# Structural Shielding Design and Evaluation for Megavoltage x- and Gamma-ray Radiotherapy Facilities

This Report was prepared through a joint effort of NCRP Scientific Committee 46-13 on Design of Facilities for Medical Radiation Therapy and the American Association of Physicists in Medicine (AAPM) Task Group 57.

**James A. Deye**, *Chairman*
**James E. Rodgers, Vice Chair**
**Raymond K. Wu, Vice Chair**
**Peter J. Biggs**
**Patton H. McGinley**
**Richard C. McCall**
**Kenneth R. Kase**
**Marc Edwards**
**Robert O. Gorson**
**Jeffrey H. Kleck**
**Nisy E. Ipe**

This Report addresses the structural shielding design and evaluation for medical use of megavoltage x- and gamma-rays for radiotherapy and supersedes related material in NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use of X Rays and Gamma Rays of Energies Up to 10 MeV*, which was issued in September 1976.

The descriptive information in NCRP Report No. 49 unique to **x-ray therapy installations of less than 500 kV** (Section 6.2) **and brachytherapy is not included in this Report** and that information in NCRP Report No. 49 for those categories is still applicable.

Similarly **therapy simulators are not covered** in this report and the user is referred to the recent Report 147 for shielding of imaging facilities.

# New Issues since NCRP # 49

- New types of equipment with energies above 10 MV,

- Many new uses for radiotherapy equipment,

- Dual energy machines and new treatment techniques,

- Room designs without mazes,

- Varied shielding materials including composites,

- More published data on empirical methods.

**1) Introduction** (purposes, units, basic principles)

**2) Calculational Methods**

**3) Workload, Use Factor and Absorbed-Dose Rate Considerations**

**4) Structural Details**

**5) Special Considerations** (skyshine, side-scatter, groundshine, activation,ozone, tomotherapy, robotic arms,IORT, Co-60)

**6) Shielding Evaluations** (Surveys)

**7) Examples** (calculations)

Appendix A. Figures

Appendix B. Tables

Appendix C. Neutron Monitoring

Increased data for:

- neutron production
- capture gamma rays
- scatter fractions
- scatter albedo
- activation
- laminated barriers
- IMRT 'efficiency' factors

The quantity recommended in this Report for shielding design calculations when neutrons, as well as photons, are present is dose equivalent ($H$).
Dose equivalent is defined as the product of the quality factor for a particular type of ionizing radiation and the absorbed dose ($D$) [in gray (Gy)] from that type of radiation at a point in tissue (ICRU, 1993). The units of dose equivalent are J kg–1
with the special name sievert (Sv).

The recommended radiation protection quantity for the limitation of exposure to people from sources of radiation is effective dose ($E$), defined as the sum of the weighted equivalent doses to specific organs or tissues (*i.e.*, each equivalent dose is weighted by the corresponding tissue weighting factor for the organ or tissue) (NCRP, 1993).

In this Report, 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.

Shielding design goals ($P$) are practical values, for a single radiotherapy source or set of sources, that are evaluated at a reference point beyond a protective barrier. When used in conjunction with the conservatively safe assumptions in this Report, the shielding design goals will ensure that the respective annual values for $E$ recommended in NCRP Report No. 147 (NCRP, 2004)

The shielding design goals ($P$ values) in this Report apply only to new facilities and new construction and will not require retrofitting of existing facilities.

**Recommendation for Controlled Areas:**
**Shielding design goal (*P*) (in dose equivalent):**
**0.1 mSv week–1     (5 mSv y–1)**

**Recommendation for Uncontrolled Areas:**
**Shielding design goal (*P*) (in dose equivalent):**
**0.02 mSv week–1     (1 mSv y–1)**

$$B_{\mathrm{L}} = \frac{P\,d_{\mathrm{L}}^2}{10^{-3}\,W\,T}$$
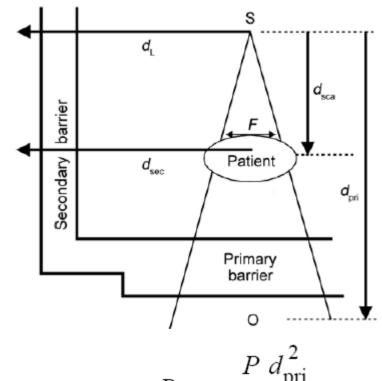
$$B_{\mathrm{ps}} = \frac{P}{a\,W\,T}\,d_{\mathrm{sca}}^2\,d_{\mathrm{sec}}^2\,\frac{400}{F}$$



$d_{\mathrm{sca}}$ = distance from the x-ray target to the patient or scattering surface (meters)

$d_{\mathrm{sec}}$ = distance from the scattering object to the point protected (meters)

$a$ = scatter fraction or fraction of the primary-beam absorbed dose that scatters from the patient at a particular angle (see Table B.4 in Appendix B)

$F$ = field area at mid-depth of the patient at 1 m (cm²)

$$B_{\mathrm{pri}} = \frac{P\,d_{\mathrm{pri}}^2}{WUT}$$

$U$ = use factor or fraction of the workload that the primary beam is directed at the barrier in question

$T$ = occupancy factor for the protected location or fraction of the workweek that a person is present beyond the barrier. This location is usually assumed to be 0.3 m beyond the barrier in question (see Table B.1 in Appendix B for recommended occupancy values)

$P$ = shielding design goal (expressed as dose equivalent) beyond the barrier and is usually given for a weekly time frame (Sv week$^{-1}$)

$d_{\mathrm{pri}}$ = distance from the x-ray target to the point protected (meters)

$W$ = workload or photon absorbed dose delivered at 1 m from the x-ray target per week (Gy week$^{-1}$)[6]

The required number (n) of TVLs is given by:

$$n = -\log(B_{\text{pri}})$$

And the barrier thickness ($t_{\text{barrier}}$) is given by:

$$t_{\text{barrier}} = TVL_1 + (n-1)\ TVL_e$$

Where the first and equilibrium TVLs are used to account for the spectral changes as the radiation penetrates the barrier

**workload** (W): The average absorbed dose of radiation produced by a source over a specified time (most often one week) at a specific location.

Gy wk$^{-1}$

| Low energy | High energy | | |
|---|---|---|---|
| 1000 | | | NCRP #49 |
| | 500 | | NCRP # 51 |
| < 350 | < 250 | | Kleck and Elsalim (1994) |
| 450 | 400 * | | Meckalakos et al (2004) <br> * dual energy machine |

$$WU]_{\text{pri}} = WU]_{\text{wall scat}}$$

$$= (W_{\text{conv}}\, U_{\text{conv}} + W_{\text{TBI}}\, U_{\text{TBI}} + W_{\text{IMRT}}\, U_{\text{IMRT}} + W_{\text{QA}}\, U_{\text{QA}} + ...)$$

$$W_{\text{L}} = W_{\text{conv}} + W_{\text{TBI}} + C_{\text{I}}\, W_{\text{IMRT}} + C_{\text{QA}}\, W_{\text{QA}} + ...$$

# The IMRT factor:

The ratio of the average monitor unit per unit prescribed absorbed dose needed for IMRT ($MU_{\textbf{IMRT}}$) and the monitor unit per unit absorbed dose for conventional treatment ($MU\text{conv}$)

$$C_{\text{I}} = \frac{MU_{\text{IMRT}}}{MU_{\text{conv}}} \qquad \left[ \; \sim 2\text{ - }10 \; \right]$$

$$MU_{\text{IMRT}} = \sum_{\text{i}} \frac{MU_{\text{i}}}{(D_{\text{pre}})_{\text{i}}}$$

**use factor (U):**

TABLE 3.1—*High-energy (dual x-ray mode) use-factor distribution at 90 and 45 degree gantry angle intervals.*[a]

| Angle Interval Center | U (%) |
|---|---|
| *90 degree interval* | |
| 0 degree (down) | 31.0 |
| 90 and 270 degrees | 21.3 (each) |
| 180 degrees (up) | 26.3 |
| *45 degree interval* | |
| 0 degree (down) | 25.6 |
| 45 and 315 degrees | 5.8 (each) |
| 90 and 270 degrees | 15.9 (each) |
| 135 and 225 degrees | 4.0 (each) |
| 180 degrees (up) | 23 |

[a]Rodgers, J.E. (2001). Personal communication (Georgetown University, Washington). Unpublished reanalysis of the survey data in Kleck and Elsalim (1994).
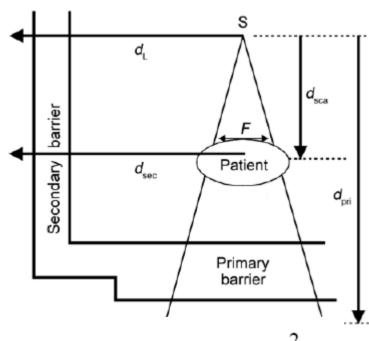
# occupancy factor (T):

TABLE B.1—*Suggested occupancy factors*[a] *(for use as a guide in planning shielding when other sources of occupancy data are not available).*

| Location | Occupancy Factor ($T$) |
|---|---|
| Full occupancy areas (areas occupied full-time by an individual), *e.g.*, administrative or clerical offices; treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, occupied space in nearby building | 1 |
| Adjacent treatment room, patient examination room adjacent to shielded vault | 1/2 |
| Corridors, employee lounges, staff rest rooms | 1/5 |
| Treatment vault doors[b] | 1/8 |
| Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, janitors' closets | 1/20 |
| Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop off areas (unattended), stairways, unattended elevators | 1/40 |

[a]When using a low occupancy factor for a room immediately adjacent to a therapy treatment vault, care *shall* be taken to also consider the areas further removed from the treatment room. The adjacent room may have a significantly higher occupancy factor and may therefore be more important in shielding design despite the larger distances involved.

[b]The occupancy factor for the area just outside a treatment vault door can often be assumed to be lower than the occupancy factor for the work space from which it opens.
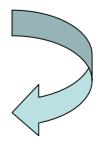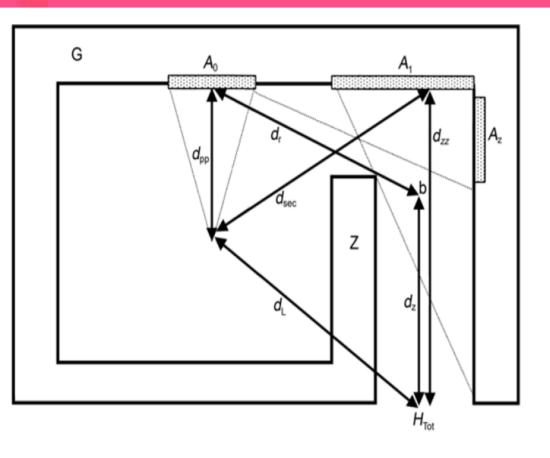
$$B_{pri} = \frac{P \, d^2_{pri}}{WUT}$$

$$\frac{W \; UT \; B_{pri}}{d^2} = H_{pri}$$

absorbed dose $\longrightarrow$ dose equivalent

**re-arranging any of the barrier transmission equations, one gets the dose equivalent beyond the barrier**

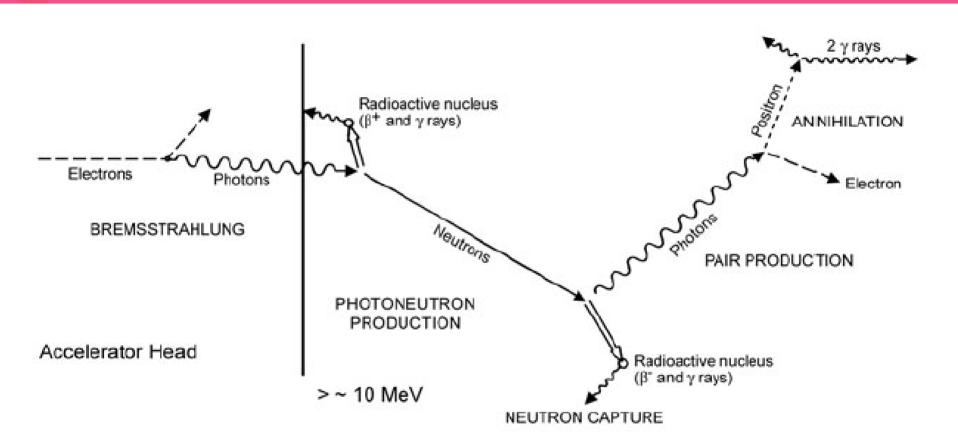$$H_S = \frac{W\,U_G\,\alpha_0\,A_0\,\alpha_z\,A_z}{(d_h\,d_r\,d_z)^2}$$

$$H_{LS} = \frac{L_f\,W_L\,U_G\,\alpha_1\,A_1}{(d_{sec}\,d_{zz})^2}$$

$$H_{ps} = \frac{a(\theta)\,W\,U_G\left(\dfrac{F}{400}\right)\alpha_1\,A_1}{(d_{sca}\,d_{sec}\,d_{zz})^2}$$

$$H_{LT} = \frac{L_f\,W_L\,U_G\,B}{d_L^2}$$

$$H_{Tot} = 2.64\left[f\,H_S + H_{LS} + H_{ps} + H_{LT}\right]$$

**Fig. 2.2.** Production of radiation types in a linear accelerator. Radiations to the right of the line have significant production cross sections in accelerators with photon energies above ~10 MeV.

| Vendor | Model | ENERGY (MV) | | $H_0$ | $Q_n$ | ref |
|---|---|---|---|---|---|---|
| | | Nominal | per TG 21 | mSv n / Gy x | neutrons per Gy x ( $\times 10^{12}$) | |
| Varian | 1800 | 18 | 16.6 | 1.02 - 1.6 | 1.22 | McGinley 2001 |
| | 1800 | 15 | Un | 0.79 - 1.3 | 0.76 | McGinley 2001 |
| | 1800 | 10 | Un | 0.04 | 0.06 | McGinley 2001 |
| | 2100C | 18 | | | 0.96 | Followill 2003 |
| | 2100C** | 18 | | | 0.87 | Followill 2003 |
| | 2300CD | 18 | | | 0.95 | Followill 2003 |
| | 2500 | 24 | | | 0.77 | Followill 2003 |
| Siemens | KD | 20 | 16.5 | 1.1 - 1.24 | 0.92 | McGinley 2001 |
| | MD | 15 | Un | 0.17 | Un | McGinley 2001 |
| | MD2 | 10 | | | 0.08 | Followill 2003 |
| | MD | 15 | | | 0.2 | Followill 2003 |
| | KD | 18 | | | 0.88 | Followill 2003 |
| | Primus* | 10 | | | 0.02 | Followill 2003 |
| | Primus* | 15 | | | 0.12 | Followill 2003 |
| | Primus** | 15 | | | 0.21 | Followill 2003 |
| Philips/Electa | SL25 | 25 | 22 | 2 | 2.37 | McGinley 2001 |
| | SL20 | 20 | 17 | 0.44 | 0.69 | McGinley 2001 |
| | SL20 | 18 | | | 0.46 | Fallowill 2003 |
| | SL25 | 18 | | | 0.46 | Fallowill 2003 |
| | SL25 | 25 | | | 1.44 | Fallowill 2003 |
| GE | Saturne41 | 12 | | | 0.24 | Fenn 1995 |
| | Saturne41 | 15 | | | 0.47 | Fenn 1995 |
| | Saturne43 | 18 | | | 1.50 | Fenn 1995 |
| | Saturne43 | 18 | | | 1.32 | Followill 2003 |
| | Saturne43 | 25 | | | 2.4 | Fenn 1995 |
| | Saturne43 | 18 | | | 1.50 | Fenn 1995 |
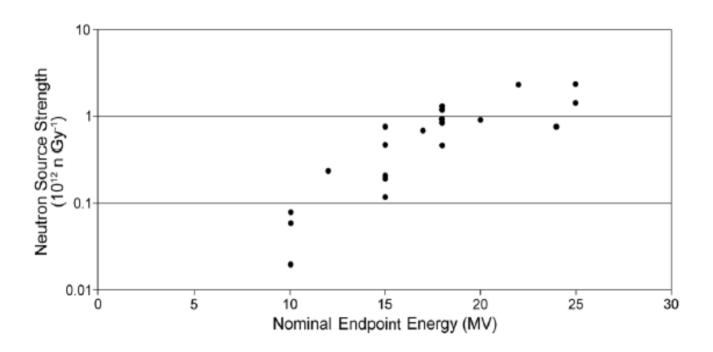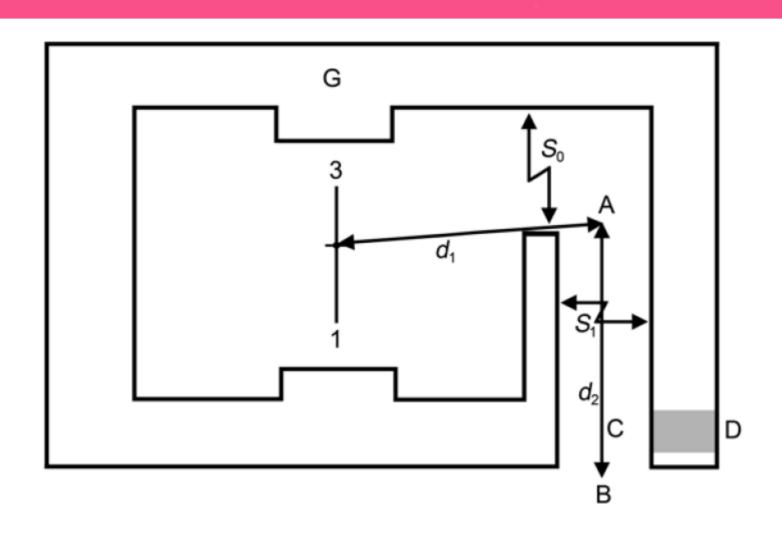
**Fig. B.1.** Graph of neutron source strength ($Q_n$) (neutrons per gray of x-ray absorbed dose at isocenter) as a function of nominal endpoint energy for data presented in Table B.9.

Weekly dose equivalent at the door due to neutron capture gamma rays:

$$H_{cg} = W_L \left\{ K\, \varphi_A\, 10^{-\left(\frac{d_2}{TVD}\right)} \right\}$$

$K$ = ratio of the neutron capture gamma-ray dose equivalent (sievert) to the total neutron fluence at Location A in Figure 2.8 (an average value of $6.9 \times 10^{-16}$ Sv m$^2$ per unit neutron fluence was found for K based on measurements carried out at 22 accelerator facilities)[10]

$\varphi_A$ = total neutron fluence (m$^{-2}$) at Location A per unit absorbed dose (gray) of x rays at the isocenter

$d_2$ = distance from Location A to the door (meters)

$TVD$ = tenth-value distance[11] having a value of ~5.4 m for x-ray beams in the range of 18 to 25 MV, and a value of ~3.9 m for 15 MV x-ray beams
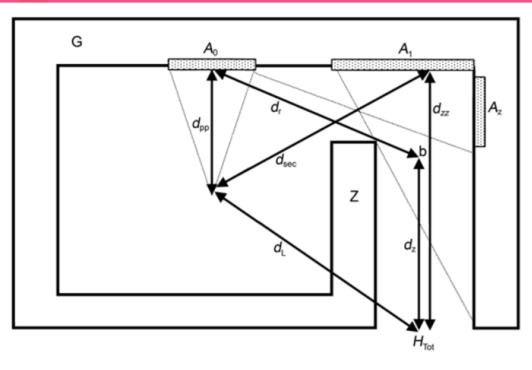
$$\varphi_A = \frac{\beta\, Q_n}{4\pi d_1^2} + \frac{5.4\, \beta\, Q_n}{2\pi S_r} + \frac{1.3\, Q_n}{2\pi S_r}$$

Weekly dose equivalent at the door due to neutrons:

$$H_n = W_L \left\{ 2.4 \times 10^{-15} \; \varphi_A \sqrt{\frac{S_0}{S_1}} \left[ 1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)} \right] \right\}$$

$S_0/S_1$ = ratio of the inner maze entrance cross-sectional area to the cross-sectional area along the maze (Figure 2.8)

$TVD$ = tenth-value distance (meters) that varies as the square root of the cross-sectional area along the maze $S_1$ ($m^2$), *i.e.*:
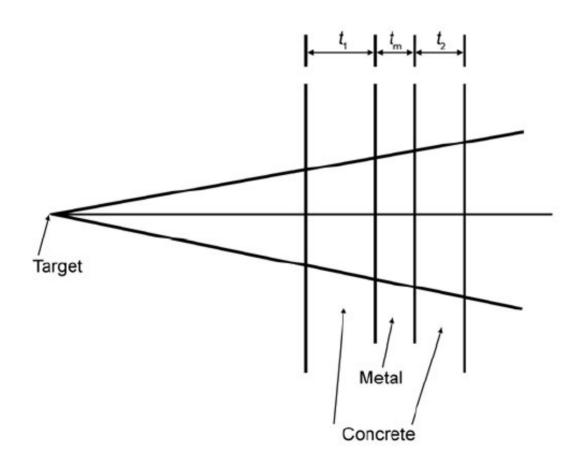
$$H_{\text{Tot}} = 2.64 \left[ f \, H_{\text{S}} + H_{\text{LS}} + H_{\text{ps}} + H_{\text{LT}} \right]$$

$$H_{\text{w}} = H_{\text{Tot}} + H_{\text{cg}} + H_{\text{n}}$$

$$H_{w} = H_{Tot} + H_{cg} + H_{n}$$

Also true for laminated barriers:

Where for <u>LOW ENERGY</u>:

$$H_{Tot} = H_{tr} = \frac{W \; UT \; B_1 B_m B_2}{d^2} \quad \text{and} \quad H_{cg} = H_n = 0$$

For <u>HIGH ENERGY</u>:

$$H_{Tot} + H_{cg} = 2.7 \left[ \frac{W \; UT \; B_1 B_m B_2}{d^2} \right]$$

$$H_n = \frac{D_o \, R \, F_{max}}{\left(\frac{t_m}{2} + t_2 + 0.3\right)} \left[ 10^{-\left(\frac{t_1}{TVL_x}\right)} \right] \left[ 10^{-\left(\frac{t_2}{TVL_n}\right)} \right]$$

McGinley (1992a) has reported on accelerators operated at 18 MV and measured neutron production coefficients ($R$) of 19 and 1.7 $\mu$Sv cGy$^{-1}$ m$^{-2}$ for lead and steel, respectively; while $R$ is decreased to around 3.5 $\mu$Sv cGy$^{-1}$ m$^{-2}$ for lead at 15 MV.

## 3.3 Time Averaged Dose-Equivalent Rates

When designing radiation shielding barriers it is usual to assume that the workload will be evenly distributed throughout the year. Therefore, it is reasonable to design a barrier to meet a weekly value equal to one-fiftieth of the annual shielding design goal (NCRP, 2004). However, further **scaling the shielding design goal to shorter intervals is not appropriate** and may be incompatible with the ALARA principle. Specifically, the **use of a measured instantaneous dose-equivalent rate (*IDR*), with the accelerator operating at maximum output, does not properly represent the true operating conditions and radiation environment** of the facility. It is more useful if the workload and 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 in this Report along with the measured or calculated *IDR*.

The TADR is the barrier attenuated dose-equivalent rate averaged over a specified time or period of operation. TADR is proportional to *IDR*, and depends on values of *W* and *U*. There are two periods of operation of particular interest to radiation protection, the week and the hour.

$$R_{\mathrm{W}} = \frac{IDR \ W_{\mathrm{pri}} \ U_{\mathrm{pri}}}{\dot{D}_{\mathrm{o}}}$$

$R_{\mathrm{w}}$ = TADR averaged over one week (Sv week$^{-1}$)

$IDR$ = instantaneous dose-equivalent rate (Sv h$^{-1}$) measured with the machine operating at the absorbed-dose output rate $\dot{D}_{\mathrm{o}}$. $IDR$ is specified at 30 cm beyond the penetrated barrier, and for accelerator measurements it is averaged over 20 to 60 s depending on the instrument response time and the pulse cycle of the accelerator

$\dot{D}_{\mathrm{o}}$ = absorbed-dose output rate at 1 m (Gy h$^{-1}$)

$W_{\mathrm{pri}}$ = primary-barrier weekly workload (Gy week$^{-1}$)

$U_{\mathrm{pri}}$ = use factor for the location

The U.S. Nuclear Regulatory Commission (NRC) specifies that the dose equivalent in any unrestricted area from external sources not exceed 0.02 mSv in-any-one-hour (NRC, 2005a). $R_h$ derives from the maximum number of patient treatments that could possibly be performed in-any-one-hour when the time for setup of the procedure is taken into account.

$$R_h = N_{max} \bar{H}_{pt}$$

$N_{max}$ = maximum number of patient treatments in-anyone-hour with due consideration to procedure set-up time

$H_{pt}$ = average dose equivalent per patient treatment at 30 cm beyond the penetrated barrier

## CONSERVATIVE ASSUMPTIONS:

> Attenuation of the primary beam by the patient is neglected. The patient typically attenuates the primary beam by 30 % or more.

> The calculations of recommended barrier thickness often assume perpendicular incidence of the radiation.

> Leakage radiation from radiotherapy equipment is assumed to be at the maximum value recommended

> The recommended occupancy factors for uncontrolled areas are conservatively high.

> The minimum distance to the occupied area from a shielded wall is assumed to be 0.3 m.

# CONSERVATIVE ASSUMPTIONS:

> when data are hard to estimate, such as in the design of accelerator facilities that will employ special procedures, safety factors are recommended

> The "two-source rule" (*i.e.*, the procedure when more than one source is involved) is applied whenever separate radiation components are combined to arrive at a barrier thickness. This has been shown to be a conservatively safe assumption since the tenth-value layer (*TVL*) and half-value layer (*HVL*) of the more penetrating radiation is always used.
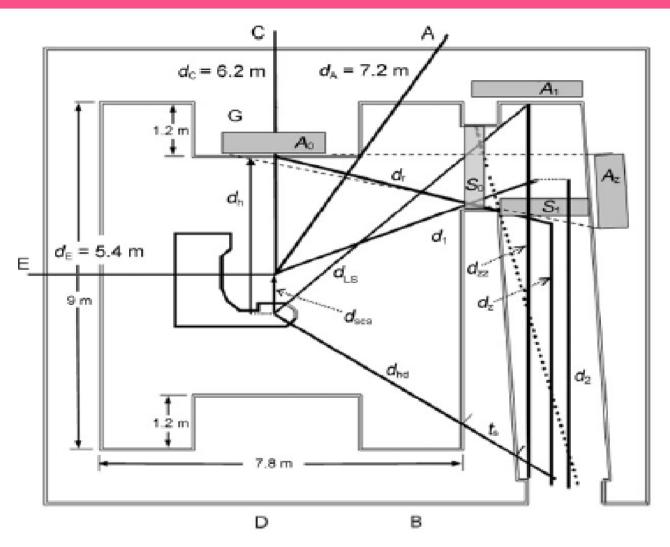
**Fig. 7.1.** Example for a dual-energy linear accelerator room with maze barrier.

# Appendix C

## Neutron Monitoring for Radiotherapy Facilities[20]

MEDICAL
PHYSICS
PUBLISHING

# SHIELDING
# TECHNIQUES

FOR
RADIATION ONCOLOGY FACILITIES

PATTON H. McGINLEY

REPORT NO. 75

# The Design of Radiotherapy Treatment Room Facilities

IPEM

THE INSTITUTE OF PHYSICS AND ENGINEERING IN MEDICINE