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Radiological protection — Medical electron accelerators — Requirements and recommendations for shielding design and evaluation

Radioprotection — Accélérateurs médicaux d'électrons — Exigences et recommandations pour la conception et l'évaluation du blindage

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2. www.iso.org/directives

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT), see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

This corrected version of ISO 16645:2016 incorporates the correction of Tables A.9 and C.6.

Introduction

Radiotherapy uses external beam radiation to kill cancer cells and shrink tumours. The use of electron linear accelerators to administer external beam radiation has spread during recent decades and is now common throughout the world. These accelerators deliver high energy electron and photon beams with increasingly high dose rates. Although the use of radiotherapy is well established, irradiation techniques have continued to evolve and are becoming increasingly complex. Examples include modulation of beam intensity, availability of high dose rate modes, arctherapy, helical intensity modulated radiotherapy, robotic arm accelerators, and dedicated devices for intra-operative radiotherapy. The shielding design of treatment rooms has been evolving with these changes. The higher radiation workload associated with most of these techniques can impact the shielding materials used. The irradiation technique can also impact the geometry to be considered in the shielding calculations.

IEC 60601-2-1 relates to the design and the construction of the accelerators in order to ensure the safety of their operation[1]. In addition, several national[2][3] or international (IAEA Safety Reports Series Report No. 47, 2006) reports propose recommendations concerning the installation and the exploitation of these accelerators, the safety devices, the design and the calculation of protections, the radiological control and monitoring. National standards have been established in certain countries[4][5]. Moreover national regulations impose particular rules of protection against radiation, in particular relating to the definition of the controlled areas and the calculation of shielding.

Taking into account the developments of new irradiation techniques and of new designs of treatment room facilities on the one hand, and the variety of guides or normative documents on the other hand, it appeared judicious to establish an international standard to be used as a general framework. This standard is intended to be complementary to the other international standards (IEC and IAEA).

The following items are discussed in the standard:

— types of accelerators: conventional accelerators with and without flattening filter (FF and FFF operating modes), devices for helical intensity modulated radiotherapy and robotic arm accelerator, dedicated machines for intra-operative radiotherapy;

— radiation fields: electrons, X photons and neutrons (direct, scattered, leakage), neutron capture gamma rays;

— Treatment room geometry: maze without and with door, no maze with direct door;

— materials of protection: concrete (ordinary or high density), metals, laminated barriers (concrete and metal), hydrogenated materials, earth and others;

— design of the radiotherapy facility:

— calculation methods of the shielding, including neutrons, various types of installations and shielding geometries;

— evaluation of the impact of the maze and calculation of the protection of the entrance door;

— evaluation of the impact of the ducts (ventilation and air-conditioning, high voltage and fluids) and additional protections;

— shielding design assumption and goals;

— Radiation survey of the completed installation to ensure national requirements have been met and the shielding and design is fit for purpose after installation of the accelerator.

Radiological protection — Medical electron accelerators — Requirements and recommendations for shielding design and evaluation

1 Scope

This International Standard is applicable to medical electron linear accelerators i.e. linear accelerators with nominal energies of the beam ranging from 4 MV to 30 MV, including particular installations such as robotic arm, helical intensity modulated radiotherapy devices and dedicated devices for intra operative radiotherapy (IORT) with electrons.

The cyclotrons and the synchrotrons used for hadrontherapy are not considered.

The radiation protection requirements and recommendations given in this International Standard cover the aspects relating to regulations, shielding design goals and other design criteria, role of the manufacturers, of the radiation protection officer or qualified expert and interactions between stakeholders, radiations around a linear accelerator, shielding for conventional and special devices (including shielding materials and transmission values, calculations for various treatment room configurations, duct impact on radiation protection) and the radiological monitoring (measurements).

NOTE 1 Annex A provides transmission values for the most common shielding materials.

NOTE 2 Annex B provides supporting data for shielding calculation.

NOTE 3 Annex C provides an example of calculation for conventional device and standard maze.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60976, *Medical electrical equipment — Medical electron accelerators — Functional performance characteristics*

IAEA Safety Reports Series Report No. 47, *Radiation protection in the Design of Radiotherapy Facilities (2006)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60976 and the following apply.

3.1 Quantities

3.1.1
absorbed dose
D
quotient of $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass dm thus

$$D = \frac{d\bar{\varepsilon}}{dm}$$

Note 1 to entry: In this document, the absorbed dose is defined for radiation produced by a linear accelerator at a specific location: the absorbed dose to water at the isocentre (at 1 m from the source for conventional devices) at a reference depth in water in electron equilibrium conditions (for example at the depth of maximum absorbed dose).

Note 2 to entry: The unit of absorbed dose is joule per kilogram ($J{\cdot}kg^{-1}$), and its special name is gray (Gy).

[SOURCE: ISO 12749-2:2013, 4.1.6.7][6]

3.1.2
absorbed dose rate
output rate
DR_0
dose absorbed per unit of time

Note 1 to entry: In this International Standard, in the absence of specific indication, the absorbed dose rate is defined for radiation produced by a linear accelerator at a specific location: the absorbed dose rate to water at the isocentre (at 1 m from the source for conventional devices) at a reference depth in water in electron equilibrium conditions (for example at the depth of maximum absorbed dose).

Note 2 to entry: The unit of absorbed dose rate is gray per second ($Gy{\cdot}s^{-1}$). The usual unit for medical accelerators is gray per hour ($Gy{\cdot}h^{-1}$).

3.1.3
dose equivalent
H
product of *D* and *Q* at a point in tissue, where *D* is the absorbed dose (3.1.1) and *Q* is the quality factor for the specific radiation at this point, thus: $H = D \times Q$

Note 1 to entry: The unit of dose equivalent is joule per kilogram ($J{\cdot}kg^{-1}$), and its special name is sievert (Sv).

[SOURCE: ISO 12749-2:2013, 4.1.6.8][6]

3.1.4
IMRT ratio
C_I
ratio of the average monitor unit per unit prescribed absorbed dose needed for IMRT (MU_{IMRT}) and the monitor unit per unit absorbed dose for conventional treatment (MU_{conv})

$$C_I = \frac{MU_{IMRT}}{MU_{CONV}}$$

3.1.5
instantaneous dose-equivalent rate
IDR
"ambient/personal" dose-equivalent rate ($Sv{\cdot}h^{-1}$) as measured with the linear accelerator operating at the absorbed dose rate DR_0 ($Gy{\cdot}h^{-1}$)

Note 1 to entry: This is the direct reading of the ratemeter that gives a stable reading in dose-equivalent per hour. *IDR* is specified at a reference point (30 cm) beyond the penetrated barrier.

3.1.6
effective dose
E
summation of all the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor

3.1.7
occupancy factor
T
fraction of time the areas adjacent to the treatment room are occupied by an individual or group during linear accelerator operation

3.1.8
orientation or use factor
U
fraction of the time during which the radiation under consideration is directed at a particular barrier

3.1.9
reflection coefficient
α
fraction of radiation (e.g., fluence, energy fluence) expressed by the ratio of the amount backscattered to that incident

3.1.10
shielding design goal
P
practical values of dose equivalent, for a single radiotherapy source or set of sources, evaluated at a reference point beyond a protective barrier

Note 1 to entry: The shielding design goals ensure that the respective annual values for effective dose limit defined by national regulation or IAEA/ICRP for controlled and uncontrolled areas are not exceeded.

3.1.11
(patient) scatter fraction
***a*(*θ*)**
ratio of absorbed dose at 1 m from a tissue-equivalent scattering object to the absorbed dose measured at the isocentre with the object removed

Note 1 to entry: This quantity is a function of the scatter angle (*θ*), incident beam quality, and beam area. A scattering phantom is typically a water-equivalent volume representing a standard human being.

3.1.12
tenth-value distance
TVD
distance that a specified radiation travels under broad beam condition in order to reduce the radiation field intensity to one-tenth of its original value

3.1.13
tenth-value layer
TVL
thickness of a specific material that reduces a specified radiation field intensity by a factor of 10 of its original value, under broad beam condition

Note 1 to entry: *TVL* is expressed in m or cm of a defined material or in kg/m^2 (thickness × density).

Note 2 to entry: TVL_1 and TVL_2 are the first and the second tenth-value layer thicknesses, respectively.

Note 3 to entry: TVL_e is the equilibrium tenth-value layer, thickness for each subsequent tenth-value layer in the region in which the directional and spectral distributions of the radiation field are practically independent of thickness.

Note 4 to entry: TVL_c is the cumulative tenth-value layer, approximate value based on large attenuation measurements: for a given thickness *t*, $TVL_c = -t/\log(B)$.

3.1.14
time averaged dose-equivalent rate
TADR
barrier attenuated dose-equivalent rate averaged over a specified period of accelerator operation

Note 1 to entry: *TADR* is proportional to instantaneous dose-equivalent rate (*IDR*), and depends on the values of workload (*W*) and orientation or use factor (*U*).

3.1.15
transmission factor (or barrier transmission)
B
ratio of radiation field intensity at a location behind the barrier on which radiation is incident to the field intensity at the same location without the presence of the shield, for a given radiation type and quality

Note 1 to entry: *B* is a measure of the shielding effectiveness of the barrier.

3.1.16
workload
W
average absorbed dose to water of radiation produced by a linear accelerator, at the isocentre at a reference depth in water in electron equilibrium conditions, over a specified period averaged over a year

Note 1 to entry: The workload is specified in Gray (Gy).

Note 2 to entry: The time period should be consistent between shielding design goals and workload.

Note 3 to entry: The isocentre is at 1 m from the source for conventional devices.

Note 4 to entry: The reference depth in water is for example the depth of maximum absorbed dose.

3.2 Definitions

3.2.1
barrier (or protective barrier)
protective wall of radiation attenuating material(s) used to reduce the dose equivalent on the side beyond the radiation source to an acceptable level compatible with national legislation or international guidance

3.2.2
primary barrier
wall, ceiling, floor or other structure designed to attenuate the direct radiation emitted from the target or source that passes though the collimator opening (useful beam) to an acceptable level compatible with national legislation or international guidance

3.2.3
secondary barrier
wall, ceiling, floor or other structure not struck by the primary beam and designed to attenuate the leakage and scattered radiations to an acceptable level compatible with national legislation or international guidance

3.2.4
controlled area
defined area in which specific protection measures and safety provisions are or could be required for controlling exposures or preventing the spread of contamination in normal working conditions, and preventing or limiting the likelihood and magnitude of potential exposures

Note 1 to entry: This implies that access, occupancy, and working conditions are controlled for radiation protection purposes.

[SOURCE: IAEA BSS][7]

3.2.5
geometrical field size
geometrical projection as seen from the centre of the front surface of the radiation source on a plane perpendicular to the axis of the beam of the distal end of the beam limiting device or collimator

Note 1 to entry: The field is thus of the same shape as the aperture of the beam limiting device.

Note 2 to entry: The projected field size is specified at a particular distance from the target, e.g. at the isocentre 1 m from the target or at the reference distance of the device.

[SOURCE: IEC 60976:2007]

3.2.6
helical intensity modulated radiotherapy
radiotherapy using a linear accelerator that delivers treatment with a slit beam adjustable by a multileaf collimator (MLC) and that rotates continuously around patient with geometry resembling diagnostic computed tomography (CT), with concomitant motion of the couch

Note 1 to entry: Helical intensity modulated radiotherapy is often called tomotherapy.

3.2.7
intensity-modulated radiation therapy
IMRT
treatment procedure requiring, in general, the coordinated control of photon or electron fluence, beam orientation relative to the patient, and beam size, either in a continuous or a discrete manner, and as pre-determined by a treatment plan

Note 1 to entry: The primary purpose of IMRT is to improve the conformity of the dose distribution to the planned target volume, while minimizing dose to surrounding healthy tissue.

[SOURCE: IEC 60976:2007]

3.2.8
isocentre
point defined by intersection of the gantry axis of rotation and the beam centerline of a linear accelerator

Note 1 to entry: For conventional linear accelerator, the isocentre is located at 1 m from the radiation source.

3.2.9
leakage radiation
radiation, except the useful beam, coming from the accelerator head and other beam-line components

Note 1 to entry: It is attenuated by shielding in the treatment head as specified by IEC 60601–2-1[1].

3.2.10
members of the public
persons who are not occupationally exposed by a source or practice under consideration

Note 1 to entry: When being irradiated as a result of medical care, patients are not considered as members of the public.

3.2.11
nominal energy
energy stated by the manufacturer to characterize the radiation beam

Note 1 to entry: "MV" is used when referring to accelerating voltages and the end point energy of a bremsstrahlung spectrum, while "MeV" is used when referring to monoenergetic photons or electrons

[SOURCE: IEC 60976:2007]

3.2.12
occupied area
room or other space, indoors or outdoors, that is likely to be occupied by any person, either regularly or periodically during the course of the person's work, habitation or recreation, and in which an ionizing radiation field exists because of radiation sources in the vicinity

3.2.13
radiation protection officer
person technically competent in radiation protection matters relevant for a given type of practice who is designated by the registrant, licensee or employer to oversee the application of relevant requirements

[SOURCE: IAEA BSS][7]

3.2.14
qualified expert
individual who, by virtue of certification by appropriate boards or societies, professional licence or academic qualifications and experience, is duly recognized as having expertise in a relevant field of specialization, e.g. medical physics, radiation protection, occupational health, fire safety, quality management or any relevant engineering or safety specialty

[SOURCE: IAEA BSS][7]

3.2.15
robotic arm accelerator
device composed by a linear accelerator mounted on a 6D robotic arm allowing a multi-directional delivery of the dose

Note 1 to entry: The robotic arm is referred to as 6 degrees of freedom because movements are made for 3 translational motions (X, Y and Z) and 3 rotational motions.

Note 2 to entry: The “geometric isocentre” is a reference point in the room that serves as the origin for several coordinates systems related to robot and imaging calibration.

3.2.16
scattered radiation
radiation that, during passage through matter, is changed in direction, and the change is usually accompanied by a decrease in energy and intensity

3.2.17
secondary radiation
radiation produced by scattering from the areas struck by the primary X-ray beam or leakage radiation through the treatment head of the linear accelerator

3.2.18
supervised area
defined area in which specific protection measures and safety provisions are or could be required for controlling normal exposures during normal working conditions, and preventing or limiting the extent of potential exposures

3.2.19
tertiary radiation
radiation produced by scattering from areas struck by leakage radiation, secondary radiation and primary electron beam bremsstrahlung

4 Shielding design goals and other design criteria

4.1 Shielding design goals

Shielding design goals (*P*) are levels of dose equivalent (*H*) used in the design calculations and evaluation of barriers constructed for the protection of workers or members of the public. Different shielding design goals shall be defined for supervised, controlled and public areas. They have to be in accordance with existing national regulation or if not available according to IAEA basic safety standards on radiation protection related to effective dose limits for workers and members of the public.

The *P* value (Sv) set by national authorities should be a fraction of dose limits for workers or for members of the public. They can be expressed as weekly values (mSv/week) since the workload (*W*) for a radiotherapy equipment has traditionally a weekly format. But according to national regulation, other time periods can be used.

Shielding design goals (*P*) are practical values that are evaluated at a reference point beyond a protective barrier for the workload W proposed by the radiotherapy department.

4.2 Shielding design assumptions

A radiotherapy facility that uses the assumption proposed above would produce effective dose values lower than the regulation statements for supervised, controlled and public areas. This is the result of the conservatively safe nature of the shielding design methodology recommended.

Some design assumption should be made:

— the minimum distance to the occupied area from a shielded wall (or barrier) is assumed to be 0,3 m (considered as representative for whole body exposure);

— attenuation of the primary beam by the patient should be neglected;

— calculations of recommended barrier thickness for primary barrier assume perpendicular incidence of the radiation except for robotic arm accelerator for which oblique incidence should be considered;

— leakage radiation from radiotherapy equipment is assumed to be at the maximum value recommended by IEC 60601-2-1[1] for the radiotherapy device, although in practice the leakage radiation is often less than this value;

— the primary barrier width (w) shall be sufficient to extend at least 0,3 m beyond the edge of a geometrical field of maximum size rotated 45°. For a square f m x f m field, the minimum value of w is given by:

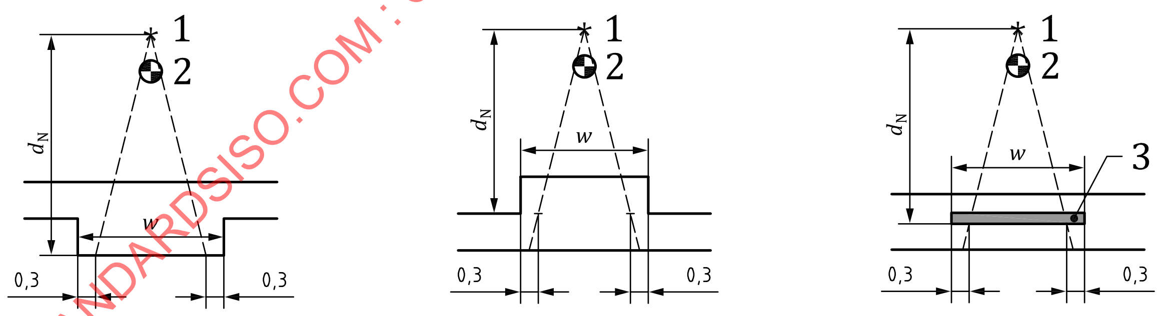
$$w = \left(f \ / \ 1\ \text{m}\right)\sqrt{2}d_{\text{N}} + 0,6\ \text{m} \qquad (1)$$

where d_N is the distance from the target to the far side of the most narrow part of the barrier, in metres.

The distance from the target to the narrow point of the primary barrier should be measured at the top of the barrier, not at the same height as isocentre.

Figure 1 illustrates the typical locations for the narrowest point of the barrier.

Dimensions in metres



a) b) c)

Key

1 target

2 isocentre

3 metal

Figure 1 — Primary barrier width

5 Role of the manufacturers, of the radiation protection officer or qualified expert and interactions between stakeholders

5.1 General

Ensuring adequate protection for both the facility workers and the general public from linear accelerator radiation is a cooperative effort. Clause 5 provides general guidance on the roles, responsibilities, and interaction among the various stakeholders involved in this process.

5.2 Linear accelerator manufacturer

The manufacturer of the linear accelerator shall provide detailed technical documents containing at least the following information:

a) dimension sheets containing:

- the dimensions of the linear accelerator;
- the minimum treatment room dimensions (length, width and height) for the accelerator itself but also for allowing full extension of the treatment couch in any direction. For isocentric equipment, the isocentre-to-wall clearance, minimum clearance from the treatment room floor to the ceiling shall be defined. For non isocentric equipment, the possible primary beam orientation shall be described; the isocentre height and the distance from the isocentre to the rear wall need to be specified;
- minimum dimensions, location and requirements for control room. Specification, and location, inside or outside the treatment room, of technical rooms which may contain parts of the associated equipment necessary for accelerator;
- information on ducting requirements for electrical cables, waterpipes, heating and air-conditioning ventilation ducts etc. necessary to operate the equipment in the treatment room.

b) Functional performance characteristics

The protective shielding design shall take into account the different types of radiation emitted by the accelerator according to the data provided by the manufacturer which shall contain at least the following:

- the reference distance, in m, defined as for:
- X-radiation: specified distance measured along the axis of the beam from the source of X-radiation (front surface of the X-radiation target) to the isocentre or to a specified plane for non-isocentric equipment;
- electron radiation: specified distance measured along the axis of the beam from the virtual source of electrons to the isocentre or to a specified plane for non-isocentric equipment;
- the available nominal energies of the beam and the available associated absorbed dose rates at reference distance under conditions of maximum build-up in a phantom (maximum dose) for reference field, (10x10) cm^2 or specified reference field size, and the maximum radiation fields for both X-radiation and electron radiation.

In addition to the nominal energy of the beam, the way to achieve a uniform dose for clinical X-radiation beams shall be mentioned: flattening filter (FF) or flattening filter free (FFF). The FF scatter photons are one of the major sources of linear accelerator head scatter. The FFF operating mode results in an increase in dose rate, softening of X-ray spectra, reduction in head scattered radiation, therefore the rate of photo-neutron generation for both the FF and FFF modes are substantially equivalent.

For the purposes of this International Standard, it is assumed that the dose rate at the reference distance may be obtained for larger distances in accordance with the inverse square law.

— the dimensioned shape of the maximum geometric radiation fields at the reference distance for X-radiation and electron radiation for every radiation type available;

— the highest absorbed dose rate to water of the neutron radiation contamination in X-ray and electron beams to the extent that they are required for radiation protection measures against neutrons;

— the highest absorbed dose rate to water of the X-ray radiation contamination in the electron beam;

— the distribution of the maximum leakage radiation (x-radiation and neutron); the spatial distribution of the absorbed dose rate of the radiation emerging from the radiation source assembly outside the maximum radiation beam cross-section for the operating state and the operating parameters at which the highest dose rates outside the radiation beam occur;

This distribution may, for example, be specified in the form of isodose sheets or by an analytical expression from which the highest dose rate can be determined for every surrounding area.

— availability of a beamstopper and description of geometric characteristics (largest primary beam and angle of scattered radiation intercepted, distance from reference point…), nature and thickness of the shielding material and attenuation factor for primary beam.

5.3 Shielding material vendor

The shielding vendor is responsible for providing accurate drawings and information describing their products for use in the shielding evaluation.

The usual materials for radiation shielding are normal or high density concrete, steel, or lead for which the attenuation properties (*TVL*) are well known and related to density.

Most published data assume a density for concrete of 2350 kg.m^{-3} but variation according to the used aggregate have been shown. Any concrete with a density higher than 3000 kg.m^{-3} can be considered as high density concrete. The increased density is achieved by adding various higher density aggregates to increase photon attenuation. Common among these are iron ores and minerals (haematite, limonite, magnetite …).

The shielding material supplier should:

— specify the overall density and composition of the shielding material. If Monte Carlo calculations are to be performed, further information about the composition nature by weight for the different component of the mix (aggregate, cement, additional material, water in %) and atomic composition for different elements (Ca, Fe, H, O, Si… in %) relevant to evaluate the shielding properties shall be provided;

— ensure, in collaboration with the structural engineer, quality control of produced concrete in order to respect the required density otherwise adjustment is needed to determine the required barrier thickness to achieve the shielding goal.

Instead of concrete, pre-moulded high density interlocking blocks of different density are commercially available or specific patented building methods such as dry mineral filling between thin prefabricated concrete walls are also used.

If the above data needed are not available, the supplier shall provide radiation attenuation characteristics such as *TVL* for X-rays or neutrons in the energy range of the accelerator and all relevant data available. For therapy installations operating above 8 MV, activation of material within the shielding shall be considered and available data provided.

Linear accelerators operating with nominal energies of the beam above 8 MV may require door shielding for neutrons and photons; the door supplier shall provide any relevant data to assess attenuation property: thicknesses and composition of layers.

5.4 Architectural firm/general contractor

To ensure that the facility is built according to the intent of the licensee, the contract between the architectural firm and general contractor should specify the following responsibilities.

The architectural firm is responsible for researching the existing structure (if any). This includes providing information on the existing and planned usage of the space around the linear accelerator. The architect shall also prepare drawings that accurately show the installed linear accelerator location, along with the location and nature of the shielding surrounding the linear accelerator. The architectural firm is also responsible to review the shielding evaluation report to ensure the shielding described in that report is incorporated into the design. In some cases, some or the entire role of the architect may be performed by a general contractor or a shielding vendor.

The general contractor has responsibility to ensure the facility is constructed with shielding that is consistent with the shielding evaluation report. The general contractor shall also ensure that the radiation protection officer or qualified expert has accurate drawings and other relevant information needed to have an accurate understanding of the structure. The general contractor has the responsibility to coordinate with the radiation protection officer or qualified expert any situation arising during construction that may compromise the shielding. In particular, shielding for locations where structural constraints exist shall be coordinated between stakeholders.

5.5 Radiation protection officer or qualified expert

The radiation protection officer or qualified expert for the electron accelerator installation shall provide, in closed collaboration with the other stakeholders (medical physicist, radiation oncologists…) detailed documents containing the specifications essential for construction and the intended operation. The shielding plan should use conservative shielding assumptions to reach the facility's shielding goal although these shielding assumptions also should be realistic.

The documents shall contain information according to national regulation. They shall at least contain the following specifications:

— drawings of the buildings, rooms and external facilities belonging to the radiation therapy department and of any neighbouring buildings, rooms and traffic areas from which the dimensions and distances required for radiation protection computations can be derived;

— data on existing building structure (material, thickness);

— the division of the rooms within the radiation therapy department and their use;

— workplaces and occupied areas within the radiation therapy department;

— specifications regarding the intended demarcation of supervised, controlled or prohibited areas;

— type and use of areas outside the radiation therapy department and related occupancy factors T for uncontrolled areas on basis of conservative assumption;

— details of the intended operating modes [combination of radiation type, radiation energy including FF and FFF mode, beam direction and as consequence determination of orientation or use factor U, possible positions of the radiation head, intensity modulated radiation therapy (IMRT) and the frequency of use];

— the maximum number of each type of intended treatment and the related mean dose at the reference point during the reference period defined for achieving the shielding goal. (workload);

— specific requirements regarding type of treatments planned to be realized and their impact on dimensions of the treatment room. For example, a total body irradiation (TBI) procedure requires a larger treatment distance to one wall. For intra-operative procedures (IORT) that require extensive support staff and equipment, the room may need to be larger.

The radiation protection officer or qualified expert should provide a shielding evaluation report that demonstrates the barriers in the structure (material type, thickness, and location) provide adequate protection for the staff and general public. A clear statement of all assumptions used to generate the shielding design shall be included in the report. He shall ensure that a radiation survey after machine installation is performed and that a report is provided demonstrating the dose rate outside the structure housing the linear accelerator is suitable for occupancy by the staff and, for locations with uncontrolled access, the general public.

5.6 The licensee

As required by local or national regulations, the radiation survey report shall be submitted by a representative of the licensee to the appropriate regulatory authority for approval prior to the start of clinical commissioning.

6 Radiation fields around a linear electron accelerator

6.1 General

There are various radiation components that contribute to the ambient dose equivalent rate at a given point outside the treatment room:

- X-ray radiation
  - primary X-ray beam;
  - primary electron beam bremsstrahlung;
  - leakage X-ray radiation;
  - scattered X-ray radiation;
  - tertiary X-ray radiation;
- neutron radiation (primary X-ray > 8 MV)
  - direct neutron radiation;
  - scattered and thermal neutron radiation;
  - primary barrier neutron radiation;
- γ radiation (primary X-ray > 8 MV)
  - maze γ radiation;
  - door γ radiation;
  - primary barrier γ radiation.

6.2 X-ray radiation

6.2.1 Primary X-ray beam

The primary X-ray beam is the collimated X-ray radiation produced in the head of the accelerator and used to treat the patients. It is a bremsstrahlung radiation generated by the slowing down of the accelerated electrons in a thick target of high atomic number (tungsten, gold). The selection of the transmission curves to be used for shielding calculations for the primary barriers shall account for the polyenergetic nature of the spectrum and the broad beam geometry[8][9]. The term “nominal energy” used by the manufacturers doesn’t refer necessarily to the accelerating voltage, it refers to BJR 11 or BJR 17 definitions[10][11].

Care should be taken with the definition of the nominal energy of the beam, because it has changed with time, corresponding to different energy spectra (see Table 1)[12]. When considering published data for primary X-ray transmission calculations, check the energy definition related to the data and the energy definition of the accelerator to be installed. By default, a conservative approach is to use data related to BJR 11 energy definition.

Table 1 — Comparison of BJR 11 and BJR 17 MV definitions

BJR 11 (MV)	4	6	10	15	18	20	24
BJR 17 (MV)	4	6	10	16	23	25	30

Generally linear electron accelerators produce X-ray beams with a single nominal energy (typically 6 MV) or with multiple nominal energies (between 6 MV and 18 MV).

6.2.2 Primary electron beam bremsstrahlung

Linear electron accelerators also produce electron beams used for the treatment of patients, with generally 5 or 6 possible energies (from 4 MeV to about 20 MeV). For conventional accelerators, broad electron beams are generated by scattering foils.

The primary electron beam is contaminated with bremsstrahlung X-rays, with two different components:

— X-rays present in the electron beam;

— X-rays generated by the electron beam outside the linac (i.e. in the air, in the patient and in the primary shielding barriers).

Since the shielding thickness against the bremsstrahlung generated by the electron beam is in any case greater than the electron range, it suffices to calculate the shielding requirements for the bremsstrahlung (no separate shielding is required for the primary electrons).

6.2.3 Secondary X-ray radiation

The secondary X-ray component is made of two components: leakage radiation and scattered radiation.

Leakage X-ray component is bremsstrahlung radiation created in the head of the linear accelerator and transmitted through the head shielding, outside the region defined by the beam limiting device.

The energy spectrum of the leakage radiation is softened as compared to the primary X-ray beam, leading to different transmission values[8]. This should be taken into account for shielding calculations, but a conservative approach is to consider the leakage component with the same transmission values as the primary beam.

IEC 60601-2-1[1] specifies design requirements for linear accelerators in order to limit the exposure due to leakage X-rays, and gives the maximum allowed contribution to the dose equivalent around the linear accelerator.

Scattered radiation that originates from the impact areas of the primary X-ray beam:

— secondary X-rays scattered from the patient;

— secondary X-rays scattered from a primary barrier.

The energy spectrum of the scattered photons is degraded as compared to the primary photon beam, with the mean energy decreasing as the scattering angle increases. This leads to different transmission values for different scattering angles.

The scattered radiation intensity depends on the energy of the primary beam, on the scattering angle and, for photons scattered by a barrier, on the incident angle and on the barrier material (wall reflection coefficient).

References:

— scattered by patient: fraction, energy and *TVL*: [IAEA SRS 47][2][13];

— scattered by barrier: wall reflection coefficients: [IAEA SRS 47][2][14].

These effects should be taken into account for shielding calculations. A conservative approach is to consider, for small scattering angles, that the scattered component has the same transmission values as the primary beam.

6.2.4 Tertiary X-ray radiation

Tertiary X-ray radiation originates from the impact areas of secondary X-ray radiation as well as from the impact area of the primary electron beam bremsstrahlung. In case of facilities with a maze, the tertiary X-ray component reaches the entrance door and should be calculated for shielding evaluation at the entrance.

The energy of the tertiary radiation is degraded as compared to the primary photon beam and this point has to be taken into account for shielding calculations.

6.3 Neutron radiation

6.3.1 General

X-rays above a given energy incident on a nucleus (atomic number Z, mass number A) produce photonuclear reactions according to:

$$X + Z^{A} \rightarrow Z^{(A-1)} + n \text{ or } Z^{A}\,(X, n)\,Z^{(A-1)}$$

For this to take place, the photon energy shall be higher than the binding energy of the least bound nucleon. The value of this threshold energy is dependent on the atomic number Z (see Table 2)[15][16].

In practice, the photoneutron production becomes significant regarding radiation protection issues when the nominal energy of the primary X-ray beam is higher than 8 MV. Neutrons are produced in the head of the linac and also in the primary barrier.

In the energy range of linear accelerators, the dominant mechanism of photoneutron production is giant dipole resonance. As a consequence:

— the emission of neutrons can be considered as isotropic[17];

— the energy spectrum is described by a Maxwellian distribution, with an average energy of about 1-2 MeV for heavy nuclei[14] and the average neutron energy can be considered as independent from the nominal energy of the X-ray beam[18];

— the photoneutron yield increases with increasing nominal energy of the beam[2][19][20].

For a given nominal energy, the photoneutron yield depends on the linac model because the X-ray spectrum can vary strongly from one model to another[9][21][22].For a given model, the neutron fluence depends on the secondary and tertiary collimation settings[23][24].

Neutron production in electron operating mode is much lower than in photon mode principally because direct production of neutrons by electron-nuclear reactions is at least two orders of magnitude lower than photonuclear production.

The above characteristics of neutron production shall be considered for radiation protection purposes around a linear accelerator.

Table 2 — Threshold energies and photonuclear reaction cross sections for typical nuclides[15][16]

Element	Mass number A	Abundance %	E_{th} MeV	σ_{max} mb
C	12	98,9	18,7	< 10
N	14	99,6	10,6	≅ 15
O	16	99,8	15,7	≅ 10
Cr	52	83,8	12,0	≅ 70
	53	9,5	7,9	≅ 70
Mn	55	100	10,2	≅ 70
Fe	56	91,7	11,2	≅ 60
Ni	58	68,1	12,2	≅ 25
	60	26,2	11,4	≅ 70
Cu	63	69,2	10,8	≅ 80
	65	30,8	9,9	≅ 90
W	182	26,3	8,1	≅ 400
	183	14,3	6,2	≅ 450
	184	30,7	7,4	≅ 400
	186	28,6	7,2	≅ 400
Au	197	100	8,1	≅ 550
Pb	206	24,1	8,1	≅ 600
	207	22,1	6,7	≅ 600
	208	52,4	7,4	≅ 650

6.3.2 Direct neutron radiation

Direct neutron radiation is the neutron component produced in the head of the linac. Neutron production in the head is mainly due to (γ,n) reactions in tungsten materials (flattening filter, primary collimator, jaws, MLC...).

Due to the intrinsic shielding of the head (W or Pb), characteristics of the neutron field outside the region defined by the non-adjustable beam limiting device (leakage neutrons) are different from those of the in-field neutrons: the energy spectrum is degraded by inelastic scattering and (n, 2n) reactions and the fluence is reduced by a factor of about 2[15][23][25]. As the maximum solid angle defined by the primary collimator and the maximum adjustable field size is only 1 % of 4π, it is possible to take as a good approximation, the hypothesis that all the direct neutrons are leakage neutrons.

Although there are different locations of neutron production within the linear accelerator head, it is justified to approximate it by using the point of divergence of the primary X-ray beam as sole origin of neutrons from the linac head. Fluence of the direct neutron component as a function of the distance from the source can be described by an inverse square law.

6.3.3 Scattered and thermal neutron radiation

Direct neutrons are scattered from the walls, the floor and the ceiling of the treatment room and a part of them are thermalized. As a consequence, the neutron energy spectrum around linear accelerator is softened as compared to the direct neutron spectrum: it is the combination of direct, scattered and thermalized neutrons[15].

Fluence of the indirect neutron component cannot be described by an inverse square law as a function of the distance from the source[15][26].

In a facility with a maze, a part of the neutrons produced in the treatment room reach the entrance door and this neutron component shall be calculated for shielding evaluation at the entrance.

6.3.4 Primary barrier neutron radiation

When the nominal energy of the photon beam is higher than 8 MV, neutrons are also produced in the barriers hit by the primary X-ray beam. Depending on the composition and the thickness of the barriers, those neutrons can significantly contribute or not to the exposure outside the treatment vault.

For concrete barriers (normal or high density concretes), neutron production within the barrier is strongly compensated by self-attenuation, leading to insignificant contribution outside the vault[15].

When a barrier contains a high proportion of metallic constituents, neutron production in the barrier can be significant and not compensated by self-attenuation. In this case, neutron radiation generated in the barrier should be taken in consideration for shielding calculations. This is especially the case when walls or ceilings are reinforced by one or more lead or steel layers[27][28].

6.4 γ radiation

6.4.1 General

When the nominal energy of the primary X-ray beam is higher than 8 MV, secondary γ radiation is produced together with neutrons. The γ component results from the two following processes:

— slow neutron capture (see Table 3):

$$n_{slow} + Z^{A} \rightarrow Z^{(A+1)} + \gamma \text{ or } Z^{A}\ (n_{slow}, \gamma)\ Z^{(A+1)}$$

— photonuclear reaction, with de-excitation of the new nucleus[2]:

$$X + Z^{A} \rightarrow Z^{*(A-1)} + n \text{ and } Z^{*(A-1)} \rightarrow Z^{(A-1)} + \gamma$$

6.4.2 Maze γ radiation

Slow neutron capture occurs principally in shielding materials situated in the maze. Normal or high density concretes contain elements that have non negligible neutron capture cross sections: Si, Ca, S, Fe, Ba. For ordinary concrete, the average energy of emitted γ rays is 3,6 MeV and maximum energy is about 10 MeV[15][29].

The γ component reaching the entrance door shall be calculated for shielding evaluation at the entrance[2].

6.4.3 Door γ radiation

Slow neutron capture also occurs in the door, especially when it contains borated polyethylene (BPE). Usually, doors have a multilayer structure made of successive layers of hydrogen-rich material (paraffin, polyethylene or borated polyethylene) and metal (steel (Fe, Ni, Cr) or lead), or made of three layers of metal, hydrogen-rich material, and metal.

The γ component generated in the door shall be taken into account in the construction of the door (composition, thickness and order of the different layers). The energy of the neutron capture γ radiation produced in BPE is 478 keV[2].

6.4.4 Primary barrier γ radiation

In primary barriers, neutron capture occurs in the concrete. In addition, if the barrier is reinforced with metal layer, photonuclear reactions with γ emission take place in the metal (steel, lead).

The γ component generated in the primary barrier should be taken into account for shielding calculations. For concrete barriers, some neutron transmission values include it implicitly[2][30]. For barriers reinforced with metal slabs, the additional dose equivalent due to metal capture γ rays should be evaluated[2][31].

6.4.5 Air γ radiation

Activation products are generated in the air by photonuclear reactions. Therefore, facility should ensure that air ventilation is adequate to remove air activation products and ozone, to meet local air quality standard.

7 Shielding materials and transmission values

Shielding materials shall be chosen not only for their radiological properties but also considering their mechanical and chemical properties, fire resistance, long time stability and cost. Activation characteristics of the materials shall be known for the type and energy of radiations to be attenuated by the shielding.

Quality control of the shielding materials shall be performed during the construction phase, before using the accelerator, in particular, control of the homogeneity (composition and density). Periodic evaluation of the shielding efficiency should be done throughout the life of the installation.

For any barrier, shielding materials shall be chosen in function of the nature of radiation components to be attenuated:

— photon components (X and *γ*): materials containing mainly high or medium Z elements are more effective, like: lead, iron, high density concretes (density > 3) and ordinary concretes (density around 2,3);

— neutron components: materials with a significant proportion of light elements are more effective, especially hydrogenated materials, like: paraffin, polyethylene and ordinary concretes; borated materials allow thermal neutron capture and are the most efficient materials (but expensive), like: borated polyethylene (BPE), pentahydrated Borax and colemanite-based concrete; for an extensive discussion about neutron radiation protection shielding, see ISO 14152[32], considering that the in-field neutron spectrum produced by linear electron accelerators is close to a ^{252}Cf fission spectrum[15].

For multilayer shielding with one or more metallic layers (especially reinforced primary barrier and door), neutron production has to be taken into account for nominal energies of the beam greater than 8 MV: a sufficient thickness of hydrogenated material has to be placed beyond the metallic layer.

For multilayer shielding with neutron-absorbing layer (for instance: door), γ production by neutron capture has to be taken into account: a sufficient thickness of high Z material has to be placed beyond the neutron-absorbing layer.

For any shielding material and any barrier (primary, secondary, door), information regarding photon and/or neutron attenuation properties are to be known: the data used for *TVL* values shall have been measured or determined by Monte Carlo simulations, and the materials and methods used for the *TVL* evaluation should be known. Tables of *TVL* values for the most common shielding materials and for photon components (primary, scattered and leakage X radiations) are given in Annex A. If *TVL* data are provided by the national regulatory authority in a given nation, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy and a given material is recommended. Attention should be paid to the fact that for a given type of concrete (for instance ordinary concrete), manufacturing can differ significantly from one concrete to another, in particular regarding density, elemental composition (a small difference in hydrogen content can have a significant impact on neutron transmission) and homogeneity (distribution of the aggregates in the concrete).

Regarding secondary X-ray radiations, the energy of X-ray scattered by the patient decreases as the scattering angle increases and the leakage X-ray component is softened as compared to the primary X-ray radiation, so the *TVL* values of the materials used for the secondary barriers should take these characteristics into account (see Tables A.5 to A.8) [IAEA SRS 47]. A conservative alternative is to consider primary *TVL* values for secondary patient scattered and leakage X-ray radiations.

In presence of a maze, energy spectra of scattered X-ray and of neutron capture γ photons are softened, together with energy spectrum of scattered neutrons. The energy spectrum softening of radiations reaching the door shall be taken into account for the choice of *TVL* values of the shielding materials used at the treatment room entrance (materials used for the door and for the surrounding walls) (see Table A.9) [IAEA SRS 47].

For neutron components, *TVL* shall refer to dose equivalent attenuation and should take into account the gamma component induced in the shielding material by neutron capture. For ordinary concrete and polyethylene, neutron *TVL* for treatment room shielding and for door shielding at the end of a maze can be estimated by linear functions of the direct neutron average energy and of neutron average energy at the door, respectively[15] (see Figure A.7). For concrete, a conservative approach is to consider a *TVL* value of 25 cm for treatment room shielding [IAEA SRS 47][2][4][5][15].

When different *TVL* values are provided for a given radiation quality and a given shielding material (TLV_1, TVL_2, TVL_3, TVL_e, TVL_c), for sake of simplicity, a unique value can be used, *TVL*, which should be the more relevant one depending on the thickness t of the shielding barrier: TVL_c corresponding to thickness *t* if it is provided, and if not:

— if $t \approx TVL_1$, then $TVL = TLV_1$;

— if $t \approx TVL_1 + TVL_2$, then $TVL = (TLV_1+TVL_2)/2$;

— if $t >> TVL_1+TVL_2$:

— if $TVL_{(i+1)} > TVL_i$, then $TVL = \max(TVL_i)$;

— if $TVL_{(i+1)} < TVL_i$, then $TVL = \text{mean}(TVL_i)$.

Photon thickness *TVL* values [cm] for any ordinary concrete or earth with their density ρ shall be calculated from TVL_{ref} data obtained for a reference ordinary concrete of density ρ_{ref} by applying an inverse density law:

$$\text{TVL} = TVL_{ref} \times \frac{\rho_{ref}}{\rho}$$

Photon *TVL* values for a given high density concrete should be specific data obtained for that particular concrete and if such data are not provided, the thickness *TVL* values [cm] shall be calculated from data obtained for a reference ordinary concrete of density ρ_r by applying the above inverse density law. This is a conservative rule as usually, true *TVL* values of high density concretes are lower than the one obtained by the inverse density law because of pair production in high Z components at high energies.

Neutron thickness *TVL* values [cm] are considered to be equivalent for any ordinary concrete of density ρ_i. Neutron *TVL* values for a given high density concrete should be specific data obtained for that particular concrete and if such data are not provided, neutron thickness *TVL* values [cm] are considered to be similar to ordinary concrete values because the hydrogen content does not vary significantly between different concretes[30].

For primary barriers, if the accelerator produces narrow beams (radius or half-side less than to the range of secondary electrons) and is mainly used with narrow beams, transmission data for broad beams can be used. This is a conservative rule as narrow beams are less penetrating than broad beams whose scattered component enhances the dose behind a barrier (build-up effect).

For accelerators with FFF operating mode at a given end point energy, energy spectrum of the primary X-ray beam is degraded as compared to the energy spectrum of the FF operating mode. If the accelerator is exclusively used with the FFF modality, specific *TVL* values can be considered for primary and patient scattered X-ray radiations[33]. If both FF and FFF modalities are regularly used, a conservative approach should be followed, which is taking into account *TVL* values of the FF operating mode.

8 General formalism for shielding calculation

The recommended radiation protection quantity for limitation of exposure of people is effective dose E[6]. Operational quantities such as dose equivalent H^* or dose equivalent H_p are defined by ICRU in order to estimate the effective dose[6]. As a convention, for the purpose of the document, dose equivalent represents one of these quantities chosen according to the goal of the shielding evaluation.

If a time period is not mentioned, the dose equivalent during the reference period (year, week, hour...) defined for the shielding design goal P (Sv) (see 4.1) is assumed.

For any radiation component (r) (see 6.1), the calculated shielded dose equivalent ($H_{tr,r}$), that is the transmitted dose equivalent, is given by the following equation (Sv):

$$H_{\mathrm{tr,r}} = H_{\mathrm{u,r}} \, B_{\mathrm{r}} \qquad (2)$$

where

$H_{u,r}$ is the unshielded dose equivalent related to radiation r (dose equivalent without the barrier) (Sv);

B_r is the radiation transmission factor for radiation r and the barrier.

The thickness of the barrier shall be such that $H_{tr,r} = P/T$:

$$B_{\mathrm{r}} = P / \left(T \times H_{\mathrm{u,r}}\right) \qquad (3)$$

where T is the occupancy factor, to correct for the occupancy of the area.

T values depend on the countries, they should be defined by users or by national regulation. Suggested T values are given in Table 3.

Table 3 — Suggested values for the occupancy factor T [IAEA SRS 47, Table 3][2]

Type of area	T
Offices, reception areas, laboratories, shops, children's play areas, nurse's stations, staff rooms Control room	1
Wards, patient rooms	0,2
Patient examination and treatment rooms	0,5
Corridors	0,2
Toilets, bathrooms, outside areas with seating	0,1
Stairways, unattended waiting rooms, store rooms (not film)	0,05

For any radiation, r, and any area adjacent to the treatment room, $H_{u,r}$ (Sv) is calculated taking into account the orientation or use factor (U):

$$H_{u,r} = W_r \times R_r \times U_r \quad (4)$$

where

W_r is the workload for radiation r (W or W_L: see 9.3.2 and 10.3.3) (Gy);

R_r is $H_{u,r}$ per unit of W_r (considering $U_r = 1$) (Sv/Gy);

U_r is the orientation or use factor (U) for radiation r.

The workload W shall include also the linear accelerator usage not associated to patient treatment (e.g. QA, maintenance, and physics developmental activities). A separate workload allocation may be appropriate for modalities such as Stereotactic Radiosurgery (SRS), Stereotactic Body Radiotherapy (SBRT), or Total Body Irradiation (TBI) if such use is planned for the facility.

The leakage workload (W_L) is equal to the conventional workload (W) if IMRT is not used. Intensity Modulated Radiotherapy (IMRT) requires an increase in monitor units (MU) compared to conventional radiotherapy. The ratio of the average monitor unit per unit prescribed absorbed dose needed for IMRT (MU_{IMRT}) and the monitor unit per unit absorbed dose for conventional treatment (MU_{conv}) is called the IMRT ratio C_I (3.1.4).

MU_{IMRT} is the average total monitor unit required to deliver a unit prescribed absorbed dose per fraction for "i" cases of IMRT treatment plan[2].

MU_{conv} is the monitor unit required to deliver the same unit absorbed dose to a phantom at the reference depth at 100 cm source-to-isocentre distance, using field size 10 cm × 10 cm.

Value of C_I can range from 2 to 10 and shall be defined by the medical physicist involved in the radiotherapy centre. 2,5 can be considered as a typical value for C_I.

The IMRT factor is given by:

$$\text{IMRT factor} = C_I \times F_{IMRT} + (1 - F_{IMRT}) \quad (5)$$

where F_{IMRT} is the fraction of treatments realized with IMRT technique.

The leakage workload (W_L) is then given by:

$$W_L = W \times \text{IMRT factor} \quad (6)$$

For primary barrier, U shall be evaluated and defined by the radiation protection officer or qualified expert. International recommendations (IAEA, NCRP) propose for an isocentric accelerator static or dynamic mode: 0,25; for robotic arm accelerator: 0,05. For leakage and scattered radiation components (leakage and scattered X-rays, neutrons, maze and door neutron capture γ), an orientation or use factor $U = 1$ should be considered.

In the case of barrier with a unique material, the thickness (t) of the barrier can be determined using tenth-value layers based on the energy of the accelerator, radiation component considered and type of shielding material (see Tables A.1 to A.9), using the relationship $B_r = 10\hat{}\left[-t / TVL\right]$.

The required number (n) of *TVL*s is given by:

$$n = -\log(B_r) \qquad (7)$$

and the barrier thickness (t) in metres is given by:

$$t = n \times TVL \ (TVL \text{ in metres}) \qquad (8)$$

If the chosen shielding material is concrete, because concrete density may be lower than anticipated, a suitable margin should be considered, for example by adding a 0,3 *TVL* (corresponding to one half value layer), particularly for poured concrete.

The total radiation exposure to any one individual from multiple sources shall be considered in all calculations to ensure that the total exposure to the individual is below the applicable limit. Multiple sources can be multiple radiation components for a given nominal energy of the beam, multiple nominal energies for a given accelerator, and multiple accelerators or other sources of radiations. The thickness of a given barrier shall be such that the total sum of the shielded equivalent doses ($H_{tr,r}$) due to the different sources is lower or equal to P/T.

9 Shielding calculation for conventional devices

9.1 General

In conventional radiotherapy, the linear accelerator is mounted on a gantry, with the beam able to point in any direction within a vertical plane of rotation. A primary barrier is shielding that reduces the radiation from this beam. The linear accelerator also produces secondary radiation (leakage and scattered) in all directions. A secondary barrier is shielding that reduces this secondary radiation. For some linear accelerators, the machine may incorporate a beam stopper that reduces the primary radiation to a dose rate that is similar to the secondary radiation. In such cases, the beam stopper shall be included in the calculations for primary barrier.

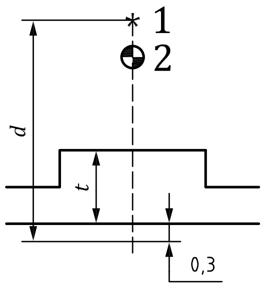
9.2 Primary barriers

9.2.1 Radiation components

Radiation components that should be taken into account for primary shielding evaluation are primary X-ray beam and, for nominal energies of the beam > 8 MV, direct neutron radiation and primary barrier neutron radiation. However, in-beam direct neutrons are of a much lower level than the photons and in addition, the in-beam neutron *TVL* in concrete is less than the primary photon *TVL*, resulting in in-beam neutrons which are negligibly small beyond a primary barrier that does not contain metal. For primary barriers containing metal at nominal energies of the beam greater than 8 MV, photoneutrons generation may be significant and shall be evaluated. As the in-beam neutron component is well below the photoneutron component created in the barrier, it is unnecessary to model in-beam neutrons in shielding calculations.

The primary barrier calculations with normal incidence use the geometry illustrated in Figure 2. If the radiation incidence is oblique, calculations should be done considering a normal incidence: this is a simple and conservative assumption.

Dimensions in metres



Key

1 target

2 isocentre

Figure 2 — Primary barrier distances

9.2.2 Barrier with a unique material

The unshielded X-ray dose equivalent ($H_{u,p}$) (Sv) is given by Formula (9).

$$H_{u,p} = \frac{W \times U}{d^2} \tag{9}$$

where

- W is the workload specified for the period of reference (Gy);
- U is the orientation or use factor;
- d is the distance from the target to the protected point in metres including 0,3 m distance from outer surface of barrier to the point of occupancy.

The shielded X-ray dose equivalent ($H_{tr,p}$) (Sv) is given by Formula (10).

$$H_{tr,p} = H_{u,p} \times B_p \tag{10}$$

where

B_p is the X-ray transmission factor for the barrier.

9.2.3 Barrier with multiple layers

The transmission factor is calculated separately for each layer of material in the barrier, with B_p calculated by multiplying the transmission factor for these layers together. The transmission factor for layer i is given by:

$$B_i = 10\hat{}\left[-t_i / TVL_i\right] \tag{11}$$

where TVL_i and t_i are the TVL and the thickness of layer i, respectively (m).

If metal is used in a primary barrier at energies of the beam above 8 MV, photoneutrons produced in the metal contribute to the total shielded dose. The positioning of the metal within the barrier is important and shall be at a sufficient depth from the external surface so that the neutron dose and photo-neutron dose are attenuated by the material external to the metal and the total dose including the attenuated X-ray dose on the exterior is acceptable.

The neutron dose equivalent ($H_{tr,n}$) (Sv) at 0,3 m beyond a primary barrier can be estimated using the simple analytical expression given in Formula (12)[2][19].

$$H_{tr,n} = \frac{W \times U \times R \times F_{max}}{\frac{t_m}{2} + t_2 + 0,3} 10^{-t_1/TVL_x} 10^{-t_2/TVL_n} \quad (12)$$

where

W	is the workload specified for the period of reference (Gy);
U	is the orientation or use factor;
t_1 and t_2	are the inside and outside layer thicknesses in metres;
t_m	is the metal thickness in metres;
R	is the neutron production constant; (Sv neutron per Gy X-ray per beam area, in $Sv{\cdot}Gy^{-1}{\cdot}m^{-2}$), For a 18 MV X-ray beam, the following reported values can be used for R: 19×10^{-4} and $1,7 \times 10^{-4}$ $Sv{\cdot}Gy^{-1}{\cdot}m^{-2}$ for lead and steel, respectively; for a 15 MV X-ray beam, an R value of $3,5 \times 10^{-4}$ $Sv{\cdot}Gy^{-1}{\cdot}m^{-2}$ is reported for lead[27];
F_{max}	is the maximum field area at isocentre (m^2);
TVL_x(m)	is the primary X-ray TVL for the material before the metal (see Tables A.1 and A.2);
TVL_n(m)	is the photoneutron TVL for the material after the metal (see Figure A.7).

If there is more than one layer of metal in the barrier, then the contribution is calculated separately for each layer with the neutron contribution of each metal layer added together.

The neutron capture gamma radiation generated in the neutron-attenuating material outside the metal shall also be evaluated. A conservative estimation of the gamma component is about 2 x $H_{tr,p}$ for steel and concrete laminates at 15 MV and 18 MV photon beam energies[2][31].

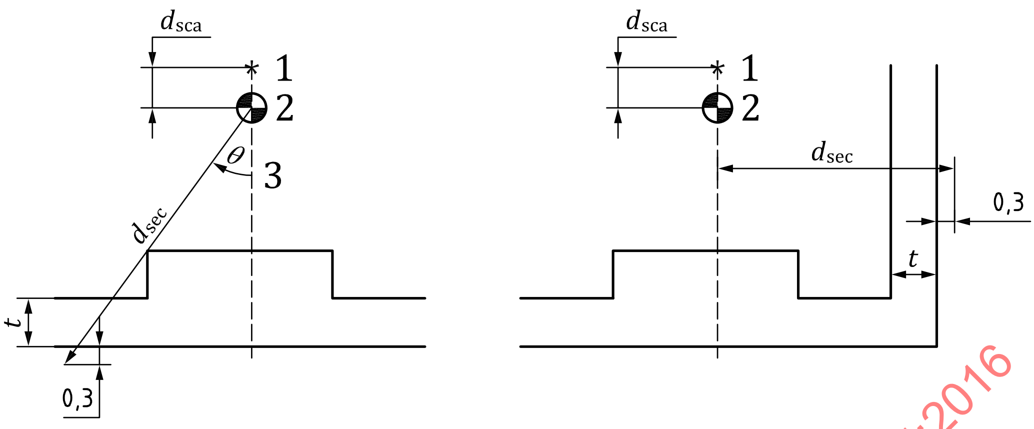
Formula (12) is an empirical formula based on measurements on different installations and is associated with not insignificant uncertainties. Another method for shielding evaluation of a laminated primary barrier is to perform Monte Carlo simulation using a primary X-ray source energy spectrum published in the scientific literature, density and elemental composition (weight or atom fraction) of the barrier as accurate as possible and an adequate transport code (managing transport of photons, electrons, positrons and neutrons, photoneutron production and neutron capture gamma generation, in the appropriate energy range and for the elemental composition of the different layers of the barrier). Attention should be paid to the fact that for a given type of concrete (for instance ordinary concrete), manufacturing can differ significantly from one concrete to another, in particular regarding density, elemental composition (a small difference in hydrogen content can have a significant impact on neutron transmission) and homogeneity (distribution of the aggregates in the concrete).

9.3 Secondary barriers

9.3.1 Radiation components

The secondary radiation comes from two sources: leakage (l) from the shielding around the target and scattered (s) radiation from the patient and from a primary barrier. Scatter from primary barrier shall not be included because it is not significant for secondary barriers. For accelerators > 8 MV, both X-ray and neutron leakage shall be considered. The secondary barrier unshielded dose rate for lateral secondary barriers is calculated using the geometry in Figure 3.

Dimensions in metres



Key

1 target

2 isocentre

3 scatter angle

Figure 3 — Secondary barrier distances

9.3.2 Barrier with a unique material

9.3.2.1 Leakage

The X-ray leakage unshielded dose equivalent due to leakage from the accelerator head ($H_{u,L}$) (Sv) is given by Formula (13).

$$H_{u,L} = \frac{W_L \times U \times 10^{-3}}{d^2_{sec}} \quad (13)$$

where

W_L is the leakage workload for the period of reference (Gy);

U is the orientation or use factor, assumed to be 1 for leakage radiation;

d_{sec} is the distance from isocentre (averaged position of the target) to the protected location in metres.

10^{-3} is the X-ray leakage fraction.

The 10^{-3} value reflects the IEC 60601-2-1 standard requirement that the average X-ray leakage outside the beam shall be less than 0,1 % of the dose at isocentre at a distance of 1 m from the source of leakage[1]; it is also a conservative assumption for FFF operating mode as removal of the flattening filter reduces head leakage by reducing integral target current requirements for the same delivered dose[33].

The X-ray leakage shielded dose equivalent ($H_{tr,L}$) (Sv) is given by Formula 14.

$$H_{tr,L} = H_{u,L} \times B_L \quad (14)$$

Where B_L is the leakage transmission factor calculated from the X-ray leakage *TVL* (see Table A.5).

For nominal energies of the beam greater than 8 MV, neutron leakage is included in the calculated secondary shielded dose rate. Neutron leakage is calculated using the same approach as for X-ray leakage [Formulae (13) and (14)], except with a different neutron leakage fraction and *TVLs* (see

Figure A.7). Neutron leakage fraction depends on primary X-ray end point energy and on the accelerator model [IAEA SRS 47, Table 10]. For FFF operating mode, a conservative assumption is to consider the same neutron leakage fraction as for the FF modality, as removal of the flattening filter reduces head leakage by reducing integral target current requirements for the same delivered dose[33].

9.3.2.2 Patient scatter

The unshielded patient scatter dose equivalent ($H_{u,PS}$) (Sv) is given by Formula (15).

$$H_{u,PS} = \frac{a(\theta) \times W \times U \times (F_{max} / 0,04)}{d_{sca}^2 \times d_{sec}^2} \quad (15)$$

Where

d_{sca} is the target to isocentre distance in metres;

d_{sec} is the secondary distance from isocentre to the point protected in metres;

$a(\theta)$ is the patient scatter fraction relative to primary at 1 m distance for a 0,04 m² field size for scattering angle θ at depth 15 mm for energy 6 MV and 25 mm for higher energies (see Table B.1). For accelerators with FFF operating mode, specific a(θ) values shall be considered[33];

F_{max} is the maximum field area at isocentre in m²;

U is the orientation or use factor for scatter, assumed to be 1 for all the walls.

The patient scatter shielded dose equivalent (H_{PS}) (Sv) is given by Formula (16).

$$H_{tr,PS} = H_{u,PS} \times B_{PS} \quad (16)$$

Where B_{PS} is the patient scatter transmission calculated from the patient scatter *TVL* (See Tables A.6 to A.8).

9.3.3 Barriers with multiple layers

With multiple layers of shielding material, transmission is calculated individually for each layer, with the total transmission being the product of the transmission for each individual layer. The order of the material may be important when the barrier is constructed out of metal and hydrogenated material, for instance lead and polyethylene. Neutron capture gammas in the polyethylene are not explicitly modelled for secondary radiation. This implies that a layer of polyethylene should not form the outside of shielding in a secondary barrier. In a secondary barrier containing lead and polyethylene, the polyethylene should be sandwiched between two approximately equal layers of lead. The outer layer of lead provides shielding adequate to attenuate the capture gamma rays. The inner layer of lead, although ineffective at capturing neutrons, decreases neutron energy making the polyethylene more effective.

10 Doors and mazes

10.1 General

The shielding required at the entrance to a linear accelerator treatment room can be reduced or eliminated by including a maze in the room design. A maze with a single bend prevents direct radiation from reaching the entrance, with the amount of scattered radiation reduced in both magnitude and energy as the maze length increases. Additional bends in the maze further reduce radiation reaching the entrance, with at least three bends typically needed to eliminate the need for a door at the entrance.

A typical door includes lead, with paraffin or borated polyethylene also included for linear accelerator energies above 8 MV. A relatively modest lead thickness effectively eliminates X-ray scatter radiation.

Greater lead thickness is necessary to attenuate the capture gamma rays associated with neutron production. If a door includes paraffin or borated polyethylene, at least half the lead shall be on the room-exterior side of the door to mitigate capture gammas associated with neutron capture in the door.

A single legged maze is a maze with a single bend (see Figures 4 to 9). Typical dimensions include a 5 m long inner maze wall, a maze width of 2 m to 2,5 m and inner entrance width of 2 m to 3 m. The maze height is typically 3 m, with a lintel in some cases used to reduce the effective inner maze entrance height.

For a single-legged maze, the calculations described below predict the unshielded dose rate at the maze entrance within approximately a factor of two (underestimation or overestimation). These calculations can be adapted for maze configurations with more than a single bend (e.g. see Figures 10 and 11 for a two-legged maze) and for configurations without maze or without door (see 10.5 and 10.6). Monte Carlo simulation can also be used as an alternative approach.

If Monte Carlo simulations are used, they shall be performed using the correct geometry (treatment room, maze and treatment room entrance), primary X-ray and neutron energy spectra published in the scientific literature, density and elemental composition of all barriers as accurate as possible and an adequate transport code (managing the transport of photons, electrons, positrons and neutrons, photoneutron production and neutron capture gamma generation in the appropriate energy range and for the elemental composition of the different barriers). Attention should be paid to the fact that for a given type of concrete (for instance ordinary concrete), manufacturing can differ significantly from one concrete to another, as referred previously in 9.2.3.

10.2 Radiation components

The maze calculation includes: wall scatter radiation, radiation patient scatter and radiation leakage scatter. Wall scatter is radiation from the primary beam that is reflected from the primary barrier and then subsequently reflected by the wall at the end of the maze. Patient scatter is radiation scattered by the patient under treatment that is subsequently reflected by the wall at the end of the maze. Leakage scatter is the X-ray leakage that is reflected by the wall at the end of the maze.

In addition to the three types of scatter cited above, the calculated dose at the entrance also shall include a conventional secondary direct leakage through the inner maze wall. In situations where the entrance is beyond a primary barrier, a primary barrier calculation is appropriate instead of a direct leakage calculation.

For nominal energies of the beam higher than 8 MV, the shielded dose equivalent associated with neutrons is added with the dose from the four radiation components identified above when calculating the total shielded dose equivalent. This includes not only the neutron dose-equivalent, but also the capture gamma dose associated with neutron capture in the maze.

10.3 Standard maze

10.3.1 Maze X-ray scatter calculations

10.3.1.1 General

Normally, the plane of rotation of the accelerator gantry is parallel to the inner maze wall. Wall scatter calculation is different if the plane of rotation is perpendicular to the inner maze wall. The distribution of the patient scatter and leakage scatter calculations do not depend on the orientation of the plane of rotation.

After each of the individual X-ray scatter components has been calculated, the total unshielded dose equivalent ($H_{u,XS}$) (Sv) at the maze door is obtained by summing the dose equivalent components considered above.

$$H_{u,XS} = H_{u,ps} + H_{u,S} + H_{u,LS}$$

where

$H_{u,ps}$ is the unshielded dose equivalent for the period of reference (Sv) at the maze door due to patient-scattered radiation;

$H_{u,S}$ is the unshielded dose equivalent for the period of reference (Sv) at the maze door due to scattering of the primary beam from primary barrier;

$H_{u,LS}$ is the unshielded dose equivalent for the period of reference (Sv) at maze door due to single scattered head-leakage radiation.

For wall scatter calculation, attenuation of the primary beam in the patient should not be considered (conservative assumption). For the patient and wall scatter calculations, the most extreme geometry should be used, with a factor (U) equal to 1 (conservative assumption). Leakage scatter shall be calculated with a factor (U) equal to 1 using the average target location (isocentre).

10.3.1.2 Patient scatter

The unshielded dose equivalent due to patient scatter ($H_{u,PS}$) (Sv) is given by Formula (17). See Figure 4.

$$H_{u,PS} = \frac{a(\theta) \times W \times U \times (F_{max} / 0,04) \times \alpha_1 \times A_1}{d_{sca}^2 \times d_{sec}^2 \times d_{zz}^2} \quad (17)$$

where

d_{sca} is the target to isocentre distance in metres;

d_{sec} is the distance from isocentre to the wall at the end of the maze in metres;

d_{zz} is the maze length from the wall to the entrance in metres;

W is the workload for the period of reference in Gray;

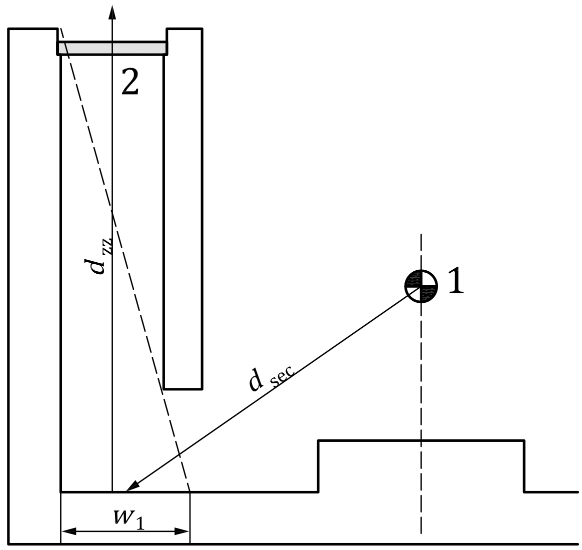
U is the orientation or use factor;

$a(\theta)$ is the patient scatter fraction (see 9.3.2) normalized for (0,2 × 0,2) m^2 field size;

F_{max} is the maximum field area in m^2 (same area assumed for patient scatter in secondary calculation);

α_1 is the reflection coefficient in m^{-2} depending on energy of patient scattered radiation, wall material, incidence and reflection angles (see Tables B.2 and B.3); a conservative value of 0,5 MeV can be considered for the mean energy of patient scattered radiation;

A_1 is the area in m^2 of maze back wall that can be seen from outer maze entrance, $A_1 = w_1 \times h$ where w_1 is the width of the area in metre and h is the height of the room in metre.



Key

1 isocentre

2 door

Figure 4 — Patient scatter distances

10.3.1.3 Wall scatter

10.3.1.3.1 Wall scatter with the plane of rotation parallel to the inner maze wall

For this geometry, the unshielded dose equivalent at the entrance due to wall scatter is calculated using the geometry in Figure 5. The unshielded dose equivalent due to wall scatter ($H_{u,S}$) (Sv) is given by Formula (18).

$$H_{u,S} = \frac{W \times U \times \alpha_0 \times A_0 \times \alpha_z \times A_z}{d_H^2 \times d_r^2 \times d_z^2} \quad (18)$$

where

d_H is the target to primary barrier distance in metres;

d_r is the distance from the primary barrier to the inner maze entrance in metres;

d_z is the distance from the inner maze entrance to the entrance in metres;

W is the workload for the period of reference in Gray;

U is the orientation or use factor;

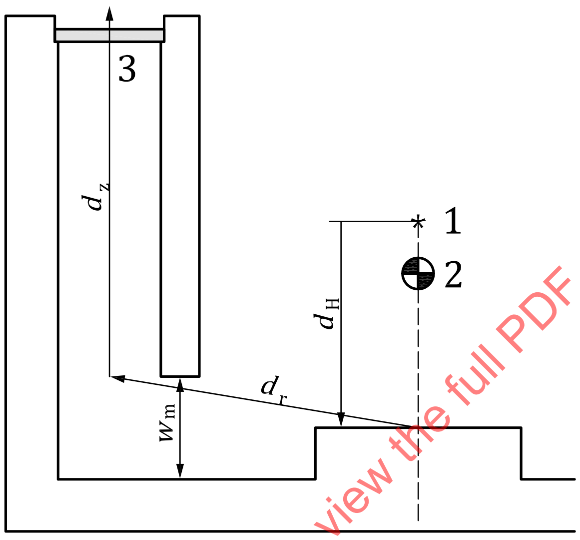
α_0 is the reflection coefficient in m^{-2} depending on the nominal energy of the X-ray beam, wall material of primary barrier and incidence and reflection angles (see Tables B.2 and B.3); for accelerators with FFF operating mode, specific α_0 values shall be considered[33];

A_0 is the beam area in m^2 at first reflection wall for the maximum field size; $A_0 = (0,4\ d_H)^2$ for a 40 cm × 40 cm field at 1 m;

α_z is the reflection coefficient in m^{-2}, depending on energy of scatter by primary wall, wall material of maze and incidence and reflection angles (see Tables B.2 and B.3); a value of 0,5 MeV is usually assumed for the energy of primary wall scattered radiation, but a value of 0,25 MeV is more conservative;

A_z is the cross section of the inner maze entrance in m^2, $A_z = w_m \times h$, where w_m is the inner maze entrance width in metre and h is the height of the room in metres.

Fraction of the primary beam transmitted through the patient is not considered.



Key

1 target

2 isocentre

3 door

Figure 5 — Wall scatter distances with plane of rotation parallel to inner maze wall

10.3.1.3.2 Wall scatter with plane of rotation perpendicular to inner maze wall

If the plane of rotation is perpendicular to the inner maze wall, the unshielded dose equivalent at the entrance due to wall scatter is calculated using the geometry in Figure 6. The unshielded dose equivalent due to wall scatter ($H_{u,S}$) (Sv) is given by Formula (19).

$$H_{u,S} = B \frac{W \times U \times \alpha_0 \times A_0}{d_H^2 \times d_z^2} \tag{19}$$

where

d_H is the target to maze primary barrier distance in metres;

d_z is the distance from the wall to the entrance in metres;

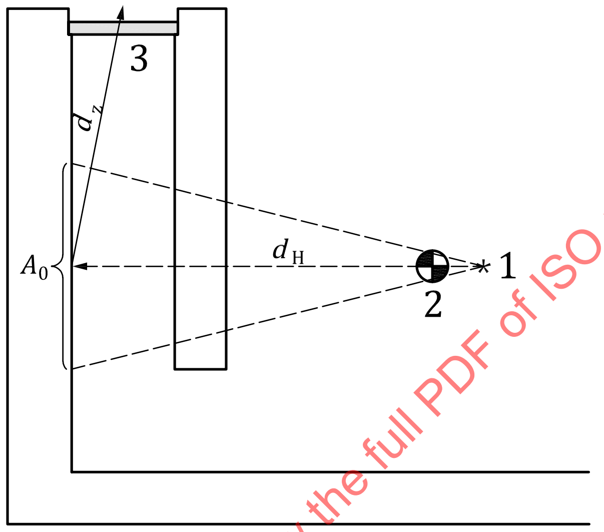
W is the workload for the period of reference in Gray;

U is the orientation or use factor;

B is the maze wall transmission factor using primary *TVL* (See Annex A);

α_0 is the reflection coefficient in m^{-2}, depending on the nominal energy of the X-ray beam, wall material of maze primary barrier and incidence and reflection angles (see Tables B.2 and B.3); for accelerators with FFF operating mode, specific α_0 values shall be considered[33];

A_0 is the beam area in m^2 at reflection wall for the maximum field size; $A_0 = (0{,}4\ d_H)^2$ for a 40 cm × 40 cm field at 1 m.



Key

1 target

2 isocentre

3 door

Figure 6 — Wall scatter distances with plane of rotation perpendicular to inner maze wall

10.3.1.4 Leakage scatter

The unshielded dose equivalent at the entrance due to leakage scatter is calculated using the geometry in Figure 7. The leakage scatter unshielded dose equivalent ($H_{u,LS}$) (Sv) is given by Formula (20).

$$H_{u,LS} = \frac{10^{-3} \times W_L \times U \times \alpha_1 \times A_1}{d_{sec}^2 \times d_{zz}^2} \tag{20}$$

where

d_{sec} is the distance from the average target location (isocentre) to the wall at the end of the maze in metres;

d_{zz} is the maze length from the wall to the entrance in metres;

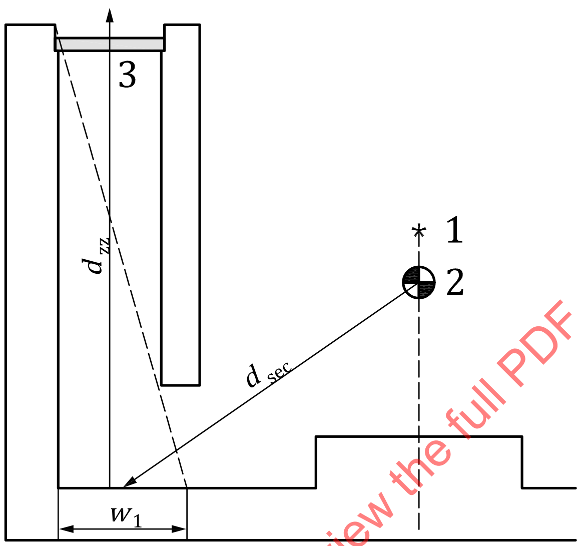
W_L is the workload for the period of reference in Gray;

U is the orientation or use factor equal to 1;

α_1 is the reflection coefficient in m^{-2}, depending on leakage X-ray energy, material of maze back wall and incidence and reflection angles (see Tables B.2 and B.3); a value of 1,5 MeV can be considered for the mean energy of leakage radiation[8][19]; for accelerators with FFF operating mode, specific α_1 values can be considered[33];

A_1 is the area in m^2 of maze back wall that can be seen from outer maze entrance, $A_1 = w_1 \times h$ where w_1 is the width of the area in metre and h is the height of the room in metres.

10^{-3} is the X-ray leakage fraction (see 9.3.2).



Key

1 target

2 isocentre

3 door

Figure 7 — Leakage scatter distances

10.3.2 X-ray direct Leakage

The unshielded dose equivalent (including maze wall transmission but not the door transmission) at the entrance due to leakage ($H_{u,L}$) (Sv) is given by Formula (21). See Figure 8.

$$H_{u,L} = \frac{W_L \times U \times 10^{-3} \times B}{d_L^2} \quad (21)$$

where

d_L is the distance from the average target location (isocentre) to the protected point in metres;

B is the transmission factor of the maze wall;

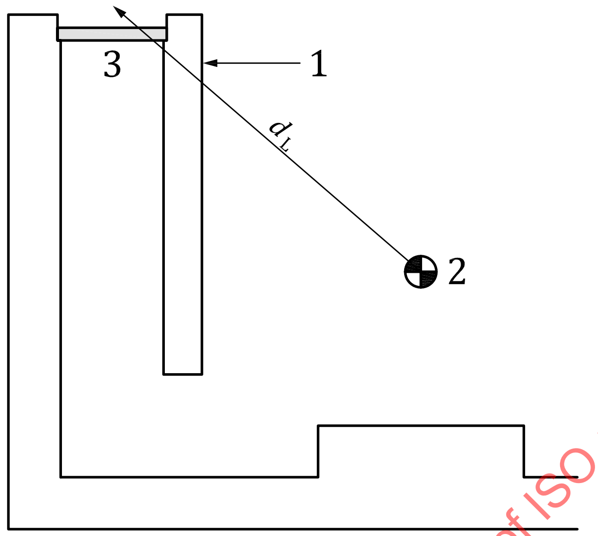
W_L is the leakage workload for the period of reference in Gray;

10^{-3} is the X-ray leakage fraction (see 9.3.2);

U is the orientation or use factor equal to 1.

The maze wall transmission is calculated using the leakage *TVL* of the maze wall material (See Table A.5).

If the treatment room layout causes another location to have a significantly higher unshielded dose, the calculation may be made to this location. In this case, an adjustment may be made reflecting orientation or use factor with the target in this orientation.



Key

1 maze wall

2 isocentre

3 door

Figure 8 — Direct leakage distance

10.3.3 Maze neutron and capture gamma calculations

For accelerators with nominal energy of the beam greater than 8 MV, note that neutron leakage through the wall and door is generally a negligible component of the shielded dose equivalent at the entrance.

On the contrary, neutron transmission down the maze shall be included in the dose equivalent calculation at the maze entrance. This dose equivalent shall include not only neutrons, but also gamma rays associated with neutron capture in the maze. An analytical calculation is described below [IAEA SRS 47][34].

The first step is to calculate the total neutron fluence at point A per Gy workload (ϕ_A) (neutrons/m²·Gy). The calculation is given by equation (22) and uses the geometry illustrated in Figure 9.

$$\varphi_A = \frac{\beta \times Q_n}{4\pi \times d_1^2} + \frac{5,4\ \beta \times Q_n}{2\pi \times S_r} + \frac{1,3\ Q_n}{2\pi \times S_r} \quad (22)$$

Where

β is the accelerator head shielding transmission factor (1 for lead, 0,85 for tungsten);

Q_n is the neutron source strength (neutrons per X-ray unit dose at isocentre) (neutrons/Gy)]. Q_n depends on the nominal energy of the beam and on the accelerator model, for a given energy. Q_n values are given in IAEA SRS 47, Table 9, in[2] and in[22] for modern accelerators. Depending on the model, the Q_n value for a 18 MV modern accelerator ranges between 0,428 and 1,26 × 10^{12} at 18 MV and between 0,144 and 0,742 × 10^{12} at 15 MV[2][22];

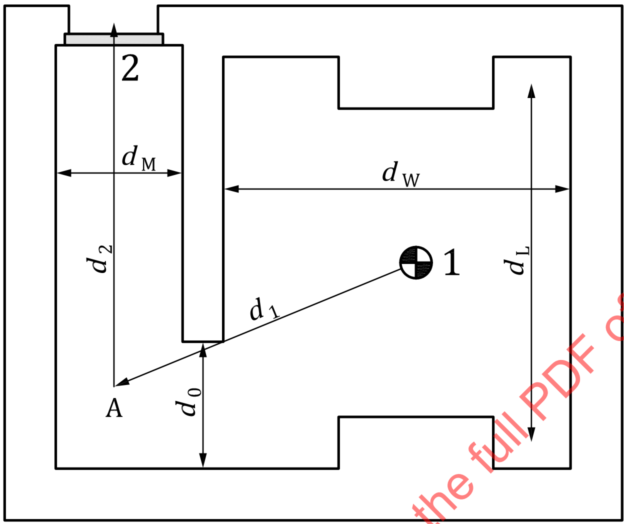
S_r is the treatment room total reflection surface in m², given by Formula (23):

$$S_r = 2\,(d_L\, d_W + h\, d_L + h\, d_W) \tag{23}$$

where

h is the room height in metres;

d_W and d_L are width and length of the treatment room in metres.



Key

1 isocentre

2 door

Figure 9 — Maze neutron distances

Formula (24) gives the capture gamma unshielded dose equivalent at the entrance ($H_{u,\gamma}$) (Sv).

$$H_{u,\gamma} = W_L \times U \times K \times \phi_A \times 10^{-d_2 / TVD_\gamma} \tag{24}$$

where

d_2 is the distance from point A to the protected point in metres;

TVD_γ is the capture gamma tenth-value distance (m); a value of 6 m can be used[2];

K is the ratio of capture gamma dose equivalent to neutron fluence at point A (Sv·m^2/neutrons) [IAEA SRS 47][2]; a value of 6,9 × 10^{-16} Sv·m^2/neutrons can be used (average value from measurements on different facilities)[2];

W_L is the leakage workload for the period of reference in Gray;

U is the orientation or use factor equal to 1.

It is also a conservative assumption for FFF operating mode as removal of the flattening filter reduces accelerator head leakage by reducing integral target current requirements for the same delivered dose[33].

Formula (25) gives the entrance neutron unshielded dose equivalent ($H_{u,n}$) (Sv).

$$H_{u,n} = W_L \times U \times 2,4 \times 10^{-15}\ \phi_A \left(\frac{S_0}{S}\right)^{1/2} \left[1,64 \times 10^{-(d_2/1,9)} + 10^{-(d_2/TVD_n)}\right] \tag{25}$$

where

S_0/S is the ratio of inner maze entrance cross-section area ($S_0 = d_0 \times h$), in m^2, to maze cross-section area ($S = d_M \times h$) in m^2, where d_0 (in metres) and d_M (in metres) are the widths of the inner maze entrance and of the maze, respectively, and h is the maze height (in metres);

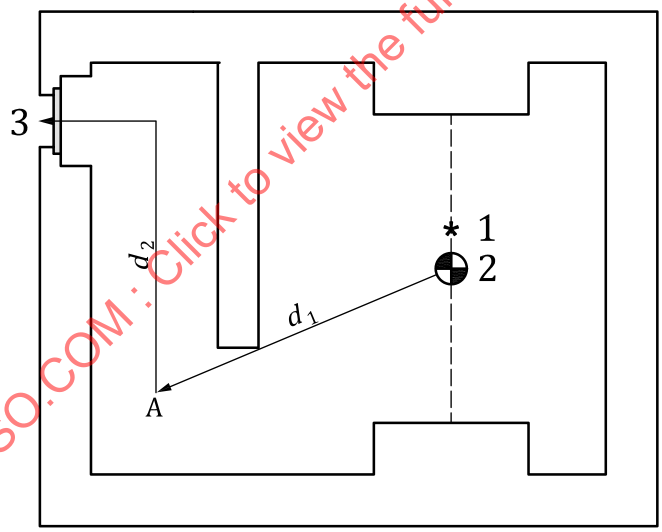
TVD_n is the neutron tenth-value distance in metres; $TVD_n = 2{,}06 \times S^{1/2}$[2];

W_L is the leakage workload for the period of reference in Gray;

U is the orientation or use factor equal to 1.

10.4 Two legged maze

When the maze has more than one bend, the final distance in the maze neutron calculation is measured along the maze centreline to the entrance. This is illustrated for the distance d_2 from Figure 10. Furthermore, the additional maze bend reduces roughly the unshielded dose equivalent for neutrons by a factor of three compared to a maze with a single bend and the same total length [IAEA SRS 47][2].



Key

1 target

2 isocentre

3 door

Figure 10 — Neutron calculation geometry with additional bend in maze

Scattered X-ray radiation undergoes an additional interaction if the treatment room entrance is not visible from the far end of the maze, with an additional scatter factor added to account for interaction. The portion of the maze wall visible from the treatment room entrance determines the area (A_M) (m^2)

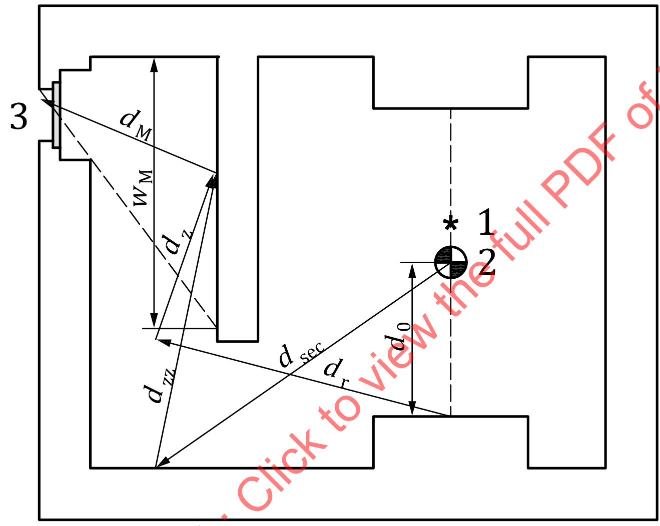
used in calculating the additional factor, as illustrated in Figure 11. The additional scatter factor is given by:

$$\alpha \cdot A_M \ / \ d_M^2 \tag{26}$$

where

- α is the reflection coefficient (m^{-2}) (see Tables B.2 and B.3); a value of 0,5 MeV can be assumed for the energy of incident radiation, but a value of 0,25 MeV is more conservative;
- d_M is the distance from the wall opposite the entrance to the entrance in metres;
- A_M is the area in m^2 of maze wall that can be seen from the treatment room entrance, $A_M = w_M \times h$ where w_M is the width of the area (in metres) and h is the height of the room (in metres).

The distances d_Z and d_{ZZ} extend to the wall opposite the entrance (see 10.3).



Key

1 target

2 isocentre

3 door

Figure 11 — Scatter calculation geometry with additional bend in maze

Another method of calculation is to use Monte Carlo simulations to evaluate the transport of X-ray, neutron and gamma components in the maze and the transmission of the radiations through the door.

10.5 No maze - Direct-shielded doors

10.5.1 General

As described in 10.3, linear accelerator treatment rooms traditionally include a maze between the entrance to the treatment room and the machine. The treatment room size can be significantly reduced if this maze is eliminated, with entrance to the room via a direct-shielded door installed in a secondary barrier wall. A direct shielded door shall shield not only X-rays but also leakage neutrons for primary nominal energies above 8 MV. The door itself is a secondary barrier, with shielding calculated as described in 9.3.

A maximum gap of about 10 mm between wall and door is acceptable after allowing for fit-and-finish in the wall construction. The door design should provide a 200 mm minimum overlap beyond the inside surface of the shielding at in the entrance walls, see Figure 12. The limited overlap of the door with the entrance to the accelerator room may require additional specialized shielding. 10.5.2 describes the shielding at the far side of the door, which is a secondary barrier calculation with a specialized geometry. 10.5.3 describes a method for adapting maze calculations to assess the shielding required at the near side of the entrance.

10.5.2 Shielding at the far side of a direct-shielded door entrance

As illustrated in Figure 12, a direct leakage path occurs at the far lateral edge of the door. To compensate for the relatively short slant thickness through the corner of the entrance, additional material is typically added beyond the door and in the entrance wall as shown in Figure 13. If sufficient space exists, normal weight concrete added at the far side of the entrance can be sufficient with no additional shielding at this location. When space is limited, high density concrete is typically added beyond the door with lead added to the entrance wall. Borated polyethylene lining inside the high density concrete may also be appropriate.

The shielding calculation at the far side of the entrance uses the standard secondary calculation methodology described in 9.3. The slant thickness through the wall at the corner (d_W) (m) is given by Formula (27).

$$d_W = \frac{d_o}{\cos(\theta)} - \frac{d_g}{\sin(\theta)} \quad (27)$$

where

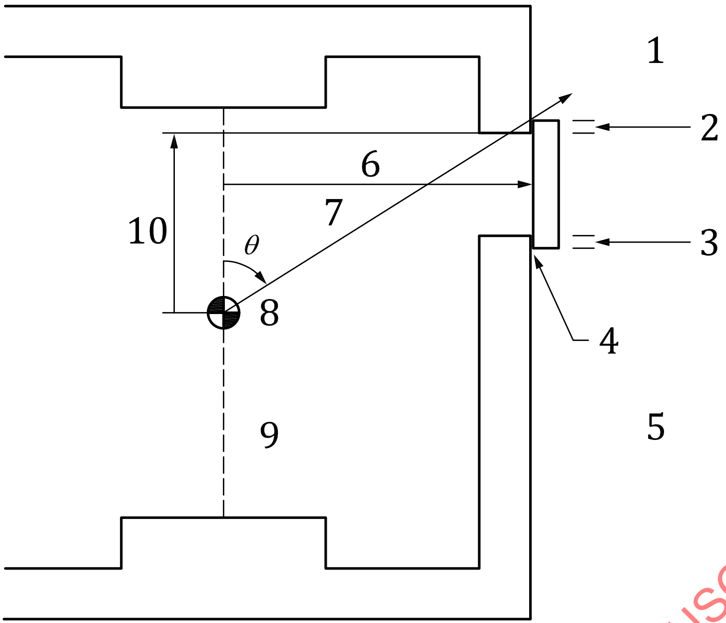
d_o is the door overlap beyond the entrance in metres;

d_g is the gap between the concrete wall and the door in metres;

$$\theta = \operatorname{atan}\frac{d_d}{d_f + d_o}$$

where d_f is the distance from isocentre to the far side of the entrance.

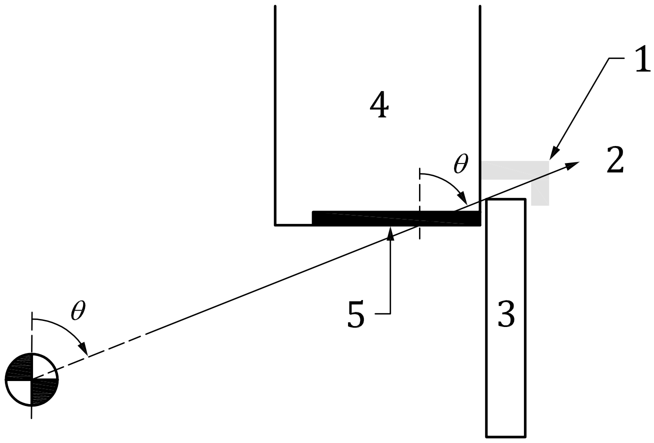
The slant thickness through the concrete (d_C) is then given by d_W minus the slant thickness through the lead added to the wall, $d_L/\cos(\theta)$, where d_L is the lead thickness in metre: $d_C = d_W - d_L/\cos(\theta)$.



Key

1 protected point (0,3 m beyond door enclosure)
2 door overlap beyond far side of entrance (d_o)
3 200 mm overlap typical
4 gap between wall and door (d_g)
5 typical gap 10 mm
6 isocentre to door (d_d)
7 secondary distance
8 isocentre
9 gantry plane of rotation
10 isocentre to far side of entrance distance (d_f)

Figure 12 — Slant thickness at far side of direct shielded door



Key

1 shielding added beyond secondary barrier
2 protected point (0,3 m beyond added material)
3 door
4 secondary barrier
5 lead added to entrance wall

Figure 13 — Material added to entrance on far side of direct shielded door

10.5.3 Shielding at the near side of a direct-shielded door entrance

10.5.3.1 General

The geometry at the near side of the entrance is similar to that of a maze, implying the same sources of leakage, scatter, and neutron-related radiation are present. Unlike a maze, single-interaction wall scatter from one lateral primary barrier has a direct path to the near side of the door, making the shielding requirements for the other sources of scattered radiation negligible in comparison.

10.5.3.2 Primary X-ray wall scatter to near side of entrance

The wall scatter unshielded dose equivalent at the near side of the entrance is calculated using the geometry in Figure 14. The unshielded dose equivalent due to wall scatter ($H_{u,S}$) (Sv) is given by Formula (28).

$$H_{u,S} = \frac{W \times U \times \alpha_0 \times A_0}{d_0^2 \times d_Z^2} \qquad (28)$$

where

d_0 is the target to primary barrier distance in metres;

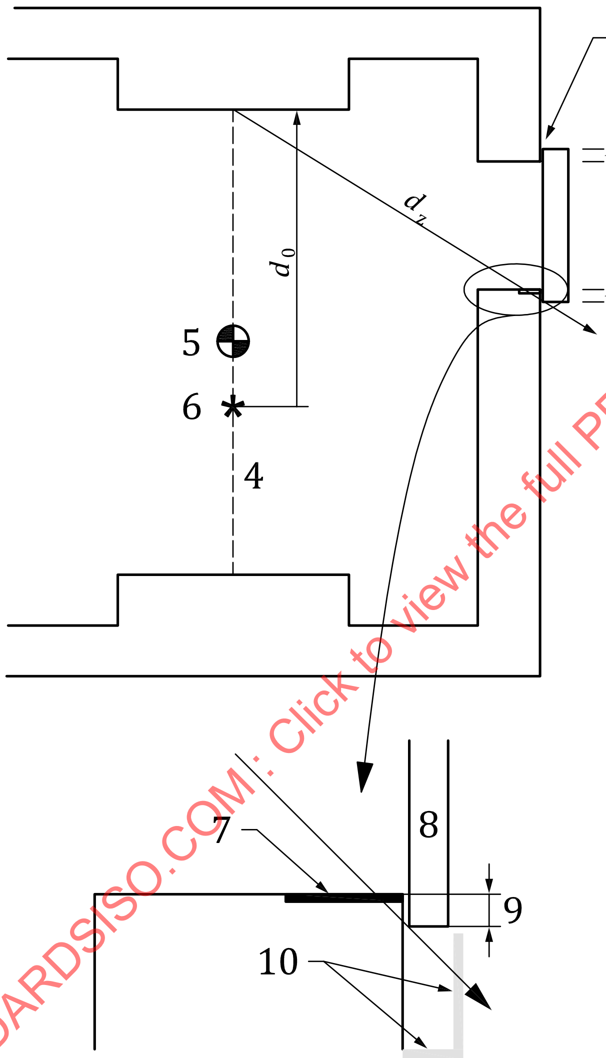
d_Z is the distance from the primary barrier to the protected location in metres;

W is the workload for the period of reference in Gray;

U is the orientation or use factor (conservative assumption: $U = 1$);

α_0 is the reflection coefficient in m^{-2}, depending on primary X-ray end point energy, wall material and incidence and reflection angles (see Tables B.2 and B.3); for accelerators with FFF operating mode, specific α_0 values shall be considered[33];

A_0 is the beam area in m^2 at first reflection wall for the maximum field size.



Key

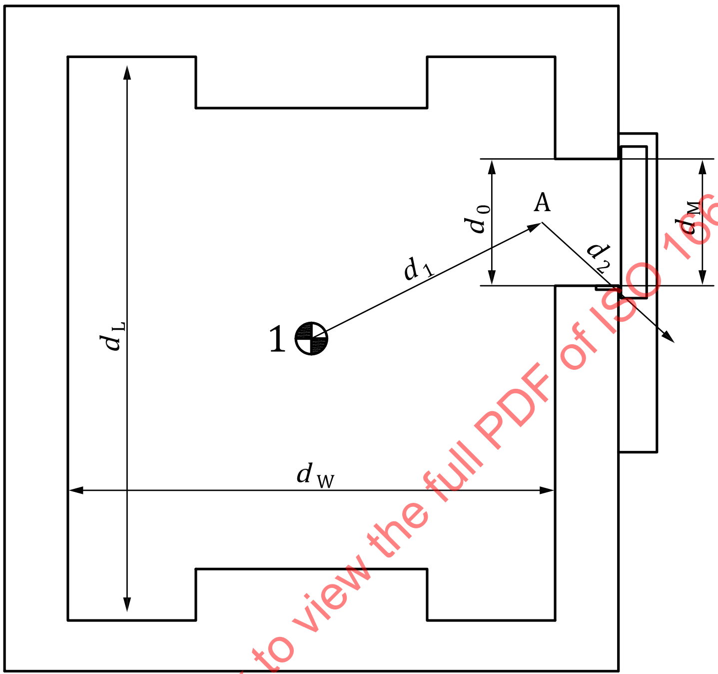
1 typical gap 10 mm
2 200 mm typical door overlap
3 protected point (0,3 m beyond door enclosure)
4 target rotational plane
5 isocentre
6 target
7 lead added to entrance wall
8 door
9 door overlap
10 borated polyethylene added beyond secondary barrier

Figure 14 — Material added to entrance on near side of direct shielded door

10.5.3.3 Neutrons and capture gammas at near side of entrance

For accelerators greater than 8 MV, neutron transmission through the near side of the door shall be included in the dose equivalent calculation. This dose equivalent shall include not only neutrons, but also gamma rays associated with neutron capture. This calculation adapts the maze neutron calculation addressed in 10.3.3.

Using the geometry in Figure 15, the first step is to calculate the total neutron fluence at point A per Gy workload (ϕ_A) (neutrons/m²·Gy) using Formulae (22) and (23).



Key

1 isocentre

Figure 15 — Neutron fluence calculation at near side of direct-shielded door

Formula (24) then gives the capture gamma unshielded dose at the near side of the entrance ($H_{u,\gamma}$) (Sv). Similarly, Formula (25) gives the neutron unshielded dose-equivalent at the near side of the entrance ($H_{u,n}$) (Sv).

The distance through the near side of the entrance to the protected location is drawn just beyond the edge of the door. Providing adequate shielding at the near side of the entrance typically requires lead added to the entrance walls. Depending on the regulatory requirements and the amount of overlap of the door at the near side of the entrance, lining the door housing with thick borated polyethylene may also be needed. Thickness of borated polyethylene greater than 5 cm are not recommended since capture gamma rays generated in the borated polyethylene could become significant compared to the neutrons.

10.6 No door at maze entrance

When there is a maze and no door at the maze entrance, the area around the entrance may have a higher dose equivalent than is suitable for a full occupancy location. A calculation is therefore required.

The radiation at the entrance falls into two broad categories: direct leakage radiation and scattered radiation. The standard secondary barrier calculation is applied to the direct leakage, with radiation inversely proportional to the square of the distance from isocentre. In addition, the protection provided by the walls next to the entrance is included when calculating the direct leakage to the left or right of the entrance.

In contrast, the scattered radiation can be expected to be roughly inversely proportional to the square of the distance from the entrance (d) (m). Assuming the dose is uniformly radiated in a hemisphere beyond the entrance, the average scatter dose equivalent [$H_d(ave)$] (Sv) at distance d away from the entrance with cross-sectional area A_Z (in m^2) is given by:

$$H_d(ave) = H_S \times A_Z \, / \, (2\pi d^2) \tag{29}$$

where H_S is the scatter dose equivalent at the entrance (Sv).

NOTE This expression makes physical sense only at distances sufficiently large for the source of scattered radiation (A_Z) to be considered as a point source.

Because this radiation consists of scattered neutrons and photons, the intensity is proportional to the wall surface area visible near the entrance. The visible surface area can be expected to scale with cos(θ), where θ is the angle to the protected location relative to a vector that is normal to the plane of the entrance. This results in a dose equivalent [$H_d(\theta)$] (Sv) at distance d and angle θ as given by Formula (30).

$$H_d(\theta) \approx H_d(ave)\, 2\cos(\theta) \tag{30}$$

Directly in front of the entrance $\theta = 0$ is applicable.

If the calculated neutron dose equivalent at the entrance is slightly higher than desired, lining the maze with borated polyethylene may be appropriate, see Reference [35]. Lining the maze walls at the exterior entrance or at the opposite end of the maze near the treatment room interior opening with a combination of polyethylene and boron results in reduction of the neutron and capture gammas dose equivalents at the entrance.

10.7 Door Calculations

10.7.1 General

If *TVL* data are provided by the national regulatory authority in a given nation, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy and a given material is recommended.

10.7.2 Maze door calculations

Door transmission is calculated with separate *TVL*s for each type of radiation.

For X-ray direct leakage, the door transmission is calculated using the leakage *TVL*s for the door shielding materials (see Table A.5)[2]. For a short maze, the direct leakage path to the protected location may not pass through the door, in which case no transmission should be included for the door for the direct leakage.

Maze X-ray scatter transmission through the door can be calculated using tenth-value layers (*TVL*s) specific to the degraded energy spectrum of the X-rays reaching the door. For patient scatter and wall scatter radiation that undergo two interactions before reaching the door, 0,2 MeV energy can be assumed[2], with transmission based on broad beam *TVL*s (see Table A.9). For leakage scatter that undergoes only one interaction, 0,3 MeV average energy can be assumed[19], with transmission based on broad beam *TVL*s (see Table A.9).

When the nominal energy of the primary X-ray beam is higher than 8 MV, neutron and the associated capture gamma radiation are likely the dominant source of radiation near the door.

The average neutron energy at the maze entrance is about 100 keV for all accelerators [IAEA SRS 47] [2]; corresponding conservative *TVL* values are 8 cm for paraffin/polyethylene and 16 cm for concrete (see Table A.9) [IAEA SRS 47][2][4][5][15].

For capture gamma radiation, average energy of 3,6 MeV and maximum energy of about 10 MeV can be assumed[15][29], with transmission based on broad beam *TVLs* (see Table A.9).

10.7.3 Direct Shielded Door Calculations

For a direct shielded door, the door transmission is calculated using a standard secondary barrier calculation. The door includes lead to attenuate the X-rays. For accelerators with nominal energy of the primary X-ray beam higher than 8 MV, hydrogenated material like borated polyethylene or paraffin are also included to attenuate neutrons.

Conservative neutron *TVL* values are 15 cm for paraffin/polyethylene and 25 cm for concrete (see Table A.9 and Figure A.7)[4][5][15].

Average capture gamma energy of 3,6 MeV and maximum energy of 10 MeV can be assumed for γ *TVL* (see Table A.9)[15][29].

11 Shielding calculations for special devices

11.1 General

Some adaptations of linear accelerators differ sufficiently from the conventional gantry configuration to warrant special discussion on how to adapt the shielding calculation in Clauses 9 and 10. One example is a compact linear accelerator mounted on a robotic arm used for stereotactic radiotherapy. A second example is helical intensity modulated radiotherapy, which delivers IMRT using a beam geometry resembling diagnostic CT.

11.2 Robotic arm accelerator

These systems combine a compact linear accelerator mounted on a robotic arm that allows the radiation beam to be directed at any part of the body from [virtually] any direction. The treatment plan is achieved by using a large number of radiation beams compared to a conventional linear accelerator, resulting in a relatively low orientation or use factor in any particular direction (U = 0,05 is recommended[2] for shielding calculations). Any wall shall be considered to be a primary barrier (except the ceiling if the system cannot point at it, in such case a secondary calculation shall be done for the ceiling).

The leakage workload shall be calculated using a value of C_I (IMRT ratio) equal to 15[2]. Because of the high leakage workload and the low primary orientation or use factor, both primary and secondary barrier calculation shall be performed for each wall, with the results added to yield the total dose equivalent. Scatter is negligible for walls, and shall not be included in the wall calculations.

If the system has a variable target to isocentre distance [or source-axis-distance (SAD)] the shielding calculations shall assume a constant SAD (considered to be the nominal value of SAD).

The maze calculation for that type of accelerator includes primary beam wall scatter and leakage scatter. The leakage scatter calculation is unchanged from the approach used for a conventional linear accelerator. As for secondary barrier calculations, if only small field sizes are used, patient scatter may be considered as negligible. Unlike a conventional maze, the primary beam wall scatter is single interaction scatter, since the beam can be directed toward the end of the maze, and the reflection coefficient and the tenth value layers used to calculate attenuation at the entrance shall take this point into account.

The dose equivalent at entrance shall include a calculation of the primary plus leakage radiation passing through the wall to the entrance.

The direct path transmission provided by the door uses the conventional primary and leakage *TVLs*.

11.3 Helical intensity modulated radiotherapy

The field shape is adjustable in the inferior-superior patient direction by a MLC. The system may include a primary beam stopper.

The system traditionally operates in a helical mode. In this mode, the slit beam of radiation continuously rotates around patient. All treatments in the helical mode use IMRT, with a relatively high IMRT ratio (C_I = 16 is typical[36]).

Calculations are made using the leakage workload, W_L:

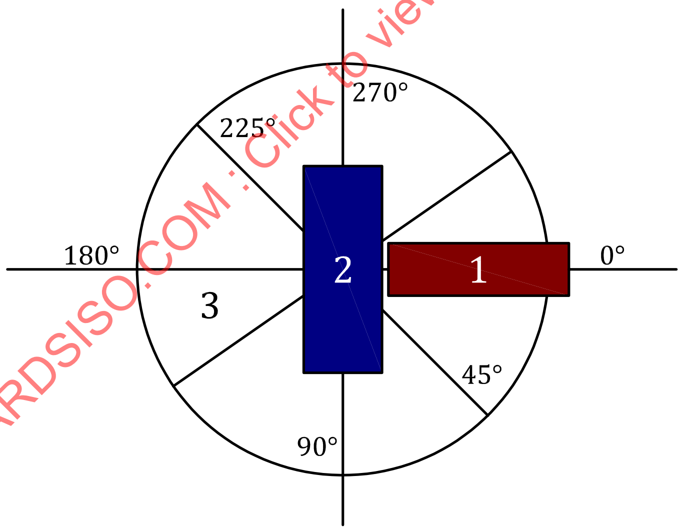
$$W_L = W \times \text{IMRT factor}$$

where IMRT factor = C_I (F_{IMRT} = 1) (see 9.3.2).

The unshielded X-ray dose equivalent, H_u, is the combination of all components: leakage ($H_{u,L}$), patient scatter ($H_{u,PS}$) and primary ($H_{u,P}$) transmitted through the beam stopper. H_u varies as a function of the angle in the room (see Figure 16) and is ≤ 0,02 % × W_L at a distance of 1 m from the isocentre. Isoexposure profiles provided by the manufacturer should be used in these shielding calculations.

In addition to the helical treatment mode, a topographic treatment mode is optional. Unlike the helical treatment mode, treatments are performed with the gantry in various static positions, instead of with the gantry continuously rotating. This reduces the number of monitor units required to deliver a prescribed dose to the patient, resulting in shorter treatment times and a lower IMRT ratio (~10). The combined leakage, scatter, and primary radiation requiring shielding in the topographic mode is less than 0,01 % of the leakage workload in all directions.

It should be assumed that radiation is less than 0,1 % of the leakage workload for shielding calculations.



Key

1 couch

2 gantry

3 exterior

Figure 16 — TomoTherapyTM geometry

11.4 Dedicated device for intra operative radiotherapy with electrons

These dedicated devices for intraoperative radiotherapy (IORT) use a linear accelerator that delivers only electron beams (maximum energy of about 12 MeV) with a very high dose rate (up to around

40 Gy/min), to deliver single fraction high dose directly in contact to the target tissue in the patient. Electron beams are collimated by cylindrical applicators of low Z material (plastic or aluminium).

These are mobile systems designed to be used in standard operating rooms. The gantry and the head have many degrees of freedom allowing the beam to be directed in many directions. Some systems include a primary beam block, others not. There is no bending magnet and no or thin scattering foil, leading to strong reduction of leakage X-rays as compared to conventional devices. Because of the limited maximum energy, neutron production is not a concern. In normal clinical use, primary electrons are stopped in the patient, so the radiation components to be considered for radiation shielding calculations are only secondary radiations: patient scattered X-rays, head leakage X-rays (not negligible) and contamination electrons (coming from the applicator, not negligible). If one cannot exclude device use without scattering body or with scattering body too thin to stop all the primary electrons, and if the device has no primary beam block, shielding evaluation shall consider the electron primary component and evaluate the impact of X-rays generated in the primary shielding barriers (walls and floor) by the MeV electron beam of maximum energy.

All photon and electron radiation components are anisotropic. Shielding calculations shall be done with machine specific data regarding anisotropic radiation yields and specific photon *TVL* values for leakage and for scattered X-rays. Data regarding the anisotropic field shall be provided by the manufacturer and used in shielding calculations. *TVL* data shall have been measured or determined by Monte Carlo simulations, and the materials and methods used for the *TVL* evaluation should be known. Attention should be paid to the fact that the scattered X-ray field could not follow an inverse square law as a function of the distance if the reference distance is only 1 m from the scattering body.

If very high absorbed dose rates (greater than 10 $Gy \cdot min^{-1}$) are used in standard operating rooms without reinforcements of the protective barriers (walls, floor and ceiling), some areas surrounding the operating room shall be forbidden to the public and the workers during operation, and a system shall be used to prevent access to these areas during accelerator use, with a treatment interrupt interlock connected to the machine.

As dedicated IORT devices are mobile, special formal procedures shall be put in place in order to ensure permanent location of the device in the dedicated rooms (operating and storing rooms), and to prevent operation during storage.

12 Ducts

12.1 Duct impact on radiation protection

There are three kinds of ducts penetrating a treatment room: ducts for electrical cables (devoted to physics measurements), for fluids and anaesthesia gases, and for heating, ventilation and air-conditioning (HVAC). The duct penetration leads to two kinds of impact on radiation protection: radiation passes through the interior of the duct (from the duct interior opening to the duct exterior opening) and passes through a reduced barrier thickness (for oblique incidence or for duct with single or multiple bends in the barrier).

The ducts for electrical cables and for fluids have typically small size (maximum diameter of around 10 cm) and have little impact on radiation protection if they are correctly positioned (see below). On the contrary, HVAC ducts have large dimensions, with penetration typically on the order of 1 m wide by 0,5 m high), which requires special attention and specific shielding calculations.

12.2 Recommended location and geometry

Ducts for electrical cables and for fluids should be placed either in the floor at a sufficient depth either penetrate a vault wall slantways, with an angle of around 45° and the duct interior opening near the floor in order to prevent radiation from passing directly through the interior of the duct.

When there is a maze, HVAC ducts shall penetrate the vault above the door. In the absence of maze, HVAC ducts shall penetrate the vault in a secondary barrier, as far as possible from the accelerator head and such a way that radiation cannot pass directly through the interior of the duct: penetration shall be oblique or alter direction in the shielding barrier.

12.3 Additional shielding

12.3.1 General

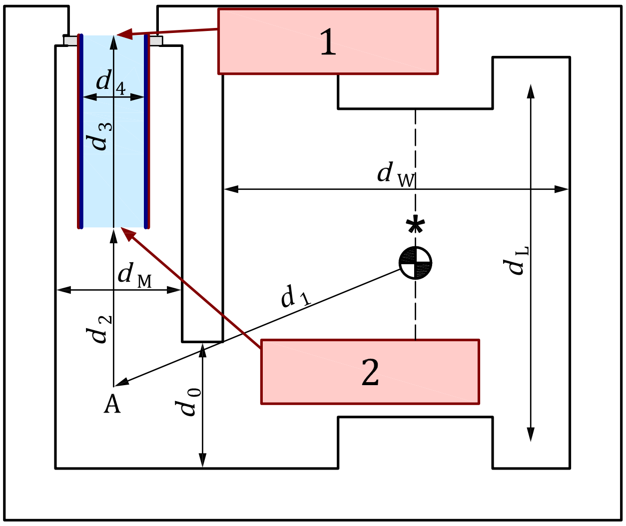
Except for treatment rooms with little or no shielding at the entrance (i.e. for a very long maze and / or low energy machine), shielding is generally required for the HVAC ducting. One approach to provide this shielding is a baffle (straight or bended shelf beneath the duct or lintel in front of the interior opening of the duct) constructed of either concrete or the same material as the door. Alternatively, the duct can be wrapped with the same shielding material as the door. Another method is to have the duct pass through a concrete chicane of two baffles in the space between the treatment room ceiling and the false ceiling in the long leg of the maze. These baffles are built as part of the concrete ceiling of the treatment room. The duct can also start parallel and close to one wall and then go obliquely to run parallel and close to the opposite wall. A concrete baffle originating on the opposite side of the maze to the duct is placed before and after the transition.

The design and sizing of the additional shielding (baffle or wrap) requires specific calculations. Analytical methods described below or Monte Carlo simulations may be used to evaluate the transport of X-ray, neutron and gamma components and the transmission of the radiations through the interior of the duct and through the reduced barrier thickness. These calculations shall be done using the correct geometry (treatment room, maze and duct penetration). If Monte Carlo simulation is used, it shall be done using primary X-ray and neutron energy spectra published in the scientific literature, density and elemental composition of all materials as accurate as possible and an adequate transport code (managing the transport of photons, electrons, positrons and neutrons, photoneutron production and neutron capture gamma generation in the appropriate energy range and for the elemental composition of the different materials).

The duct can be wrapped with the same shielding material as the door, but with the material thickness on the order of 1/3 as much as is contained in the door. The shelf or wrapping extends at least 3 times the width of the penetration. The calculation of the dose due to the radiations reaching the HVAC duct exterior opening (above the door) can be made with the analytical approach described below.

12.3.2 Neutron and capture gamma radiation passing through the interior of the shielded duct

An example of the geometry for the neutron calculation is illustrated in Figure 17 for a duct wrapped in shielding material. If a shelf is placed beneath the duct to provide the shield, the dimension d_4 (m) is equal to the maze width (d_M). The neutron dose equivalent at the duct shielding interior opening ($H_{n,DIO}$) (Sv) is calculated using Formula (25) where d_2 is the distance from point A to the duct shielding interior opening (m), TVD (in metres) is 2,06 × $S^{1/2}$ and S is the maze cross-section area, in m^2.



Key

1 duct shielding exterior opening

2 duct shielding interior opening

Figure 17 — Maze HVAC duct shielding

The neutron dose equivalent at the duct shielding exterior opening ($H_{n,DEO}$) (Sv) is then calculated using Formula (31),

$$H_{n,DEO} = H_{n,DIO} 10^{-(d_3/TVD_{duct})} \tag{31}$$

where

d_3	is the length of the duct shielding in metres;
TVD_{duct} (m)	is 2,06 x $S_{duct}^{1/2}$;
S_{duct}	is the duct cross-section area in m^2, $S_{duct} = d_4 \times d_5$, where d_4 and d_5 are the width and the height of the duct shielding, respectively, in metres.

Depending on geometry, the ratio of capture gamma dose equivalent to maze neutron dose equivalent ranges from 0,2 to 0,5[15]. The capture gamma unshielded dose equivalent at the duct exterior opening can be conservatively assumed to be 0,5 of the neutron dose equivalent.

12.3.3 X scattered radiation passing through the interior of the shielded duct

The fraction of scattered radiation (patient scatter, wall scatter, leakage scatter) passing through the duct can be calculated using Formulae (17) to (20), with one difference: the visible area of the reflecting maze wall is given by the duct shielding height and length. Figure 18 illustrates the geometry and the calculation of the maze wall height (H_M) (in metres) visible from the duct exterior opening.

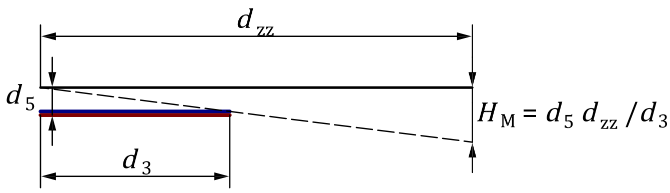


Figure 18 — Reflecting maze wall height visible from duct exterior opening

12.3.4 Scattered radiation passing through the walls of the duct shielding

The calculation of the fraction of scattered radiation (patient scatter, wall scatter, leakage scatter) passing through the walls of the duct is similar to that for the door at the end of the maze, except the shielding material and slant angle. Since the maze radiation passes at an oblique angle through the duct shielding, a 45 ° slant angle can be assumed in the calculation.

12.3.5 Dose equivalent at HVAC duct exterior opening

Assuming the dose is uniformly distributed in a hemisphere beyond the duct exterior opening, the average dose equivalent [$H_d(ave)$] (Sv) at distance d (in metre) away from the baffle opening with cross-sectional area A_Z (in m^2) is given by Formula 32.

$$H_d(ave) = H_{DEO} \cdot A_Z / (2\pi d^2) \quad (32)$$

where H_{DEO} is the dose equivalent at the duct exterior opening (Sv).

Because this radiation consists of scattered neutrons and photons, the intensity is proportional to the surface area visible through the duct opening. The visible surface area scales with cos(θ), where θ is the angle to the protected location relative to a vector along the centreline of the baffle opening. This results in a dose equivalent at a protected location at distance d and angle θ [$H_d(\theta)$] as given by Formula 33 (Sv).

$$H_d(\theta) = H_d(ave) \cdot 2\cos(\theta) \quad (33)$$

13 Special considerations

13.1 Skyshine

13.1.1 General

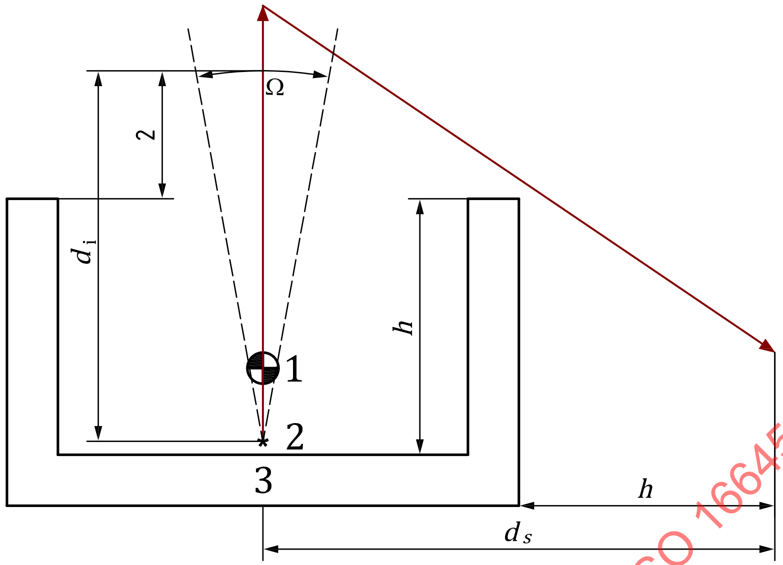
Skyshine refers to radiation scattered by the atmosphere that reaches occupied locations outside the treatment room. This particular source of radiation is significant only if the ceiling is lightly shielded, which implies there shall be no potential occupancy above the accelerator. Vigilance is required to prevent unauthorized roof access, a system shall be used to prevent access when the accelerator is in operation.

Empirical analytical approaches are described below for calculation of the X-ray and neutron skyshine dose equivalents. However, these methods are approximate and precise evaluation can be done by Monte Carlo simulation.

13.1.2 X-ray skyshine radiation

X-ray skyshine is calculated using the geometry in Figure 19.

Dimensions in metres



Key

1 isocentre

2 target

3 floor

Figure 19 — X-Ray skyshine geometry

The anticipated skyshine unshielded dose equivalent ($H_{u,sky}$) (Sv) is given by Formula (34)[2].

$$H_{u,sky} = \frac{0,025 \times W \times U \times \Omega^{1,3}}{d_i^2 \times d_s^2} \tag{34}$$

where

d_i is the distance from the target to a point 2 m above the roof in metres;

d_s is the distance from isocentre to the point protected in metres;

W is the workload specified for the period of reference in Gray;

U is the orientation or use factor for the beam oriented toward the ceiling; secondary radiation is not a significant contributor to skyshine exposure;

Ω is the solid angle of the radiation beam (steradian) (0,122 for 0,4 m × 0,4 m beam)

When there is an existing ceiling barrier, the transmission through this barrier shall be taken into consideration when determining the anticipated skyshine dose equivalent.

The roof here is considered to be at the top of the lateral barrier. This calculation is imprecise and should be used with caution (at least with a multiplicative factor of 2).

As shown in Figure 19, the point protected is outside the wall by a distance that is equal to the wall height. Measured data indicate that this is the location experiencing highest dose rate. If the unshielded dose equivalent exceeds the maximum permissible shielded dose (P/T), material shall be added to the roof, with attenuation calculated using the primary *TVL*.

13.1.3 Neutron skyshine radiation

At machine energies greater than 8 MV, neutron skyshine shall be considered as well. The most critical geometry in this case is with the target above isocentre (see Figure 20). The skyshine unshielded neutron dose equivalent ($H_{u,ns}$) (Sv) at lateral distances less than 20 m is given by (adapted from Reference[2]):

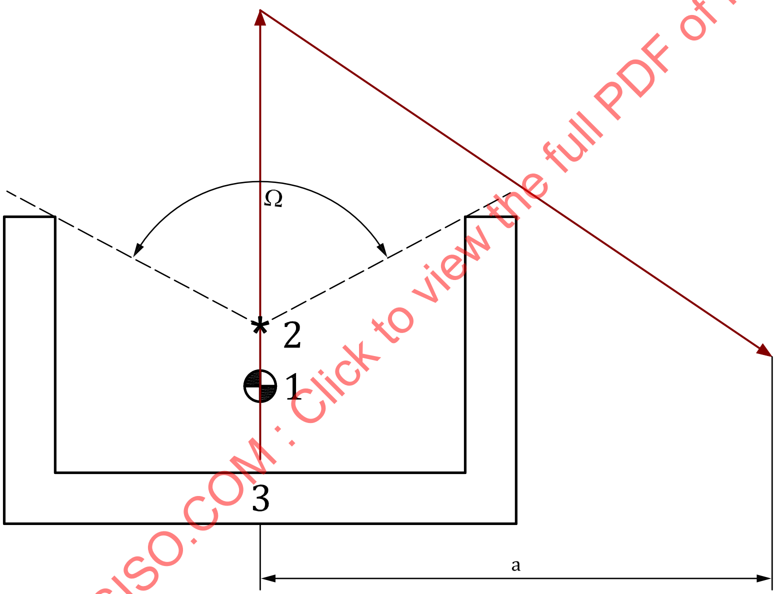
$$H_{u,ns} = \frac{5,4 \times 10^{-4}\ H_{pri} \times \Omega}{2\pi} \quad (35)$$

where

H_{pri} (Sv) is the neutron dose equivalent within the beam at isocentre [IAEA SRS 47];

Ω is the solid angle (steradians) of the shield walls subtended by the target.

Formula (35) assumes the ratio of neutron fluence is the same as the ratio of neutron dose equivalent. No orientation or use factor is applied since neutron skyshine can be observed for any beam orientation. This calculation is imprecise and should be used with caution (at least with a multiplicative factor of 2).



Key

1 isocentre

2 target

3 floor

a Up to 20 m lateral distance.

Figure 20 — Neutron skyshine geometry

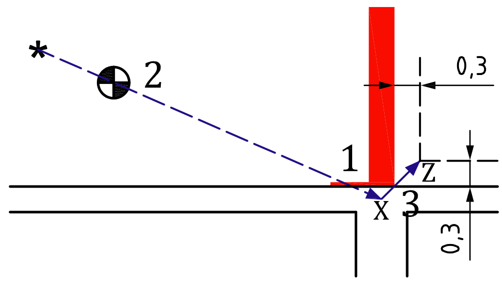
If the combined unshielded photon dose equivalent and neutron dose equivalent exceed the maximum permissible shielded dose, material shall be added to the roof. Neutron attenuation is calculated using the primary neutron *TVL*. Note that metal in the ceiling barrier would result in a substantial increase in neutron skyshine compared to the calculation above due to photoneutron generation in the metal. Consequently, metal should not be used to shield a ceiling for skyshine.

13.2 Groundshine radiations

Because primary barriers constructed of lead are relatively thin, scattered radiation through the floor may exceed the direct radiation through the wall when the beam is pointed at the bottom of the wall (see Figure 21). This radiation is referred to as groundshine.

Shielding calculations may be done with analytical methods or Monte Carlo simulations. If calculations indicate groundshine is excessive, lead can be added to the floor next to the wall, as shown in Figure 21.

Dimensions in metres



Key

1 primary transmission to point X

2 isocentre

3 scatter transmission from point X to point Z

Figure 21 — Basic groundshine geometry

13.3 Joints and junctions

A cold joint is discontinuity between layers of concrete that occurs when a layer is allowed to harden before the next layer is poured. Although undesirable, such a joint is acceptable if located at a suitable location. A cold joint shall not be located at least 1 m above or below the elevation of isocentre.

When using lead brick, steel plate or modular concrete blocks, the junctions shall be staggered between layers. Any junction between steel plates or concrete blocks shall not be aligned with isocentre.

When using precast blocks, joints should be tongued and grooved.

14 Shielding evaluation (experimental verification)

14.1 General

Immediately after the accelerator has been made operational, a preliminary survey shall be carried out to ensure that radiation exposures to person working near the facility do not exceed the applicable shielding design goal and time averaged dose equivalent rate. Once the accelerator has been made completely operational and an initial calibration has been completed, a complete radiation survey shall be conducted.

All occupied areas near the facility shall be evaluated for the purpose of determining whether the shielding design goal is achieved and whether any person is likely to receive more than the recommended applicable annual effective dose values for controlled and uncontrolled areas.

After any changes of structural design and periodically as defined by national regulation, evaluation of shielding shall be carried out.

14.2 Measuring equipment and methodology

The survey instrument should have both rate and integrate modes and adequate range(s) to cover expected measurements (e.g. up to 50 mGy h^{-1}). For accelerators operating above 8 MV, a portable neutron survey instrument should be used to determine the neutron dose equivalent per monitor unit and the dose-equivalent rate ($\hat{H}$). Each of the instruments used for the final measurements shall have a current calibration traceable to the national standards.

The test conditions for checking of structural shielding are:

— all measurements should be made at least 0,3 m beyond the barrier or door considered as representative of whole body dose equivalent or at the points of calculation including the maze entrance;

— maximum absorbed dose rate intended for operation, at maximum photon energy; for some accelerator with FFF mode, it is relevant to consider the mode providing the higher dose rate for the higher energy available in FFF mode;

— primary barrier: maximum useful beam and collimators rotated through 45° so that the diagonal of the radiation field is along the length of the barrier, directed at each barrier in turn. These measurements are performed without any phantom material in the radiation beam. It is especially important to survey the region where the primary barrier changes to a secondary barrier to confirm that the length of the primary barrier is adequate;

— other barriers including door or maze entrance and egress of ducts which cannot be hit by primary beam: maximum useful beam directed at least with the gantry at 0°, 90°, 180° and 270°. Measurements shall be performed with phantom material in the beam at the isocentre to simulate the patient. The junctions between secondary and primary barriers should be measured carefully to ascertain whether or not there is any leakage from small angle scatter at the edges of the primary barrier;

— for wall shielding, measurements across a range extending between a distance of 0,1 m and 0,5 m behind the shielding and between a height of 0,5 m and a height of 2 m above the floor; measurements should also be made at junctions between the ceiling slab and the walls;

— for ceiling shielding, measurements in the room above the irradiation room, at a 0,5 m height above the floor;

— for floor shielding, measurements in the room below the irradiation room, at a 2 m height above the floor;

— If the facility is an existing one that has been upgraded for a higher energy machine, then measurements shall be made at the junctions of additional shielding or modifications.

The evaluation of the area dose measurements shall be initially based on the reference planning values. If the permissible area dose values are exceeded, the intended operating mode (operating values, radiation directions, workload) shall be taken into consideration.

If any defects in the shielding are identified further measurements should be made at these positions using the appropriate type of detector.

If it is decided that an area requires on-going evaluation after the facility begins operation, either film or optically-stimulated luminescence dosimeters or thermoluminescent dosimeters (TLDs) may be used for photons, while solid-state nuclear track detector dosimeters or a hybrid TLD may be used for neutrons.

14.3 Evaluation

When designing radiation shielding barriers, it is usual to assume that the workload is evenly distributed throughout the year. Therefore, it is reasonable to design a barrier to meet a weekly or a monthly value. The use of a measured instantaneous dose rate, *IDR* [instantaneous dose equivalent rate measured at a reference point at 0,3 m beyond the penetrated barrier (Sv·h^{-1})], with accelerator operating at maximum output, does not properly represent the true operating condition and radiation environment of the facility. It is more useful if the workload and orientation or use factor are considered together with the *IDR* when evaluating the adequacy of a barrier. For this purpose, the concept of time averaged dose equivalent rate, *TADR*, is used with the measured *IDR*.

TADR is the barrier attenuated dose equivalent rate averaged over a specific time or period of operation *Tr* (Sv·Tr^{-1}). *TADR* is proportional to *IDR* and depends on the values of workload *W* and orientation or use factor *U*:

$$TADR = IDR \times W \times U \;/\; DR_0 \tag{36}$$

where

W is the workload associated to the energy considered for the period of reference *Tr* (Gy·Tr^{-1}). If there is sufficient design margin, the total workload should be attributed to the highest energy, with survey measurements performed only at the highest energy. Otherwise *TADR* at each photon beam energy, combined with the workload at isocentre for each one, is determined. The total measured *TADR* is then the sum of the *TADR* for each energy;

DR_0 is the absorbed dose rate at isocentre for the energy considered (Gy·h^{-1}).

The dose equivalent rate for the period of reference *Tr* should be calculated from survey measurements.

The beam-on time for the period of reference *Tr* and for the energy MV is calculated as follows (h·Tr^{-1}):

$$\text{beam-on time} = W \;/\; DR_0 \tag{37}$$

The *TADR* (Sv·Tr^{-1}) is calculated from the *IDR* and beam-on time as follows:

$$TADR = U \times IDR \times \text{beam-on time} \tag{38}$$

The *TADR* for secondary barrier leakage measurements is based on the leakage workload W_L (Gy·Tr^{-1}), which includes an adjustment for IMRT.

The X-ray leakage beam-on time for each energy is calculated as follows (h·Tr^{-1}):

$$\text{leakage beam-on time} = W_L \;/\; DR_0 \tag{39}$$

The X-ray leakage *TADR* (Sv·Tr^{-1}) is calculated from IDR_L (Sv·h^{-1}) due to leakage and leakage beam-on time (h·Tr^{-1}) as follows:

$$LeakageTADR = IDR_L \times \text{leakage beam-on time} \tag{40}$$

where IDR_L is the instantaneous dose equivalent rate due to leakage radiation (Sv·h^{-1}).

The neutron leakage *TADR* is calculated in the same fashion as photon leakage *TADR*, except using the measured neutron dose rate and the neutron leakage beam-on time. In general, the neutron leakage beam-on time is the same as the X-ray leakage beam-on time. If the survey is performed only at the highest energy, the leakage workload associated with energies less than 8 MV in the shielding evaluation report can be excluded from the neutron leakage workload, resulting in a neutron leakage workload that may be significantly less than the X-ray leakage workload.

In general, the *TADR* beyond a secondary barrier consists of a combination of scatter, X-ray leakage and neutron leakage. For conventional devices, X-ray scatter is insignificant for the walls that are not adjacent to the primary barrier. However, scatter is often the largest source of radiation for secondary barriers immediately adjacent to a primary barrier. Unlike leakage, scatter is based on the primary workload (not the leakage workload) and hence does not increase with IMRT. The secondary dose rate next to a primary barrier is often sufficiently low that there is need to distinguish between leakage and scatter. However distinguishing between measured scatter and leakage may be appropriate to avoid overstating the total *TADR* for the secondary barrier adjacent to a primary barrier if there is insignificant design margin.

The scatter plus leakage exposure rate is measured with the beam pointed at the primary barrier adjacent to the secondary barrier. The measured leakage dose rate is the dose rate measured at the same location, but with the beam pointed in at least one of the other three gantry orientations. The leakage contribution to *TADR* is then calculated as described above based on the leakage dose rate ($Sv{\cdot}h^{-1}$). The average scatter exposure rate is given by ($Sv{\cdot}h^{-1}$):

average scatter dose rate =

U [(scatter + leakage) measured dose rate - measured leakage dose rate] (41)

The same orientation or use factor applied to the primary barrier is also applicable to scatter measurements.

The scatter *TADR* is calculated as follows ($Sv{\cdot}Tr^{-1}$):

scatter *TADR* = average scatter dose rate x beam-on time (42)

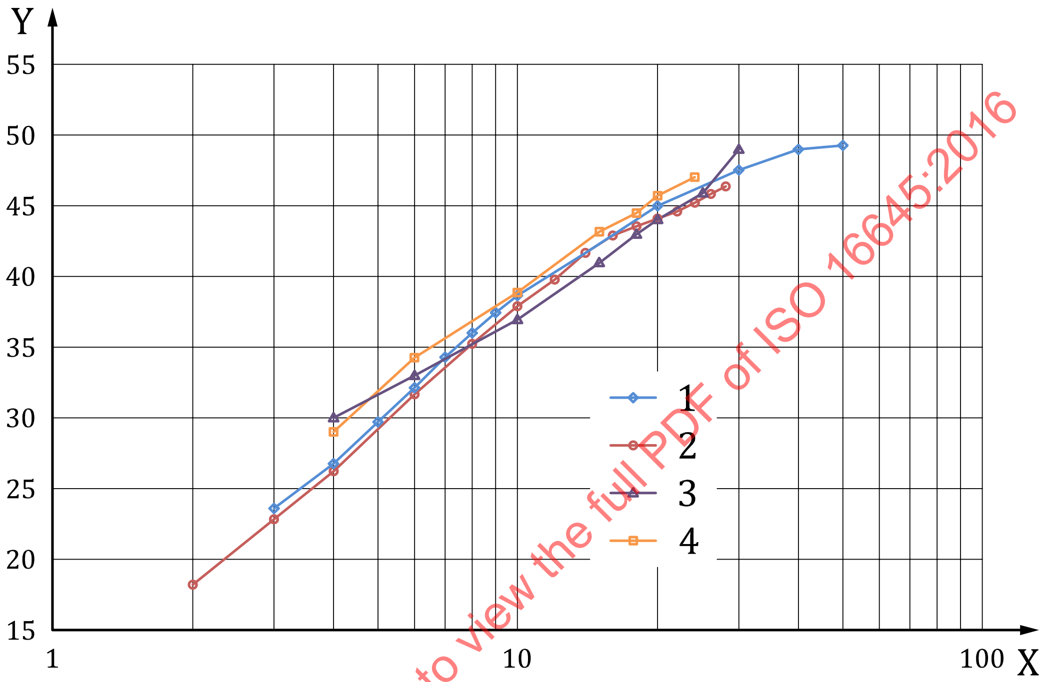
Here beam-on time is the primary beam-on time calculated as described above.

15 Indication, warning signs, interlocks

Requirements of IEC/TR 61859 for radiotherapy treatment room design shall be complied[37].

Annex A
(informative)

Tenth value layers for the most common shielding materials



Key

X maximum energy (MV)

Y primary photon *TVL* for concrete 2,35 (cm)

1 DIN Figure 3 (*TVLc*)

2 DFI Table 2 (*TVLc*), density scaled using data from 2,2 density concrete

3 NCRP 151 Table B.2 (*TVLe*)

4 IAEA SRS 47 Table 4 (*TVLc*)

Figure A.1 — Primary photon *TVL* values for ordinary concrete (density 2,35 g·cm^{-3})

Table A.1 — Primary photon *TVL* values for ordinary concrete (density 2,35 g·cm^{-3})

IAEA 47 (Table 4)		NCRP 151 (Table B.2)		DIN (Figure 3)		DFI (Table 2)	
E (MV)	*TVLc* (cm)	*E*[a] (MV)	*TVLe* (cm)	*E* (MV)	*TVLc* (cm)	*E* (MV)	*TVLc*[b] (cm)
				3	23,6	4	26,2
				4	26,8	6	31,6
4	29,0	4	30	5	29,7	8	35,3
6	34,3	6	33	6	32,1	10	37,9
10	38,9	10	37	7	34,3	12	39,8

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy is recommended.

[a] BJR 11 MV definition.

[b] Density scaled using data from density 2,2 g·cm^{-3} concrete.

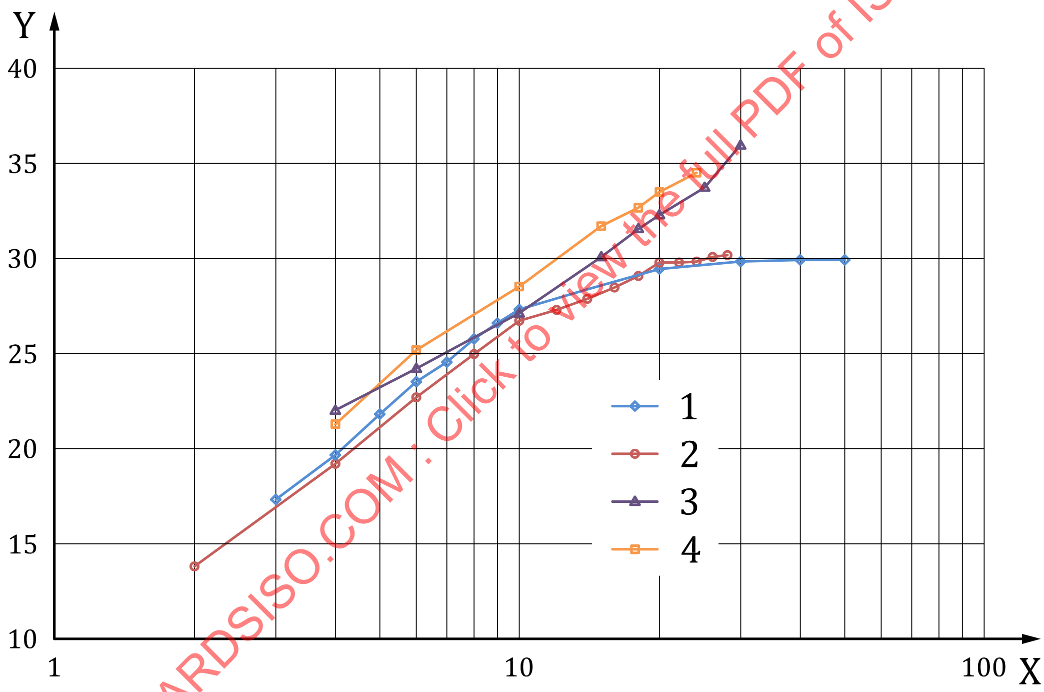
Table A.1 *(continued)*

IAEA 47 (Table 4)		NCRP 151 (Table B.2)		DIN (Figure 3)		DFI (Table 2)	
E (MV)	*TVL*c (cm)	*E*[a] (MV)	*TVL*e (cm)	*E* (MV)	*TVL*c (cm)	*E* (MV)	*TVL*c[b] (cm)
15	43,2	15	41	8	36,0	14	41,7
18	44,5	18	43	9	37,5	16	42,9
20	45,7	20	44	10	38,7	18	43,5
24	47,0	25	46	20	44,9	20	44,1
		30	49	30	47,5	22	44,7
				40	48,9	24	45,2
				50	49,2	26	45,8
						28	46,3

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy is recommended.

a BJR 11 MV definition.

b Density scaled using data from density 2,2 g·cm^{-3} concrete.



Key

X maximum energy (MV)

Y primary photon *TVL* for heavy concrete 3,2 (cm)

1 DIN Figure 3 (*TVL*c)

2 DFI Table 2 (*TVL*c)

3 NCRP 151 Table B.2 (*TVL*e), density scaled using Table A.1

4 IAEA SRS 47 Table 4 (*TVL*c), density scaled using Table A.1

Figure A.2 — Primary photon *TVL* values for high density concrete (density 3,2 g·cm^{-3})

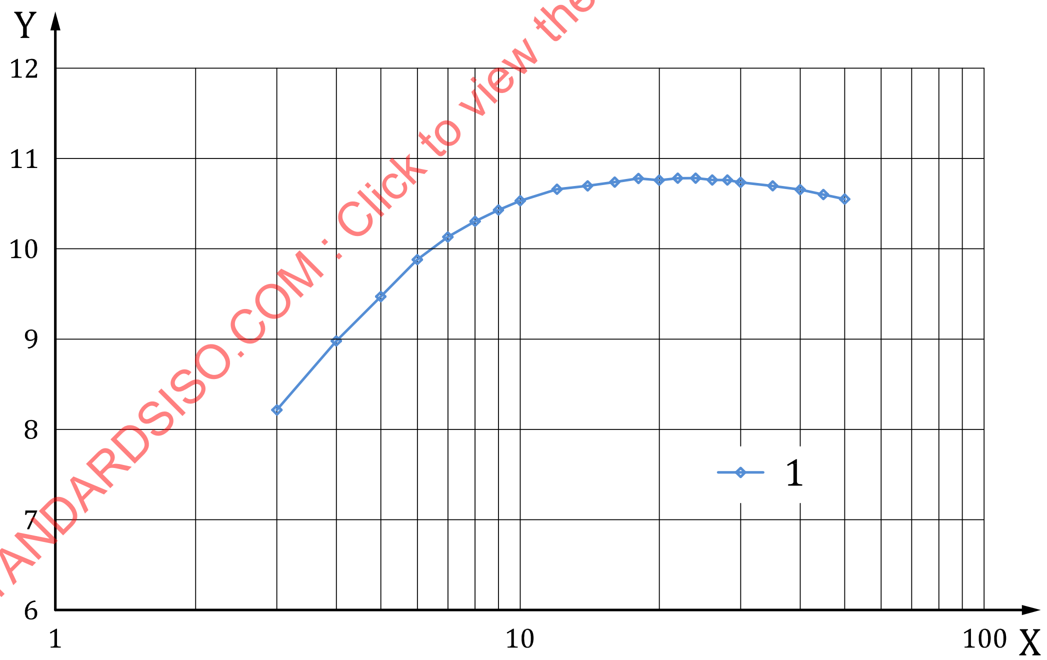
Table A.2 — Primary photon *TVL* values for high density concrete (density 3,2 g·cm^{-3})

IAEA 47 (Table 4)		NCRP 151 (Table B.2)		DIN (Figure 3)		DFI (Table 2)	
E (MV)	*TVLc*[b] (cm)	*E*[a] (MV)	*TVLe*[b] (cm)	E (MV)	*TVLc* (cm)	*E* (MV)	*TVLc* (cm])
				3	17,4	4	19,2
				4	19,6	6	22,7
4	21,3	4	22,0	5	21,8	8	25,0
6	25,2	6	24,2	6	23,5	10	26,7
10	28,6	10	27,2	7	24,6	12	27,3
15	31,7	15	30,1	8	25,8	14	27,9
18	32,7	18	31,6	9	26,7	16	28,5
20	33,6	20	32,3	10	27,4	18	29,1
24	34,5	25	33,8	20	29,5	20	29,7
		30	36,0	30	29,8	22	29,8
				40	29,9	24	29,9
				50	29,9	26	30,1
						28	30,2

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy is recommended.

[a] BJR 11 MV definition.

[b] Density scaled using Table A.1.



Key

X maximum energy (MV)

Y primary photon *TVL* for steel (cm)

1 DIN Figure 3 (*TVLc*)

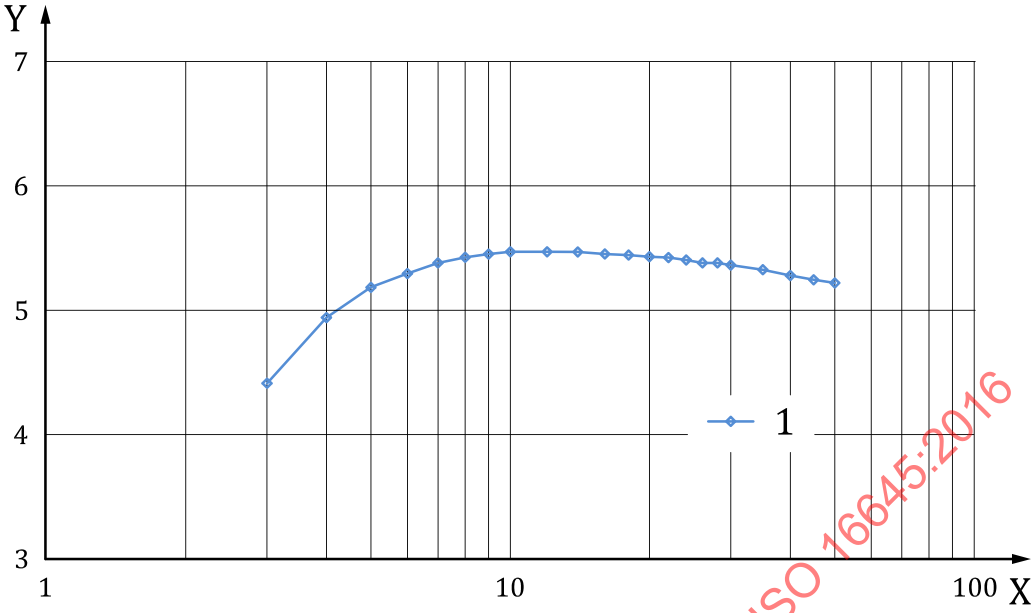
Figure A.3 — Primary photon *TVL* values for steel (density 7,8 g·cm^{-3})

Table A.3 — Primary photon *TVL* values for steel (density 7,8 g·cm−3)

IAEA 47 (Table 4)		NCRP 151 (Table B.2)		DIN (Figure 3)		DFI (Table 2)	
E (MV)	*TVL*c (cm)	*E*[a] (MV)	*TVL*e (cm)	*E* (MV)	*TVL*c (cm)	*E* (MV)	*TVL*c (cm)
4	9,1	4	9,9	3	8,2	4	9,0
6	9,8	6	10,0	4	9,0	6	9,8
10	10,5	10	11,0	5	9,5	8	10,3
15	10,8	15	11,0	6	9,9	10	10,5
18	11,1	18	11,0	7	10,1	12	10,6
20	11,1	20	11,0	8	10,3	14	10,6
24	10,7	25	11,0	9	10,4	16	10,7
		30	11,0	10	10,5	18	10,7
				12	10,7	20	10,8
				14	10,7	22	10,8
				16	10,7	24	10,8
				18	10,8	26	10,7
				20	10,8	28	10,7
				22	10,8		
				24	10,8		
				26	10,8		
				28	10,8		
				30	10,7		
				35	10,7		
				40	10,7		
				45	10,6		
				50	10,6		

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy is recommended.

[a] BJR 11 MV definition.



Key

X maximum energy (MV)

Y primary photon *TVL* for lead (cm)

1 DIN Figure 3 (*TVLc*)

Figure A.4 — Primary photon *TVL* values for lead (density 11,3 g·cm⁻³)

Table A.4 — Primary photon *TVL* values for lead (density 11,3 g·cm⁻³)

IAEA 47 (Table 4)		NCRP 151 (Table B.2)		DIN (Figure 3)		DFI (Table 2)	
E (MV)	*TVLc* (cm)	*E*[a] (MV)	*TVLe* (cm)	*E* (MV)	*TVLc* (cm)	*E* (MV)	*TVLc* (cm)
4	5,3	4	5,7	3	4,4	4	5,0
6	5,5	6	5,7	4	4,9	6	5,3
10	5,6	10	5,7	5	5,2	8	5,5
15	5,7	15	5,7	6	5,3	10	5,6
18	5,6	18	5,7	7	5,4	12	5,6
20	5,5	20	5,7	8	5,4	14	5,6
24	5,2	25	5,7	9	5,5	16	5,6
		30	5,7	10	5,5	18	5,6
				12	5,5	20	5,5
				14	5,5	22	5,4
				16	5,5	24	5,4
				18	5,4	26	5,4
				20	5,4	28	5,4
				22	5,4		
				24	5,4		
				26	5,4		
				28	5,4		

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy is recommended.

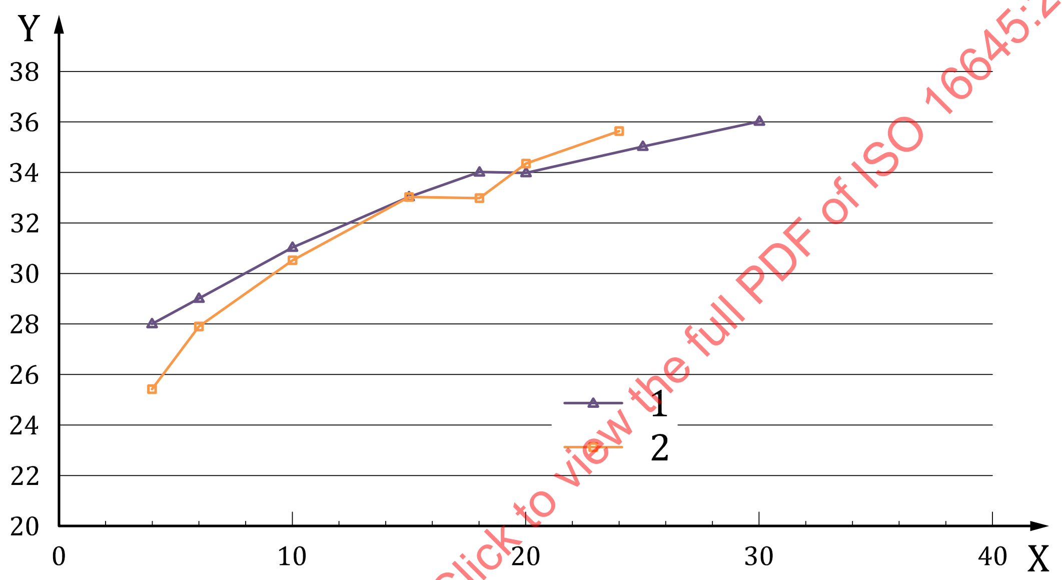
[a] BJR 11 MV definition.

Table A.4 *(continued)*

IAEA 47 (Table 4)		NCRP 151 (Table B.2)		DIN (Figure 3)		DFI (Table 2)	
E **(MV)**	***TVL*****c (cm)**	***E*****[a] (MV)**	***TVL*****e (cm)**	***E*** **(MV)**	***TVL*****c (cm)**	***E*** **(MV)**	***TVL*****c (cm)**
				30	5,4		
				35	5,3		
				40	5,3		
				45	5,2		
				50	5,2		

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy is recommended.

[a] BJR 11 MV definition.



Key

X maximum energy (MV)

Y X leakage *TVL* in concrete 2,35 (cm)

1 NCRP 151 Table B.7 (*TVL*e)

2 IAEA SRS 47 Table 4 (*TVL*c)

Figure A.5 — Leakage photon *TVL* values for ordinary concrete (density 2,35 g·cm^{-3})

Table A.5 — Leakage photon *TVL* values (cm) for ordinary concrete (density 2,35 g·cm^{-3}), steel and lead

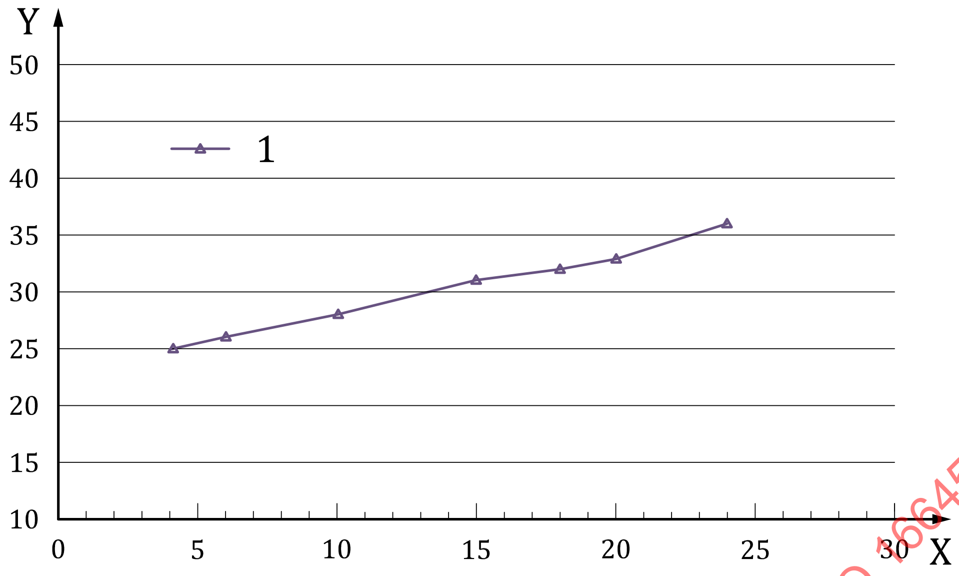
Leakage X (90°)				
	Ordinary concrete		**Steel**	**Lead**
	IAEA 47 (Table 4)	**NCRP151 (Table B.7)**	**IAEA 47 (Table 4)**	**IAEA 47 (Table 4)**
E **(MV)**	***TVL*****c**	***TVL*****e**	***TVL*****c**	***TVL*****c**
4	25,4	28	7,9	4,7
6	27,9	29	8	4,5
10	30,5	31	8,5	4,6
15	33	33	8,7	4,7

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy and a given material is recommended.

Table A.5 *(continued)*

Leakage X (90°)				
	Ordinary concrete		Steel	Lead
	IAEA 47 (Table 4)	NCRP151 (Table B.7)	IAEA 47 (Table 4)	IAEA 47 (Table 4)
E (MV)	*TVL*c	*TVL*e	*TVL*c	*TVL*c
18	33	34	8,7	4,7
20	34,3	34	8,8	4,9
24	35,6		8,9	5,1
25		35		
30		36		

NOTE If *TVL* data are provided by the national regulatory authority, then these shall be used in that nation. In other cases, for conservative calculations, the use of the largest *TVL* value for a given energy and a given material is recommended.

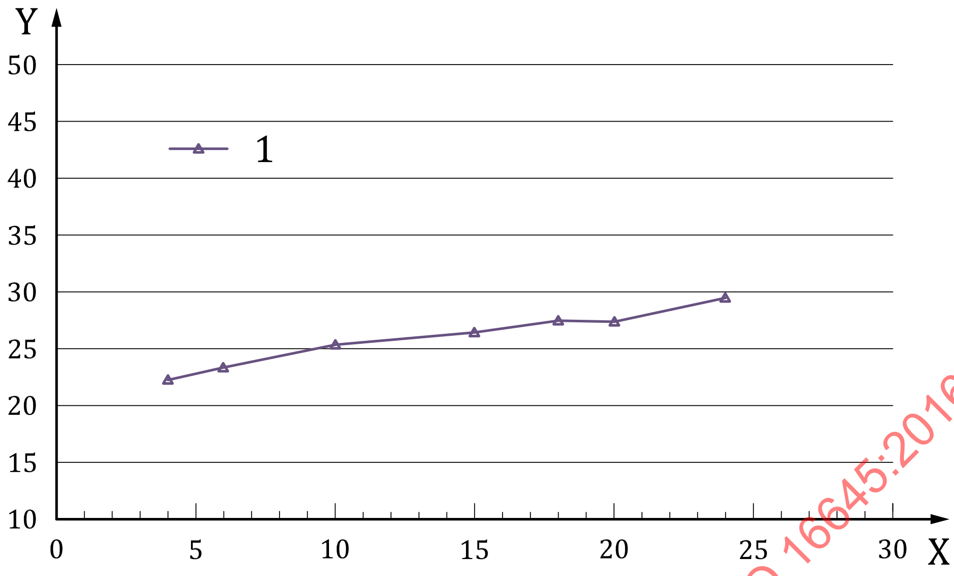


Key

X maximum energy (MV)

Y 30° X scattered *TVL* in concrete 2,35 (cm)

1 NCRP 151 Table B.5a

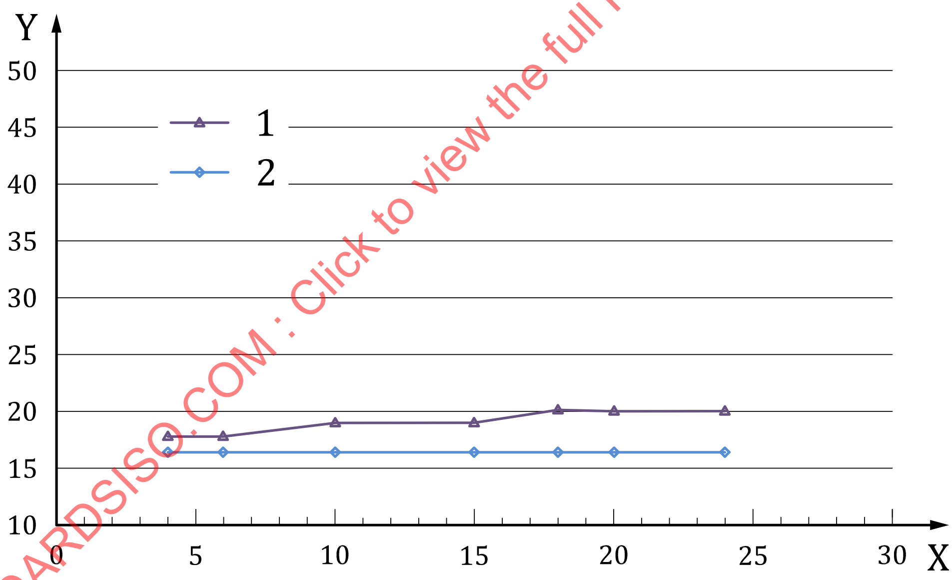


Key

X maximum energy (MV)

Y 45° X scattered *TVL* in concrete 2,35 (cm)

1 NCRP 151 Table B.5a



Key

X maximum energy (MV)

Y 90° X scattered *TVL* in concrete 2,35 (cm)

1 NCRP 151 Table B.5a

2 DIN 2012/DIF 2004 Tables 2/4

Figure A.6 — Patient scattered photon *TVL* values for ordinary concrete (density 2,35 g·cm^{-3}) and for different scattering angles