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Overview & Basis of Design for NCRP Report 151

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

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This Report was prepared through a joint effort of NCRP Scientific Committee 46-13 on Design of Facilities for Medical Radiation Therapy and AAPM Task Group 57.

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Learn

- Calculation methods
- W, U, T, IDR, TADR, R_W, R_h,
- Dose at maze door
- Neutron, capture gamma at door
- Laminated primary barrier

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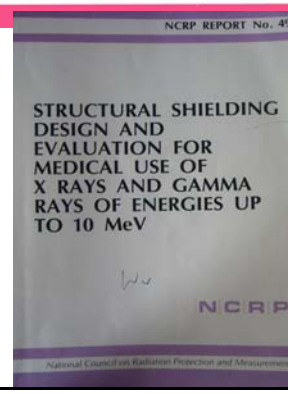

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This Report addresses the structural shielding design and evaluation for medical use of megavoltage x- and gamma-rays for radiotherapy and supersedes related material in NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use 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.

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New Issues since NCRP # 49

- New types of equipment,
- Some with energies above 10 MV,
- Many new uses for radiotherapy equipment,
- Dual energy machines,
- Room designs without mazes,
- Varied shielding materials including composites,
- More published data on empirical methods.
- Instantaneous Dose Rate interpretation problems

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Increased data for:

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

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Public Dose Limits
for continuous exposure

- Annual limit of 1 mSv ED for man-made sources excluding background and exposures from personal medical care
- Unless can be documented otherwise, per site limit is 0.25 mSv

NCRP 116 (1993)

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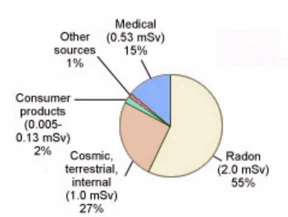
Public Dose Limits

0.25 mSv / yr per site

Annual background radiation doses in USA
3.6 mSv / yr



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Rewrite of NCRP 49
Came to a stop

Until NCRP issued
Statement 10

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- Marty Weinhous
- Don Frey
- Richard Morin
- Bob Dixon
- …

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NCRP

National Council on Radiation Protection and Measurements
7910 Woodmont Avenue / Bethesda, MD 20814

Recent Applications of the NCRP Public Dose Limit Recommendation for Ionizing Radiation

NCRP Statement No. 10, December 2004

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Design Dose Limit
for Public Area

- Statement 10 allows the annual Design Dose Limit to increase to 1 mSv
- But the conservative recommendations contained in NCRP Reports must be followed

NCRP Statement 10 (2004)

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Report No. 147 - Structural Shielding Design for Medical X-Ray Imaging Facilities (Jan 2005)

Report No. 148 - Radiation Protection in Veterinary Medicine

Report No. 151 - Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities (Dec 2005)

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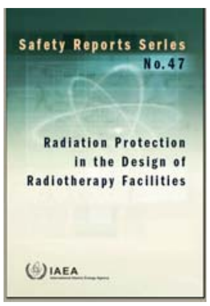

H.M. Morgan, UK
Raymond K. Wu, USA

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1) Introduction - purposes, units, basic principles
2) Calculational Methods
  Maze & Door – Melissa Martin
  Direct shielded door – Pat McGinley
3) Workload, Use Factor and Absorbed-Dose Rate Considerations
4) Structural Details – Dan Bourland, Peter Biggs
5) Special Considerations - Skyshine, side-scatter, groundshine – Tom Potts, Peter Biggs
  Tomotherapy – Melissa Martin
  CyberKnife – Jim Rodgers
6) Shielding Evaluations – Mark Towsley, Nisy Ipe
7) Examples (calculations) – Melissa et al
Appendix C. Neutron – Nisy Ipe

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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).

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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 this report are not exceeded.

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.

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TABLE 2. SUMMARY OF RECOMMENDED/LEGAL EFFECTIVE DOSE LIMITS AND DESIGN EFFECTIVE DOSE LIMITS

Dose limit	IAEA [1]	USA	United Kingdom
Occupational exposure dose limit	20 mSv per year averaged over 5 consecutive years and 50 mSv in any single year	Implied annual limit of 10 mSv, cumulative dose of age × 10 mSv, and 50 mSv in any single year [9]	20 mSv in a year or 100 mSv in 5 consecutive years and 50 mSv in any single year [7]
Design limit for occupational exposure		Fraction of 10 mSv annually [9]	6 mSv in a year [7] IDR is 7.5 μSv·h^{-1} [6]
Public dose limit	1 mSv in a year	Infrequently, 5 mSv annually, and continually, 1 mSv annually [9]	1 mSv in a year [7]
Design limit for public area		1 mSv annually [10] 20 μSv in any hour [8]	0.3 mSv in a year [7] IDR is <7.5 μSv·h^{-1} [6] TADR is <0.5 μSv·h^{-1}[6] TADR2000 <0.15 μSv·h^{-1}

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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})

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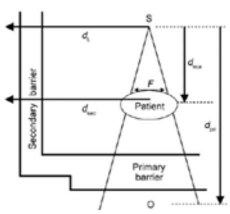
$$B_L = \frac{P\, d_L^2}{10^{-3}\, W\, T}$$

$$B_{ps} = \frac{P}{aWT}\, d_{sca}^2\, d_{sec}^2\, \frac{400}{F}$$



d_{sca} = distance from the x-ray target to the patient or scattering surface (meters)
d_{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 (cm^2)

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

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_{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]

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

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

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

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

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

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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) * dual energy machine

$$WU]_{pri} = WU]_{wall\ scat} = (W_{conv}\, U_{conv} + W_{TBI}\, U_{TBI} + W_{IMRT}\, U_{IMRT} + W_{QA}\, U_{QA} + \ldots)$$

$$W_L = W_{conv} + W_{TBI} + C_I\, W_{IMRT} + C_{QA}\, W_{QA} + \ldots$$

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The IMRT factor:

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})

$$C_I = \frac{MU_{IMRT}}{MU_{conv}} \quad [\sim 2 - 10]$$

$$MU_{IMRT} = \Sigma_i \frac{MU_i}{(D_{pre})_i}$$

C_I (CyberKnife) = 15

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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).

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occupancy factor (T):

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

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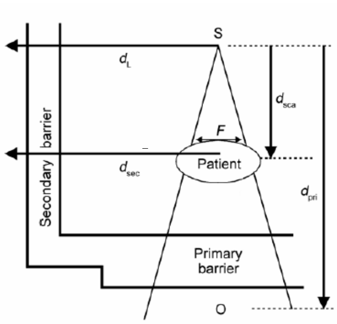

re-arranging any of the barrier transmission equations, one gets the dose equivalent beyond the barrier

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

$$H_{pri} = \frac{WUTB_{pri}}{d^2}$$

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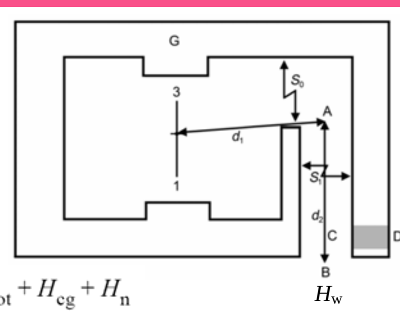
Dose at maze door



$$H_w = H_{Tot} + H_{cg} + H_n$$

Scatter & Leakage + Capture Gamma + Neutron

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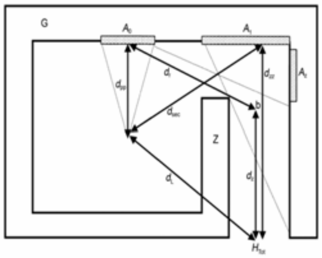

$$H_S = \frac{W\, U_G\, \alpha_0\, A_0\, \alpha_z\, A_z}{(d_h\, d_r\, d_z)^2}$$

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

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

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

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

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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 6.9×10^{-16} Sv m^2 per unit neutron fluence was found for K based on measurements carried out at 22 accelerator facilities)[10]

φ_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

$$\varphi_A = \frac{\beta\, Q_n}{4\pi d_1^2} + \frac{5.4\, \beta\, Q_n}{2\pi S_r} + \frac{1.3\, Q_n}{2\pi S_r}$$

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Vendor	Model	ENERGY (MV) Nominal	per TG 21	H_0 mSv n / Gy x	Q_n neutrons per Gy x ($\times 10^{12}$)	ref
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	Followill 2003
	SL25	18			0.46	Followill 2003
	SL25	25			1.44	Followill 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

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Weekly dose equivalent at the door due to neutrons:

Kersey's equation

$$H_n = W_L\, (H_0)\left(\frac{S_0}{S_1}\right)\left(\frac{d_0}{d_1}\right)^2 10^{-\left(\frac{d_2}{5}\right)}$$

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

H_0 at d_0 = 1.41 m tabulated in Table B.9

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Modified Kersey's equation:

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

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.*:

$$TVD = 2.06 \times \sqrt{S_1}$$

Wu and McGinley, 2003

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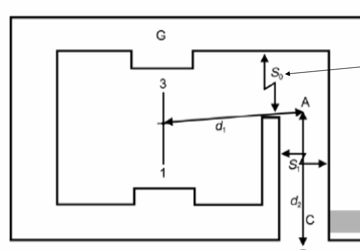
$$H_n = W_L \left\{ 2.4 \times 10^{-15}\, \varphi_A \sqrt{\frac{S_0}{S_1}} \left[1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)} \right] \right\}$$



Smaller the better

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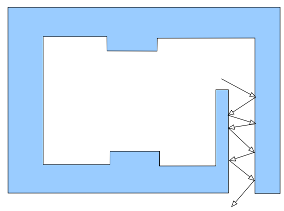
$$H_n = W_L \left\{ 2.4 \times 10^{-15} \varphi_A \sqrt{\frac{S_0}{S_1}} \left[1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{TVD}\right)} \right] \right\}$$

$$TVD = 2.06 \times \sqrt{S_1}$$



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Laminated Primary Barrier

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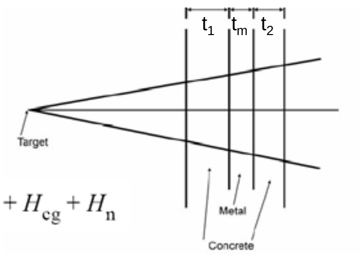

$$H_w = H_{Tot} + H_{cg} + H_n$$

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Where for LOW ENERGY:

$$H_{Tot} = \frac{WUTB_1B_mB_2}{d^2} \quad \text{and } H_{cg} = H_n = 0$$

For HIGH ENERGY:

$$H_{Tot} + H_{cg} = 2.7 \text{ x } \left[\frac{WUTB_1B_mB_2}{d^2} \right]$$

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

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neutron

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

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

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Instantaneous Dose Rate

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US Regulations

Nuclear Regulatory Commission

Many State Regulations

2 mR (20 μSv) in any one hour

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20 μSv (2 mR) in any one hour

This is not a measured doserate reading

not the same as 20 μSv / hr

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Measured IDR can be deceptive

Originally for Co-60 and the like

Linacs use pulsed beams

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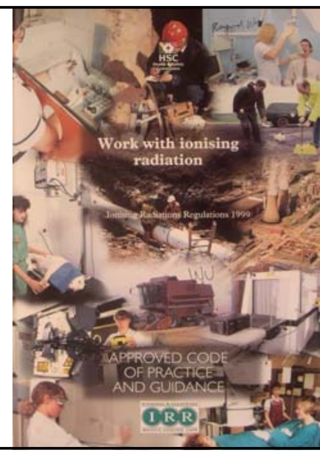
British Regulations

Approved Code of Practice – IRR (1999)

Public Area – where IDR ≤ 7.5 μSv / hr

As a result, user must reduce treatment doserate or increase shielding thickness



Health & Safety Commission

1999, UK

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20 μSv (2 mR) in any one hour

to assure adequate shielding if W is exceedingly low

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Instantaneous Dose Rate (IDR) in NCRP 151:

- Unit in Sv week^{-1}
- Measured value depending on the absorbed-dose output rate of machine
- Specified at 30 cm beyond the barrier
- U = 1
- For accelerator measurements it is averaged over 20 to 60 s depending on the instrument activation response time and the pulse cycle of the accelerator
  (In UK – averaged over 1 minute)

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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.

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Weekly TADR

$$R_W = \frac{IDR\ W_{pri}\ U_{pri}}{\dot{D}_o}$$

R_W = TADR averaged over 40-hr week (Sv week^{-1})
IDR = instantaneous dose-equivalent rate (Sv h^{-1}) measured at $\dot{D}_o$

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

If R_w x T is less than P, the barrier is adequate

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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.

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

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

$\overline{H}_{pt}$ = average dose equivalent per patient treatment at 30 cm beyond the penetrated barrier

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The in-any-hour R_h is related to R_w

$$R_h = \left(\frac{N_{max}}{\overline{N}_h}\right) \times \frac{R_W}{40}$$

N_{max} is the maximum number of patient treatments in any hour

$\overline{N}_h$ is the average number of patient treatments in an hour

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The in-any-hour R_h is related to R_w

$$R_h = \left(\frac{N_{max}}{\overline{N}_h}\right) \times \frac{R_w}{40}$$

R_h not to exceed 20 µSv-h^{-1} becomes the design goal if workload is exceedingly low

IDR not to exceed 20 µSv-h^{-1}

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NCRP 151 is just a report

How to translate this into regulations

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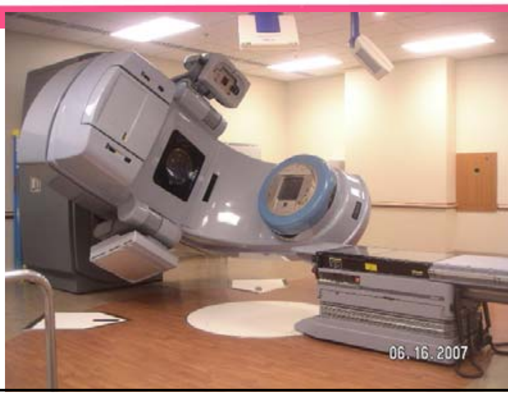

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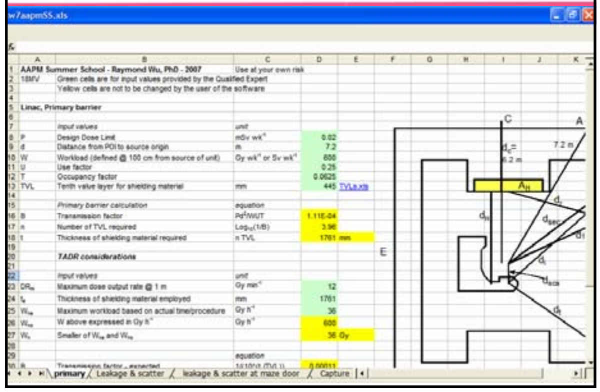

w7aapmSS.xls

	A	B	C	D	E
1	AAPM Summer School - Raymond Wu, PhD - 2007		Use at your own risk		
2	18MV	Green cells are for input values provided by the Qualified Expert			
3		Yellow cells are not to be changed by the user of the software			
4					
5	Linac, Primary barrier				
6					
7		*Input values*	unit		
8	P	Design Dose Limit	mSv wk^{-1}	0.02	
9	d	Distance from POI to source origin	m	7.2	
10	W	Workload (defined @ 100 cm from source of unit)	Gy wk^{-1} or Sv wk^{-1}	600	
11	U	Use factor		0.25	
12	T	Occupancy factor		0.0625	
13	TVL	Tenth value layer for shielding material	mm	445	TVLs.xls
14					
15		*Primary barrier calculation*	equation		
16	B	Transmission factor	Pd^2/WUT	1.11E-04	
17	n	Number of TVL required	$Log_{10}(1/B)$	3.96	
18	t	Thickness of shielding material required	n TVL	1761	mm
19					
20		***TADR considerations***			
21					
22		*Input values*	unit		
23	DR_o	Maximum dose output rate @ 1 m	Gy min^{-1}	12	
24	t_b	Thickness of shielding material employed	mm	1761	
25	W_{ap}	Maximum workload based on actual time/procedure	Gy h^{-1}	36	
26	W_{ws}	W above expressed in Gy h^{-1}	Gy h^{-1}	600	
27	W_s	Smaller of W_{ap} and W_{ws}		36	Gy
28					
29			equation		
30	B	Transmission factor - expected	[illegible]	0.00011	

primary / Leakage & scatter / leakage & scatter at maze door / Capture

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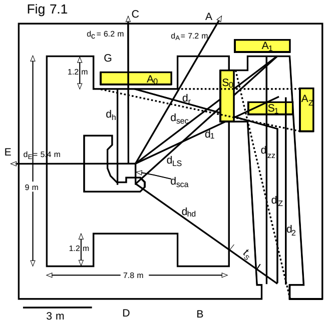
Fig 7.1



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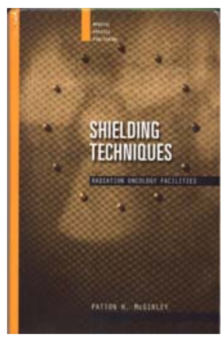

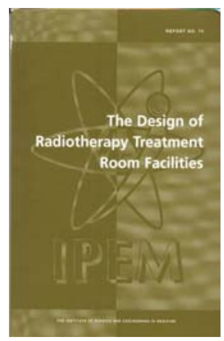

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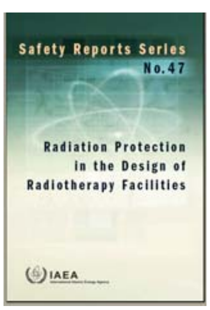

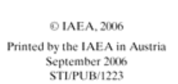

http://www-pub.iaea.org/MTCD/publications/PDF/Pub1257_web.pdf

Pub 1223

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Learned

- Calculation methods
- W, U, T, IDR, TADR, R_W, R_h,
- Dose at maze door
- Neutron, capture gamma at door
- Laminated primary barrier

THANK YOU

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British Regulations

Ionising Radiations Regulations

- Controlled Area - where workers are likely to get > 6 mSv / yr - e.g. inside treatment room
- Supervised Area - where people are likely to get > 1 mSv / yr - e.g. treatment console

IRR (1999)

British Regulations

Approved Code of Practice - IRR

- Supervised Area - where TADR is less than 7.5 μSv / hr (ave over 8 h), and IDR ≤ 500 μSv / hr (ave over 1 min)
- Public Area - where TADR is less than 0.5 μSv / hr, and IDR ≤ 7.5 μSv / hr

ACOP-IRR (2000)