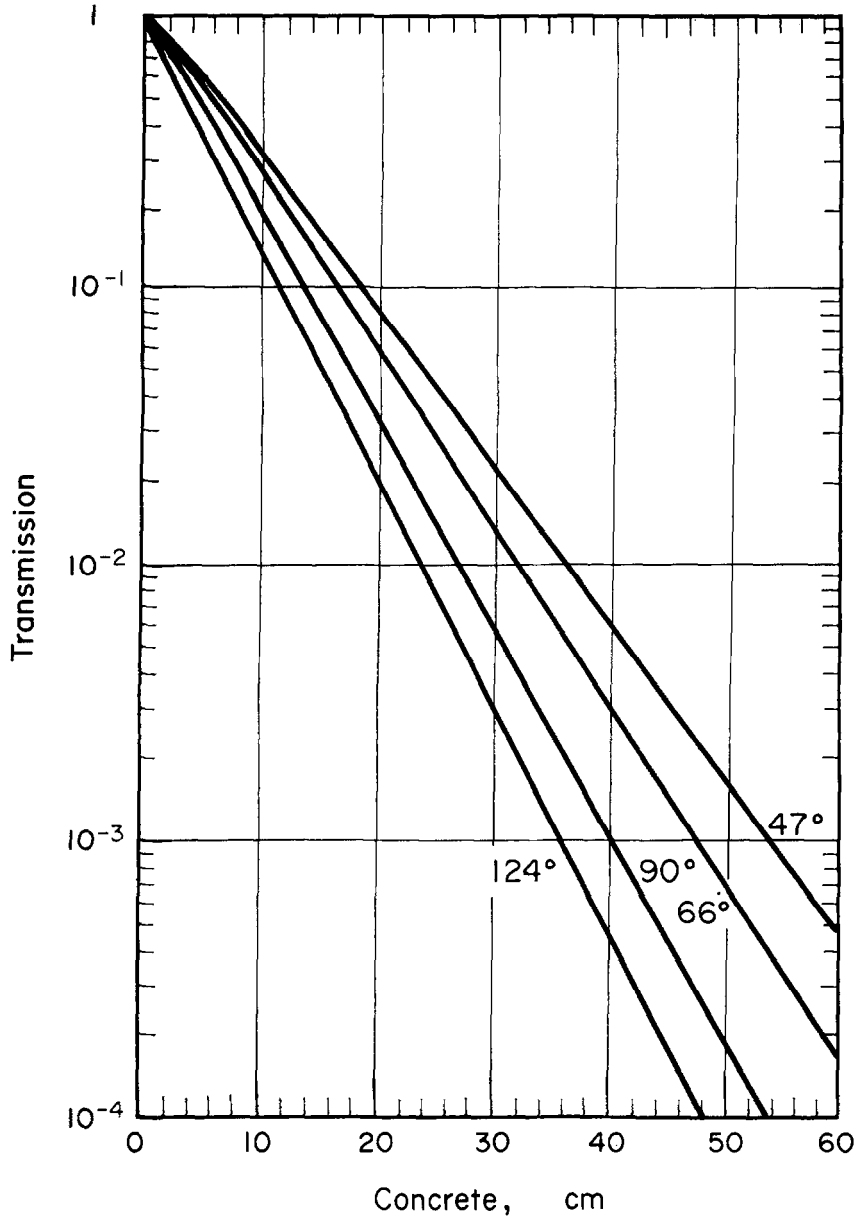

Fig. 25. Broad-beam transmission of ^{60}Co gamma rays scattered at various angles from a patient-simulating phantom through concrete, density 2 350 kg m^{-3}.

transmission of the shield has been reduced to as low a figure as is reasonably achievable, economic and social factors having been taken into consideration.

(249) Similarly for scattered radiation the equation for the boundary constraint is:

$$B_s = \frac{100 \cdot P \cdot d_s^2}{WTS}$$

P and T are the same as above. W is the same unless the distance between source and scatterer is

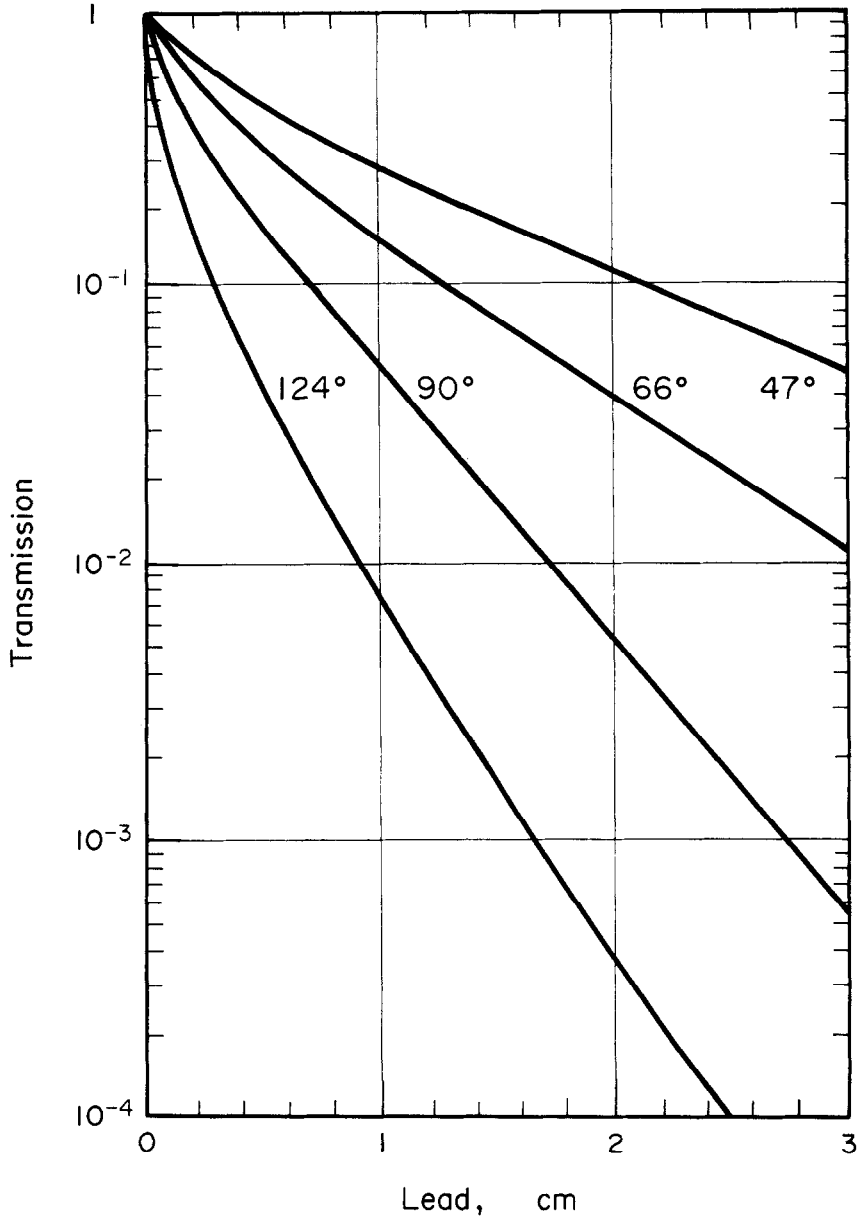

Fig. 26. Broad-beam transmission of ^{60}Co gamma rays scattered at various angles from a patient-simulating phantom through lead, density 11 350 kg m^{-3}.

not 1 m, in which case it should be modified in accordance with the inverse square law. Values of S, being the per cent of the incident absorbed dose rate scattered to 1 m, may be derived from Figs. 21 and 22 and Table 6. Allowance shall be made for the scattering area. d_s is the distance in metres from the source of scattered radiation and the point of interest.

(250) The same technique of optimization as described above shall then be applied.

(251) For leakage radiation, the number of tenth-value thicknesses N_{TVT} corresponding to the boundary condition transmission of a shield is given by:

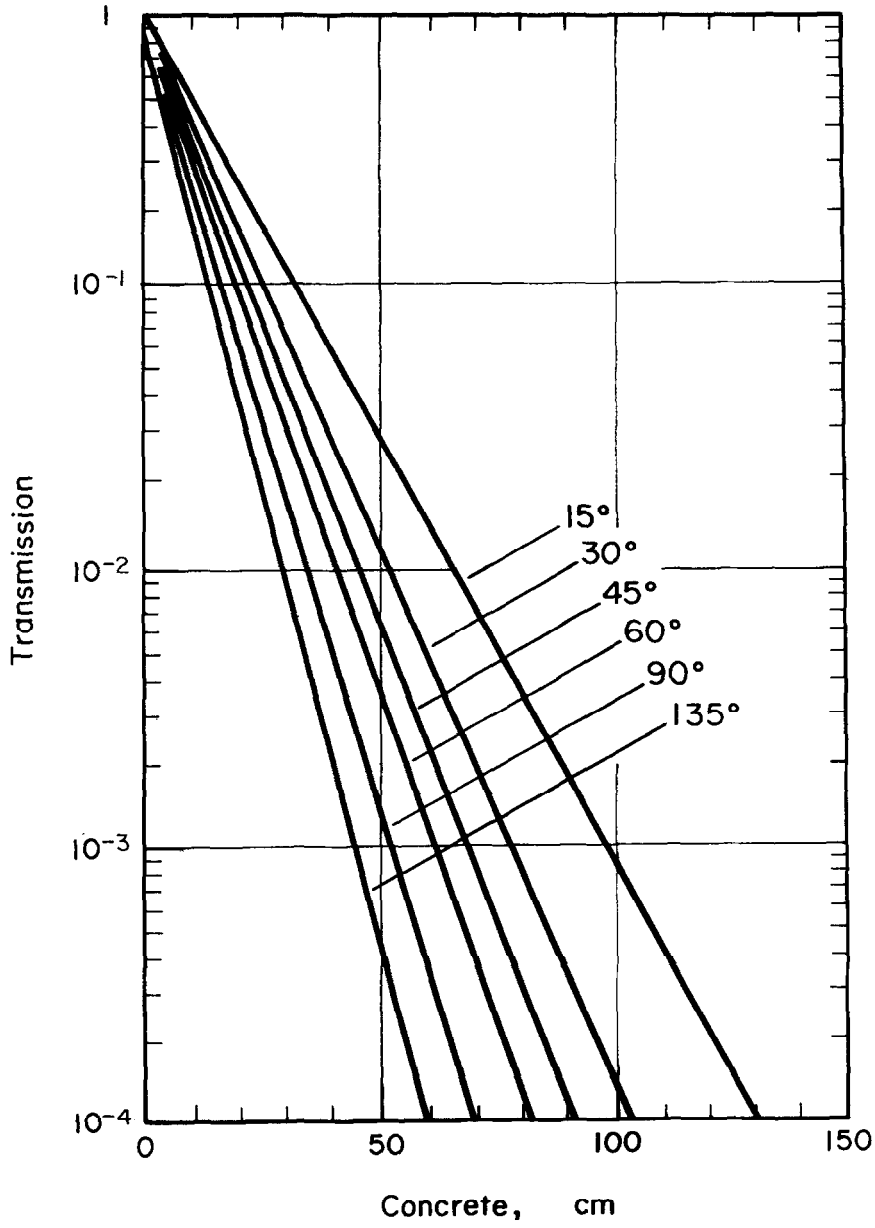

Fig. 27. Broad-beam transmission of 6 MV x rays scattered at various angles from a patient-simulating phantom through concrete, density 2 350 kg m^{-3}.

$$N_{TVT}=\log_{10}\frac{W_L T}{d^2 P}$$

T, d and P are the same as above, W_L is the weekly leakage kerma rate in air at 1 m from the source. The number of half-value thicknesses N_{HVT} is 3.3 N_{TVT}. The shield thickness corresponding to the calculated number of tenth-value thicknesses or half-value thicknesses is obtained by multiplying N_{TVT} or N_{HVT} by the values given in Tables 3 and 4.

Optimization Applied to Protective Shielding

(252) After the boundary conditions have been calculated the same techniques of optimization as mentioned above shall be employed. The following is an example of the application of optimization to a radiographic room and to a 4 MV radiation therapy installation.

(253) For the purpose of illustrating the optimization process, it is assumed that both the radiographic installation and the 4 MV radiation therapy room have a useful life of 20 years and that there are four full-time equivalent radiation workers to be protected in each case. For the radiographic room the results are shown in Table 7; it can be seen that the cost for decreasing the shielding design limit from 1 mSv to 0.1 mSv per week was $800, leading to a reduction of 3.6 man sievert in 20 years. Hence the cost per man sievert averted was about $220. However, if the design limit was reduced from 0.1 mSv to 0.01 mSv per week, the cost of shielding increased by an additional $1 600 for a reduction of only 0.36 man sievert, leading to a cost per man sievert averted of $4 400.

(254) A similar analysis has been carried out for the radiation therapy installation. In Table 8 it is shown that the cost per man sievert averted was $2 500 when the design limit was reduced from 1 mSv to 0.1 mSv per week and $35 000 when the design limit was reduced from 0.1 mSv to 0.01 mSv per week.

(255) The Commission does not recommend any specific value for a man sievert averted; this is a matter that must be left to the judgment of the responsible authorities in individual countries. Another variable is the cost of construction which may vary considerably among different countries and at different locations in the same country.

Table 7. Optimization of the shielding for a radiographic room

	Design limit (mSv wk^{-1})		
	From 1.0 to 0.1 to 0.01		
Cost of shielding[a]	$3 200	$4 000	$5 600
Incremental cost increase	$800	$1 600	
Reduction in collective dose (man-Sv)[b]	3.6	0.36	
Cost per man-Sv averted	$220	$4 400	

[a] Based on Braestrup and Wyckoff (1973) corrected for inflation.
[b] Assuming a useful life of 20 years for the installation and four full-time equivalent workers to be protected.

Table 8. Optimization of the shielding for a 4 MV radiation therapy installation

	Design limit (mSv wk^{-1})		
	From 1.0 to 0.1 to 0.01		
Cost of shielding[a]	$44 000	$53 000	$65 500
Incremental cost increase	$9 000	$12 500	
Reduction in collective dose (man-Sv)[b]	3.6	0.36	
Cost per man-Sv averted	$2 500	$35 000	

[a] Based on Braestrup and Wyckoff (1973) corrected for inflation.
[b] Assuming a useful life of 20 years for the installation and four full-time equivalent workers to be protected.

(256) In actual practice, the cost per man sievert averted may be considerably greater than the calculated values in the above illustrations because of the many assumptions that are made in shielding design which tend to overestimate the radiation attenuation requirements. For example, the patient is assumed not to intercept the primary beam in the calculation of primary protective barriers. For secondary protective barriers, the leakage radiation from the source housing is assumed to be the maximum permitted. It also has been common practice to overestimate the expected workload, occupancy factors and use factors. The result of these conservative assumptions is that the maximum dose equivalent to individuals is often less than $\frac{1}{10}$ of the authorized dose equivalent limit and the average effective dose equivalent is often less than $\frac{1}{30}$ of the dose equivalent limits for individuals. As a result, the total number of man sievert saved by the additional shielding may be 10–30 times less than in the examples shown in Tables 3 and 4. Therefore when applying optimization analyses one must use realistic assumptions in carrying out protective shielding design calculations.

Table 9. Primary x-ray beam shielding for boundary condition of 50 mSv y^{-1} [a]

Potential (kV)	Effective workload (mA · min per week)[b]	cm lead required at source distances of				cm concrete required at source distances of			
		1 m	2 m	4 m	8 m	1 m	2 m	4 m	8 m
50	500	0.04	0.03	0.02	0.01	3.4	2.5	1.6	0.9
	125	0.03	0.02	0.01	0.01	2.5	1.6	0.9	0.4
	30	0.02	0.01	0.01	—	1.6	0.9	0.4	—
	8	0.01	0.01	—	—	0.9	0.4	—	—
75	500	0.10	0.08	0.05	0.03	9.7	7.4	5.0	3.0
	125	0.08	0.05	0.03	0.02	7.4	5.0	3.0	1.2
	30	0.05	0.03	0.02	—	5.0	3.0	1.2	—
	8	0.03	0.02	—	—	3.0	1.2	—	—
100	1 000	0.24	0.19	0.14	0.09	17.0	13.6	10.4	7.1
	250	0.19	0.14	0.09	0.05	13.6	10.4	7.1	4.1
	60	0.14	0.09	0.05	0.03	10.4	7.1	4.1	1.5
	16	0.09	0.05	0.03	—	7.1	4.1	1.5	—
150	1 000	0.30	0.25	0.19	0.14	25.5	21.1	16.8	12.3
	250	0.25	0.19	0.14	0.09	21.1	16.8	12.3	8.0
	60	0.19	0.14	0.09	0.05	16.8	12.3	8.0	4.0
	16	0.14	0.09	0.05	0.02	12.3	8.0	4.0	0.8
200	40 000	0.66	0.58	0.51	0.43	46.3	41.0	35.9	30.6
	10 000	0.58	0.51	0.43	0.35	41.0	35.9	30.6	25.4
	2 500	0.51	0.43	0.35	0.28	35.9	30.6	25.4	20.1
	625	0.43	0.35	0.28	0.20	30.6	25.4	20.1	15.0
250	40 000	1.26	1.09	0.91	0.74	51.8	46.5	41.0	35.4
	10 000	1.09	0.91	0.74	0.59	46.5	41.0	35.4	29.8
	2 500	0.91	0.74	0.59	0.44	41.0	35.4	29.8	24.1
	625	0.74	0.59	0.44	0.31	35.4	29.8	24.1	18.6
300	40 000	2.38	2.04	1.70	1.36	58.4	52.5	46.3	40.2
	10 000	2.04	1.70	1.36	1.04	52.5	46.3	40.2	34.0
	2 500	1.70	1.36	1.04	0.76	46.3	40.2	34.0	27.8
	625	1.36	1.04	0.76	0.52	40.2	34.0	27.8	21.9
400	40 000	4.05	3.49	3.02	2.50	65.0	59.0	53.0	46.8
	10 000	3.49	3.02	2.50	2.02	59.0	53.0	46.8	40.6
	2 500	3.02	2.50	2.02	1.54	53.0	46.8	40.6	34.4
	625	2.50	2.02	1.54	1.12	46.8	40.6	34.4	28.5

[a] This table is constructed from the transmission data in Figs. 6, 7 and 10. Air attenuation is not taken into account.
[b] Shielding is calculated for the exact fraction of the initial workload required by the layout of each section of the table.

Boundary Condition Shielding for X Rays up to 400 kV

(257) Examples for boundary condition shielding (primary beam) are given in Table 9 for x-ray diagnosis in the range of 50–150 kV and for x-ray therapy between 200–400 kV.

(258) The density of lead is 11 350 kg m^{-3}, and of concrete 2 350 kg m^{-3}. The table is constructed directly from the information in this Appendix, but the 75 kV concrete data are based on interpolation.

(259) The potentials, workloads and distances selected encompass the ranges of these parameters in medical and dental diagnosis and in conventional therapy.

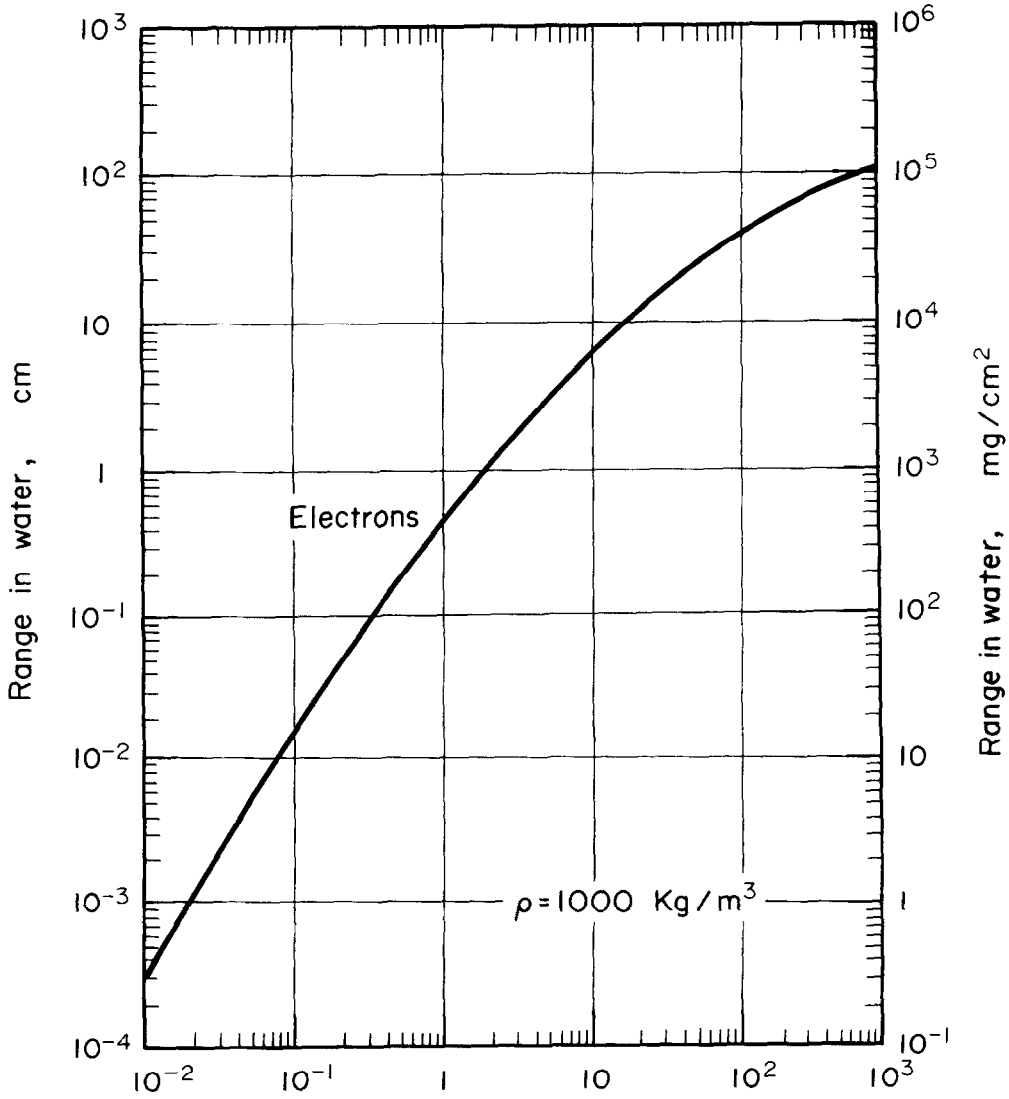

Fig. 28. Range of electrons in water.

Range Energy Curves for Electrons

(260) Range–energy curves for electrons in water and lead are presented in Fig. 28 and Fig. 29, respectively. The range shown is the continuous slowing down approximation range, R_{csda}. The curves are obtained from Fano (1964). Since secondary radiation which may be produced is not considered in these curves, care must be taken when applying the data in practical shielding calculations. These range–energy curves yield a cautious estimate of the shielding normally required for beta sources of activity less than about 100 mBq, if a range corresponding to the maximum beta energy is used. With more active sources, bremsstrahlung produced by the deceleration of the beta particles may also need to be shielded.

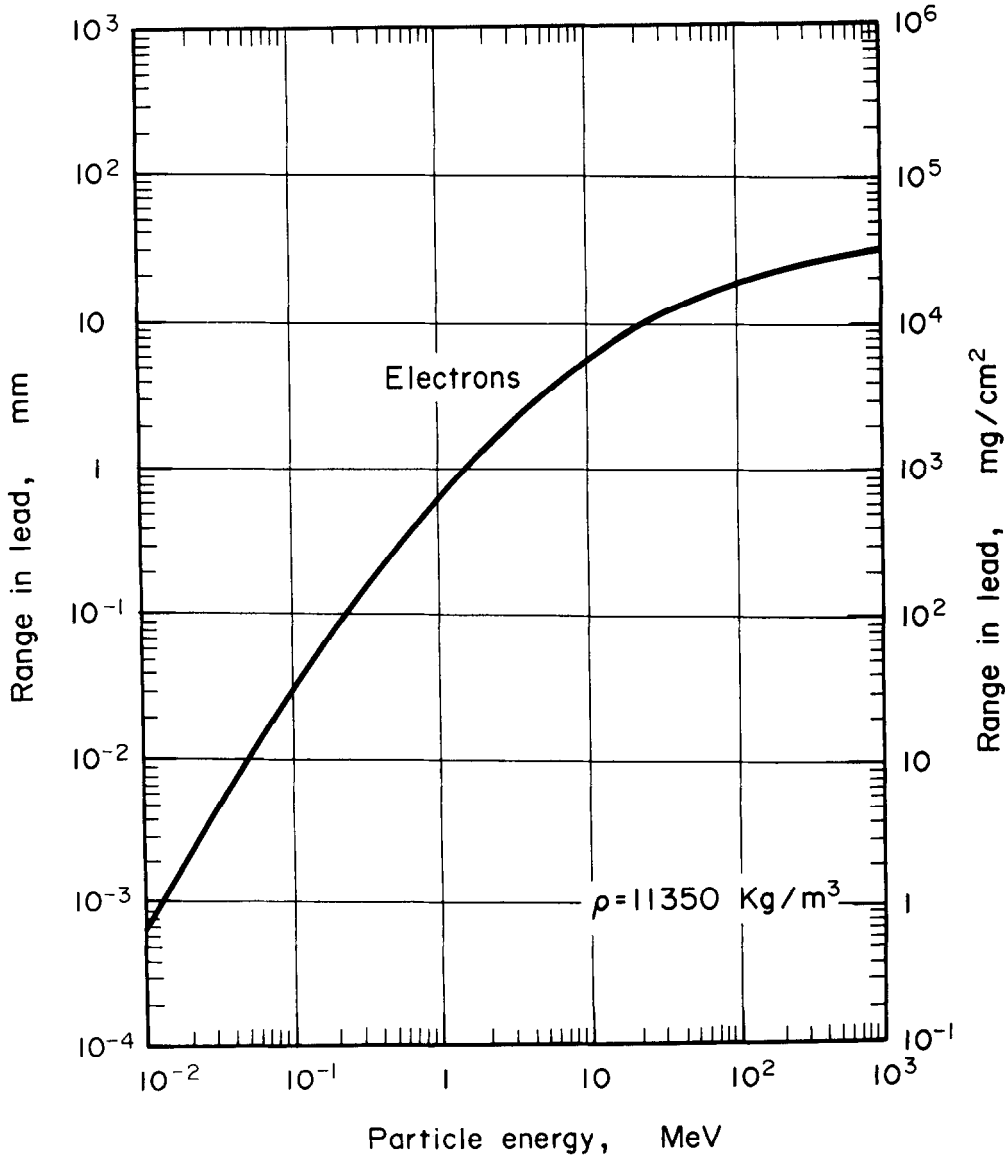

Fig. 29. Range of electrons in lead.

Table 10. Equivalent HVT in Al and Cu (mm) for Bremsstrahlung spectra with the homogeneity coefficient as parameter

	HVT in Cu (mm)			
	Homogeneity coefficient (%)			
HVT in Al (mm)	98–100	90	80	60
0.6	0.0184	0.0187	0.0190	0.0195
0.8	0.0241	0.0245	0.0248	0.0255
1.0	0.0302	0.0306	0.0309	0.0317
1.5	0.0453	0.0460	0.0466	0.0480
2.0	0.0612	0.0621	0.0636	0.0660
2.5	0.0781	0.0796	0.0812	0.0850
3.0	0.0965	0.0985	0.100	0.106
4.0	0.136	0.140	0.145	0.159
5.0	0.184	0.191	0.198	0.223
6.0	0.239	0.250	0.264	0.305
8.0	0.375	0.405	0.444	0.560
10.0	0.565	0.642	0.725	
12.0	0.895	1.01	1.27	
14.0	1.35	1.57	1.90	
16.0	2.05	2.45		
18.0	3.10			
20.0	4.30			
23.0	6.05			

	HVT in Al (mm)			
	Homogeneity coefficient (%)			
HVT in Cu (mm)	98–100	90	80	60
0.020	0.656	0.647	0.637	0.615
0.025	0.830	0.818	0.805	0.780
0.03	0.995	0.985	0.968	0.945
0.04	1.32	1.31	1.29	1.26
0.05	1.65	1.63	1.60	1.55
0.06	1.96	1.93	1.89	1.83
0.08	2.55	2.51	2.46	2.37
0.10	3.10	3.05	2.99	2.86
0.15	4.30	4.20	4.12	3.85
0.20	5.31	5.16	5.05	4.66
0.25	6.19	6.00	5.81	5.35
0.3	6.98	6.73	6.48	5.93
0.4	8.30	7.95	7.60	6.90
0.5	9.35	8.90	8.45	7.60
0.6	10.4	9.70	9.20	8.23
0.8	11.5	11.0	10.4	9.25
1.0	12.6	11.9	11.3	
1.5	14.5	13.8	13.0	
2.0	15.9	15.1	14.2	
2.5	16.9	16.1		
3.0	17.8			
4.0	19.5			
5.0	21.2			
6.0	22.8			

Half Value Layer

(261) It is useful to be able to convert between HVL in Al and Cu. The relation is somewhat dependent on the extent to which the beam is monoenergetic. Tables 10 and 11 give values taken from Seelentag and Panzer (1980); the homogeneity coefficient appearing in Table 10 is the ratio of the first to the second HVL and is a measure of homogeneity in the energy of the beam.

Table 11. Approximate equivalent half-value thicknesses (mm) for low energy spectra (to be used only for Al-to-Cu conversion)

HVT material	
Al	Cu
0.10	0.0060
0.15	0.0070
0.20	0.0085
0.25	0.0095
0.3	0.011
0.4	0.013
0.5	0.016
0.6	0.019

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